University of Delhi
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PhD Thesis

Search For New Phenomena In High Energy Interactions

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Todo list

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Chapter 1

The LHC and CMS Machine

In this chapter, the working and the design parameters of Large Hadron Collider (LHC) and its one of main purpose detector, Compact Muon Solenoid (CMS), are briefly described.

1.1 The Large Hadron Collider

The famous quote "history repeats itself" applies well to the High Energy Physics (HEP) experiments. The starting point of experimental particle physics is the Rutherford α-particle scattering, which is suggested by Ernest Rutherford and carried out by the two assistant Hans Geiger and Ernest Marsden in early 20th century [1]. In this experiment Rutherford suggested to aim the beam of α-particles to the thin gold foil and using the experimental findings they suggested the well known structure of today's atom, in which the most of mass centered at core of atom which is known as nucleus and the electrons rotates around the nucleus. Even now we are doing the same thing just the method changed from "natural accelerator"[1] to the "man-made" accelerator that can accelerate particles with the velocity close to the speed of light. The design and working of the accelerator has changed a lot over a period of time in going from MeV to GeV and in the TeV range. Now, these machines are not only used in HEP experiments, but also extends their arenas to treating human beings from cancer therapy, radioisotope production, 3-D x-ray, also to the industry for uses like material processing, sterilization, security scan,

Add citations to the applications

[1] radioactivity and cosmic rays

water treatment, and many more.

The LHC is a hadron collider which can accelerate two proton beams, moving in opposite direction, to a maximum of 14 TeV energy in a 26.7 km long tunnel which is about 100 m underground. The LHC is the latest and most-powerful accelerator everbuilt. It is a proton-proton collider built to improve our understanding of fundamental physics. It started on 21^{st} October 2008 and is positioned in the same tunnel that earlier had Large Electron Positron Collider (LEP). The LEP collaboration decided to switch to hadron collider because of following advantages:

- Hadron collider can reach a higher Center Of Mass (COM) energy, because of much lower synchrotron radiation [2] emitted by hadrons as compared to electrons. Synchrotron radiation loss is directly proportional to $(Energy/mass)^4$.

- As hadrons are composite particles, they allow us to scan over wide range of energies.

For any particle accelerator, there are mainly three components. In case of LHC, they are:

- Beam pipes

- Accelerating structure

- Magnet system

1.1.1 Beam Pipes

At LHC, there are two beam pipes each with diameter ≈6.3 cm in which proton beams travel in opposite directions. To avoid beam instability and loss of beam particles due to collision with gas molecules; the beam pipes are kept at ultra-high vacuum[3] 1.013×10^{-13} bar pressure.

[2] The radiation emitted by a charged particle during acceleration in a circular path is known as synchrotron radiation. As the particles loses energy in emission of this radiation an additional energy must be provided to keep the beam at constant energy.

[3] At LHC, three different vacuum systems are used. First one is used for beam pipe; second one for insulating the cryogenically cooled magnets and third one is used for insulating the helium distribution. In the latter two it just acts as a thermal insulator as the cryogenic parts are kept at 1.9 K ($-271.3°C$)

1.1.2 Accelerating Structure

Another main part of any particle accelerator is its accelerating structure. A accelerator in the TeV range can not start from rest and go to the TeV range in one go; it should go into several stages depending on the energy. At LHC, the journey of proton starts with grabbing the proton from Hydrogen gas and subsequently going into 5 different stages. The stages can be decreased but could not be decreased to just one. Here, at LHC there are five different stages before reaching to LHC and in between it serves several other experiments at each stage, which are shown pictorially in Figure 1.1. The stages for proton acceleration are:

- Grab proton source: The source of proton is Duoplasmatron [2]. It strips electron from hydrogen gas and creates a plasma of protons, electrons and molecular ions. This plasma expands towards the extraction electrodes and a proton beam is formed. This feeds protons to LINAC2.

- LINAC2 (Linear accelerator-2): It is the starting point of proton's journey in the LHC accelerator complex. Here, protons reaches to an energy of 50 MeV using the radio-frequency (RF) cavities[4] where they also gains 5% in mass. LINAC2 further feeds to the Proton Synchrotron Booster (PSB).

- PSB: It takes 50 MeV proton beams from LINAC2 and accelerate them to 1.4 GeV for injection into Proton Synchrotron (PS).

- PS: It is one of key component in the LHC accelerator complex. It increases the energy of protons up-to 25 GeV and feeds to super proton synchrotron.

- Super Proton Synchrotron (SPS): It has a circumference of 7 km where protons are accelerated to an energy of 450 GeV. Then via two transmission line protons are then injected into LHC ring.

- LHC: It grabs two proton beams from SPS which are injected into opposite directions in parallel pipes. In LHC, proton beams can be accelerated up-to 7 TeV.

The CERN accelerator complex is shown in Figure 1.2.

[4] A RF cavity is an metallic cavity that accelerates the charged particles using the electromagnetic field.

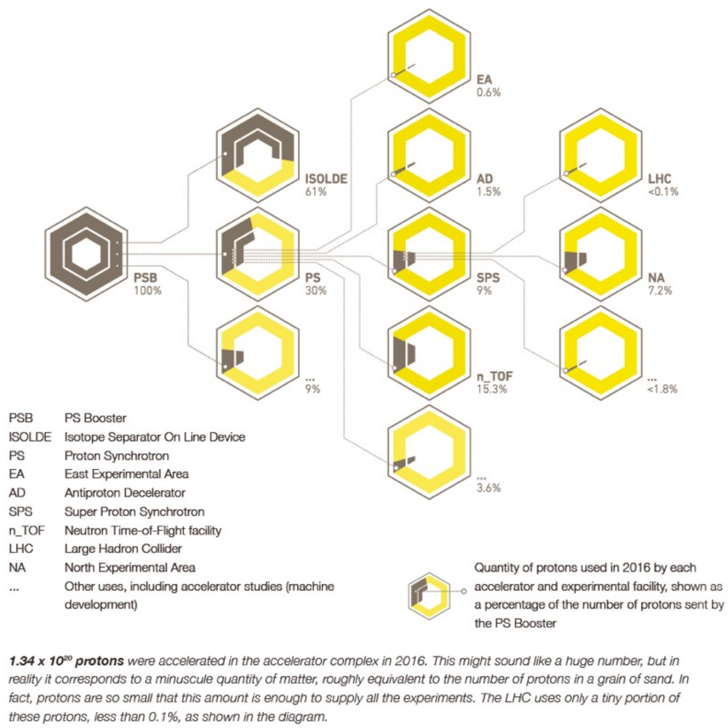

Figure 1.1: Other experiments at the LHC accelerating chain [3]

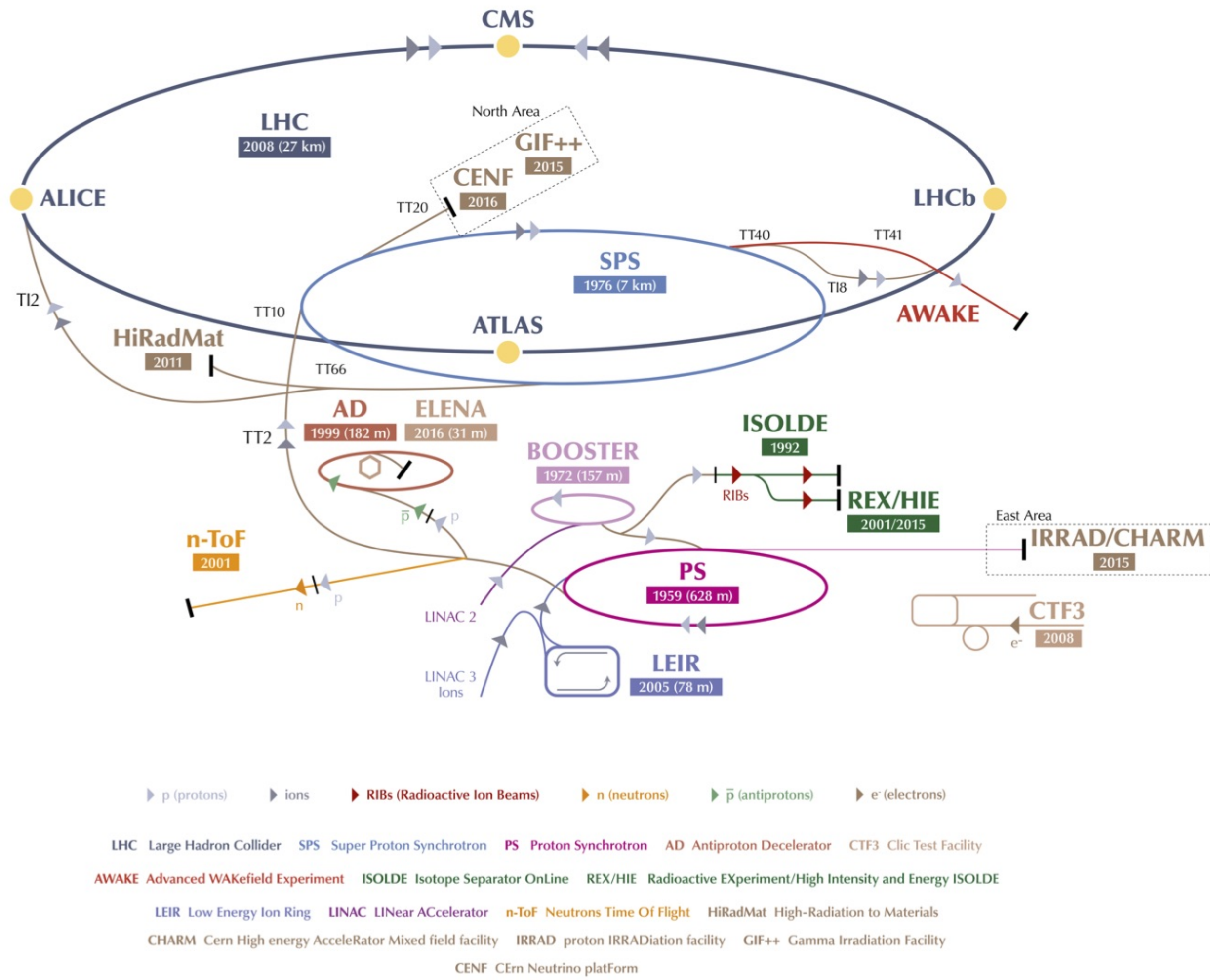

Figure 1.2: LHC accelerator chain along with all its other experiments which uses proton beam from other part of accelerator either from PSB, PS or SPS[4]

1.1.3 Magnet System

As the LHC is a circular collider; magnet system is one of the core parts and gives particles a circular trajectory in the LHC beam pipes. To be economical LHC has been made in eight arcs and eight straight sections instead of a perfect circle. Apart from bending the beam, it is also necessary to focus the beam as the same charge protons try to diverge. To focus the beam a pair of quadrapole magnets is used. One focuses the beam width while other focuses the beam height. Quadrapole magnet geometry is shown in Figure 1.3. A total of 858 quadrupole magnets are installed in LHC to keep the beam focused. Sextupole magnets are also used for proper focusing as every proton in the beam is not exactly with the same energy and on thee same path. Several other magnetic multi-poles are used to keep the beam focused in case the beam suffers from gravitational interactions over protons, electromagnetic interactions among bunches, electron clouds from pipe wall, and so on. Different types of magnets used in LHC are listed here [5]. Besides, there are eight sets of "inner triplets" used at the four interaction points (IPs) to focus the beams while colliding to increase the luminosity. Here the size of bunch goes from 0.2 mm to 17 μm at the interaction point of ATLAS or CMS. At the interaction point of ALICE or LHCb it is 71 μm. Summary of important parameters of LHC is given in Table 1.1.

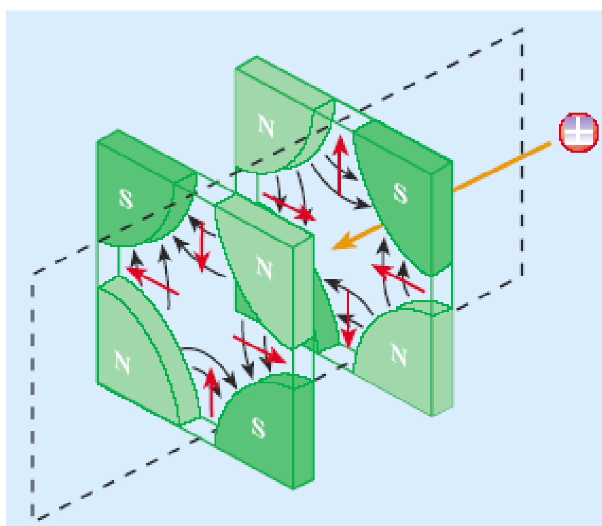

Figure 1.3: Pair of quadrupole magnets.

Parameters	**Value**
Circumference of LHC ring	26658.883 m
Maximum dipole magnetic field	8.33 T
Dipole operating temperature	1.9 K
Maximum stored energy per beam (nominal)	362 MJ
Maximum stored energy per beam (2012)	143 MJ
Maximum stored energy per beam (2016)	266 MJ
Beam energy at Injection	450 GeV
Beam energy at collision (nominal)	7 TeV
Beam energy at collision (2012)	4 TeV
Beam energy at collision (2016)	6.5 TeV
Maximum instantaneous luminosity (nominal)	10^{34} cm$^-2$ s^{-1}
Maximum instantaneous luminosity (2012)	7.7×10^{33} cm$^-2$ s^{-1}
Maximum instantaneous luminosity (2016)	1.4×10^{34} cm$^-2$ s^{-1}
Number of bunches per proton beam (nominal)	2808
Number of bunches per proton beam (2012)	1380
Number of bunches per proton beam (2016)	2076
Maximum number of protons per bunch	1.6×10^{11}
Protons/bunch (average at start of collision) (nominal)	1.15×10^{11}
Protons/bunch (average at start of collision) (2012)	1.5×10^{11}
Protons/bunch (average at start of collision) (2016)	1.1×10^{11}
Bunch collision frequency (nominal)	40 MHz
Bunch collision frequency (2012)	20 MHz
Bunch collision frequency (2016)	40 MHz
Bunch length (at injection)	1.7 ns
Bunch length (at collision)	1.05 ns
Energy spread (at injection)	1.9×10^{-3}
Energy spread (at collision)	0.45×10^{-3}
Half crossing angle (nominal)	143 μrad
Half crossing angle (2012)	146 μrad
Half crossing angle (2016)	185 μrad
$\beta *$ (nominal)	0.55 m
$\beta *$ (2012)	0.6 m
$\beta *$ (2016)	0.4 m
RMS beam size at IP1 & IP5	17 μm
RMS beam size at IP2 & IP8	71 μm
ϵ_n(transverse emittance, rms, normalized) (at injection)	3.5 μm
ϵ_n(transverse emittance, rms, normalized) (at collision point)	3.75 μm
total longitudinal emittance (at injection)	1.0 eVs
total longitudinal emittance (at collision)	2.5 eVs
Average mean pile-up (nominal)	25
Average mean pile-up (2012)	20
Average mean pile-up (2016)	40
Energy loss per turn at 14 TeV	7 keV
Energy loss per turn for electrons at 104.6 GeV	40,000 keV

Table 1.1: LHC technical parameters for proton-proton collisions: nominal, 2012 and 2016 values.[6, 7, 8, 9].

1.1.4 Few key requirements

The HEP collider is mainly characterized by the two parameters: center of mass (COM) energy and the luminosity. The production rate of heavier particles like Higgs increases with COM energy. The luminosity is proportional to the number of events per second so it should be maximized. Luminosity is defined as:

$$L = \frac{k_b N_b^2 f_{rev} \gamma}{4\pi \epsilon_n \beta^*} \tag{1.1}$$

where,
k_b is the number of bunches per ring,
N_b is the number of protons per bunch,
f_{rev} the revolution frequency,
ϵ_n is the normalized RMS transverse beam emittance (same in both)
β^* is the beta-function at the interaction point

Based on the definition of luminosity, we can maximize it by following means:

- By decreasing beam emittance, ϵ_n.
- By improving the cryogenic system. As the factor $k_b.N_b$ is limited by thermal energy produced by synchrotron radiation.
- By decreasing beam-beam effect [10, 11]. As it scales with N_b/ϵ_n which causes the spread in betatron tunes [12].
- Also, the space charge [13] scales with N_b/ϵ_n.

1.2 Experiments at the LHC

In LHC there are four IPs where two proton beams are made to collide. At every IP one detector is placed. They are ATLAS, CMS, ALICE, and LHCb as shown in Figure 1.4. Also, there are two more small detectors LHCf and TOTEM installed close to the IP of the two main detectors ATLAS and CMS respectively.
ATLAS (A Toroidal LHC Apparatus) and **CMS** (Compact Muon Solenoid) are large general-purpose[5] detectors having similar design and similar

[5] Here, general purpose means this machines will be used for many different kind of physics searches.

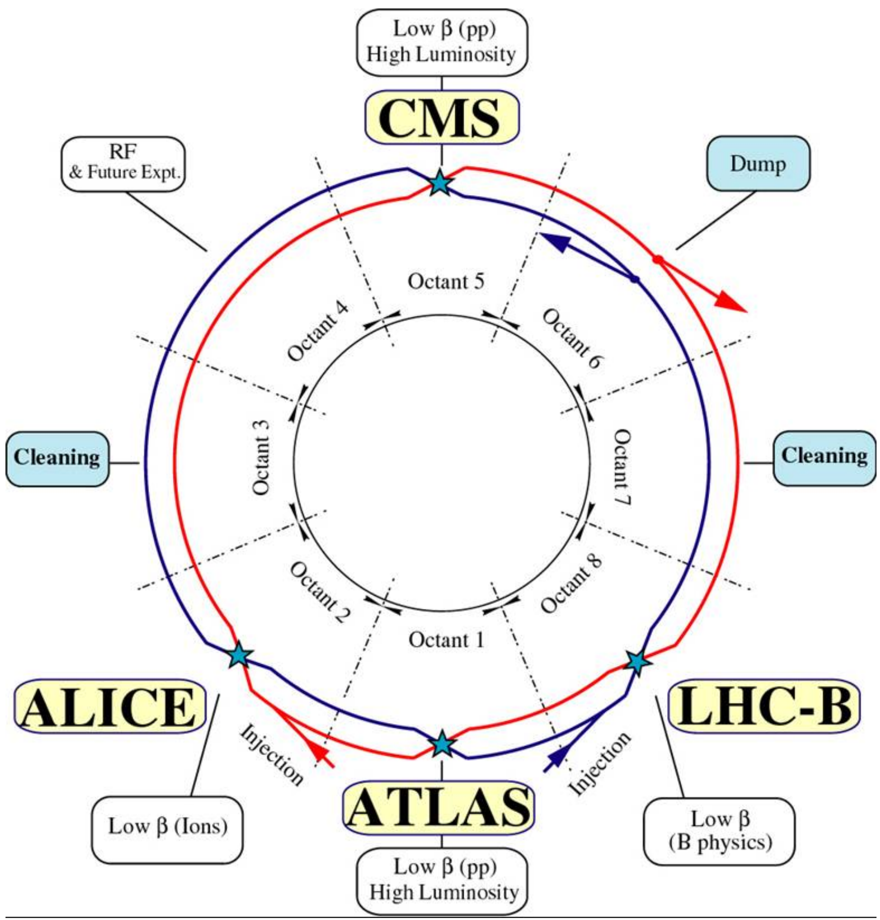

Figure 1.4: LHC geometry with arcs and straight sections.

goal. CMS detector will be described in detail in Section 1.3. The main difference in the two is in their magnet systems. One additional choice that affects this is the momentum resolution for muons. The momentum resolution for muons, $\Delta p_T/p_T$, are proportional to $B^{-1}L^{-2}$, where B is magnetic field and L is distance of momentum measurement from the IP of detector. So, To improve the momentum resolution there are two possible choices.

1. Increase the magnetic field with compact design, or
2. Work with low magnetic field with long lever arm, L

There is also a third possibility to improve the momentum resolution by increasing the leaver arm as well as magnetic field, but it increases the cost of the detector by several factors. So, CMS chooses the first point, i.e., to increase the magnetic field with compact design[6] while ATLAS chooses the design with low magnetic field with long lever arm.

ALICE (A Large Ion Collider Experiment) is a heavy-ion detector. It is specially designed for the study of strongly interacting matter at high densities in quark-gluon plasma phase.

LHCb (Large Hadron Collider beauty) is made asymmetrically with respect to the IP of the detector. It is made specially to study the slight differences between the matter-antimatter through the study of b-quarks.

LHCf (Large Hadron Collider forward) and **TOTEM** (TOTal cross-section, Elastic scattering and diffraction dissociation Measurement at the LHC) are located near ATLAS and CMS respectively, for the study of forward physics.

1.3 CMS Experiment

In the HEP detectors there are two different categories of conditons are imposed. They are:

- restrictions imposed from the accelerator conditions.
- restrictions because of physics goal.

Restrictions imposed on detector from the LHC are:

[6] This is why there is word **compact** in the name of CMS.

- **High luminosity delivered by LHC:** As the delivered luminosity is high this implies every-time the two proton bunches cross each other there will be more than one p-p interactions[7]. This is one of greatest challenges. This implies more than 1000 particles passes through detector during every p-p collision. This imposes condition that the detector should be highly granular this results with increase number of channels that should be synchronized with each other.

- **Event rate:** At LHC, the two proton bunches crosses each other at every 25 ns. So, the response time for all the sub-system of detector should be less than 25 ns.

- **Produced radiation:** At every 25 ns the detectors are bombarded with more than 1000 particles so all the sub-detectors should be radiation hard including its electronics, cables, glue, screws, and so on.

Restrictions imposed on detector from physics goal are:

- Good muon identification and momentum resolution ($\approx 1\%$ at 100 GeV).

- Efficient triggering and tracking of b-jets and τ's.

- High resolution electromagnetic calorimeter to detect electrons and photons.

- Good missing transverse energy resolution and di-jet mass resolution requires a "hermetic" hadron calorimeter with full geometric coverage and fine lateral segmentation.

Based on the above condition CMS detector was designed in cylindrical shape having each detector on top of other with beam pipe at center. To have full geometric coverage it is designed with a barrel region and two endcap regions. Main part of the CMS detector is its superconducting magnet system with a high magnetic field of 4 Tesla to accurately

[7] More than one p-p interaction in one bunch crossing is known as pile-up. It can be theoretically calculated as the product of inelastic p-p cross-section (σ_{inel}), instantaneous luminosity (L) and the mean time interval between two collision, ($< t >$).

$$mean\ pile-up = \sigma_{inel} \times L \times < t > \tag{1.2}$$

measure the high momentum particles and its muon system. Muon system kept outside the magnet but sandwiched in its return yoke. While the tracking system and calorimeters are placed inside the magnet. CMS detector design is shown in Figure 1.5.

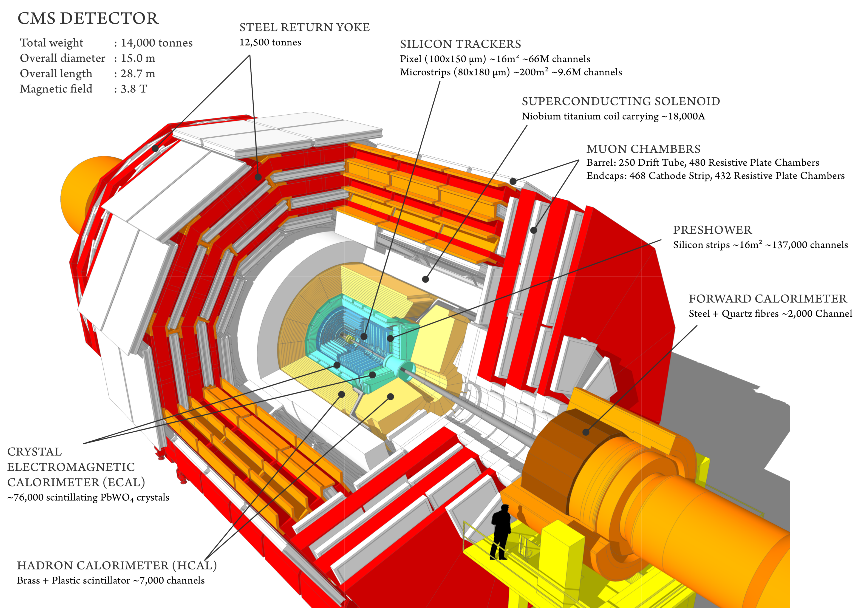

Figure 1.5: CMS detector drawing

1.3.1 Coordinate System

Right handed coordinate system is used having origin at the nominal IP (Figure 1.6). Z-axis is along the beam direction in such a way so that x-axis will point radially to the center of LHC ring and y-direction is pointing upwards. The azimuthal angle, ϕ, is measured in x-y plane from x-axis and the polar angle, θ, is measured from z-axis. Instead of describing a particle at some polar angle we prefer to use the variable pseudo-rapidity. It is defined as

$$\eta = -ln[tan(\theta/2)] \tag{1.3}$$

In hadron collider use of pseudo-rapidity is motivated from the invariance of its difference, $\Delta\eta$. Also, the particle density remains constant in barrel region of detector measured in equal rapidity intervals.

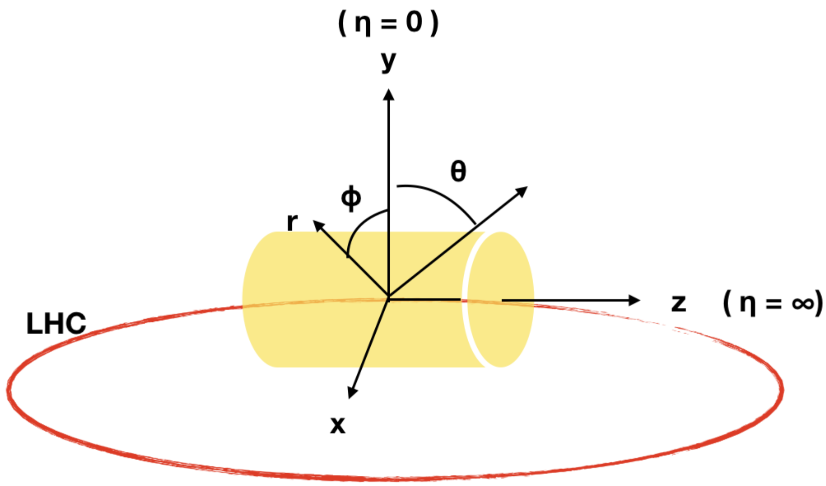

Figure 1.6: Right handed coordinate system used by CMS.

1.3.2 CMS sub-systems

Magnet

Magnet system of CMS consists of a superconducting solenoid magnet with 3.8 T magnetic field. It is 12.5 m in length and 6 meter in inner diameter. The high magnetic field ensures the appropriate bending power of the high-energy charged particles to precisely measure its momentum. It is shown separately in Figure 1.7.

Tracker

Tracker is the first detector that encounter the particles emerging from the p-p collision. Its purpose is to measure precisely the tracks of all particles passing through it. It consists of 3 layers of silicon pixel detector to precisely measure the primary vertex, secondary vertex and the impact parameter along with 10 layers of silicon micro-strip detector. Tracker has length of 5.8 m and outer diameter 2.6 m.

Calorimetry

In general, calorimeter is a device that measure energy of particles by depositing them into it. In CMS its divided into Electromagnetic CALorimeter (ECAL) and Hadronic CALorimeter (HCAL). ECAL as the name

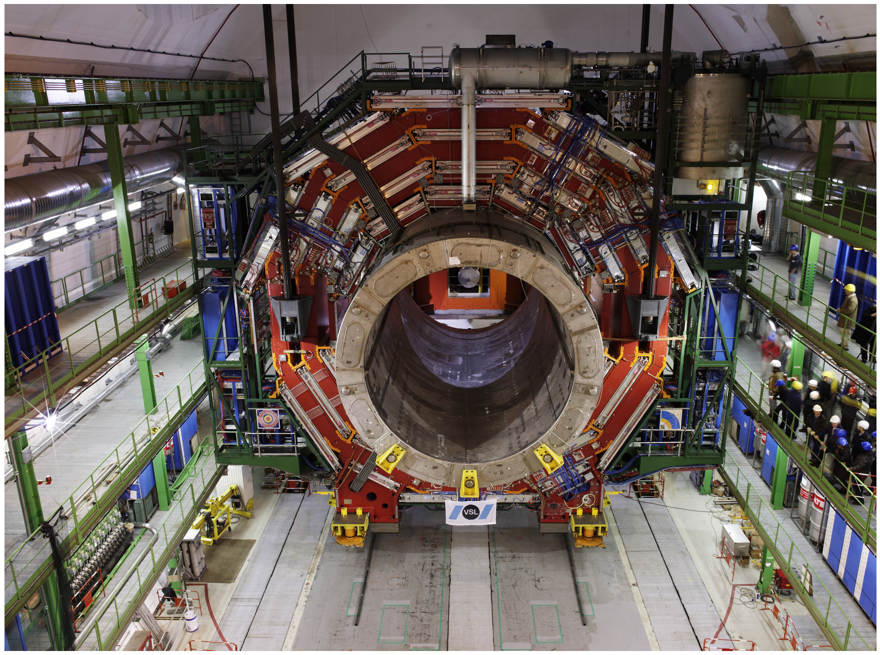

Figure 1.7: CMS Magnet system

suggest its designed to measure the particles that primely interacts via electromagnetic interaction while HCAL is designed to measure particles that interacts via strong nuclear interactions.

ECAL is placed after tracker for detecting the electrons and photons. It is made from lead tungstate ($PbWO_4$) having coverage upto $\eta < 3.0$ including pre-shower system in forward region. The scintillation produced in barrel region is detected by Avalanche photo-diodes and in endcaps it is collected by vacuum photo-triodes. In terms of radiation length[8], X_0, its thickness is $25X_0$ which guarantees almost full shower containment.

In between ECAL and magnet system, brass/scintillator sampling HCAL with coverage upto $\eta < 3.0$ is placed. To have a full geometric coverage HCAL is extended upto $\eta < 5.0$ using forward sampling iron/quartz-fibre calorimeter. This is crucial to measure the (missing) transverse energy of the event.

[8]define it.

The Muon System

From the name of CMS detector its evident that the precise detection of muons is one of main target of CMS detector. The presence of muons in the final state in many interesting physics like the decay of Higgs boson into ZZ to 4 leptons. Specially, the case in which all 4 leptons are muons are known as "gold platted" as we can detect muons efficiently over high background at LHC. So, the detection and efficient reconstruction is very important for muons. At CMS, muon system has mainly three functions. They are identification of muons, momentum measurement and triggering. The strong superconducting magnet system with its return yoke of CMS also helps use to acquire good momentum measurement and triggering capabilities. The return yoke of magnet system also serves as the hadron absorber. The cross-sectional view of muons system is shown in Figure 1.8. It is described in details in Chapter **??**

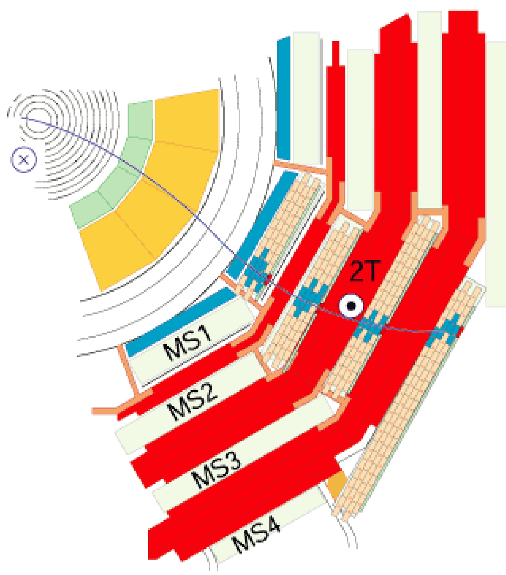

Figure 1.8: A muon leaves curved trajectory in LHC and the bending changes as the magnetic field direction of solenoid inside and outside are opposite.

1.3.3 CMS Trigger and Data Acquisition system

In CMS, every second about 1 billion p-p collision is happening. But, till now we don't have a switch with the required bandwidth that can transfer huge data for further processing, and even if we have one, then there is only few fraction of data that are interesting for new physics or help to understand the existing one as most of the collisions are the low-energy glancing collision instead of head on interaction. So, the concept of trigger was introduced first by ZEUS experiment [14] to select the potentially interesting events that can reduce the event rate to just few hundreds such that it will be possible to store and transfer that data for further analysis. The trigger is designed in such a way that it can efficiently accept the interesting events and rejects the non-interesting events.

The CMS trigger system was designed in two steps, level 1 (L1) trigger which is custom hardware process running synchronously with the LHC bunch crossing frequency of 40 MHz and the High Level Trigger (HLT) [15]. L1 trigger selects the events based on the information of calorimeter and muon system. But this decision can't take place within 25 ns so a latency of 3.2 μs was added. The maximum allowed frequency at L1 stage is 100 kHz. Then the complete information is sent to HLT processing farm to reduced the event rate to $\sim$100 Hz. The remaining information is sent to Tier-0 centers to store and use it for offline analysis.

1.3.4 CMS Offline Computing

Once the decision was taken by trigger system it is ready to be analyzed offline. But, before that the raw data need to be processed to convert it into understandable physics objects like electrons, muons, photons, jets, and so on. This step is known as object reconstructions which is most CPU intensive task in the data processing chain of CMS. In this step one need to reconstruct the primary vertices, track finding algorithms, identify electrons, photons, muons, reconstruct jets, apply b-tagging algorithm to reconstruct b-jets, run detector specific filtering and so on. To perform all these steps CMS developed its own software which is known as CMSSW. This is based on Event Data Model (EDM) centered around the concept of event. Here, an event is a C++ object container for all raw and reconstructed data related to a certain collision. These events are stored in ROOT files [16]. The CMSSW event processing model consists of one executable called cmsRun, and many plug-in modules. These modules contain all the necessary codes for the event processing such as calibration and reconstruction algorithms [17]. To do the analysis, we also need Monte Carlo (MC) simulations of various Standard Model processes and new physics models. MC events are generated at parton level. Then showering and hadronization is applied and finally these events are put through the GEANT4 [18] based CMS detector simulation. The result is data similar to what one obtains from the actual detector. This MC data can then also be reconstructed as if it were actually detector data.

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