TESTING OF CMS ENDCAP RPC AND DETERMINATION OF THE TOP QUARK MASS FROM HIGH $P_T$ JETS AT LHC

By
IJAZ AHMED

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External Examiner: 

Research Supervisor: Prof. Hafeez R. Hoorani

Examinng Committee:
Aut IJAZ AHMED

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DEDICATED TO

MY LOVING AMMAN JEE, ABBA JEE AND MY WIFE
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Abstract

Resistive Plate Chambers (RPCs) are gaseous parallel plate detectors with high volume resistivity of the order of $10^{10} \ \Omega \ cm$. Large area RPCs with 2 mm single gaps operated in avalanche mode provide above 98% efficiency and a time resolution of around 1 ns up to a flux of several $kHz/cm^2$.

A prototype RPC was tested in the presence of muon beam having a momentum of 200 $GeV/c$ from X5 beam at SPS (CERN) accelerator. The gamma irradiation facility was used to reproduce almost same background as during the operation of LHC. The real data of RPC was taken and then analyzed with different analysis programs. Due to the encouraging results of the RPCs, the production of endcap RPCs for CMS experiment on large scale was started.

The cosmic test facility was developed locally in order to test the assembled RPCs with cosmic ray muons. Main aim was the quality control and quality assurance of the RPCs. To perform this test the electronics hardware, e.g. Data Acquisition system, readout and trigger electronics were used. The Beam test and the Cosmic test results were in agreement with CMS requirements.

A promising method for the top mass reconstruction in CMS is presented. Basic idea is to produce highly boosted top quarks inside the two parts of the detector. Due to which the decay angles would be very close to the top flight direction and therefore the mass of the calorimetric objects (clusters, cells, seeds) in a large cone around top direction is correlated with the real top mass. This analysis technique is sensitive to the energy deposited by the underlying event, pileup and calorimeter noise.

The Standard Model of particle physics predicts that the top quark will decay into a bottom quark and a $W$ boson approximately 100% of the time. The bottom quark will hadronize and produce a jet of hadronic particles. The $W$ bosons can decay either into a
charged lepton and a neutrino or a pair of quarks. This dissertation focuses on the top quark ($t\bar{t}$) events in which one $W$ decays hadronically and the other decays leptonically.

The method uses a special Monte Carlo sub-sample of the single lepton plus jet events where the top has high transverse momentum ($P_T > 200 \text{ GeV}/c$), available with acceptable statistics at LHC due to the high $t\bar{t}$ production rate. From studies made with both the fast and full detector simulation programs, it is shown that an error of 0.9 $\text{ GeV}/c^2$ in the mean of the peak translates to an error of 1.145 $\text{ GeV}/c^2$ on the measured top quark mass ($m_{jjb}$) after calibration, while an accuracy of 1-1.5% in the reconstructed top quark mass from clusters $m_{clus}^{top}$ can be achieved, using data at low luminosity of LHC ($10\text{ fb}^{-1}$).
Certificate

It is certified that the work contained in this dissertation was carried out by Ijaz Ahmed under my supervision.

Supervisor

(Prof. Dr. Hafeez R. Hoorani)
National Centre for Physics
Quaid-i-Azam University
Islamabad 45320

Submitted through:

(Prof. Dr. Pervez A. Hoodbhoy)
Chairman
Department of Physics
Quaid-i-Azam University
Islamabad 45320
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Chapter 1

The Large Hadron Collider

The study of high-energy physics fills a peculiar niche in the endeavor to expand the limits of human knowledge. The aim is to understand the workings of the universe at the most fundamental level. That is, one desires to identify those constituents of matter which may not be subdivided any further and to describe completely all of the interactions between them. The study proceeds by probing the structure of matter progressively at higher scales of energy.

High-energy physics deals basically with the study of the ultimate constituents of matter and the nature of the interactions between them. Experimental research in this field of science is carried out with giant particle accelerators and their associated detection equipment. High energies are necessary for two reasons; first, to localize the investigations to the very small scales of distance associated with the elementary constituents, one requires the radiations of smallest possible wavelength and highest possible energy; secondly, many of the fundamental constituents have large masses and require correspondingly high energies for their creation and study.

In the quest for higher interaction energies, the CERN (The European Laboratory for Particle Physics) Laboratory has played a leading role in developing colliding beam machines. First were the Intersecting Storage Rings (ISR) proton-proton collider commissioned in 1971, and then Proton Synchrotron (PS) in 1973 discovered the weak neutral currents by the Gargamelle experiment at CERN [1]. The proton-antiproton collider at the Super Proton Synchrotron (SPS), which came on the air in 1981 and produced the massive W and Z particles two years later, confirming the unified theory of electromagnetic and weak forces [2][3][4]. Then at Large Electron-Positron Collider (LEP) [5], where measurements unsurpassed in quantity and quality are testing our best description of sub-atomic Nature, the Standard Model, to a fraction of 1% soon to reach one part in a thousand. By 1996, the LEP energy was doubled to 90 GeV per beam in LEPII, opening up an important new discovery domain. More high precision results are expected in abundance at Large Hadron Collider (LHC), which will substantially improve our present understanding.
1.0.1 Design of the LHC

The LHC (Large Hadron Collider) is an accelerator whose circumference is 27 Km and it lies an average of 100 m below ground, between Lake Geneva and the Jura mountain, which will bring protons into head-on collision at higher energies (14 TeV) than ever achieved before to allow scientists to penetrate still further into the structure of matter and recreate the conditions prevailing in the Universe just $10^{-12}$ seconds after the “Big Bang” when the temperature was $10^{16}$ kelvin. The accelerator will produce not only higher energy but also a higher luminosity - the probability of collision between particles - than has been achieved before and it will reveal the behaviour of fundamental particles of matter which has never been studied.

The LEP collider has been removed after October 2000 when it had completed its mission of improving our understanding of the Standard Model, which is, so far, our best description of sub-atomic Nature. All evidence indicates that new physics, and answers to some of the most profound questions of our time, lie at energies around 1 TeV (1 TeV = 1,000 GeV).

The machine parameters relevant for the operation of CMS are listed in Table 1.1. The LHC machine comprises 1232 dipole magnets, with Radio Frequency (RF) cavities providing a “kick” that results in an increase in the proton energy of 0.5 MeV/turn. The underground LHC tunnel is shown in Fig. 1.1.

To extend the reach of new physics to as high mass scales as possible and to increase the production cross section of the processes of interest, it is important to increase the centre of mass energy as much as possible. However high energy beams need high magnetic bending fields. The maximum achievable energy at LHC is constrained by the magnetic field needed to keep beams circulating

$$B = \frac{p}{0.3 \rho},$$

(1.0.1)

where $p$ is the particle momentum and $\rho$ is the orbit radius [6]. The requirement that LHC has to fit inside the existing LEP tunnel fixes $\rho = 4.3$ Km, therefore, if $p$ is chosen equal to 7 TeV, then from Eq. 1.0.1, $B = 5.4$ T is obtained. However in the LHC tunnel protons are not bended continuously but the 1232 superconducting magnets act only in the eight curvilinear segments so they are forced to work at 8.3 T, the highest operational magnetic field for affordable superconducting magnets. LHC magnet coils are 14 metres long and narrow, the inner diameter being 56 mm, so two superconducting magnetic channels will be housed in the same yoke and cryostat (a unique configuration which saves space). LHC magnet coils are made of copper-clad niobium-titanium cables and will be operated at 1.9 K above absolute zero. This unusually low limit puts new demands on cable quality and coil assembly. A picture of an LHC magnet is shown in Fig. 1.2.

Magnets are kept cold with superfluid helium, which has extremely efficient heat transfer properties, allowing kilowatts of refrigeration to be transported over more than a kilometre with a temperature increase of less than 0.1 K. Friction can create normally-conducting hot-spots which quench the magnet out of its cold, superconducting state. A quench in any of the 1232 LHC superconducting magnets will disrupt machine operation for several hours.

With the beam energy limited, another way to increase the rate of events with interesting
Figure 1.1: The LHC in the underground with a circumference of about 26.7 km. The caverns for the new experiments CMS and ATLAS are under construction at points 5 and 1 respectively. The LHC experiment ALICE replaces the LEP experiment L3 at point 2 and the experiment LHCb replaces the LEP experiment DELPHI at point 8. The cavern of the LEP experiment ALEPH at point 4 will be used to house the RF systems and at point 6 (LEP experiment OPAL) the beam dump will be installed. In the foreground around the experiment ATLAS and 72 m higher the SPS which delivers the proton beams to the LHC is visible.
Table 1.1: Summary of important LHC design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$10^{34}$ $cm^{-2}s^{-1}$</td>
</tr>
<tr>
<td>Energy per beam</td>
<td>7.0 TeV</td>
</tr>
<tr>
<td>Dipole filed</td>
<td>8.33 T</td>
</tr>
<tr>
<td>Coil aperture</td>
<td>56 mm</td>
</tr>
<tr>
<td>Distance between aperture</td>
<td>194 mm</td>
</tr>
<tr>
<td>Injection energy</td>
<td>450 GeV</td>
</tr>
<tr>
<td>Circulating current</td>
<td>0.56 A</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>7.48 m</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>24.95 ns</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>2835</td>
</tr>
<tr>
<td>Stored beam energy</td>
<td>350 MJ</td>
</tr>
<tr>
<td>Normalized transverse emittance</td>
<td>3.75 $\mu$m</td>
</tr>
<tr>
<td>r.m.s bunch length</td>
<td>0.075 m</td>
</tr>
<tr>
<td>Full crossing angle</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>Beam lifetime</td>
<td>22 h</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>10 h</td>
</tr>
<tr>
<td>Energy loss per beam</td>
<td>7 KeV</td>
</tr>
<tr>
<td>Critical photon energy</td>
<td>44.1 eV</td>
</tr>
<tr>
<td>Total radiated power per beam</td>
<td>3.8 kW</td>
</tr>
</tbody>
</table>

Physics is to raise the luminosity. The event rate of a specific process $x$ is given as

$$N_x = \sigma_x L,$$  \hspace{1cm} (1.0.2)

where $L$ is the luminosity and $\sigma_x$ is the cross section of the process. The luminosity for a collider is

$$L = \frac{\gamma f k_B N_p^2 \epsilon_n}{4\pi \beta^*} F,$$  \hspace{1cm} (1.0.3)

where $\gamma$ is the Lorentz factor, $f$ is the revolution frequency, $k_B$ is the number of bunches, $N_p$ is the number of protons/bunch, $\epsilon_n$ is the normalized transverse emittance (with a design value of 3.75 $\mu$m), $\beta^*$ is the betatron function at the Interaction Point (IP), and $F$ is the reduction factor due to the crossing angle [7]. The nominal energy of each proton beam is 7 TeV. The design luminosity of $L = 10^{34}$ $cm^{-2}s^{-1}$ leads to around 1 billion proton-proton interactions per second. Fig. 1.3 shows the collision signature of the proton-proton bunches having opposite momenta with 14 TeV centre of mass energy.

For the LHC the bunch crossing time will be 25 ns corresponding to a bunch separation of 7.5 m. The transverse dimensions of the beam at the interaction point can be squeezed down to 15 $\mu$m. To be able to fill new bunches into the LHC and operate the beam dump it is necessary to order the proton bunches in trains followed by some empty bunches, which
Figure 1.2: Picture of a superconducting magnet being installed in the LHC tunnel, the two channels for the proton beams are clearly visible. LHC will use about 1200 dipole magnets 14.2 m long which will reach a field strength of 8.3 Tesla.

Figure 1.3: Collision between two proton beams
allows total 2835 of the 3557 available spaces with 25 ns separation. The only remaining way to increase the luminosity is to increase the number of protons in each bunch, which is however limited by electromagnetic forces between the colliding bunches. The number of observed events for a specific process \( x \) is given as

\[
n_x = L \sigma_x \epsilon,
\]

(1.0.4)

with \( \sigma_x \) the cross section of the process, \( \epsilon \) the detection efficiency and \( L \) the integrated luminosity

\[
L = \int \mathcal{L} dt
\]

(1.0.5)

or the integral of the luminosity during the effective time the machine is running. A standard year at the LHC is supposed to give a total running time of \( t = 10^7 \) s.

In the start-up period (the first six months of LHC operation) the instantaneous luminosity should be increased starting from the value of \( 2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1} \). In the very first period only 43 equidistant bunches will circulate to perform a deep test of the accelerator. Then the number of bunches and the luminosity will be gradually increased up to \( 0.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \).

In these first six months an integrated luminosity of \( 0.4 \text{ fb}^{-1} \) of data should be collected to calibrate the detectors with physics samples (\( Z \rightarrow l^+l^-, \mu\mu, ... \)).

After a shut-down of six months due to hardware improvement, LHC should work, in the next three years, at \( L = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \), the so called low luminosity regime. Then luminosity will be finally increased to \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) for the high luminosity data taking period. If LHC is assumed fully efficient, \( 20 \text{ fb}^{-1} \) per year during the three years at low luminosity for a total of \( 60 \text{ fb}^{-1} \) should be collected. Nominally the period of high luminosity data taking will last at least five years for a total of \( 500 \text{ fb}^{-1} \).

The high requirement on luminosity is the reason for the choice of a proton-proton collider. While a proton-antiproton collider has the advantage that both counter-rotating beams can be kept in the same beam pipe, producing the enormous amounts of antiprotons required for the high luminosity is not realistic and would be more expensive than the proton-proton solution with separate beam pipes. The charge asymmetry introduced with a proton-proton collider is not a serious problem for the physics analysis.

In the collisions at high transferred momentum, the real interaction center of mass energy \( \sqrt{s} \) is smaller than the center of mass energy of the machine \( \sqrt{\hat{s}} \)

\[
\sqrt{\hat{s}} = \sqrt{x_a x_b s},
\]

(1.0.6)

where \( x_a \) and \( x_b \) are the fractions of the proton momentum carried by the colliding partons inside the protons. If \( x_a \approx x_b \approx x \), then

\[
\sqrt{\hat{s}} = x \sqrt{s}.
\]

(1.0.7)

So the production of a 100 GeV/c^2 mass particle needs two partons carrying 1% of the proton momentum, while a particle with a mass of 5 TeV/c^2 can be produced only with an interaction between partons with \( x \approx 36\% \).

The dynamics described above does not have a motionless centre of mass in the LHC reference
frame, but on the average there is a boost along the direction of the two beams. For this reason, boost invariant quantities have to be defined to characterize the event. The more important are the transverse momentum $p_T$, defined as the magnitude of the projection of the momentum $p$ on a plane perpendicular to the beam axis, and the rapidity

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \tanh^{-1} \left( \frac{p_z}{E} \right),$$  \hspace{1cm} (1.0.8)$$

with $E$ energy and $p_z$ projection of the momentum of the particle along the beam axis [8]. Under a boost in the $z$ direction with velocity $\beta$, $y \rightarrow y - \tanh^{-1} \beta$ and hence the rapidity distribution $dN/dy$ is invariant. In the ultrarelativistic approximation $m/|\vec{p}| \ll 1$, the rapidity may be expanded to obtain

$$y = -\ln[\tan \left( \frac{\theta}{2} \right)] \equiv \eta,$$  \hspace{1cm} (1.0.9)$$

with $\cos \theta = p_z/|\vec{p}|$. Eq. 1.0.9 defines the pseudorapidity $\eta$, approximately equal to $y$ if $m/|\vec{p}| \ll 1$ and $\theta \gg 1/\gamma$ and in any case measurable when either the mass or the momentum of a particle are unknown.

The number of simultaneous proton-proton inelastic interactions which take place in each bunch crossing is given by a Poisson distribution with an average of [9]

$$< n > = \frac{L \sigma_{pp}^{\text{tot}} \cdot t}{f}$$  \hspace{1cm} (1.0.10)$$

The total proton-proton cross section as a function of the centre of mass energy gives an average of 25 simultaneous interactions ($\sim 5$ at low luminosity) in each event with an expected value of the total proton-proton cross section $\sigma_{pp}^{\text{tot}} \sim 80 \text{ mb}$ (diffractive events are also included).

Out of all these interactions, those with production of high mass objects such as vector bosons or Higgs particles are often called physics events. The term is misleading since all interactions of course contain physics but the dominating QCD-jet processes with low energy transfer are believed to contain little unknown physics and are thus regarded as background without new physics information. The difference between the total cross section and the cross section of the interesting physics processes is in many cases greater than ten orders of magnitude. The absolute majority of interactions, called minimum bias events, are fusion processes of gluons or quarks with a small energy transfer resulting in events with many hadrons of low momentum and nothing else. The distributions of the minimum bias events as a function of $\eta$ and $p_T$ is shown in Fig. 1.4. It is important to notice that the particle distribution is flat in the region $|\eta| < 6$ and that the average $p_T$ of the particle is about 0.5 GeV/c. Every time a high $p_T$ collision occurs, it is then shadowed on average by 25 low $p_T$ events which are called pile-up. Pile-up is one of the serious difficulties at LHC and has a big impact on the detector design. Requirements for a detector to be operated at LHC are the fast response in order to avoid superpositions between collisions belonging to different bunches (typical response times are between $20-50 \text{ ns}$), and a high granularity to cope with the 20 events and 1 000 tracks produced on average per bunch crossing.
In addition to this a detector installed at LHC must be radiation hard, to operate in such a high particle fluence. The fluence near the interaction point, integrated over 10 years of data taking, is about $10^{17}$ neutrons/cm$^2$ or about $10^7$ Gy. This flux can damage the detector components and lead to a signal reduction or in the worst case to the detector breaking. Every single component of the detector must pass stringent quality controls, as described in the next chapter.

In LHC the energy available in the collisions between the constituents of the protons (the quarks and gluons) will reach the TeV range, that is about 10 times that of LEP and the Fermilab Tevatron. In order to maintain an equally effective physics programme at a higher energy $E$ the luminosity of a collider (a quantity proportional to the number of collisions per second) should increase in proportion to $E^2$. This is because the De Broglie wavelength associated to a particle decreases like $1/E$ and hence the cross section of the particle decreases like $1/E^2$. Whereas in past and present colliders the luminosity culminates around $\mathcal{L} = 10^{32} cm^{-2}s^{-1}$, in the LHC it will reach $\mathcal{L} = 10^{34} cm^{-2}s^{-1}$. This will be achieved by filling each of the two rings with 2835 bunches of $10^{11}$ particles each. The resulting large beam current ($I_b = 0.53$ A) is a particular challenge in a machine made of delicate superconducting magnets operating at cryogenic temperatures.

### 1.1 Experiments at LHC

The LHC consists of four main detectors. The CMS detector will be described in more detail in the following chapter. The ATLAS detector will have the same goals as the CMS detector. The ALICE detector would be for heavy ion collisions studies when the LHC accelerator ring is used to accelerate heavy ions of Pb. The LHCb will operate for the study of the B-physics and
B hadrons properties. A short introduction of the rest of these experiments are described below:

1. Compact Muon Solenoid (CMS)
2. A Toroidal LHC Apparatus (ATLAS)
3. A Large Ion Collider Experiment (ALICE)
4. The Large Hadron Collider Beauty Experiment (LHCb)

The complete experimental set-up of LHC and the four detectors is shown in Fig. 1.5.

1.1.1 ATLAS experiment

The ATLAS geometry is the familiar tracker-calorimeter-muon chamber onion skin configuration as can be seen in Fig. 1.6. The overall detector layout is largely determined by the configuration magnetic fields, which are based on an inner thin super-conducting magnet surrounding the inner detector cavity, and large super-conducting air core toroids consisting of independent coils arranged as eight fold symmetry outside the calorimeters. This magnet configuration makes it possible to build a high resolution, large-acceptance and robust stand-alone muon spectrometer with minimal constraints on the calorimeters and inner detector. The inner detector is contained within a cylinder of 6.80 m full length and 1.15 m radius and is surrounded by a solenoid providing a 2 T magnetic field parallel to the beam axis. High performance pattern recognition, momentum and vertex measurements, and enhanced
electron identification are achieved by combining discrete high-resolution pixel and strip detectors in the part of the tracking volume closest to the interaction point, with continuous tracking straw-tubes with transition radiation capability in the outer part.

The calorimeter system surrounds the inner detector cavity. It is composed of an inner electromagnetic and an outer hadronic component. A high-granularity lead/Liquid Argon (LAr) electromagnetic sampling calorimeter (ECAL), with excellent performance in terms of energy and position resolution, covers the range $|\eta| < 3.2$. In the end-caps, the LAr technology is also used for hadronic calorimeters (HAC), which share the cryostat with the ECAL end-caps. The same cryostat also houses the special LAr forward calorimeters which extend the coverage up to $|\eta| = 4.9$. The bulk of the HAC is provided by a novel scintillator tile calorimeter, which is separated into a large barrel and two smaller extended barrel cylinders, one on each side of the barrel. The LAr calorimeter is contained in a cylinder with an inner radius of 2.25 m and extends longitudinally to 6.65 m, along the beam axis. The outer radius of the scintillator tile calorimeter, which supports and integrates the solenoid flux-return iron yoke, is 4.25 m and its half-length is 6.10 m.

The muon spectrometer surrounds the calorimeters. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates a large field volume and strong bending power with a light and open structure. Multiple scattering effects are therefore minimal, and an excellent muon momentum resolution is achieved with three stations of high-precision tracking chambers. For triggering, the muon instrumentation is equipped with fast Resistive Plate Chambers (RPC).

The global dimensions of the ATLAS detector are defined by the muon spectrometer. The outer chambers of the barrel are at a radius of about 11 m. The length of the barrel toroid coils is 13 m, and the third layer of the forward muon chambers, mounted on the cavern wall, is located at 21 m from the interaction point. The total weight of the ATLAS detector is 700 tons.

### 1.1.2 The ALICE experiment

The heavy-ion detector ALICE (A Large Ion Collider Experiment) has emerged as a common design from the heavy-ion community currently working at CERN and a number of groups new to this field from both nuclear and high-energy physics. It is a general-purpose heavy-ion experiment, sensitive to the majority of known observables (including hadrons, electrons, muons and photons), and it will be operational at the start-up of LHC.

With ALICE we want to measure the flavour content and phase-space distribution, event by event, for a large number of particles whose momenta and masses are of the order of the typical energy scale involved (temperature $\sim \Lambda_{QCD} \sim 200$ MeV). The experiment is designed to cope with the highest particle multiplicities anticipated for $Pb - Pb$ reactions ($dN_{ch}/dy = 8000$). In addition to heavy systems (e.g. $Pb - Pb$), the ALICE Collaboration will study collisions of lower-mass ions, provide reference data for the nucleus–nucleus collisions. The ALICE detector has been designed according to the following criteria:

- A single dedicated heavy-ion detector is foreseen at the initial stage of LHC. It has to
cover, as completely as possible the full range of sensitive signatures. Its design must be conservative and robust.

- In addition to addressing particular signals which look most promising today, we will search in an unbiased way for qualitative and quantitative differences between pp and nucleus–nucleus collisions in a number of final states (hadrons, leptons, photons).

- The detector will concentrate on physics at midrapidity, maximum energy density, which are the unique features of LHC compared to the lower energy machines SPS and RHIC.

- An open geometry will facilitate future modifications and upgrades if first physics results suggest focusing on specific signals, selective triggers or larger acceptance.

**Experimental conditions**

The average event-rate for Pb–Pb collisions at the LHC will be of the order of $10^4$ minimum-bias collisions per second. Of these, a few per cent (100 events/s) correspond to the most interesting central collisions, with maximum particle production. The low interaction rates lead naturally to an approach which combines large geometrical acceptance with simple central-collision triggers and a high data-taking rate.

These rates are matched with the dead-time of our slowest detector and the capabilities of our DAQ system. A large collected sample of central collisions will allow unbiased search for signals, including ‘surprises’ not predicted by current theories, a feature of particular importance in the rapidly evolving field of relativistic heavy-ion physics. In the initial phase, running times comparable with the present SPS ion program will be adequate to collect
sufficient statistics. Therefore, we will base our rate estimates on $10^6$ s/year heavy-ion running time (10% of the total), yielding a few $10^7$ central events collected for offline analysis.

The main emphasis will be on data taking at the highest possible energy density, i.e. with Pb beams. In addition, running with one or two intermediate-mass ion species will provide the necessary means to vary the energy density. Running with protons will be required initially to commission the detector and to provide reference data for the nuclear programme. Schemes are under investigation that would allow pp running at luminosities adapted to the rate capability of the detector without any adverse effect on the high-luminosity interaction regions. A design change made recently to the LHC RF system will permit asymmetric beam collisions, in particular p–nucleus reactions. These will be important for disentangling initial state effects, like nuclear shadowing, from final state interactions in hard probe signals, like jet quenching and quarkonium production. As both luminosity and particle multiplicity in p–A are expected to be between the extremes of pp and A–A, ALICE should be well suited to make use of this new possibility. A longitudinal view of ALICE detector is shown in Fig. 1.7.

![ALICE Detector](image)

Figure 1.7: The ALICE detector

### 1.1.3 LHCb experiment

The LHCb detector [11] is a single-arm forward spectrometer dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. It is housed in the underground pit located at one of the interaction points (IP8) along the LHC ring. The experimental setup is shown in Fig.1.8. To accommodate the spectrometer in the present cavern, without the need for substantial civil engineering work, the beam crossing point has
been displaced from the center of the cavern by about 11 m, constraining the total length of the detector to 20 m; the overall dimensions are about $6 \times 5 \times 20$ m$^3$. Thus, the acceptance of the detector, defined by the aperture of the magnet, is 300 mrad in the horizontal plane (i.e., the bending plane of the magnet), and 250 mrad in the vertical plane (non-bending plane). A right-handed coordinate system is defined centred on the interaction point, with $z$ along the beam axis and $y$ pointing upwards. The detector design has gone through a number of optimisation phases. These changes are referred to as the reoptimisation. Figure 1.6 shows the reoptimised design of the LHCb detector geometry; one can see, from left to right:

- the vertex locator (VELO)
- the upstream Ring-Imaging Cherenkov detector (RICH1)
- the trigger tracking (TT)
- the magnet
- the tracking system(T1,T2,T3)
- the downstream Ring-Imaging Cherenkov detector (RICH2)
- the preshower (SPD/PS)
- the electromagnetic calorimeter (ECAL)
- the hadronic calorimeter
- the muon system

### 1.1.4 The Standard Model

Table 1.2 lists the fermion fields that make up the standard model, along with their $SU(3)_c \times SU(2)_L \times U(1)_Y$ quantum numbers [12]. The index $i = 1, 2, 3$ on each field refers to the generation, and the subscripts L, R refer to the chirality of the field ($\Psi_{L,R} \equiv \frac{1}{2}(1 \pm \gamma_5)\Psi$). The left-chiral and right-chiral fields corresponding to a given particle have different $SU(2) \times U(1)$ quantum numbers, which leads to parity violation in the weak interaction. Let’s break the Lagrangian of the standard model into pieces. First consider the pure gauge interactions, given by

$$L_{Gauge} = \frac{1}{2g^2_S} Tr G^{\mu\nu} + \frac{1}{2g^2} Tr W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}, \quad (1.1.1)$$

where $G^{\mu\nu}$ is the field-strength tensor of the gluon field, $W^{\mu\nu}$ is that of the weak-boson field, and $B^{\mu\nu}$ is that of the hypercharge-boson field. These terms contain the kinetic energy of the gauge bosons and their self interactions. Next comes the gauge interactions of the fermion (“matter”) fields,

$$L_{Matter} = i \bar{Q}_L^i D Q^i_L + i \bar{u}^i_R Du^i_R + i \bar{d}^i_R Dd^i_R + i \bar{L}^i_L DL^i_L + i \bar{e}^i_R De^i_R \quad (1.1.2)$$
Table 1.2: The fermion fields of the standard model and their gauge quantum numbers.

<table>
<thead>
<tr>
<th>Field</th>
<th>SU(3) c</th>
<th>SU(2) L</th>
<th>U(1) Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^i_L$</td>
<td>$u^i_L$</td>
<td>$c^i_L$</td>
<td>$t^i_L$</td>
</tr>
<tr>
<td>$u^R_i$</td>
<td>$u^R_i$</td>
<td>$c^R_i$</td>
<td>$t^R_i$</td>
</tr>
<tr>
<td>$d^R_i$</td>
<td>$d^R_i$</td>
<td>$s^R_i$</td>
<td>$b^R_i$</td>
</tr>
<tr>
<td>$L^i_L$</td>
<td>$\nu^i_{eL}$</td>
<td>$\nu^i_{\mu L}$</td>
<td>$\nu^i_{\tau L}$</td>
</tr>
<tr>
<td>$e^R_i$</td>
<td>$e^R_i$</td>
<td>$\mu^R_i$</td>
<td>$\tau^R_i$</td>
</tr>
</tbody>
</table>

These terms contain the kinetic energy and gauge interactions of the fermions, which depend on the fermion quantum numbers. For example,

$$DQ_L = \gamma^\mu (\partial_\mu + igS G_\mu + igW_\mu + ig' B_\mu) Q_L$$

(1.1.3)

since the field $Q_L$ participates in all three gauge interactions. A sum on the index $i$, which represents the generation, is implied in the Lagrangian.

We have constructed the simplest and most general Lagrangian, given the fermion fields and gauge symmetries. The gauge symmetries forbid masses for any of the particles. In the case of the fermions, masses are forbidden by the fact that the left-chiral and right-chiral components of a given fermion field have different $SU(2) \times U(1)_Y$ quantum numbers. For example, a mass term for the up quark,

$$\mathcal{L} = -m_u u^L R + h.c.,$$

(1.1.4)
is forbidden by the fact that \( u_L \) is part of the SU(2) doublet \( Q_L \), so such a term violates the SU(2) gauge symmetry (it also violates \( U(1)_Y \)). Although we only imposed the gauge symmetry on the Lagrangian, it turns out that it has a good deal of global symmetry as well, associated with the three generations. Because all fermions are massless thus far in our analysis, there is no difference between the three generations - they are physically indistinguishable. This manifests itself as a global flavor symmetry of the matter Lagrangian, Eq. 1.1.9, which is invariant under the transformations

\[
Q^i_L \rightarrow U^{ij}_{Q_L} Q^j_L, \\
u^i_R \rightarrow U^{ij}_{\nu_R} \nu^j_R, \\
\bar{d}^i_R \rightarrow U^{ij}_{\bar{d}_R} \bar{d}^j_R, \\
L^i_L \rightarrow U^{ij}_{L_L} L^j_L, \\
e^i_R \rightarrow U^{ij}_{e_R} e^j_R,
\]

where each \( U \) is an arbitrary \( 3 \times 3 \) unitary matrix.

**Electroweak symmetry breaking**

The theory thus far is very simple and elegant, but it is incomplete - all particles are massless. We now turn to electroweak symmetry breaking, which is responsible for generating the masses of the gauge bosons and fermions. In the standard model, electroweak symmetry breaking is achieved by introducing another field into the model, the Higgs field \( \phi \), with the quantum numbers shown in Table 1.3. The simplest and most general Lagrangian for the Higgs field, consistent with the gauge symmetry, is

\[
L_{Higgs} = (D^\mu \phi)\dagger D_\mu \phi + \mu^2 \phi\dagger \phi - \lambda (\phi\dagger \phi)^2. \tag{1.1.5}
\]

The first term contains the Higgs-field kinetic energy and gauge interactions. The remaining terms are (the negative of) the Higgs potential, shown in Fig. 1.9. The quadratic term in the potential has been chosen such that the minimum of the potential lies not at zero, but on a circle of minima

\[
< \phi^0 > = \frac{\mu}{\sqrt{2\lambda}} \tag{1.1.6}
\]

<table>
<thead>
<tr>
<th>SU(3)</th>
<th>SU(2)</th>
<th>( U(1)_Y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Table 1.3: The Higgs field and its gauge quantum numbers.
where $\phi^0$ is the lower (neutral) component of the Higgs doublet field. This equation defines the parameter $\nu \approx 246 \, GeV$, the Higgs-field vacuum-expectation value. Making the substitution $\phi \equiv (0, \frac{\nu}{\sqrt{2}})$ in the Higgs Lagrangian, Eq. 1.1.5, one finds that the W and Z bosons have acquired masses,

$$V(x,y) = \lambda (x^2 + y^2)^2 - \mu^2 (x^2 + y^2)$$

with $\lambda = 0.5$, $\mu^2 = -15$ and $\lambda = 0.5$, $\mu^2 = 15$.

Figure 1.9: The Higgs potential. The neutral component of the Higgs field acquires a vacuum-expectation value $\langle \phi^0 \rangle = \frac{\nu}{\sqrt{2}}$ on the circle of minima in Higgs-field space.

$$M_W = \frac{1}{2} g \nu$$  \hspace{1cm} (1.1.7)$$

$$M_Z = \frac{1}{2} \sqrt{g^2 + g'^2}$$  \hspace{1cm} (1.1.8)$$

from the interaction of the gauge bosons with the Higgs field. Since we know $g$ and $g'$, these equations determine the numerical value of $\nu$. The Higgs sector of the theory, Eq. 1.1.5, introduces just two new parameters, $\mu$ and $\lambda$. Rather than $\mu$, we will use the parameter $\nu$ introduced in Eq. 1.1.6. The parameter $\lambda$ is the Higgs-field self interaction, and will not figure into our discussion. Fermion masses and mixing, in quantum field theory, anything that is not forbidden is mandatory. With that in mind, there is one more set of interactions, involving the Higgs field and the fermions. The simplest and most general Lagrangian, consistent with the gauge symmetry, is

$$\mathcal{L}_{Yukawa} = -\Gamma_u^i \bar{Q}_L^i \phi^* u_R^j - \Gamma_d^i \bar{Q}_L^i \phi d_R^j - \Gamma_e^i \bar{L}_L^i \phi e_R^j + h.c.$$  \hspace{1cm} (1.1.9)$$

where $\Gamma_u, \Gamma_d, \Gamma_e$ are $3 \times 3$ complex matrices in generation space. We have therefore apparently introduced $3 \times 3 \times 3 \times 2 = 54$ new parameters into the theory, but as we shall see, only a subset of these parameters are physically relevant. These so-called Yukawa interactions of the Higgs field with fermions violate almost all of the $[U(3)]^5$ global symmetry of the
fermion gauge interactions, Eq. 1.1.2. The only remaining global symmetries are the subset corresponding to baryon number

$$Q_L^i \to e^{i\frac{\theta}{3}} Q_L^i$$  
$$u_R^i \to e^{i\frac{\theta}{3}} u_R^i$$  
$$d_R^i \to e^{i\frac{\theta}{3}} d_R^i$$

and lepton number

$$L_L^i \to e^{i\phi} L_L^i$$  
$$\ell_R^i \to e^{i\phi} \ell_R^i$$

The conservation of baryon number and lepton number follow from these symmetries. These symmetries are accidental; they are not put in by hand, but rather follow automatically from the field content and gauge symmetries of the theory. Thus we can say that we understand why baryon number and lepton number are conserved in the standard model. Replacing the Higgs field with its vacuum-expectation value, \( \phi = (0, \frac{\nu}{\sqrt{2}}) \), in Eq. 1.1.9 yields

$$\mathcal{L}_M = -M_{ij}^u u_L^i u_R^j - M_{ij}^d d_L^i d_R^j - M_{ij}^\ell \ell_L^i \ell_R^j + h.c.,$$  

(1.1.10)

where

$$M_{ij}^f = \Gamma_{ij} \frac{\nu}{\sqrt{2}}$$  

(1.1.11)

are fermion mass matrices. The Yukawa interactions are therefore responsible for providing the charged fermions with mass; the neutrinos, however, remain massless (we will discuss neutrino masses shortly). The complete Lagrangian of the standard model is the sum of the gauge, matter, Higgs, and Yukawa interactions,

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge} + \mathcal{L}_{Matter} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$  

(1.1.12)

This is the simplest and most general Lagrangian, given the field content and gauge symmetries of the standard model. Given this Lagrangian, one can proceed to calculate any physical process of interest. However, it is convenient to first perform field redefinitions to make the physical content of the theory manifest. These field redefinitions do not change the predictions of the theory; they are analogous to a change of variables when performing an integration. To make the masses of the fermions manifest, we perform unitary field redefinitions on the fields in order to diagonalize the mass matrices in Eq. 1.1.10:

$$u_L^i = A_{ui}^j u_L^j, \quad u_R^j = A_{uj}^i u_R^i$$  
$$d_L^i = A_{di}^j d_L^j, \quad d_R^j = A_{dj}^i d_R^i$$  
$$\ell_L^i = A_{\ell i}^j \ell_L^j, \quad \ell_R^j = A_{\ell j}^i \ell_R^i$$  
$$\nu_L^i = A_{\nu i}^j \nu_L^j$$
1.1.5 Lepton colliders versus hadron colliders

Leptons are fundamental particles and we have no evidence that they are made up of anything smaller. Hadrons (protons, pions, neutrons, kaons etc.) are not fundamental – they are made up of quarks and anti-quarks and the gluons that hold them together. In a lepton beam of known energy, each particle has this energy and so precision measurements of interactions in a detector are possible, balancing the energy before the event with the observed energy afterwards.

In a hadron beam, however, each hadron’s energy is shared out between its constituent particles in a constantly changing way. At high energies, interactions are between the quarks and gluons rather than between the hadrons as a whole, and so the initial energy of the two colliding particles cannot be known very accurately.

The two types of machines compliment each other: hadron colliders are useful for discovering new physics or searching for new particles as they explore a wide range of collision energies with one beam energy. Lepton machines can be used for precision measurements of particles after their discovery.

For example, the W and Z particles were discovered in CERN’s SPS synchrotron by colliding protons and antiprotons. The LEP collider was then built to measure the Z mass to very high precision by colliding electrons and positrons at precisely the rest energy of the Z. In electron-positron colliders the particles loose every second through synchrotron radiation an amount of energy much larger than the beam stored energy. This loss must be continuously compensated by the RF system, and as a consequence this phenomenon limits the attainable energy while providing damping of particle oscillations. These effects are unimportant in the LHC because owing to the larger mass of the particles the energy radiated during the same time is only a tiny fraction of the beam energy. They will become significant in proton machines at much higher energies (around 100 TeV). However in the LHC the power emitted, about 3.7 kW, cannot be neglected as it has to be absorbed by the beam pipe at cryogenic temperature. This affects the installed power of the refrigeration system and is an important cost issue. In addition the synchrotron light impinges on the beam pipe walls as a large number of hard U.V. photons. These release absorbed gas molecules, which then increase the residual gas pressure, and liberate photo-electrons, which are accelerated across the beam pipe by the strong positive electric field of the proton bunches. These photoelectrons add to the cryogenic load and may induce an instability of transverse coupled bunch modes.

1.1.6 Physics Goals at LHC

- In the tremendously successful Standard Model of elementary particles, the interactions of the fundamental fermions leptons and quarks are mediated by gauge bosons obeying $SU(3) \times SU(2) \times U(1)$ symmetry. More specifically, the electro-weak interaction is described by spontaneously broken $SU(2) \times U(1)$ gauge symmetry. This leads to the emergence of massive vector bosons, the W and Z, which mediate the weak interaction, while the photon of the electromagnetic force remains massless. It also leads to the
existence of a scalar Higgs field with a non-zero expectation value. The Higgs Boson is virtually the only missing link in the theory, and the currently expected value for its mass is less than about half a TeV. At the LHC center-of-mass energy of 14 TeV, experiments will probe the entire allowed mass range for the SM Higgs boson and either discover it or be able to exclude it.

- As experiments probe deeper into matter, exploring ever smaller distances, the corresponding cross-sections become smaller. Given the LHC energy of $\sqrt{s} =$14 TeV, collider luminosity becomes a very important factor in the discovery potential. Unfortunately, high luminosity also means high rates of background. At the LHC luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, there are an average of about fifteen hadronic interactions per bunch crossing [13].

- Muon detection is the most natural and powerful tool to detect interesting events over the background. A “gold plated” signal of the Higgs Boson is its decay into $Z - Z$ or $Z - Z^*$ which in turn decays into four charged leptons. If the leptons are muons, the best 4-particle mass resolution can be achieved, and muons are less affected than electrons by radiative losses in the tracker material. The four-lepton channel is crucial for the discovery of the SM Higgs boson in the mass range from $\sim 130$ GeV up to $\sim 750$ GeV.

- Possible extensions of the Standard Model lead to the existence of other gauge fields. The LHC allows the discovery or exclusion of new gauge bosons with masses below $\sim 4$ TeV more than an order of magnitude heavier than the W and Z. For the highest discovery reach, precision measurements of high energy muons ($P_t > 1$ TeV) in $Z \rightarrow \mu^+ \mu^-$ are important.

- Lepton and photon isolation criteria are essential to extract most of the signals searched for at the LHC. Since muons can be measured within jets, which is generally not the case for electrons and photons, muons make it possible to determine directly the lepton and photon isolation rejection factors. The possibility of measuring muons in jets is also a powerful tool for b-jet tagging, exploiting the $b \rightarrow \mu$ decay, which is essential in a number of Higgs studies, top studies, and SUSY searches.

- An appealing extension of the Standard Model is Supersymmetry: it allows the unification of the three couplings of the gauge interactions at a very high energy scale. Superpartners for all the presently observed particles are expected at the TeV mass scale. There are also multiple Higgs bosons. In the Minimal Supersymmetric Model for example, these are designated $h^0$, $H^0$, $A^0$ and $H^\pm$. At the LHC, Supersymmetry will be probed over the entire theoretically plausible mass range. Muons are again an essential tool not only for the discovery of these Supersymmetric particles, squarks, gluinos, sleptons, etc., but also in determining their properties.
Chapter 2

Compact Muon Solenoid Detector

Although the Standard Model (SM) of particle physics has so far been tested to exquisite precision, it is considered to be an effective theory up to some scale $\Lambda \approx \text{TeV}$. The prime motivation of the Large Hadron Collider (LHC) is to elucidate the nature of electroweak symmetry breaking for which the Higgs mechanism is presumed to be responsible. The experimental study of the Higgs mechanism can also shed light on the mathematical consistency of the SM at energy scales above about 1 TeV. However, there are alternatives that invoke more symmetry such as supersymmetry or invoke new forces or constituents such as strongly-broken electroweak symmetry, technicolour, etc. An as yet unknown mechanism is also possible. Furthermore there are high hopes for discoveries that could pave the way toward a unified theory. These discoveries could take the form of supersymmetry or extra dimensions, the latter often requiring modification of gravity at the TeV scale. Hence there are many compelling reasons to investigate the TeV energy scale. Hadron colliders are well suited to the task of exploring new energy domains, and the region of 1 TeV constituent centre-of-mass energy can be explored if the proton energy and the luminosity are high enough. The beam energy (7 TeV) and the design luminosity ($\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$) of the LHC have been chosen in order to study physics at the TeV energy scale. Hence a wide range of physics is potentially possible with a sevenfold increase in energy and a hundred-fold increase in integrated luminosity over the current hadron collider experiments. These conditions also require a very careful design of the detectors.

The availability of high energy heavy-ion beams at energies over 30 times higher than at the present day accelerators will allow us to further extend the range of the heavy-ion physics programme to include studies of hot nuclear matter.

The focus of this chapter is to present a concise yet complete overview of the strategy of the Compact Muon Solenoid (CMS) experiment [14] to exploit the physics opportunities presented by the LHC, from the operational procedures of the detectors and the handling of data to the tools needed to reconstruct high-level physics objects and perform the physics analyses.

The construction of the CMS subsystems [15, 16, 17, 18, 19, 20] is nearly complete and installation and commissioning of some subsystems is well underway in the CMS surface assembly hall at Cessy in France, near Geneva (LHC point 5).
2.1 Coordinate conventions

The coordinate system adopted by CMS has the origin centered at the nominal collision point inside the experiment, the y-axis pointing vertically upward, and the x-axis pointing radially inward toward the center of the LHC. Thus, the z-axis points along the beam direction toward the Jura mountains from LHC Point 5. The azimuthal angle $\phi$ is measured from the x-axis in the $x-y$ plane. The polar angle $\theta$ is the angle between the particle being considered and the undeflected beam. Pseudorapidity is a handy variable to approximate the rapidity if the mass and momentum of a particle are not known. It is an angular variable defined by $\eta = -\ln \tan(\theta/2)$. Table 2.1 shows the relation between $\theta$ and $\eta$ for some round values. Thus the momentum and energy measured transverse to the beam direction, denoted by $P_T$ and $E_T$ respectively, are computed from the x and y components. The imbalance of energy measured in the transverse plane is denoted by $E_T^{\text{miss}}$.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>90</th>
<th>45</th>
<th>40.4</th>
<th>15.4</th>
<th>15</th>
<th>10</th>
<th>5.7</th>
<th>2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>0</td>
<td>0.88</td>
<td>1</td>
<td>2</td>
<td>2.03</td>
<td>2.44</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

2.1.1 Experimental challenge

The total proton-proton cross-section at $\sqrt{s} = 14$ TeV is roughly 100 mb. At design luminosity the general-purpose detectors will therefore observe an event rate of approximately $10^9$ inelastic events/s. This leads to a number of formidable experimental challenges [21].

The online event selection process “trigger” must reduce the approximately 1 billion interactions/s to no more than about 100 events/s for storage and subsequent analysis. The short time between bunch crossings, 25 ns, has major implications for the design of the readout and trigger systems.

At the design luminosity, a mean of about 20 inelastic (hard-core scattering) collisions will be superimposed on the event of interest. This implies that around 1000 charged particles will emerge from the interaction region every 25 ns. The products of an interaction under study may be confused with those from other interactions in the same bunch crossing. This problem clearly becomes more severe when the response time of a detector element and its electronic signal is longer than 25 ns. The effect of this pile-up can be reduced by using high granularity detectors with good time resolution, resulting in low occupancy. This requires a large number of detector channels. The resulting millions of detector electronic channels require very good synchronization.

The large flux of particles coming from the interaction region leads to high radiation levels, requiring radiation-hard detectors and front-end electronics.
2.2 Compact Muon Solenoid Detector

The Compact Muon Solenoid (CMS) detector is a general purpose particle detector to be operated at Large Hadron Collider at CERN in Geneva for 2007 experiment. The overall dimensions of the CMS detector are a length of 21.6 m, a diameter of 14.6 m and a total weight of 12500 tons. The thickness of the detector in radiation lengths (Fig. 2.1) is greater than 25 $X_0$ for the ECAL, and the thickness in interaction lengths (Fig. 2.1) varies from $7-11 I$ for HCAL depending on . Also shown in both figures is the material depth at each muon station.

a) Forward Region

b) Backward Region

c) The Very Forward Calorimeter

Figure 2.1: (Left), material thickness in radiation lengths after the ECAL, HCAL, and at the depth of each muon station as a function of pseudorapidity. The thickness of the forward calorimeter center (HF) remains approximately constant over the range $3 < |\eta| < 5$ (not shown). (Right), Material thickness in interaction lengths after the ECAL, HCAL, and at the depth of each muon station as a function of pseudorapidity. The thickness of the forward calorimeter (HF) remains approximately constant over the range $3 < |\eta| < 5$ (not shown) Forward Region.
The barrel detector covers the region \((45^\circ \leq \theta \leq 135^\circ)\) with \(\eta \leq 1.3\). The endcap detector covers the region \(0.9 \leq \eta \leq 2.4\) with forward region \((0^\circ \leq \theta \leq 45^\circ)\) and Backward Region \((135^\circ \leq \theta \leq 180^\circ)\), while the forward calorimeter region ranges \((3 \leq \eta \leq 5)\). The main subdetectors of CMS are: Inner Trackers, Calorimeters, Magnet system and a Muon system, which are shown in Fig. 2.2 [22].

2.2.1 Inner Tracking System

By considering the charged particle flux at various radii at high luminosity (Table 2.2), 3 regions can be delineated:

- Closest to the interaction vertex where the particle flux is the highest \((10^7/s \text{ at } r < 10 \text{ cm})\), pixel detectors are placed. The size of a pixel is \(\approx 100 \times 150 \text{ } \mu m^2\), giving an occupancy of about \(10^{-4}\) per pixel per LHC crossing.

- In the intermediate region \((20 < r < 55 \text{ cm})\), the particle flux is low enough to enable use of silicon microstrip detectors with a minimum cell size of \(10 \text{ cm} \times 80 \text{ } \mu m\), leading to an occupancy of \(\approx 2 - 3\%\) LHC crossing.

- In the outermost region \((r > 55 \text{ cm})\) of the inner tracker, the particle flux has dropped sufficiently to allow use of larger-pitch silicon microstrips with a maximum cell size of
Table 2.2: Hadron fluence and radiation dose in different radial layers of the CMS Tracker (barrel part) for an integrated luminosity of 500 fb$^{-1}$ (10 years).

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>Fluence of fast hadrons($10^{14} cm^{-2}$)</th>
<th>Dose (kGy)</th>
<th>Charge particle flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>32</td>
<td>840</td>
<td>$10^8$</td>
</tr>
<tr>
<td>11</td>
<td>4.6</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1.6</td>
<td>70</td>
<td>$6 \times 10^6$</td>
</tr>
<tr>
<td>75</td>
<td>0.3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>115</td>
<td>0.2</td>
<td>1.8</td>
<td>$3 \times 10^3$</td>
</tr>
</tbody>
</table>

25 cm × 180 μm, whilst keeping the occupancy to 1%.

Even in heavy-ion (Pb-Pb) running, the occupancy is expected to be at the level of 1% in the pixel detectors and less than 20% in the outer silicon strip detectors, permitting track reconstruction in the high density environment. The layout of the CMS tracker is shown in

![Figure 2.3: The tracker layout](image)

Figure 2.3. The outer radius of the CMS tracker extends to nearly 110 cm, and its total length is approximately 540 cm.

Close to the interaction vertex, in the barrel region, are 3 layers of hybrid pixel detectors at a radii of 4.4, 7.3, and 10.2 cm. The size of the pixels is 100 × 150 μm$^2$. In the barrel part, the silicon microstrip detectors are placed at $r$ between 20 and 110 cm. The forward region has 2 pixel and 9 microstrip layers in each of the 2 Endcaps. The barrel part is separated into an Inner and an Outer Barrel. In order to avoid excessively shallow track crossing angles, the Inner Barrel is shorter than the Outer Barrel, and there are an additional 3 Inner Disks in the transition region between the barrel and endcap parts, on each side of the Inner Barrel. The total area of the pixel detector is 1 m$^2$, whilst that of the silicon strip detectors is 200 m$^2$, providing coverage up to $|\eta| < 2.4$. The inner tracker comprises of 66 million pixels and 9.6 million silicon strips [23].
Strip Tracker

The barrel tracker region is divided into 2 parts: a TIB (Tracker Inner Barrel) and a TOB (Tracker Outer Barrel). The TIB is made of 4 layers and covers up to $|z| < 65 \text{ cm}$, using silicon sensors with a thickness of 320 $\mu\text{m}$ and a strip pitch which varies from 80 to 120 $\mu\text{m}$. The first 2 layers are made with “stereo” modules in order to provide a measurement in both $r - \phi$ and $r - z$ coordinates. A stereo angle of 100 mrad has been chosen. This leads to a single-point resolution of between $23 - 34 \mu\text{m}$ in the $r - \phi$ direction and 230 $\mu\text{m}$ in $z$. The TOB comprises of 6 layers with a half-length of $|z| < 110 \text{ cm}$. As the radiation levels are smaller in this region, thicker silicon sensors (500 $\mu\text{m}$) can be used to maintain a good S/N ratio for longer strip length and wider pitch. The strip pitch varies from 120 to 180 $\mu\text{m}$. Also for the TOB the first 2 layers provide a “stereo” measurement in both $r - \phi$ and $r - z$ coordinates. The stereo angle is again 100 mrad and the single-point resolution varies from 35–52 $\mu\text{m}$ in the $r$ direction and 530 $\mu\text{m}$ in $z$.

The endcaps are divided into the TEC (Tracker End Cap) and TID (Tracker Inner Disks). Each TEC comprises 9 disks that extend into the region $120 \text{ cm} < |z| < 280 \text{ cm}$, and each TID comprises 3 small disks that fill the gap between the TIB and the TEC. The TEC and TID modules are arranged in rings, centred on the beam line, and have strips that point towards the beam line, therefore having a variable pitch. The first 2 rings of the TID and the innermost 2 rings and the fifth ring of the TEC have ”stereo” modules. The thickness of the sensors is 320 $\mu\text{m}$ for the TID and the 3 innermost rings of the TEC and 500 $\mu\text{m}$ for the rest of the TEC. The layout of silicon strip tracker is shown in Fig. 2.4. The entire silicon strip detector consists of almost 15,400 modules, which will be mounted on carbon-fibre structures and housed inside a temperature controlled outer support tube. The operating temperature will be around $-20^\circ\text{C}$.
Pixel Tracker

The pixel detector consists of 3 barrel layers with 2 endcap disks on each side on them (Fig. 2.4). The 2 end disks, extending from 6 to 15 cm in radius, are placed on each side at $|z| = 34.5$ cm and 46.5 cm.

In order to achieve the optimal vertex position resolution, a design with an “almost” square pixel shape of $100 \times 150 \, \mu m^2$ in both the $(r, \phi)$ and the $z$ coordinates has been adopted. The barrel comprises 768 pixel modules arranged into half-ladders of 4 identical modules each. The large Lorentz effect (Lorentz angle is $23^\circ$) improves the $r - \phi$ resolution through charge sharing.

The endcap disks are assembled in a turbine-like geometry with blades rotated by $20^\circ$ to benefit from the Lorentz effect also. The endcap disks comprise 672 pixel modules with 7 different modules in each blade.

The spatial resolution is measured to be about 10 $\mu m$ for the $r - \phi$ measurement and about 20 $\mu m$ for the $z$ measurement. The detector is readout using approximately 16000 readout chips, which are bump-bonded to the detector modules. Figure 2.5 shows a view of the pixel tracker of CMS at high luminosity configuration. The whole pixel tracker fills an radial area of $3.7 \leq r \leq 21$ cm and longitudinal area of $-50 \leq z \leq 50$ cm.

Figure 2.5: Layout of pixel detectors in the CMS tracker at its high luminosity configuration.

Tracker control and readout scheme

The Silicon Strip Tracker (SST) readout system is based on a front-end APV25 readout chip [24], analogue optical links [25] and an off-detector Front-End Driver (FED) processing board [26]. The APV25 chip samples, amplifies, buffers and processes signals from 128 channels of a silicon strip sensor. Each microstrip is readout by a charge sensitive amplifier with $\tau = 50$ ns. The output voltage is sampled at the beam crossing rate of 40 MHz. Samples are stored in an analogue pipeline for up to the Level-1 latency of 3.2 $\mu s$. Following a trigger, a weighted sum of 3 samples is formed in an analogue
circuit. This confines the signal to a single bunch crossing and gives the pulse height. The buffered pulse height data from pairs of APV25 chips are multiplexed onto a single line and the analogue data are converted to optical signals before being transmitted via optical fibres to the off-detector FED boards. The output of the transmitting laser is modulated by the pulse height for each strip. The FEDs digitize, process and format the pulse height data from up to 96 pairs of APV25 chips, before forwarding zero-suppressed data to the DAQ online farm. The electronics noise/channel of the tracking system is about 1000 to 1500 electrons before and after irradiation, respectively. The SST control system comprises \( \approx 300 \) control rings that start and end at the off-detector Front-End Controller (FEC) boards [27]. Slow-control commands, clock and Level-1 triggers are distributed via digital optical links to Digital Opto-Hybrids (DOH) [28], which perform optical-to-electrical conversion before the control signals are distributed to the front-end electronics.

The Pixel Tracker readout system is described in detail in [10]. A single pixel barrel module is readout by 16 Read-Out Chips (ROCs). In the endcaps, the number of ROCs per module varies from 2 to 10. Each ROC reads an array of \( 52 \times 80 \) pixels. analogue signals and corresponding pixel addresses are stored in a data buffer, waiting for the Level-1 trigger decision. Following a Level-1 trigger accept, data are transmitted on optical links to FED boards. In the barrel, groups of 8 or 16 ROCs are connected to 1 link, whereas in the endcaps there are 21 or 24 ROCs per link. The 40 Pixel FEDs perform digitization and data formatting.

**Performance of the tracker** The performance of the tracker is illustrated in Figure 2.6, which shows the transverse momentum and impact parameter resolutions in the \( r \)- and \( z \) planes for single muons with a \( p_T \) of 1, 10 and 100 \( \text{GeV}/c \), as a function of pseudorapidity. The material inside the active volume of the tracker increases from \( 0.4 X_0 \) at \( \eta = 0 \) to around \( 1 X_0 \) at \( |\eta| \approx 1.6 \), before decreasing to \( 0.6 X_0 \) at \( |\eta| = 2.5 \).

### 2.2.2 Electromagnetic calorimeter

The Electromagnetic Calorimeter (ECAL) is a hermetic, homogeneous calorimeter comprising 61200 lead tungstate (\( \text{PbWO}_4 \)) crystals mounted in the central barrel part, closed by 7324 crystals in each of the 2 endcaps.

CMS has chosen lead tungstate scintillating crystals for its ECAL. These crystals have short radiation (\( X_0 = 0.89 \text{ cm} \)) and Moliere (2.2 cm) lengths, are fast (80% of the light is emitted within 25 ns) and radiation hard (up to 10 Mrad). However, the relatively low light yield (30 \( \gamma/\text{MeV} \)) requires use of photodetectors with intrinsic gain that can operate in a magnetic field. Silicon avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps. In addition, the sensitivity of both the crystals and the APD response to temperature changes requires a temperature stability (the goal is 0.1° C). The use of \( \text{PbWO}_4 \) crystals has thus allowed the design of a compact calorimeter inside the solenoid that is fast, has fine granularity, and is radiation resistant.
The barrel section (EB) has an inner radius of 129 cm. It is structured as 36 identical “supermodules,” each covering half the barrel length and corresponding to a pseudorapidity interval of $0 < |\eta| < 1.479$. The crystals are quasi-projective (the axes are tilted at 3° with respect to the line from the nominal vertex position) and cover 0.0174 (i.e. 1°) in $\Delta \phi$ and $\Delta \eta$. The crystals have a front face cross-section of $\approx 22 \times 22$ mm$^2$ and a length of 230 mm, corresponding to 25.8 $X_0$.

The endcaps (EE), at a distance of 314 cm from the vertex and covering a pseudorapidity range of $1.479 < |\eta| < 3.0$, are each structured as 2 “Dees”, consisting of semi-circular aluminium plates from which are cantilevered structural units of $5 \times 5$ crystals, known as “supercrystals.” In the ECAL TDR [18] the basic mechanical unit was envisaged to hold $6 \times 6$ crystals. The change was accommodated by a corresponding increase in the lateral size of the crystals. The endcap crystals, like the barrel crystals, off-point from the nominal vertex position, but are arranged in an x-y grid (i.e. not an $\eta - \phi$ grid). They are all identical and have a front face cross-section of $28.6 \times 28.6$ mm$^2$ and a length of 220 mm ($24.7 X_0$). A preshower device is placed in front of the crystal calorimeter over much of the endcap pseudorapidity range. The active elements of this device are 2 planes of silicon strip detectors, with a pitch of 1.9 mm, which lie behind disks of lead absorber at depths of 2 $X_0$ and 3 $X_0$.

**Electronic readout**

After amplification by a multi-gain preamplifier, the signal, shaped to peak after about 50 ns, is sampled and digitized at 40 MHz in 1 of 3 selected 12-bit ADCs used for each channel. A dynamic range of over 15 bits is attained. For each trigger, consecutive digitizations within
a defined time frame (250 ns) are read out. In order to obtain the amplitude of a digitized pulse, the samples within the time frame are weighted and summed. The noise performance has been measured in several supermodules and found to be close to the original specification of approximately 40 MeV/channel.

**Performance of the electromagnetic calorimeter**

The performance of a supermodule was measured in a test beam. Representative results on the energy resolution as a function of beam energy are shown in Fig. 2.7. The energy resolution, measured by fitting a Gaussian function to the reconstructed energy distributions, has been parameterized as a function of energy:

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} + \frac{N}{E} + C,$$

(2.2.1)

where $S$ is the stochastic term, $N$ the noise and $C$ the constant term.

![Figure 2.7: ECAL supermodule energy resolution, $\sigma_E/E$, as a function of electron energy as measured from a beam test. The upper series of points correspond to events taken with a $20 \times 20 \text{ mm}^2$ trigger and reconstructed using a containment correction. The lower series of points correspond to events selected to fall within a $4 \times 4 \text{ mm}^2$ region. The energy was measured in an array of $3 \times 3$ crystals with electrons impacting the central crystal.](image)

2.2.3 Hadronic Calorimeter

The design of the hadron calorimeter (HCAL) [16] is strongly influenced by the choice of magnet parameters since most of the CMS calorimetry is located inside the magnet coil (Fig. 2.7) and surrounds the ECAL system. An important requirement of HCAL is to minimize the non-Gaussian tails in the energy resolution and to provide good containment and hermeticity for the $E_T^{\text{miss}}$ measurement. Hence, the HCAL design maximizes material inside
the magnet coil in terms of interaction lengths. This is complemented by an additional layer of scintillators, referred to as the hadron outer (HO) detector, lining the outside of the coil. Brass has been chosen as absorber material as it has a reasonably short interaction length, is easy to machine and is non-magnetic. Maximizing the amount of absorber before the magnet requires keeping to a minimum the amount of space devoted to the active medium. The tile/fibre technology makes for an ideal choice. It consists of plastic scintillator tiles read out with embedded wavelength-shifting (WLS) fibres. The WLS fibres are spliced to high attenuation-length clear fibres outside the scintillator that carry the light to the readout system. This technology was first developed by the UA1 collaboration [29] and at Protvino [30] and has been used in the upgrade of the CDF endcap calorimeter [31]. The photodetection readout is based on multi-channel hybrid photodiodes (HPDs). The absorber structure is assembled by bolting together precisely machined and overlapping brass plates so as to leave space to insert the scintillator plates, which have a thickness of 3.7 mm. The overall assembly enables the HCAL to be built with essentially no uninstrumented cracks or dead areas in $\phi$.

The gap between the barrel and the endcap HCAL, through which the services of the ECAL and the inner tracker pass, is inclined at 53° and points away from the centre of the detector.

**Hadron barrel**

The hadron barrel (HB) part of HCAL consists of 32 towers covering the pseudorapidity region $-1.4 < \eta < 1.4$, resulting in 2304 towers with a segmentation $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$. The HB is constructed in 2 half barrels. Details of the HB design, together with the performance of production modules measured in CERN test beams, may be found in [32]. The HB is read out as a single longitudinal sampling. There are 15 brass plates, each with a thickness of about 5 cm, plus 2 external stainless steel plates for mechanical strength. Particles leaving the ECAL volume first see a scintillator plate with a thickness of 9 mm rather than 3.7 mm for the other plates. The light collected by the first layer is optimized to be a factor of about 1.5 higher than the other scintillator plates.

**Hadron outer**

The hadron outer (HO) detector contains scintillators with a thickness of 10 mm, which line the outside of the outer vacuum tank of the coil and cover the region $-1.26 < \eta < 1.26$. The tiles are grouped in 30 $\phi$-sectors, matching the $\phi$ segmentation of the DT chambers. They sample the energy from penetrating hadron showers leaking through the rear of the calorimeters and so serve as a “tail-catcher” after the magnet coil. They increase the effective thickness of the hadron calorimetry to over 10 interaction lengths, thus reducing the tails in the energy resolution function. The HO also improves the $E_T^{miss}$ resolution of the calorimeter. HO is physically located inside the barrel muon system and is hence constrained by the geometry and construction of that system. It is divided into 5 sections along $\eta$, called “rings” -2, -1, 0, 1, and 2. The fixed ring-0 has 2 scintillator layers on either side of an
iron absorber with a thickness of about 18 cm, at radial distances of 3.850 m and 4.097 m, respectively. The other mobile rings have single layers at a radial distance of 4.097 m. Each ring covers 2.5 m in $z$. HO scintillators follow the HCAL barrel tower geometry in $\eta$ and $\phi$.

**Hadron endcap**

Each hadron endcap (HE) of HCAL consists of 14 $\eta$ towers with $5^\circ \phi$ segmentation, covering the pseudorapidity region $1.3 < |\eta| < 3.0$. For the 5 outermost towers (at smaller $\eta$) the $\phi$ segmentation is 5 and the segmentation is 0.087. For the 8 innermost towers the $\phi$ segmentation is 10, whilst the segmentation varies from 0.09 to 0.35 at the highest $\eta$. The total number of HE towers is 2304. Details of the HE design, together with the performance of production modules measured in CERN test beams, may be found in [33].

**Hadron forward**

Coverage between pseudorapidities of 3.0 and 5.0 is provided by the steel/quartz fibre Hadron Forward (HF) calorimeter. Because the neutral component of the hadron shower is preferentially sampled in the HF technology, this design leads to narrower and shorter hadronic showers and hence is ideally suited for the congested environment in the forward region. The front face is located at 11.2 m from the interaction point. The depth of the absorber is 1.65 m. The signal originates from Cerenkov light emitted in the quartz fibres, which is then channeled by the fibres to photomultipliers. The absorber structure is created by machining 1 mm square grooves into steel plates, which are then diffusion welded. The diameter of the quartz fibres is 0.6 mm and they are placed 5 mm apart in a square grid. The quartz fibres, which run parallel to the beam line, have two different lengths (namely 1.43 m and 1.65 m) which are inserted into grooves, creating 2 effective longitudinal samplings. There are 13 towers in $\eta$, all with a size given by $\Delta \eta \approx 0.175$, except for the lowest- $\eta$ tower with $\Delta \eta \approx 0.1$ and the highest- $\eta$ tower with $\Delta \eta \approx 0.3$. The segmentation of all towers is $10^\circ$, except for the highest- $\eta$ one which has $\Delta \phi = 20^\circ$. This leads to 900 towers and 1800 channels in the 2 HF modules. Details of the HF design, together with test beam results and calibration methods, may be found in [32].

**Performance of the hadron calorimeter**

For the performance of the HCAL, it is usual to look at the jet energy resolution and the missing transverse energy resolution. The granularity of the sampling in the 3 parts of the HCAL has been chosen such that the jet energy resolution, as a function of $E_T$, is similar in all 3 parts. This is illustrated in Fig. 2.8. The resolution of the missing transverse energy ($E_{T\text{miss}}$) in QCD dijet events with pile-up is given by $\sigma(E_{T\text{miss}}) \approx 1.0\sqrt{\Sigma E_T}$ if energy clustering corrections are not made, while the average $E_{T\text{miss}}$ is given by $E_{T\text{miss}} \approx 1.25\sqrt{\Sigma E_T}$. 
Figure 2.8: The jet transverse energy resolution as a function of the simulated jet transverse energy for barrel jets (|\eta| < 1.4), endcap jets (1.4 < |\eta| < 3.0) and very forward jets (3.0 < |\eta| < 5.0). The jets are reconstructed with the iterative cone R = 0.5 algorithm.

2.2.4 Magnet system

The required performance of the muon system, and hence the bending power, is defined by the narrow states decaying into muons and by the unambiguous determination of the sign for muons with a momentum of \( \approx 1 \) TeV/c. This requires a momentum resolution of \( \Delta p/p \approx 10\% \) at \( p = 1 \) TeV/c. The CMS magnet system consists of a superconducting coil, the magnet yoke (barrel and endcap), a vacuum tank and ancillaries such as cryogenics, power supplies and process control. The main parameters of magnet system are given in Table 2.3. It will be the largest superconducting magnet system in the world. The energy stored into it, if liberated, will be enough to melt 18 tons of gold. Fig. 2.9 shows the superconducting magnet system. The magnetic flux generated by the superconducting coil is returned via a 1.5 m thick saturated iron yoke. This yoke is designed as a 12-sided cylindrical structure.

<table>
<thead>
<tr>
<th>Field</th>
<th>4 Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner bore</td>
<td>5.9 m</td>
</tr>
<tr>
<td>Length</td>
<td>12.9 m</td>
</tr>
<tr>
<td>Number of turns</td>
<td>2168</td>
</tr>
<tr>
<td>Current</td>
<td>19.5 kA</td>
</tr>
<tr>
<td>Stored energy</td>
<td>2.7GJ</td>
</tr>
<tr>
<td>Hoop stress</td>
<td>64 atm</td>
</tr>
<tr>
<td>Weight</td>
<td>12000 tons</td>
</tr>
</tbody>
</table>
The yoke is divided into the barrel and the endcap yoke. The barrel yoke is a 12-sided cylindrical structure, divided into five rings. It is 13.2 m long, giving a total iron mass of about 7000 tonnes for the barrel. The central barrel ring, centered on the interaction point, supports the superconducting coil. Each barrel ring is made up of three iron layers. Connecting brackets join together the steel plates forming the three layers and provide the required structural rigidity. The central barrel ring is the only stationary part around the interaction point and it is used to support the vacuum tank and the superconducting coil. The other four barrel rings and the endcap disks slide on common floor rails, running in the beam direction, to allow insertion and maintenance of the muon stations. As shown in the Table 2.4 below, the flux reduction with increasing field is very significant.

Table 2.4: Changing the magnetic field from 4 T to 3 T the occupancy in the inner tracker increases by about 40% in the outmost parts of the barrel region and by about 25% in the outer parts of the forward disks. In contrast, it decreases by about 20% in the innermost areas like the silicon barrel detector. For the electromagnetic calorimeter, the trapping of low-momentum charged particles results in a reduced particle flux.

<table>
<thead>
<tr>
<th>Magnetic Field</th>
<th>Mean Transverse Energy Density (GeV/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barrel</td>
</tr>
<tr>
<td></td>
<td>$\eta = 0$</td>
</tr>
<tr>
<td>0 T</td>
<td>0.5</td>
</tr>
<tr>
<td>2 T</td>
<td>0.3</td>
</tr>
<tr>
<td>4 T</td>
<td>0.15</td>
</tr>
</tbody>
</table>
2.2.5 Muon system

The muon system has three purposes: muon identification, muon trigger, and muon (signed) momentum measurement. Performance requirements follow the physics goals, including the maximum reach for unexpected discoveries, and the background environment of LHC at its highest luminosity. A robust 4 T solenoid-based system is the key to the CMS design. Comprehensive simulation studies have indicated that the physics goals can be achieved if the muon detector has the following functionality and performance:

- **Muon Identification**: at least $16 \lambda$ of material is present up to $\eta = 2.4$ with no acceptance losses.

- **Muon Trigger**: the combination of precise muon chambers and fast dedicated trigger detectors provide unambiguous beam crossing identification and trigger on single and multimuon events with well defined $p_T$ thresholds from a few $GeV$ to 100 $GeV$ up to $\eta = 2.1$.

- **Standalone Momentum Resolution** from 8 to 15% $\sigma_{p_T}/p_T$ at 10 $GeV$ and 20 to 40% at 1 TeV.

- **Global Momentum Resolution** after matching with the Central Tracker from 1.0 to 1.5% at 10 $GeV$, and from 6 to 17% at 1 TeV. Momentum-dependent spatial position matching at 1 TeV less than 1 $mm$ in the bending plane and less than 10 $mm$ in the non-bending plane.

- **Charge Assignment** correct to 99% confidence up to the kinematic limit of 7 TeV.

- **Capability of Withstanding** the high radiation and interaction background expected at the LHC.

Centrally produced muons are measured 3 times: in the inner tracker, after the coil, and in the return flux. Measurement of the momentum of muons using only the muon system is essentially determined by the muon bending angle at the exit of the 4 T coil, taking the interaction point (which will be known to $\approx 20 m$) as the origin of the muon. The resolution of this measurement (labelled “muon system only” in Fig. 2.10) is dominated by multiple scattering in the material before the first muon station up to $P_T$ values of 200 $GeV/c$, when the chamber spatial resolution starts to dominate. For low-momentum muons, the best momentum resolution (by an order of magnitude) is given by the resolution obtained in the silicon tracker (“inner tracker only” in Fig. 2.10). However, the muon trajectory beyond the return yoke extrapolates back to the beam-line due to the compensation of the bend before and after the coil when multiple scattering and energy loss can be neglected. This fact can be used to improve the muon momentum resolution at high momentum when combining the inner tracker and muon detector measurements (“full system” in Fig. 2.10). Three types of gaseous detectors are used to identify and measure muons [17]. The choice of the detector technologies has been driven by the very large surface to be covered and by the different radiation environments. In the barrel region ($|\eta| < 1.2$), where the neutron induced background is small, the muon rate is low and the residual magnetic field in the chambers
is low, drift tube (DT) chambers are used. In the 2 endcaps, where the muon rate as well as the neutron induced background rate is high, and the magnetic field is also high, cathode strip chambers (CSC) are deployed and cover the region up to $|\eta| < 2.4$. In addition to this, resistive plate chambers (RPC) are used in both the barrel and the endcap regions. These RPCs are operated in avalanche mode to ensure good operation at high rates (up to $10 \, kHz/cm^2$) and have double gaps with a gas gap of 2 mm. The inner bakelite surfaces of the RPC is coated with linseed oil for good noise performance. The RPCs provide a fast response with good time resolution but with a coarser position resolution than the DTs or CSCs. The RPCs can therefore identify unambiguously the correct bunch crossing.

The DTs or CSCs and the RPCs operate within the first level trigger system, providing 2 independent and complementary sources of information. The complete system results in a robust, precise and flexible trigger device. In the initial stages of the experiment, the RPC system will cover the region $|\eta| < 1.6$. The coverage will be extended to $|\eta| < 2.1$ later.

The layout of one quarter of the CMS muon system for initial low luminosity running is shown in Fig. 2.11. In the Muon Barrel (MB) region, 4 stations of detectors are arranged in cylinders interleaved with the iron yoke. The segmentation along the beam direction follows the 5 wheels of the yoke (labeled YB-2 for the farthest wheel in $-z$, and YB+2 for the farthest is $+z$). In each of the endcaps, the CSCs and RPCs are arranged in 4 disks perpendicular to the beam, and in concentric rings, 3 rings in the innermost station, and 2 in the others. In total, the muon system contains of the order 25 000 $m^2$ of active detection planes, and nearly 1 million electronic channels.

**Drift Tubes**

The Barrel Detector, consists of 250 chambers organized in 4 layers (stations labeled MB1, MB2, MB3 and MB4 with the last being the outermost) inside the magnet return yoke, at radii of approximately 4.0, 4.9, 5.9 and 7.0 m from the beam axis. Each of the 5 wheels
Figure 2.11: Layout of one quarter of the CMS muon system for initial low luminosity running. The RPC system is limited to $|\eta| < 1.6$ in the endcap, and for the CSC system only the inner ring of the ME4 chambers have been deployed.

of the Barrel Detector is divided into 12 sectors, with each covering a $30^\circ$ azimuthal angle. Chambers in different stations are staggered so that a high-$p_T$ muon produced near a sector boundary crosses at least 3 out of the 4 stations. There are 12 chambers in each of the 3 inner layers. In the 4th layer, the top and bottom sectors host 2 chambers each, thus leading to a total of 14 chambers per wheel in this outermost layer. The MB1, 2 and 3 chambers consist of 12 planes of aluminium drift tubes; 4 $r-\phi$ measuring planes in each of the 2 outermost “superlayers,” separated by about $20\,\text{cm}$ and sandwiching a z-superlayer comprising 4 z-measuring planes. The MB4 station does not contain the z-measuring planes. The maximum drift length is $2.0\,\text{cm}$ and the singlepoint resolution is $\approx 200\,\mu\text{m}$. Each station is designed to give a muon vector in space, with a $\phi$ precision better than $100\,\mu\text{m}$ in position and approximately 1 mrad in direction. Each DT chamber has 1 or 2 RPCs coupled to it before installation, depending on the station. In stations MB1 and MB2, each package consists of 1 DT chamber sandwiched between 2 RPCs. In stations MB3 and MB4, each package comprises 1 DT chamber and 1 RPC, which is placed on the innermost side of the station. A high-$p_T$ muon thus crosses up to 6 RPCs and 4 DT chambers, producing up to 44 measured points in the DT system from which a muon-track candidate can be built. Fig. 2.12 shows the structure of the drift tube.

Cathode Strip Chambers

The Muon Endcap (ME) system comprises 468 CSCs in the 2 endcaps. Each CSC is trapezoidal in shape and consists of 6 gas gaps, each gap having a plane of radial cathode strips
and a plane of anode wires running almost perpendicularly to the strips. All CSCs except those in the third ring of the first endcap disk (ME1/3) are overlapped in phi to avoid gaps in the muon acceptance. There are 36 chambers in each ring of a muon station, except for the innermost ring of the second through fourth disks (ME2/1, ME3/1, and ME4/1) where there are 18 chambers. The gas ionization and subsequent electron avalanche caused by a charged particle traversing each plane of a chamber produces a charge on the anode wire and an image charge on a group of cathode strips. The signal on the wires is fast and is used in the Level-1 Trigger. However, it leads to a coarser position resolution. A precise position measurement is made by determining the centre-of-gravity of the charge distribution induced on the cathode strips. Each CSC measures up to 6 space coordinates \((r, \phi, z)\). The spatial resolution provided by each chamber from the strips is typically about 200 \(\mu m\) for ME1/1). The angular resolution is of the order 10 \(mrad\). Figure 2.13 shows schematically CSCs used in CMS muon detector.
Resistive Parallel Plate Chambers

Resistive parallel plate chambers are fast gaseous detectors whose information is at the base of the triggering process. The RPCs combine a good spatial resolution with a time resolution of 1 ns, comparable to that of scintillators. The RPC is a parallel plate counter with the two electrodes made of very high resistivity plastic material. This allows the construction and operation of very large and thin detectors that can operate at a high rate and with a high gas gain within developing streamers or catastrophic sparks. The high gain and thin gap result in a small but very precise delay for the time of passage of an ionizing particle. The electric field inside a RPC is uniform. Electrons made free by the ionizing particle near cathode generate a larger number of secondary electrons (exponential multiplication). A proper threshold setting allows the detection of a signal dominated by the electrons generated near the cathode. The threshold setting determines to a large extent the time delay of the pulse, the time resolution and also the efficiency. With a proper choice of the resistivity and plate thickness, the rate capability can reach several thousand $Hz/cm^2$. Figure 2.14 shows a combination of two RPC gaps. One of the two resistive plates holds a glued array of small 2 mm thick spacers having a typical pitch of 10 cm. Also glued on the plate is the border that will guarantee the chamber tightness. The second plate is then placed on top and the detector is completed.

The total area covered by the RPCs reaches 4000 $m^2$. The particle rate varies from 1 up to 1000 $Hz/cm^2$ depending on the angle. In total of the order of $10^{16}$ p-p collisions per year will be seen. On the average 25 $P−P$ collisions take place every 25 ns. The first level single muon trigger has to reduce this rate down to about 1 $kHz$, i.e. six orders of magnitude.

2.2.6 Trigger and data acquisition

The LHC bunch crossing rate of 40 MHz leads to $10^9$ interactions/sec at design luminosity. Data from only about $10^2$ crossings/sec can be written to archival media; hence, the trigger
system has to achieve a rejection factor of nearly $10^6$. The CMS trigger and data acquisition system [19, 20] consists of 4 parts: the detector electronics, the Level-1 trigger processors (calorimeter, muon, and global), the readout network, and an online event filter system (processor farm) that executes the software for the High-Level Triggers (HLT).

**Level-1 trigger**

The size of the LHC detectors and the underground caverns imposes a minimum transit time for signals from the front-end electronics to reach the services cavern housing the Level-1 trigger logic and return back to the detector front-end electronics. The total time allocated for the transit and for reaching a decision to keep or discard data from a particular beam crossing is $3.2 \mu s$. During this time, the detector data must be held in buffers while trigger data is collected from the front-end electronics and decisions reached that discard a large fraction of events while retaining the small fraction of interactions of interest (nearly 1 crossing in 1000). Of the total latency, the time allocated to Level-1 trigger calculations is less than $1 \mu s$.

In Table 2.5 a list of kinematic thresholds for physical object selection at level 1 has been presented. Custom hardware processors form the Level-1 decision. The Level-1 triggers involve the calorimetry and muon systems, as well as some correlation of information between these systems as shown in Fig. 15. The Level-1 decision is based on the presence of “trigger primitive” objects such as photons, electrons, muons, and jets above set $E_T$ or $p_T$ thresholds. It also employs global sums of $E_T$ and $E_T^{\text{miss}}$. Reduced-granularity and reduced-resolution data are used to form trigger objects. At startup the Level-1 rate will be limited to 50 kHz (the design value is 100 kHz). Taking a safety margin of a factor of 3 into account for simulation uncertainties, as well as beam and detector conditions not included in the simulation programs, leads to an estimated rate of 16 kHz. The design value of 100 kHz is set by the average time to transfer full detector information through the readout system.

Much of the logic in the trigger system is contained in custom Application Specific Integrated Circuits (ASICs), semi-custom and gate-array ASICs, Field Programmable Gate Arrays (FPGAs), Programmable Logic Devices (PLDs), and discrete logic such as Random

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Threshold (GeV)</th>
<th>Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron/photon</td>
<td>29</td>
<td>3.3</td>
</tr>
<tr>
<td>Di-electron/di-photon</td>
<td>17</td>
<td>1.3</td>
</tr>
<tr>
<td>Muon</td>
<td>14</td>
<td>2.7</td>
</tr>
<tr>
<td>Di-muon</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>Single tau-jet</td>
<td>86</td>
<td>2.2</td>
</tr>
<tr>
<td>Two tau-jets</td>
<td>59</td>
<td>1.0</td>
</tr>
<tr>
<td>Jet$^*E_T^{\text{miss}}$</td>
<td>88*46</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Access Memories that are used for memory Look-Up Tables (LUTs). Where possible and where the added flexibility offers an advantage and is cost effective, designs incorporate new FPGA technology. During the Level-1 decision-making period, all the high-resolution data is held in pipelined memories. Commodity computer processors make subsequent decisions using more detailed information from all of the detectors in more and more sophisticated algorithms that approach the quality of final reconstruction.

High-level triggers

Upon receipt of a Level-1 trigger, after a fixed time interval of about 3.2 \(\mu s\), the data from the pipelines are transferred to front-end readout buffers. After further signal processing, zero suppression and/or data-compression, the data are placed in dual-port memories for access by the DAQ system. Each event, with a size of about 1.5 MB, is contained in several hundred front-end readout buffers. Through the event building “switch”, data from a given event are transferred to a processor. Each processor runs the same high-level trigger (HLT) software code to reduce the Level-1 output rate of 100 kHz to 100 Hz for mass storage.

The use of a processor farm for all selections beyond Level-1 allows maximal benefit to be taken from the evolution of computing technology. Flexibility is maximized since there is complete freedom in the selection of the data to access, as well as in the sophistication of the algorithms.

Table 2.6 shows a list of kinematic thresholds for physical object selection at high level trigger. Various strategies guide the development of the HLT code. Rather than reconstruct all possible objects in an event, whenever possible only those objects and regions of the detector that are actually needed are reconstructed. Events are to be discarded as soon as
### Table 2.6: High Level trigger thresholds at low luminosity

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Threshold (GeV)</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>Di-electrons</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>Photon</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td>Di-photons</td>
<td>40,25</td>
<td>5</td>
</tr>
<tr>
<td>Muon</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>Di-muon</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Single tau-jet</td>
<td>86</td>
<td>1</td>
</tr>
<tr>
<td>Two tau-jets</td>
<td>59</td>
<td>3</td>
</tr>
<tr>
<td>Jet* $E_T^{miss}$</td>
<td>180*123</td>
<td>5</td>
</tr>
</tbody>
</table>

possible. This leads to the idea of partial reconstruction and to the notion of many virtual trigger levels, e.g., calorimeter and muon information are used, followed by use of the tracker pixel data and finally the use of the full event information (including full tracking).

#### 2.2.7 Physics and detector requirements

**Search for the higgs boson**

In the design phase of CMS and ATLAS in the early 1990s, the detection of the SM Higgs boson was used as a benchmark to test the performance of the proposed designs. It is a particularly appropriate benchmark since there is a wide range of decay modes depending on the mass of the Higgs boson.

The current lower limit on the mass of the Higgs boson from LEP is $114.4 \text{ GeV}/c^2$. In the vicinity of this limit, the branching fractions of the Higgs boson are dominated by hadronic decays, which are difficult to use to discover the Higgs boson at the LHC due to the large QCD backgrounds and the relatively poor mass resolution that is obtainable with jets. Hence, the search is preferentially conducted using final states that contain isolated leptons and photons, despite the smaller branching ratios.

The natural width of the Higgs boson in the intermediate – mass region ($114 \text{ GeV}/c^2 < m_H < 2m_Z$) is only a few MeV, and the observed width of a potential signal will be dominated by the instrumental mass resolution. In the mass interval $114 - 130 \text{ GeV}/c^2$, the two-photon decay is one of the principal channels likely to yield a significant signal. Central exclusive production of the Higgs might offer the only way to access the $b\bar{b}$ decay mode. The Higgs boson should be detectable via its decay into 2 Z bosons if its mass is larger than about $130 \text{ GeV}/c^2$ (one of the $Z$’s is virtual when $m_H$ is below the ZZ threshold). For $2m_Z < m_H < 600 \text{ GeV}/c^2$ the ZZ decay, with its four-lepton final states, is the mode of choice.

In the region $600 < m_H < 1000\text{ GeV}/c^2$, the cross section decreases so that higher branching fraction modes involving jets or $E_T^{miss}$ from W or Z decays have to be used. The
jets from W and Z decays will be boosted and may be close to each other in $\eta - \phi$ space.

The dominant Higgs-boson production mechanism, for masses up to about 700 GeV/$c^2$, is gluon-gluon fusion via a t-quark loop. The WW or ZZ fusion mechanism becomes important for the production of higher-mass Higgs bosons. Here, the quarks that emit the Ws or Zs have transverse momenta of the order of W and Z masses. The detection of the resulting high-energy jets in the forward regions ($2 < |\eta| < 5$) can be used to tag the reaction, improving the signal-to-noise ratio and extending the range of masses over which the Higgs can be discovered. These jets are highly boosted and their transverse size is similar to that of a high-energy hadron shower.

More recently, the fusion mechanism has also been found to be useful for detecting an intermediate mass Higgs boson through channels such as $qq \rightarrow qqH$, followed by $H \rightarrow \tau\tau$.

Search for supersymmetric particles

The decays of supersymmetric particles, such as squarks and gluinos, involve cascades that, if $R$-parity is conserved, always contain the lightest SUSY particle (LSP). The latter is expected to interact very weakly, thus leading to significant $E_T^{\text{miss}}$ in the final state. The rest of the cascade results in an abundance of leptons and jets (particularly b-jets and/or $\tau$-jets). In GMSB schemes with the LSP decaying into a photon and gravitino, an increased number of hard isolated photons is expected.

Search for new massive vector bosons

The detector requirements for high momenta can be determined by considering decays of high-mass objects such as $Z' \rightarrow e^+e^-$ and $\mu^+\mu^-$. The discovery of an object like a $Z'$ boson will, very likely, be limited by the statistical significance of the signal. Ways of distinguishing between different models involve the measurement of the natural width and the forward backward asymmetry, both of which require sufficiently good momentum resolution at high $p_T(\Delta p_T/p_T < 0.1$ at $p_T \approx 1$ TeV/$c$) to determine the sign of the leptons and a pseudorapidity coverage up to $\eta = 2.4$.

Extra dimension

The existence of extra dimensions can lead to a characteristic energy scale of quantum gravity, $M_D$, which is the analogue of the Planck mass in a D-dimensional theory, and which could lie just beyond the electroweak scale. In terms of experimental signatures, 3 regimes can be distinguished [34] Cis-Planckian, where $E \ll M_D$, leading to signals involving the emission of gravitons that escape into extra dimensions, e.g. $pp \rightarrow \text{jet} + \text{graviton} \rightarrow \text{jet} + E_T^{\text{miss}}$, ii) Planckian, $E \approx M_D$, leading to model-dependent signatures. In string-theory motivated models there are Regge-like excitations that manifest themselves as Z-like resonances with TeV separations in mass, iii) Trans-Planckian, $E >> M_D$, leading to anomalous high mass dijet production and to mini black hole production with spectacular decays involving equal and democratic production of fundamental particles such as leptons, photons, neutrinos, W,
Z, jets, etc. The resulting production and kinematic distributions could allow the determination of the Hawking temperature, the mass of the black holes, the number of extra dimensions, etc.

**Standard model**

The LHC will also allow studies of QCD, electroweak, and flavour physics. Precision studies can give indications for physics beyond the SM, providing complementary information with respect to direct searches. As an example, extensive tests of QCD will be possible through the measurement of the production of jets and direct photons with transverse energies up to 3-4 TeV and from cross-section measurements which fall by 11 orders of magnitude. Top quarks will be produced at the LHC with a rate measured in Hz, thus the opportunity to test the SM couplings and spin of the top quark is available provided good identification of b-jets in the decays is possible. Searches for flavour changing neutral currents, lepton flavour violation through $\tau \to 3\mu$ or $\tau \to \mu\gamma$, measurements of $B^0_s \to \mu\mu$, measurements of triple- and quartic gauge couplings, etc. can open a window onto new physics. Finally, in association with TOTEM, CMS will be able to cover the full range of diffractive physics as well.

**Heavy-ion physics**

The recent results from RHIC indicate that very strongly interacting nuclear matter is produced in high energy heavy-ion collisions. The most striking experimental signatures of the produced matter are the suppression of high $p_T$ particles (jet quenching) and the strong elliptical flow approaching the hydrodynamic limit. The increase in collision energy from $\sqrt{s_{NN}} = 200$ GeV/$c^2$ at RHIC to 5500 GeV/$c^2$ at LHC will allow the extension of studies of jet quenching to much higher $p_T$ and the identification of fully formed jets. The measurements of energy flow at LHC will stringently test the liquid-like behavior of the hot nuclear matter. The increased energy will also allow studies of presently inaccessible hard probes like $\Upsilon$ and $Z^0$. The studies of jet quenching, energy flow, and quarkonium production will require large-acceptance, high-resolution calorimeters and tracking devices, as well as a flexible trigger.
Chapter 3

Physics of Resistive Plate Chambers

3.1 Interactions of particles with matter

The particle detector has to be able to reveal the presence of eight particles (and their corresponding antiparticles): electrons, muons, protons, neutrons, photons, charged pions, charged kaons and neutral kaons. These particles leave characteristic trails as they lose energy when they travel through a material, be it a gas, a liquid or a solid. This energy loss can be of different forms:

- Electrically charged particles lose energy by colliding with atomic electrons of the material (excitation, ionization) and by the emission of bremsstrahlung when they scatter off the nuclei.

- Strongly interacting particles can in addition lose energy through hadronic interactions (inelastic nuclear collisions, nuclear excitation, splitting).

- Photons lose energy by Compton scattering with atomic electrons or they disappear completely in the processes of Photo Electric Effect and pair production.

In this section the basic interaction mechanisms of particles with matter are summarized briefly [35]. The energy loss of charged particles due to ionization and excitation is fundamental to most particle detectors and the RPC, which is the topic of this chapter and is therefore described in more detail.

3.1.1 Energy loss due to ionization and excitation

We consider a relativistic charged particle scattering with atomic electrons, e.g.

$$\mu^+ + \text{atom} \rightarrow \mu^+ + \text{atom}^+ + e^-.$$
If the distance of closest approach is large compared to the size of the atom (a distant collision), the atom will react as a whole to the variable electromagnetic field of the charged particle. The result can be excitation or ionization of the atom. If the distance of closest approach is of the order of the atomic dimensions, (a close collision) the interaction involves the passing particle and one of the atomic electrons. As a consequence, the electron is ejected from the atom with considerable energy (knock-on electrons). We define [36] distant collisions: Any collision resulting in the ejection of an electron of energy smaller than a predetermined value.

close collisions: Any collision resulting in the ejection of an electron of energy larger than \( \nu \). If \( \nu \) is sufficiently large (and the corresponding impact parameter sufficiently small) we can treat all close collisions by considering the atomic electrons as free particles. A limiting energy \( \nu \) of 10 to 100 keV simultaneously satisfies the two conditions specified above for practically all cases of importance in the field of high energy phenomena.

The Differential Collision Cross-Section

We [35] note the atomic differential cross section that a particle with energy \( E \) loses an energy between \( E' \) and \( E' + dE' \) in a collision with an atom

\[
\frac{d\sigma}{dE'} |_{\text{col}}
\]

Then

\[
\rho \frac{N_A}{A} \frac{d\sigma}{dE'} |_{\text{col}}
\]

is the average number of collisions with an energy loss between \( E' \) and \( E' + dE' \) per unit length in a material with density \( \rho \) [g/cm\(^3\)] and atomic number \( A \) [g/mol]. \( N_A \) [1/mol] is Avogadro’s number. This leads to the average energy loss per length \( dx \),

\[
-\frac{dE}{dx} |_{\text{col}} = \frac{N_A}{A} \int_{E_{min}}^{E_{max}} E' \frac{d\sigma}{dE'} |_{\text{col}} dE' = \rho \frac{N_A}{A} k_{\text{col}}
\]

In literature one often finds the thickness \( dx \) measured in g/cm\(^2\) and the energy loss \(-\frac{dE}{dx} |_{\text{col}}\) given in MeV cm\(^2\)/g. We will note \(-\frac{1}{\rho} \frac{dE}{dx} |_{\text{col}}\) instead, which leaves \( dx \) with the unit length. Let \( k_{\text{col}(<\nu)} \) represent the energy loss resulting from distant collisions and \( k_{\text{col}(>\nu)} \) the energy loss resulting from close collisions, then the total energy loss is given by the sum of the two

\[
-\frac{1}{\rho} \frac{dE}{dx} |_{\text{col}} = \frac{N_A}{A} (k_{\text{col}(<\nu)} + k_{\text{col}(>\nu)}).
\]

The distant Collisions

For the calculation of the energy loss due to distant collisions \( k_{\text{col}(<\nu)} \) it is important to take into account the binding of the electrons to the atoms. The average ionization energy \( I \)
[MeV] of the atoms should appear in the formula. Bethe obtained the following result with the help of Born’s approximation [37, 38]

\[ k_{\text{col}(\nu)} = \frac{C}{\beta^2} \left[ \ln \frac{2m_e c^2 \beta^2 \gamma^2 \nu}{I^2} - \beta^2 \right] \] (3.1.5)

Here we have

- \( C \) - a constant defined by \( C = 2\pi Z z^2 r_e^2 m_e c^2 \) [MeV cm\(^2\)] and connected to the Particle Data Groups constant \( K \) [39] by \( C = z^2 Z K / 2N_A \),
- \( Z \) - the atomic charge number of the material,
- \( z \) - the charge of the incident particle in unit charges,
- \( r_e \) - the classical electron radius \( r_e = e^2 / 4\pi \epsilon_0 m_e c^2 \),
- \( m_e \) - the electron mass,
- \( e \) - the electron charge,
- \( \epsilon_0 \) - the dielectric constant of the vacuum,
- \( c \) - the speed of light,
- \( \beta \) - the velocity of the particle in units of \( c \) and
- \( \gamma \) - is given by \( 1 / \sqrt{1 - \beta^2} \) as usual.

Eq. 3.1.5 is valid for particles of any kind, with positive or negative charge and with velocity large compared to the velocity of the atomic electrons.

**Close Collision**

For close collisions we start with an investigation of the maximum transferable energy. As mentioned previously, a close collision of the particle with an atomic electron is not necessarily different from a collision between a charged particle and a free electron. The application of the principles of conservation of energy and momentum leads to the following relation for the maximum kinetic energy, that can be imparted to a free electron in a collision by a particle of mass \( m \) and momentum \( p \) [39].

\[ E_{\text{max}} = \frac{2m_e p^2}{m^2 + 2\gamma m_e m + m_e^2} \] (3.1.6)

For very relativistic particles (\( E_{\text{kin}} \approx E, pc \approx E \)) Eq. 3.1.6 becomes

\[ E_{\text{max}} \approx \frac{E^2}{2m_e c^2} + E \] (3.1.7)

For example, in a muon-electron collision the maximum transferable energy is \( E_{\text{max}} \approx E^2 / (E + 11) \), when the energy of the muon \( E \) is measured in GeV. A 200 GeV muon can be practically stopped by a head-on collision with an electron, because in this extreme relativistic case almost the total energy (\( \approx 95\% \)) in transferred to the electron. The energy loss due to close collisions \( k_{\text{col}(\nu)} \) is calculated by integration (\( \nu << E_{\text{max}} \))

\[ k_{\text{col}(\nu)} = \int_{\nu}^{E_{\text{max}}} E' \frac{d\sigma}{dE'} |_{\text{col}} \ dE' \] (3.1.8)
For particles with Spin 0, mass \( m \) larger than the mass of electrons and energy small compared to \( E_c = m^2c^2/m_e \), we get

\[
k_{\text{col}(>\nu)} = \frac{C}{\beta^2} \left[ \ln \frac{E_{\text{max}}}{\nu} - \beta^2 \right].
\] (3.1.9)

**Total Energy Loss**

The total energy loss for heavy particles is calculated using Eqs. 3.1.4, 3.1.5 and 3.1.9 as ..

\[
-\frac{1}{\rho} \frac{dE}{dx} \bigg|_{\text{col}} = \frac{C N_A}{\beta^2 A} \left[ \ln \frac{2m_e c^2 \beta^2 \gamma^2 E_{\text{max}}}{I^2} - 2\beta^2 \right]
\] (3.1.10)

As expected, this expression is independent of the arbitrary value of \( \nu \). \( E_{\text{max}} \) may be substituted from Eq. 3.1.6. For electrons and positrons Eq. 3.1.10 must be modified somewhat for two reasons. One is the small mass of the incident electron/positron; the assumption that the incident particle remains undeflected during the collision process is therefore invalid. The other reason is that for electrons the collisions are between identical particles and we must take into account their indistinguishability. The maximum energy transfer allowed becomes \( E_{\text{max}} = E_{\text{kin}}/2 \), where \( E_{\text{kin}} \) is the incident electrons kinetic energy. The total energy loss for electrons and positrons is calculated from Eqs. 3.1.4, 3.1.5, 3.1.6, 3.2.8. With \( \beta \approx 1 \), one obtains [36]

\[
-\frac{1}{\rho} \frac{dE}{dx} \bigg|_{\text{col}} = \frac{C N_A}{A} \left[ \ln \frac{\pi^2 \gamma^3 (m_e c^2)^2}{I^2} - a \right]
\] (3.1.11)

where \( a = 2.9 \) for electrons and \( a = 3.6 \) for positrons.

**The Density Effect**

For relativistic particles, the value of the transverse electric field increases with the energy. As a consequence, the distant collision contribution to the total energy loss due to ionization and excitation increases as \( \ln(\beta\gamma) \) [39]. Since materials become polarized, the electric field of the particle is partly screened. This introduces the density effect correction \( \delta \). At very high energies \( \delta \) becomes

\[
\delta \rightarrow 2\ln(h\omega_p/I) + 2\ln(\beta\gamma) - 1
\] (3.1.12)

Here \( h\omega_p \) is the plasma energy of the medium that is defined by

\[
h\omega_p = \sqrt{4\pi N_e r_e^2 m_e c^2/\alpha}
\] (3.1.13)

with the electron density \( N_e \) and the fine structure constant \( \alpha \approx 1/137 \). Eq. 3.1.10

\[
-\frac{1}{\rho} \frac{dE}{dx} \bigg|_{\text{col}} = \frac{C N_A}{\beta^2 A} \left[ \ln \frac{2m_e c^2 \beta^2 \gamma^2 E_{\text{max}}}{I^2} - 2\beta^2 - \delta^2 \right]
\] (3.1.14)

This is the Bethe-Bloch equation for the energy loss due to ionization and excitation for particles heavier than electrons. Fig. 3.1 shows the energy loss due to ionization and excitation of muons in copper versus the muon momentum. The density effect correction becomes important for muon momenta \( p_\mu \gtrsim 200 \text{ MeV/c} \).
Statistical Fluctuations of the Energy Loss due to Ionization and Excitation

The quantity \( \frac{dE}{dx}_{\text{col}} \) is the average energy loss due to Ionization and Excitation in a layer of the medium with thickness \( \delta x \). The real energy loss will fluctuate around this average value from event to event. The energy loss distribution is called the Landau distribution [40] and is skewed towards high values (the Landau tail). Only for a thick layer, where the energy loss exceeds one half of the original particle energy, the distribution becomes roughly Gaussian [39].

3.1.2 Other Interaction Mechanisms of Radiation with Matter

The energy loss due to ionization and excitation is not the only interaction process of radiation with matter. Charged particles can also lose energy by radiation (bremsstrahlung). The energy loss connected with the processes of transition radiation and Cherenkov radiation are negligible, nevertheless they are important processes for identification of charged particles. Moreover, we distinguish three processes in which photons interact with matter: the Photo Electric Effect, the Compton Effect and the Pair Production.

Radiation Loss by Charged Particles

When the distance of closest approach of a fast charged particle becomes smaller than the atomic radius, the deflection of its trajectory in the electric field of the nucleus becomes the most important effect. Let \( \frac{d\sigma(\Theta)}{d\omega} \bigg|_{\text{scat}} \) be the differential atomic cross section that a particle of momentum \( p \) and velocity \( v = \beta c \) undergoes a collision which deflects its trajectory into
the solid angle $d\omega$ at angle $\Theta$ to its original direction of motion. If one neglects both the
finite dimension of the nucleus and the shielding of its field by the atomic electrons, one
obtains the well-known Rutherford scattering formula [41, 42]

$$\frac{d\sigma(\Theta)}{d\omega} \bigg|_{\text{scat}} = \frac{z^2 Z^2 r^2}{4} \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4(\Theta/2)} \quad (3.1.15)$$

Then the term $\frac{N_A \rho \frac{d\sigma}{d\omega}}{A} \bigg|_{\text{scat}}$ gives the average number of collisions per length in a medium of
density $\rho$ with scattering of the particle into $d\omega$. The multiple Coulomb scattering distribution is roughly Gaussian for small angles but at larger angles it behaves like Rutherford
scattering, having larger tails than does a Gaussian distribution [39, 43, 44]. In some cases a
photon of energy comparable with that of the deflected particle is emitted during the scattering process, e.g.

$$e^+ + \text{nucleus} \rightarrow e^- + \gamma + \text{nucleus}'$$

Radiation phenomena occur at distances of the order of the atomic radius so that the screening of the electric field of the nucleus by the atomic electrons has to be taken into account
[45]. However, the field acting on the particle during the deflection process can be considered
as the Coulomb field of a point charge $Ze$ at the center of the nucleus [36]. The mean energy
loss of an electron due to bremsstrahlung is [39]

$$-\frac{1}{\rho} \frac{dE}{dx} \bigg|_{\text{rad}} = \frac{E}{X_0}. \quad (3.1.16)$$

The characteristic amount of matter traversed is called the radiation length $X_0$, measured
in g/cm$^2$. $x = X_0/\rho$ is the mean length of electron trajectory through a medium of density $\rho$, over which the high energy electron loses all but $1/e$ of its energy by bremsstrahlung. Approximate formulas for $X_0$ are given in [41]. The energy loss by radiation depends strongly
on the absorbing material. For each material we can define a critical energy $E_c$ at which the radiation loss equals the ionization loss. For electrons we find

$$E_c = \frac{610 \text{MeV}}{Z + 1.24} \quad \text{for solids and} \quad E_c = \frac{710 \text{MeV}}{Z + 0.92} \quad \text{for gases.} \quad (3.1.17)$$

Using Eqs. 3.1.17, the critical energy for copper ($Z = 29$) is 20 MeV and for helium ($Z = 2$) it is 243 MeV. Bremsstrahlung dominates the energy loss above this energy; ionization dominates at lower energies. At sufficiently high energies, radiative processes become more important than ionization for all charged particles. The mean energy loss due to
bremsstrahlung of a charged particle of mass $m$ and charge $ze$ (where $e$ is the charge of the electron) is found from Eq. 3.1.16 by scaling with $D = (m_e/m)^2$, where $m_e$ is the electron mass. The critical energy scales with $1/D$. For muons in copper the two energy loss mechanisms are compared in Fig. 3.1. The critical energy is around 800 GeV.
Cherenkov Radiation

If the velocity of a particle is larger than the velocity of light in the medium (\( \nu > nc \), \( n = \) the refractive index of the material), it emits Cherenkov radiation at a characteristic angle \( \Theta_c \) given by \( \cos \Theta_c = 1/n\beta \) [39]. The number of emitted photons with a wavelength \( \lambda \) is

\[
\frac{d^2N}{dEdx} \bigg|_{cer} = \frac{2\pi \alpha z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right).
\]

The energy loss connected with this process is negligible but it is used in the detection and identification of particles (electron/pion separation, pion/proton separation and other). Cherenkov counters utilize one or more of the properties of Cherenkov radiation: the existence of a threshold for Cherenkov radiation, the dependence of \( \Theta_c \) on the velocity \( \nu = \beta c \) of the particle and/or the dependence of the number of emitted photons on the velocity of the particle.

Transition Radiation

Characteristic transition radiation is used for identifying fast electrons in Transition Radiation Detectors (TRDs; for example, see [46]). Consider a particle of charge \( ze \) crossing a boundary between vacuum and a material with a plasma frequency \( \hbar \omega_p \) given by Eq. 3.1.13. For typical radiator materials (Styrene) it is about 20 eV. The radiated energy is

\[
E_{thr} = \alpha z^2 \gamma \hbar \omega_p \frac{\omega_p}{3}.
\]

The typical emission angle is \( 1/\gamma \). Several layers of material lead to several boundaries which increases the radiated energy. The radiated energy increases with \( \gamma \). Since electrons are in general the fastest particles observed in an experiment (due to their low mass), TRDs can provide electron/pion separation in the momentum range \( 0.5 \text{ GeV}/c \lesssim p \lesssim 100 \text{ GeV}/c \) [46].

Photon Interactions with Matter

We distinguish three processes in which photons interact with matter:

**Photo Electric Effect:** The interaction of the photon with the atom as a whole leads to the Photo Electric Effect. The photon is absorbed and an electron is emitted from the atom, e.g.

\[
\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-
\]

The cross section falls at high energies roughly as \( Z^5/\hbar \omega \) [41], where \( Z \) is the atomic charge number of the absorber material and \( \hbar \omega \) is the energy of the photon. The Photo Electric Effect is important up to energies of around 100 keV(10 MeV) for materials like carbon with \( Z = 6 \) (lead with \( Z = 82 \)).

**Compton Scattering:** The interaction of the photon with a free electron leads to the Compton Effect. The photon transfers a part of its energy and momentum to the electron initially at rest, e.g.
\[ \gamma + e \rightarrow \gamma' + e' \]

The cross section is proportional to \( Z/h\omega \) [41]. The Compton effect is important for photon energies from about 100 eV to about 1 GeV (10 GeV) in carbon (lead).

**Pair Production:** The interaction of the photon with the Coulomb field of the nucleus leads to the phenomenon of Pair Production, whereby the photon disappears and an electron and a positron come into existence simultaneously, e.g.

\[ \gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}' \]

The Feynman diagram is similar to that of bremsstrahlung, e.g.

\[ e^- + \text{nucleus} \rightarrow e^- + \gamma + \text{nucleus}' \]

The cross sections of the two processes are therefore closely related. The cross section for pair production is proportional to \( Z^2 \). At high energies it becomes independent of the energy of the photon and screening of the electric field of the nucleus by the atomic electrons has to be taken into account. Then the cross section becomes [41]

\[ \sigma_{\text{pair}} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0} \]

(3.1.20)

**Hadron Interactions with Matter** The strong interaction plays an important role in the detection of hadrons (\( p, \bar{p}, n, \bar{n}, \pi^\pm, K^\pm, K^0 \)), e.g.

\[ p + \text{nucleus} \rightarrow \pi^+ + \pi^- + \pi^0 + \ldots + \text{nucleus}' \]

When the secondary charged pions hit other nuclei, a hadronic cascade develops. Hadronic cascades also have an electromagnetic component from \( \pi^0 \rightarrow \gamma \gamma \). The total cross section for nucleons has an elastic and inelastic part. The multiplicity grows logarithmically with the energy [41] and the particles are produced in a narrow cone around the forward direction. Hadronic cascades are fundamental to the operation of hadronic calorimeters. Part of the energy of the incident hadron is spent to break up nuclear bonds. This fraction of the energy is invisible in hadron calorimeters. Further energy is lost by escaping particles like neutrinos and muons as a result of hadron decays \( \pi^\pm \rightarrow \mu^\pm + \nu \). Since the fraction of lost binding energy and escaping particles fluctuates considerably, the energy resolution of hadron calorimeters is systematically inferior to electromagnetic calorimeters.

### 3.1.3 Energy Loss and Particle Detection with RPCs

The topic of this thesis are Resistive Plate Chambers (RPCs), which are gaseous avalanche detectors. When charged particles traverse the gas gap of an RPC, they lose a fraction of their kinetic energy by excitation and ionization of atoms or gas molecules. The energy loss per unit of path length for particles heavier than electrons is given by the Bethe-Bloch equation (Eq. 3.1.14). If an atom in the gas is ionized by the inelastic collision of the traversing particle, free charge carriers are deposited close to the position of the encounter. If the atom
is not ionized but brought to an excited state, it promptly loses the excitation energy by the emission of a photon or an Auger electron. The photons will be absorbed by Photo Electric Effect as long as their energies are larger than the minimum ionization potential, or they escape. The energy escaping in the form of photons is not detected by a gaseous particle detector like the RPC. Electrons and highly relativistic charged particles other than electrons also lose energy by bremsstrahlung. As was mentioned previously, this process becomes the main energy loss mechanism, if the energy of the particle is above the critical energy $E_c$. However, most of the lost energy disappears in the form of the radiated photons and the RPC does not respond to that energy loss. This leaves us with the energy loss due to ionization and excitation being the important fundamental mechanism underlying the operation of RPCs. The energy loss due to ionization and excitation is shown for different materials in Fig. 3.2. Primary clusters of free charge carriers (electron-ion pairs) are deposited along the trajectory of the particle. In the gas gap of the RPC they are collected and multiplied by a strong uniform electric field and the propagation of the growing number of charges induces a signal on the read out electrodes. The primary ionization is characterized by the average number of clusters per unit length and by the cluster size distribution.

Figure 3.2: The energy loss for muons passing through different absorbers.
3.2 General Description of RPC

3.2.1 Overview

The Resistive Plate Chamber (RPC) using Bakelite plates was developed some years ago by Santonico and Cardarelli [47]. The RPCs are gaseous parallel-plate detectors that combine good spatial resolution with a time resolution comparable to that of scintillators. They are therefore well suited for fast space-time particle tracking as required for the muon trigger at the LHC experiments.

An RPC consists of two parallel plates, made out of phenolic resin (bakelite) with a bulk resistivity of $10^{10} - 10^{11} \, \Omega \cdot \text{cm}$, separated by a gas gap of a few millimeters [17]. The whole structure is made gas tight. The outer surfaces of the resistive material are coated with conductive graphite paint to form the HV and ground electrodes. The read-out is performed by means of aluminum strips separated from the graphite coating by an insulating PET film.

So far, RPCs have been operated in streamer mode, i.e. the electric field inside the gap is kept intense enough to generate limited discharges localized near the crossing of the ionizing particle. However, the rate capability obtained in such operational conditions is limited ($\sim 100 \, \text{Hz/cm}^2$) and not adequate for LHC.

A significant improvement is achieved by operating the detector in the so-called avalanche mode [48]; the electric field across the gap (and consequently the gas amplification) is reduced and a robust signal amplification is introduced at the front-end level. The substantial reduction of the charge produced in the gap improves the rate capability by more than one order of magnitudes.

An RPC is capable of tagging the time of an ionizing event in times shorter than the 25 ns between two successive bunch crossings (BX). A fast dedicated muon trigger detector, based on RPCs can therefore identify unambiguously the relevant BXs with which the muon tracks are associated, even in the presence of the high rate and background expected at LHC. Signals from such detectors directly provide the time and the position of a muon hit with the required accuracy.

The trigger based on such a detector has to perform three basic functions simultaneously [49]:

- identify candidate muon track(s);
- assign a bunch crossing to the candidate track(s);
- estimate their transverse momenta.

All these functions must be performed with high efficiency in an environment where due to the gamma and neutron background, the hit rates may reach $10^3 \, \text{Hz/cm}^2$. A total of six layers of RPCs will be embedded in the barrel iron yoke, two located in each of the muon stations MB1 and MB2 and one in each of the stations MB3 and MB4. The redundancy in the first two stations will allow the trigger algorithm to perform the reconstruction always on the basis of four layers, even for low $P_T$ tracks, which may be stopped inside the detector.
In the forward region, the iron will be instrumented with four layers of RPCs to cover the region up to $\eta = 2.1$. However, a possibility for upgrading the system up to $\eta = 2.4$ is kept open.

### 3.2.2 Specific conditions and requirements

The RPCs should fulfill some basic specific requirements: good timing, low cluster size, good rate capability. Moreover, they are expected to respond with high intrinsic efficiency and to withstand long term operation in high background conditions.

Good time performance is crucial for triggering with high efficiency.Muon identification within a 25 $\text{ns}$ window requires not only a few nanoseconds resolution, but also that the tails of the signal time distribution stay within the window. This implies that the time walk due to the propagation of the signals along the strips and to the possible rate variation (which may affect the drift velocity), should be kept within a few nanoseconds. In CMS, long strips are used in the barrel region where rate effects are negligible, while very short strips are used in the endcap where the rate problem is more severe. The total tolerable time walk introduced by both effects should not exceed $4 - 5$ $\text{ns}$.

In Fig. 3.3 the achievable trigger efficiency, computed using a full simulation of the CMS trigger detector [50], is shown as a function of the RPC time resolution and efficiency. Results only refer to muons generated in the region $-0.09 < \eta > 0.09$ with $50 < p_T < 70$ GeV/$c$ and subject to a $p_T$ cut of 5 GeV/$c$. A more detailed discussion of the trigger algorithm performance will be presented in section 5.10. The cluster size (i.e. the number of contiguous strips which give signals at the crossing of an ionizing particle) should be small.

![Figure 3.3: Dependence of the trigger efficiency on the RPC time resolution (a) and on the RPC efficiency (b) for muons generated in the region $-0.09 < \eta < 0.09$ with $50 < p_T < 70$ GeV/$c$ and subject to a $p_T^\text{cut}$ of 5 GeV/$c$.](image-url)
(≤ 2) in order to achieve the required momentum resolution and minimize the number of possible ghost-hit associations.

Finally, the rate capability should reach $1 kHz/cm^2$ ($ε > 95%$ at $1 kHz/cm^2$). According to recent computations, the hit rate associated with the neutron and gamma background is $20 Hz/cm^2$ in the barrel region and reaches a maximum of $250 Hz/cm^2$ in the forward region at $η = 2.1$. A reasonably safe estimate of $1 kHz/cm^2$ gives therefore the highest rate at which the RPCs are expected to operate.

The full exploitation of the RPC time capability requires working at gains as high as $10^7$. This makes the high rate operation sensitive to the resistance of the electrodes, because a sizable voltage drop is generated in the gas gap by the flow of the current across the resistive plates. This point will be discussed in detail in Section 5.2.2. Moreover, in a parallel plate chamber like an RPC, a large voltage has to be applied to generate a field intensity sufficient for electron multiplication; this makes the energy dissipated in the gas non-negligible. A limit not much larger than $2 W/m^2$ should be achieved. This effect can be limited by an appropriate choice of the gas mixture and the gap width.

In Table 3.1 the main requirements are listed. It is also important to avoid, during the operation, the occurrence of streamers because the large amount of charge involved increases the current unnecessarily.

<table>
<thead>
<tr>
<th>Table 3.1: CMS requirements for RPCs</th>
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<tbody>
<tr>
<td>Efficiency</td>
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<td>Time resolution</td>
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<td>Average cluster size</td>
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<td>Operation plateau</td>
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<td>no. of streamers</td>
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</table>

### 3.3 Principle of Operation

In this section the relevant detector parameters and the basic physical principles underlying the RPC signal formation will be briefly discussed. The electrode resistivity mainly determines the rate capability, while the gap width determines the time performance. Other parameters, such as the gas cluster density and the electrode thickness, are also important and should be optimized to achieve the best performance. In Fig. 3.4 a simple model of the charge formation in an RPC is schematically presented: a cluster of no electrons, produced by an ionizing particle, ignites the avalanche multiplication. An electronic charge $Q_e(d)$ is then developed inside the gap of height $d$. The drift of such charge towards the anode induces on the pick-up electrode the fast charge $q_e$, which represents the useful signal of the RPC.
Figure 3.4: Model of the charge formation in the RPC gap

The power supply has to move the charge $q_s$ in the circuit outside the gap in order to compensate the charge collected on the electrodes. If $\alpha$ is the number of ionizing encounters per unit length undergone by one electron and the attachment coefficient $\beta$ the number of attaching encounters per unit length, the effective ionization coefficient can be defined as $\eta = \alpha - \beta$. An RPC is said to work in “avalanche” or “low gain mode” if the condition $\eta d < 20$ is satisfied. It has been shown [51] that, in this case, the average fast charge $q_e$ of a single avalanche can be evaluated as:

$$< q_e > = \frac{k}{\eta d} < Q_e(d) > = q_{el} n_o \frac{k}{\eta d \lambda + \eta} \epsilon^\eta d$$

where $k = (\epsilon_r \frac{d}{S})/(\epsilon_r \frac{d}{S} + 2)$ is a constant depending on material parameters, and

- $q_{el}$ is the electron charge,
- $n_o$ is the average size of the primary cluster from which the avalanche originated,
- $\lambda$ is the cluster density in the gas mixture (i.e. the number of primary clusters/unit length produced by an ionizing particle),
- $\epsilon_r$ is the relative dielectric constant of the electrode,
- $d$ is the gap width,
- $s$ is the electrode thickness.

For a given $\eta d$, the factors $k$ and $\lambda$ should be as large as possible, in order to maximize the useful signal on the strip. For an avalanche producing $\approx 10^7$ electrons: This is the fast signal by integration we find a charge of 460 $fC$ on the pick-up strips (1/15 of the total 7 $pC$ charge of the electrons in the avalanche). Our detector threshold of 100 $fC$ is similar to
the threshold mentioned by the other researchers in the field of RPCs. The average charge produced on the strip is 10 times this amount, thus on average we have avalanches producing is $pC$ of electron charge ($10^8$ electrons).

This simple model represents a valid approximation for our discussion. However, more clusters may develop in the gap. A better estimate of the average induced charge can be obtained by means of Monte Carlo simulations, where fluctuations of the avalanche can also be considered.

The current in the pick-up electrode is produced by the movement of charge. The magnitude and sign can be calculated from $i = qEwv$, where $Ew$ is the normalized weighting field and $v$ is the velocity of the charge $q$, the concept of which has been described by Radeka.

### 3.3.1 Gas-Ionization Avalanche Mode

Avalanche mode is the mode of operation used for metallic parallel plate chambers (PPCs). The RPC (especially when operated in avalanche mode) can be considered as a PPC with resistive electrodes. It is well known that PPCs need to be constructed with a gap tolerance of $\sim 5 \text{ micron}$; however this is not the case with RPCs due to the resistive plates. *These resistive plates have two beneficial effects,*

- The first is to limit the maximum amount of current so that streamers do not form sparks;
- The second is that variations in gain associated with unavoidable changes in gap dimension are reduced. For example, consider an RPC with a nominal gap of $2 \text{ mm}$, however in some region the gas gap is a little smaller. As the applied voltage is increased, this area will reach the field necessary for gas gain before the rest of the chamber. Since there is gas gain, the dark current will also start to increase in this region; as the plates are resistive this current will generate a voltage drop across the resistive plates which in turn reduces the field across the gas gap. Thus, in general, one can just increase the voltage until the whole active area of the RPC is at full efficiency and allow the resistivity of the plate to limit the field any hot spots. To make this technique work well one needs plates of high resistivity, sufficient dark current and also that the dark current increases quickly with voltage as soon as gas gain is reached) and an operating mode that allows one to increase the voltage at will.

During the avalanche process an electron can either multiply through an ionizing collision or be captured by a freon molecule to form a negative ion. The avalanche is terminated by the electrons arriving at the anode. The movement of positive ions is slow and plays no role in the shape of the fast pulse. The cross section for electron capture by a freon molecule is strongly peaked towards low energies. At low electric fields, where the kinetic energy gained by the electron between collisions is low, the attachment coefficient $\eta$ is high and the Townsend coefficient $\alpha$ is low. The number of electrons produced in an avalanche is

$$N = N_0e^{\alpha x}$$ (3.3.2)
where $N_0$ is the initial number of electrons, $x$ is the distance of avalanche from the electrodes and $\alpha$ is the Townsend coefficient. So in order to operate RPC in avalanche, $\alpha x < 20$ and the multiplication factor $\frac{N}{N_0} < 10^8$.

For freon we replace $\alpha$ in the above equation with the effective $\bar{\alpha} = \alpha - \eta$, and this increases linearly with $E$ (rather than the exponential rise observed in gas mixture containing freon, so for as gas mixtures not containing freon, one would expect a) faster drop in efficiency on reducing the voltage b) longer efficiency plateau (since there is a slower rise in gas gain).

### 3.3.2 Gas-Ionization Spark Mode

The advantage of operating an RPC in the spark mode is that the signal is fast and is able to be processed without a preamplifier. In most cases this spark pulse is preceded by a precursor pulse. The the main disadvantage is that the detector cannot be operated at high rate.

**Streamer Mode:** Streamer mode operation easily satisfies these requirements; thus RPC operated in streamer mode have a relatively less tolerance on the gap dimension. However streamers produce a large amount of charge and thus there is a severe rate limitation at LHC, one is forced to use avalanche mode. An obvious and relevant question concerns the gap tolerance required of RPCs operated in avalanche mode. For example, the ATLAS experiment uses a single gap; CMS experiment proposes double gap design with the readout strips sandwiched between two of these RPC modules. In both cases, avalanche mode operation is proposed.

### 3.3.3 Material specification and basic parameters

**Electrodes composition and surface treatment**

The resistive electrodes are usually made of bakelite (phenolic resin) plates covered with a thin layer of melamine. The bulk resistivity $\rho$ of the bakelite plates should be optimized according to the required rate capability, which is strongly dependent on it. There are two main effects: first, the time constant $\tau = \epsilon_0 (\epsilon_r + 2) \rho$ of an elementary RPC cell involved in an avalanche process is smaller at lower resistivity; moreover, at very high rate, the flow of total current through the plates becomes important and produces a drop of voltage $V_d$ across them. A lower “effective voltage” is therefore applied to the gas gap, resulting in a lower gas amplification. Both effects can be reduced by choosing an appropriate low value for the bulk resistivity. By simple electrostatic considerations [52], the voltage drop can be estimated as

$$V_d = 2 < Q_e > r \rho$$  \hspace{1cm} (3.3.3)

where $r$ is the rate/cm$^2$, $\rho$ is the bulk resistivity and the other quantities have already been introduced. Assuming, for example, $< Q_e > = 25$ pC and $r = 10^8$/cm$^2$, a value of $\rho$ in the range $1 - 2 \times 10^{10}$ $\Omega$cm should be used to limit $V_d$ to few tens of volts. A larger voltage drop
would influence not only the rate capability, but also the pulse delay due to the change of drift velocity.

The surface quality of the electrode is crucial in reducing spontaneous discharges which might affect the rate capability of the chamber. Recently, a major improvement in the quality of the surface has been obtained by using more precise tools in the production procedure. The roughness $R_a$, defined as the vertical deviation of the surface from its average profile, has been measured on different bakelite sheets. Recent production has reduced the "roughness" of the surface by a factor of 6. The linseed oil treatment [53], which has been traditionally employed to smooth the electrode surface, is not crucial for the detector operation, provided the bakelite plates have good surface quality and the assembly is cleanly and correctly done.

Gas mixture

The gas cluster density $\lambda$ is crucial for exploiting the best detector performance. In principle, $\lambda$ should be as large as possible to maximize the signal and to achieve high efficiency (see equation 3.3.1). Recently, 2 mm gap RPCs have been successfully operated with a $C_2H_2F_4$ based mixture ($\lambda \sim 5 \text{ clusters/mm}$). Lower density gas mixtures (for example, argon-based mixtures) have $\lambda \sim 2.5 \text{ clusters/mm}$ and do not allow high efficiency with low streamer contamination [52].

The drift velocity of electrons in different $C_2H_2F_4$ based mixtures at various electric fields has been recently measured [54, 55]. In Fig. 3.5 the results for a 90% $C_2H_2F_4$, 10% $i-C_4H_{10}$ mixture are shown. In the region of interest (streamer free operation) the drift velocity grows linearly with the applied electric field. At high rate, where the effective field applied to the gap is reduced, as discussed previously, the decrease of drift velocity may result in a longer response time. Again, a bakelite resistivity value in the range $1 - 2 \times 10^{10} \Omega cm$ will keep this effect within the requirements.

![Drift velocity graph](image)

Figure 3.5: Drift velocity for the 90% $C_2H_2F_4$, 10% $i-C_4H_{10}$ gas mixture. The streamer operation region refers to a 2 mm gap RPC.
Gap width

The gap width affects the time performance of the detector. Fig. 3.6 shows the simulated achievable time resolution as a function of the gap width, assuming a gas cluster density $\lambda = 5 \text{ clusters/mm}$ and an electron drift velocity $v = 130 \mu m/\text{ns}$. Also the full width at the base (FWAB), defined as the time interval containing 95% of the events, is given. The performance, as expected, becomes poorer at wider gaps, due to the larger fluctuations present during the avalanche development. A 2 mm gap width seems the most appropriate choice.

3.3.4 Double gap design

More gaps may be put together to increase the signal on the read out strip, which sees the sum of the single gap signals. This makes it possible to operate single-gaps at lower gas gain (lower high voltage) with an effective detector efficiency which is the OR of the single-gap efficiencies.

The RPC proposed for CMS is made of two gaps with common pick-up strips in the middle (hereafter referred to as a double-gap RPC). A simplified layout of the double-gap design is shown in Fig. 3.7a. Alternatively, in the cases where the signal extraction is difficult, the layout shown in Fig. 3.7b could be adopted, with two independent read-out planes located externally and having their signals ORed, strip by strip, before entering the frontend. In both cases, the total induced signal is the sum of the two single-gap signals. Several studies on double-gap RPCs have been already reported in [51, 56]. The predicted

Figure 3.6: Simulated time resolution as a function of the gap width.

resolution of the 2 mm single-gap time response is about 1.4 ns. This value seems to be a lower limit, related to the statistical processes taking place during the avalanche development and to the walk produced by the signal amplitude fluctuations. However, other effects, such
as electronic noise and local variations of electric field must be taken into consideration, to account for the realistic experimental resolution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakelite thickness</td>
<td>2 mm</td>
</tr>
<tr>
<td>Bakelite bulk resistivity</td>
<td>$1 - 2 \times 10^{10} \Omega \cdot cm$</td>
</tr>
<tr>
<td>Gap width</td>
<td>2 mm</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>$95% C_2H_2F_4, 4.5% i - C_4H_{10}, 0.5% SF_6$</td>
</tr>
<tr>
<td>Operating high voltage</td>
<td>9.0 - 9.5 kV</td>
</tr>
<tr>
<td>no. of gaps</td>
<td>3</td>
</tr>
</tbody>
</table>

### 3.3.5 RPC construction and tools

Recent R&D results have shown that RPCs suitable for operation at low gain and high rate can be constructed using materials and technologies developed in the past and already employed for the L3 and BABAR mass productions. Only a few basic physical parameters (gas mixtures, plates resistivity, plate surface treatment) need to be adapted in order to meet the CMS operation requirements.

The large production of RPCs for CMS can therefore be made on an industrial basis, following well established procedures developed several years ago by R. Santonico [47]. The construction requires two rectangular 2 mm thick bakelite plates kept at a fixed distance (2 mm ± 30 μm) by insulating spacers about 10 mm in diameter distributed over the entire surface in a square mesh of 100 × 100 mm$^2$. A schematic layout of an RPC is shown in Fig. 3.8.

The bakelite plates are first selected on the basis of their resistivity, which should be
peaked around $2 \times 10^{10} \Omega \text{cm}$ and distributed over a wide range ($\pm 1 \times 10^{10} \Omega \text{cm}$). At the same time, a sample surface roughness test is performed. Basic steps for the construction are:

- the bakelite plates are cut to the required dimensions.
- one side of each bakelite plane is painted with graphite (surface resistivity about 300 $k\Omega$ per square).
- on the graphite coated surface a 0.3 mm thick PET film is glued to provide HV insulation.
- two such plates are glued together (graphite on the outside) with the spacer mesh on the inside, and a narrow (order of 7 mm) frame all around to form the basic chamber.

After drying, gas inlets are mounted at the four corners and an additional araldite seal is placed around the entire package. The construction of the single-gap chamber terminates with the connection of the HV cables. Then each chamber is tested for gas leaks, flushed for at least 48 hours and a first V/I plot is made, which is checked against the resistivity values measured at the beginning of the process.

The production capability of the existing tools is about $15-20$ large size single-gaps/day. An important constraint for the CMS detector design is determined by the maximum size of available bakelite plates (1.3 m in width and about 4 m in length). Also the tools have been developed to treat plates not larger than the quoted dimensions. The CMS design, therefore, should be optimized to contain RPC module sizes within the above limits.

Finally two single-gaps are superimposed to form a double-gap chamber with the spacers overlapped. Although this introduces some dead area, it ensures that, after the assembly, no deformation of the gaps is produced.
In parallel to the above steps, a special tool is devoted to the production of the read-out strip planes. They are made by milling a 40 $\mu$m aluminum sheet glued on a 100 $\mu$m thick PET film.

### 3.3.6 Charge carriers in avalanche development

The mechanism of the avalanche originating from a single electron cluster, drifting in an electric field whose intensity is below the streamer mode of operation (Raether condition), is well established. We recall it briefly, in order to introduce our symbols. Consider the $j$-th cluster ($j=1$ is the cluster closest to the cathode), in the trail left by an ionizing particle, and be $n_j$ and $x_j$ the cluster initial size and position, respectively. The number of ion pairs produced in the avalanche is

$$n_{ip}(x) = n_j e^{\eta(x-x_j)} \tag{3.3.4}$$

It is easy to compute how the charge in the gap is distributed among charge carriers when the front of the avalanche has propagated from $x_j$ to $x$. The charge of free electrons is

$$Q_e(x) = Q_j e^{\eta(x-x_j)} \tag{3.3.5}$$

being $Q_j = q_{el} n_j$ ($q_{el}$ is the electron charge). The charge of negative ions is:

$$Q^-_i (x) \approx \frac{\beta}{\eta} Q_e(x) \tag{3.3.6}$$

and that of positive ions is

$$Q^+_i (x) \approx \frac{\alpha}{\eta} Q_e(x) \tag{3.3.7}$$

under the assumption $\eta(x-x_j) \gg 1$. Statistical corrections to take into account fluctuations of $x_j$ and $n_j$ can be simply done, being them statistically independent processes. From Poisson statistics and simple considerations [58] the probability of finding the $j$-th cluster lying between $x$ and $x + dx$ is

$$P_j(x) dx = \frac{x^{j-1}}{(j-1)!} \lambda^j e^{-\lambda x} dx \tag{3.3.8}$$

$\lambda$ being the cluster density in the mixture. Fluctuations of cluster size $n_j$ have been modeled in a number of ways [59]. Here we simply assume that Poisson statistics is adequate, since secondary ionization collisions made by each primary electron are a small number of independent events. Thus the probability of finding a cluster having size between $n$ and $n + dn$ is

$$P(n) dn = \frac{\mu^n}{n!} e^{-\mu} dn \tag{3.3.9}$$

$\mu$ being the average cluster size. The average charges for the $j$-th cluster can be computed as:

$$< Q_e(x) > = q_{el} \mu e^{nx} \left( \frac{\lambda}{\lambda + \eta} \right)^j \tag{3.3.10}$$
\[ < Q^-(x) > = \frac{\beta}{\eta} < Q_e(x) > \]  \hspace{1cm} (3.3.11)

\[ < Q^+(x) > = \frac{\alpha}{\eta} < Q_e(x) > \]  \hspace{1cm} (3.3.12)

### 3.3.7 Current signal induced on pick-up electrodes

As known, a point-like charge \( Q(P) \) moving in an electric field \( E(P) \), inside a multi-electrode detector, induces on a pick-up electrode a short circuit current signal given by the generalized Ramo’s theorem [60], expressed as

\[
i(t) = -\int_{-\infty}^{t} Q(P(\tau))\Phi_w(P(t-\tau)) \times v_d(P(\tau)) d\tau
\]  \hspace{1cm} (3.3.13)

where:

- \( P = P(t) \) is the motion equation of the charge \( Q \) in the active volume of detector
- \( v_d(P) \) is the drift velocity of the charge in the electric field \( E(P) \) due to the power supplies feeding the detector
- \( \Phi_w(P) \) is the weighting field in the active volume, determined by removing power supplies and injecting into the pick-up electrode a unit delta impulse of voltage
- \( \times \) indicates scalar product

The RPC having planar electrodes, we can assume \( E(P) = E_0 = \text{const} ; v_d(P) = v_d = \text{const} \), and the motion equation reduces to \( x = v_d t + x_0 \) (x being the coordinate orthogonal to electrodes). Moreover, vectors \( \Phi_w \) and \( v_d \) are parallel. In order to evaluate the weighting field, we need the electrical model of RPC. This model, limited to the bakelite area \( A \) interested by an avalanche. \( C_g \) represents the active volume of detector. If \( d \) is the gap width, \( s \) the bakelite thickness, \( \rho \) its resistivity and \( \epsilon_r \) its relative dielectric constant, then capacitances and resistances appearing in the circuit can be evaluated as:

\[
C_g = \epsilon_0 A/d, \quad C_b = \epsilon_r \epsilon_0 A/s, \quad R_b = \rho s/A, \quad R_c \text{ is the carbon layer resistance (} \approx 100 \text{ k}\Omega/\square \text{)} \quad \text{and} \quad R_s \text{ is the bakelite surface resistance. The coaxial cables represent the readout strip (pick-up electrode), terminated at both ends; } C_a, C_c \text{ are coupling parasitic capacitances and their value is typically } \gg C_g.
\]

Assuming that the signal formation time is much smaller than any circuit time constant, we can neglect the effect of neighboring regions. The equivalent circuit reduces, after removing power supply. By injecting at \( Y \) a unit delta voltage \( \delta(t) \), the weighting field (i.e. the field inside capacitor \( C_g \)) results

\[
\Phi_w(t) = -\text{grad}V_g = \delta(t)\Phi_w
\]  \hspace{1cm} (3.3.14)

Here \( V_g \) is the potential function inside \( C_g \),

\[
\Phi = k/d
\]  \hspace{1cm} (3.3.15)
and
\[ k = \frac{C_b}{C_b + 2C_g} = \frac{\epsilon_r d/s}{\epsilon_r d/s + 2} = \text{const} \] (3.3.16)

The output short circuit current is then:
\[ i(t) = -Q(x)\Phi_w \times v_d = kQ(x)\frac{v_d}{d} \] (3.3.17)

This is the single cluster response of RPC. The same factor \( k \) appeared in [61]. The fast charge which is visible in the circuit outside the detector can be computed by integrating 3.3.17 and using 3.3.5:
\[ q_e \approx \frac{k}{\eta d} < Q_e(d) > \] (3.3.18)

where \( < Q_e(d) > \) is the total electronic charge collected on the anode. Typically \( 1/(\eta d) \) is \( \simeq 5 \div 7 \).

In the case of our RPC, \( s = d = 2 \text{ mm} \) and \( \epsilon_r = 5 \), so that \( k \simeq 0.7 \).

The signal decreases by increasing the gap width; however, one has to take into account the tradeoff between the intensity of induced signal and the streamer probability that, as outlined in [62], decreases by increasing the gap width.

As known, the RPC proposed for CMS is made of two gaps with pick-up strips in the middle [63]. In this geometry each single gap signal must be reduced by the factor \( k \) given in (3.3.4). The total induced signal will be the sum of the two.

It is interesting to see what happens in a multigap geometry [64] where the strips are outside. one can see that in this case the reduction factor \( k \) is:
\[ k = \frac{C_b}{nC_b + (n+1)C_g} = \frac{\epsilon_r d/s}{n\epsilon_r d/s + (n+1)} \] (3.3.19)

In the same conditions as the double gap (same gap width, same gas mixture, same gas gain,...) and with \( n=3 \), one gets \( k \approx 0.26 \), whatever the gap in the stack. Assuming that all the three gaps fire, the signal induced on the strip would be at most one half that of a double gap, even in the optimistic hypothesis of full induction between the strip and the farthest gap.

It is also interesting to compute the ratio of the fast charge induced on the pick-up electrode, \( q_e \), to the total charge, \( q_s \), moved outside by the applied voltage. Of course, \( q_s \) is half the total charge in the gap and can be computed for example from (9).

Using preceding equations, one finds
\[ \frac{q_e}{q_s} = \frac{k}{\alpha d} \] (3.3.20)

independent of any attachment.

### 3.3.8 Measurement of \( \alpha \) and \( \eta \)

The average fast charge induced on the pick-up electrode by a single cluster can be computed as a function of \( \eta \) by means of (3.3.18), if \( \lambda \) and \( \mu \) are known. The contributions of all clusters
in the trail can be added to find the total charge collected on respective electrodes. This implies that avalanches originated from each cluster are considered as developing independently on each other.

An extrapolation of some known results [65] allows us to estimate the coefficient $\lambda$ in the case of the two gas mixtures which have been studied in [62]. We will use $\lambda = 5 \text{ clusters/mm}$ for the $C_2H_2F_4$ based mixture (90% $C_2H_2F_4$ and 10% $i-C_4H_{10}$), and $\lambda = 2.5 \text{ clusters/mm}$ for the argon based mixture (70% argon, 5% $i-C_4H_{10}$, 10% $CO_2$ and 15% $C_2H_2F_4$). In both cases the average primary cluster size $\mu$ has been assumed equal to 3 (see for example [58], [65]).

From Eq.(3.3.10)-(3.3.12), one can see that, whatever the charge carrier, the contribution of the j-th cluster to the total charge collected is the fraction $\lambda = (\lambda + \eta)$ of the (j-1)-st one. Since in 2 mm gaps with moderate gas gain $\eta \approx 10 \text{ mm}^{-1}$, we can conclude that a negligible error is made by considering only the contributions from the first two clusters of the trail. Fig. 3.9 shows the average fast charge $q_e$ vs. $\eta$, as obtained by 3.3.18 under previous assumptions. This curve can now be used to predict the gas coefficient $\eta$ at an experimental condition such that a given signal charge $q_e$ is obtained. According to results reported in [62] it is assumed $q_e = 0.9 \text{ pC}$ for the $C_2H_2F_4$ based mixture and $q_e = 0.5 \text{ pC}$ for the argon based mixture. These values were obtained assuming equivalent operating conditions in both gases, i.e. the middle of plateau where efficiency is maximum and streamer fraction is about 1% . The corresponding operating voltages are respectively 9500 V and 5200 V. By inspection of Fig. 3.9, $\eta$ can be evaluated as:

$\eta \sim 9.2 \text{ mm}^{-1}$ at HV=9500 V in the $C_2H_2F_4$ based mixture

$\eta \sim 9.2 \text{ mm}^{-1}$ at HV=5200 V in the argon based mixture.

It is interesting to remark that, at equivalent operating conditions (i.e. same gas amplification, same streamer probability), the fast charge, induced on the pick-up strip, is much larger when using $C_2H_2F_4$. The electronegativity of the freon mixture can also be evaluated by comparing the experimental result $q_e/q_s = 0.019$ with the prediction of (3.3.20). We find $\alpha = 18 \text{ mm}^{-1}$ and the attachment coefficient is:

$\eta \sim 8.8 \text{ mm}^{1-}$ at HV=9500 V in the freon based mixture.

### 3.3.9 The Temperature Behaviour for RPCs

The use of RPC for the detection of the space-time profile of extensive air showers requires a specific optimization of this technology, in particular concerning temperature effects on efficiency and time resolution. In fact, for a large array located, for instance, at a mountain site, one expects environmental conditions more severe than in a normal laboratory.

The temperature behaviour for RPCs at lower temperature the gas density is higher and this is equivalent to a larger gas gap that requires a larger operation voltage.

A change in gas density is equivalent to a change in operating voltage according to the general rule of “constant field to density ratio”. For a perfect gas the density is proportional to the inverse of the absolute temperature, so that the rule of a constant $\text{field} \times \text{temperature}$ product is expected.
The plate resistivity determines the effective voltage acting on the gas gap, according to the relationship \( V_{\text{eff}} = HV - RI \), where \( HV \) is the supply voltage, \( R \) the electrode resistance and \( I \) the operation current. The resistivity temperature coefficient for the phenolic materials constituting the plates is about \(-0.1^\circ\text{C}^{-1}\). Due to the negative sign, rise in temperature results in a lower resistance and therefore in a higher effective voltage.

### 3.4 Sensitivity to Neutron and Photon

The dangerous background is due to low energy photons produced with a flux \( \Phi(E)\alpha E^{-1} \) that extends up to about 10 MeV. For a luminosity of \( 10^{34}\text{cm}^{-2}\text{s}^{-1} \) and with a suitable shielding the computed flux is \((10^4 - 10^5) \text{Hz/cm}^2\) [66]. The sensitivity of RPC, averaged over the particle spectrum is estimated in the range \( 10^{-3} - 10^{-2} \). Under these hypothesis the detectors should be operated at rates higher than 100 Hz/cm\(^2\). It is thus of primary importance to measure the sensitivity of RPC to low energy photons and neutrons and to prove their safe operation at high intensity. Recently there has been another development which affects the use of RPCs at future colliders. At the SSC the background of low-energy neutrons has been calculated to be \( 10^6 \text{Hz/cm}^2 \), which can be reduced to \( 10^5\text{Hz/cm}^2 \) with some modification to the layout of magnets. The probability that an RPC detects the neutron has been measured to be \( 6 \times 10^{-3} \). This is believed to be due to the neutron undergoing an elastic collision in the surface layer of the resistive plate with the recoil proton entering the gas volume. Thus it appears that the background counting rate may well be in excess of
3.5 Comparison of Wide and Narrow Gap

As previously stated that the avalanche process can lead to a spark breakdown. If one choose to work in avalanche mode one needs to use a sensitive amplifier. The occurrence of sparks had to be minimized to avoid firing neighbouring amplifiers; this would lead to large cluster sizes.

The gas gap in an RPC is used both for gas gain via the avalanche process and also as the source of primary ionization. The avalanche pulse is generated by a multiplicative gas gain across the gas gap, thus the largest gain is from electrons that traverse the whole gap. An electron that is produced at a distance $x$ from the anode will have a gain of

$$Gain = C^{(x/D)}$$

(3.5.1)

where $D$ is the distance between the anode and cathode plate, and $G$ is the gain of an electron traversing the whole gap. A minimum ionizing particle traversing a volume containing argon (a typical gas used in gaseous detectors) produces 30 primary ionization clusters per cm (thus 3 clusters/mm on average). Using Poisson statistics one finds a 5% probability that there are no clusters of primary ionization in the first millimeter of the gas gap. We wish to work close to 100% efficiency; this implies that the gain for a single electron over the remaining gap has to be large enough to produce a pulse that can be discriminated by our electronics ($10^5$ electrons). Thus for the limiting case (no clusters in the first millimeter) there remains only 1 mm of the 2 mm gas gap to produce an avalanche signal above discrimination level. If we set the avalanche gain to be $10^5$ across this 1 mm, then one has a gain of $10^{10}$ for an electron that avalanches over the full 2 mm. However, for a chamber with an 8 mm gas gap, there remains 7 mm for the avalanche process; thus, in this case, one sets the gain to be $10^5$ over 7 mm, which gives a gain of $5.2 \times 10^5$ for an electron that traverses the full 8 mm. Thus there is a dramatic reduction of dynamic range of avalanche pulse size ($10^5$ is reduced to 5.2) with a larger gas gap (2 mm increased to 8 mm). As sparks are usually associated with a high density of possible ions ($10^8$ is the threshold for the production of sparks in parallel plate chambers with metallic plates), it would be no surprise if a larger gas gap reduces the probability of sparks. We have performed a measurement to check this and have found a 30% probability of a spark for a 2 mm gas gap working at maximum avalanche efficiency of 95%. This spark probability drops to zero for an 8 mm gap. Additionally, using the above reasoning, it is difficult to work at efficiencies above 95% with a 2 mm gap (if normal types of gas mixtures are in use). However with a larger gap one can be sensitive to avalanches from electrons origination further than 1 mm from the cathode. Thus chambers with larger gas gaps will have higher detection efficiency.

Another aspect of avalanche mode operation is that the gas gain varies strongly with the electric fields and thus with physical size of the gas gap. We have used the measurements of the Townsend coefficient by Sharma and Sauli [58] in which they are considered a 2 mm and 6 mm gas gap with various mixtures of argon and isobutane and have also chosen to vary...
the gap dimension by $\pm 100 \ \mu m$; this would seem a reasonably obtainable value for the mass production of thousands of square meters of RPC. For a gas gap of $2 \ mm$ with the gain set to $10^4 \ mm^{-1}$ also found a variation in gain from $\sim 7 \times 10^2 \ mm^{-1}$ to $5 \times 10^5 \ mm^{-1}$ (a gain ratio of $\sim 700$) as the gap width varies from $2.1$ to $1.9 \ mm$. However varying the $6 \ mm$ gas gap, the gain form $\sim 3 \times 10^3/5 \ mm$ to $\sim 4 \times 10^4/5 \ mm$ (a gain ratio of $\sim 13$). If one works at higher gains, setting the single electron gain to be $10^5$, the $2 \ mm$ gap has a gain variation from $\sim 4 \times 10^3 \ mm^{-1}$ to $\sim 1 \times 10^7 \ mm^{-1}$ (a gain ratio of $2500$ ) for the $\pm 100 \ \mu m$ gap variation. For the $6 \ mm$ gas gap, the corresponding gain variation is from $\sim 2 \times 10^4/5 \ mm$ to $\sim 6 \times 10^5/5 \ mm$ (a gain ratio of $30$). The exact variation depends on the gas mixture, and of course it is possible that careful selection of the gas could reduce this effect. However, there are also other constraints (such as gas flammability). From this we learn the following: a chamber with a $2 \ mm$ gas gap and built with reasonable mechanical tolerances can not be operated with a gas gain of $10^4 \ mm^{-1}$, if high efficiency is the goal (since increasing the gap to $2.1 \ mm$ reduces the gain to $\sim 700$, which is too low a gain to produce gains of the order of $10^5 \ mm^{-1}$). Therefore the $2 \ mm$ gas gap will have yet another factor of $\sim 2000$ in dynamic range on top of the $10^5$ produced by the distribution of primary ionization. However RPCs with wide gaps ($6 \ mm$) in this example can tolerate a gap variation of $\pm 100 \ \mu m$).

So it is clear that the narrow gap RPC has superior timing compared to the side gap RPC; however the $8 \ mm$ RPC has superior rate capability. It should be noted that the $2 \ mm$ and $8 \ mm$ are the extremes. The tolerance in the distance between two plates depends upon the size of the chambers and the number of spacers used.

The Problem of Uniformity

For avalanche mode in the double gap, the read-out strips have to be equipped with sensitive amplifiers. Dark current usually shows up as extra noise and thus should be kept low. One is usually obliged to operate somewhere close to the knee of the efficiency plateau since one needs to limit the probability of creating streamers and also to keep any produced streamers of limited charge. There is a tendency to try and increase the rate capability by decreasing the plate resistivity; however high resistivity plates can help to even out irregularities in the gas gap. Additionally, for the $2 \ mm$ gap RPC, a large time walk is observed. The time walk is being caused by the change in drift velocity with electric field. This time walk of $10 \ ns/kV$ imposes a strong constraint on the gap tolerance if good timing is needed.

A time walk of $10 \ ns/kV$ with a nominal working voltage of $10 \ kV$ implies that the $2 \ mm$ gap constructed with a 20 micron variation would have time shifts of $1 \ ns$. Thus the $2 \ mm$ gap RPC (operated in avalanche mode) needs to be constructed with a gap tolerance of some tens of microns just to achieve good timing. This is not easy to realize, especially for the large sized modules planned for LHC. Additionally, in the case of a double gap RPC for the two gaps to act truly in parallel, the avalanche signal from each gap has to occur simultaneously; thus the field in each gap has to be somewhat similar, which constrains the gap size of the two gaps to be identical. We regard this rather exact gap tolerance as a critical issue when constructing large modules.
3.5.1 Effect of Temperature on Efficiency

The vast majority of temperature dependence of the efficiency can be attributed to the variation of gas density with temperature. At lower temperature the gas density is higher and this is equivalent to a larger gas gap that requires a larger operating voltage.

Assuming that the operating voltage, for a given gas depends only on the field/density ratio and that the temperature changes occur at fixed pressure and volume the detection efficiency for an ideal gas must be a function of \( \text{voltage} \times \frac{T}{T_0} \), where \( T \) is the actual gas temperature and \( T_0 \) an arbitrary assumed reference temperature.

If the voltage scale is renormalized by the factor \( \frac{T}{T_0} \), with \( T_0 = 293 \text{ K} \), the detection efficiency vs \( HV \times \frac{T}{T_0} \) is essentially the same for all the temperatures [68][69]. The efficiency curve also depends on the front-end threshold; decreasing the threshold the efficiency curve shifted towards the lower voltages.

3.5.2 The Multi-gap RPC

The multi-gap RPC has a series of smaller gas gaps. The exterior plates are equipped with electrodes and act as anode and cathode; however extra resistive plates will further subdivide the gas gap. These plates are electrically floating but take the correct voltage (due to electrostatics and the flow of positive ions and electrons from the sub-gaps) and act as sub-cathodes and sub-anodes. One important feature is that the field is defined by the applied voltage across the total gas gap; thus it is the same in all sub-gaps (even if the intermediate resistive plate is displaced). Thus avalanches in all sub-gaps occur simultaneously and the induced signal is truly the sum of all the gaps.

The multi-gap technique allows us to add many internal spacers, since we can arrange them to have through-going particles passing through a maximum of one spacers. Since the spacer has a higher relative dielectric constant (\( \varepsilon \sim 4 \)) than gas, the electrostatic coupling between the avalanche and the pick-up strips is enhanced. This will help alleviate any reduction in efficiency around a spacer. However it should be noted that these internal spacer bars will help eliminate the need for external large flat plates, originally thought necessary for constructional purposes.

One can imagine that this device gives an equivalent performance of a small gap at high pressure but with the gap tolerance given for the larger total gap. An advantage of the small gap is that the time walk is 0.4 ns/kV unlike the conventional 2 mm gap RPC. The plates of high resistivity could reduce high gain or hot spots, which also show that this large multi-gap RPC does not benefit from this effect, even though the plate resistivity is \( 10^{11} \Omega.cm \); the reason being the low dark current and the slow increase of dark current with voltage. Thus to build a uniform RPC one either needs a design where unavoidable changes in gap dimension have a small effect as shown in Fig. 3.10 [70].
Figure 3.10: A typical example of multi-gap RPC with glass electrodes is shown

3.5.3 Effect of the linseed oil surface treatment on the performance of resistive plate chambers

Typical crude linseed oil [71] is a natural organic mixture of mainly linolenic acid (SO-65%), linoleic acid (14-24%) and oleic acid (16-26%). It is commonly used, after heating refining, in special paints and coatings.

Surface treatment of the internal bakelite electrodes is a necessary step to reduce the noise and the dark current of bakelite RPCs operated in streamer mode. The overall result seems to be the smoothness of the surface. However, the absence of the oiling agent does not sensitively affect other parameters such as efficiency, cluster size and charge distribution. It is not excluded however that the effect of the linseed oil (i.e. a smoother surface) could be directly obtained within the industrial process of the bakelite foil production. Currents and single rate are the quantities most affected by the surface treatment of the electrodes beyond the optical/mechanical properties. A factor 4 less in currents and at least a factor 10 less in single rate is achieved using standard oiled RPCs operated in streamer mode [72].
Chapter 4

RPC Beam Test, Cosmic Test and Data Analysis

In this chapter we describe the beam test of a full scale prototype RPC which was performed at Gamma Irradiation Facility (GIF), CERN using X5 beam of 200 GeV/c muons, while the RPC cosmic tests were performed in the presence of cosmic ray muons, with locally developed testing facility for CMS experiment. In order to carried out these tests the hardware, e.g, Data Acquisition system (DAQ), readout/front-end electronics and triggers electronics were used. In the first part Beam test and then Cosmic tests results will be discussed.

4.1 CMS Endcap RPC Project

An experimental setup of Data Acquisition System (DAQ) is developed in Pakistan to test the endcap Resistive Plate Chambers, which will be installed in Compact Muon solenoid experiment at Large Hadron Collider. The muon end cap RPC layout in CMS experiment consists of four stations designated as RE1, RE2, RE3 and RE4. The four stations are symmetrical with respect to the Z=0 plane in + and - direction. The layout is shown in Fig. 4.1. Station 1 is subdivided into 36 φ sectors (10 each) shown in Fig. 4.2. Each sector is composed of RE/1/1, RE/1/2 and RE/1/3 chambers. The chamber RE/1/1 is positioned at different Z (as shown in Fig. 4.1). Stations 2,3 and 4 will be subdivided into 18 sectors (20 degrees each) as shown in Fig. 4.2. Each sector is composed of one RE*/1, two each of RE*/2 and RE*/3 chambers. (* denotes the station number ). All chambers consist of three gaps, except RE/3/1 and RE/4/1 which consist of two gaps. The gaps are referred in the following order: gap (i), (ii) and (iii), as shown in Fig. 4.3a and 4.3b.

The strip read out plane is located between the gaps and is divided into segments denoted as a, b, c and d in this document. Segment 'a' is always located at the highest region of the chamber. Each segment will have thirty-two (except RE 1/2 which has 30) 5/16 strips for every ten degree sector. Twenty degree eta segments have 64 strips. Fig. 4.4 shows the η segments. Eta regions per chamber are given in Table 4.1.

The position of the front-end board for each η region is fixed so as to minimize the total
Figure 4.1: Layout of RPC chambers and trigger towers

Figure 4.2: (Left), 10° sector of station 1, (right), 20° sector of RE 2,3,4

Figure 4.3: Gap segmentation
Figure 4.4: $\eta$ segments

Figure 4.5: Signal extraction layout
Table 4.1: The \( \eta \) segmentations of the RPCs in four muon stations with 12 regions

<table>
<thead>
<tr>
<th>Chamber type</th>
<th>no. of ( \eta ) regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE1/1</td>
<td>4</td>
</tr>
<tr>
<td>RE1/2</td>
<td>3</td>
</tr>
<tr>
<td>RE1/3</td>
<td>3</td>
</tr>
<tr>
<td>RE2/1</td>
<td>4</td>
</tr>
<tr>
<td>RE2/2</td>
<td>3</td>
</tr>
<tr>
<td>RE2/3</td>
<td>3</td>
</tr>
<tr>
<td>RE3/1</td>
<td>3</td>
</tr>
<tr>
<td>RE3/2</td>
<td>3</td>
</tr>
<tr>
<td>RE3/3</td>
<td>3</td>
</tr>
<tr>
<td>RE4/1</td>
<td>2</td>
</tr>
<tr>
<td>RE4/2</td>
<td>3</td>
</tr>
<tr>
<td>RE4/3</td>
<td>3</td>
</tr>
</tbody>
</table>

time jitter of the signal. Fig. 4.5 a, b and c show signal extraction from chambers covering two, three and four eta segments respectively. In the following tables relevant information about the dimensions of chambers, gaps active areas and pick up strips are given. As the chambers, gaps and strips are trapezoidal dimensions of the top side (B), bottom (C) and the vertical height (D) are given for complete description. \( R_i, R_o \) and \( Z \) specify the positions on end cap yokes. In Table 4.2 a general data for each chamber is summarized. The active area corresponds to the graphite-coated area of the continuous gap. Active area sides are offset inwards by 15 \( \text{mm} \).

Table 4.2: Chamber data for each CMS muon station

<table>
<thead>
<tr>
<th></th>
<th>RE1/1</th>
<th>RE1/2</th>
<th>RE1/3</th>
<th>RE2/1</th>
<th>RE2/2</th>
<th>RE3/1</th>
<th>RE3/2</th>
<th>RE3/3</th>
<th>RE4/1</th>
<th>RE4/2</th>
<th>RE4/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of channels  ( \pm Z )</td>
<td>36*2</td>
<td>36*2</td>
<td>36*2</td>
<td>18*2</td>
<td>36*2</td>
<td>18*2</td>
<td>36*2</td>
<td>36*2</td>
<td>18*2</td>
<td>36*2</td>
<td>36*2</td>
</tr>
<tr>
<td>( \eta ) segments</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>( \phi ) coverage, degree</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Strips/( \eta ) segments</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>64</td>
<td>32</td>
<td>64</td>
<td>32</td>
<td>32</td>
<td>64</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>No. of channels per chamber</td>
<td>128</td>
<td>96</td>
<td>96</td>
<td>256</td>
<td>96</td>
<td>192</td>
<td>96</td>
<td>96</td>
<td>128</td>
<td>96</td>
<td>96</td>
</tr>
</tbody>
</table>
4.2 The X5 Irradiation Facility

The irradiation facility is located downstream of the final dump of the X5 beam [73]. It is a zone, inside which a gamma source irradiates the large detectors developed mainly for the LHC experiments, with a view to create background conditions similar to those existing in the experiments during the operation of the LHC machine. A weak muon flux from the X5 beam may be sent through those detectors and tagged by two wire chambers in between the X5 dump and the detectors to be tested. The purpose of the tests is typically to measure whether the detection efficiency and the resolution of the detectors are affected by the background radiation and if so, by how much. A system of lead filters that can be moved in front of the source, allow the user to reduce the flux by factors up to 1000. The position of each hardware is pointed out in Fig. 4.6.

The maximum size of the detectors that can be tested in this facility is 3 meters horizontal and 6 meters vertical size. Note the presence of a second collimator, allowing to irradiate crystals in a narrow cone perpendicular to the X5 beam axis.

4.2.1 Muons from the X5 and X7 beams

Both the X5 and X7 beams may provide the zones downstream of them with muons, whether they are wanted (Gamma Irradiation Facility in X5C) or not (CHORUS emulsion downstream of X7 beam). This section describes the mechanism responsible for the muons coming along with these beams. The understanding of these mechanisms may help to get a better...
control over the muons.
The situation is quite different depending on whether the test beams are run in secondary or tertiary beam mode. A summary of good operating conditions for the Gamma Irradiation Facility is given in the summary below.

**X5 OR X7 AS TERTIARY BEAM**

The schematic explanation of Tertiary beam is shown in Fig. 4.7 The average decay length of charged pions is $55 \times p$ meters where $p$ denotes the pion momentum in $GeV/c$. At e.g. 120 $GeV/c$ the average decay length is therefore about 6600 meters. Over the length of 100 meters between the splitter (the last big bend before the X5 and X7 targets) and the first bends in the X5 and X7 beams, some 1.5% of the pions decay as $\pi \rightarrow \mu + \nu$. The average pion intensity in each branch of the H3 beam is about $10^7$ pper SPS cycle. As a result:

$$> 10^5 \mu \text{ are produced over 100 meters.}$$

The pion decay kinematics implies that

$$0.57 < p_{\mu} / p_{\pi} < 1.0$$

The X5, X7 beams will transport these muons if they are tuned to momenta in this range.

- Muons will always have $80 \pm 20\%$ of the H3 momentum.
- The setting of the X5, X7 beams decide where they go.
A common situation for tracking tests (e.g.) is a high-momentum tertiary beam with $p_{X5,X7}$ well above 57% of the H3 momentum. In that condition the muons from H3 follow the X5, X7 line and enter the Gamma Irradiation Facility, respectively the CHORUS emulsions. In that case, typically some $10^4$ muons per burst are contained within an area of $10 \times 10 \, cm^2$ (this is related to the ratio of the X5, X7 momentum band and the 43% of $p_{H3}$ phase space band accessible for muons from pion decay). The remaining muons are widely spread over several square meters. One can find the schematic diagrams at different beam momentum positions in Fig. 4.8

X5 or X7 as Secondary Beam

Secondary beams are limited in beam intensities mainly by radiation levels in the hall. Typically the allowed intensities are of the order of $x \times 10^5$ particles per burst, where $x$ is somewhere in the range between 1 and 10. This means that the pion flux downstream of the splitters has to be reduced to this rate as well. Consequently this contribution to the muon flux at the end of the beams is reduced by more than an order of magnitude to $< 10^3$ muons per burst.

Fortunately, two other sources are now present in addition:

1. **Muons from pions in the X5 beam**
   This source exists only if H3 and X5 are running pion beams as in Fig. 4.9. Again, typically 1.5% of pions decay, hence some $x \times 10^3$ are produced. The $P_t$ in the decay is limited to 30 MeV/c for $ap_L$ close to 120 GeV/c, therefore the laboratory frame decay angle is about 0.25 mrad. The lateral spread at the GIF (4 RMS) is therefore about $4 \times 0.25 \times 100 \, mm = 100 \, mm$

   Several $10^3 \mu$ from X5 pion decay

   Note that at high positive beam momenta ($> 160 GeV/c$), the particle production mechanisms favour protons over pions. At these momenta, the muon flux will therefore be a lot lower.

2. **Muons produced in the final beam dump**
   Several $10^5$ particles are dumped in the final dump of the beam line. Probably a few thousands of particles leave the exit of this dump. However, the momentum and angular distribution of those is poorly known. The total muon flux during secondary pion mode running at maximum flux is therefore again close to $10^4$ muons per burst in $10 \times 10 \, cm^2$. 
1. Low \( X_5 \) momentum

\[ 10^7 x^\pm \]

\[ \approx 10^3 \ x, e \]

\[ \mu \]

\[ \approx 100 \text{ m} \]

2. \( X_7 \) momentum opposite sign of \( H_3 \)

\[ 10^7 x^\pm \]

\[ \approx 10^3 \ x, e \]

\[ \mu \]

\[ \approx 100 \text{ m} \]

3. Momentum of \( X_7 \) high, but opposite to \( H_3 \)

\[ 10^7 x^\pm \]

\[ \approx 10^3 \ x, e \]

\[ \mu \]

\[ \approx 100 \text{ m} \]

Bent back by return fields

Figure 4.8: Schematic explanation of a few typical situations is shown.
Figure 4.9: Muons from pion beam are shown.

Figure 4.10: Schematic diagram of experimental setup used for testing full-scale RE2/2 prototype in the GIF area at CERN.
4.3 Beam test of the RPC

The Test Beam experiment is used to measure the performance parameters of the given detector in the presence of a beam. The forward RPCs assembly and quality control detail is explained in [75][76].

4.3.1 Chamber Construction Detail

The schematic diagram of a 2 mm double gap RPC is shown in Fig. 4.10 [74]. The chambers were built with 2 mm thick bakelite plates to enclose a 2 mm gas gap. The gas volume was sealed with four bakelite bars running along the length of the chambers. The gas is allowed to pass through the chamber from a small gap and spacers which were glued between two bakelite plates with distance separation between two consecutive spacers. The purpose of spacers was to maintain the 2 mm gap uniform and also for gap tightness. The graphite was painted onto the outer surfaces of the plates. The outermost sides of the bakelite sheets are connected with the high voltage while the central sheet is grounded. In this way a strong electric field was generated across the gap. The plane of readout strips was segmented on a 200 mm myler sheet with 1.5 mm inter strip spacing to pick up signals from both gas volumes. One full gap and two cut gaps were superimposed together in order to sandwich the strips running between the two gaps. The charge was induced on the strips from both chambers to enhance the signal amplitude. An external aluminum frame surrounded the chambers to ensure the rigidity and protection. In addition the high voltage connectors and gas inlets and outlets were mounted on the enclosed aluminum frame.

Figure 4.11: The structure of double gap RPC
4.3.2 Experimental Setup

Fig. 4.11 shows the schematic diagram of the muon and gamma sources with their distances from prototype RPC and Beam chambers. The prototype RPC was tested using the Gamma Irradiation Facility (GIF) at X5 testbeam [74]. The muon beam was delivered by SPS (Super Proton Synchrotron) accelerator, with an average momentum of 200 $GeV/c$. The RPC belongs to the muon system of CMS and will be used to detect the muons. So the prototype RPC was exposed to the beam of muon particles.

The data acquisition system was triggered by a set of scintillators and three Beam Chambers (BC), which were used to record the passage of beam particles. The particles from the X5 beam were tagged by two wire beam chambers (BC’s) having a spatial resolution less than 200 $\mu m$. The RPC was placed vertically between beam chambers and scintillators at a distance of 3200 mm and 5100 mm from BC1 and BC2 respectively. The distance between the RPC and source was 130 cm. The height of the beam with respect to the ground was 126 cm. Beam chambers placed upstream allow the muon tracking. A full scale prototype RPC is placed on the test stand vertically in front of the muon beam, as shown in Fig. 4.12. The performance of the RPC was tested with the help of gamma source in GIF, which was provided by a $^{137}Cs$ isotope source to simulate the background in the future LHC experimental environment. This background flux in the forward and backward regions due to low energy photons (up to 100 $MeV$) may reach up to a level of $10^5 cm^{-2} s^{-1}$. To mimic the background conditions we used a gamma source of 740 $GBq$ having energy of the order of 661 $keV$. There was a system of moveable lead filters which reduced the flux of photons by an order of $10^4$. Tests were performed with absorption 1 (ABS 1, i.e. no filters), absorption 2, 5 and 10 (ABS 2, ABS 5 and ABS 10 i.e absorption factors 2, 5, and 10 with respect to ABS 1).

The effective counting rate of chamber was determined from the time difference between two consecutive clusters [77]. The signals picked-up from the strips were pre-amplified and then discriminated with 200 mV threshold before feeding to a TDC (Time to Digital Converter). The time of an RPC signal is always recorded with respect to the trigger signal. The width of the gas gap was 2 $mm$. The strips were trapezoidal in shape and there were 32 strips per $\eta$ segment. The average strip length was 548 $mm$ and strip pitch was 18.7 $mm$ - 21.7 $mm$. For readout electronics we used the ASIC (Application-Specific Integrated circuit) supplied by the Bari group. The ASIC is designed and manufactured using 0.8 $\mu m$ BiCMOS technology.

The charge sensitivity of the preamplifier was 2 $mV/fC$ and the nominal discrimination threshold was set to 87.5 $fC$ (175 $mV$). The signal from the readout electronics were fed into multihit TDC (LeCroy 2277) with a 64 $\mu s$ gate and sensitivity upto 1 $ns$. The TDC was set in common stop mode. The gas mixture used was 96% $C_2H_2F_4$ and 3.5% iso-$C_4H_{10}$ and 0.5% $SF_6$ as quenching gas. This mixture of gas will be used in the real experiment in 2007.
4.4 Test Beam Results

The first forward endcap RPC test was performed to estimate the most important parameters of the RPC. Some basic plots related to Beam Chambers and RPC are shown in Fig. 4.13. In this figure, top left plot shows the number of strips fired by the incident ionizing particles in a selected time window, top right plot demonstrates the hit occupancy on the strips, bottom left plot represents time distribution relevant to the Beam chambers, while bottom right plot shows the time distribution on the 32nd strip in a selected time window.

4.4.1 Dark Current

The detector draws some amount of current even when the source is off, this current is known as dark current. For the efficient performance of the chamber, the value of the dark current should be minimal. Fig. 4.14 shows the variation of the average dark current for three gaps i.e. top small gap, top large gap and full gap. Under the highest gamma radiation background (656 Hz/cm$^2$), the dark current reaches about 200 $\mu$A/m$^2$, 240 $\mu$A/m$^2$, 280 $\mu$A/m$^2$ for top small, large gap and full gap respectively at high voltage value of 10.5 KV. The highest power consumption for full gap can then be calculated as, $10.5 \, kV \times 280 \, \mu A/\, 1.1694 \, m^2 = 2.5 \, W/m^2$, which satisfies the CMS requirement of less than 3 $W/m^2$ for an RPC.

4.4.2 Efficiency

At each HV point, the efficiency of the chamber was determined as the ratio of the number of correct chamber responses to the number of correct triggers. The correct chamber response
Figure 4.13: Top left plot shows the total number of strips fired by; the through to going particle; within 25 nsec time window. Top right plot demonstrates number of hits produced on each strip. Bottom left plot represents the Beam Chambers timing. Bottom right figure reflects the timing of RPC in 25 nsec.

Figure 4.14: The amount of dark current per square meter vs high voltage shown for three gaps used in the construction of the chamber.
is defined as at least one hit read by the RPC strips within the expected time window for triggered events. A correct trigger is an event with a beam track that goes through the active area of the RPC. This is computed using the beam chambers information and the geometrical parameters shown in Fig. 4.15. The efficiency of the RPC in a given time window is defined according to [47],

$$\epsilon = \frac{[\left(\frac{N_{ob}}{N_t}\right) - P_s]}{1 - P_s}$$  \hspace{1cm} (4.4.1)

where $N_{ob}$ is the number of observed events, $N_t$ is the number of total events and $P_s$ is the probability of the spurious hits. The probability of the spurious hits is determined by counting the hits in a time window delayed by 100 ns after the trigger. Fig. 4.15 shows the typical efficiencies of the detector for different intensities of the source and at discrimination threshold value 200 mV. The increase in threshold value only shifted the efficiency plateau at higher voltage values. Threshold control on front end electronics discriminators gives the probability to set the efficiency and noise rate in proper limits. The efficiencies were computed for a 25 ns time window centered at the mean arrival time of the fastest strip. The efficiency is maximal when the source is off.

The efficiency is plotted at threshold of 200 mV. The value of the efficiency is approximately 98.3% at operating voltage (voltage at which the efficiency becomes maximum and is independent of the applied voltage). The efficiency plateau starts at 9.5 kV and ends at 10.5 kV except at ABS 1. For good performance of the RPC [78] its efficiency plateau should lie in the range of 300 V. It is clear from the Fig. 4.15 that efficiency plateau of the RPC

![Figure 4.15: The efficiency of the chamber vs applied high voltage is shown for various source conditions at given signal threshold of 200 mV.](image-url)
used is more than 300 V in case of ABS1, while 1000 V in other photon fluxes. The study performed in [49] shows that the maximum efficiency and length of plateau are dependent on gas mixture. The broad range of efficiency plateau ensures the long term performance of the RPC even in the high rate environment.

### 4.4.3 Time Resolution

Time resolution is defined as the RMS width of a gaussian function fit to the signal time distribution, which is one of the most important parameters for a fast muon trigger system. The CMS specification for RPC’s time resolution is better than 3 ns. The time resolution has been calculated and plotted in Fig. 4.16 and Fig. 4.17. Its value is independent on the intensity of the source: it is 1.26 ns when the source is on and 1.24 ns when the source is off, which is well below the consecutive bunch crossing time difference 25 nsec at LHC.

The main resolution figure is determined by a Gaussian fit to the time distribution of the most likely strip within 25 nsec, and the timing tails are characterized as the fraction of events whose distance to the mean value exceeds the gaussian profile of muon bunch.

Good efficiency and timing properties will be crucial for the performance of the trigger algorithm, the latter in particular will play a very delicate role, since individual hits have to be assigned to the right bunch crossing. In the study performed in [49], it is clear that trigger efficiency is approximately 99% with an RPC of time resolution less than 3 ns. The fast timing performance of RPC ensures high trigger efficiency due to high RPC efficiency.
4.4.4 Cluster Size

A hit is defined as the signal recorded on a single readout strip. To define a cluster, we first ordered in time all the hits in the RPC and then searched for the clusters. A cluster is defined by grouping adjacent strips with hits inside a time window of $\Delta t = 20 \text{ ns}$ centered around the fastest strip. It is important that cluster size should be small in order to achieve the required momentum resolution and minimize the number of possible ghost-hit associations. For good performance of the RPC, the mean cluster size should not be greater than three. It is clear from Fig. 4.18 that in the region of operating plateau (9.5 - 10.5 KV), the cluster size is below 3. For more details about the cluster and cluster counting see [79].

The cluster size (i.e. the number of contiguous strips which give signals at the crossing of an ionizing particle) should be small ($\leq 3$) in order to achieve the required momentum resolution and minimize the number of possible ghost-hit associations.

4.4.5 Rate Capability

Rate capability is defined as how many number of particles a detector can handle in unit time. Mathematically rate is defined as

$$R = \left[ \frac{(N_c)}{N_{\text{events}}A\Delta t} \right]$$  \hspace{1cm} (4.4.2)

where $R$ is the rate, $N_c$ is the number of cluster found in time interval $\Delta t$ and $N_{\text{events}}$ is the number of events. The chamber counting rate is estimated by using the clusters.
Figure 4.18: The mean cluster size distribution as a function of high voltage is shown.

Figure 4.19: Time difference between two consecutive clusters. The straight line fit gives the slope of the curve which corresponds to the parameter $a$, which is defined in the text.
Time difference between random events are well described by an exponential distribution characterized by a probability density function,

\[ f(t) = a \exp(-at) \] (3)

where 't' is the time and 'a' represents the average rate at which events are occurring. In Fig. 4.19 the time difference between two consecutive clusters over 32 strips with ABS1 are shown. The slope of the curve gives directly the overall counting rate in units of ns\(^{-1}\). We estimate a rate of 800 Hz/cm\(^2\) averaged over 32 strips area under the maximum flux from the gamma source (ABS1) with applied voltage of 10 kV. The noise rate is defined as the number of fired strips per second outside the trigger window. A noise rate up to 10Hz/cm\(^2\) is considered acceptable. For good operation of RPC’s the rate capability required is 1 kHz/cm\(^2\). The hit rate associated with the neutron and gamma background is 20 Hz/cm\(^2\) in the barrel and reaches a maximum of 250 Hz/cm\(^2\) in the forward region at \(\eta = 2.1\). A reasonably safe estimate of 1 kHz/cm\(^2\) gives therefore the highest rate at which RPC’s are expected to work. The rate capability is plotted by counting the clusters and is shown in Fig. 4.20. The rate is very low when the source is off and its value goes upto 1.1 kHz/cm\(^2\) with efficiency 92%.

**4.5 The Experimental Setup for RPC Cosmic Test**

This section describes the setup used to study the general performance of the RPCs. The cross-section of the RPC has been exposed for cosmic ray test shown in Fig. 4.21. The experimental area for the RPC testing is located in NCP laboratory. The necessary ingredients
for cosmic tests, high voltage power supplies, gas flow rate controller, gas mixture, trigger setup and data acquisition systems are in operational mode. Currently cosmic ray muon test facilities are working properly with full strength. The hodoscope (cosmic ray muon stand) is able to house ten chambers at a time which can be tested simultaneously. The chambers are placed horizontally. Temperature of the laboratory is kept constant by air-conditioning systems, while humidity and temperature is monitored continuously with the help of proper devices. The cosmic ray muon test stand for the RPC consists of a muon trigger system

![Figure 4.21: Cosmic ray muon telescope for RPC testing.](image)

that is provided by a set of scintillators located on the top and bottom of the test tower. It is based on the two double layers of scintillators covering an area of 190 cm × 160 cm. Fig. 4.22 shows the scintillator locations S1 on top and S2 on bottom of the tower. They are all connected in logical AND. The overall trigger signal used follows the trigger logic (S1 AND S2). The trigger system is supported by a mechanical structure which allows one dimensional displacement of the scintillators along the strip length to cover the chambers area. The gas system is based on a mass flow meter and controllers. The gas mixture is composed of 96.5% C_2H_2F_4, 3.5% iso-C_4H_{10} and 0.5% SF_6. This mixture is distributed to the chambers with the help of gas pipes via a parallel system. The gas composition is monitored continuously. The high voltage (HV) power supply distribution is based on the Universal Multichannel CAEN/SY1527 unit which has the internal processor and internal network connections. The DAQ system consists of two VME crates housing 15 TDC modules sampled by 40 MHz clock (which corresponds to 25 ns time sensitivity). Each TDC processes the LVDS signals after amplification and discrimination, which are further processed by the data acquisition system. TDCs are operated in the common stop mode. When the trigger arrives the data is transmitted to a PC for storage and analysis. A summary of the chamber
4.5.1 RPC testing method

After the conditioning of chambers, their testing is started. In this test the chambers are characterised from the point of view of their efficiency, dark current, strip occupancy, cluster size, time resolution and rate capability. In order to start the testing, RPCs, scintillators and FEBs are switched on. High Voltage of RPCs is varied from 8.2 - 9.2 kV with steps of 0.2 kV and from 9.2 - 9.6 kV with steps of 0.1 kV difference. An online DAQ program, running on the VME based Pentium CPU, is controlling the test. For each High Voltage point, DAQ run begins 20,000 events with software generated random trigger. All the commands or data issued by a connected computer on LINUX operating system to a module must therefore pass through crate controller, because crate controller is the only module which can issue commands and is thus the master of the dataway. All other modules (TDCs) are slaves to the crate controller. Crate controller always occupies the last two stations of the crate from the right hand side.

The behaviour of the dark current, temperature and humidity is also monitored against each voltage. Temperature and humidity in the lab is maintained by an air-conditioning systems. Suitable temperature and humidity for testing is 20 - 22 °C and 35 - 40% respectively.

For our chamber the avalanche operating point was found at 9.6 kV. The induced performance is stored into the RPC Production Database, which is based on the MySQL. Data for each chamber is also accessible through web interface. Different scripts and JAVA applets are used to display summary plots.
pulses on the strips are observed on the oscilloscope. The trigger system is supported by a mechanical structure which allows one dimensional displacement of the scintillators along the strip length. The signals from the scintillators are used to trigger the system and set a time reference to the measurements. The 8 PMT signals of each scintillator plane are connected via the discriminators to an “OR” unit. The output of the two “OR” units are then passed to an “AND” logical unit, whose output serves as a trigger signal for the readout system. The signals from the “OR” units, delayed by 100 $\text{ns}$ go through the NIM-ECL converter to the TDC unit, via the ASD-TDC card.

Above mentioned RPC testing procedure is repeated in the Intersecting Storage Ring (ISR) CERN.

4.5.2 Detection of Muons

The acquisition program for the experiment was obtained from a pre-existing acquisition program developed in C++ and some Classes of ROOT. The pre-existing acquisition program was designed to readout the data from TDCs. The whole setup is based on muon trigger and readout electronics. Readout electronics is directly connected to a computer through a VME crate controller which is handling all the digital modules installed in crate to get data from detectors and scintillators in digital mode. In crate we have TDCs and other electronics as well.

When charged particles (mostly muons) ionize the gas of the RPC, an avalanche is formed by multiplication in the gas. The avalanche charge is collected by the anode and produces an induced charge on the external readout electrode, representing the prompt signal of the RPC. The signals are readout at a fixed frequency and are stored in a temporary memory. The RPC readout strips are connected to the FEBs by coaxial cables via the adapter boards. The FEBs are connected with TDCs through connectors which are put in VME crate. A TDC is used to read out the information from the FEBs and transfer the information to the computer. Signals from the RPC is amplified and digitalized to LVDS in the FEB and then converted to ECL signals in the custom-made LVDS-ECL converter boards. The ECL signals are fed into the START inputs of the multihit TDC and the trigger signals from scintillators into the STOP inputs of the TDC. Signals from the chamber are also fed into the STOP inputs of the TDCs. When a trigger is detected the DAQ read the data from the TDC and stores it in a binary output file for further offline analysis. In parallel, the program continuously plots a set of histograms which enable the online monitoring of the data and equipment performances. The histograms are automatically stored on the DB (Data Base). After the acquisition of data, we start analysis. The schematic diagram of the whole offline analysis program is shown in Fig. 4.23
4.6 Experimental Results and Discussion

4.6.1 Data Analysis
To read and analyze the data, an off-line analysis software (DAQ program) has been developed in C++ using LINUX operating system. This off-line analysis program reads the binary output of the DAQ code, processes it and generates the plots/histograms. The results are analyzed using standard high-energy physics analysis tool ROOT. The results are stored in the form of histograms.

4.6.2 RPC Parameters
Using the data and custom developed software the plots of the following RPC parameters are obtained:

- Strip Occupancy
- Efficiency
- Cluster Size
- Dark Current
Strip Occupancy

Strip response profiles are created and they serve two main purposes: first, to ensure that the chamber is connected properly to the DAQ system and second, to ensure all readout strips are active and working properly as they are supposed to.

Improper soldering of connections can lead to strips that appear to be dead in strip response profile. Each RPC contains total number of 96 readout strips and each of them is supposed to be in proper working condition. There can be some noisy strips, which show large number of hits and there can be some dead strips also, which show no signal or hit. A hit is defined as a signal recorded on a single readout strip. Normally strip resistance is 50 Ω and each strip draws 5 μA current on average. In this way all the strips of RPC are checked and faulty strips are observed. If chamber has more than 2 noisy or dead strips, then chamber is rejected and reassembled to remove this noisy and/or dead strips so that it can fulfill the CMS requirement. We tested a large number of chambers. The plots of strip occupancy for the chambers CMS-RE-2/2-PK-032 and CMS-RE-2/3-PK-015 at 9.4 kV are shown in Fig. 4.24 and Fig. 4.25 respectively. In these plots there is no dead strip except the strip number 32 in Fig. 4.25, which is noisy. It means at this strip, number of hits are large. It is due to the high voltage cable which is passing near this strip profile.

The response of each strip within a chamber is tested. The three peaks are expected because the strips are split into three sections along the lengths of the chambers. The strips running from 1-32, 32-64, 64-96 corresponds to three separate sections of the chambers.

![Figure 4.24: The response of fired strips from the cosmic ray muons.](image)

Cluster Size

Another important parameter of chamber performance is the cluster size. This is measured for every chamber at several voltages. To define a cluster, we first ordered in time all the hits of a particular RPC and then search for clusters. All simultaneously-fired adjacent strips
form a cluster. The cluster size of a chamber is defined as “the average value of the cluster size distribution, sampled in the first 25 $ns$ of the trigger window (100 $ns$)”. A cluster size should be small in order to achieve the required momentum resolution and to minimize the ghost-hit associations. For the efficient performance of the RPCs and the CMS criteria regarding cluster size, it should be less than three hits per strip. The cluster size can be reduced by changing the Front-End electronics thresholds to optimal value. The plots of the cluster size for the chambers **CMS-RE-2/2-PK-032** and **CMS-RE-2/3-PK-015** are shown in Fig. 4.26 and Fig. 4.27 respectively. If we look at these plots the cluster size is less than three. So we can say that both the plots are in good agreement with the CMS criteria. The formation of clusters from $8.6 \, kV$ to $9.6 \, kV$ is not uniform, it grows with increase in
the high voltage.

Figure 4.27: Mean cluster size of RE-2/3

**Efficiency**

Chamber efficiency is obtained with the “coincidence” method by evaluating the ratio between the number of events in which RPC has at least one fired strip in the trigger window (100 ns) and the total number of recorded events, with correction for spurious hits [77]. The efficiency is defined as [47]:

\[
\varepsilon = \frac{(N_{ob}/N_t) - P_s}{1 - P_s}
\]  

(4.6.1)

where \(N_{ob}\) is the number of observed events, \(N_t\) is the number of total events and \(P_s\) is the probability of the spurious hits. The probability of the spurious hits is determined by counting the hits in a time window delayed 100 ns after the trigger. The value of the efficiency should be greater than 95% at operating voltages and the efficiency plateau starts at 9.5 kV. For good performances of RPC, its efficiency plateau should lie in the range of 300 V. The maximum efficiency and length of plateau depends upon the gas mixture. The efficiency plots of the chambers CMS-RE-2/2-PK-032 and CMS-RE-2/3-PK-015 are shown in Fig. 4.28 and Fig. 4.29 respectively.

When the voltage is small, the ionization in the chamber is small which results in small current in the gap. As we increase the voltage efficiency also increases, which shows that the ionization in the gap is more and chamber draws more current. After the 9.2 kV the behaviour of efficiency is linear. The operating voltage starts at 9.2 kV to 9.6 kV and operating plateau is greater than 300 volts. The value of efficiency is almost > 95% at high voltage. The same chambers were tested at CERN, and similar results were reproduced.
Figure 4.28: Efficiency curve of RE-2/2.

Figure 4.29: Efficiency curve of RE-2/3.
Dark Current

When there is no particle coming inside the detector, even then, the detector draws some amount of current. This current is known as dark current. The dark current is very important parameter. For entire period the chamber is connected to high voltage, currents through each of the gas gaps are monitored. Given that current should be constant in time, any major deviations from this are indicators of a problem with the gas gaps or chamber electronics. For the efficient performance of the chamber the value of the dark current should be minimum. Temperature and humidity in the lab is also recorded because the performance of RPCs and resistivity of bakelite are functions of these parameters. Plots of dark current for the chambers CMS-RE-2/2-PK-032 and CMS-RE-2/3-PK-015 are shown in Fig. 4.30 and Fig. 4.31 respectively.

In these plots the dark current is less than 5 $\mu$A, which is the requirement of CMS. Finally all above parameters are analyzed, from which the overall behavior of the chamber is reflected, and in this way good RPCs are distinguished. On this basis, chambers are accepted or rejected.

![Figure 4.30: Plot of Dark Current for CMS-RE-2/2-PK-032.](image)

4.7 Conclusion

The performance of 2 mm wide double gap RPC, with bulk resistivity of $3 \times 10^{10}$ $\Omega$cm, has been studied. It was a full-scale prototype. The main characteristics such as efficiency, time resolution, rate capability, strip occupancy, dark current and cluster size have been studied. All the parameters of RPC necessary to check the performance of RPC are shown in Table 4.3. On the basis of Beam test results obtained it can be concluded that the prototype RPC has performed well and the current design is suitable for mass production.
Figure 4.31: Plot of Dark Current for CMS-RE-2/3-PK-015.

Figure 4.32: The RPCs of second muon station of the CMS in the regions RE2/2 and RE2/3 after commissioning are shown.
Table 4.3: Comparison between the test results and the CMS required results.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>CMS requirements</th>
<th>test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resolution</td>
<td>&lt; 3 nsec</td>
<td>&lt; 1.5 nsec</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt; 95%</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td>Rate capability</td>
<td>&gt; 1kHz/cm²</td>
<td>&gt; 1kHz/cm²</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt; 2 – 3 W/m²</td>
<td>&lt; 2.5 W/m²</td>
</tr>
<tr>
<td>Plateau region</td>
<td>&gt; 300 V</td>
<td>400-1000 V</td>
</tr>
</tbody>
</table>

of RPCs. The above cosmic test results show that the endcap RPC meet all the CMS quality control and quality assurance issues [17], so they are suitable for the installation in the CMS detector. Successfully installed RPCs are shown in Fig. 4.32. Since we are in the process of mass production of the chambers, we need to make sure, that they are as simple and cheap as possible without compromising on their performance and they should meet the CMS requirement which are imposed on the RPCs.

The comparison table between the CMS required results and the results obtained from the cosmic and beam tests are summarized below in Table 4.3. If any chamber does not fulfill these requirements then it is not accepted and sent back to remove that problem. In our experimental results all the parameters of the RPC have fulfilled all the requirements which are imposed by the CMS collaboration.
Chapter 5

Top Quark Physics at LHC

The top quark is, according to the Standard Model (SM), a spin-1/2 and charge-2/3 fermion, transforming as a colour triplet under group $SU(3)$ of the strong interactions and as the weak-isospin partner of the bottom quark. The top quark was discovered at the Tevatron in 1995 [80], completing the third generation of quarks within the standard model. It is the heaviest elementary particle yet discovered with a mass close to the scale of electroweak symmetry breaking, which was determined by direct Tevatron measurements to $m_t = 174.3 \pm 5.1$ GeV [81]. Subsequently, its mass was precisely measured to be $M_{top} = (178.04.3)$ GeV/$c^2$ [82]. At present the statistical error is still dominating. In contrast at the LHC, which will be a top factory, this systematic uncertainty can be essentially reduced by the requirement of considerably higher transverse jet momenta. Here the theoretical uncertainty on the transverse momentum spectrum of the top quark in the $t\bar{t}$ production constitutes the dominating contribution.

One of the most interesting top measurements will be the precise determination of the top quark mass, which allows in particular the improvement of the accuracy of supersymmetric exclusion limits. The measurement of the helicity states of the W boson from the top quark decay within the percent level will allow to search for deviations of the standard model. The measurement of the $t\bar{t}$ spin correlation constitutes the direct check of the top quark spin one half and thus a fundamental test of the quark spins in general and the QCD itself. Moreover, the investigation of the cross section of the heavy quark production in high energetic hadronic collisions is important for the design of experiments at existing and future accelerators and also in the domain of cosmic ray physics [83]. Beyond the standard model, a heavy Higgs boson above the $t\bar{t}$ production threshold may become relevant.

The mass of the top quark can also be inferred from electroweak measurements at LEP and SLD for example. The ratio of the $Z$ boson decay width into $b\bar{b}$ pairs to its decay width into hadrons $R_b = \frac{\Gamma(Z\rightarrow b\bar{b})}{\Gamma(Z\rightarrow had)}$ is sensitive to the top quark mass through loop corrections including contributions from highly virtual top quarks. The combined analysis yields $m_t = 150 \pm 25$ GeV [84]. Kinematical fits to precisely measured electroweak observables at LEP lead to the limits $m_t = 172^{+14}_{-11}$ GeV [85]. Further aspects and properties of the top quark are described in the following.
5.1 Properties of the top quark

5.1.1 Yukawa coupling

The top quark acquires its mass via the Yukawa coupling $g_t = \frac{2^{3/4} G_F^{1/2}}{\lambda} m_t$ to a Higgs boson after spontaneous symmetry breaking. However its value cannot be predicted by the standard model since particle masses are free parameters which have to be determined experimentally. Beside the top quark pole mass, which is defined as the particle pole in the perturbative top quark propagator, the renormalized top quark mass $m_t(\mu)$ given at a renormalization scale $\mu$ defined in the $\overline{MS}$ scheme is convenient. At the scale $\mu = m_t$ the renormalized mass is $m_t \approx 165 \text{ GeV}$ and the difference to the pole mass $m_t - m\pi$ is about $10 \text{ GeV}$. In view of such big differences in different mass conventions any observable supposed to measure the top quark mass with an accuracy of $1 - 2 \text{ GeV}$ has to tell which mass is actually determined. A particular measurement determines a mass parameter accurately to the extent to which higher order corrections to matrix elements of the process are small. Measuring the top quark mass through pair production near threshold in $e^+e^-$ collisions at future linear colliders, the theoretical uncertainty of the renormalized top mass $m_t$ in the $\overline{MS}$ scheme is $0.15 \text{ GeV}$. This uncertainty is less than half of what could be achieved by parameterizing the cross section with the top quark pole mass [86] (p.441). The reason for the larger uncertainty using the concept of the pole mass lies in the intrinsic ambiguity of the pole mass of the order $\Lambda_{QCD}$. This will take affect at the LHC and future colliders with still improved precision.

5.1.2 Decay width

The decay width of the top $\Gamma_t$ will be difficult to measure but its theoretical accuracy lies within 1%. Since the mass of the top quark exceeds the Wb production threshold its decay width is expected to be dominated by the two-body decay $t \rightarrow Wb$. Neglecting higher order corrections and the b quark mass the prediction of the standard model is given by

$$\Gamma(t \rightarrow bW) = \frac{G_F m_t^3}{8\pi \sqrt{2}} \left( 1 - \frac{m_W^2}{m_t^2} \right)^2 \left( 1 + 2 \frac{m_W^2}{m_t^2} \right)$$

[87] (vol. II, p. 314). The numerical value of the top width for a mass of $m_t = 175 \text{ GeV}$ is $\Gamma_t = 1.54 \text{ GeV}$, corresponding to a lifetime of about $\tau_t = 1/\Gamma_t \approx 4.23^{-25} \text{s}$. This is much shorter than the typical hadronization time $\tau_{had} \sim 1/\Lambda_{QCD}$. Thus no top flavoured hadrons or $t\bar{t}$ quarkonium bound states can be formed.

5.1.3 Radiative corrections

Since the top quark mass in combination with the W boson mass allows to test the standard model and to set constraints on the mass of the Higgs boson it is very important to improve the precision of the measured top quark mass. The Higgs boson, the W boson and the
top quark contribute via radiative corrections (as loop contribution) to observables already measured at LEP and SLC, so that the measured observables together with the measured values of the W and top mass restrict the allowed mass range of the Higgs boson as shown in Fig. 5.1.

The relative importance of these corrections depends on the functional form of the correction as well as value of the physical parameter. Because of the large mass of the top quark, there are many radiative corrections in which the top quark plays a pivotal role. Here, we only discuss what is generally considered the most important aspect of the top quark mass, \( m_t \), in electroweak physics: its role in the prediction of the mass, \( m_H \), of the hypothetical Higgs boson. For a more complete catalog of the role of the top quark in the Standard Model see [88] and [89].

The Standard Model predicts that at tree level the mass of the W boson and the Z boson are related via:

\[
\frac{m_W}{m_Z} = \frac{g'}{\sqrt{g'^2 + g^2}} \equiv \cos \theta_W
\]

(5.1.2)

where \( \theta_W \) is the weak mixing angle. It is convenient to re-write these equations and to express the mass of the W boson in terms of the other measured quantities. At tree-level

![Figure 5.1: Constraints on the Higgs mass using the measured top quark and W boson masses. The closed curves correspond to experimental limits on \( m_t \) and \( m_W \). The shaded band indicates for different Higgs masses the values allowed in the standard model.](image)
this can be written as:

$$m^2_W = \frac{\pi \alpha}{\sqrt{2} G_F \sin^2 \theta_W}$$  \hspace{1cm} (5.1.3)

Higher level corrections lead to modifications of this expression which can then be written as \[90\].

$$m^2_W = \frac{\pi \alpha}{\sqrt{2} G_F \sin^2 \theta_W (1 - \Delta r)}$$  \hspace{1cm} (5.1.4)

where $\Delta r$ contains the higher order corrections. The contribution from the top quark can be written to first order as:

$$(\Delta r)_{\text{top}} = -\frac{3 G_F m_t^2}{8 \sqrt{2} \pi^2} \frac{1}{\tan^2 \theta_W}$$  \hspace{1cm} (5.1.5)

Figure 5.2: Top quark one loop contribution to the W and Z boson masses.

Figure 5.3: Higgs boson loop contribution to the W and Z boson masses.
which are depicted as Feynman diagrams in Fig. 5.2. The Higgs boson also contributes to $\Delta r$ via radiative corrections and to first order the correction can be written:

$$\left(\Delta r\right)_{\text{Higgs}} \approx \frac{11 G_F m_Z^2 \cos^2 \theta_W}{24 \sqrt{2} \pi^2} \ln \frac{m_H^2}{m_Z^2}$$

which at one loop has the contributions shown in Fig. 5.3.

The most striking difference between the two contributions is that while the $W$ boson mass has a contribution from the top quark mass which scales as the top quark’s mass squared, the contribution to the $W$ boson mass is only logarithmically dependent on the Higgs boson mass. Due to the corrections from $\Delta r$ from the Higgs boson and the top quark, in order to predict $M_W$ the values of the Higgs boson mass and the top quark mass must be known as well. The Higgs boson has yet to be observed. However, one can turn the argument around and find an expression for the Higgs boson mass from the equations above.

![Figure 5.4: $\chi^2$ fit for the prediction of the mass of the Higgs boson, $m_H$, from precision electroweak data from Ref. [91]](image)

A graphical representation of this relationship is shown in Fig. 5.3 provided by Ref. [91]. The diagonal bands are lines of constant Higgs mass ranging from the current lower bound on $m_H$ to the currently predicted upper bounds [8], around 1 TeV. The dashed ellipse is a 68% confidence level from direct measurements of $m_W$ and $m_t$. The solid ellipse is a 68% confidence level from indirect constraints on precision electroweak data [91]. Hence, precision measurements of $m_W$ and $m_t$ can be used to make a prediction for $m_H$. One can already
see that direct measurements prefer a light Higgs boson as indicated in a $\chi^2$ fit from all electroweak data shown in Fig. 5.4 also from Ref. [91]. Note, however, that because of the one-loop diagrams in Fig. 5.2 the dependence of $\Delta r$ depends only logarithmically on the mass of the Higgs boson. The different curves represent fits using different values of $\alpha$, the electromagnetic coupling constant. The values for $\alpha$ originate in different corrections to the coupling from the strong interaction at low energy.

Although the contribution to $\Delta r$ from the top quark is rather strong (quadratically dependent), the contribution from the Higgs boson mass is rather weak (logarithmic). Thus, in order to significantly constrain the Standard Model prediction of the Higgs boson mass the uncertainty on both the top quark mass and the W boson mass must be rather small. With precision measurements, the top quark mass can be used to test the predictions of the Standard Model.

Recent experimental constraints on the Higgs boson mass are consistent with the standard model [85]. Providing valuable input for future experiments with a final precision of the W mass from LEP expected to be $\sim 40$ MeV, a precision of about $1 \text{ GeV}$ in the top mass would yield a prediction in the Higgs boson mass of $\delta m_H/m_H \leq 40\%$ [92].

### 5.1.4 Anomaly

In the standard electroweak model, if one looks at triangle diagrams of the form illustrated in Figure 5.5, one finds that they diverge in a way that cannot be removed by the usual renormalization procedures [93, 94]. However each flavour of fermion which can ‘run around’ inside the loops makes a separate contribution to this process. It turns out that if one adds up the contributions from each fermion in a generation, then the divergences will exactly cancel, provided that the sum of electric charge for these fermions is zero [94]. (Note that each quark gets counted three times, once for each color state.) Thus, presence of top would ensure the cancellation of these anomalies. However, while this is the simplest way to eliminate this problem, it may be the only way, so this argument in itself is not conclusive [95].

### 5.1.5 $B^0 - \bar{B}^0$ Mixing

The $B^0$ and $\bar{B}^0$ mesons can mix with each other through box diagrams involving internal quark lines. Within the standard model, the top contribution dominates; in fact, a fairly heavy top ($m_t \geq 45 \text{ GeV}$) is required to explain the observed level of $B^0 - \bar{B}^0$ mixing [96]. However, it is possible to build models in which other states can supple the needed contribution, so this argument is also, on its own, not conclusive.
5.1.6 Forward Backward Asymmetry in $e^+e^- \rightarrow b\bar{b}$

In the context of the electroweak standard model, particles are grouped into $SU(2)$ spin multiplets. Each particle (or more precisely, each helicity state of each particle) thus has a spin quantum number called the weak isospin (denoted $T_3$) which is integral if there are an odd number of particles in the multiplet and half-integral otherwise. The strength of the weak interaction depends in part on the value of $T_3$, so $T_3$ can be measured under some conditions. This has been done for the reaction $e^+e^- \rightarrow b\bar{b}$, which can be mediated by either a photon or a $Z^0$. The interference between these two processes gives rise to an asymmetric angular distribution for $b$ production; the amount of this asymmetry depends on the weak isospin of the left-handed $b$-quark $T_{3L}$. Experimentally, the data [97] give $T_{3L} = -0.504^{+0.018}_{-0.011}$, implying that the left-handed $b$-quark is a member of an isospin doublet. Its partner is, by definition, the top quark.

5.1.7 Bottom Decays

Suppose that top did not exists and both helicity states of $b$ were $SU(2)$ singlets. Then the $b$ would not interact with $W$’s and could decay via the usual weak processes. But the $b$ is observed to decay; the only way that standard model could be made to accommodate this to postulate that the $b$ mixes with a lighter quark through some mechanism; the lighter quark, being in a $SU(2)$ doublet, could then decay normally through a virtual $W$. However, if this were to be the case, then the corresponding process involving a $Z$ would also be present, with a cross-section of at least 12% that of the first process [98]. However, the experimental upper limit for this ratio is several orders of magnitude less than this value[99, 100]. This is a further indication that the bottom must be in a $SU(2)$ doublet with the top.
5.2 \( t\bar{t} \) Production at LHC

At the Tevatron, the dominant mechanisms for top production are expected to be the pair production process \( q\bar{q} \to t\bar{t} \) and \( gg \to t\bar{t} \) [101]. The lowest order diagrams for these processes are illustrated in Figures 5.6 and 5.7. Of these, the \( q\bar{q} \to t\bar{t} \) process dominates over \( gg \to t\bar{t} \) for the top masses of interest.

The leading order processes for the production of a \( t\bar{t} \) pair in hadron-hadron collisions are [102]

\[
q(p_1) + \bar{q}(p_2) \to t(p_3) + \bar{t}(p_4) \tag{5.2.1}
\]

\[
g(p_1) + g(p_2) \to t(p_3) + \bar{t}(p_4), \tag{5.2.2}
\]

Where two incoming partons of the hard subprocess, either two gluons or a quark antiquark pair, carry the four momenta \( p_1 \) and \( p_2 \). The outgoing top and antitop quarks carry the four momenta \( p_3 \) and \( p_4 \). The Feynman graphs contributing to the matrix elements in \( O(\alpha_s) \) are shown in the Figs. 5.6 and 5.7. The squared matrix elements averaged over initial and summed over final colour and spin states are given by

\[
\left| M \right|^2(q\bar{q} \to t\bar{t}) = \left(4\pi\alpha_s\right)^2 \frac{8}{9} \left(2 \left(\frac{p_1 \cdot p_3}{(p_1 + p_2)^4}\right) + \frac{m_t^2}{(p_1 + p_2)^2}\right), \tag{5.2.3}
\]

\[
\left| M \right|^2(gg \to t\bar{t}) = \left(4\pi\alpha_s\right)^2 \left(\frac{(p_1 + p_2)^4}{24(p_1 \cdot p_3)(p_2 \cdot p_3)} - \frac{3}{8}\right) \times \left(\frac{(p_1 \cdot p_3)^2 + (p_2 \cdot p_3)^2}{(p_1 + p_2)^4}\right) + \frac{4m_t^2}{(p_1 + p_2)^2} - \frac{m_t^4}{(p_1 \cdot p_3)^2(p_2 \cdot p_3)^2}, \tag{5.2.4}
\]

with the four vector product defined as \( (p_a \cdot p_b) = E_aE_b - \vec{p}_a \vec{p}_b \). The differential partonic cross section
Figure 5.7: Feynman graphs for the production of a $t\bar{t}$ pair via the gluon fusion in lowest order. The t channel amplitude (a), the u channel amplitude (b) and the three gluon vertex (c). The bulk of the $t\bar{t}$ pairs, about 87%, is expected to be produced by these processes at the LHC.

\[
d\sigma = \frac{1}{2(p_1 + p_2)^2} \frac{d^3p_3}{(2\pi)^32E^3} \frac{d^3p_4}{(2\pi)^32E^4}(2\pi)^4\delta^4(p_1 + p_2 - p_3 - p_4)[M]^2
\]

(5.2.5)

is obtained by including the flux factor for the incoming partons $2(p_1 + p^2)^{-2}$ and the terms arising from the phase space of the $2 \rightarrow 2$ scattering process. The differential hadronic cross section

\[
d\sigma = \int_0^1 \int_0^1 dx_1 dx_2 f_1(x_1, Q^2) f_2(x_2, Q^2)d\sigma
\]

(5.2.6)

follows from the partonic one by folding it with the parton density functions of the incoming protons, which give the probability of finding a parton ($q, \bar{q}$ or $g$) with momentum fraction $x \in (0, 1)$ in the proton at a given $Q^2$ scale which is ambiguous but of the order of invariant top quark mass squared.

The $t\bar{t}$ production at the LHC with a hadronic center of mass energy of $\sqrt{s} = 14$ TeV yields a LO cross section of about 560 pb assuming a top mass of $m_t = 175$ GeV. Calculations of the NLO cross section predict about 800 pb. A variation of the top mass of $\pm 5$ GeV yields a change in the cross section of about 12% with decreasing cross section for increasing top masses [86]. Furthermore the variation of the renormalization and factorization scale in the calculation of the NLO cross section, which is of the order $O(\alpha_s^3)$ gives rise to higher order corrections. In detail, a variation of the scale $\mu = m_t$ by a factor of two yields a 10% variation of the cross section [86] using the MRST99 parton density functions. [103].

For the production of an on-shell $t\bar{t}$ pair the energy equivalent of two top masses is sufficient. Just above this threshold the production reaches its maximum and low proton momenta fractions below $x \simeq 0.03$ are favoured. The gluon density of the proton dominates in this range and one expects that about 87% of the $t\bar{t}$ events are produced by the gluon gluon fusion processes of Fig. 5.7. The remaining fraction is expected to be produced by the
quark antiquark annihilation of Fig. 5.6 (it will be shown that the fractions depend, to the percent level, on the parton density functions used). This is different at the Tevatron, where the $p\bar{p}$ center of mass energy is $\sqrt{s} = 1.8$ TeV (Run I). Here the quark antiquark annihilation process dominates with about 90% over the gluon fusion [104]. This large fraction will be slightly reduced (about 2%) in the new Run II with $\sqrt{s} = 2$ TeV due to the rise of the gluon density in the proton towards lower $x$ while the valence quark density (and antiquark density in the antiproton) decreases. On the other hand an optional upgrade of the LHC, to a center of mass energy of $\sqrt{s} = 28$ GeV would lead to a further increase of the already dominating gluon fusion in the $t\bar{t}$ production (about 5%). This may slightly increase the systematic uncertainty in the mass of the reconstructed top due to the uncertainty in the gluon density (see the discussion about the parton density functions in section 4.3). It constitutes also an important issue in the investigation of the $t\bar{t}$ spin correlation and its improvement [86].

The top production cross section has been computed in perturbative QCD for both the $\alpha_s^2$ leading order (LO) and $\alpha_s^3$ next-to-leading order (NLO) terms. In a region where perturbation theory is valid, the NLO contribution should be small compared to the LO terms. However, for top production at the Tevatron, the NLO contributions are worryingly large: for the $gg$ process, the NLO contribution is about 70% of the LO terms [105]. (The situation is better for the $qq$ process, where the size of the NLO contribution is about 20% that of LO.) The major contributor to the large difference between LO and NLO is found to be processes involving the emission of soft initial state gluons. Fortunately, it is possible, through a technique called resummation, to calculate the sums of the dominant logarithms from these processes to all orders in perturbation theory. This calculation has recently been carried out by Laenen, Smith, and Van Neerven; the results are summarized in [105]. This depends on two unknown scale factors. The first is the usual renormalization scale $\mu$. The second is required by the fact that the gluon series being resummed eventually diverges due to non perturbative effects when $\alpha_s$ becomes large. The solution is simply to stop the resummation at a specific scale $\mu_0$, which should be bounded roughly by the DQCD scale $\Lambda$ on the low end and by $m_t$ on the high end. The value chosen for this parameter may be different for the $q\bar{q}$ and $gg$ channels. The scales chosen for the central value in the plot are $\mu = m_t$, $\mu_0(q\bar{q}) = 0.1m_t$, and $\mu_0(gg) = 0.25m_t$. For the upper limit, the non perturbative scales are lowered to $\mu_0(q\bar{q}) = 0.05m_t$ and $\mu_0(gg) = 0.2m_t$. The lower limit was determined by taking the soft gluon series out to only one additional term ($O(\alpha_s^4)$) rather than summing the entire series [106].

5.3 Top quark decay

Within the standard model, a top with $m_t > m_W + m_b$ will almost always decay into a (real) $W$ and a $b$. (The presently known values for the elements of the CKM mixing) imply that the branching ratio for $t \rightarrow W + s$ is less than about 0.2%, $t \rightarrow W + d$ should be smaller still.) The $b$ will form a jet, while the $W$ will decay into either a lepton-neutrino pair or a quark-antiquark pair. To a good approximation, each possible final state of the $W$ is equally probable; however, one must remember to count each quark flavour three times,
since quarks come in three colours. Thus, the probability for the W to decay into each of the three lepton flavours is about 1/9, and the probability for it to decay into each of the two available quark states is about 1/3. Since there are two tops in each event, and since the W's decay independently, the events may be classified based on how the W's decay as shown in Table 5.1. The production and decay of a $t\bar{t}$ pair in the semileptonic decay channel is shown in Fig. 5.8.

Table 5.1: The possible decay modes of W bosons from $t\bar{t}$ and their corresponding branching ratios.

<table>
<thead>
<tr>
<th>W decay mode</th>
<th>$W \rightarrow e\nu_e(1/9)$</th>
<th>$W \rightarrow \mu\nu_\mu(1/9)$</th>
<th>$W \rightarrow \tau\nu_\tau(1/9)$</th>
<th>$W \rightarrow q\bar{q}(2/3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu_e(1/9)$</td>
<td>1/81</td>
<td>1/81</td>
<td>1/81</td>
<td>2/27</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu_\mu(1/9)$</td>
<td>1/81</td>
<td>1/81</td>
<td>1/81</td>
<td>2/27</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu_\tau(1/9)$</td>
<td>1/81</td>
<td>1/81</td>
<td>1/81</td>
<td>2/27</td>
</tr>
<tr>
<td>$W \rightarrow q\bar{q}(2/3)$</td>
<td>2/27</td>
<td>2/27</td>
<td>2/27</td>
<td>4/9</td>
</tr>
</tbody>
</table>

Table 5.2: Overview of all uncertainty components for the top quark mass estimators, extrapolated to a better understanding of both the proton collisions at the LHC and the detector performance.

<table>
<thead>
<tr>
<th>Uncertainty Component</th>
<th>Gaussian fit $\Delta m_t$ GeV/$c^2$</th>
<th>standard selection $\Delta m_t$ GeV/$c^2$</th>
<th>Gaussian ideogram $\Delta m_t$ GeV/$c^2$</th>
<th>Full scan ideogram $\Delta m_t$ GeV/$c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile-up (5%)</td>
<td>0.32</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Underlying event</td>
<td>0.5</td>
<td>0.35</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Jet energy scale (1.5%)</td>
<td>2.90</td>
<td>1.05</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Radiation ($\Lambda_{QCD}, Q^2_0$)</td>
<td>0.80</td>
<td>0.27</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Fragmentation (Lund b, $\sigma_q$)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>b-tagging (2%)</td>
<td>0.80</td>
<td>0.20</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>0.30</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Parton density functions</td>
<td>0.12</td>
<td>0.10</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>3.21</td>
<td>1.27</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>Statistical uncertainty (10 fb$^{-1}$)</td>
<td>0.32</td>
<td>0.36</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>3.23</td>
<td>1.32</td>
<td>1.15</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.8: Sketch of the $t\bar{t}$ decay topology in the case of the semileptonic decay channel. The two incoming gluons carrying the proton momentum fractions $x_1P$ and $x_2P$ respectively produce a $t\bar{t}$ pair which is balanced in $p_\perp$ taking the two incoming gluons as longitudinal axis. The top quarks decay in a $W$ boson and a $b$ quark. Here one $W$ boson decays to a charged lepton and the corresponding (anti-)neutrino. The other $W$ boson decays into a light $q\bar{q}$ pair which will be detected as the $b$ quark through the jets of their fragmentation products.

5.3.1 Single lepton plus jets sample

The single lepton plus jets topology, $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow (l\nu)(jj)b\bar{b}$ arises in $2 \times 2/9 \times 6/9 \approx 29.6\%$ of all $t\bar{t}$ events [107]. One expects, therefore, production of almost 2.5 million single lepton plus jet events for an integrated luminosity of $10^{33} \text{ fb}^{-1}$, corresponding to one year of LHC running at $10^{33} \text{ s}^{-1} \text{ cm}^{-2}$. The presence of a high $P_T$ isolated lepton provides an efficient trigger. The lepton and the high value of $E_T^{\text{miss}}$ give a large suppression of backgrounds from QCD multi-jets and $b\bar{b}$ production.

For the single lepton plus jets sample, it is possible to fully reconstruct the final state. The four momentum of the missing neutrino can be reconstructed by setting $M^\nu = 0$, assigning $E_T^{\nu} = E_T^{\text{miss}}$, and calculating $p_T^\nu$, with a quadratic ambiguity, by applying the constraint that $M^\nu = M_W$. The total background, dominated by $W$+jet production, leads to a signal-to-background ratio (S/B) of 18.6. Tighter cuts can be used to select a particularly clean sample.

The recent systematic and statistical errors for the top mass determination in the semileptonic channel is shown in Table 5.2 [108].
5.3.2 Di-lepton sample

Di-lepton events, where each $W$ decays leptonically, provide a particularly clean sample of $t\bar{t}$ events, although the product of branching ratios is small, $2/9 \times 2/9 = 4.9\%$. With this branching ratio, one expects the production of over 400,000 di-lepton events for an integrated luminosity of 10 $fb^{-1}$.

The presence of two high $p_T$ isolated leptons allows these events to be triggered efficiently. Backgrounds arise from Drell-Yan processes associated with jets, $Z \to \tau^+\tau^-$ associated with jets, $WW + jets$.

5.3.3 Multi-jet sample

The largest sample of events consists of the topology $t\bar{t} \to W^+W^-b\bar{b} \to (jj)(jj)b\bar{b}$. The product of branching ratios of $6/9 \times 6/9 = 44.4\%$ implies production of 3.7 million multi-jet events for an integrated luminosity of 10 $fb^{-1}$. However, these events suffer from a very large background from QCD multi-jet events. In addition, the all-jet final state poses difficulties for triggering. The top quark mass measurement in CDF and D0 for each different channel are shown in Fig. 5.9. The errors mentioned include both statistical as well as systematic errors.

Figure 5.9: Summary of the best top-quark mass results from Run I and Run II from both CDF and D0. These are combined to give the most precise determination of the top-quark mass. This world average is shown as the last point.
Chapter 6
Simulation Tools and Reconstruction Methods

6.1 Important terms and formulas

The frequently used formulas in this analysis are given in Table 6.1.

Table 6.1: Formulas used in this analysis

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invariant mass</td>
<td>( m^2 = p^\mu p^\mu = E^2 - \vec{p}^2 )</td>
</tr>
<tr>
<td>Transverse momentum</td>
<td>( p_T^2 = p_x^2 + p_y^2 )</td>
</tr>
<tr>
<td>Transverse mass</td>
<td>( m_T^2 = m^2 + p_T^2 = E^2 - p_z^2 = (E + p_z)(E - p_z) )</td>
</tr>
<tr>
<td>Transverse energy</td>
<td>( E_T = E \sin \theta )</td>
</tr>
<tr>
<td>Pseudo-rapidity</td>
<td>( \eta = -\ln (\tan \theta / 2) )</td>
</tr>
<tr>
<td>Jet cone radius</td>
<td>( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} )</td>
</tr>
<tr>
<td>Clusters invariant mass</td>
<td>( m_{clus}^2(\Delta R) = E^2 - p^2 = (\sum_{i=0}^{n\Delta R} E_i)^2 - (\sum_{i=0}^{n\Delta R} P_i)^2 )</td>
</tr>
</tbody>
</table>

6.1.1 Pile-up treatment

Protons are grouped in bunches of \( \sim 10^{11} \) protons colliding at a given interaction point every 25 ns. Since the interaction rate is \( \sim 10^9 \) events/s when running at high luminosity, on average 25 soft interactions (minimum bias events) occur simultaneously at each crossing [109]. These give rise, every 25 ns, to about 1000 charged particles in the detector over the pseudo-rapidity region \( |\eta| < 2.5 \). Therefore, when a high-\( p_T \) event is produced during a bunch crossing, this event is overlapped, on average, with 25 additional soft events, which are therefore called pile-up. In order to extract the interesting high-\( p_T \) event from the pile-up,
one can exploit the fact that particles from minimum-bias events have small $p_T$. The pile-up is one of the most serious difficulties for the experimental operation at the LHC and has had a major impact on the detector design, with three main consequences. First, the LHC detectors must have a fast response time, otherwise the signal from the detector would be integrated over many bunch crossings and therefore the pile-up would be too large. Typical response times of the LHC detectors are in the range of $20 - 50 \, ns$, which correspond to integrating over 12 bunch crossings and therefore summing 2550 minimum bias events on average. Such a fast response requires sophisticated and highly-performing readout electronics. Furthermore, the LHC detectors must have a fine readout granularity, in order to minimize the probability that particles from the pile-up traverse the same detector element as an interesting object. This implies a large number of electronic channels, and therefore high cost and a challenging detector operation (calibration, monitoring, etc.). Finally, the LHC detectors must be radiation resistant, because there is a high flux of particles coming from the $pp$ collisions. The total inelastic cross section at the LHC is assumed to be $\sigma \approx 80 \, mb$. The LHC will operate at a bunch crossing rate of $40 \, MHz$. Only $80\%$ of the bunches will be filled, resulting in an effective bunch crossing rate of $32 \, MHz$. The instantaneous luminosity in the first two years after start-up is expected to be $\mathcal{L} = 2 \times 10^{33} \, cm^{-2}s^{-1}$ and subsequently upgraded to $\mathcal{L} = 10^{34} \, cm^{-2}s^{-1}$ in a second phase. The average number of inelastic non-diffractive interactions per bunch crossing is 25 at high and 5 at low luminosity. Both the detailed simulation and reconstruction chain OSCAR/ORCA and FAMOS [110][111][112] allow the overlay of pile-up events, according to a Poisson distribution on top of real signal events, exactly as for real data.

### 6.2 Event Reconstruction

When an event is recorded by the CMS detector it consists of a large collection of analogue to digital converter (ADC) counts from all of the detector systems. In order to perform an analysis of the underlying physics this raw information must be processed to reconstruct the properties of the physics objects in the event. This chapter discusses the process of reconstructing these objects from the raw data.

#### 6.2.1 Calorimeter Reconstruction

The calorimeter signal consists of the collection of electrons, positrons and photons from the pair production, bremsstrahlung and excitation/ionization of $PbWO_4$ crystals. The signal is then digitized and sent through a series of readout electronics. As in the case of the central tracker, the first step is to correct (on a cell by cell basis) the number of ADC counts due to intrinsic differences in cell to cell response and electronic readout. The next step is to convert the ADC counts into an energy deposition in $GeV$. The calibration comes from test beam results (where particles of known energy were targeted on portions of the
calorimeter and in situ calibration (reconstructing the invariant mass of particles whose mass is known to much higher precision than the resolution of the calorimeter). After finding the deposition in each cell, the cell energies are summed in towers of equal \( \eta \) and \( \phi \). While taking this sum, the high energy approximation is made such that the particles are assumed to be massless. In this approximation, the energy and momentum are equivalent such that an 'energy four-vector' may be constructed given by:

\[
(E, E\sin\theta\sin\phi, E\sin\theta\cos\phi, E\cos\theta)
\] (6.2.1)

The towers are then assigned direction variables given by:

\[
\phi = \frac{E_x}{E_y} \quad (6.2.2)
\]

\[
\theta = \tan^{-1}\left(\frac{\sqrt{E_x^2 + E_y^2}}{E_z^2}\right) \quad (6.2.3)
\]

The tower energies and direction are then used in reconstructing the energies and directions of electrons, photons, and jets.

### 6.2.2 Muon reconstruction

Muon reconstruction is performed in three stages: local reconstruction (local-pattern recognition), standalone reconstruction and global reconstruction. The muon reconstruction algorithm used by the HLT is seeded by the muon candidates found by the Level-1 muon trigger, including those candidates that did not necessarily lead to a Level-1 trigger accept [113]. Starting from a seed, the chambers compatible with the seed are identified and local reconstruction is performed only in these chambers. Standalone muon reconstruction uses only information from the muon system, while global-muon reconstruction uses also silicon tracker hits. The HLT standalone and global reconstruction are called Level-2 and Level-3 reconstruction, respectively.

The standalone reconstruction starts with the track segments from the muon chambers obtained by the local reconstruction. The state vectors (track position, momentum, and direction) associated with the segments found in the innermost chambers are used to seed the muon trajectories, working from inside out, using the Kalman-filter technique. Finally, the track is extrapolated to the nominal interaction point (defined by the beam-spot size: \( \sigma_{xy} = 15 \mu m \) \( \sigma_z = 5.3cm \)) and a vertex-constrained fit to the track parameters is performed. Starting from a standalone reconstructed muon, the muon trajectory is extrapolated from the innermost muon station to the outer tracker surface, taking into account the muon energy loss in the material and the effect of multiple scattering. The GEANE package is currently used for the propagation through the steel, the coil and the calorimeters.
6.2.3 Missing Transverse Energy

The offline missing transverse energy is defined as the negative vector sum of the transverse energy in the electromagnetic and hadronic calorimeter towers, \( E_T^{\text{miss}} = - \sum_i (E_i \sin \theta_i) \hat{n}_i \), where \( E_i \) is the energy of the i-th tower, \( \hat{n}_i \) is a transverse unit vector pointing to the center of each tower, and \( \theta_i \) is the polar angle of the tower; the sum extends to \( |\eta| < 5 \).

The presence of a neutrino in the final state can only be detected via the imbalance of momentum in the plane transverse to the beam. It is reconstructed from the vectorial sum of all the calorimeter cells which survive from clustering threshold. Since the coarse hadronic calorimeter has significantly more noise, it is found that only using the cells in the coarse hadronic calorimeter which are part of a jet improves the missing transverse momentum resolution. The missing transverse momentum is then corrected for the jet energy scale, electromagnetic scale, muon momentum and muon energy loss in the calorimeter. Since most of the measurements for the missing transverse momentum are made with the calorimeter which measures energy deposition the term ‘missing transverse energy’ is commonly used in place of missing transverse momentum.

6.2.4 B-tagging

Identifying b-jets relies on the properties of the production and the weak decay of b-hadrons. The most important one is the relatively large lifetime of b-hadrons of about 1.5 ps \((c\tau \approx 450 \mu m)\) (leading to a flight distance that is observable with high resolution tracking detectors. This leads to secondary vertices displaced from the primary event vertex and charged particle tracks incompatible with the primary vertex. b-hadrons have a high mass and large multiplicity of charged particles in the final state (about five charged particles on average per b-hadron decay). Because of the hard b-fragmentation function, the b-hadron in a b-jet carries a large fraction of the jet energy. Since b-hadrons may decay semi-leptonically, in about 20% (per lepton species) of the cases an electron or muon is produced inside a b-jet. At the LHC, b-tagging will be typically applied to jets. Permanent jet reconstruction algorithms are thus necessary. Several jet reconstruction algorithms are available in CMS. They are described together with their performance in [114]. For the studies in this Note, the iterative cone algorithm with a cone size of 0.5 has been used. The input used for the jet clustering are the towers from the electromagnetic and hadronic calorimeters applying a variable noise subtraction. A calibration as deduced from the Monte Carlo simulation has been applied to correct the raw jet energy.

Most of the b-hadron properties used for b-tagging can only be exploited using charged particle tracks because only tracking detectors offer the spatial resolution needed to detect e.g. the significant flight path of b-hadrons. Efficient track reconstruction, and in particular precise spatial reconstruction close to the interaction point, is thus the key ingredient. Track finding was performed using the combinatorial track finder applying a Kalman filter technique [115]. For b-tagging, a physics motivated lifetime based definition of the sign of the track impact parameters is used. The impact parameter is signed as positive if the track is reconstructed to originate downstream the primary vertex with respect to the jet direction,
negative otherwise. The following track selection cuts are applied:

- at least 8 reconstructed hits in total (pixel and silicon strip detectors);
- at least 2 reconstructed hits in the pixel detectors;
- transverse momentum $p_T > 1 \text{ GeV}/c$;
- $\chi^2/dof$ of the track fit < 10;
- transverse impact parameter with respect to the reconstructed primary vertex < 2 mm to reject charged particle tracks having their origin from sources showing much larger displacement from the primary vertex (e.g. $V^0$ decays, photon conversions and nuclear interactions in the beampipe or the first layers of the pixel detector); to first order, the impact parameter is invariant under boosts of the b-hadron.

Fig 6.1 shows non-b jet mistagging efficiency versus the b-jet tagging efficiency in the barrel ($|\eta| < 1.4$) and forward part ($1.4 < |\eta| < 2.4$) of the detector for QCD jets with transverse momenta between 500 $\text{ GeV}/c$ and 800 $\text{ GeV}/c$.

![Figure 6.1: Non-b jet mistagging efficiency versus b-jet tagging efficiency for c-jets (triangles), uds-jets (circles) and g-jets (stars) obtained for jets in a QCD sample for transverse jet momenta between 50 $\text{ GeV}/c$ and 80 $\text{ GeV}/c$ in the barrel ($|\eta| < 1.4$, left) and forward ($1.4 < |\eta| < 2.4$, right) regions of the detector.](image)

Charged particle tracks are associated to a jet if they are within a cone of $\Delta R < 0.3$ with respect to the jet axis. To measure a flight path or displaced tracks not having their origin at the primary event vertex, precise reconstruction of the coordinates of the primary event vertex is crucial. The resolution and efficiency to find the correct primary vertex depends on the event topology (e.g. the number of charged particles at the primary vertex). The spatial resolution is typically between $10 - 40 \mu m$ in the transverse plane and $15 - 50 \mu m$
in the z-direction. The primary vertex finding efficiency is greater than 95% for most of the physics channels with a sufficiently large multiplicity of charged particle tracks in the final state [116] for details).

### 6.3 Event simulation

Because of the complexity of the processes being studied and their interaction with the detector it is necessary to rely on computer simulations of both signal and background events to model the response of the detector. These simulations proceed through a number of steps each using Monte Carlo techniques. Thus, to simulate an event and take into account all what happens in a high energy physics experiment, one has to provide the following steps:

- event generation;
- simulation of the interaction of the generated particles with the detector;
- simulation of the digitization phase;
- local and global event reconstruction.

#### 6.3.1 Event generator

First an 'event generator' which describes the production mechanism at the hard scattering level is used to generate simulated events. It provides a generation of high energy physics events, namely hard interactions between elementary particles such as electrons, positrons, protons and antiprotons in various combinations. They contain theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial- and final-state parton showers, multiple interactions, fragmentation and decay. The PYTHIA [117] program is used to describe the hard scattering process for $t\bar{t}$ signal. The PYTHIA program was interfaced with CMKIN [118] in order to perform the hadronization process. The output is then processed through the OSCAR [110] based on GEANT4 [119] simulation which performs the detector simulation.

#### 6.3.2 Detector response

The next step involves modeling the response of the detector to the particles in the final state of the event. It contains:

- **Detector Description**: Materials, shapes, geometrical hierarchies and positions as well as specific attributes (e.g. sensitive detector) of the CMS detector are described. Description of the CMS magnetic field.
• **Physics Processes**: The physics interactions (transportation, decay, electromagnetic and hadronic processes e.g. ionization, multiple scattering, bremsstrahlung, inelastic processes etc) for all types of particles (photons, electrons, muons, neutrinos, pions, kaons, protons, neutrons etc) in the event.

• Particle tracking and propagation in the detector (in matter) and magnetic field.

• User actions Miscellaneous selection cuts, tracking parameters, specific actions for tuning and monitoring a simulation application.

### 6.3.3 Digitization

The last step is to simulate the digitization of the analog signals from the detector. This is done by a program called ORCA [111] for full simulation, while FAMOS for fast CMS simulation. At this level the following steps are performed:

• Takes the input in the form of hits generated by previous step.

• Position, where a particle entered a sensitive detector volume.

• Direction of the particle, Exit point of the particle.

• Energy deposited.

• ionization of gas in drift tube muon chamber, drift of particles to wire, avalanche, signal.

• Detector electronics (analog to digital conversion, data compression).

• Parameterizations of actual processes used.

• full emulation of Level-1 Trigger electronics [120].

• pile-up inclusion.

### 6.3.4 Reconstruction

• **Detector-specific processing**: Data unpacking, cluster finding, hit reconstruction, tracking, applying calibration constants.

• **Global Tracking**: include hits from different subsystems, e.g. Tracker and Muon System for muons.

• **Vertex Finding**: Bases on Tracks found in the previous step.

• **Particle Identification**: Produce objects used in physics analyses, e.g. electrons, photons, muons, jets,...

• Both Offline Reconstruction and High-Level Trigger reconstruction.
6.4 Simulated signal

6.4.1 Full Simulation

For the studies presented in this analysis, the CMS detector response was simulated using the package OSCAR. It is an application of the Geant4 toolkit for detector description and simulation. OSCAR is used to describe the detector geometry and materials. It also includes and uses information about the magnetic field. OSCAR reads the individual generated events and simulates the effects of energy loss, multiple scattering and showering in the detector materials with Geant4. The digitization (simulation of the electronic response), the simulation of the Level-1 and High-Level Triggers (HLT), and the offline reconstruction of physics objects were performed with the CMS full-reconstruction ORCA package.

6.4.2 Fast Simulation

The same analysis is performed with the fast parameterized simulation FAMOS [112]. FAMOS has been tuned to the detailed simulation and reconstruction and is roughly about a factor 1000 faster. FAMOS allows to perform e.g. accurate sensitivity scans in a large parameter space of a model for new physics.

A fast simulation is not meant to be a replacement of the full simulation. Its purpose is to produce some final analysis object in the shortest possible time, compatibly with the level of accuracy required to satisfy the needs of the task it is used for. Emulation of intermediate quantities, as digitized or reconstructed detector hits, could also be provided. Fast simulation emulates the combined result of detector simulation and reconstruction, and it is therefore generally tuned and validated with the full simulation results (while full simulation is tuned and validated with the real data).

The data samples which are used, are generated by a PYTHIA-130 event generator. While for the reconstruction, a framework for CMS fast detector simulation FAMOS-140 of the particles interactions is used.

This version of PYTHIA implements the full spin correlation. The energy scale for the calculation must be specified. Typically, this is measured by the momentum transfer of the hard scattering of the two primary partons. The momentum transfer squared is signified by $Q^2$. The scale for the calculation was taken to be $Q = m_t$.

The leptonically decaying $W$ boson was allowed to decay into one muon and one neutrino. Again PYTHIA was used to provide the branching ratio and cross-section of the undergone physics process. The parton distribution function (PDF), which describes the probability of finding a parton with momentum fraction $x$ inside the proton was taken to be the CTEQ6.1M [121] distribution function.
6.5 Event selection in high $P_T$ lepton plus jets channel

More than one top mass estimators are required in any experiment, and the high top analysis is one of them [122]. The basic idea of this analysis has been taken from the high $P_T$ top quark analysis performed using the ATLAS detector geometry [123][124]. Since the $t\bar{t}$ production rate is sufficiently large, one can make tight cuts and still accept a sample of reasonable events for which the statistical error on $m_{top}$ will be smaller as compared with the systematic error. So one could, for example, require that the top and anti-top quarks have high momentum in a transverse plane. Due to the high $P_T$ sample, the highly boosted top quarks decay almost back-back, and the daughters from the top decays would appear in two distinct hemispheres of the detector. In order to reconstruct the invariant mass of the calorimetric objects in a large cone around the top direction, it is essential and crucial to estimate precisely the top direction itself. the real top mass. This back-to-back topology will greatly reduce the combinatorial problem of having to select which jets have to be combined to reconstruct the $t \rightarrow bjj$ candidate. Backgrounds other than would also be reduced at high $P_T$. Furthermore, the higher average energy of the jets to be reconstructed should reduce the sensitivity to systematic effects due to the jet energy calibration and negative effects of gluon radiation. The reason we are taking the high $P_T$ tops is to get the three jets from the hadronic top decay close to each other so that they can be collected in one well defined cone with a large opening angle. This phenomenon will be sensitive to the energy deposited by the underlying event, pileup and calorimeter noise. The best measurement of the top quark mass is achieved

Figure 6.2: The lepton+jets final state
in the lepton plus jets channel, since it features a relatively high number of signal candidates, moderate background levels and allows for a full reconstruction of top quark momenta with reasonable accuracy. The signatures of the lepton plus jets channel comprises electron or muon, missing transverse energy and four jets. The schematic diagram of the lepton plus jets channel is shown in Fig. 6.2. The branching fraction of this channel is about 29% and corresponds to 2.5 million semi-leptonic events, which is one of the advantages over the di-leptonic channel. However, W+multijets background is large and require certain techniques and strategies to improve signal to background ratio. We will focus on the method where the isolated muons are used to tag the event and the value of $m_{\text{top}}$ is extracted as the invariant mass of the three jet systems arising from the hadronic top quark decay.

The study of high $P_T$ top is to produce the top anti-top pairs with sufficient high transverse momentum almost above 200 GeV, due to which tops have decay angles very close to the top flight direction and therefore the mass of the calorimetric objects (clusters, cells, seeds) in a large cone around top direction is correlated with the real top mass. Having higher top boost, the opening angle between $W$ and $b$ from top decay are expected to be much smaller. Therefore the jet cone is reconstructed with a very narrow cone size equal to 0.3. One could calculate the mass of the objects which are in a larger cone around top quark direction. For this reason top quark needs to have a larger $P_T (> 200 \text{ GeV})$. Hence one needs to make an event selection in such a way, which selects events with a high $S/B$ ratio.

In this section the selection criteria that is designed to preferentially select $t\bar{t}$ events over background processes. The lepton + jets channel event signature consists of four high $p_T$ jets, a high $p_T$ charged muon, and significant missing transverse energy. There are two stages of event selection: the event pre-selection and the topological selection. The pre-selection is used to obtain a sample of $t\bar{t}$ decaying purely semi-leptonic and generation of even a small amount of data with pre-selection cuts provide equivalence of a large amount of expected real data. The topological selection is used to select the $t\bar{t}$ semi-leptonic events from that sample and to suppress the background processes.

### 6.5.1 Pre-selection

At the generator level top pair pre-selection is done by applying hard $P_T$ cut on top anti-top pairs in the center of mass of the hard scattering system with $P^{\text{top}}_T > 200 \text{ GeV}$ and $|\eta^{\text{top}}| < 3.0$. Additionally one of the $W$s from the top quark decay is forced to decay leptonically $t \rightarrow bW \rightarrow b\mu\nu$, $P^\mu_T > 30 \text{ GeV}$ and $|\eta^\mu| < 2.0$, while the second $W$ is allowed to decay hadronically $t \rightarrow bW \rightarrow bq\bar{q}(q = u, d), (\bar{q} = c, s)$. In addition the partonic level quarks are required to have $P^q_T > 20 \text{ GeV}$ and $|\eta^q| < 2.5$. This pre-selection topology gives rise to the cross-section by PYTHIA that is equivalent to 6.85 pb selected out of 492 pb (LO PYTHIA) per lepton flavor, which corresponds to approximately 1% of the total $t\bar{t}$ cross-section at leading order as shown in Table 6.2. The $t\bar{t}$ lepton plus jets events can be selected using signatures such as two high $P_T$ central light non b-tagged jets from $W \rightarrow q + \bar{q}$, two b-tagged jets, missing $E_T$ and a charged muon from $W \rightarrow l + \nu$ decay. This study is done using a full GEANT simulation of the CMS calorimeter combined with a parameterized b-tagging algorithm. The expected statistics for $7.23 \text{ fb}^{-1}$ integrated luminosity is roughly 9214 signal
Table 6.2: Overview of number of the events simulated with fast detector simulation, their corresponding cross-section and integrated luminosity.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>No. of Events with Pile-up</th>
<th>Int. Luminosity (fb⁻¹)</th>
<th>Cross-section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt → bWbW → bqqblν</td>
<td>49535</td>
<td>7.23</td>
<td>6.85</td>
</tr>
</tbody>
</table>

Events after event selection in leading jets reconstruction scheme, but without including the W mass window cut.

At the partonic level a pre-selection is performed in order to extract purely semi-leptonic data within the huge amount of total data. The main reason to choose $P_T$ cuts is to reduce the background from low $P_T$ jets from gluon radiation and jet production from QCD events. But it also helps to stay away the jet reconstruction thresholds and trigger inefficiencies at low $P_T$. A high $P_T$ muon is more likely to come from the W decay than from a heavy flavour decay.

Initially a study has been done at the parton level with jets and lepton momenta smeared to take into account the CMS detector performance. The purpose of this study is to find the optimal selection criteria for the semi-leptonic high top production, which suppresses the backgrounds to a negligible level. For this study a fast detector simulation is used with the specific trigger requirements and pile-up (minbias events) are taken into account. The pile-up events are included in the signal events. A further study with full CMS detector simulation needs to be done later.

The simulation allows specification of the top quark mass. Samples were generated setting the input top quark mass to 165, 175, 185 GeV/c². Table 6.3 shows an overview of the signal samples generated. The slope of the developed top quark mass estimator was estimated with event samples at three different input top quark masses: 170, 175 and 185 GeV/c including low-luminosity pile-up collisions, but with same pre-selection cuts as mentioned above.

Table 6.3: Overview of the $t\bar{t}$ lepton + jets samples used in the analysis.

<table>
<thead>
<tr>
<th>Top Quark Mass (GeV/c²)</th>
<th>Generated Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>19270</td>
</tr>
<tr>
<td>175</td>
<td>49535</td>
</tr>
<tr>
<td>185</td>
<td>19980</td>
</tr>
</tbody>
</table>

Particles distributions at Partonic Level

It is essential to first observe the distinct features of a high $P_T$ sample at the parton level. The $P_T$ distributions of the top quark and its pseudo-rapidity are shown in Fig. 6.3.
average $P_T$ of the top quark (and $W$ boson) is observed around 286 $GeV$ (and 170 $GeV$) see also Fig. 6.5 with opening angle between two $W$-like quarks. The mean values confirm that the jets are produced with a high boost in the hadronic top hemisphere. The main goal is to reconstruct the top quark mass from the invariant mass of calorimeter clusters which includes the combined jets, with their overlap in space, including all energy deposition around top quark direction. To determine the appropriate size of the cone around the top direction it is important to know about the spatial distance of the three quarks resulting from the hadronic top decay; two partonic light jets from $W$ and one associated b-jet. In Fig. 6.4, the top and the corresponding b-quark and $W$ boson distances are shown. The mean values should be lower, which are expected due to the high $P_T$ boost of the top, with an average separation of 0.8 and 0.4 respectively.

The $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ distance between the closest and furthest quarks from the top axis have been shown in Fig. 6.6, from which it is estimated that the majority of the events lie less than 1.2 parton jet cone sizes apart.

The $\Delta R$ distance between two hadronic quarks is shown in Fig. 6.5, which clearly indicates that most of the events lie below $1.3 - 1.4$, which means that energy sharing between the jets will be taken into account later on during the reconstruction procedure. This is the reason for reconstructing the jets with a cone size of 0.3 for low luminosity.
Figure 6.4: $\Delta R$ distance between the generated top quark and the b-quark at the parton level(left), and the $\Delta R$ distance between the top quark and the $W$-boson at the partonic level(right).

Figure 6.5: $\Delta R$ distance between two quarks from hadronic $W$-boson decay(left), partonic $W$-boson transverse momentum distribution.
6.5.2 Topological selection

Muon Identification and isolation

The muons are reconstructed and identified in this analysis using GlobalMuonReconstructor method in FAMOS, which uses the global information from the muon system of CMS. In this analysis $W \rightarrow e\nu$ is not considered. The global muon multiplicity in the final state with pre-selection cuts is shown in Fig. 6.6. This plot shows that in several events, more than one muons gives the hint of non-isolation of muons, which mean isolation of muons with the help of CMS tracking detectors. Since global muons are the result of Level 1 Global Muon Trigger (GMT) system. Therefore the High Level Trigger (HLT) is employed later for isolation from other background muons.

All those global muons should be considered as isolated muons, provided the ratio of the sum of all the transverse momentum of tracks from the tracker (silicon micro-strip+ pixel hybrid) except muon itself to the transverse momentum of the reconstructed global muon is less than 5%, within the cone size of $\Delta R < 0.2$ and $\Delta R > 0.01$ around the reconstructed global muon. The minimum $P_T$ requirement for the isolated muon to be considered a good muon used in this analysis, is above 30 GeV and the absolute pseudorapidity should be less than 2, which is used at pre-selection level. Our study shows that most of the events contain one isolated muon, while efficiency of our $P_T$ and $\eta$ cuts to select a good isolated muon is more than 92%. The $P_T$ and $\eta$ spectra of isolated muons are shown in Fig. 6.8. The sharp edges of the distributions show the selection cuts employed.
Figure 6.7: Jet multiplicity and the global muons multiplicity distributions are shown.

Figure 6.8: This plot shows the $P_T$ spectrum and the $\eta$ distribution of the reconstructed isolated muon in the leading jets scheme.
Jets reconstruction and identification

Jets are defined as localized energy depositions in the calorimeters and are usually reconstructed using an iterative clustering algorithm with a fixed cone of radius $\sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.3$ in $\eta - \phi$ space [13]. Jets are ordered in transverse energy, $E_T = E \sin \theta$, where $E$ is the scalar sum of energy deposited in the calorimeter towers within the cone, and $\theta$ is the angle formed by the beam-line, the event vertex, and the cone center. Jets with uncorrected $E_T > 20$ GeV and with $|\eta| < 3$ are used throughout this analysis.

In order to fully reconstruct the single-leptonic $t\bar{t}$, it is crucial to apply jet algorithms to segregate the b-tagged jets from light jets. The jets are reconstructed by applying the iterative cone algorithm with $\Delta R = 0.3$. Due to the fact that we are not using standard cone size, the clustering in $E_{cal} + H_{cal}$ towers is done without using the default calibration method. The $E_T$ scheme is used for recombination due to the uncalibrated jets. For the identification of b-jets from other non b-tagged jets, the secondary displaced vertex based $CombinedBTagging$ algorithm is used [125]. The main signatures in $t\bar{t} \rightarrow b\ell\mu\nu q\bar{q}$ are the presence of high $P_T$ b-jets from top decay. The tagging of b-jets is an important tool used to select top quark events to suppress background. The logarithm b-tag discriminant distribution is shown in Fig. 6.9. The b-tag discriminant variable is used above 1.0 (b-tagging efficiency gives 60%) for jets to be tagged as b-jets, while less than 1.0 for jets which are tagged as non b-jets. On the basis of this variable the discrimination between light jets and b-jets is performed. The jet multiplicity and the global muons multiplicity which are used to identify the isolated muons are shown in Fig. 6.7.

Three different methods of event selection are explored in detail to achieve a more efficient way of top mass reconstruction. This method will be used as the top direction for further analysis later on.
6.6 Results based on Fast Simulation

Three different approaches of jets selection are explored to reconstruct the top quark mass. The corresponding purity number of $W$-bosons are also determined after Jet-Parton Matching (JPM) as follows:

6.6.1 Top mass selection using leading jets

In the leading jets selection method, the selection cuts required on isolated muon is the same as mentioned before in pre-selection section. The plane perpendicular to the direction of the isolated muon is used to divide the detector into two hemispheres. The b-jet belonging to the hadronically decaying top is expected to be found in the hemisphere opposite to the muon. Considering only jets with $P_T > 20.0 \text{ GeV}$ and $|\eta| < 2.5$, the cuts require at least 2 b-tagged jets. In each event two highest $P_T$ light jets and two highest $P_T$ b-jets are selected. The distributions of the leading b-jets and leading lights jets are shown in Fig. 6.10. The four momenta of the both light jets are determined to make the di-jet invariant mass ($m_{jj}$). The two highest $P_T$ non b-tagged jets are chosen as the di-jet candidates for the decay. The number of events is reduced by a factor of 3 with 2 b-tagged jets, as compared to the 1 b-tagged requirement. The di-jet invariant mass distributions for events with at least one or two b-tags are shown in Fig. 6.11. Asking for two b-tag greatly reduce the background and helps in reducing the tail of the distribution. Of the two highest $P_T$ b-jets, the one with the largest angle to the muon is considered to be the one from the hadronically decaying top and are called hadronic b-jet. So that four possible combinations are considered due to the presence of two leading light jets and two quarks from hadronic $W$ decay. The maxima is taken of the first two combinations and rest of two, then the minima of the resultant two variables. The variable that is used for Jet-Parton Matching (JPM) is shown in Fig. 6.12. A Gaussian fit is applied on the reconstructed di-jet mass distribution after JPM from uncalibrated di-jet system, for those events in which both of jets are matched within a cone size 0.4 of the $W$-like quarks from the $W \rightarrow jj$ decay in the Monte Carlo truth information. The di-jet distribution is shown in Fig. 6.13 (Left), while the rest of the plots in this figure will be referred in the upcoming sections. The gaussian fit is made on the uncalibrated $m_{jj}$ candidate and the mean value obtained is of the order of $\approx 65.24 \text{ GeV/c}^2$ which are correctly matched with partons. The fitted mean value is 65.24 GeV, which is used as the nominal reference mass value around which the $W$ mass window cut of $|m_{jj} - m_{nom}| \text{ GeV}$ is implemented. Di-jet with $45.24 < m_{jj} > 85.24$ is then combined with the b-tagged jets from the hadronic hemisphere (i.e. b-jet with the largest angle to the lepton) to form $t \rightarrow jjb$ candidates. With all these cuts the overall efficiency is 8.5% and other backgrounds are reduced to a negligible level. The reconstructed $P_T$ spectrum and invariant mass distribution of the accepted $jjb$ combinations is shown in Fig. 6.14, while a breakdown of the event’s selection efficiency with different kinematical cuts is shown in Table 6.4. The double peak can be seen in the reconstructed top quark $P_t$ spectrum. First peak at low $P_t$ values is from the wrong jet combination, may be we exchange the leptonic b-jet into hadronic b-jet, or may be one of the 4 leading jets was coming from the gluon
Figure 6.10: The top row plots show the distributions of the first and the second leading light jet $P_T$ with 108 $GeV$ and 51 $GeV$ mean values respectively, after identifying the jets with combined b-tagged discrimination criteria. The bottom row plots are for the first highest $P_T$ and the second highest $P_T$ b-jets $P_T$ distribution, whose mean values lie at 129 $GeV$ and 72 $GeV$ respectively.
Figure 6.11: Di-jet invariant mass distribution of the selected jj pairs from leading jets selection for at least one b-tag (left), and same W reconstructed mass with at least 2 b-tagged jets.

Figure 6.12: Two quarks matched with two jets correctly when $\Delta R < 0.4$. 
Figure 6.13: Truly reconstructed W invariant mass distributions are shown. The gaussian fit after jet-parton matching (JPM) for all three different selection criterions are implemented.

radiation and soft QCD events. While second peak corresponds to the correct combinations, because at pre-selection level we demand high $P_T$ jets. For jet-to-parton matching angle in

Table 6.4: Events selection topology of leading jets selection and measurements of W-boson and top mass

<table>
<thead>
<tr>
<th>Kinematical cuts</th>
<th>Selection efficiency %</th>
<th>no. of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>before selection</td>
<td>100</td>
<td>49535</td>
</tr>
<tr>
<td>no. of iso. muons</td>
<td>93.6</td>
<td>46370</td>
</tr>
<tr>
<td>$\geq 1$ iso. muon $P_T &gt; 30$ GeV</td>
<td>92.7</td>
<td>45920</td>
</tr>
<tr>
<td>$\geq 1$ reco. light jet $P_T &gt; 20$ GeV</td>
<td>91.1</td>
<td>45117</td>
</tr>
<tr>
<td>$\geq 2$ reco. light jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$\geq 1$ reco. b- jet $P_T &gt; 20$ GeV</td>
<td>55.6</td>
<td>27543</td>
</tr>
<tr>
<td>$\geq 2$ reco. b-jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_W</td>
<td>&lt; 20$</td>
</tr>
</tbody>
</table>

case of two quarks we use 0.4 whereas for the case of single quark we use 0.2. The fraction of selected events in which the W boson is correctly reconstructed from the light jets is about 42.7%, whereas for one quark matching is 18.17% . To optimize the $P_T$ selection cut on the jets different values were tried, raising the jet $P_T$ cut at 25 GeV and 30 GeV. After all the kinematical cuts these resulting efficiencies are equal to 5.3% and 4% respectively. It is observed that the softer $P_T$ cut on the jets gives nicer distributions with more events and a sharp peak. Finally, the high $P_T(top)$ requirement is imposed by requiring $P_T(jjb) > 200$
$GeV$. With these cuts the overall signal efficiency is 2%. In this way, background from sources other than $t\bar{t}$ is reduced to a negligible level. The invariant mass of the accepted $jjb$ combinations after high $P_T$ cut is shown in Fig. 6.15. The top $P_T$ as a function of the $\Delta R$

Figure 6.14: (Left) Reconstructed $P_T$ distribution of top quark using $b$ jet and two leading jets in a hadronic top decay $t \rightarrow jjb$. (Right) The invariant mass distribution of the $jjb$ candidate.

distance between the two jets coming from $W$ decay is shown in Fig. 6.16. From this figure one can see that when the top quark $P_T$ increases, the resulting two jets from the $W$ decay become very close in space. Fig. 6.17 demonstrates the $P_T$ dependence on the reconstructed three jet invariant mass, no significant dependence of mass on $P_T$ of top quark is observed

6.6.2 Top mass selection using exactly four jets scheme

In this event selection, exactly four leading jets in the order of maximum $P_T$ are chosen from a collection of all types of jets ($u, d, c, s, b$) from the $BTagJet$ branch. The muon $P_T$ requirement is the same in all selection methods.

After classifying two of the four reconstructed jets as light quark and b-quark jets, only two jets combinations are left behind. These four jets should have $P_T > 20$ GeV. Efficiencies of the selected events are shown in Table 6.5. After matching the reconstructed light jets with the parton jets as before, the purity of the $W$-boson jet assignment has been observed as 43.26% after one quark and 20.98% after 2 quarks matching with jets. The corresponding distributions of reconstructed $W$ boson and top quark are shown in Fig. 6.18.
Figure 6.15: Dependence of the reconstructed top $p_T$ with the $\Delta R$ distance between two jets coming from the hadronic $W$ decay.

Figure 6.16: Dependence of the reconstructed value of $m_t$ on the reconstructed value of $P_T^{\text{top}}$ for the exclusive single lepton plus jets sample.
Figure 6.17: The reconstructed top $m_{jjb}$ invariant mass distribution from the $t \to jjb$ uncalibrated jets in the high $P_T$ leading jets selection is shown.

Figure 6.18: After four jets selection with $P_T > 20 \text{ GeV}$ and identifying at least 2 b-jets and 2 non b-jets, the di-jet candidate $m_{jj}$ invariant mass distribution after rescaling $W_{jj}$ to 65.24 GeV, is shown (left). Combining the furthest b-jet from the muon to make the candidate $m_{jjb}$ (right) shows a mean value at 142 GeV, which is expected due to using un-calibrated jets with a cone size $\Delta R = 0.3$. 
Figure 6.19: The left plot demonstrates the $W$ boson mass spectrum from all possible di-jet combinations from all the events without any selection after $P_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. The middle plot describes the reconstructed di-jet mass distribution from those two jets in each event which lie closest to the $W$ nominal mass equal to 65.24 GeV in a window of 20 GeV. While the most right plot is like the previous one but with additional requirement of at least one isolated good muon.

Figure 6.20: Reconstructed top mass spectrum in the scheme of choosing di-jet invariant mass close to the $W$-boson nominal mass.
Table 6.5: Events selection topology using four jets criteria

<table>
<thead>
<tr>
<th>Kinematical cuts</th>
<th>Selection efficiency %</th>
<th>no. of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>before selection</td>
<td>100</td>
<td>49535</td>
</tr>
<tr>
<td>no. of iso. muons</td>
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</tr>
<tr>
<td>$\geq 1$ iso. muon $P_T &gt; 30$ GeV</td>
<td>92.7</td>
<td>45916</td>
</tr>
<tr>
<td>reco. light jets $P_T &gt; 20$ GeV</td>
<td>92.7</td>
<td>45915</td>
</tr>
<tr>
<td>exactly four reco. light jets $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>exactly 2 reco. light jets</td>
<td>8.0</td>
<td>3941</td>
</tr>
<tr>
<td>exactly 2 reco. b-jets</td>
<td>8.0</td>
<td>3941</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_W</td>
<td>&lt; 20$</td>
</tr>
</tbody>
</table>

Table 6.6: Events selection topology with the selection of jets having invariant mass close to W nominal mass event by event.

<table>
<thead>
<tr>
<th>Kinematical cuts</th>
<th>Selection efficiency %</th>
<th>no. of events</th>
</tr>
</thead>
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<tr>
<td>before selection</td>
<td>100</td>
<td>49535</td>
</tr>
<tr>
<td>$\geq 1$ iso. muon $P_T &gt; 20$ GeV, $</td>
<td>\eta</td>
<td>&lt; 2.0$</td>
</tr>
<tr>
<td>$2jj \rightarrow W, P_T &gt; 20$ GeV, $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$\geq 2$ reco. b-jets $P_T &gt; 20$ GeV, $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_W</td>
<td>&lt; 20$</td>
</tr>
</tbody>
</table>

6.6.3 Top mass selection using jets ($m_{jj}$) close to nominal $W$ mass

In this method two light jets are chosen in each event whose $P_T$ values lie above 20 GeV and $|\eta| < 2.5$. Also which have a di-jet invariant mass from $W \rightarrow jj$ which lie close to the $W$-boson nominal mass. At the same time two leading $P_T$ b-jets are selected in each event with $P_T > 20$ GeV and $|\eta| < 2.5$ and one isolated muon is required with $P_T > 30$ GeV and $|\eta| < 2.0$. The complete kinematical event selection with corresponding efficiencies is shown in Table 6.6. After this selection the true quarks from the $W$-boson are matched to the selected jets in about 40.6% of the events after one quark matching and 20.76% after both quarks matching with light jets. The corresponding selection efficiencies for jets $P_T > 25$ GeV and $P_T > 30$ GeV, are 7% and 5% respectively. The $W$ boson and the top quark invariant masses are shown in Figs. 6.19 and 6.20 respectively. The leptonic $W$ boson transverse mass $m_{\mu\nu}$ is shown in Fig. 6.21.

In several events $m_{\mu\nu}$ stays at lower values. This behaviour reflects the events in which $x$ and $y$ components of the momentum of $W$ boson are close to zero and $z$ component becomes maximum. So these events correspond to the endcap CMS region, while peak shows the events with negligible $z$ component or in the central region of the detector. Fig. 6.22 shows the calibrated distributions of the top quark mass in the three different approaches. The shift of mean values towards higher values can be be seen clearly. This happens by multiplying
the calibration coefficient \( (m_W/m_{jj}) \) to the \( m_{jjb} \) candidates, where \( m_W \) is the nominal mass, while \( m_{jj} \) is the reconstructed di-jet mass.

![Figure 6.21: The leptonically reconstructed W mass from \( W \to \mu\nu \) with requiring at least one good isolated muon and missing transverse energy with \( E_T > 30 \) GeV without the neutrino Z-component solutions. The missing \( E_T \) has been extracted from the particles.](image)

6.7 Conclusion

In this chapter three different scenarios to select high-\( P_T \) top events were presented. The performance of the different approaches was compared using Monte Carlo truth information. For that purpose

- Jet-Parton Matching is used to exactly measure the mean gaussian fitted value of the uncalibrated \( m_{jj} \) candidate.
- Three different types of selection criteria are explored for hadronic top mass reconstruction.
- Four jets selection criteria results in low efficiency with higher \( W \) purity
- Jets with invariant mass close to \( W \) have higher efficiency with intermediate purity of \( W \).

The leading jet scheme has been used further to reconstruct the \( m_{clus}^{top} \) in the next chapter.
Figure 6.22: Reconstructed top mass distributions for three selection techniques after multiplying the correction factor, which is the ratio of the measured and the gaussian fitted $W$ invariant mass mean value.
Chapter 7

Top mass reconstruction using a large cluster

To take advantage from the particular topology of the high $P_T$ top sample, a special algorithm for the top mass reconstruction is developed. For the events passing the pre-selection cuts as described in previous chapter, the top quark direction was determined. In this chapter top mass will be measured strongly depending on the CMS calorimetric system [126].

7.1 Top mass reconstruction from large calorimeter clusters

Once high $P_T$ top quark candidate has been selected, jets associated with it are close to each other in space and it is no longer required that a b-jet is tagged. The invariant mass of $t \rightarrow bjj$ is reconstructed using two light jets with high $P_T$ and one b-jet. Once the invariant mass of top candidate is known one can also determine its direction of flight. Using this direction of flight of top we have $\Delta R(top, clus)$ for all the clusters. The variable $\Delta R$ is shown in Fig. 7.1. From this figure clearly one can see the large cone mean value from first peak as a big bump at lower values, implies at low distance. While the second peak which lies around 3.14 value, predicts the region where both jets decay back to back. This technique is particularly useful in reducing system errors arising due to jet calibration. It is also useful to avoid the intrinsic complexities of effects due to energy leakage outside a narrow cone. In this analysis we have used several cone sizes for optimizing the value of reconstructed top quark mass around its nominal mass value of $m_t = 175 \text{ GeV}/c^2$, while the latest world average mass of top quark is $172.5 \pm 1.3(stat) \pm 1.9(syst) \text{ GeV}/c^2$ [127]. This method is not based on any particular model, but is strongly dependent on the detector (calorimeters) behaviour. The selected $jjb$ combinations are required to have $P_T > 200 \text{ GeV}$. With this selection criteria, one gets approximately only 2% of the total event, which corresponds to 945 events. The direction of the top quark is determined from the jet momenta.

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7.1.1 Identification of calorimetric Layers

In order to add the calorimeter clusters from different selected cones, calorimeter is subdivided into three calorimeter layers as shown in Fig. 7.2. The partitions of the calorimeters are performed on the basis of $r$ (radial) and $Z$ (longitudinal) coordinates in CMS. The layer 1 in $(r, Z)$ space corresponds to the values $(r < 170 \text{ cm}, |Z| < 350 \text{ cm})$, while layer 2 corresponds to $(r < 300 \text{ cm}, |Z| < 350 \text{ cm})$. The least energetic clusters belong to the layer 1, which is called Electro-magnetic Calorimeter (ECAL), shows electronic noise contribution among the clusters related to high $P_T$ cone. On the other hand layer 2 is characterized as Hadronic Calorimeter (HCAL). The $E_T$ distributions of the clusters belonging to both layers are shown in Fig. 7.3. The clusters pseudorapidity coverage is shown in Fig. 7.4. The energy of clusters is summed separately for two layers. The reconstructed clusters transverse energy in each layer as a function of clusters coverage in the detector is shown in Fig. 7.5. A large cone is drawn around the top quark direction. The top mass is determined by adding the energies of all calorimeter clusters (cells) in this cone, (a calorimeter cell has a size of $(\Delta \eta \times \Delta \phi = 0.0175 \times 0.0175$), while one calorimeter tower has size of $(\Delta \eta \times \Delta \phi = 0.087 \times 0.087$). The effective invariant mass of all the clusters inside a big cone is calculated according to the following formula:

$$m_{jj} = (E^2 - \bar{P}^2) = \left( \sum_{i=1} E_i \right)^2 - \left( \sum_{i=1} \bar{P}_i \right)^2$$  \hspace{1cm} (7.1.1)

where the sum runs over all reconstructed clusters with energy above a certain threshold (100 $MeV$) inside the cone. In our analysis, we assume all clusters to be massless, which implies that
Figure 7.2: The number of calorimetric layers as a function of clustering pseudorapidity coverage. Layer 1 corresponds to ECAL and layer 2 corresponds to HCAL.

Figure 7.3: $E_T^{clus}$ distributions of ECAL and HCAL.
Figure 7.4: Pseudo-rapidity coverage of all type of clusters.

Figure 7.5: The clusters transverse energy as a function of pseudorapidity of clusters.
\[ m \approx 0 \quad (7.1.2) \]
\[ E^2 = \vec{p}^2 \quad (7.1.3) \]
\[ P_x = E(\sin\theta)(\cos\phi) \quad (7.1.4) \]
\[ P_y = E(\sin\theta)(\sin\phi) \quad (7.1.5) \]
\[ P_z = E(\cos\theta) \quad (7.1.6) \]

After adding energies of all the clusters the invariant mass \( M_{\text{clus}}^{\text{top}} \) spectrum is obtained, shown in Fig. 7.6 for different cone sizes which exhibits a clean peak at the \( \Delta R = 1.3 \). By looking at these plots one can expect a statistical uncertainty about \( \delta m = 1 - 1.6 \text{ GeV}/c^2 \) on top mass. The reconstructed top mass from clusters after Gaussian fit for each cone size, shows a strong dependence on the cone size. The Fig. 7.7 shows the number of clusters corresponding to each cone size for all events. Fig 7.8 clearly shows, how number of clusters depend on \( M_{\text{clus}}^{\text{top}} \). This behavior is attributed to the effects of the underlying event (\( U E_{\text{clus}} \)) from the multiple interaction (MUI) among partons of the colliding pairs of protons. A small contribution may rise from the minbias events (pileup) or the readout electronic noise, which add more energy during the \( M_{\text{clus}}^{\text{top}} \) reconstruction. Fig. 7.9 represents the \( E_{\text{clus}}^T \) values scanned with fixing cone size at different \( \eta \) regions. Two peaks can be seen clearly in the small \( \eta \) regions, so due to the small number of clusters the peak at low \( E_{\text{clus}}^T \) is referred to the ECAL relevant clusters and the more energetic clusters belongs to the HCAL.

Additional effects may come from the initial and final state radiation (ISR/FSR). In the absence of the underlying event and for cone sizes which are sufficiently large to contain all three jets from the hadronic top decay, the fitted mass should be independent of the cone size. Therefore a method has been developed to estimate and subtract this contribution from the underlying event by using the calorimeter clusters, which are not associated with the high \( P_T \) top products. More detail about the estimation of underlying event energy is described in the next section.

### 7.1.2 Estimation of Underlying event Contribution

Everything except the higher order process of interest are called Underlying Events (\( U E_{\text{clus}} \)), while process with low transverse energy and with low multiplicity are called pileup or minbias events. In this particular case the pileup and electronic noise contribution is usually negligible as compared to the \( U E_{\text{clus}} \) contribution, because of the presence of energetic jets in the event due to high \( P_T \) cut. The \( U E_{\text{clus}} \) contribution per calorimeter cluster has been estimated from the same high \( P_T \) top sample using the reconstructed calorimeter hits. It represents the average transverse energy \( E_T \) deposited per calorimeter cluster per event, once all the clusters relevant to the high \( P_T \) products are excluded. The method which we have adopted to estimate \( U E_{\text{clus}} \) proportion in each cluster’s transverse energy, is as follows: Calorimeter clusters which are far away from jets are used for \( U E_{\text{clus}} \) estimation. We define jet isolation variable \( \text{min}\Delta R \) as the closest distance between a cluster and a jet. This variable
Figure 7.6: The strong dependence of $m_{top}^{clus}$ on $\Delta R(top, clus)$ is shown with gaussian fit. This dependence demonstrates the underlying event contribution in each cone.

Figure 7.7: The number of clusters corresponding to each cone
Figure 7.8: The dependence of $M_{\text{clus}}^{\text{top}}$ on $\Delta R(\text{top, clus})$ is shown, which is almost linear.

Figure 7.9: The $E_T^{\text{clus}}$ distributions inside a fixed jet isolation cone of 1.3 in different regions of the CMS detector. The two sharp peaks point towards the ECAL (low energy clusters) and HCAL (more energetic clusters at higher $E_T^{\text{clus}}$ values). Increase in the number of clusters with increasing cone size merges both peaks into a single peak.
is used for scanning jet isolation for all clusters in the calorimeter as shown in Fig. 7.10. For the purpose of summation of clusters transverse energy, we have subdivided calorimeter into 2 main layers whose $E_T$ distributions are shown separately in Fig. 7.11. The first layer represents Electro-magnetic Calorimeter (ECAL) and 2nd layer represents the Hadronic Calorimeter (HCAL). We have estimated $UE_{clus}$ contribution on layer by layer basis.

![Figure 7.10: The jet isolation cone distribution is shown.](image)

The minimum $\Delta R(jets,clus)$, indicates the jet isolation cut for calorimeter clusters. The estimated mean $E_T$ for isolated clusters and mean number of clusters obtained in each case are shown in Table 7.1 for layer 1 and similarly in Table 7.2 for layer 2. The averaging is taken on all possible rapidity regions and jet isolation cuts ranges within the calorimeter acceptance ($|\eta| < 3$). Finally the $UE_{clus}$ energy value 93.6 MeV from layer 1 and 342 MeV from layer 2 is obtained. These values are subtracted from each cluster separately layer by layer in order to calculate invariant mass of clusters $M_{clus}^{top}$, which can finally be correlated with the real top mass.

Figs. 7.11 and 7.12 show the effect on $M_{clus}^{top}$ before and after $UE_{clus}$ subtraction respectively. The resultant mean fitted value is in $\Delta R = 1.3$ is still 25% less than the nominal top quark mass, which needs to be calibrated, and will be a subject of study in future. It can be seen that the cluster invariant mass distribution in $\Delta R = 1.3$ is very narrow and has a sharp peak around mean value. Three samples of high $P_T$ top events, but with different input top quark mass in the generator with 165 GeV/$c^2$, 175 GeV/$c^2$, 185 GeV/$c^2$ were produced and analyzed in exactly the same way as previously explained. For all the samples the $UE_{clus}$ energy estimate per calorimeter cluster was kept the same, no mass scale calibration was used. The purpose of this exercise is to predict whether the reconstruction method is able to determine the input top mass, independently of its value. In Fig. 7.13 the resulting top mass $m_{top}^{jib}$ at cone size 1.3, in each sample is plotted versus the input top quark mass in the generator. A correlation with a slop about 0.786 is observed. This means that an error of 0.9
Figure 7.11: Reconstructed $m_{clus}^{top}$ spectrum obtained using a cone size of $\Delta R = 1.3$ around the top direction.

Figure 7.12: The $m_{clus}^{top}$ spectra fitted with gaussian function after the $UE_{clus}$ is subtracted.
Table 7.1: Underlying event estimation method for Layer 1 (ECAL).

<table>
<thead>
<tr>
<th>$\Delta R(jets, clus)$</th>
<th>$\eta &lt; 0.7$</th>
<th>$\eta &lt; 1.4$</th>
<th>$\eta &lt; 2.1$</th>
<th>$\eta &lt; 3.0$</th>
<th>$\eta &gt; 2.5$</th>
<th>$\eta &lt; 5.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R = 0.7$</td>
<td>201.24</td>
<td>173.59</td>
<td>102.26</td>
<td>102.26</td>
<td>53.99</td>
<td>78.73</td>
</tr>
<tr>
<td></td>
<td>76</td>
<td>181</td>
<td>708</td>
<td>708</td>
<td>309</td>
<td>1383</td>
</tr>
<tr>
<td>$\Delta R = 0.8$</td>
<td>199.50</td>
<td>172.54</td>
<td>100.71</td>
<td>100.71</td>
<td>53.99</td>
<td>77.43</td>
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<td>66</td>
</tr>
<tr>
<td>$\Delta R = 0.9$</td>
<td>198.50</td>
<td>171.20</td>
<td>99.28</td>
<td>99.28</td>
<td>54.01</td>
<td>76.23</td>
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<td>630</td>
<td>630</td>
<td>303</td>
<td>1285</td>
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<td>$\Delta R = 1.1$</td>
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<td>54.17</td>
<td>73.79</td>
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<td>546</td>
<td>295</td>
<td>1175</td>
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<tr>
<td>$\Delta R = 1.5$</td>
<td>192.99</td>
<td>164.27</td>
<td>91.25</td>
<td>69.88</td>
<td>54.77</td>
<td>69.88</td>
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<tr>
<td></td>
<td>16</td>
<td>55</td>
<td>372</td>
<td>922</td>
<td>268</td>
<td>922</td>
</tr>
</tbody>
</table>

in the mean of the peak translates to an error of $0.9/0.786 = 1.145 \text{ GeV}/c^{2}$ on the measured top mass from jets.

7.2 Results with Full Detector Simulation

A similar analysis as the one presented with FAMOS was repeated with the sample of fully simulated events of the CMS detector. The main points of the analysis and in particular the ones that differ from the fast simulation are presented here. The variation of the mean values for different cone sizes is shown in Fig. 7.14. The peak values in the case of ORCA are higher than those of FAMOS. Due to the clustering of the by default calibrated jets in ORCA, the average transverse energies of the clusters are larger. The difference between the fast and full simulation can be attributed to the shower shape development. The $UE_{clus}$ was evaluated following the same procedure as with the fast simulation data shown in Tables 7.3 and 7.4. The average $UE_{clus}$ is about 117 $MeV$ for ECAL, and 396 $MeV$ for HCAL, which is a bit larger than the fast simulation but calculated over a much larger number of clusters. This was used for all the full simulation studies described below.

The $m_{clus}^{top}$ average value is 161 GeV in $\Delta R = 1.3$, lower by 8% from the generated top quark mass. To verify that the re-calibration procedure studied with the ORCA data works equally well in the full simulation, the most promising method of using the inclusive top sample was studied. An official sample of 347811 fully simulated inclusive $t\bar{t}$ events was used. This sample was generated with PYTHIA-130, simulated with OSCAR-245, digitized with ORCA-761 and reconstructed with ORCA-871. The analysis was carried out with ROOT. The same cuts as in the fast simulation analysis described in previous
chapter were used. At the end of high $p_T$ cut only 93 events left behind. The W boson was first reconstructed using the jets, and then the $m_{top}^{clus}$ invariant mass was calculated for several $\Delta R$ values. In summary, the full simulation data show similar results as fast simulation, and confirm the competitiveness of the proposed reconstruction method.

### 7.3 Summary and conclusion

The hadronic top quark mass reconstruction has been studied in the top anti-top pair production process using fast Monte Carlo as well as full simulation of CMS detector geometry. Three different selection criteria have been proposed for the optimization of selection cuts which allow the reconstruction of the top mass in a most efficient manner with a negligible background, thanks to the high $p_T$ top cut. We studied the reconstructed W-boson and top quark masses from different selections. It turns out that the method which selects the W-boson di-jet candidates closest to the nominal $W$ mass, gives the highest efficiency and a good purity. The four-jet scheme provides a higher purity of top sample but with lower efficiency. We have explored different ways to select the top events and have determined the direction of hadronically decaying top quark from leading jets approach.

We describe an alternative method to estimate the top mass using high $p_T$ top anti-top events in the lepton plus jets channel. We present an event selection for these events and show that it is possible to observe the energy deposited by the hadronic top decay in a cone around the reconstructed top flight direction. Since the invariant mass of the calorimeter clusters in such a cone depends on the cone size due to the underlying event, a first step towards the estimation and data-based subtraction of underlying event activity is presented.

| $\Delta R(jets, \text{clus})$ | $|\eta| < 0.7$ | $|\eta| < 1.4$ | $|\eta| < 2.1$ | $|\eta| < 3.0$ | $|\eta| > 2.5$ | $|\eta| < 5.0$ |
|---------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $\Delta R = 0.7$          | 626.89      | 509.19      | 445.77      | 363.00      | 236.77      | 326.78      |
|                           | 38          | 88          | 134         | 229         | 182         | 352         |
| $\Delta R = 0.8$          | 623.07      | 503.17      | 439.69      | 356.43      | 236.76      | 321.39      |
|                           | 33          | 80          | 125         | 218         | 181         | 33          |
| $\Delta R = 0.9$          | 618.47      | 496.66      | 433.11      | 349.36      | 236.69      | 315.67      |
|                           | 29          | 73          | 116         | 180         | 330         |             |
| $\Delta R = 1.1$          | 614.85      | 485.24      | 420.82      | 335.58      | 236.35      | 304.62      |
|                           | 22          | 22          | 22          | 22          | 22          | 22          |
| $\Delta R = 1.5$          | 599.83      | 459.49      | 394.11      | 306.64      | 237.03      | 283.05      |
|                           | 8           | 28          | 56          | 136         | 169         | 253         |

Table 7.2: Underlying event estimation method for Layer 2 (HCAL)
The reconstruction method was verified by generating three samples with three different input top masses 165 GeV/c², 175 GeV/c² and 186 GeV/c². A correlation with a slop about 0.786 is observed between input and reconstructed top masses. This means that an error of 0.9 in the mean of the peak translates to an error of 1.145 GeV/c² on the measured top quark mass from jets. This means that with 50K events which corresponds to 7.3 fb⁻¹, one can expect a statistical uncertainty of about 1.145 GeV/c² on top mass. The top quark mass with and without $UE_{clus}$ subtraction was measured and tried to make $m_{clus}^{top}$ independent of the cone around top flight direction. one can expect a statistical uncertainty about $\delta m = 1 - 1.6$ GeV/c² on top mass $m_{clus}^{top}$. The final calibration and more precise $UE_{clus}$ subtraction method in the $m_{clus}^{top}$ measurement will be the subject of future study.
Figure 7.14: The $m_{clus}^{top}$ spectra with different cone sizes in full simulation.
Table 7.3: $UE_{clus}$ estimate in the full simulation high $P_T$ sample for (ECAL).

| $\Delta R(jets, clus)$ | $|\eta| < 0.7$ | $|\eta| < 1.4$ | $|\eta| < 2.1$ | $|\eta| < 3.0$ | $|\eta| > 2.5$ | $|\eta| < 5.0$ |
|-------------------------|---------------|---------------|---------------|---------------|---------------|---------------|
| $\Delta R = 0.7$       | 129.48        | 109.93        | 114.3         | 114.3         | 151.6         | 122.36        |
|                         | 249           | 599           | 704           | 704           | 119           | 890           |
| $\Delta R = 0.8$       | 129.8         | 109.36        | 114.18        | 114.18        | 151.48        | 122.78        |
| $\Delta R = 0.9$       | 129.38        | 108.46        | 113.92        | 113.92        | 151.66        | 123.24        |
|                         | 184           | 476           | 570           | 570           | 115           | 748           |
| $\Delta R = 1.1$       | 128.07        | 105.75        | 112.88        | 112.88        | 151.7         | 124.23        |
|                         | 126           | 358           | 439           | 439           | 110           | 608           |
| $\Delta R = 1.5$       | 124.55        | 102.1         | 112.53        | 128.93        | 150.411       | 128.93        |
|                         | 45            | 163           | 216           | 361           | 97            | 361           |

7.4 Publications


8. I. Ahmed "Data Acquisition System for RPC testing". (to be submitted as CMS NOTE).
Table 7.4: $U E_{clus}$ estimate in the full simulation high $P_T$ sample for (HCAL).

| $\Delta R(jets,clus)$ | $|\eta| < 0.7$ | $|\eta| < 1.4$ | $|\eta| < 2.1$ | $|\eta| < 3.0$ | $|\eta| > 2.5$ | $|\eta| < 5.0$ |
|------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $\Delta R = 0.7$      | 567.14      | 478.16      | 453.13      | 411.58      | 222.86      | 307.49      |
|                        | 69          | 164         | 254         | 402         | 976         | 911         |
| $\Delta R = 0.8$      | 564.66      | 474.18      | 449.2       | 407.5       | 222.41      | 302.75      |
|                        | 61          | 149         | 234         | 379         | 673         | 61          |
| $\Delta R = 0.9$      | 565.25      | 469.15      | 445.2       | 403.43      | 222.02      | 298.10      |
|                        | 52          | 133         | 214         | 357         | 670         | 863         |
| $\Delta R = 1.1$      | 564.32      | 458.94      | 436.89      | 394.24      | 221.02      | 287.86      |
|                        | 36          | 36          | 36          | 36          | 36          | 36          |
| $\Delta R = 1.5$      | 537.36      | 431.17      | 413.65      | 368.13      | 214.7       | 262.88      |
|                        | 13          | 46          | 94          | 211         | 636         | 695         |
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[127] hep-ex/0603039
Appendix A

The PYTHIA package [117] is a general-purpose generator for hadronic events in $pp$, $e^+e^-$ and $ep$ colliders. It contains a subprocess library and generation machinery, initial- and final-state parton showers, underlying event, hadronisation and decays, and analysis tools. PYTHIA contains around 240 different $2 \rightarrow 2$ (and some $2 \rightarrow 1$ or $2 \rightarrow 3$) subprocesses, all at leading order. The subsequent decays of unstable resonances ($W$, $Z$, top, Higgs, SUSY, . . . ) brings up the partonic multiplicity, for many processes with full spin correlations in the decays. The external processes can be evolved through the showering and hadronisation (like internal ones).

The final-state shower is based on forward evolution in terms of a decreasing timelike virtuality $m^2$, with angular ordering imposed by veto. The framework is leading-log, but includes many NLL aspects such as energymomentum conservation, $\alpha_s(p_T^2)$ and coherence. Further features include gluon polarisation effects and photon emission.

The initial-state shower is based on backwards evolution, i.e. starting at the hard scattering and moving backwards in time to the shower initiators, in terms of a decreasing spacelike virtuality $Q^2$. Initial and final showers are matched to each other by maximum emission cones.

The composite nature of hadrons (and resolved photons) allows for several partons from each of the incoming hadrons to undergo scatterings. Such multiple partonparton interactions are instrumental in building up the activity in the underlying event, in everything from charged multiplicity distributions and long-range correlations to minijets and jet pedestals. The interactions are described by perturbation theory, approximated by a set of more or less separate $2 \rightarrow 2$ scatterings; energy conservation and other effects introduce (anti)correlations.

The scatterings are colour-connected with each other and with the beam remnants.

The Lund string model, used for hadronisation, is based on a picture with linear confinement, where (anti)quarks or other colour (anti)triplets are located at the ends of the string, and gluons are energy and momentum carrying kinks on the string. The string breaks by the production of new $q\bar{q}$ pairs, and a quark from one break can combine with an anti-quark from an adjacent one to form a colour singlet meson.

Unstable particles are allowed to decay. In cases where better decay models are available
elsewhere, e.g. for $\tau$ with spin information or for B hadrons, such decays can be delegated to specialised packages.

At present the parameters from almost all PYTHIA common blocks (see BLOCK DATA PYDATA) could be set via data cards. With the CMKIN these parameters could be set in data card file with the following format (note, that only capital letters should be used):

- Common cards for CMKIN

Below we present the list of PYTHIA parameters used for full event simulation. Some of these parameters correspond to the old multiple interactions scenario, namely Rick Fields Tune A [?].

- $\text{MSTP}(2) = 1 : 1$(first)/$2$(second) order running $\alpha_s$
- $\text{MSTP}(33) = 0 : $ do not include K-factors in hard cross sections
- $\text{MSTP}(51) = 7 : $ PDF set (here is CTEQ5L)
- $\text{MSTP}(81) = 1 : $ multiple parton interactions is switched ON
- $\text{MSTP}(82) = 4 : $ defines the multiple parton interactions model
- $\text{PARP}(67) = 1. : $ amount of initial-state radiation
- $\text{PARP}(82) = 1.9 : $ Pt cut-off for multi-parton interactions
- $\text{MSTJ}(11) = 3 : $ choice of the fragmentation function
- $\text{MSTJ}(22) = 2 : $ allow to decay those unstable particles
- $\text{PMAS}(5,1) = 4.8 : $ the mass of b-quark
- $\text{PMAS}(6,1) = 175.0 : $ the mass of t-quark
- $\text{PARP}(85) = 0.33 : $ gluon production mechanism in multiple interactions
- $\text{PARP}(86) = 0.66 : $ gluon prod. mechanism in multiple interactions.