Massive Stable Charged Particle Signatures in Simulations at the LHC

by

James B. Silva

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Author ....
Department of Physics
May 9, 2008

Certified by ....
Gunther M. Roland
Associate Professor
Thesis Supervisor

Accepted by ....
Professor David E. Pritchard
Senior Thesis Coordinator, Department of Physics

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1 Massive Stable Charged Particles and LED Theories

The importance of heavy stable charged (HSCP) particles lies in the exploration of extensions to the standard model. Extensions of the standard model attempt to solve current problems in the standard model such as the Hierarchy Problem. The Hierarchy Problem centers on the lack of an explanation in the standard model for the weakness of the force of gravity compared to the other forces of nature. Current research in particle physics has been directed at investigating the phenomenon of black hole production predicted by Extra Dimension Models that attempt to resolve the Hierarchy problem[1]. The Large Hadron Collider (LHC) at CERN will allow the TeV energy range to be explored where black hole production might begin to occur at a significant rate as predicted by Large Extra Dimension (LED) models. The LED models center around the concept of a N dimensional universe where $N > 3$, by introducing the concept that the force of gravity can be diluted by the $(N - 3)$ dimensions, thus solving the Hierarchy Problem. Horst Stöcker and Benjamin Koch have published predictions on production of black holes using PYTHIA[2] and CHARYBDIS[3] in proton-proton collisions[4] as well as heavy ion events such as Pb+Pb in the Koch paper[5]. Other papers been published that are general survey on black holes at the Large Hadron Collider [6][5]. These surveys describe the yield rates of mini black holes, motivation for mini black hole production, and possible characteristics of mini black holes in detector data.

The analysis of heavy stable charged particles in this project is based on a "muon-like" HSCP $500GeV$ particle. A "muon-like" particle is a particle that has identical properties to that of a muon, but possesses a different rest mass. The Reissner-Nordström metric[7] describes empty space surrounding a charged black hole as described by Chandrasekhar's[7]. It is possible to estimate the radius of a charged black hole as $\frac{MG}{c^2}$ by finding the horizon in the Reissner-Nordström metric. The radius of $500GeV$ muon like particle would then be approximately $1.188 \cdot 10^{-28} cm$ in comparison to the values $10^{-32} cm$ and $10^{-36} cm$ for a muon and electron respectively. This gives an idea of the relative size of radii of theoretical black holes that are proportional to the Gravitational constant. According to Large Extra Dimension theories the actual value of G may be in reality greater than that observed therefore the radii may be in the range such that a muon-like $500 GeV$ particle would be a quantum black hole. The actual energy levels at which this quantum black hole production may occur varies in different extra dimension theories. However, the implications of large extra dimension theories are that heavy particles can exhibit black hole like behavior. The analysis of massive particles is only minimally related to these implications as there are many more motivations for the analysis of such heavy particles. The use of massive particles to study the Higgs field has also been proposed[8]. The Exotica group in the CMS collaboration has prepared to analyze heavy stable charged particles, black holes, and heavy neutrinos. In this project I expand on some of the techniques developed by the Exotica group and the developers of the custom physics package for the CMSSW analysis framework in the CMS collaboration.

In this project I have simulated events using the CMS event generation framework to explore the signatures of heavy stable charged particles at CERN. This project is part of the search for massive stable charged particles in the CMS collaboration. The analysis of data in this project centers on the energy loss of leptons and lepton-like particles created by using extensions to the standard generation resources in CMS. The analysis begins with the determination of the energy loss and momentum. The energy loss of the particles distinguishes the particles in multiple sections of the detector. The analysis then proceeds to study the muons at momentum ranges where the particles can be distinguished and follows correlations in the energy loss. The average of this correlated energy loss is then calculated to determine areas of interest for distinguishing heavy stable charge particles and the standard muon. The project expands on current research by elaborating on Stöckers paper using the simulations to guide possible analysis of CMS data[5].

2 CMS Experiment

2.1 The Apparatus

The Compact Muon Solenoid(CMS) Collaboration was established to study high energy physics at the TeV range, discover the Higgs boson, study physical theories beyond the standard model, and conduct heavy ion collisions. The CMS detector was designed to meet these goals. The experiment is located at European Organization for Nuclear Research (CERN) and is part of the Large Hadron Collider (LHC) project that has been funded under collaboration of countries worldwide. Proton-Proton collisions are scheduled to begin fall 2008. The CMS detector is one of six detectors interspersed along the collision tracks for the LHC. The other detectors in placed along the Large Hadron Collider's track are ALICE (A Large Ion Collider Experiment), an experiment optimized for heavy ion collisions, ATLAS (A Toroidal LHC ApparatuS), a general purpose experiment like CMS, LHCb optimized for bottom quark related physics, LHCf optimized for the study of paricles in the forward region, and the Total Cross Section, Elastic Scattering and Diffraction Dissociation (TOTEM) optimized for cross-section measurements and physics that can calibrate machine luminosity . Figure[0-1] displays a cross-section of the CMS detector and the possible trajectory of particles in the detector. Protons that have been accelerated to seven TeV ($10^{12}eV$), with a luminosity of $10^{34}cm^{-2}s^{-1}$ are concentrated using powerful magnets into two beams of particles that collide with a small probability due to their size. However, the large numbers of particles in a beam allows for a large number of collisions despite the small probability of an individual collision. The high energy of the collisions then allows particles to be created that could not have been created in previous detectors such as the Tevatron at Fermilab. The particles created by the collision scatter in different directions in the detector designed to trigger on events based on energy in the calorimeters. The detector consists of three main sections; the silicon tracker, the calorimeters, and the muon chambers. Each of these detector parts is composed of smaller parts such as the inner and outer barrel of the silicon tracker. The calorimeters are comprised of two sections; the electromagnetic calorimeters that is made of lead tungstate and designed to measure the energies of entering electrons and photons as seen in figure[0-1], and the hadron calorimeters made of materials such as brass interspersed with scintillators designed to measure the energies of hadrons (i.e. protons, pions, and neutrons). The muon detector is composed of three parts; drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC). The drift tubes are used in the central region of the barrel while the cathode strip chambers are used as endcaps. The experiment is also capable of performing heavy ion collisions such as those studied at Brookhaven National Laboratory, except for the much larger energy available at the LHC. The collider has the capability of colliding at center of mass energies of approximately $5.5 TeV$ for Pb+Pb at a luminosity of $10^{27} cm^{-2} s^{-1}$. The state where quarks and gluons behave freely is called the quark gluon plasma and is believed to have existed in the early universe before the universe began to cool by expansion. It is the hope that the quark-gluon plasma can be explored through these heavy ion collisions.

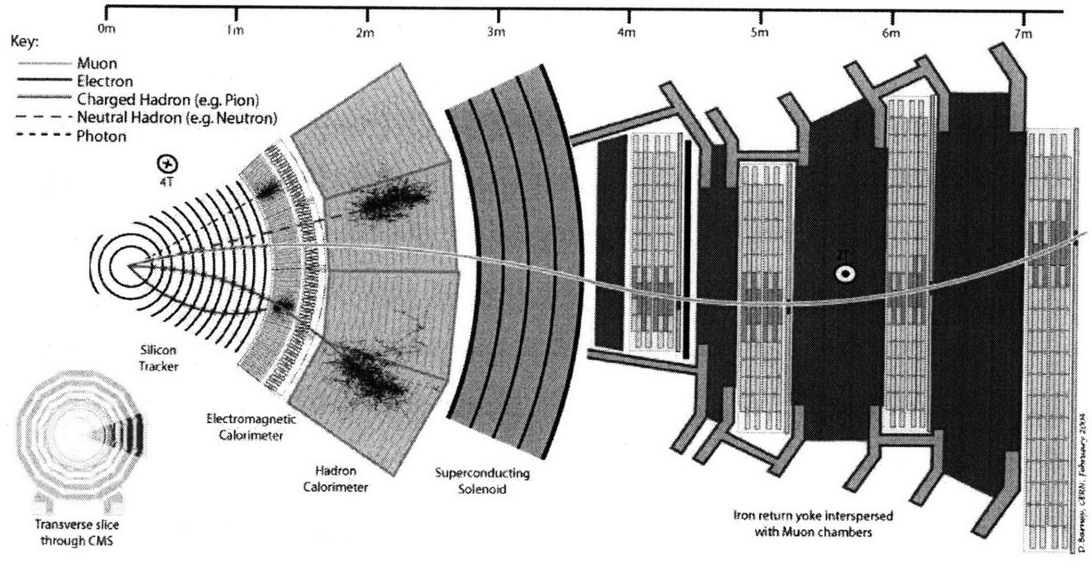

Figure 0-1: CMS Detector cross-section and possible particle trajectory

The data acquired by the detector is of order of a terabyte/s which is then pared into the large gigabyte/s range and stored in petabyte archives for analysis. The overwhelming amount of data produced by the experiment compels the creation of a filtering mechanism known as a trigger that can determine when a physical event is interesting enough to be archived.The paring of data is done through various trigger mechanisms which include a Level-1 trigger and High Level Trigger. The Level 1 trigger is a hardware trigger on the muon resistive plate chambers and electromagnetic calorimeters that reduces the event rate by three orders of magnitude. The High Level Trigger is software based and reduces the event rate by another three orders of magnitude. The triggering mechanism occurs in all the detector sections to increase the ratio of interesting data to that which is kept in data archives. The Compact Muon Solenoid(CMS) provides a greater resolution at detecting muons than the ATLAS detector of the Large Hadron Collider experiment. This is primarily due to the solenoid and muon chambers. The greater resolution for muon detection of the CMS detector is a valuable asset for the search of heavy muon-like particles that are analyzed in this experiment. As observed in figure[0-1] a muon would travel the farthest path through the calorimeters and into the muon chambers allowing for differentiation between muons and other particles based on the interactions or lack thereof within the detector sections. This particle trajectory can then be used to identify a muon passing through the detector.

2.2 The CMSSW Analysis Framework

The large amount of computing power needed in the CMS experiment has necessitated the exploration of new methods of physical analysis. The CMSSW analysis framework fulfills the requirements of such a high data output by implementing computing concepts such as grid computing. CMSSW refers to a collection of software that has been developed by physics groups around the world. The CMSSW[9] framework includes interfaces with various generators including PYTHIA[2], CHARYBDIS[3], and HERWIG[10]. The software also includes its own "particle gun" within the framework. The framework is designed to allow CERN's ROOT[11] analysis framework to be extended to include the objects created in CMSSW. CERN's ROOT[11] analysis framework is the basis of CMSSW [9]and is commonly used to perform physics analysis in high energy physics. There are two possible paths for analysis; the generation/reconstruction/analysis of simulated data , and the reconstruction and analysis of archived data. However the framework is designed to make the reconstruction and analysis of data independent of the source of the data that may be from Monte Carlo methods or archived data. This compatibility allows for analysis of data to be streamlined before a single byte of data has been obtained, therefore allowing for the publication of data in a shorter time frame. The simulation of data is aided by the GEANT4[12]program and detector geometry simulators. This simulation program allows for expansion into super-symmetry physics through the use of the "Custom Physics" package. In this project extensions to the standard simulation package are required for the generation and simulation of the HSCP particles. These extensions are created through the use of the "Custom Physics" package which allows for the use and creation of particles of interest such as the $500GeV$ muon-like particle analyzed in this project.

The generation/reconstruction/simulation sequence of particles begins with the generation using a generator or the particle gun provided by the CMSSW framework. All of the generators in the package are based on monte carlo techniques. The Monte Carlo in the framework can be made more realistic by including vertex smearing effects, pile-up events, as well as misalignment scenarios. Vertex smearing is compensation for the fact that the monte carlo generators produce events that always come from the $(0, 0, 0)$ position which does not always occur in real data. In this project, all generation was done through the particle gun provided by the CMSSW framework. The CMS Exotica group has provided support in general techniques for extending the CMSSW package to create heavy particles such as the $500GeV$ muon-like particle. The Exotica group will perform analysis of black holes, heavy stable charged particles (HSCP), as well as other exotic particles that are predicted by extensions of the standard model. In this project all generation/reconstruction/simulation was done by coercing CMSSW_1_7_5 into successfully completing the particle creation and analysis sequence. Once a particle is generated it must be be simulated using GEANT4. The simulation process simulates the interactions that a particle would undergo passing through the elements of the detector. This process is followed by digitization which simulates the electronic response of particles in the detector. Reconstruction is the final step in which the response is turned into abstract data types that represent a particle or track. Reconstruction and the others steps in creating analysis objects are usually done by standard sequences that are supplied by the framework. This data type representation was created as part of the EDM[9] package that forms the foundation of the CMSSW framework. This data is then used for analysis using EDM plug-ins that are created by the user although basic analysis can be performed using extension to ROOT. EDM plug-ins allow for easy event to event access and modularization for analysis

The analysis of data is done through a C++ based packages for analysis. These packages are controlled using configuration files that are interpreted via the *cmsRun* interface that controls the order of the EDM plug-ins and other modules in the data chain. The framework is designed to encourage modularization such that a single program can be used to perform various tasks for various types of data. An extension to ROOT has also been created called FWLite, which essentially loads necessary libraries so that analysis within ROOT is theoretically possible. However, due to the non-native support of CMSSW in ROOT, the analysis is performed in a more convenient manner in EDM plug-ins. The analysis objects produced in the framework are ROOT objects to allow for manipulation and viewing through the use of ROOT. In this project EDM plug-ins were used to perform the analysis but plots were manipulated using scripts for ROOT. The energy loss and momentum data were accessed through EDM plug-ins and used to create plots of the energy loss as functions of momentum.

3 Distinguishing Massive Stable Charged Particles Through Energy Loss

The characteristics of the energy loss of leptons are dominated by electromagnetic interactions and to a smaller extent nuclear collisions. The electrons of the atoms in the matter through which the particles of interest travel are excited and occasionally ionized by these electromagnetic interactions. The electromagnetic interactions are dependent on the charge of the particle therefore this feature in the energy loss should be identical for both the heavy particle and the standard muon because they have identical charge values. This interaction would imply that the particle should travel in a trajectory that is approximately a straight line and the energy loss should be similar in every interaction such that the energy loss as a function of momentum of a particle undergoing only electromagnetic interactions should be constant but having a natural statistical fluctuation. The velocity attained by a particle given a certain amount of kinetic energy is dependent on the mass of a particle as seen from the equation $p = \gamma m v$ where m is the mass. This velocity is important in determining the probability of a charged particle colliding with a particle of opposite charge.

The large mass of HSCP particles implies that they should travel at lower velocities for the energy ranges studied. The data has displayed HSCP particles at low velocities. By determining the smallest kinetic energy observed in a detector section it is possible to determine the lowest velocity observed for the HSCP data set. This cutoff energy for the muon should not be observed for the muon because the cutoff energy of the generated particle is $1GeV$ which corresponds to $\beta \approx 0.99$ for the muon and $\beta \approx 0.06$ for the HSCP particle. The cutoff energy should be observed in the the HSCP particle were velocities are low enough to cause instability in the path of the particle. This cutoff energy is observed in figure[0-6]. This velocity dependence implies that the rate of collisions should increase as the velocity decreases. However, the trajectory of the particle should still approximate a straight line due to the large mass of the particle relative to the particle that is being interacted with such as the electron which is approximately eight orders of magnitude smaller than the HSCP particle particle and four orders of magnitude lighter than the standard muon. These facts imply that a heavier particle should be more susceptible to nuclear collisions until it reaches the velocity that allows it to escape the electromagnetic interactions therefore energy loss should distinguish the standard muon with the HSCP particle. This analytical reasoning has guided the analysis of this project.

3.1 The Approximation of Energy Loss Due to Single Collisions in Muons

To explore the relationship between the mass of the particle and the energy loss caused by a single scattering process. Let the generated particle have a mass M and m be the mass of the particle that our initial particle interacts with which we will assume is an electron that is located in the matter that composes the detector. If we assume that our generated particle is moving at a velocity much higher than electrons in the matter of the detector. This assumption is valid because the electron is bound to matter and the generated particle has a reasonable velocity. An elastic collision will also be assumed. This assumption is reasonable because one can expect that under the previous conditions and the fact that the generated particle is at least eight orders of magnitude heavier. Conservation of momentum would yield equation[1].

$$M \cdot v = M \cdot v_f + m_e \cdot v_e \tag{1}$$

Conservation of energy yields equation[2].

$$\frac{M \cdot v^2}{2} = \frac{M \cdot v_f^2}{2} + \frac{m_e \cdot v_e^2}{2} \tag{2}$$

Solving for v_f yields $v_f = \frac{(M-m_e)\cdot v}{M+m}$. One can then determine the energy loss caused by the collision by calculating $Q = \frac{M \cdot v^2}{2} - \frac{M \cdot v_f^2}{2}$. This leads to equation[3] where E is the initial kinetic energy.

$$Q = \frac{M \cdot v^2}{2} \cdot \frac{4Mm_e}{(M+m_e)^2} = E \cdot \frac{4Mm_e}{(M+m_e)^2} \tag{3}$$

Now one can determine Q values for both generated particle values. For the muon one obtains a value $Q = 0.192E$. The value obtained for the heavy particle is $Q = 4.0880 \cdot 10^{-6}E$. If one decides to treat nuclear scattering in a similar matter one can obtain values for the Q of those processes. From this analysis one obtains approximate bounds of $Q = 0.4E$ for the standard muon and $Q = 0.0075E$ for the HSCP particle. This analysis only provides an idea of ideal conditions that give bounds for the amount of energy loss for a single collision. This analysis does not account for the contribution of electromagnetic processes that are dominant but shows the small order of the collisions for the HSCP particle. The value of this calculation lies in determining the maximum amount of energy obtained for a collision with an electron. This maximum value determines b_{max} in the classical energy loss due to ionization.

3.2 Energy Loss through Ionization in Matter

The energy loss of our charged particle is due to the interactions with matter in the detector. It is necessary to calculate this energy loss. Following the logic of Leo [13] Let our heavy charged particle have a charge Z, mass M, and a velocity v as it passes through a medium. The interaction has an impact parameter b. The impulse is calculated to determine the energy transferred to the electron of mass m_e and charge e in the medium.

$$I = \int F dt = e \int E_{\perp} dt = e \int E_{\perp} \frac{dx}{v} \tag{4}$$

$$\text{From Gauss' Law} \Rightarrow \int E_{\perp} 2\pi b dx = 4\pi z e \tag{5}$$

$$\Rightarrow I = \frac{2ze^2}{bv} \tag{6}$$

The energy obtained by the electron is then given by,

$$\Delta E = \frac{I^2}{2m_e} = \frac{2z^2e^4}{m_e v^2 b^2} \tag{7}$$

Let the electron density in the medium be given by N_e such that the energy loss per length is given by equation[8].

$$\frac{dE}{dx} = -\frac{4\pi z^2 e^4}{m_e v^2} N_e \ln \frac{b_{max}}{b_{min}} \tag{8}$$

Assuming the interaction occurs in a time span smaller than the period of the electron such that the process is not adiabatic equation[8] becomes equation[9] where $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ and $\overline{\nu}$ is the mean frequency of the electron over all bound states.

$$\frac{dE}{dx} = -\frac{4\pi z^2 e^4}{m_e v^2} N_e \ln \frac{\gamma^2 m v^3}{z e^2 \overline{\nu}} \tag{9}$$

This formula is valid for heavy charged particles of order of an alpha particle. A formula that accounts for quantum effects[13] is known as the Bethe-Bloch formula[10].

$$\frac{dE}{dx} = -2\pi N_a r_e^2 m_e c^2 \rho \frac{z}{A} \frac{Z^2}{\beta} [\ln(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2}) - 2\beta^2] \tag{10}$$

In this equation ; N_a is Avogrado's number, I mean excitation potential, A is the atomic weight of material, ρ is the density of the absorbing the material, z charge of material, and W_{max} is the maximum energy that could be transferred in a single collision. This equation[10] can be supplemented with shielding effect corrections as well as a density effect correction. Figure[0-2] displays predicted $\frac{dE}{dx}$ for copper as a function of energy with shell/density corrections and without[13].

4 Energy Loss of Leptons in CMS simulations

The energy loss of leptons is the foundation upon which the analysis of data in this project is based. The energy loss is calculated in GEANT4[12] in the CMSSW[9] framework by subtracting the final kinetic energy by the initial kinetic energy after a unit step in the propagation of a particle by GEANT4[14]. The muons were followed through a detector section and the average energy loss in a detector section was kept in the data set for analysis. Muons were generated with energies ranging from $1GeV$ to $1100GeV$. A muon has a rest

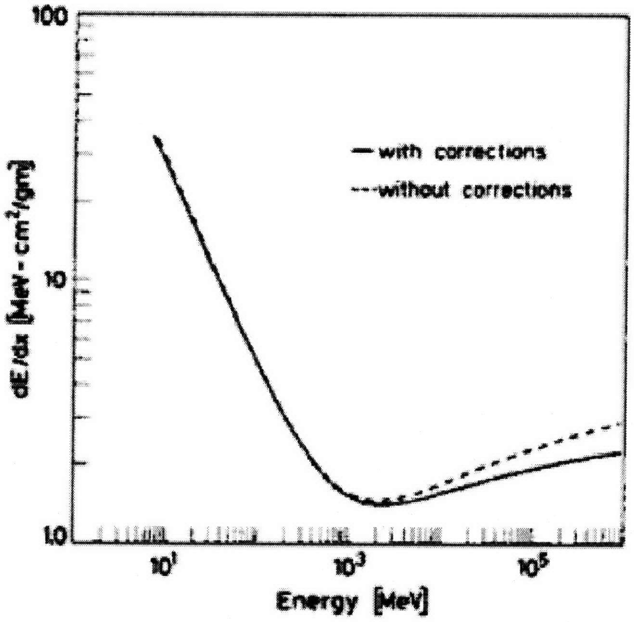

Figure 0-2: Bethe-Bloch predicted $\frac{dE}{dx}$ for copper as a function of energy with shell/density corrections and without[citation see text]

mass of approximately $0.1057GeV$ which is fairly large relative to the rest mass of an electron that is $0.511MeV$. Figure[0-3] displays the momentum distribution of the muon particles generated. The events allow for the creation of anti particles of the generated particles. This energy range was chosen to be the energy range to be explored for all of the events in this project. Figure[0-3] also displays a statistical shape that centers about high $500GeV$ range as expected due to the $1 - 1100GeV$ range chosen. This distribution of momenta is reasonable for the amount of events analyzed.

Electrons were also created to explore the behavior of leptons of a smaller rest mass than the muon. The electrons created were also given energies ranging from $1GeV$ to $1100GeV$. However, the amount of events generated for the electrons is smaller than the amount of muon events generated due to the amount of computing power and memory necessary to create and archive electron events. The third type of particles generated were created through the use of expansions to the CMSSW possible through the use of the "Custom Physics" package

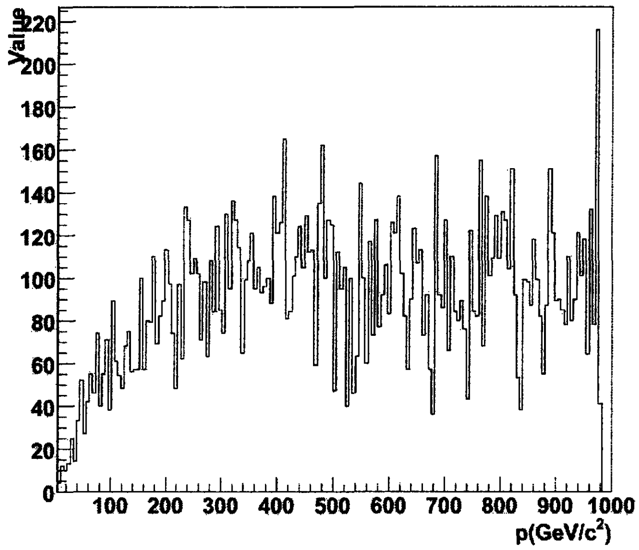

Figure 0-3: Standard muon momentum distribution

provided in the framework. This particle is a $500GeV$ rest mass particle with identical charge as that of a muon. The kinetic energy given to this particle ranges from $1GeV$ to $1100GeV$ just like the other particles generated. 5000 events of this HSCP were created to be compared with 5000 events of the standard muon particle. The energy loss was then normalized by averaging the energy loss data to determine $\Delta\overline{E}$. The energy loss data was normalized by the average data loss to callculate $\frac{\Delta E}{\Delta \overline{E}}$ before it was plotted. Figure[0-4] displays the normalized energy loss as function of total momentum for a standard muon in the tracker and muon detector sections. The associated σ for this energy loss are $\sigma_{muon} = 0.15$ and $\sigma_{tracker} = 0.61$. To plot the energy loss data from all the detector section subsections were plotted into the same plot hence for a detector section such as the muon chambers the data for the drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC) were all plotted in the same figure. In the figure it is observed that the energy loss is constant across the momentum range except for statistical variations that appear to be more significant for the tracker section of the detector. The energy loss is characterized by a dominance of electromagnetic interactions and the smaller less probable effect of nuclear collisions. These

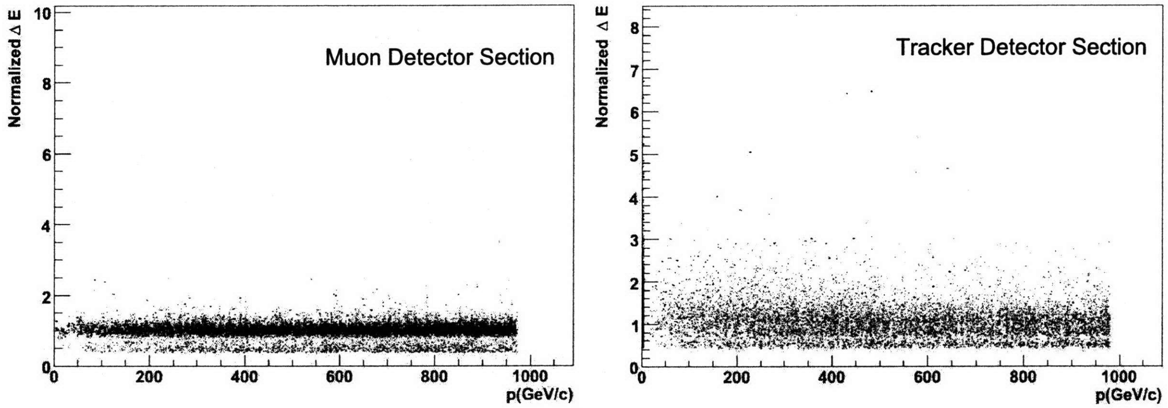

Figure 0-4: Normalized standard muon energy loss as a function of particle momentum for muon detector (left) and tracker detector (right) section

interactions are not strong enough to deviate from a straight line trajectory.

Figure[0-5] displays the normalized energy loss of electrons as a function of momentum for the tracker section of the detector. The associated σ for this energy loss is $\sigma_{tracker} = 0.61$. The energy loss in the tracker section of the detector is similar to that of the muon except for a larger magnitude. The light mass of electrons forces the particle to move in curved paths that imply a loss of energy due to electromagnetic interactions. There is no associated energy loss data for electrons in the muon chambers because the electrons never make it past the electromagnetic calorimeters as observed in figure[0-1]. Electrons will not be analyzed to a greater depth in this project due to these qualities but the inclusion in this section is relevant for completion of describing common leptons.

Figure[0-6] displays the normalized energy loss of the heavy particles as a function of momentum. The associated σ for this energy loss are $\sigma_{muon} = 0.18$ and $\sigma_{tracker} = 0.37$. These particles behave in a similar way to muon as they travel through the muon chambers unlike the electrons. The "heavy muons" exhibit a higher energy loss than the standard muon below momenta of the order of $300GeV$. This behavior for heavy particles is expected because at the lower velocities obtained by these heavy particles there are more collision interactions with the nucleus of materials of the detector. At large velocities the electromagnetic interactions

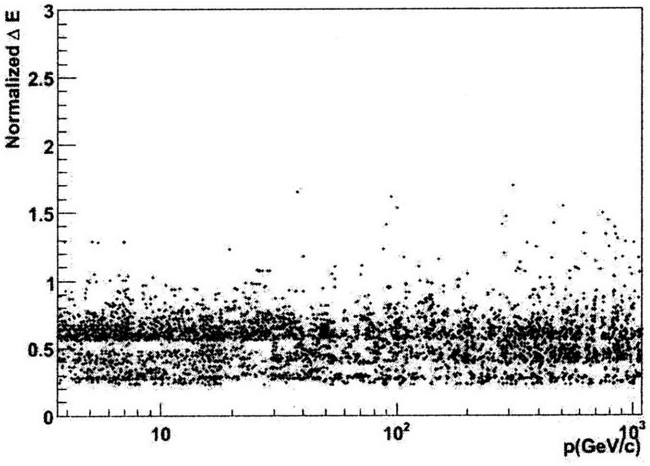

Figure 0-5: Normalized electron energy loss as a function of particle momentum in tracker detector section

dominate exhibiting continuous energy loss behavior that depends on the charge which is the same as the standard muon therefore at high velocities the heavy charged particle should have energy loss similar to the standard muon. All of these features are displayed in figure[0-6]. These HSCP particles travel in trajectories that are essentially a straight line.

5 Comparing HSCP Particles with the Standard Muon

In this project 5000 collision events were generated of the standard muon ($0.1057GeV$) and heavy particle ($500GeV$) that were given kinetic energies in the range $1-1100GeV$. The muons were followed through their path in the detector and their energy loss was plotted as a function of momentum for different detector sections. This data was then consolidated to allow for the plotting of the data for the standard muon ($0.1057GeV$) and HSCP ($500GeV$) in the same figure. Figure[0-7] is the result of the aforementioned analysis. This data was also used to create detector energy loss correlation plots and plots of the energy loss as a function of $\phi - \theta$. However, total momenta has shown to be a superior illustrative tool for differentiating the standard muon ($0.1057GeV$) and heavy particle ($500GeV$).

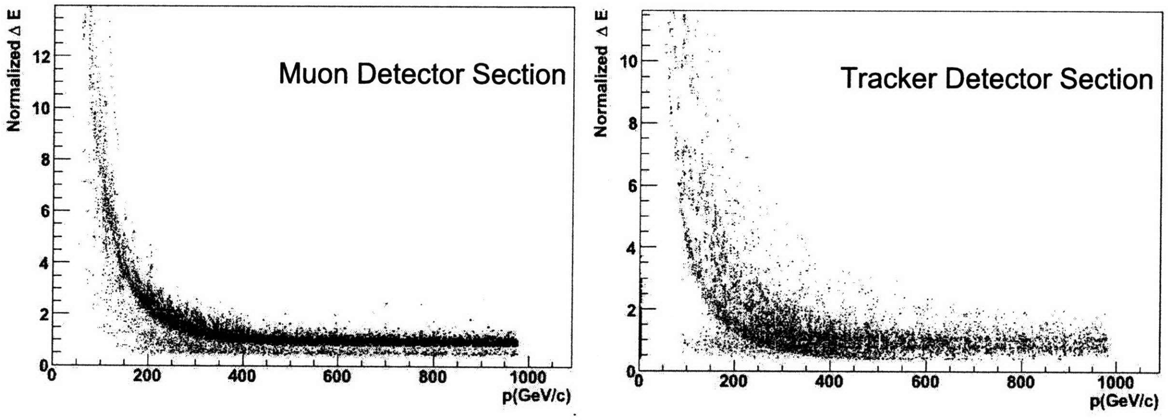

Figure 0-6: Normalized HSCP energy loss as a function of particle momentum for muon detector (left) and tracker detector (right) section

Figure[0-7] displays average energy loss of a heavy particle and its distribution in the same figure as well as the identical information for the standard muon. These plots exhibit some of the behavior predicted through the reasoning previously provided. The most notable of the predicted features are the meeting of the two curves at high enough energies. The average energy loss for both particles at momenta greater than $300GeV$ differs by less than a two percent. The averages in the plots show that the two can be distinguished by their energy losses since the average energy loss of the heavy particle is above the standard deviation of the energy loss of the standard muon. This property is best exhibited in the muon chamber data in a logarithmic plot. There also is an implied kinetic energy cutoff for detection in the detector sections. This cutoff energy is easily explained by considering the limiting case of a zero kinetic energy that should not be observed because it is in an unstable state that is susceptible to the effects of a coulomb potential on the particle.This cutoff occurs at approximately $14GeV$. This cutoff energy corresponds to a $500GeV$ particle traveling at $0.030c$.

Figure[0-8] is the plot previously described but with the energy loss normalized such that the energy loss data is divided by the average energy loss. The figure clearly shows the energy loss data approaching a constant value in the couple hundred GeV range . An interesting

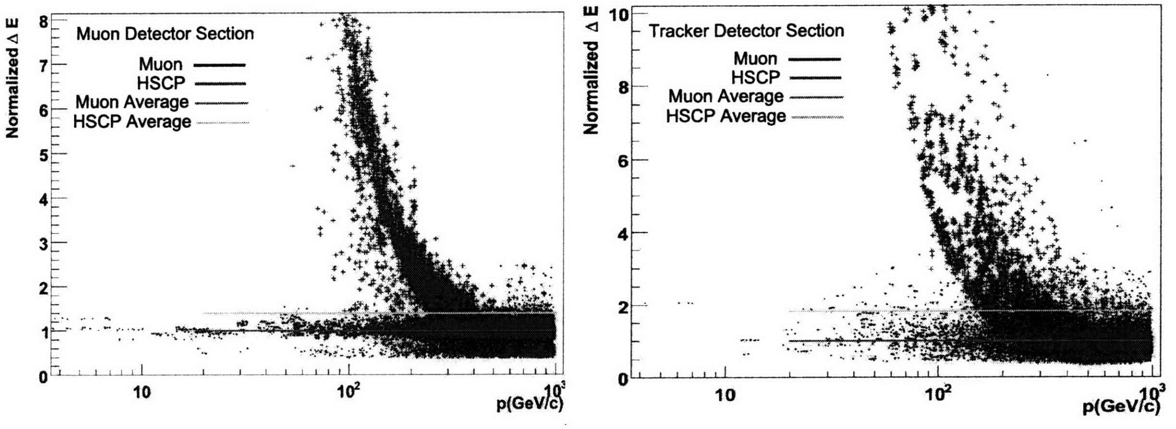

Figure 0-7: Logarithmic normalized HSCP/Standard muon energy loss as a function of particle momentum and averages for muon detector (left) and tracker detector (right) section

question that arises is how well correlated the energy loss is across different sections. This question will be explored in the section following the current one. The standard muon appears to have a larger degree of statistical fluctuation. This greater degree of statistical fluctuation has no clear explanation but can entirely be due to the effects of the filtering mechanisms applied and their effect in the resulting group of particles.

6 Detector Energy Loss Correlations

The analysis of energy loss correlations across different sections of the detector provides another method of differentiating the standard muon and HSCP particle. This analysis was conducted using the same 5000 events used for the simpler analysis of energy loss as function of momentum. In this analysis a muon was tracked across multiple sections of the detector and the energy loss was plotted for different sections that the particle may have passed through. The analysis of energy loss as function of momentum guided the analysis of energy loss correlations between detector sections. Figure[0-7] guided cuts of of momentum range to be used for analyzing correlations between detector sections. The energy range chosen for the analysis was $4 - 200 GeV$ due to the differing energy loss values for the particles analyzed in

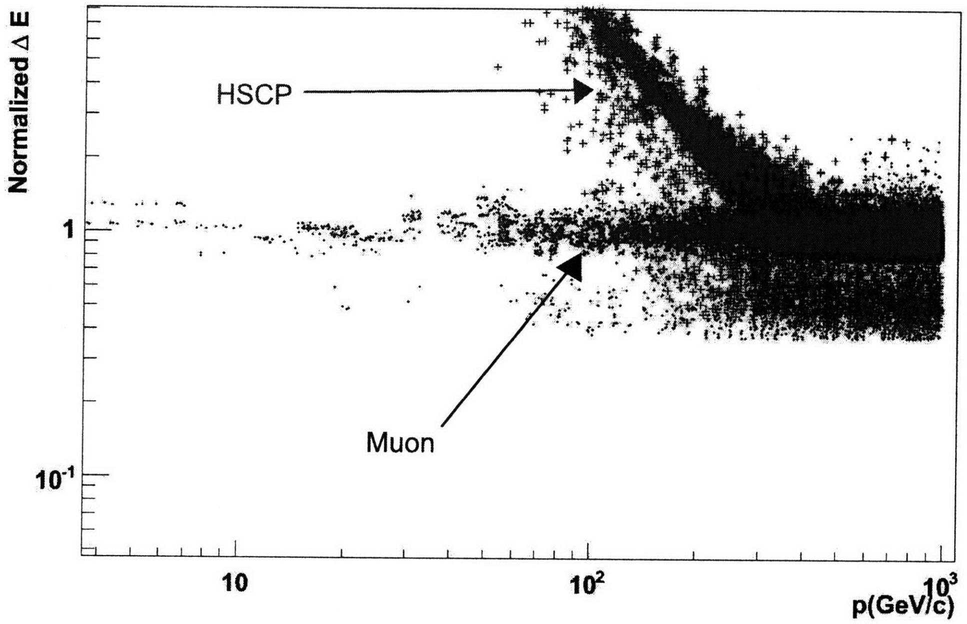

Figure 0-8: HSCP/Muon particle energy loss as a function of particle momentum comparison in muon detector section

the chosen range observed in figure[0-7]. The energy loss data was normalized in an identical method to that used in figure[0-8]. This normalization implied that a particle should have an energy loss such that the standard muon should have data points surrounding the point $(1, 1)$. The non-constant behavior of the heavy particle in the analysis range implies that the data should not surround the $(1, 1)$ point.

Figure[0-9] is the result of the energy loss correlation analysis. An interesting feature of this plot is that there are roughly three clusters of data that can be traced back to the $(0.75, 0.75)$ with the center cluster being occupied by a significantly larger amount of data. This effect in the muon correlation figure is simply explained by the fact that a particle must contain a non-zero kinetic energy greater than the total energy loss expected for the path from the collision vertex to the end of the muon chambers to be able to travel far enough to be detected in both detector sections analyzed in this project. The left and right clusters are due to the less probable events were a particle has loss a significant amount of energy loss

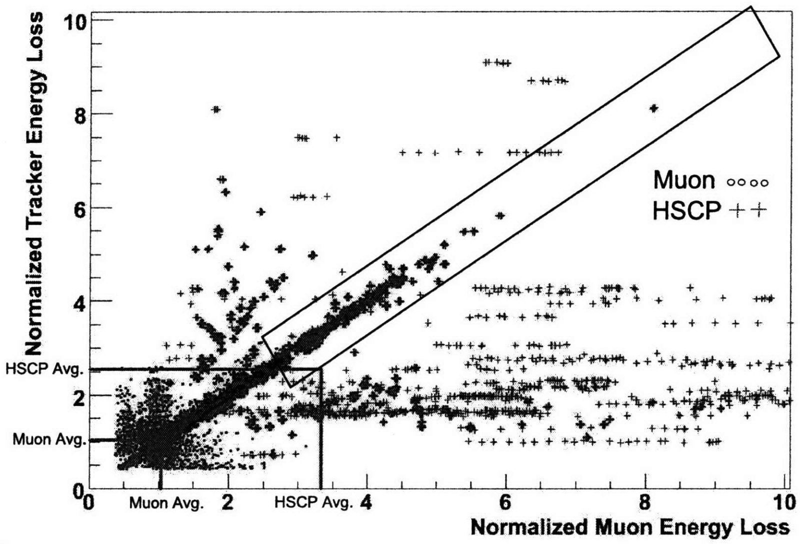

Figure 0-9: Detector section energy loss correlation. Box represents the region used for figure[0-10]

in one section of the detector. In this plot the two particles are differentiated by the ranges occupied by the energy loss data. The standard muon occupies a third of the data occupied by the HSCP particle. This filtered data can be used to calculate new average energy losses that can be used to mark of sectors for the particle. This analysis is performed in figure[0-9] by plotting a box bounded by the average energy loss of a detector section. The energy loss of the heavy particle appears to lack the symmetry observed in the standard muon due to a higher muon detector section energy loss. However, the intensity of the center cluster of the heavy particle suggest a correlation between the energy loss in both analyzed sections of the detector. The figure implies a strong correlation between the energy loss in the tracker and muon chambers sections of the detector for both particles. Figure[0-10] displays the energy loss in this strong correlation region along the $\Delta E_{muon} = \Delta E_{tracker}$ line for the larger energy loss range $\Delta E > 2.5$. It becomes clear that the HSCP particle dominates this region since 97% of the particles in this region are HSCP particles 7369 HSCP particles to 184 standard muon particles. Therefore , the combined muon chamber and tracker energy loss data shown in figure[0-10] provides a good discrimination for the selection of HSCP candidates in the momentum region up to approximately $p \approx 250\frac{GeV}{c}$ for $500GeV$ mass HSCP particles. More detailed simulations are necessary to set quantitative limits on the CMS sensitivity for these particles.

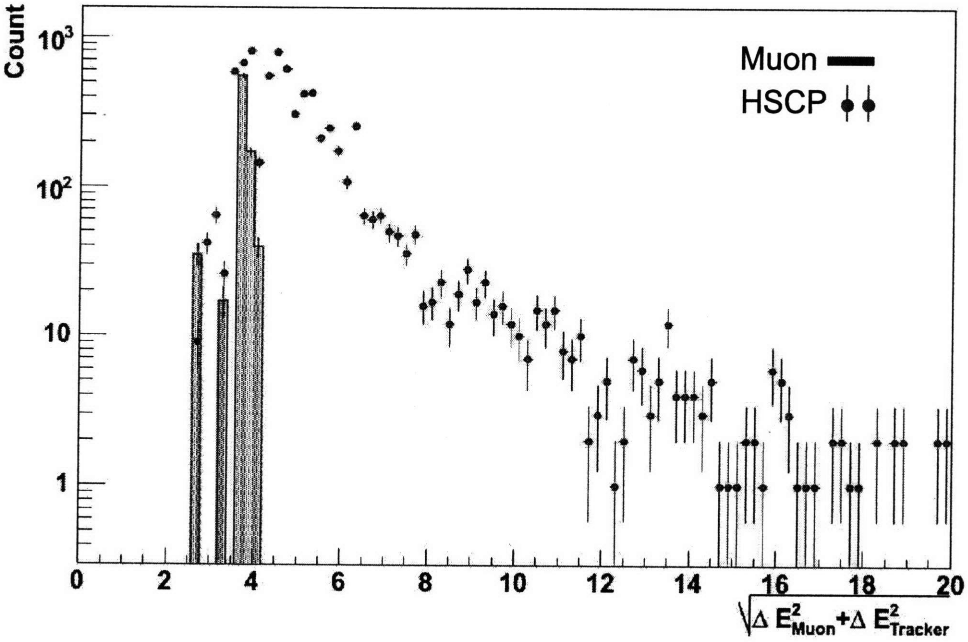

Figure 0-10: Combined muon chamber and tracker energy loss data for selected muon and HSCP candidates

7 Analysis Implications of Massive Stable Charged Particle Signatures at the LHC

The existence of heavy stable charged particles has been an area of extensive research for many research groups such as the L3 detector group that is the predecessor to the LHC research groups at CERN. The existence of heavier leptons has been predicted since the discovery of the muon and tau particles as observed in the Smith[15]. The prediction of heavy charged particles has propagated through Gauge Mediated Supersymmetry Breaking

(GMSB) theories, Large Extra Dimension theories (LED), and the little Higgs model. The Drell-Yan mechanism is expected to account for the production of these heavy charged particles. A Drell-Yan process occurs when a quark and anti-quark from different hadrons annihilate each other creating a pair of oppositely charged leptons[16]. Standard model extensions predict resonances of a collision in the TeV range can decay into two leptons of equal mass. However, searches for these heavy leptons have been unsuccessful such as the analysis conducted by the L3 collaboration[17]. This analysis sets a lower bound on the energy of possible heavy leptons. It has also been suggested that massive metastable charged particles are dark matter candidates[18]. This research has made the analysis of heavy stable charged particles a source of interesting analysis for the CMS and ATLAS collaborations. Since the initiation of this project the work on the analysis of heavy stable charged particles has increased and this is being reflected in presentations in physics conferences.

There is a confirmation of the ability to distinguish a standard muon from a HSCP particle in the the analysis of the energy loss as function of momentum in this project. The data for the HSCP particle also implies the cutoff kinetic energy detector of about $14GeV$ as observed in figure[0-7]. This kinetic energy cutoff corresponds to a $\beta \approx 0.030c$. The heavy stable charged particles appear to be traveling at speeds as low $9 \cdot 10^6 m/s$ much lower than other particles being observed. This implies that a signature of a muon-like heavy stable charged particle is detected in the muon chambers later than the standard muon. This concept could be applied to an electronics trigger for HSCP particle that is activated if a muon-like particle is detected after a predetermined time interval. There appears to be an ideal range for differentiating the two types of particles that is velocity dependent as expected. In this project a HSCP particle of mass $500GeV$ begins to be indistinguishable from a standard muon at about $320GeV$. The analysis shows that the energy range of 0 to $320GeV$ is the starting point for distinguishing searching for signatures of heavy stable charged particles. The analysis also shows that the muon appears to have a constant energy loss as a function of momentum at the kinetic energy levels in the GeV range. This shows that a muon could be used as a baseline for the determination and analysis of heavy stable charged particles.

The correlation analysis can guide analysis to be directed at the muon chambers were there is a greater resolution for the data that exhibits itself as a smaller statistical variation in the muon chambers. The correlation data exhibits a high degree of correlation between the energy loss in the tracker and muon chambers. This correlation implies that both sections can be used in conjunction to obtain better discrimination. The correlation data can also be used to analyze the probability to misidentify a HSCP particle at a certain energy loss range in a detector section. This analysis can then be used to determine the maximum value for this probability hence determining the ideal analysis point for determining the identity particle. This analysis could possibly be used for the "ad-hoc" triggers for the search of heavy stable charged particles. The analysis suggest that an example of such "ad-hoc" triggers could be based on known rates of energy loss per length for the muon and use this information to trigger of any charged particle that has a low velocity coupled with an energy loss greater than two standard deviations from the the energy loss of the muon and was detected after predetermined interval since the first detection of a muon-like particle. This trigger could be used to mark an event as a probable HSCP particle event.

8 Concluding Remarks

The analysis of heavy stable charged particles is driven by the possibility of testing extensions of the standard model which include theories of extra dimensions such as the Large Extra Dimensions. Given the advent of time and resources the analysis of this project could be extended to include more exotic particles. Particles in the TeV range would be of particular relevance due to the energy level of possible collision resonances at the LHC. This could be used to explore the relationship between particle rest mass and the velocity detected in the muon detector. This data could be used to explore the relationship between the profiles of the energy loss of particles of different mass. This analysis could obtain a possible relationship between the rest mass of an equally charged particle and the momentum were the energy loss profiles for a heavy particle and standard muon are indistinguishable. The effect of the charge of a particle on the energy loss can then be explored. This analysis should yield results that are observable than that dependent solely on the mass due to the relative magnitude of the electromagnetic forces involved.

The CMS experiment at CERN is expected begin operation in Fall 2008. The goals of this project included the exploration of the CMSSW analysis framework, ROOT framework, and C++ principles. This analysis was driven with the intent of becoming adept at programming and analysis in the framework. The initial attempt of the project was to explore the possibility of quantum black holes in the CMS experiment. The initial inquiry led to exploring a particle with large mass being confined to small volume ie massive particles. The possibility of TeV energy level resonances decaying into massive leptons as described in the Nuclear Physics article[16] led to the exploration of massively stable charged particles. This led to the analysis of $500GeV$ muon-like particles. This analysis was further justified and motivated by current research into heavy stable charged particles HSCP such as that conducted by the Exotica group in the CMS . The analysis and generation conducted by the Exotica group was based on the custom physics package provided by the CMSSW framework. The Exotica group had achieved generation in earlier versions of CMSSW and was working on extensions for current versions of CMSSW. Similar extensions were used to achieve generation in the CMSSW_1_7_5 version used for generation and analysis in this project. Research into heavy stable charged particles at CMS had not been explored in detail when the project began. Currently research on heavy stable charged particles has increased due to the stability of CMSSW releases and the increase in documentation for the newer releases of the CMSSW framework.

Using the strong correlation between energy loss in the muon detectors and tracker detectors the analysis suggest HSCP candidates should be able to be distinguished in the CMS detector. For a muon-like particle of rest mass $500GeV$ the kinetic energy cutoff for energy loss detection occurs at approximately $250\frac{GeV}{c}$. In addition, we can argue that heavy muon-like particles are best observed in the muon chambers, were they can also be observed as particles that are detected late due to their smaller velocity. The analysis suggest possible trigger algorithms that could be used to minimize computation time in analysis of heavy stable charged particle events. Our simulations of HSCP particles in the CMS detector at CERN confirmed the expected capabilities of CMS in these measurements. Furthermore, the combined muon chamber and tracker data provided good discrimination of particles up to $p \approx 250\frac{GeV}{c}$ for the $500GeV$ rest mass HSCP particle. More detailed simulations would be required to set limits on the CMS sensitivity for these particles studied.

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