

**Search for New Massive Long-Lived Neutral Particles
decaying to Photons in pp Collisions at $\sqrt{S} = 8$ TeV**

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Acknowledgements

There are many people that have earned my gratitude for their contribution to my time in graduate school.

Dedication

To those who held me up over the years

Abstract

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Chapter 1

Introduction

The main style and messaging of my thesis will look like this:

1. Introduction as to why would anyone care about neutral long lived particles.
2. What is/are the mechanisms behind a long lived particle? can you give an example and show this mechanism at work explicitly?
3. How are searches for these particles performed and why use the LHC-CMS machines? eg Is there a particular reason why this is the case? Can these experiment be done using other machines?
4. Have this searches been performed before? If yes, what are the results? What are their limits? Can you beat their limits? What makes you think you can? What advantages or edge do you have over previous results?
5. How is the experiment performed? What specific issue(s) about the LHC-CMS machine makes it an ideal instrument?
6. What results did you get? Are they better than previous results? if not why? Can one improve on the results? What is the future of this kind of search? Can it be performed again in future? What advantages do future experiments have over this current experiments?
7. What are your thoughts(conclusion) about the whole process?

8. Where does one go from here?

In this Thesis, I am going to write about three main aspects.

1. Why long-lived particles and the mechanism behind its possible existence?.
2. How to use the CMS detector to search for a long-lived particle.
3. How is the search done?
4. How do I set an upper limit on the possible existence of a long-lived particle in case I fail to observe it?
5. What is the future for long-lived particle with the increase in LHC center of mass energy and luminosity?

Our current understanding of the properties of fundamental particles which make up matter in the universe is accurately described by the Standard Model (SM). However, this model only describes visible or baryonic matter. Non-visible or non-baryonic matter which make up a larger percentage of matter content of our universe currently has very little understanding. Information concerning the age of the universe fuel speculation that Non-visible or Dark Matter (DM) as it is referred to presently must be made up of particles which have long lifetime known as Long Lived (LL) particles. In general, LL particles can be charged (electromagnetically charged i.e interact with light (photons) or color charged) as well as neutral.

Of particular interest to the scientific community are neutral LL particles; since DM is also currently understood to not interact with photons directly or interacts very weakly with visible matter. Recent results seems to be indicating that these particles if they exists could have very small mass around eV to keV mass range refered to as Warm Dark Matter (WDM) or heavy with mass around GeV to TeV mass range called Cold Dark Matter (CDM).

In this thesis we have performed a model-independent search for Neutral Massive Long Lived Particles (NMLLP) decaying to photons. NMLLP are produced in **pp** collisions by the Large Hadron Collider (LHC) with a center of mass energy $\sqrt{S} = 8$ TeV. The phenomenon we search for is that of delayed photons which can be produced from

the decay of metastable next-to-lightest supersymmetric particle (NLSP acting as our NMLLP) into a light gravitino which in this case is the lightest supersymmetric particle (LSP). Assuming a conservation of R-parity, the neutralinos are pair produced in a cascade decay of higher massive supersymmetric particles produced from pp collision. The resulting energetic and delayed or displaced isolated photons are detected in association with high transverse momentum spray of hadronic particles called jets as well as missing transverse energy. The photons and other particles produced are recorded using the Compact Muon Solenoid (CMS) detector. The CMS detector is located at one of the beam crossing or collision points (also known as Interacting Points (IP)) at Point 5 in Cessy, France. We depend on the excellent timing and energy resolution of Electromagnetic Calorimeter (ECAL) subdetector of the CMS to distinguish between high energy photons from NMLLP decay and normal photons produced in interactions excellently and precisely described by the Standard Model (SM). Finding a Long-Lived (LL) particle would address a lot of important questions in modern physics such as the following: Why is there so much matter and not anti-matter around us? Is there an explanation for the particle content and mass hierarchy as currently observed in the SM? What is the origin and existence of Dark Matter (DM)? Do all fundamental forces behave as a single force at some higher energy scale? Answers to these questions will provide a clear path for physics beyond the standard model.

This thesis is divided into the following chapters:

- Chapter 1 presents the introduction and general outline of this thesis.
- In Chapter 2, we begin with the motivation behind a search for neutral long lived particles predicted to exist in some BSM. The physics of long-lived particle is also described. This chapter also presents compelling hints from theory, experiment as well as cosmological observation which point to the possible existence of NMLLPs. An example BSM model used as guiding model to this analysis is also described leading to our event selection based on its predicted phenomenology. Previous analysis and their results are also shown.
- In Chapter 3, describes the experimental setup particularly the LHC collider and CMS detectors and also a detail description of the sub-detectors of the CMS which

have been used in our search analysis.

- In Chapter 4, we provide a detail outline of Time measurement and Calibration of ECAL in order to reliably use timing as tool to search for long-lived particles which decay into photons and electrons depositing their energy unto the crystals of the ECAL.
- Chapter 5, The reconstruction of objects referred to as photons, jets and missing transverse energy E_T^{miss} according the CMS standards is described here. The ECAL timing as useful for particle identification is presented.
- Chapter 6 hashes out our search strategy for neutral massive long-live particles.
- Chapter 7 provides an interpretation of the results obtained by our analysis in the context of Gauge Mediated Supersymmetry Breaking(GMSB).
- Chapter 8 outlines the possibility of future analysis strategy as we prepare to begin running LHC fully at $\sqrt{S} = 13$ TeV in 2015.
- Chapter 9 outlines our discussion of the analyses presented and conclusions

Some comments from Mississippi Snowmass 2013 I like.

Comments BSM?: Convener: Marcela Carena Energy Frontier comments: Kyle Cranmar: Questions: Comments: 1)Measuring couplings of Higgs now @ LHC before ILC provide Full width. 2)No clear guidance at the moment to Empirical measurements reliable the most for now. 3) Smaller and shorter time scale experiments better at the moment. Comments: Andrei de Gouvan 1) Neutrino masses do not sit well in SM 2) Dark matter also not SM

Where to find new physics? 1) Neutrino, Dark Matter ? not easy 2) New Sources of CP -Invariance violation (EDMs) sensitive to very high energy scales 3) Searches for violations 4) Precision measurements for Higgs Parameters and very rare processes? 5) Explore LHC

Comments : Jonathan Feng: 1) Neutrino Mass/theory of Flavor - Neutrino Experiments 2) Higgs Boson and Naturalness(gauge Hierarchy problem- precision measurements of Higgs Boson parameters 3) Dark Matter -Experiments and search 4) Dark

Energy and Modified gravity- Cosmological problem. 5) Matter Asymmetry - CP violations can be source to find Matter Asymmetry 6) Inflation - Evidence for New physics can be found using -Experiments of CMB

Comments: Nima-Akarni Amed 1) Neutrino Oscillations + DM 2) Conservative Ideas still required to describe nature /observed data? 3) Effective Field theory of relativistic nature can also describe Condensed Matter physics, However, never has a Scalar field been used as seen in the case of Higgs. 4) New Physics at TeV Scale making naturalness stable 5) Higgs Physics is fine-tuned thus needs precision measurements. 6) Is New physics as a result of naturalness or Not? - Test Naturalness with HL-LHC 7) HL-LHC killing naturalness? unlikely 8) If at $O(100\text{TeV})$ no New physics then fundamental shift paradigm in thinking Expts: Proton decay, DM sources, EDMs, Build $O(100\text{ TeV})$ Machines

Comments: Regina 1) Explore unnatural areas to search for new physics by designing new Tools 2) Look back at clues to gain new Ideas for new measurements 3) Exploit existing facilities but also build new facilities. 4) Explore new territories-Using Neutrino Beams, Dark Matter, precision measurements 5) Explore Old ideas in the light of new technologies. 6) Redo already performed experiments using new technologies, data taking and Analyzing technologies. Recent paper of Meta-stable particles arXiv:hep-ph/0908.0315

Question? Why is the top quark mass so different from others: Answer in SUSY?. Some impt CMS/ECAL papers to read. 1)CMSBUL-ARTICLE-2013-005 2) CMSBUL-ARTICLE-2013-023 3) CMSBUL-ARTICLE-2013-0124) ECAL Timing Prospects 5) 2013 ECAL Performancs NOTE: CMS DP -2013/016, CMS DP -2013/007

Chapter 2

Models and Phenomenology of Long Lived Particles

2.1 The Standard Model of Particle Physics

The Standard Model (SM) provides a thorough and experimentally valid description of the fundamental constituents of all the matter and its interactions (except gravity) in our universe. Predictions by this model of elementary particle physics agree with almost all of the available experimental data with unmatched precision. However, there are some theoretical and experimental difficulties with this model such as the existence of Dark Matter (DM) and neutrino masses which point to an extension of the SM to a much more general model to which the SM is embedded within. An example of such a parent model could be based on the idea of supersymmetry.

This section briefly describes the SM as pertaining to the understanding of this thesis as well as its limitations.

2.1.1 Main Components

The mathematics used to formulate the SM is known as relativistic quantum field theory. Particles are represented as quantum fields and their dynamics and interaction is based on a Lagrangian formalism using a Lagrangian density \mathcal{L} . Its main building blocks are the following:

- All of Matter around us can be described by fermion fields.
- These matter fields interact with each other mediated by vector bosons of a particular symmetry.
- These matter fields are massless and cannot mix with each other until they interact with another field called the Higgs field and in the process obtain their mass and mixing. This process is known as Higgs mechanism.

Fermions

Fundamental particles are characterized in terms of 3 quantities: Mass, Charge and Spin, where spin is a non-spatial or internal quantum number unlike mass and charge. The spin of a particle can be integer or half-integer.

Fermions are particles with half-integer spin ($\frac{1}{2}\hbar$). They obey a kind of statistics referred to as the *Fermi-Dirac* statistics meaning no two identical fermions can occupy the same state. Fermions can be massive as well as massless. They can be charged or be neutral. Fermions have anti-particles which have the same mass and spin but a different charge.

In the SM, the dynamics of fermions and their possible interactions is described by the Dirac equation given as:

$$\text{Dirac equation here!} \tag{2.1}$$

Nevertheless, there are two types of fermions: Leptons and Quarks.

Leptons can participate in electromagnetic and weak interactions and not strong interactions whereas quarks can perform all three interactions. In the SM, leptons have integer charge values and come in three families or flavours of pairs arranged in a certain mass hierarchy with the third generation being the most massive. The third generation flavour leptons can decay into the lower generation leptons through weak interactions. Each charged lepton of a particular flavour has its neutral pair partner known as its neutrino. For example, the pair partner of an electron is the electron neutrino. In the SM, neutrinos are considered massless however, numerous experiments have confirmed neutrinos have a very tiny mass and can oscillate from one flavour into another under sufficiently large distances.

Quarks also come in pairs of three flavours with the most massive third generation flavour capable of decaying to its lower generation flavours through electro-weak interactions. Each pair flavour or generation of quarks consists of an "up-type" and a "down-type" quark. Quarks have an electric charge as well as a color charge since they can participate in strong interactions. Up-type quarks like (up(c), charm(c), top(t)) have charge of $+\frac{2}{3}$ and Down-type quarks such as (down(d), strange(s), bottom(b)) have charge of $-\frac{1}{3}$. Charges are expressed in units of elementary charge e . Quarks make up the contents of a less fundamental particles like the proton using in hadron collisions and their distribution inside a proton is modelled according to Parton Distribution Functions (PDF). A full content of fermions in the SM and their properties can be seen in table **TABLE OF FERMIONS IN SM**.

TABLE AND FIGURE OF FERMIONS IN SM (2.2)

In electro-weak interactions, fermions can be distinguished as being "Left" or "Right" handed. Infact, the SM, does not provide any understanding of why only 3 generations of elementary particles have been discovered. However, from the SM, it is clear that one generation of leptons –the electron and the electron neutrino (e, ν) and one generation of quarks –the up-quark and the down quark (u, d) is enough to describe all the visible matter we see around us.

Interactions

The interaction of matter fields or fermions is mediated by force-mediating particles called bosons—meaning they have an integer spin ($n\hbar$, where n is an integer). The SM describes three different forces and their carriers. For the electromagnetic force described under the mathematical frame work of Quantum Electrodynamics (QED), the force carrier is a massless boson called the photon, γ . For the two nuclear forces: The weak force which was later in the 1960s developed in a combined electroweak framework by Sidney Glashow, Abdus Salam and Steven Weinberg[], the force-mediator are the massive vector bosons W^\pm, Z^0 discovered at CERN in 1983 []. The strong force described under the frame work of Quantum Chromodynamics (QCD) is not unified with the other two forces and is mediated by massless gluon, g . The table below show

some the property of the force mediating particles in SM.

"PLEASEINSERTTABLE/DIAGRAMFORGAUGEBOSONSHERE!" (2.3)

The current frame work of the SM was formulated with inputs from theory and results from several experiments so it is not uncommon to introduce mathematical concepts and constructs to describe the SM in an elegant manner. It is with this spirit that we will continue the rest of this section.

Fermion interaction is based on the sole concept of symmetry i.e the invariance of a Lagrangian density, \mathcal{L} , under a particular set of transformations. In the SM, these set of transformations are called local transformation or gauge transformations (symmetry groups) because they depend on space-time coordinates and can be expressed as:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \quad (2.4)$$

The symmetry groups describe the following parts of the SM interactions:

- $SU(3)_C$ defines the strong nuclear interaction where quarks with color charge C are coupled to massless eight (octet) gluons in the frame work of QCD. The surprising phenomenon here is that unlike electromagnetic interactions (QED) where massless photons cannot interact with each other, these massless gluons can interact with each other since they carry color charge. There are three color charges.
- $SU(2)_L \times U(1)_Y$ defines the electroweak interaction. The four corresponding gauge (because they are from these gauge groups) massless bosons $W_\mu^{1,2,3}, B_\mu$ mix with each other to give the physical electroweak bosons W^\pm charged and neutral Z^0 and γ . The W^\pm and Z^0 become massive after the Higgs mechanism. These bosons couple using the "charge" of the weak interaction called weak isospin T and the hypercharge Y to all fermions or matter. With W^\pm couple only to left-handed fermions and right-handed anti fermions only leading to what is known as parity violations. Using the third component of the weak isospin T_3 and the hypercharge Y , the resulting electromagnetic charge of all fermions can be defined using

the relation:

$$Q = T_3 + \frac{Y}{2} \quad (2.5)$$

In the SM, all left handed fermions have $T^3 = \pm \frac{1}{2}$ and are thus represented as multiplets of the SM, in this case isospin doublets whereas, right-handed fermions have $T^3 = 0$ and are thus isospin singlets in the SM. The table below summarises these electroweak fermion multiplets and their quantum numbers.

$$TABLE OF SM multiplets and their Quantum Numbers. \quad (2.6)$$

The $SU(2)_L \times U(1)_Y$ theory carry two coupling constants g and g' which parametrizes the strength of these interactions and they are connected to the electric charge of each fermions in the following relation:

$$e = g \sin \theta_w = g' \cos \theta_w \quad (2.7)$$

The parameter θ_w is known as the *Weinberg angle* which is not derived from the SM but measured from experiment to be equal to $\sin^2 \theta_w \approx 0.231$. The physically observed gauge bosons are a rotation of the weak eigenstates involving the Weinberg angle given as:

$$The Physical Gauge Bosons in terms of weak eigenstates. \quad (2.8)$$

This angle participates in an important phenomenon in SM known as quark mixing. Unfortunately in the current simplest state of SM, there are no lepton mixing (due to a global symmetry called lepton number conservation) even though the recent discovery of neutrino masses existence [1] hints at the possibility of such a mixing in the lepton flavour sector. Nevertheless, in the quark sector, it is possible for the W^\pm to change the flavour of a given quark, for example an up-type quark u can transition to a down-type quark d . This type of transitions are referred to as Flavour Changing Charge Currents (FCCC). However, it is not possible for Z^0 to change the flavour of a quark but also lead to small violation of parity. There is active research to discover large Flavour Changing Neutral Currents (FCNC) from certain weak interactions since most of these are suppressed. The quark mixing is entirely described using a 3 by 3 component matrix known as the

Cabibbo-Kobayashi-Maskawa (CKM) matrix given in equation below:

$$\textit{TheCKMmatrix} \tag{2.9}$$

The entire components of this matrix is measured from experiment and not derived from the SM.

Quantum Chromodynamics and Parton Distribution Functions

The strong nuclear interactions described by QCD is based on the $SU(3)_C$ gauge group. Only quarks and gluons are involved in this interaction. Each quark can exist in three different strong "charge" called *color* (dubbed are red, green and blue) thus forming a color triplet. Anti-quarks also carry opposite color charges. The color strength is the same for all three colors. Gluons unlike photons carry a combination of color and anti-color charge which lead to the self interaction of gluons. Gluons are not affected by Higgs mechanism thus remain massless after breaking of $SU(2)_Y$. Leptons carry no color and as such are color singlets thus cannot participate in strong interactions.

The value of the strong coupling α_S which determines the strength of the strong interaction depends on the momentum transfer Q^2 as do the coupling constants of the $SU(2) \times U(1)_Y$ groups. For large Q^2 , α_S approaches zero in a process in QCD referred to as *asymptotic freedom* and the quarks are nearly free while for small values of Q^2 , α_S grows large and the quarks are tightly bound. This process is also referred to as *confinement*. Quarks are always confined to hadronic bound states called baryons or mesons consisting of three quarks or a quark and anti-quark respectively.

The proton is the most stable baryon. It is made up of two up quarks and one down quark such that its electric charge is 1. These are called valence quarks. It turns out that from experiments, valence quarks are not the only quarks present in a proton. Infact it is best to describe the proton as made up of *partons*. Partons are quarks and gluons. Inside a proton, it is possible for a gluon to radiate or split up into a quark anti-quark pair. These kind of quarks are referred to as sea quarks. All partons in a proton carry the total momentum of the proton, however during proton-proton collision

in a hadron accelerator, the partons are the actual colliding particles and not the protons so it is imperative to know the momentum fraction x of an individual parton inside a proton. The momentum fraction of a parton is expressed as a *Parton Distribution Functions* (PDFs). PDFs gives the probability of finding a parton with momentum fraction x . PDFs are measured from electron-proton accelerator experiments such as HERA in Germany. The PDF is expressed as a function of the fraction of the parton momentum to the total proton momentum and the momentum transfer Q^2 from the electron interacting with the parton, $f(x, Q^2)$. Figure below shows an example of the PDFs for a few quarks and gluons and strange quarks with momentum fractions x_q and x_g respectively with a momentum transfer of Q^2 .

$$DIAGRAMOFEXAMPLEPDFs \quad (2.10)$$

It is imperative to know the PDFs very well when performing a search for physics beyond the SM as calculating scattering *cross sections* which is an experimentally observable quantity describing the probability of a particular process happening highly depends on PDFs. In addition to this, due to the PDFs, the center of mass for proton-proton collision which in actual experiment is parton-parton collision is much reduced from $\sqrt{S} = 14$ TeV as advertised in the LHC to $\sqrt{\hat{s}} \approx 2$ TeV and this depends on the particular partons involved in the parton-parton interaction.

Without the Higgs mechanism, all the particles described so far will be massless. But experiments observe massive particles, So how do we get these particles to have mass in the SM? This questions remains and important one in particle physics. However in the case of the SM, we obtain mass by "manually" breaking the gauge symmetries in the SM through the addition of mass terms into the SM Lagrangian. Thus the introduction of mass terms through the Higgs mechanism breaks the local gauge invariance in the theory which describes all the above interactions.

Higgs Mechanism

Earlier attempts prior to the 1960s for constructing a gauge theory of weak interactions had failed because the gauge bosons always end up massless. Which indicated that the

strength of the weak interaction can be infinite just like the electromagnetic interactions. However, theories were in complete contrast with results from experiments as weak interactions were understood to be limited to very small distances of about the scale of the nucleus. Thus these massless gauge bosons had to become massive.

In the Higgs-Brout-Englert [] mechanism, consist of introducing an extra weak isospin complex scalar doublet:

$$INSERTHIGGSDOUBLETHERE \tag{2.11}$$

which is invariant under the gauge symmetry group $SU(2)_L \times U(1)_Y$ and has its dynamics described by the Lagrangian density:

$$HIGGSDOUBLETLAGRANGIAN \tag{2.12}$$

where Φ is the Higgs doublet with spin-0 complex components. The parameter $\mu^2 < 0$ and the real parameter $\lambda > 0$ of the Higgs potential:

$$HIGGSPOTENTIAL \tag{2.13}$$

is chosen such that the potential $V \rightarrow \infty$ as $\Phi \rightarrow 0$. It is easily seen from the previous equation that the minimum of the potential is not longer at $\Phi = 0$ but lies at :

$$|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} = \nu \tag{2.14}$$

With this choice of parameters settings, the potential V is itself $SU(2)_L$ symmetric but any other choice of ground state breaks $SU(2)_L$ symmetry. This is referred to as the *Higgs-Brout-Englert mechanism* or *Higgs mechanism* for simplicity. This choice of parameters of the potential V can be seen in figure below.

$$puthiggspotentialpictureinhere! \tag{2.15}$$

One can then choose $\phi_1 = \phi_2 = \phi_3 = 0$ and then parametrise the higgs doublet as

small perturbations around the minimum as follows:

$$\text{equation of higgs perturbations} \quad (2.16)$$

with $h(x), \eta_i(x)$ being 4 real scalar fields. Using the gauge freedom of $SU(2)_L \times U(1)_Y$ one can choose the *unitarity gauge* where the kinetic terms for the fields $\eta_i(x)$ vanish and their with the requirement of local gauge invariance, $\eta_i(x)$ couple to the massless gauge bosons to be to become massive and the resulting Higgs doublet is expressed as:

$$\text{Higgs doublet with imaginary parts removed} \quad (2.17)$$

With the imaginary parts removed and the field $h(x)$ is identified as the physical real scalar Higgs field or Higgs boson. The ground state chosen so that the photon remains massless while the other gauge bosons including the real scalar Higgs field are massive with their masses given as:

$$\text{Eqns of Gauge boson masses and Higgs mass} \quad (2.18)$$

The Z^0 mass m_Z can also be expressed in terms of the W^\pm mass m_W and the Weinberg angle as:

$$\text{Z mass to W mass equation} \quad (2.19)$$

Thus one can easily observe that all the effects of the W and Z bosons can be described in terms of the parameters e , θ_w and ν which can be expressed in term of Fermi constant all of which were experimentally known. Thus it is fine to say that the Higgs mechanism could predict the masses of W and Z gauge bosons which were experimentally found and measured in 1983 at LEP. This discovery was one of the greatest triumphs of the SM. With the value of $\nu \approx 246$ GeV, we can then express the mass of the fermions in terms of the Yukawa coupling as (from the Yukawa sector of the Lagrangian) :

$$m_f = \lambda_f \frac{\nu}{\sqrt{2}} \quad (2.20)$$

according to the *Yukawa terms* \mathcal{L}_Y which is symmetric under $SU(2)_L \times U(1)_Y$ given by

$$YUKAWA equation \tag{2.21}$$

with λ_f dimensionless Yukawa couplings which are free parameters of the model. The search for the Higgs boson was the main purpose for the construction of the LHC at CERN and on June 04, 2012, a Higgs-like candidate particle was found whose result can be seen in figure below:

$$insert figure of Higgs boson discovery here! \tag{2.22}$$

It is important to understand that there is no fundamental reason why there should be only one Higgs field to which all fermions couple to. As we will see in other super-symmetry that there could be more than one Higgs field.

2.1.2 Decay Rate and Life Time

Of all fundamental "point-like" particles in the SM, only the electron e , and electron neutrino ν , as leptons and the up u , and down d , as quarks are "understood" to be stable. The rest of the SM particles can transform from one particle generation to another either through disintegration or oscillation. This stability is measured with respect to the age of the universe which is understood to be about 13.7 billion years old. Thus a composite particle such as the proton made up of two u and one d valence quarks although seemingly very stable can disintegrate with some theories beyond the SM predicting to remain stable in a time period of about 10^{33} years. The disintegration of a particle also referred to as decay is usually through an interaction of some sort. This interaction is between the particle and its daughter particles and can be electromagnetic, weak, strong, any pair or maybe all three types of interactions. In particle Physics, the stability of a particle is related to the conservation of a quantum number or conserved quantity such as energy, spin, angular momentum and charge. Other factors may also play an important role in determining the stability of a particle such as phase space (enough room to decay into), violation of some property such as strangeness or the mediating particle usually a boson being very massive compared to the momentum of

the parent particle. The decay rate, Γ , a quantity which can be calculated obtained from prediction made in some theory can also be measured experimentally. Its measurement provide access to the underlying type of interaction or mediating particles involved in the decay and thus can be used as a direct tool to search for other interactions beyond the current known ones. A single particle can decay into more than one type of particles. As long as the conditions for decay are met, a decay into any potential particle whose mass is less than the mass of the parent particle is possible. The decay into a particular set of particle(s) is known as a decay channel. Different decay channels can be quantified with respect to the overall total decay rate of the parent particle. This quantification is expressed as a *branching ratio (BR)*. Thus the BR gives quantitative estimate of the possibility of a parent particle decaying to specific daughter particles or through that channel.

The inverse of a decay rate is the *life time*, denoted as τ .

$$\tau = \frac{\hbar}{\Gamma} \quad (2.23)$$

A convenient way to express life time is in distance. This distance called $c\tau$, where c is the speed of light in vacuum and τ is the life time is called the *decay length*. $c\tau$ is the decay length as measured in the frame with respect to the center of mass of a moving particle. However, laboratory measurements are not done in the center of mass of the moving particle as this would be near impossible to do. So since the particle is moving with some speed with respect to a stationary laboratory, we have to take into consideration this difference in motion of frames (the moving particle frame and the stationary Laboratory frame) in understanding our measurement in the laboratory of the decay length of the moving particle and how this is translated into the true decay length of the particle. The effect we need to consider is known in special relativity as *time dilation* and the decay length is a measure of the distance between the position where the particle was produced to where it decayed. Our laboratory measurement is expressed as:

$$L = \beta\gamma c\tau \quad (2.24)$$

where $\beta = \frac{v}{c}$ with v being the speed of the moving particle and $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ is the ratio accounting for time dilation effect and from this one can translate back into the true

decay length of a particle $c\tau$. The decay length can also be expressed in terms of the momentum p of the particle where $p = \beta\gamma m$ and thus $L = \frac{p}{m}c\tau$. We see that the decay length of a particle is proportional to the momentum and inversely proportional to the mass of the particle.

The decay rate depends on quite a number of particle properties as we've mentioned earlier. As a result, the decay length for electromagnetic, can be very different to that of weak and strong interactions. The decay length of strong interactions having the shortest decay length due to the strong nature of the interaction leading high decay rates. This is followed by the weak and then electromagnetic interactions. There are some exceptions to this due to other factors playing a key role than interactions alone as we mentioned. The table and graph below show the mass and decay length of SM particles and their interaction.

TABLE SHOWING SM particle decay rates and interactions involved as well as mass V s decay length.
(2.25)

In particle physics experiments it is very challenging to measure the life time or decay length of a particle by measuring the time it travels from where it was produced to where it decayed. Rather, the number of events present initially and that observed after a time period t is used to measure the lifetime of a particle. The decay rate (or life time) of a particle is related to the number of particles observed through the equation:

$$N(t) = N_0 \exp\left(\frac{-t}{\tau}\right) = N_0 \exp\left(\frac{-\Gamma t}{\hbar}\right) \quad (2.26)$$

where $N(t)$ is the number of particles observed at an arbitrary time t and N_0 is the number of particles observed at an initial time where it is assumed no particle has decayed yet usually at $t = 0$. A distribution of the observed number of particles(usually a Poisson distribution) can be plotted with time measured. The resulting distribution if fitted with a Poisson distribution function and the parameter of the Poisson distribution function extracted to give us the decay rate or life time of a particle.

Particles with large decay length or long life time are commonly referred to as *Long-Live* (LL) particles. Many models beyond the SM predict the existence of such particle.

They are also understood to be prime candidates for particles making up DM. Before we dive into such models, it is necessary to understand in detail the decay of particles and factors which determine a particle's decay length as well as the kind of LL particles considered detectable in a multi-particle physics detector such as those at the Large Hadron Collider (LHC) CERN pursued in this thesis.

Particles described by the SM come in different types of long-lived. First, we have the stable elementary (as we currently believe) such as the electron and neutrinos. Second, we have the meta-stable elementary such as the muon and finally the (very) long-lived composite particles such as the neutrons and protons. By referring to the different classes of particles according to their life time, we can ask the question, what properties of a particle makes it stable, meta-stable or long-lived?

There are three possible answers to this question:

- A particle could be the lightest state carrying a conserved quantum number and as such remain entirely stable e.g the electron and proton.
- The decay of a particle to another lighter particle could only be made possible through some suppressed or effective coupling and as a result ends up being meta-stable e.g the muon
- If the mass of a particle is relatively close in quantity to the particle it is decaying into such that their difference in mass is quite small, the decay will be eventually suppressed. This goes by the name lack of phase space for decay e.g decay of neutron ($n \rightarrow p + e^- + \bar{\nu}_e$). In this scenario the difference in mass between the neutron (n) and the proton (p) is ≈ 1.293 MeV and as a result determines the type of associated particle produced in this decay as observed.

In this thesis, we will only be interested in Meta-Stable (MS) particles, and in particular focus on Massive Neutral Meta-Stable particles which we refer to as Neutral Massive Long-Lived Particles (NMLLP). A rather more descriptive name would be Neutral Massive Meta-Stable Particles (NMMP) since these particles are not LL in the real sense but might decay into other elementary particles which are observable at detectors and how

long-lived you refer to them depends on the possible lifetime of this particle your detector is sensitive to. As their lifetime might range from a few nanoseconds (10^{-9} s) to the age of the universe (13.7 billion years) likewise from a few μm to billions of km. Thus, our interpretation of LL particles will be those whose decay length range from a few μm to few meters or detectable size of the LHC detectors and in particular electromagnetic sector of LHC detectors.

We have restricted ourselves to electromagnetic (local U(1) gauge symmetry) neutral particles as their charge counterparts can be studied using conventional magnetic spectrometer and ionization methods as shown in this studies for Heavy Stable Charge Particles (HSCP).

2.1.3 Why Go Beyond?

The SM (Glashow, 1961; Weinberg, 1967; Salam, 1968) currently describes almost entirely all of the observed phenomena and fundamental particles of nature with unmatched precision. However, as indicated from previous sections, there is more to be understood such as:

- **General Formalism:** There are way too many parameters in the SM which are not derived within the theory but rather measured experimentally such as the Weinberg angle and the CKM matrix elements. The SM does not account for the multiplet structure of fields as well as why there are only three observed generations of particles. Currently observed neutrino masses are not required in the SM as neutrinos are considered massless in the SM. Even the Electroweak symmetry breaking is not very well understood.
- **Astrophysical:** Why is there so much matter and not anti-matter? If the Big Bang is suppose to be the correct theory about the universe existence, then matter and anti-matter must be observed in equal composition, however, Baryon asymmetry ratio show that there is more matter than anti-matter, where is all the expected anti-matter? This could be explained as charge-parity violation in weak interactions of the SM but this is quite small(not strong enough) to explain for all the observed discrepancy. Baryonic Acoustic Oscillation results also known as CMB as well as WMAP results all indicate the presence of excess matter which

does not interact with light and is collision less called Dark Matter (DM) as well as increase energy density responsible for the rapid accelerated expansion of the universe called Dark Energy (DE). All these observations cannot be explained within the SM.

- **Theory:** The SM is seen as some low energy theory of some much deeper underlying theory(SM as an effective theory) due to the fact that it cannot describe gravity. In Addition to this, the coupling constants in the SM all vary with energy and so the definite question if whether there is a much higher scale where all these couplings become a single coupling(Unification of forces). Supersymmetric extensions of the SM show unification of forces at Grand Unified Theories (GUT) energy scale of $\approx 10^{15}$ GeV.
- **Mass Hierarchy and Fine-tuning:** Why are particles masses in the standard model arranged in such a hierarchy? from neutrino masses of few eV to top mass of 173 GeV. In terms of energy scale, from the electroweak symmetry breaking scale of ≈ 100 GeV to Planck scale, $M_p = 10^{19}$ GeV, there are no other particles and especially scalars or any known interactions. The Higgs mass incredible precise contributions from higher order (loop) effects to its mass in order to maintained its experimentally observed value of ≈ 125 GeV. Understanding this precise contributions and cancellations to arrived at the expected value is referred to as the fine-tuning problem and extensions of the SM like supersymmetry provide a very natural answer as we will see later.

2.2 Beyond Standard Model Physics

The Higgs boson's mass as understood from theoretical calculations should receive contributions from higher order (loop interactions as is known) inorder to observe the experimentally measured mass of possibly 125 GeV or of order $O(100 \text{ GeV})$. However, all these corrections are said to cancel out such that the experimentally observed mass is as it is measured. The question of where these additional loop corrections disappeared into cannot be understood within the context of the SM. However, theories beyond the SM such as supersymmetry provide a natural understanding of how these loop effects

cancel out to arrive at the observed mass. To go a step further with this; the mass of a particle can be expressed as

$$m_{physical}^2 = m_{Bare}^2 + \delta m_1^2 \quad (2.27)$$

where $m_{Physical}^2$ is the true mass of the particle measured in the laboratory; in the case of the Higgs boson of order $O(100 \text{ GeV})$ while m_{Bare}^2 is the true mass of the particle which cannot be calculated or measured. δm_1^2 is the quantum one loop corrections to the true mass which can be calculated. Thus from the measured mass and the calculated one loop quantum effect mass, one can get the true mass of the particle. The quantum loop contributions can come from bosons as well as fermions. For the Higgs scenario, the Higgs can couple or interact with every particle through interactions like $\lambda_f H \bar{f} f$ for fermions and $\lambda_S |H|^2 S^2$ for scalar or bosons with λ_f and λ_S the coupling constants and not necessarily equal. The quantum one loop corrections as calculated from the following diagrams:

$$1\text{Loop diagrams for Higgs Boson/Fermion interactions.} \quad (2.28)$$

is given as:

$$\delta m_{1,f}^2 = \frac{1}{16\pi^2} |\lambda_f|^2 \left(-2\Lambda^2 + 6m_f^2 \ln \left(\frac{\Lambda}{m_f} \right) + \dots \right) \quad (2.29)$$

$$\delta m_{1,S}^2 = \frac{1}{16\pi^2} |\lambda_S|^2 \left(\Lambda^2 - 2m_S^2 \ln \left(\frac{\Lambda}{m_S} \right) + \dots \right) \quad (2.30)$$

where Λ is understood to be some cut-off scale where new kind of interaction at a much higher energy scale is needed to regulate the low energy behavior of the SM. Λ could be the Planck scale (10^{19} GeV) where this new kind of interaction is gravity. The two things to observe from this calculations is that first, corrections to the higgs bare mass m_{Bare}^2 are not proportional to the Higgs mass as is the case with other SM particles like the electron. Second, these corrections are of the order of $\approx 10^{38} \text{ GeV}^2$ with the signs reverse for fermions or scalar corrections. Despite this expected corrections to the true Higgs mass, the measured or physical Higgs mass squared $m_{H,Physical}^2$ is of the order $\approx 10^4 \text{ GeV}^2$. The only way there is an agreement between this correction and

physical Higgs mass is if the true Higgs mass, $m_{H,Bare}^2$ is fine-tuned with a precision of about 1 in 10^{17} . This enormous fine-tuning is considered a fundamental problem with the Higgs mechanism of the SM and is referred to as not *natural*. Infact, since in the SM, there is only once scalar particle which is the Higgs boson, this fine-tuning cannot be understood. However, in other models beyond the SM such as suppersymmetry, the fermion one loop quantum correction which comes with an opposite sign to the scalar one loop quantum correction with $\lambda_f = \lambda_S$, there is a cancellation and this fine-tuning can be understood. Another interpretation of this issue is through the question of why there is so much difference in energy scale between the electroweak scale $O(100 \text{ GeV})$ and the Planck energy scale $O(10^{19} \text{ GeV})$ where gravity effects to particle interaction becomes significant?. This is referred to as the *Hierarchy problem* stated above as one of the motivation to go beyond SM.

Another drawback with the SM is that of unification. It is believed that at a higher energy scale since SM seems to be describing the low energy behaviour of some parent theory, the electromagnetic, weak and strong interactions all become one interaction just as the electromagnetic and weak interaction unified into the electroweak interaction as the electroweak energy scale $\approx 100 \text{ GeV}$. i.e

$$SU(3)_C \times SU(2)_L \times U(1)_Y \subset \mathcal{G} \quad (2.31)$$

where \mathcal{G} is some larger symmetry group. In SM, this does not happen at any higher energy scale. However, in suppersymmetry, there is a clear unification of individual coupling constants or electromagnetic, weak and strong interactions at the GUT energy scale of $\approx 10^{15} \text{ GeV}$. This effect can be seen in the following figures as taken from [1].

$$PlotshowingUnificationofCouplingConstants. \quad (2.32)$$

2.2.1 Supersymmetry

In relativistic Quantum Field Theory (QFT), the idea of symmetry is used to provide a better understanding of a particle and its possible interaction with other particles. Symmetries can be classified into two broad categories: Space-Time or external symmetries

known as Poincaré (rotational and translational) symmetries also known as groups and internal or gauge (which as we saw earlier; $SU(3)_C \times SU(2)_L \times U(1)_Y$ describing the quantum numbers— color, weak and hypercharge respectively) symmetries. In a quest to include gravitational interaction along with all the other forces of nature into a unique frame work called unification, it was thought that one could combine these two classes of symmetries into a bigger class of symmetry. However, Coleman and Mandula in their so-called "no-go" theorem in 1967 [8] showed that the direct product nature of super groups; a direct approach to extending symmetries to bigger symmetries, is not possible. Thus these two class of symmetries cannot be combined into a bigger parent symmetry. This produced a challenge of finding a scenario where $[M^{\mu\nu}, T^a] \neq 0$, considering that the generators of these groups; P^μ , $M^{\mu\nu}$ and T^a corresponding to these symmetries have a direct product; Poincaré \times Gauge group, for which $[P^\mu, T^a] = [M^{\mu\nu}, T^a] = 0$. Because of this *no-go* theorem, such a parent symmetry group is not possible if one used generators of Lorentz tensors. The only way out is to find a symmetry which is generated by spinorial (particle's spin) charges instead of tensorial (space-time) charges. Such a theorem was found in 1975 by Haag, Lapuszanski and Sohnius [?] called the *Haag-Lapuszanski-Sohnius* theorem with its corresponding algebra called the *Lie-superalgebra*. The generators of these *Lie-superalgebra*, Q^α , with $\alpha = 1, \dots, N$. N is the number of generators for the supersymmetry. In this Thesis we will only be considering the case where $N = 1$ i.e only one supersymmetry generator. This is known as the minimal supersymmetry. If you are interested in learning more about extensions of this minimal version see this excellent text [?]. The generators Q^α can be expressed in terms of Weyl Spinors Q_a where $a = 1, 2$ and must satisfy anti-commutation relation with its conjugate. This is the major aspect of introducing supersymmetry. Thus for these generators to be supersymmetric, they must satisfy the following relations:

$$\{Q_a, \bar{Q}_b\} = 2(\gamma^\mu)_{ab} P^\mu, \quad [Q_a, P^\mu] = 0, \quad [Q_a, M^{\mu\nu}] = \frac{1}{2}(\Sigma^{\mu\nu})_a^b Q_b \quad (2.33)$$

where γ^μ is define such that $\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}$ and $\Sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$ and \bar{Q}_a is the Hermitian conjugate to Q_a and is also a generator. From these relations, two very fundamental consequences arise:

- Particles in a given supermultiplet have the same mass but differ in their spin by half a unit.
- There is an equal number of fermionic and bosonic degree of freedom or states in every irreducible representation of supersymmetry.

From the above observation, we define supersymmetry as the symmetry which transforms particles from one spin into another. Hence these supersymmetry generators transform fermions into bosons or bosons into fermions with the same mass.

$$Q|\mathbf{Fermion}\rangle = |\mathbf{Boson}\rangle, \quad Q|\mathbf{Boson}\rangle = |\mathbf{Fermion}\rangle \quad (2.34)$$

This reveals to us that, in supersymmetry, every particle has a partner with the same mass with supermultiplets chosen such that every SM particle with spin $0, \frac{1}{2}, 1, 2$ have a partner with spin $\frac{1}{2}, 0, \frac{1}{2}, \frac{3}{2}$ respectively in the same supermultiplets. In supersymmetry, there are three kinds of supermultiplets referred to as *Chiral*, *Vector* and *gravity* multiplets. In building a minimal supersymmetric extension of SM only the Chiral and Vector supermultiplets are used and thus we will concentrate only on these two. The following table shows the different supermultiplets as encountered in supersymmetry.

TABLE of SUSY Multiplets and spin (2.35)

So far we have mostly seen the algebraic approach to supersymmetry. However in order to build models (supersymmetric Lagrangians) and make predictions, we have to return to the idea of fields. This brings us to the idea of the so-called *superfields* first proposed and realized by my hero Abdus Salam and Strathdee [?]. Superfields are fields defined on a superspace which is an ordinary Minkowski-space, x^μ and four anti-commuting Grassmann, numbers θ . For more on this see [1]. Thus a general superfield is an operator-valued function Φ on a superspace $\Phi(x^\mu, \theta, \bar{\theta})$. Its components consist of from ordinary scalar fields (real or complex), Lorentz vector fields and Left-handed or Right-Handed Weyl (2 degrees of freedom) spinor fields. The Table below shows an example of the components which make up the superfield or supermultiplets. Each

component represents a SM particle and its super partner with the same mass.

TABLE OF A SUPERFIELD AND COMPONENTS (2.36)

In constructing the MSSM, only the Chiral and Vector supermultiplets or superfields are used.

2.2.2 Minimal Supersymmetric Standard Model

The Minimal Supersymmetric Standard Model or MSSM is an extension of the SM to include its supersymmetric partner particles.

As a result the already 19 free parameters of the SM is increased with an additional 105 free parameters. These are a lot of parameters for any fundamental theory describing elementary particle interactions and thus undermines its predictive power. Thus, a generic or parent theory must be preferred in which the number of free parameters for the theory to predict is much reduced. Through this way, it is much easier to study the theory phenomenologically. For example, the supersymmetric (SUSY) extension of the SM theory with gravity is called mSUGRA and has only 6 parameters while a SUSY extension of SM with purely gauge interaction is called Gauge Mediated Supersymmetry Breaking (GMSB) and has only 5 parameters. Other SUSY theories such as Anomalous Supersymmetry Breaking (ASB) have 6 parameters.

In this thesis, we will only talked about GMSB theories as these describe and predict the existence of LL particles. A full table of SM particles and their SUSY counterparts as understood through the MSSM can be seen in the table below.

TABLE OF SM/SUSY PARTICLES IN MSSM. (2.37)

In SUSY, the particle dynamics and interaction Lagrangian is written in terms of supermultiplets are already seen in table above. However, the superpotential is what defines the phenomenology and hence mass spectrum of the model. In MSSM, the superpotential is given as thus[?]:

$$W_{\text{MSSM}} = \bar{u}_\mathbf{y}_\mathbf{u} \mathcal{Q} H_u - \bar{d}_\mathbf{y}_\mathbf{d} \mathcal{Q} H_d - \bar{e}_\mathbf{y}_\mathbf{e} \mathcal{L} H_d - \mu H_d H_u \quad (2.38)$$

Where the objects $H_u, H_d, \mathcal{Q}, \mathcal{L}, \bar{u}, \bar{d}, \bar{e}$ are chiral superfields corresponding to the chiral supermultiplets given in table above. The dimensionless couplings $\mathbf{y}_u, \mathbf{y}_d, \mathbf{y}_e$ are 3×3 matrices known as the Yukawa couplings. One thing to note here is that instead of a single Higgs double as in the case with the SM, two Higgs double are present; H_u and H_d to give mass to up-type and down-type quarks and leptons. The superpartners of these Higgs particles which are fermions and those of the gauge bosons called gauginos mix to produce new neutral and charged fermions called Neutralinos and Charginos respectively. An aspect which is not present in the SM.

In MSSM, a combination of baryon (B) and lepton number (L) symmetries is combined to give a more fundamental symmetry called *R-Parity*[?] or *Matter Parity*[?]. From a multiplicative combination of B and L numbers, we get R-parity expressed as:

$$R_P = (-1)^{3(B-L)+2S} \quad (2.39)$$

where S is the spin of the particle. This is a conserved quantum number which is from a discrete symmetry. This symmetry commutes with supersymmetry. Thus particles in a given supermultiplet do not have the same R parity. SM particles like quarks have an Even parity $R_P = 1$ while SUSY particles like squarks have Odd parity $R_P = -1$. This has a lot of important phenomenological consequences such as the following:

- In the decay of SUSY particles, the lightest SUSY particle (LSP) have odd parity $R_P = -1$ and thus it must be absolutely stable. In addition to its absolute stability, if it is neutral and interacts only and very weakly with ordinary matter, then it is a good candidate for non-baryonic dark matter as required by cosmology.[?]
- Every SUSY particle produced which is not the LSP, will eventually decay into the LSP or an odd number of LSPs.
- SUSY particles can only be produced in pairs in a collider experiment.

Thus in generic SUSY models with minimal particle content, where the superpotential include terms which violate Lepton (L) and baryon (B) numbers; R-parity conservation can be imposed giving rise to R-parity Conserving (RPC) models with the

LSP stable while R-parity can be violated resulting to R-parity Violating (RPV) models where the LSP is unstable and decays to SM particles.

In this Thesis, we consider only RPC models since our motivation is to search for neutral stable particles motivated by them being candidates particles which make up dark matter (DM).

If SUSY is to become a theory which describes nature, then the observation of components within the same supermultiplets having the same mass, i.e $m_B = m_F$ must be unrealistic as until presently no experiment has found a selectron(SUSY partner of electron) with a mass of 0.512 MeV for example. Therefore, SUSY must be spontaneously broken. Spontaneous Supersymmetry Breaking (SSB) means that the vacuum expectation value of a scalar field(in SUSY an auxiliary field) must be non-zero. The manner in which this breaking occurs determines the phenomenology of any model. As one would imagine, there are many different ways of breaking SUSY(through gravity, gauge etc) resulting to many different SUSY models. However, in this thesis, will concentrate only on those for which gauge interactions is responsible for SUSY breaking. Such SUSY models are generally referred to as Gauge Mediated SUSY breaking models (GMBS) ranging from Pure to General Gauge Mediation (GGM) as one would easily find in the literature. We will also focus on models with Soft Breaking as we would like favour SUSY models with phenomenology within the reach of the LHC. Soft breaking would mean the SUSY breaking terms in the SUSY potential consists of only masses and terms whose couplings have positive mass dimension. This ensures the existence of particles with masses around a few TeV where they can possibly be produced at current particle colliders.

2.2.3 Soft Supersymmetry Breaking

The idea of being soft is such that the spontaneous breaking must be caused by couplings with positive mass dimension and not dimensionless coupling. Also this allows for the observed hierarchy between the electroweak energy scale 100 GeV and the Planck energy

scale 10^{19} GeV. The Lagrangian for soft SUSY breaking terms can be written as thus:

$$\mathcal{L}_{\text{Soft}}^{\text{MSSM}} = -\frac{1}{2} \left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} \right) + c.c \quad (2.40)$$

$$- m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + c.c.) \quad (2.41)$$

$$- m_Q^2 \tilde{Q}^+ \tilde{Q} - m_L^2 \tilde{L}^+ \tilde{L} - m_{\tilde{u}}^2 \tilde{u}^+ \tilde{u} - m_{\tilde{d}}^2 \tilde{d}^+ \tilde{d} - m_{\tilde{e}}^2 \tilde{e}^+ \tilde{e} \quad (2.42)$$

$$- \left(a_u \tilde{u} \tilde{Q} H_u - a_d \tilde{d} \tilde{Q} H_d - a_e \tilde{e} \tilde{L} H_d + c.c \right) \quad (2.43)$$

where M_1 , M_2 and M_3 are the superpartners of the gauge bosons of the SM symmetry group. They are referred to as the Bino, Wino and gluinos(8 gluinos because there are 8 gluons in the SM). I have intentionally omitted scalar mass terms in this Lagrangian and rather included SUSY breaking contribution to the Higgs potential.

This results in the following mass spectrum for particles in the MSSM as seen in the figure below:

$$\text{PLOT SHOWING MASS SPECTRUM IN MSSM.} \quad (2.44)$$

In summary, SUSY predicts in addition to SM particles, new particles whose spin (S) differ from their SM counterparts by half-integer. Bosons (fermions) in the SM have superpartners which are fermions (bosons) respectively. The superpartners of SM fermions are scalars comprising of sfermions (\tilde{l}), sneutrinos ($\tilde{\nu}$) and squarks (\tilde{q}) while gluinos (\tilde{g}) being fermions are the superpartners of the massless gauge bosons of strong interaction, gluons. The scalar Higgs (2 needed for obvious reasons) boson and the vector gauge bosons of electro-weak interaction have fermionic superpartners called higgsinos, winos and binos. These can mix to form a pair of mass eigenstates called charginos ($\tilde{\chi}_j^\pm, j = 1, 2$) and a quartet mass eigenstates neutralinos ($\tilde{\chi}_i^0, i = 1, \dots, 4$).

2.2.4 Gauge Mediated Supersymmetry Breaking and Phenomenology

General Model

Constructing a SUSY model requires the following items:

1. A gauge group describing the nature of particle interaction.

2. Specifying a superpotential.
3. Providing the method for SUSY breaking.

In the case of our Minimal Supersymmetric Standard Model (MSSM), we have already provided these as seen in equations, 2.4, 2.38 and 2.40-2.43. These provide the particle content and interactions we need. However, we must account for the interactions needed in the mediation of SUSY breaking down to the energy scale of the MSSM or soft terms to be observed at the LHC.

SUSY breaking is realised through the existence of a *Hidden Sector* (Hidden because it couples only indirectly and very weakly to our "observable sector" of SM particles and their superpartners) whose dynamics manages to break SUSY. The nature of this breaking is not relevant for phenomenology but rather the "mediators" which communicate the effects of this breaking to the super partners of the SM particles. Thus, these mediators or agents must couple to this "Hidden Sector" as well as the "observable sector". In gauge mediating SUSY breaking (GMSB), these agents have the usual SM gauge interactions and are called *Messenger fields*. These Messenger fields through loops (instead of normal tree level interaction) couple with the SM superpartners. As a result MSSM particle (gauginos and sfermions) get SUSY breaking masses at the loop level referred to as soft terms. The mass of this Messenger fields M_{mess} defines the energy scale of SUSY breaking. If $M_{\text{mess}} \ll M_{\text{Pl}}$ then induced SUSY breaking occurs at a much lower energy scale instead at the Planck energy scale where gravitational interactions become very significant and the effects of the breaking is first felt by these Messenger fields and later communicated to the observable sector through SM gauge interactions. In terms of energy scales, the picture is such that SSB happens at an energy scale \mathbf{F} which defines the mass of a gravity mediating superpartner particle, the gravitino as

$$m_{3/2} = \frac{\mathbf{F}}{\sqrt{3}M_{\text{Pl}}} \quad (2.45)$$

where $M_{\text{Pl}} = 1.3 \times 10^{19}$ GeV, then the energy scale \mathbf{F}_S , which is the *induced SUSY breaking* scale in the hidden sector. This along with the mass of the messenger particles M_{mess} , defines the masses of the gauginos and sfermions of the MSSB or visible sector. If $\mathbf{F}_S < \mathbf{F}$ then the interaction between the hidden sector and the fundamental SUSY breaking is weak interaction otherwise $\mathbf{F}_S \approx \mathbf{F}$ and the interaction is strong. The

consequences of this is that one would no longer expect the mass of the gravitino $m_{3/2}$ to be given as in equation (2.45) but rather suppressed by $\frac{M_{\text{mess}}}{M_{Pl}}$ in GMSB models. In the mass spectrum of these models, the gravitino mass can be varied to a very small value only bounded by cosmological results, thus making it the lightest SUSY particle (LSP). Spanning the gravitino mass is expressed as a parameter c_{grav} which directly determines the lifetime of the SUSY next to lightest sparticle decaying to the gravitino. We will see more of this ahead.

In General GMSB, a simple model of the messenger sector can be chosen to consists of chiral supermultiplets of leptons and quark with the same quantum numbers $SU(3)_C \times SU(2)_L \times U(1)_Y$ as the SM gauge groups with representations given as:

$$\tilde{\ell} \sim (1, 2, 1) \quad \tilde{\ell}' \sim (1, 2^*, -1) \quad (2.46)$$

$$\tilde{q} \sim (3, 1, -\frac{2}{3}) \quad \tilde{q}' \sim (3^*, 1, \frac{2}{3}) \quad (2.47)$$

They couple to each other via a superpotential of a gauge singlet chiral supermultiplet S with an F-term as in the O'RAIFEARTAIGH model[?]. This messenger superpotential can be given as:

$$W_{\text{mess}} = \lambda_{\ell} S \tilde{q} \tilde{q}' + \lambda_q S \tilde{\ell} \tilde{\ell}' \quad (2.48)$$

We can thus obtain SUSY breaking by allowing vacuum expectation values VEV for both S and its auxiliary components F-term as $\langle S \rangle$ and $\langle \mathbf{F}_S \rangle$ where the \mathbf{F}_S does not have to coincided with \mathbf{F} as mentioned earlier and can be parametrised as:

$$\mathbf{F} = C_{grav} \cdot \mathbf{F}_S \quad (2.49)$$

This equation indicates that the non-zero VEV for the F-term is the main cause of fundamental SUSY breaking and this breaking is transferred to the messenger particles through radiative interactions as C_{grav} is a dimensionless parameter. Diagonalising the leptons and fermions masses with their scalar superpartners leads to mass terms for

messenger particles as:

$$m_{\tilde{\ell}\ell'}^2 = |\lambda_\ell \langle S \rangle|^2, \quad m_{\tilde{\ell}}^2_{\text{scalars}} = |\lambda_\ell \langle S \rangle|^2 \pm |\lambda_\ell \langle F_S \rangle| \quad (2.50)$$

$$m_{\tilde{q}q'}^2 = |\lambda_q \langle S \rangle|^2, \quad m_{\tilde{q}}^2_{\text{scalars}} = |\lambda_q \langle S \rangle|^2 \pm |\lambda_q \langle F_S \rangle| \quad (2.51)$$

From these messenger particle mass terms, we can define a general scale for which these definitions can be trusted as:

$$M_{\text{mess}} = (\lambda_q, \lambda_\ell) \langle S \rangle \quad (2.52)$$

In pure gauge mediated SUSY breaking models (PGGM) it is required that $\lambda_q \neq \lambda_\ell$ [?] whereas in general gauge mediated (GGM) and minimal gauge mediated SUSY breaking (GMBS)[?] models, $\lambda_q \simeq \lambda_\ell \simeq \lambda$ and $M_{\text{mess}} = \lambda \langle S \rangle$

In the MSSM sector, the gauginos and scalars obtained their mass through 1-loop and 2-loop level corrections respectively. A simple diagrams for these corrections can be seen in figure .

In the minimal GBSM scenario, an additional parameter N_5 specifying the number of messenger vector-like supermultiplets transforming under $SU(5)$ so as to allow for unification of gauge couplings at the GUT energy scale ($M_{GUT} \approx 10^{16}$ GeV). N_5 may not be too large so as to avoid gauge couplings diverging before GUT scale and as such the masses of MSSM gauge and scalars particles can be written as:

$$M_a = \frac{\alpha_a}{4\pi} N_5 \Lambda \quad (2.53)$$

$$\phi_i^2 = 2\Lambda^2 N_5 \sum_{a=1}^3 C_a(i) \left(\frac{\alpha_a}{4\pi}\right)^2 \quad (2.54)$$

where $C_a(i)$ are some constants of $O(1)$, α_a are coupling constants and

$$\Lambda = \frac{F_S}{\lambda \langle S \rangle} = \frac{F_S}{M_{\text{mess}}} \quad (2.55)$$

Ofcourse for PGGM models we will have two seperate λ s defined as:

$$\Lambda_G = \frac{F_S}{\lambda_q \langle S \rangle} \quad (2.56)$$

$$\Lambda_S = \frac{F_S}{\lambda_\ell \langle S \rangle} \quad (2.57)$$

For complete description of PGGM and its parameters see [?]. Λ is called *the effective SUSY breaking scale* which defines the mass spectrum of MSSM gauginos and scalars. In GGM models [16, 17, 18], the mass of the gauginos $\mathbf{M}_a, a = 1, 2, 3$ defines the parameter space for these models. From equation we redefine the fundamental SUSY breaking scale F in terms of the effective SUSY breaking scale Λ as:

$$\mathbf{F} = C_{grav} \cdot \Lambda \cdot \mathbf{M}_{mess} \quad (2.58)$$

and hence from equation gravitino mass is re-written as:

$$m_{\tilde{G}} = C_{grav} \cdot \frac{\Lambda \mathbf{M}_{mess}}{\sqrt{3} \mathbf{M}_{pl}} \quad (2.59)$$

We observe from above equation that in GMSB models the gravitino can become very light compared to gravity mediating models. It should not be surprising when the gravitino is identified as least stable SUSY particle (LSP) in GMSB models and is seen as a candidate for DM. C_{grav} as mentioned earlier determines the decay rate and hence the lifetime of a SUSY particle decaying to the gravitino. For instantaneous decay $C_{grave} \approx 1$ whereas for non-instantaneous decays C_{grav} can be varied accordingly to achieve of-the- order-of a particle detector size lifetimes.

GMSB Phenomenology

GMSB models attract a lot of interests because of the existence of first, light gravitinos—unlike gravity mediating SUSY models which require the gravitino mass to be of the order of $\simeq 100$ GeV and as such does not play any role in collider phenomenology, GMSB models allow for gravitino masses as low as a few eV. Second, unique gravitino-scalar-chiral fermion and gravitino-gaugino-gauge boson interactions. Figure shows feynman diagrams for these interaction.

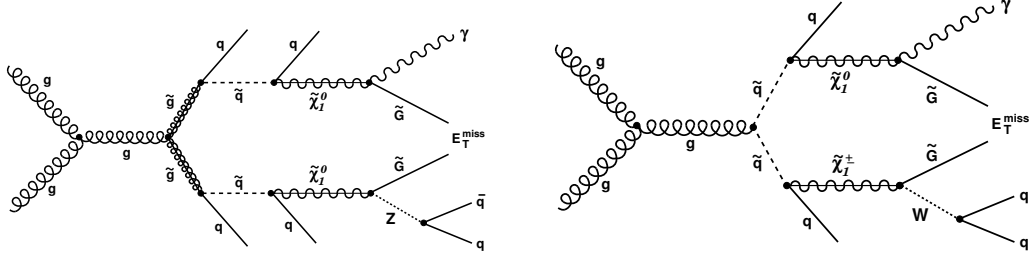


Figure 2.1: Feynman diagrams of of Gravitino interactions with superpartner pairs (ψ, ϕ) (a) and (λ, A) (b).

The presence of light gravitinos allows for the decay of any next-to-lightest MSSM particle to a gravitino as $\tilde{p} \rightarrow p\tilde{G}$ with the decay rate depending on the mass of the gravitino $m_{\tilde{G}}$ as long as R-parity is conserved. Thus every MSSM particle decay will eventually include a gravitino in its final states. This decay rate can be parametrised by C_{grav} . It is easy to see that $C_{grav} \geq 1$. Thus we define the parameter space for GMSB models as follows:

- For minimal GMSB (mGMSB): the parameter space is

$$\{\Lambda, \quad M_{\text{mess}}, \quad N_5, \quad \tan \beta, \quad \text{sgn}(\mu), \quad C_{grav}\} \quad (2.60)$$

- For General Gauge Mediation SUSY breaking (GGM): The parameter space to scan is [14, 15]

$$\{\mathbf{M}_3(\text{gluino mass}), \quad \mathbf{M}_2(\text{Wino mass}), \quad \mathbf{M}_1(\text{Bino mass}), \quad \tan \beta, \quad \text{sgn}(\mu), \quad c\tau_{NLSP}\} \quad (2.61)$$

The advantage with GGM models is that colored sparticles are not required to be heavier than their electroweak sparticles allowing for greater discovery potential at hadron collider[19]

- For Pure General Gauge Mediation SUSY breaking (PGGM): The parameter space to scan is:

$$\{\Lambda_G, \quad \Lambda_S, \quad M_{\text{mess}}\} \quad (2.62)$$

In these models, the Next-To-Lightest SUSY particle (NLSP) decays to the lightest SUSY particle (LSP), the gravitino and its SM partner. if \tilde{p} is the NLSP, then it will

decay is as follows:

$$\tilde{p} \rightarrow p + \tilde{G} \quad (2.63)$$

In mGMSB models \tilde{p} is the lightest neutralino (neutralinos come in four types and they are a mixture of Bino (\tilde{B}°), Wino (\tilde{W}°), higgsino ($\tilde{H}_u^\circ, \tilde{H}_d^\circ$) depending on the choice of parameters M_1, M_2, M_3 , or Λ , $\tan \beta$, and $sgn(\mu)$. and particle p is the photon (γ), SM(or new) Z boson (Z)(or Z') and the higgs (h). In this thesis, we will only focus on the parameter space for which the the particle $p = \gamma$ and $C_{grav} > 1$. This ensures that with the lifetime of our NLSP being finite, its decay happens *within the detector volume* and the resulting photon is delayed or non-prompt on detector time scales.

The decay rate for an NLSP to its SM partner and a gravitino goes like(details can be found in[7, ?]):

$$\Gamma(N\tilde{LSP} \rightarrow \gamma\tilde{G}) \approx \frac{m_{NLSP}^5}{\mathbf{F}^4} \quad (2.64)$$

This approximation is almost the same for the non-minimal GMSB models except that we add other parameters showing explicit dependence of how the neutralino life time can be made as long as expected in collider detectors. It is important to observe here that, the decay rate is large for smaller values of fundamental SUSY breaking scale or equivalently smaller gravitino mass provided the neutralino mass is kept fixed. Thus if m_{NLSP} is of the O(100 GeV) or more and $\mathbf{F} \ll 1000$ TeV, meaning $m_{\tilde{G}} \leq 1$ KeV, then the above decay rate is of the order than can be observed at hadron collider detectors.

2.3 Long-Lived Particles in GMSB

We have in previous discussions mentioned in passing some reasons why the study of LL particles is very important for uncovering new physics beyond the SM. In addition to mass, charge and spin being experimental handles for the search of new physics, a particle's life time or decay length is indispensable as importable parameters related to the underlying interaction type of the decay can be extracted from the decay rate and hence provide direct window towards new physics interactions beyond the SM.

2.3.1 Production and Decay of Supersymmetric Particles at Hadron Colliders

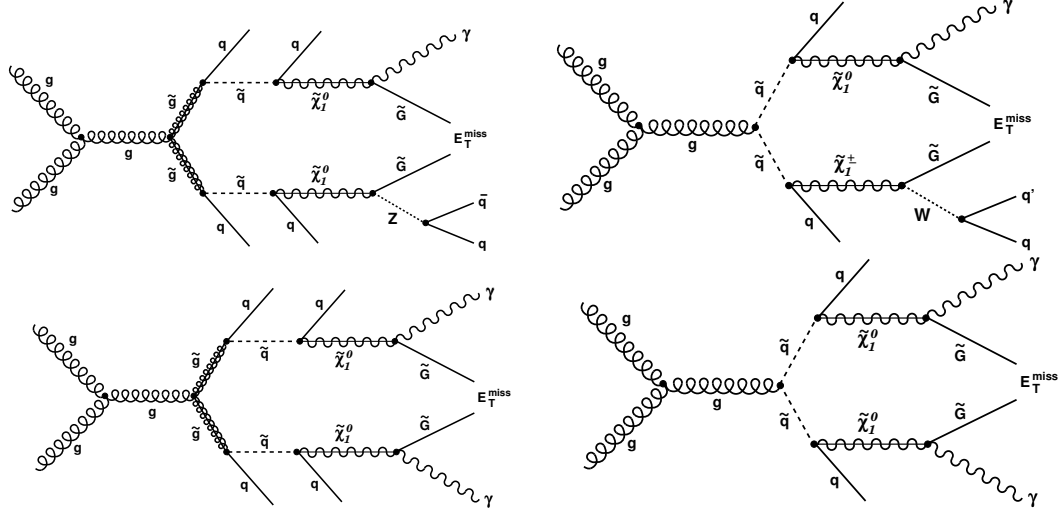


Figure 2.2: Feynman diagrams of single(top) and di(bottom) photon production from cascade decays of gluino and squark at LHC.

NLSP Decay Length

The probability for a NLSP particle produced with an energy E having mass m to travel a distance x before decaying to a photon and gravitino in the laboratory frame is given as:

$$\mathcal{P}(x) = 1 - \exp\left(-\frac{x}{L}\right) \quad (2.65)$$

where

$$L = c\tau_{NLSP} \cdot (\beta\gamma)_{NLSP} [mm] \quad (2.66)$$

and

$$(\beta\gamma) = \frac{|p|}{m} = \sqrt{\left(\frac{E}{m}\right)^2 - 1} \quad (2.67)$$

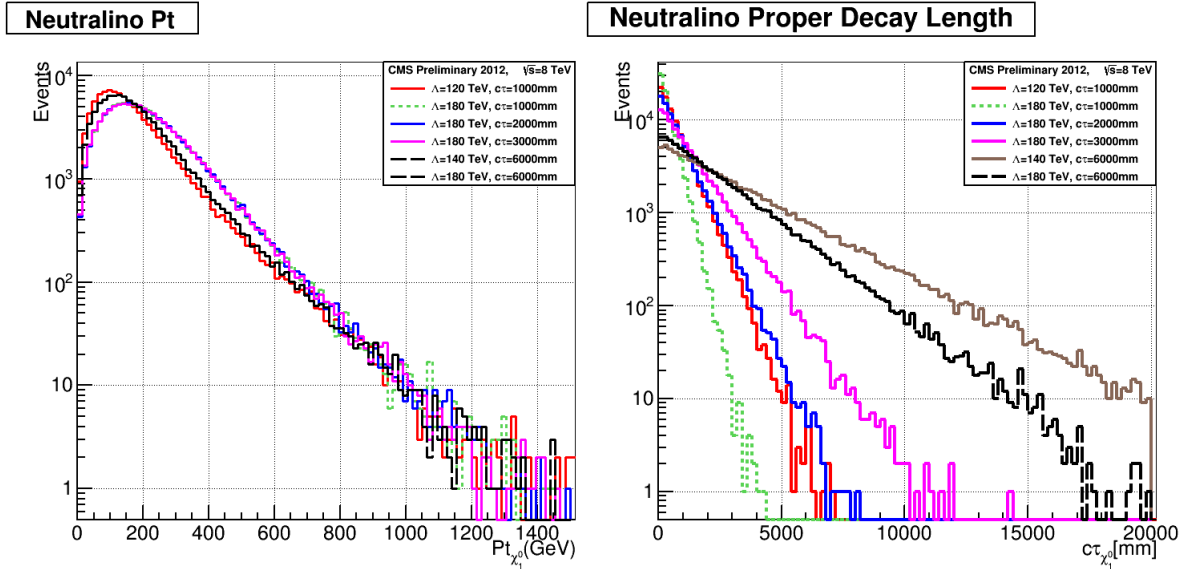
with its proper decay length as given by as (we have used equation 2.23 and 2.64 to go from decay rate to lifetime):

$$c\tau_{NLSP} \approx \left(\frac{m_{NLSP}}{\text{GeV}}\right)^{-5} \left(\frac{\sqrt{\mathbf{F}}}{\text{TeV}}\right)^4 \quad (2.68)$$

It is important to observe here that, varying \mathbf{F} changes the lifetime of the NLSP from being prompt to long-lived. This variation can be easily archived in GMSB models where the parameter C_{grav} is used so that the above proper decay length equation becomes:

$$c\tau_{NLSP} \approx C_{grav}^2 \left(\frac{m_{NLSP}}{\text{GeV}} \right)^{-5} \left(\frac{\sqrt{\mathbf{F}_S}}{\text{TeV}} \right)^4 \quad (2.69)$$

With C_{grav} , one could change the decay length of the NLSP such that its decay occurs within the volume of the detector such that the resulting photon is delayed. This gives a unique signature for discovering SUSY in hadron colliders as photons produced from SM interactions are prompt. In a simple GMSB model such as the SPS8, where the neutralino is the NLSP and gravitino is LSP, figure (??) show the kinematic properties and neutralino proper decay length distribution for the neutralino and its decayed photon in different parameter choices. The HepMC class in CMS Software (CMSSW) is used to measure and an exponential distribution as the one in (2.65) is fitted on the decay length distribution to extract its proper decay length as produced in the MC generation.



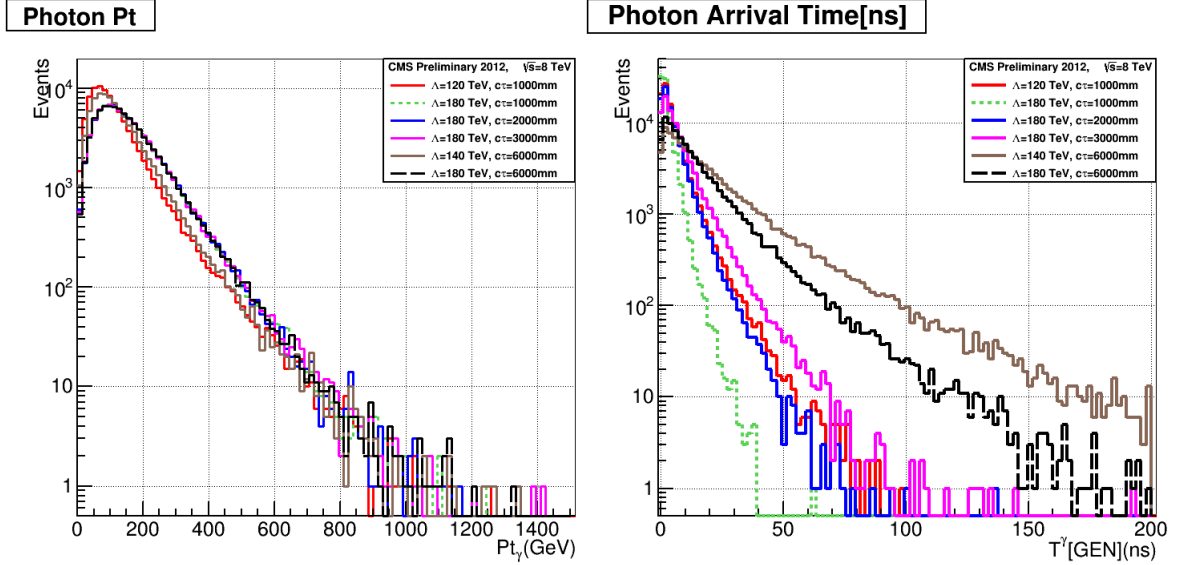


Figure 2.3: Neutralino transverse momentum distribution(top left) and proper decay length(top right) with its decayed photon transverse momentum distribution(Bottom right) and time of arrival at ECAL(Bottom right) for GMSB SPS8 model.

2.3.2 Advantages in Search for Long-Lived Particles

Finding answers to fundamental questions such as the following: What is the origin of neutrino masses, Why are there only 3 types of leptons and quarks? Where do all the parameters in SM come from? Other big questions include: What is Dark Matter (DM)? is DM made of particles? Can one detect these particles? Why is there so much asymmetry between matter and anti-matter in our universe? Is there some energy scale or early epoch in the evolution of the universe where all the fundamental forces behaved as a unique kind of force. Do baryons such as the proton exist forever? What is the lifetime of the proton? What is Dark Energy (DE)? Is the Universe expanding indefinitely? Are there other Universes? provide added impetus to search for particles BSM. We believe that the discovery of a long-live particle which are not known to exist within the current SM will provide unique access to understanding physics BSM and making measurements which can provide answers to most of the above questions. Searching for LL neutral particles decaying to photon using timing gives us a unique advantage compared to other experiments as we expect very limited background process

contribution from SM. Most of our background will be detector originated contributions. Infact, our search using lifetime gives us a wide range of search techniques depending on the lifetime of the LL particle ranging from quantitative measurements to statistics. The figure below shows the wide variety of techniques which can be used to search for LL particles in general.

ADD figure of techniques for Searches using LL (2.70)

Using equations (2.67), precise measurement of fundamental parameters in SUSY or new physics can be archived. Another advantage is that, the our search for neutral particles is unique in that a lot of previous searches been performed for charged particles but very limited for neutral LL particles since DM is speculated to be made of stable neutral particle(s) with long lifetime, we might as well go for DM. We also use lifetime because no particle with lifetime $\gtrsim 10^{-7}$ s and mass $\gtrsim 1.5$ GeV has been found and obviously because our detector has a very good timing resolution as can be seen in the section of the CMS detector in this thesis.

There have been previous attempts to search for quasi-stable neutral massive particles but all the search results show no evidence for neutral particles with long lifetime. The challenge with such an experiment is that neutral particles cannot be studied using conventional magnetic spectrometer as they are not affected by magnetic field because they are charge (local U(1) gauge symmetry) neutral. Nevertheless, there are countless theoretical as well as observational reasons why studying these particles using novel experimental techniques is very important in the field of particle physics. Some of these reasons will emerge naturally as we see in the subsequent sections below.

Motivation from Theory.

Physics BSM can be summarized to answering three major theoretical questions: Is there a reliable explanation behind the ordering in mass of SM particles as observed? This is the Hierarchy problem. Is there a single theory which can provide a derivation for all the numerous parameters (19) in the SM and also unify all the fundamental forces of nature? Grand Unified Theories (GUT). What is DM and Dark Energy (DE)? (DE is the stuff that is responsible for the accelerated expansion of our universe). And finally

being a particle physicist it is only natural to ask if DM is made up of particles and if yes, Can one construct a model which can consistently describe DM as is already the case with visible matter in SM?

Most of the efforts in the last decades in theoretical particle physics has been to find answers to the above questions.

Motivation From Experiment and Observation

As early as 1956 Reines and Cowan[?] observed that when a neutron decays into a proton and an electron, an elusive particle called neutrino is also produced. The observation of neutrinos was later incorporated into the SM. In the formulation of the SM, the neutrinos are considered massless. However, recent results from experiments [?] have shown that neutrinos of different flavours can oscillate or mix into one another. The only way they can do this is if they have a tiny but finite mass. Recent experiments measuring the different neutrino flavours and their mass difference point towards the existence of a much larger theory that can incorporate the existence of neutrino masses and the observed phenomenon of neutrino mixing in which the SM is embedded in it and can be understood as a low energy version of a much broader and deeper theory.

Galactic and supernovae observations using the Hubble and a host of other telescope as well as results from Baryonic Acoustic Oscillation (BAO) and WMAP reveal unique matter content of our universe. In addition to these cosmological observations including galaxy profiles, cluster formation, large scale structure formation and Cosmic Microwave background (CMB) power spectrum can be somehow explained by DM [?]. These observation reveals about 25% of our universe is made of DM with the current DM relic density is measured to be However, the question of "What is DM?" remains a very interesting one to both the particle physics astronomy society. Understanding DM and the rest of our universe will be crucial for future developments in high energy physics from both theory and experimental fronts. A possible property of DM is that they must be made of up long lived neutral particles. There are candidate particles from SUSY which have these properties. A few of these include lightest neutralino ($\tilde{\chi}_1^0$) and gravitino (\tilde{G}). From the GMSB point of view, because gravitinos are stable, neutral and very weakly interacting; they are seen as good candidates for the particles which

make up DM.

2.4 Previous Experiments and Results

The hunt for the discovery of DM and new particles, has led to several experimental search for neutral long-live particles decaying to photons. Obviously, negative results from these experiments has led to the putting limits of the lifetime, mass and cross section of possible existence of SUSY particles in different models of SUSY. Results from experiments(DO, CDF, CMS and ATLAS)[?, ?] in the search for Neutralino NLSP decaying to photon and gravitino and interpreted within the Snowmass Point and Slop (SPS)8 benchmark[?] scenario with parameter set be seen in figures 2.3(a) and (b). These results show that within the SPS8 model, neutralinos with mass $m_{\tilde{\chi}_1^0} \leq 245$ GeV and proper decay length $c\tau_{\tilde{\chi}_1^0} \leq 6000$ mm cannot exist at hadron colliders and thus their existence has been excluded.

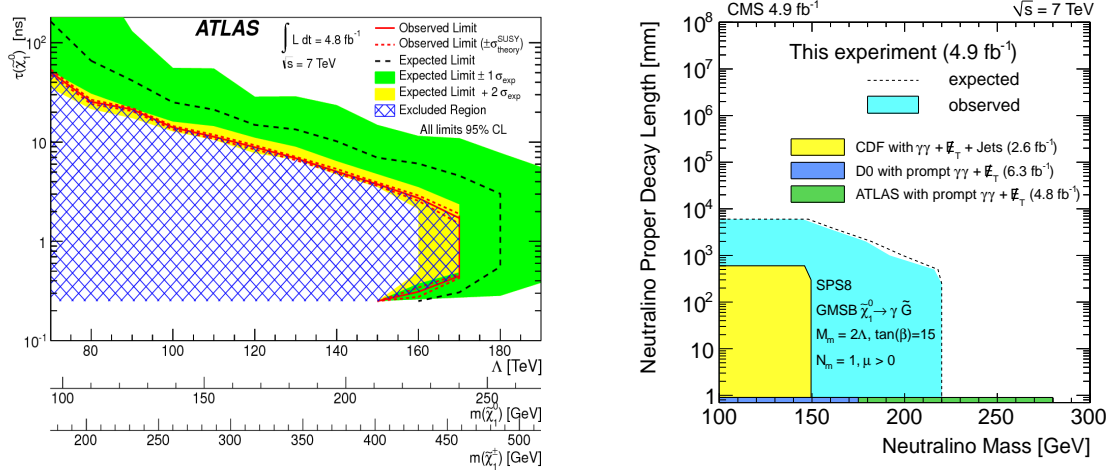


Figure 2.4: Neutralino lifetime and mass upper limit from ATLAS(left) and CMS(right) 7 TeV analysis with non-pointing photons and MET.

Chapter 3

Hadron Collider and Detector

This section describes the particle accelerator and detectors that are used to produce and detect particles at colliders. The first section describes the particle accelerator while the following section describes the CMS detectors with emphasis to those sections which are directly relevant to this analysis. A detailed description of the LHC and detectors can be found in [21] and [?].

3.1 Large Hadron Collider

3.1.1 Overview

The Large Hadron collider (LHC) is a proton-proton and heavy ion collider designed to achieve a center of mass \sqrt{S} energy of 14 TeV. It is hosted and controlled by the European Organisation for Nuclear Research (CERN). Unlike linear colliders, the LHC is a circular collider with nearly 27 km in circumference located at the border between France and Switzerland. It is designed to smash protons and ions against each other controlled by powerful magnets at officially four main locations. At each major collision point are multi-purpose particle detectors ranging from A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) both non-fixed target detectors, A Large Ion Collider Experiment (ALICE) for colliding heavy ions and finally Large Hadron Collider beauty (LHCb), a fixed target experiment for investigating the properties of B-Hadrons. We give a full description of the important parts of the LHC in the following subsections,

detail discussion of other interesting parts can be found here [21]. There are three main steps prior to colliding protons or ions at the LHC. The first is ramping up the energy of the beams followed by squeezing the beams at interaction points(CMS or ATLAS) and finally remove the separator bumps that are formed by local corrector magnets. Thus our description of the LHC will follow this three stages.

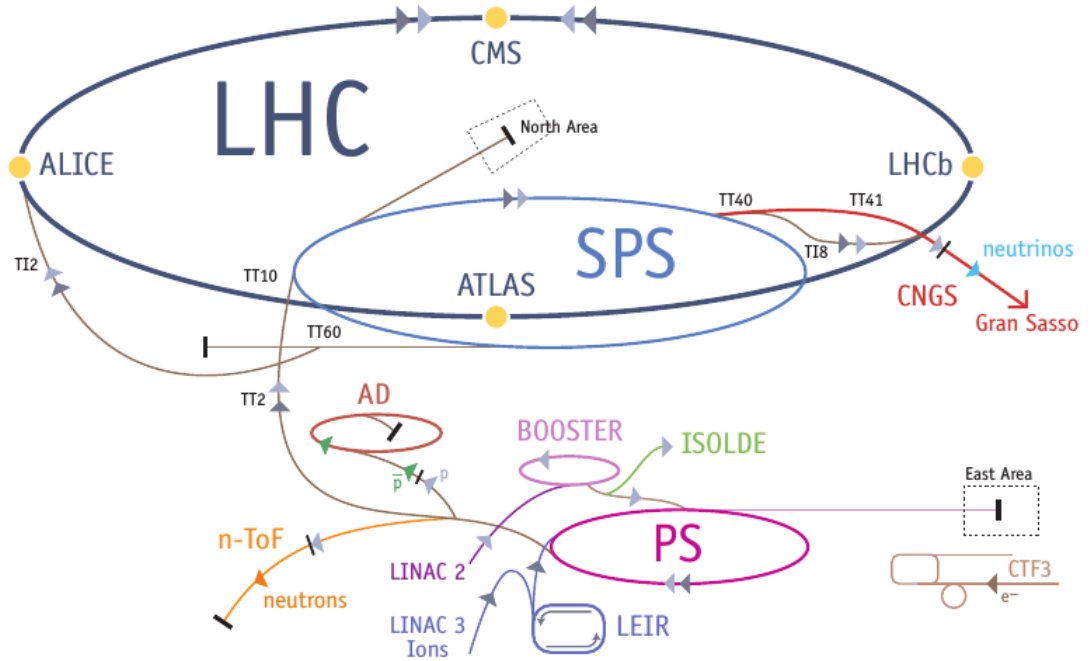


Figure 3.1: Schematic diagram showing the full Large hadron Collider. Image taken from [22]

3.1.2 Colliding Energy

Hydrogen gas is inserted into a linear accelerator called Linac2 where they are stripped off of their orbiting electrons to become hydrogen ions or protons. Under the influence of electric fields, these protons are accelerated to an energy of 50 MeV creating a stream of particles called *particle beams*. These beams are arranged in packets known as *bunches*. Particle acceleration is provided through the use of Radio-Frequency (RF) cavities containing electromagnetic fields which oscillate at a particular frequency. The protons surf this electromagnetic fields and are group in troughs of the electromagnetic

waves called RF *buckets*. The circular nature of the synchrotron accelerator ensures that the protons pass many times through a cavity and during each time their energy can be slowly increase to reach the design energy. The 50 MeV protons from the Linac2 are injected into the proton synchrotron Booster (PSB). The PSB accelerates the protons to up to 1.4 GeV and inject them into the Proton Synchrotron (PS) which pushes the protons energy to 25 GeV. These protons travelling at 99.93% the speed of light are sent to the Super Proton Synchrotron (SPS) and accelerated to an energy of 450 GeV. They are finally transferred into the LHC ring(both in a clockwise and anti-clockwise direction) and accelerated for about 20 minutes to their nominal energy of 7 TeV. As this point these protons are travelling with the speed of 99.9999% the speed of light. Powerful magnets are used to keep the beams travelling in the circular LHC ring. The advantage of circular particle colliders such as the LHC over fix target colliders is that, the energy available to make new particles called the center of mass energy denoted as \sqrt{S} is simply the sum of the energy of the two beams i.e $\sqrt{S} = E_{\text{beam1}} + E_{\text{beam2}}$ compared to $\sqrt{E_{\text{beam}}}$ for fix target experiments. In the case of the LHC, each beam is designed to have energy of 7 TeV and that makes $\sqrt{S} = 14$ TeV. Although in circular collider, an accelerating charge particles like the proton would loose energy in for the form of radiation which is inversely proportional to the mass of the charge particle to the fourth power requiring the need for continuous addition of energy after each turn to maintain the beam energy to a stable value. Since the proton's mass is about 0.938 GeV which is close to 1 GeV, this lost of energy is not very significant unlike electrons whose mass of about 0.000511 GeV making their energy lose through radiation more and thus less preferable to use as the main particles for a circular hadron collider. However, the debris of particles produced when electrons collide is much less compared to that of hadrons making analysis in a hadron collider more challenging.

3.1.3 Luminosity

Luminosity is the measurement of the number of collisions that can be produced in a collider per squared area per second. This is known as the instantaneous luminosity and it is related to the cross-section(a probabilistic measure of the possibility of a given collision process happening) through the equation:

$$N_{\text{events/sec}} = \text{Luminosity} \cdot \text{Cross Section} \quad (3.1)$$

where the luminosity \mathcal{L} is related to the total integrated luminosity (delivered luminosity over time) $L = \int \mathcal{L} dt$ and is defined in terms of accelerator (assuming round beams and equal values of beta function) parameters as:

$$\mathcal{L} = \frac{1}{4\pi} \cdot (f_{\text{rev}} n_b N_b) \cdot \frac{N_b}{\varepsilon_N} \cdot \frac{\gamma}{\beta^*} \cdot \mathcal{R}(\theta_c, \varepsilon, \beta^*, \sigma_z) \quad (3.2)$$

where N_b is the number of particles per bunch, n_b is the number of bunches, f_{rev} is the revolutionary frequency, $\gamma = E/m_p$ is the relativistic factor, ε_N is the normalised beam emittance which along with β^* , the value of the amplitude or beta function at interaction point, determines the size of the beam. \mathcal{R} is the geometrical reduction factor arising from the fact that the beams do not collide head-on but at a non-zero angle called the crossing angle or "*Piwnski angle*" ($\phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$). This effect is known as the *hour-glass effect*. From the above definition (3.2), it is evident that keeping the emittance (meaning particles in beam are confined to a small distance and have nearly the same momentum) means the likelihood of particle interaction will be greater and thus higher luminosity. However this is often not easy to archive as increasing the beam energy means reducing the beam emittance. The normalized emittance ε_N is often used as its dependence on beam energy is a squared root dependence. In the same way, lower beta values implies the width of beam is narrower or properly "*squeezed*" at interaction point resulting to an increase in number of collisions hence higher luminosity. This squeezing of depends on the quadrupole magnet configuration and powering. In addition to low beam emittance and lowest value of beta function at interaction point (β^*), one can also archive higher luminosity by using high population bunches (N_b) and collide them at high frequency.

Luminosity Measurement

Obviously using equation (3.2) to determine the instantaneous and integrated luminosity would involve a lot of uncertainty in the measurements of about 20-30%, as there are so many parameters whose value need to be measured precisely in a normal LHC operation. Rather specialised LHC runs known as "*Van der Meer Scans*"[?] are used to calibrate

specialized equipments used for determining luminosity. The method employed by CMS is using the Hadronic Forward (HF) calorimeter to make luminosity measurements. Using production rates or cross sections of well and precisely calculable processes and rewriting (3.2) as:

$$\mathcal{L} \equiv \frac{Rate_{tot}}{\sigma_{tot}} = \frac{\mu n_b f_{rev}}{\sigma_{tot}} \quad (3.3)$$

where $\mu = \langle N_{tot}/n_b \rangle$ is the *average number of interactions per bunch crossing*. CMS keeps track of "recorded" and "delivered" luminosity. Delivered luminosity refers to the luminosity delivered by LHC to CMS and one would expect this to be equal to the amount recorded. However, there are instances where the CMS detector is unable to take data either because the data acquisition chain (DAC) is busy or one of the CMS sub-detectors is temporarily down. Part of my job as a sub-detector expert during CMS data taking of LHC Run 1 was to make sure that the period of temporal unavailability of the ECAL sub-detector is as minimal as possible.

Figure 3.2: Recorded luminosity by CMS detector and LHC delivered luminosity in days/months during LHC Run 1 2012 operation.

3.1.4 Superconducting Electromagnets

The LHC design and operation uses a total of 9593 powerful magnets of different types for different purposes. Since there are two beams of protons running in clock-wise and anti-clock wise directions, the LHC uses an ingenious technique design of the magnetic field in every dipole magnet generates a vector field \mathbb{B} in each pipe pointing in opposite direction to that of the other but both always perpendicular to the beam directions. The Lorentz or magnetic force acting on the protons in both pipes always point towards the center thus keeping the beams in circular motion. In circular accelerators as the LHC and its smaller synchrotron rings, given the accelerator radius, R , the beam energy p is determined by the strength \mathbf{B} of the magnetic field. This can be easily understood using the Lorentz force such that $p[TeV] = 0.3\mathbf{B}[T] \cdot R[km]$. The LHC is a 26.659 km in circumference machine using powerful dipole magnets with magnetic field strength of about 8.33 Tesla(T) are 7 TeV to keep the protons circulating in their curved path or orbits. The LHC operates using superfluid helium for heat transport at 1.4 K(-271.3 °C)

temperature to prevent these near 1232 dipole magnets, 858 quadrupole and 6208 correcting magnets from overheating due to the energy stored in these magnets. Conventional magnetics aren't convenient for modern particle accelerators with high center of mass energy for both performance and economic reason. Rather, superconducting magnets made with modern technology using niobium-titanium (Nb-Ti) filaments strands or cables are used to provide the high magnetic field required.

Quadrupole electromagnet and correcting magnets are used to keep the particles in the beam and archive the required focus and de-focusing needed. At interaction point, the quadrupole magnets are held symmetrically around the beam pipe to help squeeze the proton beams to very low values of beta function thus ensuring that many particle collisions as possible necessary for higher luminosity.

3.1.5 Timing

The Large Hadron Collider (LHC) is designed to collide proton-proton (pp) bunches every 24.95 ns at designed luminosity. This means, the distance between each proton bunch is about 7.5 m compared to the nearly 100 m of optical fibre length which is required to transport readout information from the very front end electronics on the detectors to the back end electronics at Point 5 for processing. It is therefore imperative to have a data synchronisation system for the trigger and readout systems of the LHC experiments in order that events from every proton-proton collision are properly assigned to the particular bunch crossing (BX) which produced them. The LHC is equipped with a Timing, Trigger and Control (TTC) system with a bunch clock frequency of 40.07897 MHz whose function is to distribute synchronized LHC time to all the detectors including CMS. Timing synchronisation in the LHC is achieved using a Beam Synchronous Timing (BST) system which distributes timing using the LHC revolution frequency(at 11.246 kHz) or LHC orbit and the RF bunch crossing frequency(40.07897 MHz at 7 TeV). Thus, the LHC fast timing signals from the RF generators of the machine and orbit signals are distributed from the Preveessin Control Room (PCR) through single-mode optical fibers(about 10.1 km in length for CMS) to all LHC experiments, test beam areas, beam instrumentation around the ring and the SPS transfer lines. At CMS counting room, the LHC clock and orbit signals are recovered in the TTC Machine Interface crate (TTCmi) and later distributed to the Trigger

Control and sub-detector master TTC crates. All Level1 (L1) trigger and Data Acquisition (DAQ) pipelines are driven with a 24.95 ns cycle clock locked to the LHC machine clock. The phase difference between the LHC 40 MHz clock and the arrival of detector signals from collision to the front-end electronics must be determined and adjusted for and monitored. The determination and assignment of pulses to bunch crossings depends critically on this initial clock phase adjustments and stability. This amplitude or pattern(also known as trigger primitives) for each trigger and bunch crossing is transmitted to the regional trigger logic in digital form every crossing and is synchronised with the LHC clock. Each trigger primitive digital data is then assigned to clock cycle in a process known as bunch crossing assignment. a Detail expert description of LHC unified timing distribution system can be found here [23, 24, 25, 26].

LHC Operation Parameters 2010-2013				
Parameter	2010 value	2011 Value	2012/13 Value	Design Value
Beam energy[TeV]	3.5	3.5	4.0	7
β^* in IP 5[m]	3.5	1.0	0.6	0.55
Bunch spacing [ns]	150	75/50	50	25
Number of bunches	368	1380	1380	2808
Protons/bunch	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalised emittance[mm.rad]	≈ 2.0	≈ 2.4	≈ 2.5	3.75
Peak luminosity[$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	3.7×10^{33}	1×10^{34}
Evts/bunch crossing	4	17	37	19
Stored Beam energy(MJ)	≈ 28	≈ 110	≈ 140	≈ 362
Int. Luminosity by CMS[pb^{-1}]				-
Circumference[km]	26.659	26.659	26.659	26.659
Dipole Magnet B[T]	8.33	8.33	8.33	8.33

Table 3.1: The LHC operation parameter conditions during RUN 1:2010-2013

LHC Bunch Structure

An LHC orbit is made of about 3564 *bunch* places. However only 2808 are occupied with protons. The bunch structure is archived by breaking a continuous proton beam

into pulsed beam of separate bunches using an electromagnetic field with oscillating frequency of 400 MHz(LHC ring) in the SPS and LHC RF cavity. Thus each bunch is in an RF bucket. Each RF bucket has an energy against time profile as can be seen in figure below. The LHC filling scheme is arranged such that not all RF buckets have proton bunches. Thus there are empty buckets or beam gaps with missing bunches. These gaps are necessary to make room for the rise/fall times at SPS/LHC injection and ejection and abort kickers magnets during say LHC beam dump. The time separation between two buckets/bunches filled or unfilled is about 2.5 ns. Filling and acceleration at each RF cavity point is performed so that there are about 10^{11} protons/bunch. However, during filling and eventual bunch splitting at the PS, it is possible that some empty buckets are filled with a much smaller proton population compared to the main bunch. These less proton populated buckets can be $\Delta t = 2.5, 5.0, 7.5, \dots$ ns, trailing the main bunch labelled as Beam1 or Beam2 otherwise leading the main bunch with $\Delta t = -2.5, -5.0, -7.5, \dots$ ns. If these less populated bunches are 2.5 ns spaced in time from each other, they are referred to as *Ghost* bunches and if 5.0 ns, they are referred to as *satellite* bunches see figure (3.3).

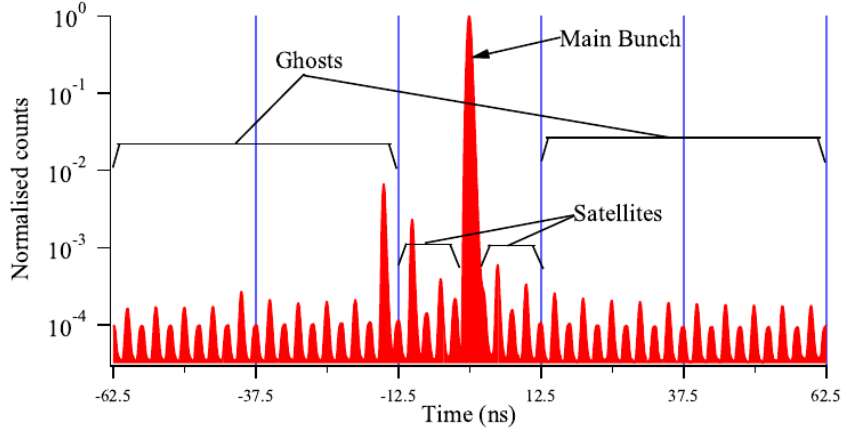


Figure 3.3: Longitudinal Profile taken with LDM detector showing definition of Ghost/Satellite bunches with respect to main bunches.

The presence of ghost/satellite bunches increase the uncertainty in LHC luminosity measurements and can also generate proton-proton interactions in the collision region. Effects on ghost/satellite bunches on instantaneous luminosity measurements have been

studied by both CMS, ATLAS and ALICE detectors [?] with their profile compared to main bunch bunches. CMS uses energy deposits in the endcap calorimeters with time space equivalent to those of ghost/satellite bunches while in ATLAS, they have also introduced a new detector called the Longitudinal Density Monitor (LDM) to study ghost/satellite bunches. The results are shown in the figure (3.4).

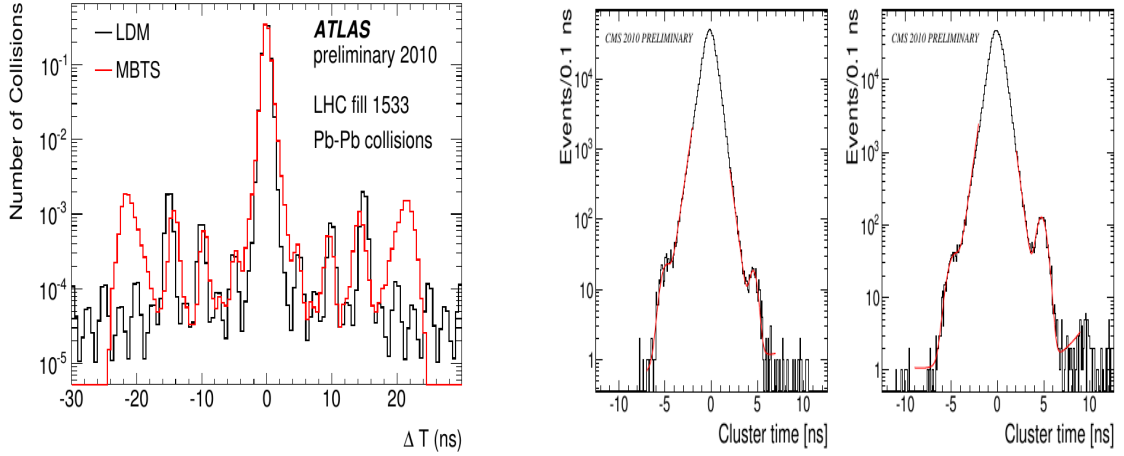


Figure 3.4: (left) Arrival time distribution(red) of ATLAS MBTS for LHC fill 1533 during 2010 Pb-Pb run and LDM profile(black) for Beam2(same for Beam1). (Right) Timing of Clusters in the CMS endcap calorimeters for fill 1089:Left: EEP detector(left side of IP $z < 0$) Right: EEM detector(right side of IP, $z > 0$). NB: Plots taken from [27] and [28]

There is the possibility that ghost/satellite - ghost/satellite and ghost - Beam1/Beam2 collisions will happen generating events at the CMS detector. This is a major background in the search for delayed photons or objects in general as these collisions can occur *in-time*(Beam1- Beam2) collisions or *out-of-time* collisions. It is thus imperative to be able to quantify this contributions in any search analysis. We will show in future studies we have performs to both "*guestimate*" and quantify these contributions in our search analysis.

Beam Halo

In addition to ghost/satellite bunches generating collisions events during collision, protons in ghost/satellite bunches can interact with collimators or gases such as H_2 , CO_2

and others in the beam pipe leading to the production of high energy muons which later bremsstrahlung and shower directly in the calorimeter detectors. Main bunches due to betatron oscillations (departure of particles from nominal orbit in the transverse direction) can also through inelastic scattering with gas molecules in beam pipe about 550 m up from interaction point (IP) (since beam cleaning is not being 100% efficient), scattering on tertiary collimators (TCT) about $z = 150$ m from IP and beam dump at about 150 m upstream CMS detector, produce through cascade decay energetic muons (sometimes muons with about 1 TeV) which bremsstrahlung in calorimeter detectors.

This kind of background from beam is referred to as *Machine Induced Background* (MIB) or *Beam-Induced Background* (BIB) and its contribution is called non-collision backgrounds as these are events observed in the detectors but not produced from the interaction point (IP). Throughout these thesis, we will refer to this kind of events as *Beam Halos or halos*. Because, they produce very high transverse momentum photons which can also be miss-identified as jets arriving in-time or out-of-time, they are a very important background in any analysis. In the later section, we will also show how we have developed new methods to identify and reject these kind of events and estimate its possible contribution to our analysis.

3.2 Compact Muon Solenoid

3.2.1 Overview

The goal of the Compact Muon Solenoid (CMS) detector is to identify particles by measuring their energies, momenta and track if applicable, as they pass through the detector. It is for this reason that the CMS apparatus is a general purpose particle detector operating about 330 feet underground at point 5 (P5) LHC in CERN, France. Its main feature is a superconducting solenoid of 6 m internal diameter providing a field of 3.8 T necessary for good momentum resolution. This field encloses an all-silicon pixel serving as a vertex detector and a strip tracker for charged particle track reconstruction, a lead-tungstate scintillating-crystals electromagnetic calorimeter (ECAL) and a brass-scintillating sampling hadron calorimeter (HCAL). Very long lived particles like muons are measured in gas-ionization detectors embedded in the flux-return iron-yoke located

at the outermost section of the detector. It has a simple cylindrical structure consisting of barrel and endcap detectors and an extensive forward calorimetry and detectors to provide a near 4π solid angle assuring good hermetic coverage. The CMS apparatus has an overall length of 21.6 m, a diameter of 14.6 m, and weighs 12,500 tonnes.

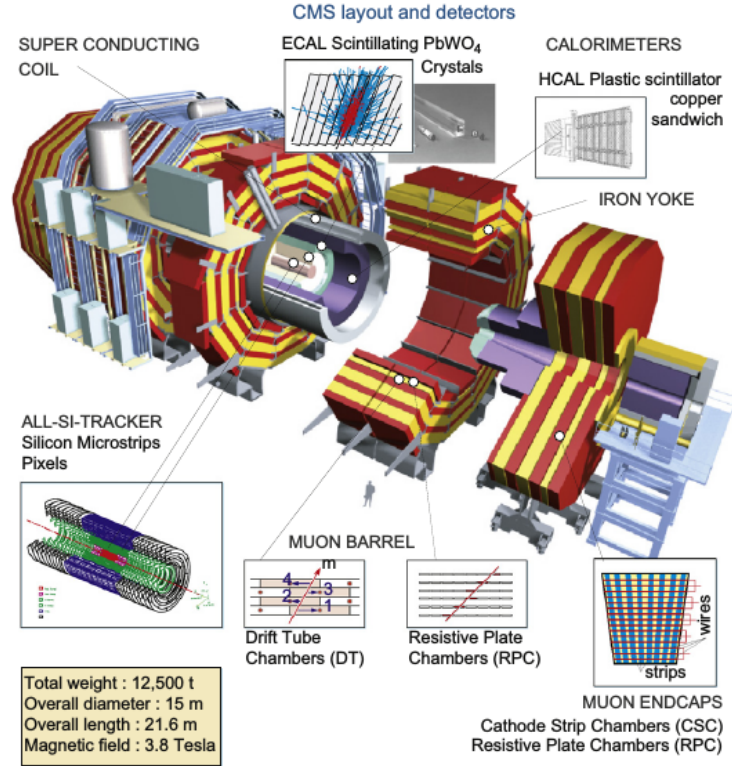


Figure 3.5: CMS Detector showing the different subdetectors and their material.

The CMS detector performance can be summarised as seen in table (3.2.1) with the material type in each sub-detector.

CMS Detector and Resolution			
Subdetector	Quantity	Resolution	Uses
Tracker	Momentum[GeV/c]	$\sigma_T/p_T \approx 1.5 \times 10^{-4} p_T + 0.005$	Silicon Pixels and Strips
ECAL	Energy[GeV]	$\sigma/E \approx 3\%/E + 0.003$	PbWO ₄ Crystals
ECAL	Time[ns]	$\sigma(\Delta t) = \frac{N}{A_{eff}/\sigma_n} \oplus \sqrt{2\bar{C}}$	PbWO ₄ Crystals
HCAL	Energy[GeV]	$\sigma/E \approx 100\%/E + 0.05$	Brass + Scintillator
Muon Chambers	Momentum[GeV/c]	$\sigma_T/p_T \approx 1\% \quad 50 \text{ GeV to } 10\% \quad 1 \text{ TeV}$	inner tracker + Muon Systems
Magnetic field	B-field strength[T]	3.8 T + 2 T	Solenoid + Return Yoke
Triggers	On/Off-line	Levels	L1(On-line) +HLT(Off-line)(L2+L3)

Table 3.2: CMS Detector Material and Resolution(Time resolution: $N \approx 35 \text{ ns}$, $\bar{C} \approx 0.020 \text{ ns}$ [?])

The CMS uses a coordinate system where the origin coincides with the center of the detector also known as the nominal collision or interaction point (IP). The direction of x , y , and z -axis with the z -axis pointing towards the Jura Mountains from P5 are shown in figure (3.2.1). A more convenient coordinate system used in expressing quantities of particles is the polar coordinates. Here, the CMS uses the azimuthal angle ϕ measured from the $x - y$ plane with $\phi = 0$ being the x -axis and $\phi = \pi/2$ the y -axis. The radial distance in this plane is denoted R and the polar angle θ measured from the z -axis is related to the *pseudo-rapidity*, η through the relation:

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

. The co-ordinate system (η, ϕ, z) and its radial distance R defines a point in the CMS detector whose volume is a cylinder.

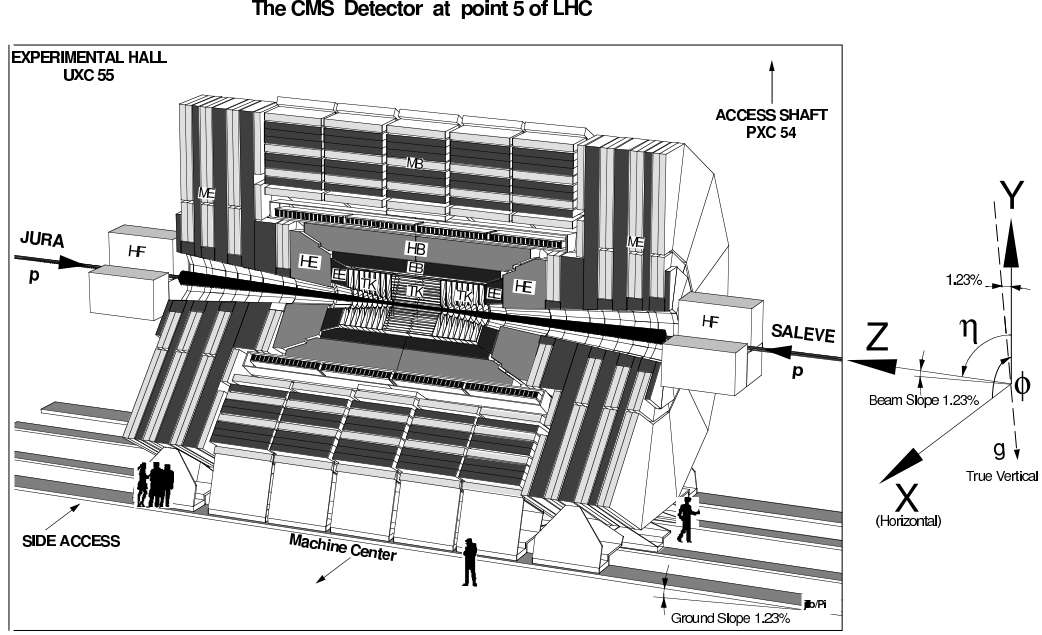


Figure 3.6: Schematic diagram of CMS detector view showing definition of coordinates as used by CMS.

In CMS, quantities such as *transverse momentum* (p_T), *transverse energy* (E_T) and *transverse missing energy* (E_T^{miss} or MET) are used to distinguish a particle's quantities in the transverse plane($x - y$ coordinate) from those along the longitudinal direction(z coordinate) or beam line. In addition to these transverse quantities, cone-like structure with the cone radius is defined as

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

are used to measure the distance between two objects in the $\eta - \phi$ plane. These cone-like structures are used for particle isolation and identification purposes. In the next sections, we describe the characteristics and functionality of each of the CMS subdetectors introducing some additional details for those used in our analysis.

3.2.2 Tracker

Particles produced from proton-proton collision traverse the tracker sub-detector first. The job of the tracker is to measure the trajectory of charged particles, which are curved because of the magnetic field produced by the magnetic coils. By measuring the curvature of these particles, the particle's momentum can be measured and its charge determined. The tracker is a silicon based detector and thus operates under the concept of ionization. It occupies a volume of 2.4 m in diameter and 5.4 m in length, consisting of pixel and strip sections geometrically arranged in cylindrical layers of barrel and disc-shaped endcaps, enclosed within the calorimeters. These sub-detectors all sit inside the 6 m in diameter solenoid magnet operating at 3.8 T. Figure (3.7) depicts a schematic picture of the tracker with three barrel layers covering a region of radius from 4 cm to 15 cm in radius and two endcap discs within 49 cm on either side of the collision point along the z axis; ten barrel layers and twelve endcap disks per side of silicon strip detectors covering a region with radius from 15 to 110 cm and within 280 cm on either side of the LHC beam axis. The total tracker acceptance region in pseudo-rapidity is $|\eta| < 2.5$. The pixel detector is used for identifying the primary and secondary vertices of particles while the inner tracker of strip detector is for tracker reconstruction.

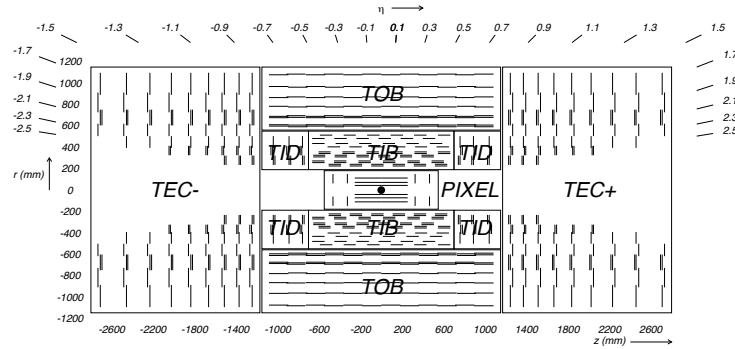


Figure 3.7: Schematic diagram of CMS Tracker showing the silicon pixel detector region (inner closer to LHC beam) and silicon strip detector region (outer).

Pixel

The pixel vertex detector occupies the inner most region, very close to the interaction region. Providing high-resolution and three-dimensional patterns of space points using

silicon pads as pixels, the primary vertex and secondary vertices arising from the decay of heavy and relatively long-lived particles such as B-mesons containing b-quarks can be identified. This is also known as impact parameter measurements. The pixel covering a region of pseudo-rapidity $|\eta| < 2.4$ compliments the track finding by providing additional space points to seeding hits in the inner tracker. Each pixel has a size of $100 \times 150 \mu\text{m}^2$ covering a total area of $\approx 1 \text{ m}^2$ and there are 66 million pixels read out by 16000 readout chips on the silicon sensors. The pixel is organised in three 53 cm long barrel layers (Pixel Barrel=PXB), positioned at radii of 4.4, 7.3 and 10.2 cm and two disks each per side (Pixel Forward=PDF), placed at ± 34.5 cm and ± 46.5 cm from the interaction point and covering a radii between 6 and 15 cm. This guarantees each charged particle track crosses at least two layers of pixels. This arrangement ensures that the pixel detector provides precise tracking points in the $r-\phi$ and z responsible for small impact parameter resolution of about $\sim 15 \mu\text{m}$. Small impact parameter resolution is important for precise secondary vertex reconstruction and position resolution crucial in the identification of objects produced with displaced vertices with life-time of about $\tau \approx 10^{-12} \text{ s}$ like mesons such as $B^{0,\pm}$, $D^{0,\pm}$, τ^\pm , which may travel a distinguishable distance ($c\tau \approx 100 \mu\text{m}$) before decaying. Because of very high radiation dose of about 100 Mrad absorbed by the pixel detector, there is currently upgrade of the complete pixel detector in preparation of LHC Run 2.

Silicon Strip Tracker

CMS silicon inner tracker surrounding the pixel detector allows for the tracks of promptly produced charged particles with $p_T = 100 \text{ GeV}/c$ to be reconstructed with a resolution in the transverse momentum p_T of about $\sim 1.5\%$. High momentum particles are less curved by the magnetic field than low momentum particles. Therefore, the tracker works complimentary with the calorimeter and muon detectors to ensure improve momentum resolution at all particle energies. The silicon micro strip tracker covers a tracking volume up to radius of 1.2 m with a length of 5.6 m. It is organised in three parts: The inner tracker with four barrel layers (Tracker Inner Barrel=TIB) and three disks per endcap (Tracker Inner Disks=TID), 6 outer barrel layers (Tracker Outer Barrel=TOB) closed by 9 wheels on both sides. (Tracker EndCap=TEC). The silicon strip is made of 15148 silicon microstrip detector modules. Each module has a set of sensors. It occupies

an active area of 200 m^2 providing a coverage in pseudo-rapidity up to $|\eta| < 2.5$. The TIB/TID delivers up to 4 $r - \phi$ measurements on a trajectory using $320\text{ }\mu\text{m}$ thick silicon micro strip sensors arranged parallel to the beam direction in the barrel and radial on the disks. The strip pitch is $80\text{ }\mu\text{m}$ on layer 1 and 2 and $120\text{ }\mu\text{m}$ on layer 3 and 4 of the TIB, leading to a single point resolution of $23\text{ }\mu\text{m}$ and $35\text{ }\mu\text{m}$, respectively. The TID also have varying pitches with both the TIB/TID enclosed by the TOB. The layering structure can be seen figure (3.2.2). The nearly 9.6 million silicon strips provide a spatial resolution measured to be about $10\text{ }\mu\text{m}$ for $r - \phi$ measurement and about $20\text{ }\mu\text{m}$ for z measurement necessary for particle trajectory reconstruction. The combined pixel and micro strip modules allows for nearly 75 million readout electronic channels in the tracker.

3.2.3 Calorimeter

A calorimeter is a device which absorbs a good fraction of energy of an incident particle and produces a signal with an amplitude proportional to the energy absorbed. This absorption is via a cascade production of secondary particles where the incident energy is directly proportional to the number of secondary particles. CMS uses two types of calorimeters: Electromagnetic calorimeters (ECAL) for absorbing the energy of electromagnetic particles such as photons and electrons and a sampling calorimeter or Hadronic calorimeter (HCAL) made of more than one type of material for absorbing the energy of hadrons such as kaons and pions through hadronic interactions. The combined calorimeter detectors of CMS covers a region in $|\eta| < 5$ making it nearly hermitic for missing energy measurements. The ECAL and HCAL are arranged in a layered manner as seen in figure (3.2.3) such that electromagnetic particles can be distinguished from hadronic particles by comparing the depth of the particle shower penetration in both calorimeters.

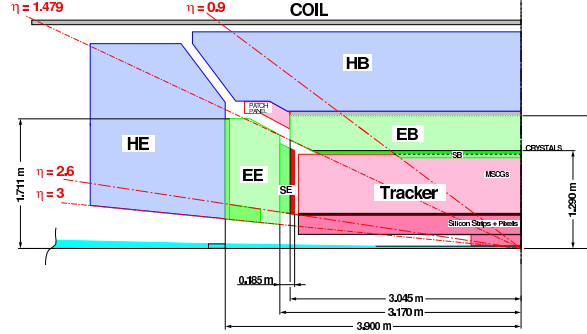


Figure 3.8: Schematic diagram of CMS calorimetry system with HCAL enclosing ECAL in the Barrel and Endcap regions.

Electromagnetic Calorimeter

The main particles to detect using ECAL detectors are photons and electrons. High energy photons and electrons are detected through their interaction with the material of the ECAL detector. During this interaction which can be either through electromagnetic showering also known as *bremsstrahlung* or electron-positron pair production, the incoming photons or electrons deposit practically almost all of their energy. The material for the CMS ECAL detector are lead-tungstate (PbWO_4) crystals. There are 75848 lead-tungstate (PbWO_4) crystals mounted in a barrel (EB) and endcap (EE) structure. PbWO_4 crystal is the appropriate choice for calorimetry by CMS for operation in the LHC environment because of its a high density (8.28 g/cm^3), short radiation length ($X_0=0.89 \text{ cm}$) and a small Molière radius (22 cm). This dense nature allows for the electromagnetic shower to develop early and therefore very likely to be fully contained within a compact device. In a high radiation dose and fast timing (25 ns bunch spacing) environment like the LHC, the choice of PbWO_4 crystals is justified because of their high radiation resistance and short scintillation decay time of the same order of magnitude as the LHC bunch crossing time: about 80% of the light is emitted in 25 ns. Since the ‘amplitude’ or ‘probability’ of a high energy photon or electron interacting with an ECAL material through (*Bremsstrahlung*) and pair production is proportional to the nuclear charge or number of electrons, Z of the material, PbWO_4 which is a high Z material is once again CMS preferred choice for calorimetry. The small Molière radius of PbWO_4 crystals ensures that on average about 95 % of the electromagnetic shower

energy is contained within the crystal volume therefore reducing the transverse spread of the electromagnetic cascade arising from multiple scattering of electrons. This improves on the estimation of the transverse position of impact of the incident particle and the fine granularity provides good precision for measuring the energy of an incoming electromagnetic particle and thus better energy resolution.

The barrel section of the ECAL covers a pseudo-rapidity of $|\eta| < 1.479$. The EB has 61,200 crystals providing a granularity of 360-fold in ϕ and (2×85) -fold in η . The crystals are mounted in a quasi-projective geometry to avoid cracks aligned with a particle trajectories, so that their axes make an angle of 3% with respect to a line vector from the nominal interaction vertex in η and ϕ directions. These EB crystals have approximately 0.0174×0.0174 in $\eta - \phi$ or $22 \times 22 \text{ mm}^2$ at the front face and $26 \times 26 \text{ mm}^2$ on the rear face. Each crystal is 230 mm long corresponding to about 25.8 X_0 radiation length. The crystals are contained in a thin-walled aveolar structure made with aluminium called submodule with their radial distance from the center of the face of the crystals to the beam line is 1.29 m. Each submodule are arranged into 4 modules of different types according to their η position with each module having about 400 to 500 crystals. The four modules make one supermodule containing 1700 crystals. The aluminium surface is coated to avoid oxidation hence coloration which causes decrease in transparency. On the rear end of each EB crystals, is glued two Avalanche Photodiodes (APD) whose purpose is to collect the scintillating light from the crystals converting light into current which is further collected by the read-out electronics. The endcap sector occupy a pseudo-rapidity region of $1.479 < |\eta| < 3.0$ with Preshower (ES) detector made of silicon strip sensors interleaved by lead placed immediately in front of it. The purpose of the preshower detector is to help separate converted from unconverted photons. There are two endcaps located in the $+z$ side of the nominal interaction and denoted EE+ and on the $-z$ side denoted as EE-. The longitudinal distance between the nominal interaction point and the center of the surface of the crystals in EE is 3.154 cm. Crystals in the EE are of identical shape group in units of 5×5 crystals called *supercrystals or SC*. Each endcap is divided into two halves called *Dees* with each Dee holding 3662 crystals. The crystals are arranged in $x - y$ grid with their front face and rear cross section of $28.62 \times 28.62 \text{ mm}^2$ and $30 \times 30 \text{ mm}^2$ respectively. Each crystal is 220 mm ($24.7 X_0$) in length. Vacuum Phototriodes (VPT) is glued on the

rear face of each crystal for scintillating light collecting and conversion into electrical signals. These photodiodes and triodes are used because of their high gain and the fact that they are not affected by the high magnetic field. Although the light-yield for PbWO_4 is rather low (≈ 70 photons/MeV), the photodiodes have internal gain (50 for APDs and 10 for VPTs) and good quantum efficiency of 75 % for APDs and 20 % for VPTs of the emission wavelength. This makes it possible that signals from incident particles with energies from a few to high GeV can be recorded. APDs and VPTs are the standard choice of photo-detectors by CMS because of their high resistance to radiation and smooth operation in a strong magnetic field environment. Photodiodes like APDs and VPTs are similar to silicon photodiodes, with the exception that they have a buried p-n junction reversed-biased at a very high electric field. The photo electrons arriving at the junction undergo avalanche multiplication giving the device a gain. The signals from the APDs and VPTs are digitized by voltage-sensitive analogue-to-digital converters are later converted to light signals which are then transported using long optical fibres to the counting room located adjacent to the experimental cavern. The energy resolution and geometric structure of the ECAL ensures that the photon or electron's arrival position at ECAL, energy and time and even the direction and shape of its electromagnetic shower in the crystals can be measured and identified respectively with good precision.

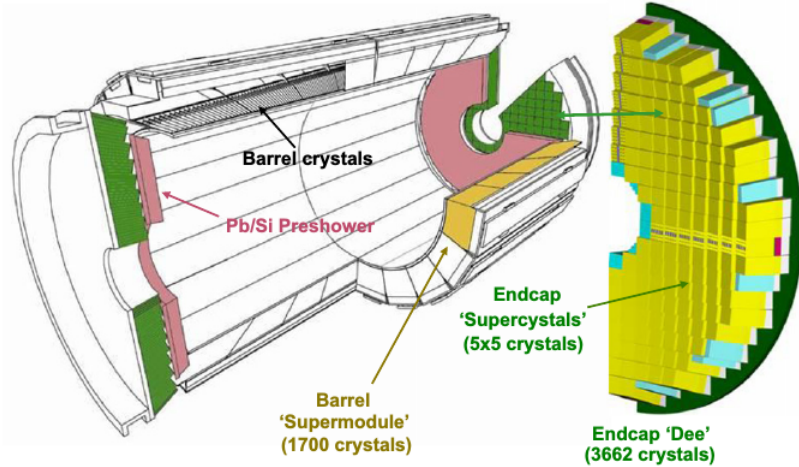


Figure 3.9: Layout of the CMS electromagnetic calorimeter showing the arrangement of crystal modules, supermodules in the barrel with the preshower in front of endcap with supercrystals.

Hadronic Calorimeter

Hadrons like protons, neutrons kaons and pions are unlike electromagnetic particle strongly interacting (strong force is the force that binds nuclei together). A hadronic shower is formed when an incident hadron undergoes an inelastic collision with the nucleus of the absorber material producing secondary hadrons which as they go through successive layers of absorber material interact inelastically with other nuclei to produce further hadrons etc. The hadronic cascade loses about 30 % of incident hadron energy through nuclear excitation of the nuclei of atoms of the absorber material. Hadronic showers start to develop later with more lateral spread and are larger in the longitudinal dimensions than electromagnetic showers. This is why the hadronic calorimeter (HCAL) is made of alternating plates of brass and plastic scintillator encompassing the ECAL. The scintillating light is readout using wavelength shifting optical fibres by photosensors in the barrel and endcap. The photosensors are hybrid photodiodes (HPD). There are ongoing upgrades to replacing the HPDs with silicon photon multipliers (SiPM). The hadronic barrel (HB) and hadronic endcap (HE) of the HCAL cover a region in pseudo-rapidity of $|\eta| < 3$. While the Hadronic Forward (HF) occupies a pseudo-rapidity region of $3 < |\eta| < 5$. The HB calorimeter is an assembly of two half barrels each composed of 18 identical 20° wedges in ϕ . Each wedge is made of flat brass alloy absorber plate parallel to beam axis with the innermost and outermost layers made up of stainless steel interleaved by plastic scintillating tiles. The first active layer is situated directly behind the ECAL in order to actively sample low energy showering particles from the support material between the ECAL and HCAL. Each scintillating tile has a size of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ and is instrumented with a single wave length shifting fiber (WLS) for better collection of light. The summed optical signals or light are converted into fast electronic signals by photo-sensors called hybrid photo-diode (HPD). This inhomogeneous design gives the HCAL, an energy resolution of $\Delta E/E \approx 0.5/\sqrt{E(\text{GeV})}$ for particles with energy above 250 GeV, much lower compared to that of homogeneous ECAL detector.

The forward hadronic (HF) calorimeters placed upstream have scintillating tiles called Beam Scintillation Counters (BSC) which in coincidence with the beam pick-up monitors (BPTX) detector helps to eliminate beam background contamination at the trigger level and is also useful for detection of hadrons in the forward region. HF

made up of steel absorbers embedded in radiation hard quartz fibers running parallel to the beam axis and providing a fast collection of Cherenkov light. The signal results from Cherenkov light emitted in the quartz fibres embedded in the steel matrix in response to charged particles. The Cherenkov calorimeter have long and short fibers which are positioned alternatively separated by 5 mm with readouts for better sampling of the different shower components. The goal of this hardware design is to give better compensation for different shower components in the hadronic shower. The HF section enables the HCAL to pick up myriad of particles coming out of the collision point. Quartz fibre has high resistance to the high radiation dose in the forward detectors and light production is through Cherenkov method than scintillation in HB and HE calorimeters.

The purpose of the HF detector is to provide a full hermetic 4π phase space coverage required for missing transverse energy calculation or MET. MET is the established as signal for very weakly interacting particles like neutrino and supersymmetric particles like gravitino which travel through the detector undetected. For $|\eta| < 1.74$ region, the HCAL cells are 0.087×0.087 rad in pseudo-rapidity(η) and in azimuth (ϕ). In the (η, ϕ) plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 ECAL crystals arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of $|\eta|$, the size of the towers increases and the matching ECAL arrays contain fewer crystals. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies subsequently used to provide the energy and direction. The ratio of the energy deposit if a particle in the ECAL crystals to that in the HCAL towers is used to distinguish between true photons from neutral hadronic showers.

3.2.4 Muon Chambers

Muons are long-lived particles capable of travelling across the entire lateral section of the CMS detector into the muon chambers producing tracks in the tracker and depositing very little fraction of their energy in the calorimeters. The muon chambers use ionization and the magnetic field from the return iron yokes to curve the tracks of charged long-live particles like muons, measuring their momentum and finally detecting them. There are three different types of muon chambers: the drift tubes (DT) chambers in the

barrel, cathode strip chambers (CSC) in the endcaps and resistive plate chambers (RPC) glued to the DT and CSC chambers. Four layers or stations of DT/RPC and CSC/RPC are embedded in an interleaved style with the iron yoke for track reconstruction and triggering. Figure (??) provides a longitudinal view of the CMS detector showing the position of the stations. The DT and CSC record track segments characterised by the position of the track and the bending angle which is used to determine the precise transverse momentum and charge of a given particle during off-line reconstruction. The RPCs are dedicated trigger chambers used to determine the candidate muon's approximate transverse momentum and bunch crossing number where the particle originates. The RPC has a timing resolution of about 3 ns.

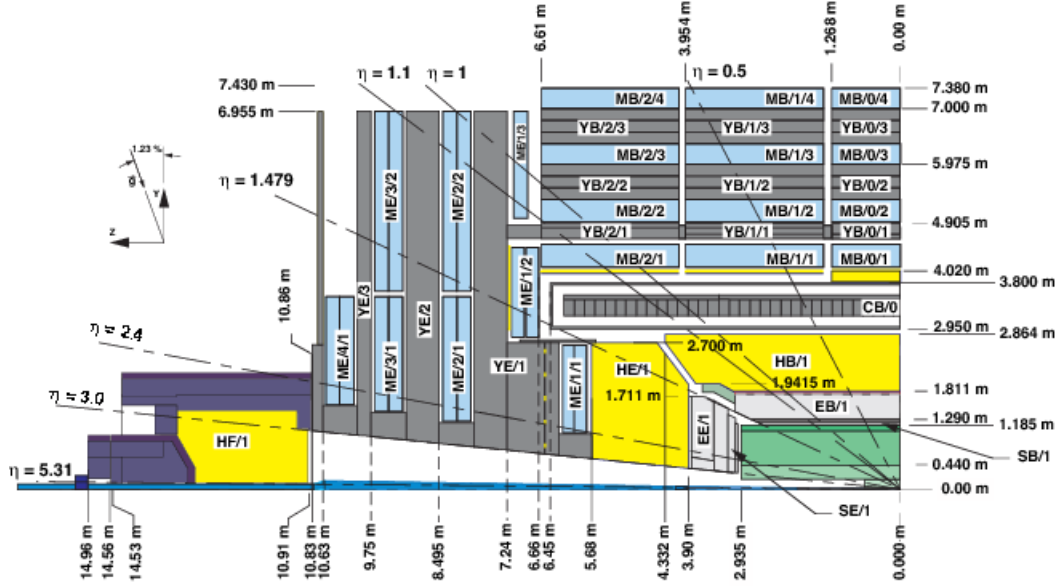


Figure 3.10: Longitudinal view of CMS showing the coverage range of its sub-detectors.

3.2.5 Particle Detection

Particle types that are identified using the CMS detector include electrons, photons, hadrons, muons, neutrinos and other weakly interacting particles. These particles depending on their charge, nature of interaction and lifetime can be identified either using some or all the sub-detectors of the CMS detector. The figure (??) show a transverse slice of the CMS detectors with tracks in the tracker and muon sub-detectors and calorimeter energy deposit showing how different particles interact with the material in

different sub-detectors thus ensuring their unique identification and reconstruction in the detector.

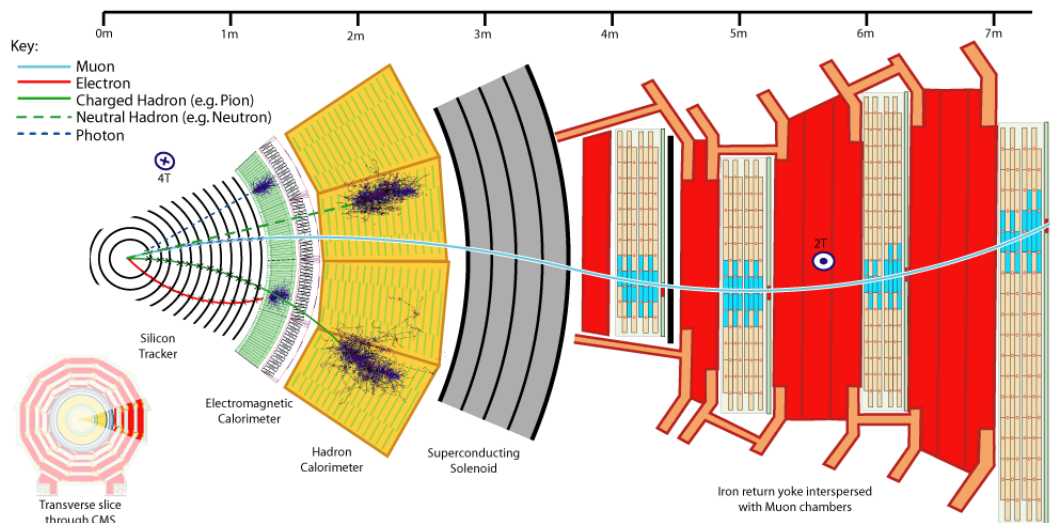


Figure 3.11: Transverse slice of the CMS detector showing how different types of particles interact and hence identified using this detector.

3.2.6 Triggering

In CMS, there are a billion interactions happening every second which means data from protons colliding 40 million times every second equivalent to the 25 ns LHC bunch crossing time interval has to be process and analyse before the next collision happens. Obviously this is impossible and infact, not every proton-proton collision will lead to the production of an interesting physics event. Thus one has to find a way of selecting only events produced from head-on proton collision with sufficient amount of energy. Even with this selection, it is not possible to process a single event in a 25 ns time frame. Thus, the CMS uses a two level triggering system for selecting interesting events and a pipeline system to temporarily store and process information from many interactions at the same time. Thus so as not to confuse particles from two different events, the CMS triggering system has a very good timing resolution and synchronization so that signals from millions of electronic channels and synchronised and identified to be produced by the same event. The CMS triggering system consist of two layers: The Level-1 (L1) and High Level Triggers (HLT) triggers. L1 triggers are hardware designed electronic

system while HLT is a farm of more than 1000 standard computers running the HLT event selection algorithm. Thus event selection begins at the L1 and HLT triggers. The L1 trigger electronics is implemented in FPGA and ASIC technology and consists of a calorimeter, muon trigger and a global trigger boards. The global trigger board makes the final decision based on the calorimeter and muon triggers to reject or keep an event for further processing at the HLT trigger. The L1 trigger is responsible for selecting the best 100,000 events each second from the initial 1 billion events from interactions happening every second. The pipeline system is used during the L1 trigger latency time of about $3.2 \mu\text{s}$. The HLT trigger using assimilated and synchronised information from different parts of the detectors recreates the entire event. The HLT runs complex algorithms relating to physics objects like matching tracks to hits from the muon chambers or energy deposits above a certain threshold in the calorimeters without tracks for electromagnetic objects. By the time this selection process is complete, there are now only 100 events per second with the remaining 99,900 thrown away. With the average event size of about 1 Megabyte, in a stable and effective LHC proton collision year or 10^7 seconds, the CMS produces about a Petabyte of data which is stored in tapes for later offline analysis. Due to the large amount of data, such analysis is performed using clusters of computers geographically connected to each other in a virtual computing environment called the LHC Computing Grid (LCG) to which the CMS is a member. This data is made available to 7 primary and later to secondary tier centres consisting of national research laboratories and universities around the world using a data transport system termed Physics Experiment Data Export (PhEDEx).

Chapter 4

Timing Reconstruction and Calibration

The time of an electromagnetic object such as a photon is extracted at the level of individual crystals called reconstructed hits (rechits). The recorded time of the photon is the crystal calibrated time where the Time-Of-Flight (TOF) as well as the time to transmit the recorded signal from the front-end detectors to the back-end readout electronics is removed such that on average the time is zero for a photon produced at the nominal proton-proton collision point and travelling at speed of light and then impinges at the surface of the crystal. There are separate algorithms for extracting and calibrating the crystals using the rechit time. This calibrated time is considered the reconstructed time (T_{RECO}). Measuring the difference in timing between any two reconstructed objects (individual crystals or electromagnetic objects) originating from the same nominal point and thus assumed in principle to have the same time give the timing resolution of the detector as well as the crystal-to-crystal synchronization factor. T_{RECO} of a photon can be defined in either of the following ways:

1. Seed Time: The time of the highest energy crystal or rechit in the highest energy basic cluster of the photon supercluster denoted as T_{SEED}
2. The Mean Time: This is the error weighted mean time of all the crystals in the

photon supercluster denoted as $T_{CLUSTER}$ or T_{MEAN} and is defined as follows:

$$T_{CLUSTER} = T_{MEAN} = \frac{\sum_{i=1}^N \frac{T_i}{\sigma_i^2}}{\sum_{i=1}^N \frac{1}{\sigma_i^2}} \quad (4.1)$$

where N is the number of crystals in seed basic cluster of photon supercluster.

4.0.7 Electromagnetic Calorimeter Readout Chain

The ECAL electronics readout system described in detailed in [41] is a light-to-light system. Energy from incoming electromagnetic objects is absorbed and converted into scintillating light by PbWO_4 crystals. This is received and converted into electrical signals by the avalanche photo-diodes. These electrical signals are digitized and finally converted back into light signals which is transported using optical fibres into the off detector electronics in the counting room at point 5. Thus one can easily classify the full readout chain of the ECAL electronics readout system as divided into an on-detector electronics and an off-detector electronics. Both electronics system are connected by a 100 m optical fibre links. A simple picture of the readout chain is shown in figFIXME:Fig readout Chain.

The on-detector electronics reads a trigger tower consisting of 5×5 crystals in $\eta \times \phi$ in barrel (EB) and *supercrystals* in endcap (EE). Five Very Front End (VFE) boards (reading out data from 5 crystals each), one Front End board (FE) two (EB) and six (EE) Giga Optical Hybrids (GOH), one Low Voltage Regulator (LVR) board and a Mother Board (MB) make up the complete on-detector electronics. Electrical Signals from the APDs (EB) are accepted by the VFE which is equipped with a Multi Gain Pre-Amplifier (MGPA), a 12-bit Analogue to Digital Converter (ADC) and a buffer. The MGPA an Application Specific Intergrated Circuit (ASIC) developed in $0.25 \mu\text{m}$ technology, pre-amplifiers, shapes and then amplifies the signals through three amplifiers with gains of 1, 6 and 12. For VPT (EE), these signals first pass through a High Voltage (HV) filter card which acts as a moderator separating very high voltages caused by the increase radiation in the EE. The full scale of the APDs and VPTs are 60 pC and 12.8 pC corresponding to $\approx 1.5 \text{ TeV}$ and $1.6\text{-}3.1 \text{ TeV}$ respectively. The full shaping of the signal takes about 40 ns. The noise for gain 12 is about $8000e^-$

for APD configuration and about $4000e^-$ for VPT configuration. The 3 analog output signals of the MPGA are digitized in parallel by the multichannel 40 MHz, 12-bit ADC. This ADCs have an effective number of bits of 10.9. The highest non-saturated signal is selected as the output signal and reported as 12 bits of the corresponding ADC with 2 bits coding the ADC number. It is possible, that when the signal is saturated and wrong signal amplitude can be produced leading to an amplitude dependence of the readout time. This effect has been studied for Gain 1 and 6 transitions and the relevant correction factors of timing produced and validated. A schematic picture of the showing the readout chain of the FE with its MPGA and ADCs showing the shaping and digitization process can be seen in figure (4.0.7).

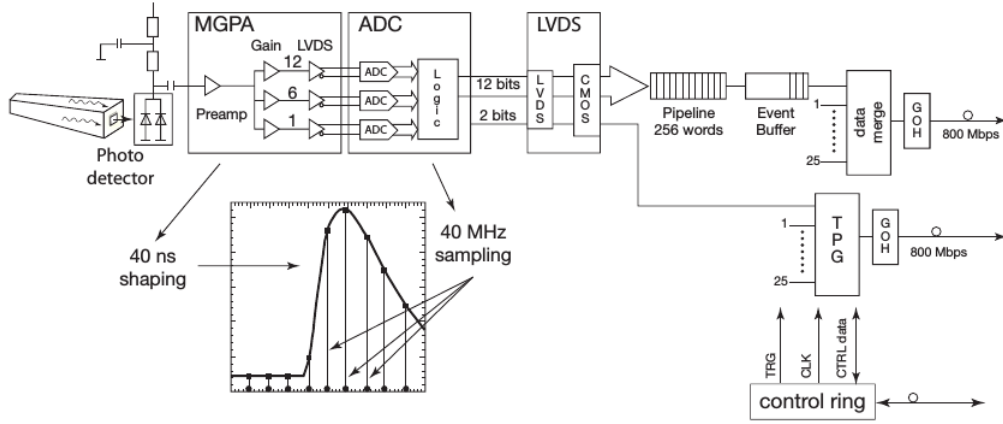


Figure 4.1: Schematic showing ReadOut Chain.

A radiation-hard buffer (LVDS) adapts a low voltage differential out put signal of the ADC to input into the FE. Signals from five identical channels are integrated and read into VFE card with a Detector Control Unit for measuring the APD leakage currents. The noise from each VFE is typically 1.1, 0.75, 0.6 ADC counts for gains 12, 6 and 1 respectively. This would be about 40 MeV for gain 12.

Digitized data from 5 VFE cards are fed into each FE through the LVDS and stored in 256-word-deep dual-ported memories called pipelines. Data pipelines can be stored for up to 128 bunch crossings. The FE is base on a ASIC called the FERNIX holding the logic to calculated the energy of 5 channels once every bunch crossing. This energy is summed in strips of 5 crystals along ϕ . Thus each VFE is serviced by a FERNIX

chip. In the case of the EE, the five strip energy sum are transported by GOH to the off-detector electronics Trigger Concentration Card (TCC) while for EB, there a sixth FERNIX which sums the five strips energy sums and calculates an electromagnetic bit which is used to identify electromagnetic shower candidates on the basis of their shower profile in a trigger tower. The trigger tower energy sums and the electromagnetic bit is transmitted to the TCC through the GOH. This process is referred to as Trigger Primitive Genration (TPG). Once a Level-1 trigger signal is received, the ten 40 MHz samples for each channel are transmitted to the off-detector electronics DCC using an identical GOH. This takes about $7.5 \mu\text{s}$. The VFE and FE cards are controlled using a 40 MHz digital optical link system and controlled by the off-detector Clock and Control System (CCS). The Off-detector electronics consist of different types of electronic boards (the CCS, TCC and DCC modules) sitting in an 18 VME-9U crates and a 1 VME-6U crate holding the Selective Read-Out Processor (SRP). This system is serving both the trigger and the Data Acquisition Systems (DAQ) paths. In the DAQ path, the DCC performs data read-out and data reduction based on flags of the SRP. While in the trigger path, at each bunch crossing, the trigger primitive generation which began in the FE is finalised and synchronised or time alignments in the TCC before transmitted to the regional calorimeter triggers. The trigger primitives each refer to a single trigger tower (25 crystal data) and consists of the summed transverse energy deposits and the electromagnetic bit charactering the lateral shower profile of the electromagnetic shower. The accept signal for accepted events is return from the global trigger after about $3 \mu\text{s}$ and the selected events are read into the data acquisition system to the filter farm where the event rate is further reduced using data from the full detector. Thus is the regional calorimeter, the ECAL trigger primitives together with the HCAL trigger primitives are used to compute the electron/photon and jet candidates as well as their transverse energy. The resulting physics objects after passing through the HLT trigger are transferred to the various tier systems for offline full event reconstruction. The ECAL also has a laser calibration systems where laser light is delivered directly to the PbWO_4 crystals using optical fibres. The laser data is used for energy and time calibration of crystals and hardware system. The crystals are energy calibrated because of the decrease in optical transmission due to the formation of color centres in the crystal. The formation of color centres is caused by irradiation. Time calibration using

laser data is also required in case of hardware timing offset especially during long short down periods of the CMS detectors.

4.0.8 Timing Extraction

The MGPA of the VFE amplifies and shapes an analogue signal from the APD/VPT of a single crystal producing a typical signal pulse as seen in figure (4.0.8).

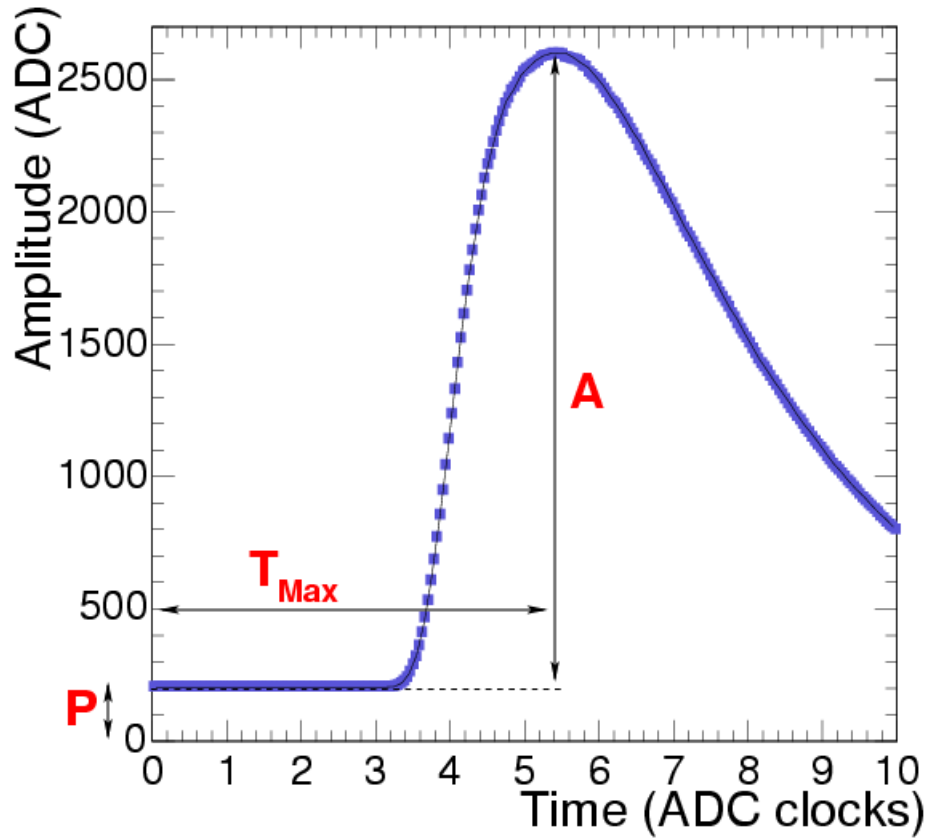


Figure 4.2: Typical pulse shape of a given signal showing signal amplitude and time.

This pulse is digitised into 10 samples by the ADC for data storage purposes. The pulse's amplitude is a measure of the energy deposited in the crystal while the time from the ADC clock with a sampling frequency of 40 MHz for 10 samples is used to extract the arrival time of the physics object depositing its energy unto the crystal. The value **P** is known as the pedestal or noise read as ADC values in the absence of

any signal. Using the 10 samples, a timing algorithm is employed to extract the time of arrival of particles to the ECAL. The goal of this algorithm is to use the maximum amplitude value of the pulse A_{MAX} , and extract its corresponding maximum value of the ADC time A_{MAX} as the time of arrival of the physics object to the crystal. Thus, ECAL timing reconstruction is defined as: Using the 10 samples of the pulse amplitude to measure T_{MAX} . Obtaining the true A_{MAX} is performed through an energy reconstruction algorithm. Extracting the arrival time is thus a matter of comparing the pulse shape obtained using the 10 samples of a scintillating channel's pulse to that of a reference shape. This reference shape is obtained from experimental measurements using Testbeam or synchronous LHC events. Figure (a) shows a distribution of the amplitude A as a function of time rather plotted for convenience as A/A_{MAX} on the vertical or y -axis and $T - T_{MAX}$ on the horizontal or x -axis. T is the time and T_{MAX} is defined as the time when the pulse reaches its maximum value, A_{MAX}

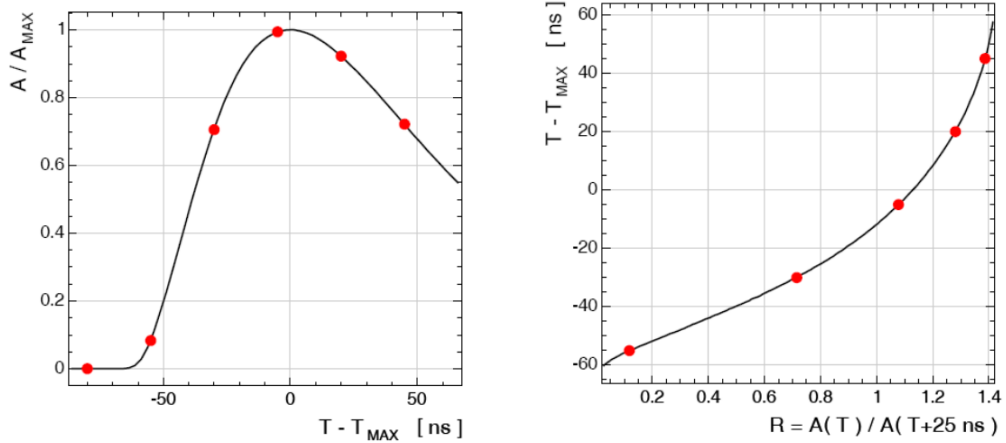


Figure 4.3: left: A measured ECAL pulse shape for each channel. Right: $T - T_{MAX}$ Vs $R(T)$ showing the distribution of $T(R)$. Solid line is reference shape or shape from testbeam while dots correspond to a 10 discrete samples corresponding to signal from a single event in a single channel or crystal.

Performing an analytical fit to compare the reference pulse shape to that from the 10 samples on the $A(T)$ distribution to obtain A_{MAX} and T_{MAX} is rather cumbersome and technically inefficient, as the amplitude of each sample depends on the pulse shape, the A_{MAX} value and also the relative position of T_{MAX} between time samples. This phase is referred to as " T_{MAX} phase". Thus, using a new variable defined as $R(T) = A(T)/A(T +$

25 ns) and instead perform an analytical fit on the distribution of $T - T_{MAX}$ Vs $R(T)$. This $T(R)$ distribution is independent on A_{MAX} and can be very well described by a polynomial of order 7. A distribution of $T(R)$ is shown in figure (4.0.8)(b) with both the four to five samples(dots) obtained from the ratio $R_i = A_i/A_{i+1}$ from each consecutive pair of samples and the reference pulse shape(continuous line). Thus each point R_i gives a quick accurate measurement of $T_{MAX,i} = T_i - T(R_i)$. The uncertainty, $\sigma_{T,i}$, on each measurement is a production of the derivative of the function $T(R)$ and the uncertainty on the value of R_i . The uncertainty on the value of R_i depends on three separate uncertainties: the noise fluctuation, σ_n of each sample, the uncertainty in the estimation of the pedestal value which is always subtracted from the measured value and the truncation during 12-bit digitization. These uncertainties are uncorrelated and can thus be added in quadrature. The reconstructed time and its error of a hit(fraction of energy deposited on a single crystal) is determine using the following equations:

$$T_{MAX} = \frac{\sum \frac{T_{MAX,i}}{\sigma_i^2}}{\sum \frac{1}{\sigma_i^2}} \quad ; \quad \frac{1}{\sigma_T^2} = \sum \frac{1}{\sigma_i^2} \quad (4.2)$$

where the sum is over all the 4 or 5 R_i ratios and the assumption is that the weights are uncorrelated.

4.0.9 Timing Resolution

Using the reconstructed timing for each channel, We can measure the timing resolution for ECAL. First, the timing resolution for ECAL can be parametrised and expressed as a sum in quadrature (uncorrelated) of three major terms accounting for the uncertainties in the timing measurement. These three contributions are: First, the noise (N) resulting from contributions from electronic noise, coherent movement of the baseline and effects due to the fact that in addition to the main or hard proton-proton collision, other soft or less energetic collisions or events are produced known as *pile up* (PU) effect. Second, the stochastic term (S) resulting from fluctuations in the photon collection time because of finite time for PbWO_4 scintillation. Finally the constant term (C) whose contribution is independent on the energy deposited but rather from effects correlated with the point of shower initiation within the crystal and systematics in the extraction of the time due to different is pulse shape for each channel. The equation for the timing resolution can

thus be expressed as shown in equation (4.3)

$$\sigma^2(t) = \left(\frac{N\sigma_n}{A} \right)^2 + \left(\frac{S}{\sqrt{A}} \right)^2 + C^2 \quad (4.3)$$

A is the measured amplitude corresponding to the energy deposited and σ_n is the intrinsic noise for individual sample with a value of ≈ 42 MeV and 140 MeV in the barrel and endcap respectively and $N = 33$ ns measured from Monte carlo simulation studies. Contribution from the stochastic term, (S) is considered small, with value of $S < 7.9 \text{ ns} \cdot \text{MeV}^{1/2}$.

To measure the timing resolution, a simple experiment was performed in which electron beams with energies between 15 GeV (GeV = Giga electron volts = 10^6 eV, 1 eV = 1.602×10^{-19} joules (J) in energy units) and 250 GeV was directed unto each crystal in a supermodule. The timing resolution measurement is obtained by extracting from the measured distribution of the difference in timing between two crystals sharing energy from the same electromagnetic shower. The advantage of this approach is that, the contribution from poor synchronisation is less as this synchronisation effects do not affect the spread but rather the average time. However, it is not blind to crystal-to-crystal synchronisation effects. Other methods used to study timing resolution is considering the timing difference between two a few group of crystals usually 5×5 crystals called basic clusters, between a complete electromagnetic shower or electron or photon.

Using equation (4.3) and neglecting the stochastic term because its contributions are negligible, the timing resolution can be expressed as:

$$\sigma^2(t_1 - t_2) = \left(\frac{N\sigma_n}{A_{eff}} \right)^2 + 2\bar{C}^2 \quad (4.4)$$

where $A_{eff} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$, $t_{1,2}$ and $A_{1,2}$ correspond to the times and amplitude measured in the two crystals and \bar{C} is their residual contribution. Measuring the timing resolution is performed by using the standard deviation of the Gaussian fit of the distribution from each slice in A_{eff}/σ_n distribution. The $\sigma(t_1 - t_2)$ against A_{eff}/σ_n of the extracted standard deviation of each slice is plotted the resulting distribution fitted to extract the noise and constant term. The results are shown in figure (??) with the noise factor $N = (35.1 \pm 0.2) \text{ ns}$ and $\bar{C} = (20 \pm 4) \text{ ns}$.

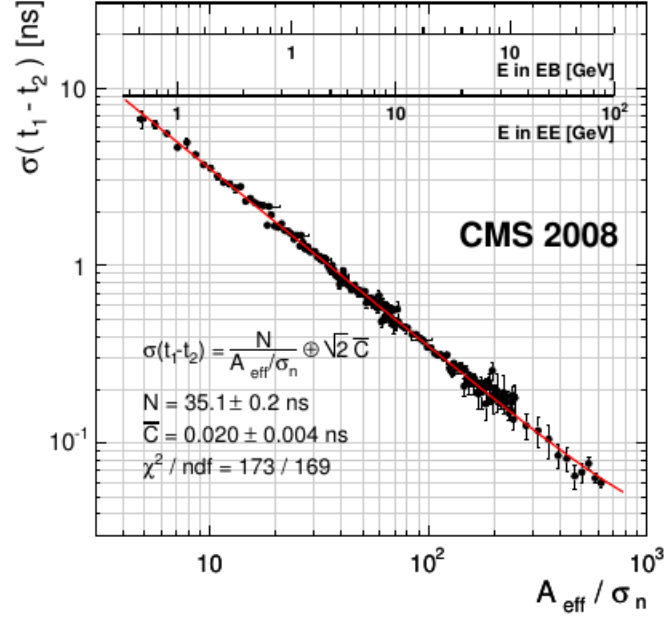


Figure 4.4: Deviation of the timing difference as a function of A_{eff}/σ_n between two crystals sharing an energy in the same electromagnetic shower obtained during electron testbeam measurements. The single crystal energy scales for barrel (EB) and end-cap (EE) is overlaid. The fitted results give $N = (35.1 \pm 0.2)$ ns and $\bar{C} = (20 \pm 4)$ ns.

A timing resolution better than 100 ps for energy values A_{eff}/σ_n greater than 400 ADC counts is obtained. This demonstrates that for a perfectly calibrated ECAL crystals and energy deposits of $E > 20$ GeV in the barrel, we can obtain a resolution better than 100 ps.

4.0.10 Timing Calibration Procedure

The timing calibration is performed such that particles travelling along a straight path with speed close to the speed of light or $\beta \approx 1$ produced from proton-proton collisions happening at the CMS luminous region or IP will arrive at the surface of an ECAL crystal with an average time of 0 ns. This means that if a particle arrives at a crystal with its arrival time significantly and positively large, then it is either because this particle is travelling with a very small velocity (slowly moving particles or $\beta \ll 1$) or it was produced with a decay path that significantly deviates from the obvious

straight path connecting the arrived at crystal to the IP or it is a particle from the decay of a temporarily stopped particle in the detector. The presence of the " T_{MAX} Phase", the difference in pulse shape between each crystal, variation in time of flight by a few nanosecond (ns) and the different intrinsic delays among channels allow for timing calibration at two separate levels. At the level of the front end electronics (FE) consisting of 5×5 crystals, one is capable of performing an initial internal timing synchronization by adjusting in steps of 1.04 ns among these crystals. Determining these values of adjustments to be made is referred to as *Hardware Synchronization*.

Offline Timing Calibration

The purpose of the offline calibration is to provide additive timing adjustments values for each channel measured from reconstructed data to account for global phase shift in timing caused by shifts in CMS clock relative to the LHC bunch crossings and de-synchronizations induced by hardware interventions occurring usually during detector repairs. The global shifts due to drifting in CMS clock relative to LHC bunch crossings can be about 1 ns while that caused by hardware intervention can be about 3 ns. The calibration constants obtained for each crystal or channel are the negative values of the average time measured from the reconstructed hits of each crystals. These crystals are kept in XML files which are then loaded into the online configuration database holding the hardware settings. The calibration procedure is as follows: first identify the existence of a timing shift occurrence using either the CMS or ECAL detector running electronic (e-Log) book or the CMS or ECAL data acquisition monitoring (DQM) results. Second, if there is a timing shift, use reconstructed crystals hits or rechits from very recently produced data to measure the calibration constants for each channel. Finally deploy the validated calibration constants in an XML format file into the online configuration database for reprocessing of CMS full datasets to be used for physics analysis. This process is repeated over and over until the entire LHC proton-proton collision period each year. At the end of each calibration process, the set of calibration constants developed for the hardware settings within a period of time is referred to as having an *interval of validity or IOVs*. The amount of data used in measuring the timing constants is defined by the amount of event statistics available and covers a particular CMS events run range. During the entire LHC run period of 2011, a total of 17 IOVs

were developed while during 2012 LHC run, a total of 44 IOVs were produced. The raw dataset used in producing the calibration constants are mostly ECAL crystals hits from Level-1 triggered events with loosely triggered electromagnetic objects including a photons, electrons and hadrons with larger electromagnetic proportions called *ElectronHad* or *PhotonHad*. These event rechits must pass the following selection criteria: The event time (an average over its rechits) must be smaller than 5 ns. Event rechits must belong to a basic cluster (cluster of about 5×5 crystals) with transverse energy of atleast 2 GeV. The signal amplitude must not be lower than 26(47) or 100 (in year 2012) ADC counts for rechits in EB(EE) corresponding to an energy of about 1(3) GeV respectively. The reconstructed rechit time must be within 5(7) ns window in EB(EE) respectively and to reduce the presence of anomalous crystal hits, the ratio of the sum of energies of the north, south, east and west neighbouring crystals excluding a crystal with the highest energy to that of the energy of the highest energy crystal must be greater than 5% or equivalently $1 - E_4/E_1 < 0.95$. This variable is known as the *swiss-cross* variable and it is very useful for rejecting events with anomalous crystal energy deposits. The selected rechits are used to make a timing distribution for each channel and if each channel has at least 10 rechits, the average time measured represents the timing calibration constants or inter-calibration coefficient to be applied for correction while the spread or variance represents the spread in this measurement. For channels with less than 10 valid rechits, the average time of all the other channels is assigned to them as their inter-calibration coefficient. validation of these constants is obtained by applying the negative value of these constants to the same or a different set of events and varying that the measured average over rechits per channel is 0 ns to within the accuracy of the calibration method and event migration in the event sample. The event migration effects are of the order of 10 ps. The figures in figure (4.0.10) shows a two dimensional distribution of the channel mean time for each crystal for all the 61,200 crystals in the EB and 1468 crystals in EE. Its shows the mean timing distribution prior to calibration and after the measured calibration constants have been applied. The full IOVs produced for the entire LHC runs 2011 and 2012 can be found here [?].

Figure 4.5: Distribution of channel timing calibration constants prior to calibration and after calibration for crystals in EB and EE.

Hardware Timing Calibration

Amplitude Dependence Timing Corrections

4.0.11 Electromagnetic Calorimeter Timing Performance

The time performance of the ECAL crystals is studied and validated using events with a Z decay i.e $Z \rightarrow e^-e^+$.

The main idea is to use two reconstructed "objects" which in principle should have the same time and then use their time difference as a measure of the timing performance. We:

1. use two crystals within the same electron super cluster.
2. use the two electrons from the Z decay.

In using electron super clusters, we considered following additional contributions to the electron time:

1. The bending of the electron path due to the presence of the 3.8 T magnetic field of the CMS detector.
2. Displaced collisions because "partons" (subparticles) in the protons of the proton-proton (p-p) bunches did not collide at exactly the collision point or Nominal Interaction point (IP).
3. The collision developed over the full duration of the overlap of the proton bunches.

The Time-Of-Flight (TOF) of the electron from the IP is considered in the time calibration algorithm of the ECAL crystals. Indeed, one assumption of using photons to time calibrate the ECAL crystals is that, they travel with the speed of light and so on average the time taken for a photon to travel from the IP until it impinges on the crystal surface is on average 0. With this assumption true only for Nominal Collisions i.e collisions originating from the IP and travelling straight to the ECAL crystals.

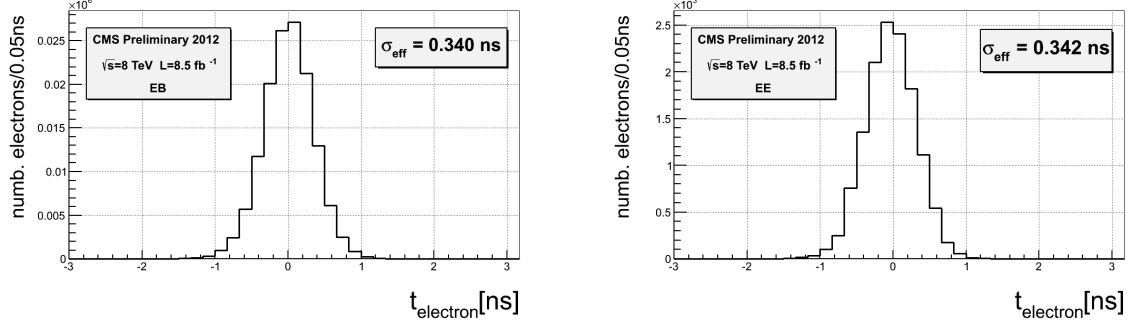


Figure 4.6: Ecal absolute time of a single reconstructed electron in $Z \rightarrow e^-e^+$ decay. The electron time is the seed (crystal with highest energy deposit) time of the electron. (a) in EB and (b) in EE

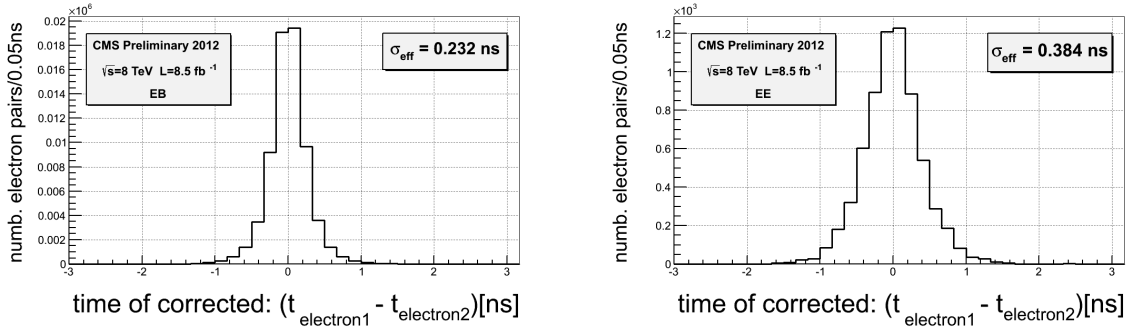


Figure 4.7: Ecal time difference between the two reconstructed electrons in $Z \rightarrow e^-e^+$ decay. The electron time is the seed (crystal with highest energy deposit) time with additional correction due to the time of flight of the electron. (a) in EB and (b) in EE

Table 4.1: Table Comparing Timing Resolution performance of 2011 Vs 2012

Chapter 5

Particle Identification and Event Reconstruction

5.1 Particle Reconstruction

We describe the reconstruction of events as done in CMS focusing on photons, electrons, Jets and Missing Transverse energy as these are the objects we study in this thesis. or electrons in the ECAL.

5.1.1 Supercluster Reconstruction

Electron reconstruction is based in the following sequence. We begin with supercluster (these are clusters of clusters) reconstruction followed by track seeds which are generated by producing pairs of pixels hits tightly matched to a cluster pair. This is known as the supercluster driven approach. The electron trajectory is built using an algorithm which builds the electron trajectory based on pixel hits. This trajectory is then fitted to get the best tracked matched to supercluster using an algorithm called the Gaussian-Sum-Filter (GSF). Only one track is matched to a super cluster and from the fitted tracks we extract its momentum and combining this with the cluster's energy through an electron algorithm we are able to reconstruct an electron called the GSFElectron. Pre-selections are applied at the level of track seeding and clusters so as to reject tracks from underlying or low energy proton-proton collision events called Pile Up (PU).

Electron reconstruction is done at track seeding stage using two major algorithms:

- Tracker driven Seeding: more suitable for low p_T electrons as well as better performance for electrons inside jets.
- ECAL driven seeding: starts by reconstructing ECAL clusters of clusters ("Super-clusters") of transverse energy $E_T > 4 \text{ GeV}/c$ and optimised for isolated electrons with some p_T range relevant for the mass of Z or W down to $p_T 5 \text{ GeV}/c$.

There are lots of good reason to study photons in a hadron collider. These reasons range from detector as well as physics as in the recent discovery of the higgs boson. However, the challenges to study photons are enormous. First photons don't leave any tracks in the tracker to the only way one can measure them is through their energy deposits in crystals in the ECAL and it is not possible to tell from which vertex point did this energy deposit came from. Another major challenge is that there are Jets everywhere in the detector arising from partons(quarks and gluons) fragmenting under QCD with a reasonable proportion of neutral and electromagnetic components also depositing energy in ECAL making the jets look more photon-like. An additional challenge come from high p_T electrons which will undergo the process of Bremsstrahlung and produce photons as these electrons interact with the tracker material sitting immediately in front of the ECAL crystals. Some contributions may arise from muons interacting with this tracker material through multiple Coulomb interaction, however, most of the times these contributions are small and can be easily modelled using Gaussian fluctuations. The electron Bremsstrahlung photon emission is highly non-Gaussian and can only be modelled from the tracker point of view using the Kalman Filter (KF) and a Gaussian-Sum Filter (GSM). To overcome, these challenges, the photon reconstruction and identification is built to get the best estimate of the photon energy and discriminate against as much jet background as possible.

5.1.2 Photon or Electron Reconstruction

EM object reconstruction is begins with clusters of energy deposited in the ECAL. Clusters of Cluster called superclusters are used to reconstruct electrons and photon and also jet objects.

5.1.3 Jet Reconstruction

5.1.4 Missing Transverse Energy

5.2 Using Timing in Particle Identification

Timing of an event is extracted from the energy supercluster deposited on the scintillating crystals of the ECAL. Using the seed crystal(basic cluster with highest energy), we can extract the time of arrival of a particular event as well as predict the vertex origin of the event and then use this to distinguish between events that occur within the LHC bunch collision called prompt events(photons) from events that arise from a new massive particle decaying into either photons

5.3 Anomalous Signals

Neutrons and charged hadrons such as protons may by pass the PbWO_4 without scintillating and striking and thus directly ionizing the silicon of the APDs to produce anomalous signals. These kind of events produced large isolated energy deposits thus are referred to as "punch through" events or "spikes". Because of the lack of scintillation, they appear much earlier (negative) in Ecal time and often populate the earlier time of the rechit time distribution. Their energy deposit ranges from a few GeV to ECAL saturation energy of ≈ 1.7 TeV. Since they do not electromagnetically shower in PbWO_4 , their electromagnetic energy shower shape is very isolated, meaning only one or two crystals may make up their energy cluster. Spikes may also have positive time and thus appear late or delayed in their arrival at ECAL which is seen in the tails of the rechit time distribution. Their late arrival time is due to the slow propagation of neutrons through the CMS detector. A lot of test beam, collision data and simulation study has been performed to study and analyse the characteristics and rejection of spikes as seen in here [42]. As a result, most of the results presented in this thesis are taken directly from [42] or redone for 2012 dataset which this analysis is based upon. It has been observed through studies using minimum bias data set(highly populated with neutrons and charged hadrons) at different center of mass energy, that the number of spikes increases with the proton collision rate as well as the charged tracks per event

i.e there is a strong linear correlation between spike rate and the center of mass energy of pp collision. The reason for this is because more neutrons and charged hadrons with enough energy are produced which "punch through" the APD and produce hikes in the rechit energy profile as read from the APDs. It is understandable that spike production is most common in the barrel compared to the endcap. Thus with increases rate of proton collision and $\sqrt{S} = 8$ TeV, it is imperative to have robust variables which can identify and reject spikes in the barrel in this analysis. The above studies show that variables defined using timing and EM energy deposits are reliable. Other variables using the timing pulse shape and EM shower profile can be use in addition to identify and rejects spikes with efficiency of 90 to 95%.

Rejection of spikes is done at online(CMS Level-1 trigger level) as well as offline and analysis level.

At online, the strip Fine-Grained Veto Bit(sFGVB) is set to 0 or 1 use to flagging an object as either a spike or a good event respectively. A detail of this can be found in [43]. For example if the sFGVB is set to 0 and the trigger tower(5×5 crystals) transverse energy is below 12 GeV, the energy deposition is considered spike-liked and the corresponding tower will not contribute to CMS triggering of that event. The sFGVB was implemented in 2011 data taking process and was measured to reject over 95% of spikes with transverse energy greater than 8 GeV (12 GeV) in 2011(2012). The figure **Figure of sFGVB** shows the difference between an good EM-cluster and a spike-like cluster at sFGVB level.

At Offline, variables making using of the single(at times double) channel(crystal) energy deposit and early arrival time of spikes are defined. In figure **Figure of Swiss X and Rechit Time**, we show the difference between spikes and normal events energy clusters explaining the variables used to identify spikes in the offline. The topological variable constructed as $1 - \frac{E_4}{E_1}$ also known as "Swiss-cross" where E_1 is the energy deposit of the central(highest energy) crystals and E_4 is the sum of the energy of the neighbouring crystals in an $\eta - \phi$ plane is used for identifying isolated spikes. The figure **Figure of Spike energy topology and Distribution of SwissX** shows the construction of the swiss-cross variable as well its distribution in data and simulation events. The peak at 1.0 in data of the distribution is due to the presence of spikes. A cut in Swiss-cross > 0.95 rejects more than 99% of isolated spikes with transverse energy greater than

10 GeV with very little impact on the efficiency of selecting electromagnetic EM showers. Other topological energy deposit variables such as $1 - \frac{E_2}{E_6}$ and $1 - \frac{E_2}{E_9}$ where E_2 is the sum of the energy of two crystals sharing the energy deposited and $E_6(E_9)$ is the sum of the neighbouring 6(pairs-of)(9) crystals in the $\eta - \phi$ plane. The $1 - \frac{E_2}{E_6}$ variable is used for the identification of isolated spikes whose energy deposit spread in two adjacent crystals while the $1 - \frac{E_2}{E_9}$ is used to identify non-isolated spikes or spikes which are found embedded in a normal Ecal supercluster.

The figure **Put figure of di-spike and non-Isolated spike construction and distribution** A cut on $1 - \frac{E_2}{E_6}$ ($1 - \frac{E_2}{E_9}$) greater than 0.95 (0.98 for tight) gives an efficiency close to 95% for events with transverse energy greater than 10 GeV for rejecting spikes with very little effect on normal EM shower reconstruction.

Another very important variable used for rejecting spikes with greater efficiency is rehit ECAL timing. Spikes and EM energy deposits show very distinct signal pulse shapes. Since spikes do not in the PbWO_4 , when the pulse shape is fitted to extract the timing of a signal, the spikes appear "early" due to faster rise time of the spike pulse. The figure **Fig of spike pulse shape and rehit time distribution for data and simulation** shows the comparison between the pulse shape for a spike candidate pulse and and true PbWO_4 scintillated event. The adjacent plots shows the distribution of the rehit time for simulation(where there are no anomalous signals) and collision data where anomalous signals have a significant contribution to out-of-time signals. A cut on timing of ± 3 ns gives greater than 90% efficiency for rejecting spikes however, in this thesis, we do not employ this timing cut as we are actually searching for delayed objects whose timing can be beyond the ± 3 ns window.

However, it is worth nothing that, these anomalous signals if not rejected will lead to a biasing in the reconstruction of other physics variables such as missing transverse energy(E_T^{miss}) as well as being miss-identified as a possible signal for delayed photons. Infact the spike rate per bunch crossing as observed in [43] was approximately 1×10^{-3} in collisions bunch crossings while in non-collision bunch crossing is of the order of 2×10^{-6} in non-collision bunch crossings. This spike rate from non-collision rate is obtained from cosmic muon data recorded during June-August 2009 while the spike rate for collision is obtained from Minimum biased(Soft proton-proton) collision events data. Thus, in this thesis, we have restricted ourselves to using only the energy topological variables

discussed in previous paragraphs to identify and reject anomalous signals.

Chapter 6

Analysis Strategy for Long-Lived Particles

6.1 Analysis Strategy

6.1.1 Signal and Background Modelling

In modern particle physics experiments, being able to do pseudo experiments which provide reliable insight into the kinematics and detector response to the physics of interest is a necessity. CMS is no exception. Using physics event generators like PYTHIA, Madgraph, SHERPA is very common. The generated events are then passed into the GEANT4 which provides a simulation of the physics of the event and the response of the CMS detector. The resulting event is known as a Monte Carlo Simulation (MC) events and the dataset is a MC dataset. In this analysis, we have used quite a number of categories of MC dataset for both the signal as well as the background. The following events were produced using PYTHIA and simulated using GEANT4.

6.1.2 Event Selection

Higher Level Triggering and DataSet

6.1.3 Background Estimation

6.1.4 Efficiency and Systematics Studies

6.2 Limit Setting

Using the excellent timing resolution as described in previous chapters, we can use the timing information of arrival photons on the ECAL to distinguish between in-time photons(prompt) as well as out of time or delayed photons.

Chapter 7

Results and Interpretation

The GMSB model is the leading model we have used as providing the signal topology in our search for NMLLP. As a result, we provide an interpretation of our above results in the context of GMSB. In GMSB, the neutralino $\tilde{\chi}_1^0$ is the NLSP and decays to the gravitino \tilde{G} the LSP(as a result of R-parity conservation) in association with a very energetic photon γ . Because of the smallness in mass difference between the $\tilde{\chi}_1^0$ and the \tilde{G} as well as the coupling, the $\tilde{\chi}_1^0$ decay to \tilde{G} is delayed and as a result, the photon emitted can arrive late in the calorimeter crystals. Measuring the arrival time of the photon on ECAL crystals, we can extract important parameters of theory of GMSB.

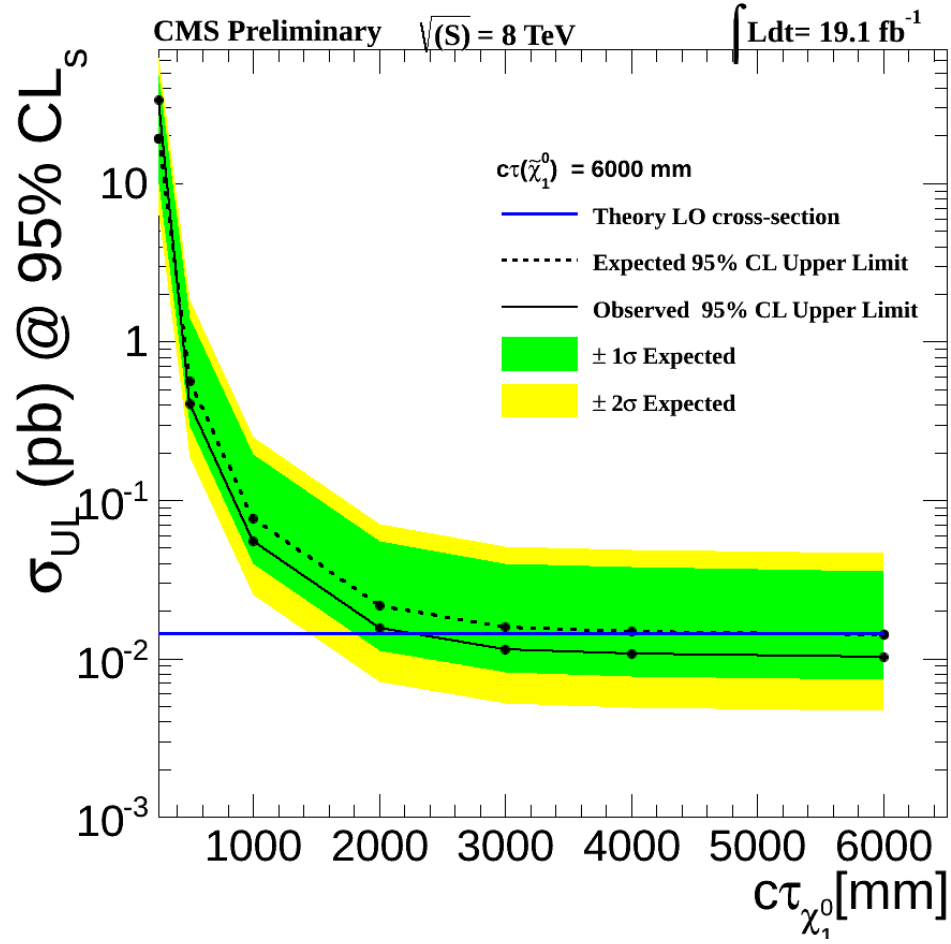


Figure 7.1: Neutralino production cross section against proper decay length upper limit interpretation in SPS8 model.

Chapter 8

Future Work

8.1 Beam Halo Monitoring (BHM)

8.2 HCAL Upgrade-Back End Electronics

Chapter 9

Conclusion

We have performed a search analysis for NMLLP decaying to photons using the time of arrival of the photon as measured by the ECAL subdetector of the CMS detector. We did not find any signal of delayed photons and as such decided to interpret our results in the context of GBSM. We also discuss some of the weakness of our analysis from a detector point of view as well future studies which can be done to improve on the search strategy and analysis. We hope that in the future, with increase in center of mass energy of the LHC collider as well as luminosity and an improve in timing resolution beyond what is already very reliable, we will surely find a new fundamental physics particle beyond what is already known in the current standard model.

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Appendix A

Glossary and Acronyms

Care has been taken in this thesis to minimize the use of jargon and acronyms, but this cannot always be achieved. This appendix defines jargon terms in a glossary, and contains a table of acronyms and their meaning.

A.1 Glossary

- **Cosmic-Ray Muon (CR μ)** – A muon coming from the abundant energetic particles originating outside of the Earth’s atmosphere.

A.2 Acronyms

Table A.1: Acronyms

Acronym	Meaning
CR μ	Cosmic-Ray Muon