# Search for Higgs Decay to Dark Matter and Trigger Studies

João Carlos Arnauth Pela
of Imperial College London

A dissertation submitted to Imperial College London
for the degree of Doctor of Philosophy

# Abstract

Here the abstract of the thesis

# Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee.

João Pela

# Acknowledgements

TODO:

- Family
- Friends
- Work colleagues (include CMS collaboration)
- more

The work presented in this thesis was supported by the Portuguese Government through Fundação para a Ciência e a Tecnologia (FCT) in the form of my PhD grant with the reference SFRH/BD/77979/2011. I am thankful for their support which allowed me to attain higher education.

# Preface

Thesis structure and so on...

*"To my grand mother"*

# Contents

# Chapter 1

# Theory

TODO:

- Global status

## 1.1 Standard Model of Particle Physics

TODO:

- Very brief summary of the Standard Model.

The Standard Model (SM) of particle physics is the currently accepted model for describing the physics of elementary particles.

| Leptons (J=1/2) | | | | |
|---|---|---|---|---|
| Generation | Particle Name | Symbol | Mass ($GeV/c^2$) | Q/e |
| $1^{st}$ | Electron | e | 0.000511 | 1 |
| | Electron Neutrino | $\nu_e$ | $< 3 \times 10^-9$ | 0 |
| $2^{nd}$ | Muon | $\mu$ | 0.106 | 1 |
| | Muon Neutrino | $\nu_\mu$ | $< 1.9 \times 10^-4$ | 0 |
| $3^{rd}$ | Tau | $\tau$ | 1.777 | 1 |
| | Tau Neutrino | $\nu_\tau$ | $< 1.82 \times 10^-2$ | 0 |

**Table 1.1:** List of leptons and their fundamental properties

| Quarks (J=1/2) | | | | |
|---|---|---|---|---|
| Generation | Particle Name | Symbol | Mass ($GeV/c^2$) | Q/e |
| $1^{st}$ | Up | u | $1.5 - 3.3 \times 10^{-3}$ | -2/3 |
| | Down | d | $3.5 - 6 \times 10^{-3}$ | 1/3 |
| $2^{nd}$ | Charm | c | 1.16-1.34 | -2/3 |
| | Strange | s | $70 - 130 \times 10^{-3}$ | 1/3 |
| $3^{rd}$ | Top | t | 169-173 | -2/3 |
| | Bottom | b | $4.13 - 4.37$ | 1/3 |

**Table 1.2:** List of quarks and their fundamental properties

| Bosons | | | |
|---|---|---|---|
| Particle Name | Mass ($GeV/c^2$) | Q/e | Spin |
| Photon ($\gamma$) | 0 | 0 | 1 |
| $W^{\pm}$ | 80.4 | $\mp 1$ | 1 |
| $Z^0$ | 91.2 | 0 | 1 |
| Gloun (g) | 0 | 0 | 1 |
| Higgs ($H^0$) | $> 114$ | 0 | 0 |

**Table 1.3:** List of bosons and their fundamental properties

## 1.2 Higgs Mechanism

Summary of the Higgs Mechanism. Should include

- Motivations
- Explanation of the mechanism itself
- Consequences
- Possible decays

## 1.3 Higgs Invisible decays

TODO:

- Explain what are SM Higgs invisible decays.
- Go over the possibility of BSM invisible decays.

# Chapter 2

# Experimental Apparatus

## 2.1 The Large Hadron Collider

The Large Hadron Collider (LHC)[1] is currently the world's largest particle accelerator and is capable to produce the highest energy particle beam ever made by mankind. This gigantic machine with a total perimeter of 26.7 kilometer was built at European Organization for Nuclear Research (CERN) in a circular tunnel at an average depth of 100 meters below ground under the Franco-Swiss border near Geneva, Switzerland. I Diagram of the LHC tunnel can be found in figure 2.1.

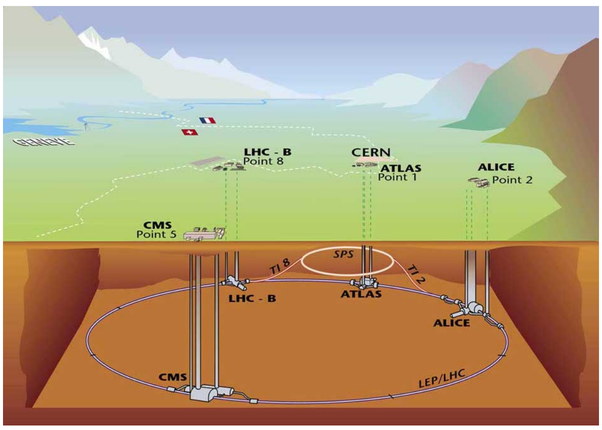


**Figure 2.1:** Underground diagram of the Geneva area showing the LHC location.

The LHC is a synchrotron machine with the capability to accelerate particles in two separated beam pipes with travel in opposite direction. These beams only cross and are allowed to collide in four specific points of the accelerator where huge particle detectors are installed to detect the products of such collisions. This experiments are name ATLAS[2], CMS[3], LHCb[4] and ALICE[5].

The accelerator as its name indicates can collide hadrons, more specifically proton or heavy ions. Up to now 3 modes of operation have been tried according to the particles being collided: proton-proton, proton-lead and lead-lead. Depending on the which configuration is chosen we are basically changing the quantity of nucleons available to each colliding element. The maximum design energy per proton is 7 TeV and for each lead nucleon 2.76 TeV. The design luminosity for proton-proton is of $10^{34}$ $cm^{-2}s^{-1}$ and for lead-lead is of $10^{27}$ $cm^{-2}s^{-1}$.

The LHC is only the last element of a complex accelerator chain which step by step increases the energy of the particles. Protons are initially obtained by stipping the electrons of hydrogen gas. The are then accelerated at the Linear Particle Accelerator 2 (LINAC2) up to the energy of 50 MeV. After this initial step they are injected into the Proton Synchrotron Booster (PSB) and the energy ramps ups to 1.4 GeV. After protons are passed to the Proton Synchrotron (PS) where energy futher increases to 25 GeV subsequently they are the injected into the Super Proton Synchrotron (SPS) where the particle energy level reached 450 GeV. Finally, protons pass to the LHC where they can be accelerated to a maximum energy of 7 TeV. A simplified diagram of the CERN accelerator chain can be found in figure 2.2.

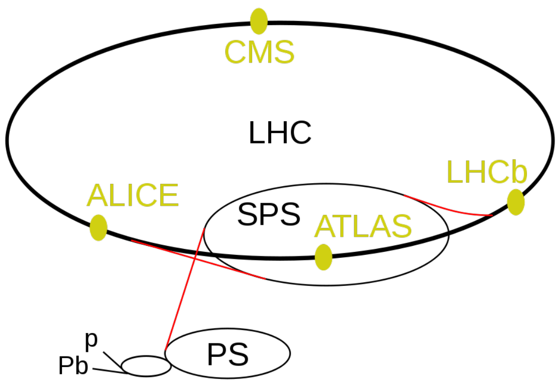


**Figure 2.2:** CERN Large Hadron Collider Experiment accelerator diagram.

Normal operation of the LHC therefore depends on the the upstream accelerators availability. The typically turn around time, the time necessary to stop the accelerator from running and restart collisions is around 2 hours. When stable beams are achieved, a single proton fill can be used to collide protons up to 24 hours, but it is common to restart more frequently to take profit of the higher collision rates possible right at the beginning of a new fill.

Some of the key parameters of the LHC proton-proton and lead-lead operation can be found in table 2.1.

| | | $pp$ | **HI** | |
|---|---|---|---|---|
| Energy per nucleon | E | 7 | 2.76 | TeV |
| Dipole field at 7 TeV | $B$ | 8.33 | 8.33 | T |
| Design Luminosity* | $\mathcal{L}$ | $10^{34}$ | $10^{27}$ | $cm^{-2}s^{-1}$ |
| Bunch separation | | 25 | 100 | ns |
| No. of bunches | $k_B$ | 2808 | 592 | |
| No. particles per bunch | $N_p$ | $1.15 \times 10^{11}$ | $7.0 \times 10^{7}$ | |
| **Collisions** | | | | |
| $\beta$-value at IP | $\beta^*$ | 0.55 | 0.5 | m |
| RMS beam radius at IP | $\sigma^*$ | 16.7 | 15.9 | $\mu$m |
| Luminosity lifetime | $\tau_L$ | 15 | 6 | hr |
| Number of collisions/crossing | $n_c$ | $\approx 20$ | - | |

* For heavy-ion (HI) operation the design luminosity for Pb-Pb collisions is given.

**Table 2.1:** The machine parameters relevant for the LHC detectors.[6]

At the LHC we are looking for extremely rare processes as is can be seen in figure 2.3 the production cross section of a SM Higgs boson is more than 9 orders of magnitude smaller than the total proton-proton cross section.

To be able to record and study such rare processes we need to produce a significant amount of collisions. For this purpose the LHC was designed to operate at high instantaneous luminosity, L. This quantity is defined as,

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} F, \tag{2.1}$$

where $N_b$ is the number of protons per bunch, $n_b$ is the number of bunches, $f_{\text{rev}}$ is the frequency of revolution, $\gamma$ is the Lorentz factor, $\epsilon_n$ is the normalized emittance, $f_{\text{rev}}$ is the beta function at the collision point and $F$ is the reduction factor due to the crossing angle.

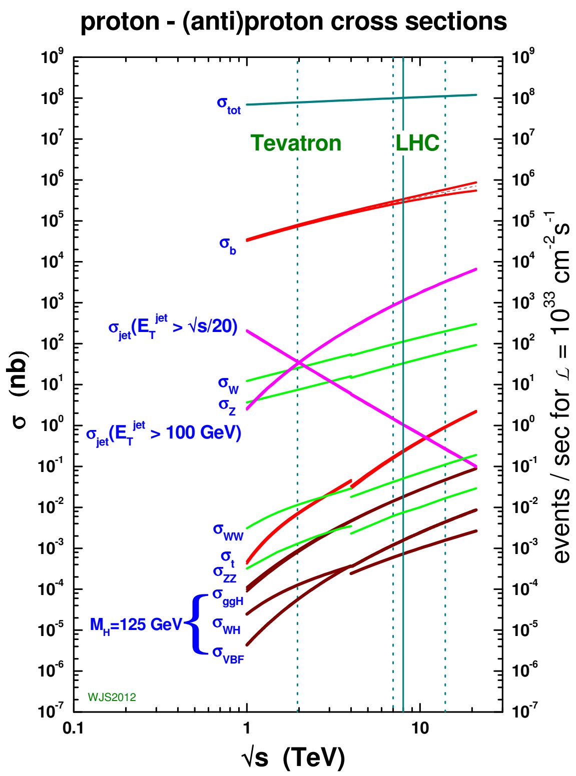


**Figure 2.3:** Cross sections for several processes for collisions of antiproton-proton and proton-proton as a function of the center of mass energy[3].

### 2.1.1 Delivered Luminosity

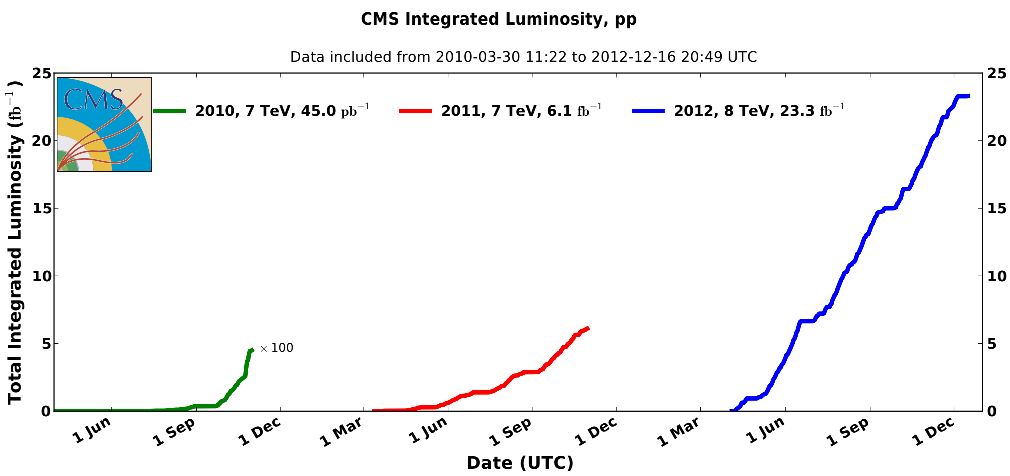


**Figure 2.4:** Cumulative luminosity versus day delivered to CMS during stable beams and for p-p collisions. This is shown for 2010 (green), 2011 (red) and 2012 (blue) data-taking.

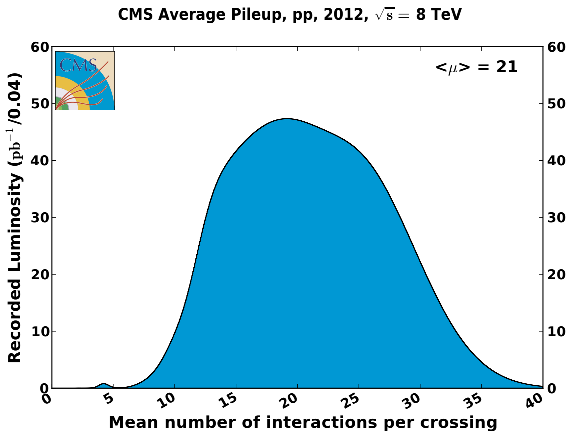


**Figure 2.5:** Mean number of interactions per bunch crossing at the CMS experiment during 2012.

## 2.2 The Compact Muon Solenoid Experiment

The Compact Muon Solenoid (CMS) experiment is a general purpose experiment located at point 5 of the LHC. It was designed to study collisions at its centre and is composed os several sub-systems in an classic onion shaped structure.

### 2.2.1 Geometry and conventions

### 2.2.2 Inner tracking system

The inner tracking system is the closest detector to the beam axis and the interaction region. Its function is to measure the trajectory of all charged particles, like electrons, charged hadrons and muons with momentum above 1 $GeV$ being produced at each LHC collision. With the help of the strong magnetic field produced by the CMS magnet particle trajectories are bent allowing for charge and momentum determination. With the resulting tracks is it then possible to determine the primary vertex as well as vertexes secondary like other lower proton-proton collision or even displaced vertexes from the decay of long lived particles like B mesons.

Building a tracking system for an experiment at the LHC is very challenging. At design luminosity an average of 1000 particles will hit such system at a rate approaching 40 $MHz$, leading to high hit density at high rate. It is therefore desirable to have a fast, efficient and high granularity detector where at each layer the occupancy should be at or below 1%. On the other hand each layer should be as thin as possible in order to not change the incoming particles trajectory or make them lose too much energy. The detector should also be radiation hard and survive for a period of at least 10 years due to its importance and location. This design requirements have lead to a tracker design entirely based on silicon detector technology.

The volume near the interaction point can be split according to the charged particle flux into three regions:

- $r < 10$ $cm$: highest particle flux, up to $\approx 10^8$ $cm^{-2}s^{-1}$ at $r \approx 4$ $cm$, pixel detectors are used. The pixel size is $\approx 100 \times 150$ $\mu m^2$, which translates into an occupancy of $10^{-4}$ per LHC bunch crossing.
- $20 < r < 55$ $cm$: particle flux decreases enough to use silicon micro-strips with a minimum cell size of 10 cm $\times$ 80 $\mu m$, leading to an occupancy of $\approx 2 - 3\%$ per LHC bunch crossing.
- $50 < r < 110$ $cm$: most outer region of the tracker, particle flux is low enough to use larger pitch silicon micro-strips. The maximum cell size is of 25 $cm$ $\times$ 180 $\mu m$, and occupancy is of the order of $\approx 1\%$.

The CMS tracker final configuration is composed of a pixel detector with three barrel layers at radii between 4.4 $cm$ and 10.2 $cm$ and 2 disks on each side of the barrel. And a silicon strip tracker with 10 barrel detection layers extending up to 1.1 $m$ with 3 plus 9 disks on each side of the barrel. A schematic of the detector module distribution can be found at figure 2.6. This detector has an acceptance covering up to pseudorapidity of $|\eta| < 2.5$ and has a total active area of about 200 $m^2$ making the largest silicon tracker ever built.

### 2.2.3 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) is an hermetic energy measurement system comprised of 61200 lead tungstate ($PbWO_4$) crystals mounted in the barrel and 7324 crystals in each of the 2 endcaps.

Lead tungstate has a fairly high density (8.28 $g/cm^3$), has a short radiation length (0.89 $cm$) and a small Moliere redius (2.2 $cm$). The crystals also have a fast scintillation decay time emitting 80% of the light yield in 25 $ns$ (the minimal bunch crossing time at the LHC). This characteristics make it a good choice for an electromagnetic calorimeter allowing a compact design with fine granularity. However, this crystals emit a fairly

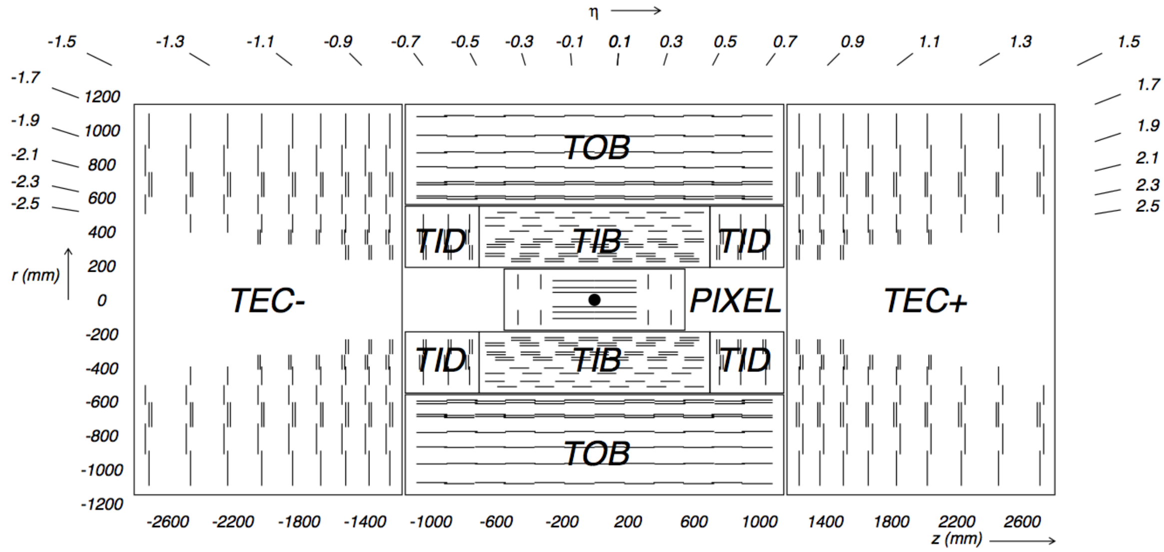


**Figure 2.6:** Schematic cross section of the CMS tracker. Each line represent a detector module. Double lines represent dual surface back-to-back detector modules.

low light yield (30 $\gamma/MeV$) which requires the use of photo-detectors with intrinsic gain which will preform well inside a magnitic field. In the barrel region silicon Avalanche photo-diodes (APD) are used and Vacuum Photo-Triodes (VPT) are used in the endcaps. To guarantee good response from both crystals and APD it is necessary to have system thermal stability, with the goal being temperature variation of less than 0.1° C.

The barrel section, the ECAL Barrel (EB), has an inner radius of 129 $cm$ and is composed of 36 identical “supermodules“, each covers the barrel length and corresponding to a pseudo-rapidity 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 endcap section, the ECAL Endcap (EE), is 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”.

figure 2.7

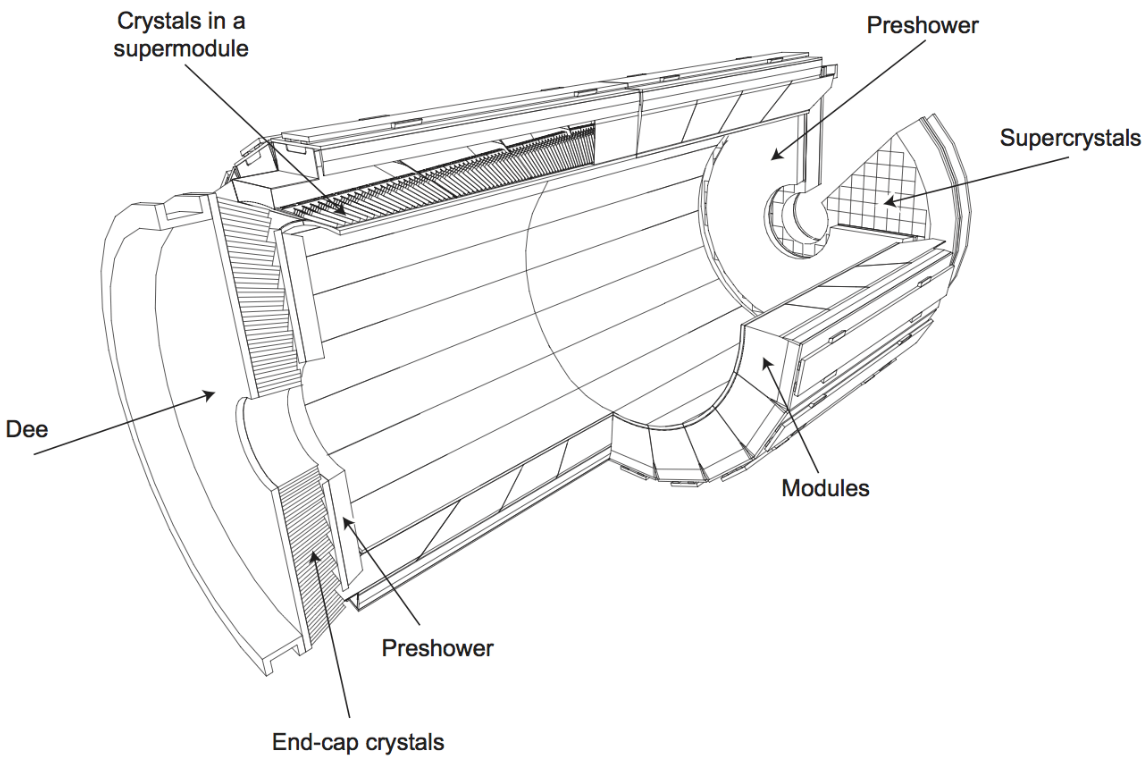


**Figure 2.7**

### 2.2.4 Hadronic Calorimeter

The Hadronic Calorimeter (HCAL) is a sampling calorimeter which is designed to measure the properties of hadron jets and indirectly neutrinos or other undiscovered particles that would result in apparent missing energy[7].

The design of the HCAL was strongly influenced by the choice of the magnet parameters since most of the calorimetry is inside of the magnet. The HCAL Barrel (HB) is limited from the beam side by the ECAL at radius $r = 1.77\ m$ and outwards by the magnet at radius $r = 2.95\ m$. This is a strict limitation on the amount of absorber material to be used. To improve the measurement capability, an outer calorimeter, the HCAL Outer (HO), is placed outside of the magnet as a *tail catcher* outside of the solenoid magnet. Closing the barrel in each side the HCAL Endcap (HE) are present with acceptance up to pseudorapidity $|\eta| < 3$. Additionally, to extend acceptance to $|\eta| < 5.2$ the HCAL Forward (HF) is installed at $11.2\ m$ from the interaction point providing excellent hermeticity for $E_{\perp}^{miss}$ measurement. A diagram of the HCAL subsystems and their location inside CMS can be found in figure 2.8.

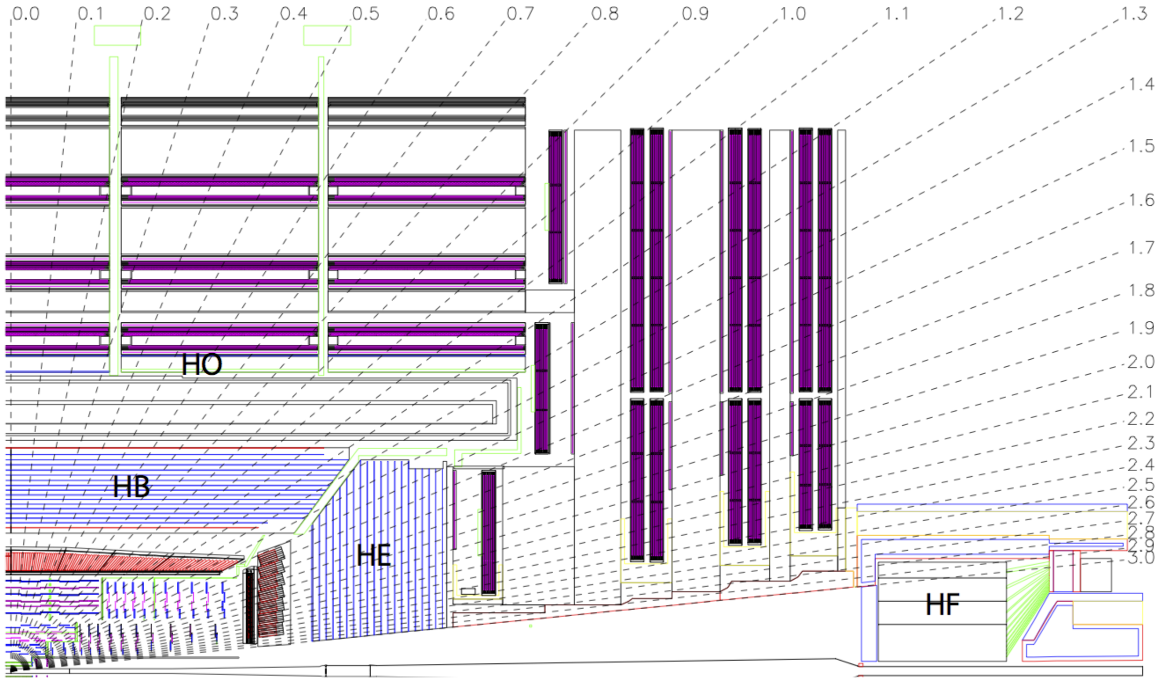


**Figure 2.8:** Longitudinal view of the CMS detector highlighting the location of the HCAL components: HB, HE HO and HF.

The HB covers the region up to $|\eta| < 1.3$ and divided into towers with segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ which corresponds to the same area of a $5 \times 5$ arrays of ECAL crystals.

The HO

The HB covers the range of $1.3 < |\eta| < 3.0$...

The HF covers the range of $3.0 < |\eta| < 5.2$...

### 2.2.5 Solenoid Magnet

### 2.2.6 Muon System

figure 2.9

| Parameter | Value |
|---|---|
| Field | 4 T |
| Inner Bore | 5.9 m |
| Length | 12.9 m |
| Number of turns | 2168 |
| Current | 19.5 kA |
| Stored Energy | 2.7 GJ |
| Hoop Stress | 64 atm |

**Table 2.2:** Parameters of the CMS superconducting solenoid

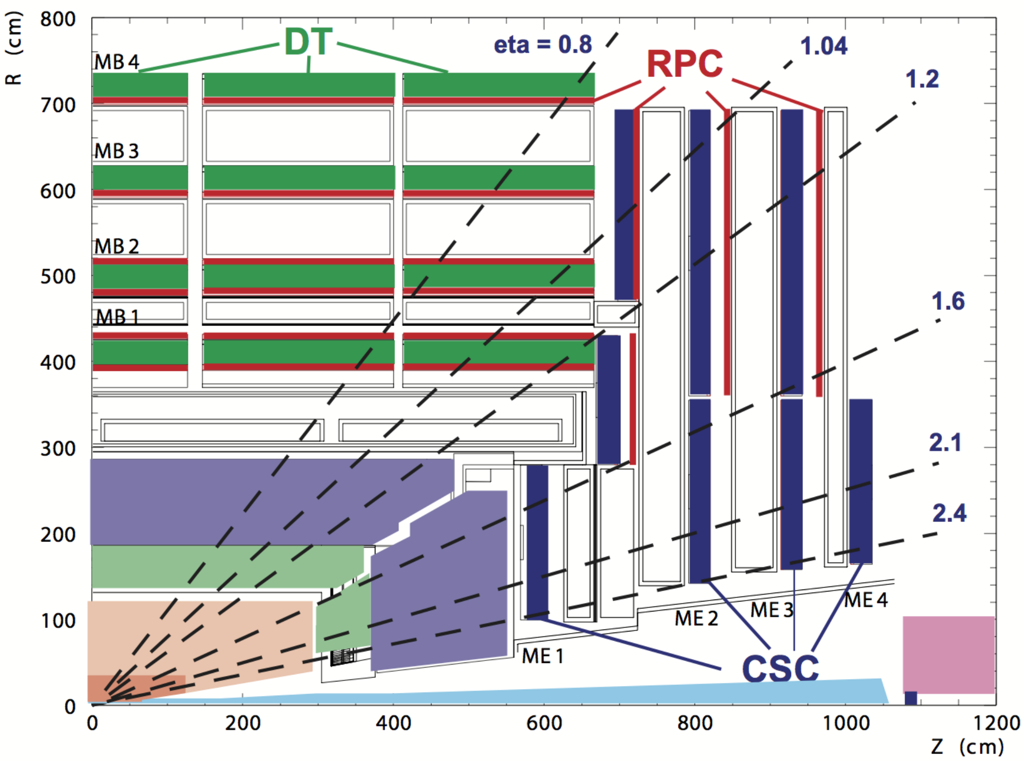


**Figure 2.9:** TODO

### 2.2.7 Data Acquisition System

The Data Acquisition (DAQ)

### 2.2.8 Trigger System

The Level 1 Trigger (L1T) and High Level Trigger (HLT)

CMS Tridas TDR[8]

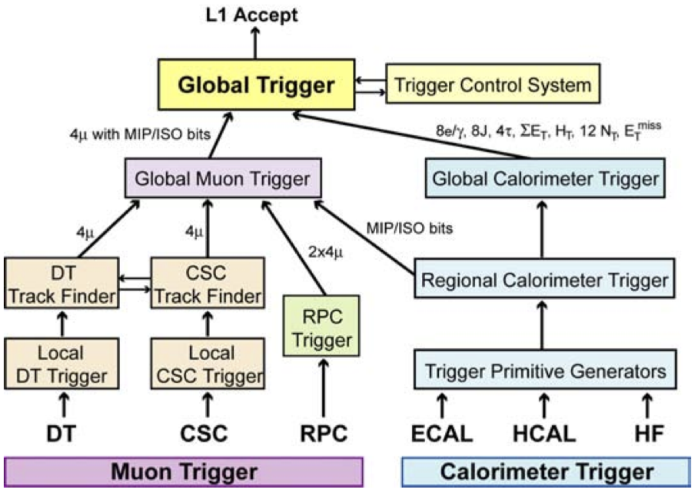


**Figure 2.10:** TODO

### 2.2.9 Computing

The Data Quality Monitoring (DQM)

### 2.2.10 Run II Updgrades

CMS L1 Trigger Upgrade TDR[9]

# Chapter 3

# Technical work

## 3.1 Level 1 Trigger Data Quality Monitoring System

Hello

# Chapter 4

# Physics Objects and Monte Carlo simulation

## 4.1 Physics objects definition

### 4.1.1 Electron

### 4.1.2 Muon

### 4.1.3 Tau

### 4.1.4 Jets

### 4.1.5 Missing Transverse Energy

## 4.2 Monte Carlo simulation

# Chapter 5

# Prompt Data Analysis

# Chapter 6

# Parked Data Analysis

# Chapter 7

# Run II Preparation

## 7.1 Run II trigger studies

## 7.2 Run II QCD Monte Carlo samples

# Chapter 8

# Conclusions

Summary of relevant results and their impact on Particle Physics

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# Acronyms

**APD** Avalanche photo-diodes. 10

**CERN** European Organization for Nuclear Research. 4, 5

**CMS** Compact Muon Solenoid. 8, 9, 11

**DAQ** Data Acquisition. 13

**DQM** Data Quality Monitoring. 14

**EB** ECAL Barrel. 10

**ECAL** Electromagnetic Calorimeter. 9, 11, 12

**EE** ECAL Endcap. 10

**FCT** Fundação para a Ciência e a Tecnologia. vi

**HB** HCAL Barrel. 11, 12, 23

**HCAL** Hadronic Calorimeter. 11, 12, 23

**HE** HCAL Endcap. 11, 12, 23

**HF** HCAL Forward. 11, 12, 23

**HLT** High Level Trigger. 13

**HO** HCAL Outer. 11, 12, 23

**L1T** Level 1 Trigger. 13

**LHC** Large Hadron Collider. 4–6, 8, 9, 23

**LINAC2** Linear Particle Accelerator 2. 5

**PS** Proton Synchrotron. 5

**PSB** Proton Synchrotron Booster. 5

**SM** Standard Model. 2, 6

**SPS** Super Proton Synchrotron. 5

**VPT** Vacuum Photo-Triodes. 10