

1 A search for highly ionizing, short tracks at the CMS detector

In this chapter a search for highly ionizing, short tracks is presented. The chapter will be structured as follows: In Sec. 1.1 a motivation will be given, followed by an overview of the general search strategy in Sec. 1.2. As the variable $\frac{dE}{dx}$ plays a crucial role in this analysis, a general introduction and different possible parametrizations will be introduced in Sec. 1.3. In this context also the conducted offline calibration of the silicon pixel detector will be explained. After presenting the simulated SM and signal samples which were used in this analysis (Sec. 1.4) the event selection is shown (Sec. 1.5). Then, the various sources of background are characterized (Sec. 1.6) and the methods to estimate their size are presented (1.7). As a final step an optimization in the search sensitivity was done, which can be found in Sec. 1.8. The chapter concludes by presenting the results of this analysis in Sec. 1.10, and after a short introduction to the statistical methods of limit setting (Sec. 1.9), the results will be interpreted in the context of Supersymmetry (Sec. 1.11).

1.1 Motivation

As it was already pointed out in Chap. ??, Supersymmetry is able to offer solutions to unexplained phenomena in astrophysics and can solve the shortcomings of the Standard Model of particle physics. Unfortunately, the unknown mechanism of supersymmetry breaking, the most general parametrization of Supersymmetry introduces over 100 new dimensions which opens up an incredibly huge phenomenologically rich space, leading to very different possible signature at particle colliders. During the Phase I run at the LHC in 2012, a variety of different searches, optimized on the hunt for supersymmetry were conducted. At the CMS and at the ATLAS experiment, taking data from proton-proton collisions, a strong focus was put on the search for hints of SUSY in the strong production sector (e.g. [1–3]). This led already to a wide exclusion in SUSY space, which nevertheless still offers some very interesting non-excluded parameter regions. The search for SUSY in more "exotic" regions gains therefore more and more attention. Typical SUSY scenarios which are not easily excluded by the general SUSY searches consists of so-called compressed spectra, where two or more particles are nearly degenerate in their masses. When mother and daughter particles are almost mass-degenerate, the remaining decay product in a two body decay can be very soft in p_T , making those scenarios very challenging to search for. Thus supersymmetric scenarios with compressed spectra are usually much weaker constrained than the corresponding scenarios without compressed spectra.

In this analysis the focus is put on the possibility of a lightest chargino (χ_1^\pm) which is almost mass degenerate with the lightest neutralino (χ_1^0). As shown in Sec. ??, long lifetimes are possible for various reasons. The scenarios presented here lead to long lifetimes of the chargino because of phase space suppression.

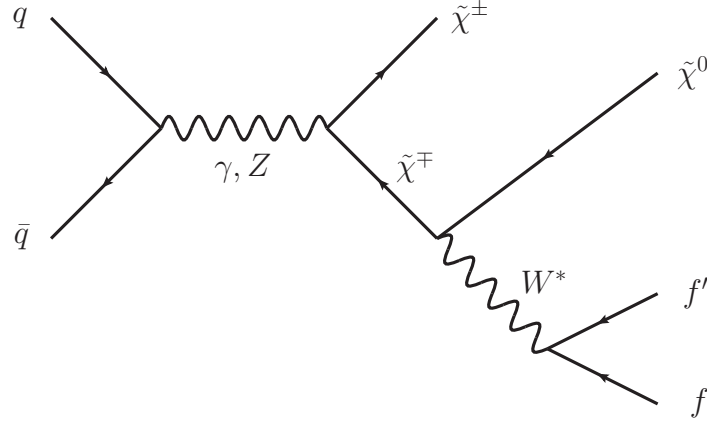


Figure 1.1: Feynman diagram showing a possible production mechanism of a chargino pair and the decay channel of a chargino.

A chargino can be produced via chargino pair production through a photon or a Z boson exchange. The chargino decays then via a virtual W boson to the lightest neutralino and fermion-fermion pair (e.g. a pion). This process is illustrated in the Feynman diagram shown in fig. 1.1.

Other possible production channels are the exchange of a supersymmetric Higgs boson or via a t-channel squark exchange. The corresponding Feynman diagrams for the tree level production channels are shown in Fig. 1.2.

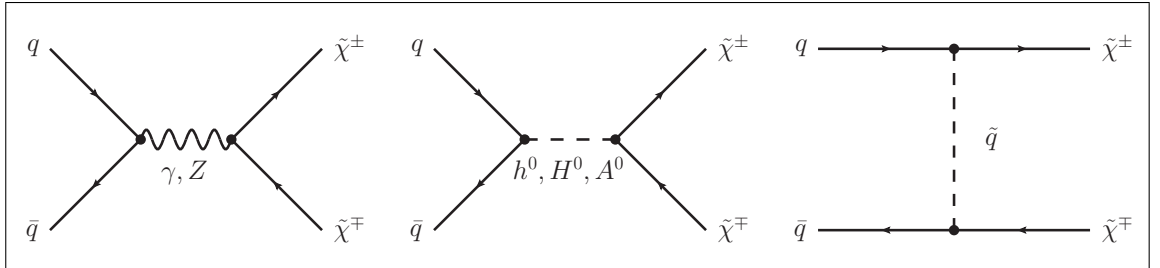


Figure 1.2: Main tree level diagrams for chargino pair production.

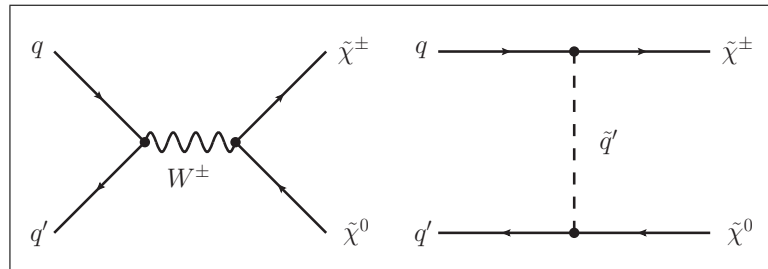


Figure 1.3: Main tree level diagrams for chargino neutralino production.

Another possibility of chargino production is the chargino neutralino production channel. On tree level, there exist two production mechanisms: the s-channel W boson exchange and the t-channel squark exchange, see Fig. 1.3 for the Feynman diagrams.

Even if the presented supersymmetric model where χ_1^\pm and χ_1^0 are nearly mass-degenerate leads to more exotic signatures at the CMS experiment, there have been already several analyses conducted in CMS which are in principle (even not all were designed to be) sensitive to these models. Among those are a search for long-lived charged particles [4], which was mainly designed for particles which have such a long lifetime that they travel through the full detector without decaying and a search for disappearing tracks [5] which looked for rather intermediate lifetimes, where the charginos decay already inside the tracker. Within [5], a study was done, based on an interpretation exercise [6] within the phenomenological MSSM (see Sec. ?? for a detailed introduction to the pMSSM), which tests the exclusion power of various analyses done at CMS.

In Fig. 1.4, the exclusion power of the search for long-live charged particles [4] in red, the search for disappearing tracks [5] in purple and a collection of various SUSY analysis from [7] in blue over the chargino mass is shown. In black the distribution of the unexcluded pMSSM parameter points vs. the chargino mass can be seen. The sampling of the parameter space points was done according to a pre-CMS likelihood function, which takes

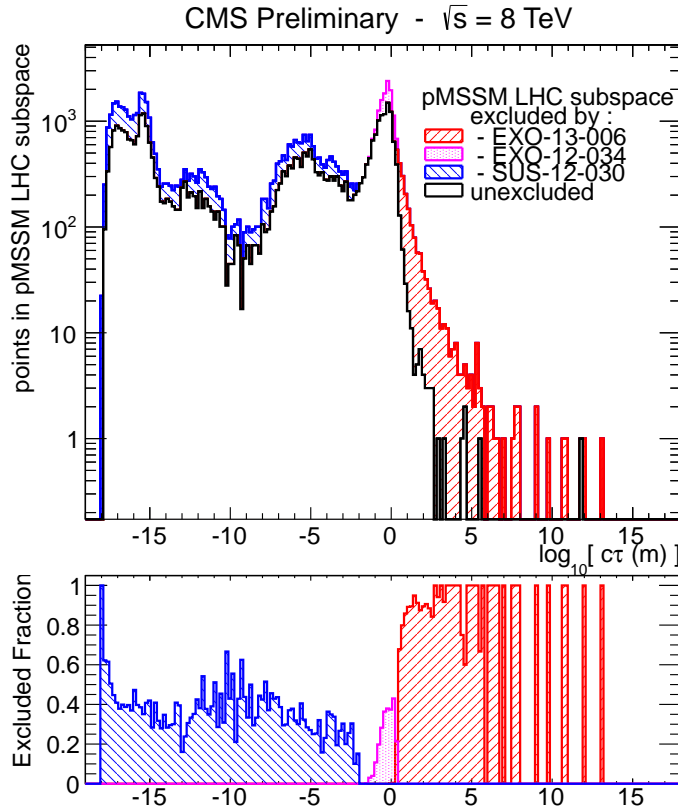


Figure 1.4: Exclusion power of various analyses dependent on chargino lifetime $[c\tau]$. Lower part of the plot shows the excluded fraction. Taken from: [click here](#).

into account electroweak precision measurements, etc. In the lower part of Fig 1.4, the excluded fraction of pMSSM points is shown. It can be seen, that the more general SUSY searches are mostly sensitive to shorter chargino lifetimes ($c\tau \lesssim 10$ cm), whereas the search for long-lived particles shows very good sensitivity for lifetimes > 100 cm. The search for disappearing tracks is sensitive on supersymmetric models with chargino lifetimes between $35 \text{ cm} \lesssim c\tau \lesssim 100 \text{ cm}$.

This analysis is targeting the gap between the disappearing track search (purple area) and the searches which are sensitive to instantaneously decaying charginos (blue area). The idea is to make use of the variable dE/dx which can be very discriminating for particles with high mass. The challenges of such a search and the general strategy of this analysis will be presented in the next section.

1.2 General search strategy

When searching for supersymmetric models with long-lived $\tilde{\chi}_1^\pm$, the strategy is of course highly dependent on the actual lifetime of the chargino. For long lifetimes, the chargino can reach the muon chambers and can be reconstructed as a muon (even with a longer time-of-flight). For lower lifetimes, the chargino can already decay inside the detector (e.g. the tracker), thus not leading to a reconstructed muon in the event, but only to an isolated track in the tracker. The detector signatures of these two scenarios are visualised in Fig 1.5, where in a cross-sectional view of the CMS detector simulated chargino-chargino events are shown. As mentioned before, this analysis targets a search for supersymmetry with charginos of lifetimes between $10 \text{ cm} \lesssim c\tau \lesssim 40 \text{ cm}$. That means that the charginos decay rather early in the detector, even at the beginning of the tracker. The distinct

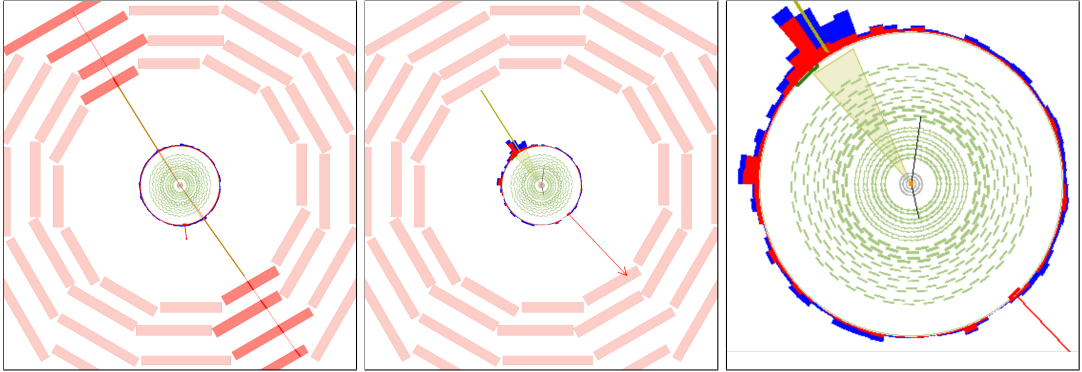


Figure 1.5: Visualisation of possible signatures of a chargino pair produced with a lifetime of $c\tau = 10$ m (left) and a lifetime of $c\tau = 0.5$ m (middle and right). In the left picture, both charginos are reconstructed as muons, which can be seen in the energy deposition in the muon chambers (red boxes). In the middle picture both charginos are only visible as tracks in the tracker (black lines), where both trajectories end inside the silicon tracker, showing the decay point point of the corresponding chargino. The right picture is a zoom of the picture in the middle. Here only the cross-section of the tracker (green wavy lines) is displayed. The red arrow shows the missing transverse energy in the event.

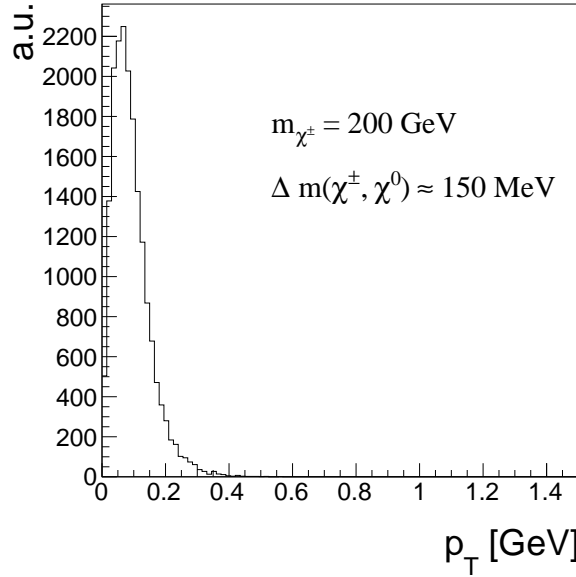


Figure 1.6: Transverse momentum distribution of pions coming from chargino decay into a neutralino with a mass gap of 150 MeV.

challenges of such an analysis, shall be listed in the following passage.

First of all, in case R-parity (see Sec. ??) is conserved, one of the decay products of the chargino, which is the lightest neutralino $\tilde{\chi}_1^0$ is stable, thus travelling through the whole detector only weakly interacting. Therefore it is not detectable. The other chargino decay product, e.g. a pion, can be hardly reconstructed, mainly because it does not origin from the primary vertex (if the chargino reaches the detector before its decay), but secondarily because it is very low in momentum because of the mass-degeneracy between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$. The momentum of the decay product is of course highly dependent on the actual mass gap between the neutralino and the chargino. A typical p_T distribution of a pion originating from a chargino decay can be found in Fig. 1.7 for a mass gap between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ of 150 MeV. The p_T distribution peaks at ~ 100 MeV and ends at $p_T \sim 400$ MeV. When the transverse momentum of a particle is very low, the particle trajectory is much more bended compared to a particle with higher p_T (see Fig. 1.7 for illustration), thus making the detection of such a particle very challenging. Because of the stronger bending, the track reconstruction efficiency decreases for particles with a transverse momentum below 1 GeV rapidly, ending at around 40% for isolated pions with a p_T of 100 MeV (see [8]).

Taking the hard or even impossible detection of the decay products of the chargino, this lead to the fact, that besides the (short) track of the chargino, nothing can be seen in the detector. Unfortunately, there is no dedicated track trigger at CMS, which makes a specific detection of those events with the help of the chargino track impossible. To be able to search for these models, one therefore need to take advantage of higher order contributions to the feynman diagrams shown in the previous sections (Figs. 1.2,1.3), resulting in initial state radiation (ISR). When the initial quarks radiate a high p_T gluon, the resulting jet can be detected and can offer a possibility to search for isolated tracks

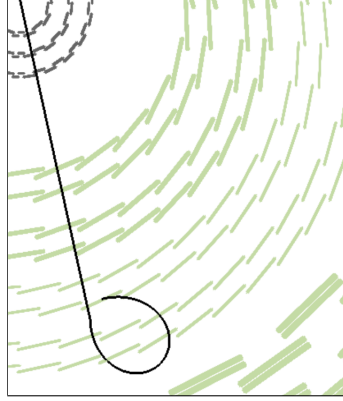


Figure 1.7: Cross-sectional view of the tracker (different tracker layers are illustrated with wavy green lines) and a simulated chargino track (black line) decays to a pion (bended black line).

in the tracker. The non-detection of the chargino's decay products plus a high p_T ISR jet lead additionally to missing transverse energy (MET) in the event. Exploiting these two circumstances, it is possible to detect chargino-pair or chargino-neutralino events with the help of Jet+MET triggers.

To select possible charginos in an event, additional requirements for isolated, high p_T tracks are needed. Those tracks can be eventually disappearing, which means that the track does not cross the full pixel and strip detector. This can happen, when the chargino decays inside the tracker. For very low lifetimes, the tracks can be very short and can have only a few hits in the detector. To define a helical path five parameters are needed, therefore a minimum of three hits are required to be able to reconstruct a particle's trajectory (see [8]). In this analysis, the massiveness of the charginos shall be exploited, on the one hand by selecting only high p_T tracks, but on the other hand by requiring a high energy deposition per path length ($\frac{dE}{dx}$). The energy deposition depends quadratically on the particle's mass for low velocities ($0.2 < \beta\gamma < 0.9$).

$$\left\langle \frac{dE}{dx} \right\rangle = K \frac{m^2}{p^2} + C \quad (1.1)$$

thus constitute a very nice discriminating variable for massive particles. A specific challenge for this analysis is the combination of searching for short tracks and utilising the energy deposition of the chargino. Unfortunately, the pixel tracker during Run I underwent only a calibration procedure at the very beginning of the start of data taking in 2011. Because of various readjustments during the year 2012, this introduced a huge non-calibration over time. In case we want to look at the $\frac{dE}{dx}$ of the tracks, there is therefore the need to recalibrate the pixel detector in order to be able to use its energy information in this analysis.

1.2.1 Comparison to existing searches

As already mentioned before, there were several analyses at CMS, which are sensitive to intermediate lifetime charginos. Most notably, the search for long lived-charged particles [4] and the search for disappearing tracks [5]. An improvement in sensitivity to shorter lifetimes compared to these analysis shall be achieved by including also very short tracks in this analysis. In [4], a minimum number of eight hits, whereas in [5] a minimum of seven hits are required. This can be very unefficient for shorter lifetimes, where most of the charginos decay already after the pixel tracker (~ 10 cm). Additionally, the search for disappearing tracks does not make use of the high energy deposition of heavy particles. On the other hand is this variable used in the search for long-lived particles, where the sensitivity decreases much quicker for shorter lifetimes (see Fig 1.4). In [5], there is a muon-veto exploited to suppress SM background coming from processes resulting in one or two muons. Additionally, it requires missing outer hits in the tracker (disappearing track), which makes this analysis especially sensitive to a shorter tracks. In the presented analysis, the strong selection on the number of hits in the tracker shall be lowered and the variable $\frac{dE}{dx}$ shall be included to increase sensitivity. Also, a muon-veto is applied to make the selection especially sensitive to very short lifetimes. **MAYBE** show here already a plot with the number of valid hits distribution to emphasize the importance of loosening the number of hits cut!

1.3 Improved dE/dx measurement of short tracks

It was already pointed out, that the inclusion of the pixel energy measurements can increase the sensitivity when searching especially for short tracks. While the silicon strip detector has already been calibrated as part of the search for long-lived charged particles [4], there was never an offline calibration done for the pixel silicon tracker. To increase the discrimination power of $\frac{dE}{dx}$, such a calibration procedure was therefore conducted within this PHD thesis.

1.3.1 Measuring dE/dx

The mean energy loss per path length of particles travelling through a layer of material can be described with the Bethe formula [9]:

$$\left\langle \frac{dE}{dx} \right\rangle = kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]. \quad (1.2)$$

It is valid, where the main energy loss originates from ionization effects which is in a region between $0.1 \lesssim \beta\gamma \lesssim 1000$. It is a function of the atomic number (Z) and the atomic mass of the absorber (A). The mean excitation energy (I) for silicon is 173 ± 3 eV [?]. T_{\max} stands for the maximum energy transfer in a single collision. The relevant particle's properties are the velocity (β), the lorentz factor (γ) and the charge (z) of the incident particle. The density correction $\delta(\beta\gamma)$ reduces the mean energy loss at high energies because of polarization effects of the material.

Even if widely used, the mean energy loss is a quantity which is “ill-defined experimentally and is not useful for describing energy loss by single particles” [10]. The problem is caused by the underlying probability distribution of a single $\Delta E/\Delta x$ measurement: the

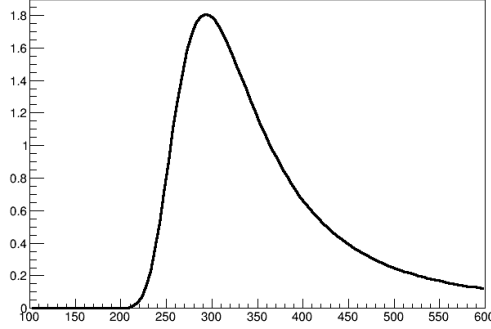


Figure 1.8: Illustration of a Landau function. Parameters were arbitrarily chosen for this figure.

Landau distribution [11]

$$p(x) = \frac{1}{\pi} \int_0^\infty e^{-t \log t - xt} \sin(\pi t) dt. \quad (1.3)$$

The Landau distribution is a highly asymmetric distribution with a long tail towards the right end (see Fig. 1.8). Theoretically it extends to infinite energies, however in nature the maximal deposited energy is of course limited by the particle's full energy. The mean and the variance of a landau distribution are not defined. Because of its high assymetry, measurements of $\langle \frac{dE}{dx} \rangle$ with only a few single measurmentse are easily biased towards high values, making the mean energy loss described by the Bethe formula to a problematic and unstable concept.

A much better observable is the most probably value (MPV): the maximum of the Landau function. The MPV is much more stable compared to the mean and is not as easily biased towards higher $\frac{dE}{dx}$ values. The most probable energy loss of a charged particle is defined by the Landau-Vavilov-Bichsel equation:

$$\Delta_p = \xi \left[\ln \frac{2mc^2 \beta^2 \gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right], \quad (1.4)$$

where $\xi = (K/Z)\langle Z/A \rangle(x/\beta^2)$. The thickness of the absorber x appears explicitly in the Landau-Vavilov-Bichsel equation making the most probable energy loss per path length $\frac{\Delta_p}{dx}$ logarithmically dependent on x . A comparison between the Bethe mean energy loss $\langle \frac{dE}{dx} \rangle$ and the most probable energy loss $\frac{\Delta_p}{dx}$ is shown in Fig. 1.9. However, when measuring tracks with around ~ 20 hits, it is obviously not too simple to extract the most probable value. Large fluctuations can still lead to biases towards higher value of the most probable $\frac{dE}{dx}$.

There are several "estimators", which try to suppress as much as possible a bias towards the high end, without introducing a bias to lower values. One of the estimator, also used in the next chapter, is the harmonic-2 estimator

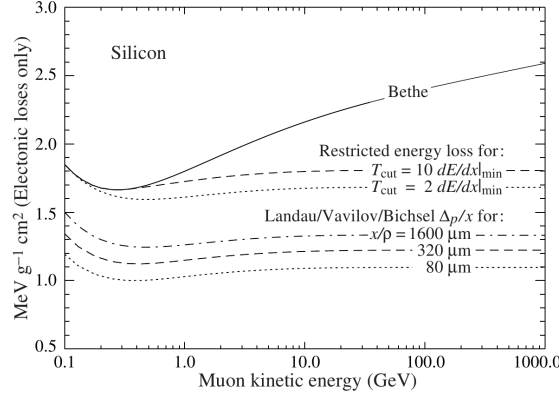


Figure 1.9: Comparison between the Bethe mean energy loss with and without restricted energy loss and the most probable energy loss described by the Landau-Vavilov-Bichsel function for different sizes of thickness. Taken from [10].

$$I_{h2} = \left(\frac{1}{N} \sum_{i=1}^N (\Delta E / \Delta x)_i^2 \right)^{-1/2} \quad (1.5)$$

$\Delta E / \Delta x$ correspond to one measurement in one tracker module. The harmonic mean of all N measurements with the power of 2 is then the estimated most probable $\frac{dE}{dx}$.

SM particles as pions and muons are minimal ionising in silicon for $\beta\gamma \sim 4$, dependent on the thickness of the material (see Fig. 1.10). For higher momenta the deposited energies increase again reaching a plateau at around $\beta\gamma \sim 100$. However, new heavy charged particles would mainly be unrelativistic because of their high mass and would therefore deposit much higher energies in the detector. This makes $\frac{dE}{dx}$ a very well discriminating variable. Thus, the energy loss per path length can be used to discriminate between SM particles and new heavy charged particles, which are usually unrelativistic because of their

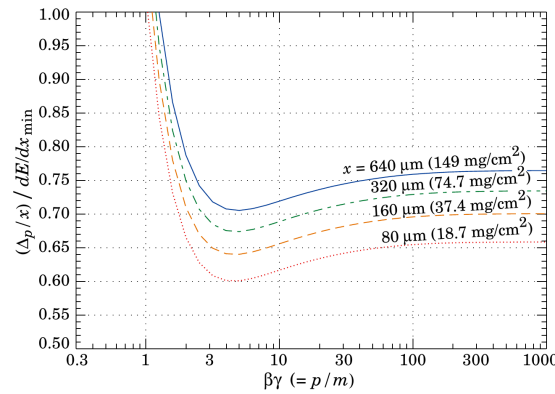


Figure 1.10: Most probable energy loss in silicon, scaled to the mean loss of a minimal ionizing particle ($388 \text{ eV}/\mu\text{m}$). Taken from [10].

high mass.

1.3.2 Gain calibration of the silicon pixel tracker

During Run I in 2012, the pixel silicon detector was continuously subjected to an energy calibration, called gain calibration. Every pixel was calibrated to the same response, such that the whole pixel tracker should be well inter-calibrated. Unfortunately, due to various reasons, such as the imperfect constancy of the reference signal, or radiation and temperature induced changes, the energy calibration was not adequate enough to use the measured energy deposition without a further offline calibration procedure. This imperfection of the gain calibration can be seen in Fig. 1.11, where the sum of the harmonic-2 estimator for all tracks ($\sum_{\text{all tracks}} I_{h2}$) over time is shown. Four different steps can be spotted. The first and the third correspond to a change in the settings of the tracker, which needed to be done because of increased radiation damages, etc. The second and fourth step show the moment where an online gain calibration was again applied. Unfortunately, although a gain calibration was carried out (even with some delay), it could not bring the average dE/dx to the same level before the change in the setting occurred. The size of the difference in the dE/dx measurement over time being around 15% is too large to use dE/dx without a further calibration.

In the following section the method of the gain calibration of the pixel silicon tracker explained. Detailed technical information about the pixel tracker can be found in Sec. ??.

Method

The main goal of the gain calibration is to get a uniform response in $\frac{dE}{dx}$ over the full data taking period in 2012. To ensure also a uniform response of all modules within one time step, also an inter-calibration on module level was carried out. The inter-calibration can in principle be done on various stages: the highest granularity would be a calibration on pixel level, followed by a calibration on ROC-level and then on module-level. Lower granularities in descending order are rings (modules with same z-position) and finally layers (3 layers in the barrel and 4 disks in the endcap). It was checked that all pixels and

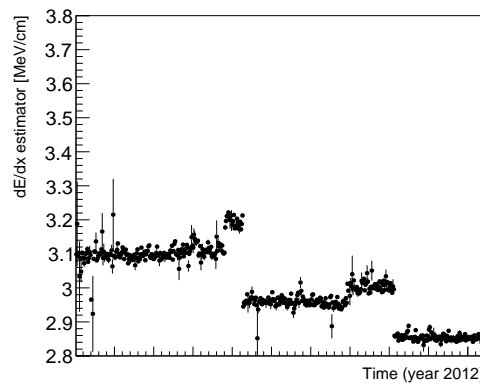


Figure 1.11: Sum of all track's dE/dx (harmonic-2 estimator) over the full year 2012. Every data point corresponds to one run.

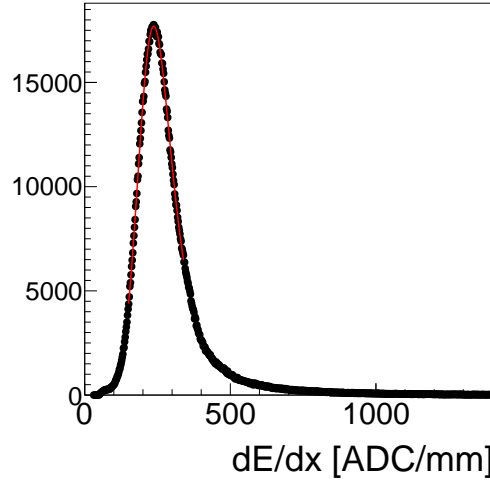


Figure 1.12: An example of the dE/dx distribution measured in ADC count per mm for one module of the CMS pixel tracker. A landau convoluted with a gaussian is fitted to the core of the distribution in an iterative procedure.

all ROCs (on one module) are well inter-calibrated, such that the inter-calibration was finally done module-wise. Of course, as a final step the well inter-calibrated pixel tracker within space and time, needs to be calibrated to the correct energy release of a MIP, to have a meaningful physical quantity. Therefore, as a last step an overall calibration factor c_{strip} was determined to calibrate the average energy deposition (using the harmonic-2 estimator) of all tracks in the pixel tracker to the average energy release in the silicon strip detector. This can be done because the strip tracker has already been calibrated in Run I within the following analysis [4]. The applied method for the gain calibration of the pixel tracker follows also the described method in [12].

The gain calibration of the pixel silicon tracker has been carried out with the help of minimal ionising particles (MIPs). MIPs in this context are not defined as particles depositing a minimum amount of energy, but more general a small amount of energy. This denotes all particles located at the plateau of the $\frac{dE}{dx}$ distribution vs. momentum (see Fig. 1.10). This ensures that all particles deposit a rather similar amount of energy such that the variation due to different momenta is suppressed. The small ionisation for particles was ensured with a momentum selection of $p > 5$ GeV. For the calibration a sample containing around 50 million “minimum bias” events was used which is specifically recorded for tracker calibration purposes. “Minimum bias” means there is neither an online nor offline selection applied.

For every module in the pixel tracker (there are 1440 modules in total), each $\Delta E/\Delta x$ measurement of all particles crossing the module is filled into a histogram. In Fig. 1.12 shows an example distribution for one module. The underlying Landau distribution can be nicely seen. However the fit was performed with a landau convoluted with a gaussian function to increase the fit performance and the stability of the fit. The measurement of $\Delta E/\Delta x$ is done in ADC counts per mm. ADC counts are a measure for the deposited charge after digitization. It consists out of a unsigned 16-bit integer (ranging from 0 to 65

535). The path length dx is calculated with

$$dx = d_{module_i} \cdot \cos(\phi_{track}), \quad (1.6)$$

where d_{module_i} is the thickness of module i and ϕ_{track_j} is the relative angle of the particle's trajectory to the axis normal of the module. With the extracted MPV, for every module an inter-calibration factor is calculated, being

$$c_{inter} = \frac{MPV[ADC/mm]}{300 \cdot 265[ADC/mm]}. \quad (1.7)$$

The factor $300 \cdot 265 [ADC/mm]$ is in principal an arbitrary number. However, it was chosen such that it corresponds approximately to the most probable energy deposition of a MIP. The calibration factor can then be used to scale every measurement in a module to a calibrated $\frac{dE}{dx}$ measurement

$$\frac{dE}{dx}_{calibrated} = \frac{\frac{dE}{dx}_{uncalibrated}}{c_{inter}} \quad (1.8)$$

The determination of the calibration factor needs to be done for every of the five time steps, shown in Fig. 1.11 independently, in order to get rid of the time dependency. Finally the overall calibration factor c_{strip} is determined.

Results

The final result is 1440·5 different calibration factors c_{inter} . These can be found in Fig. 1.13 for all five different time steps.

- Show stability plot after calibration.
- Read Loic's chapter about the gain calibration, maybe there are some interesting aspects
- Talk about MC gain calibration
- Talk about the total calibration
- Show strip plot.
-

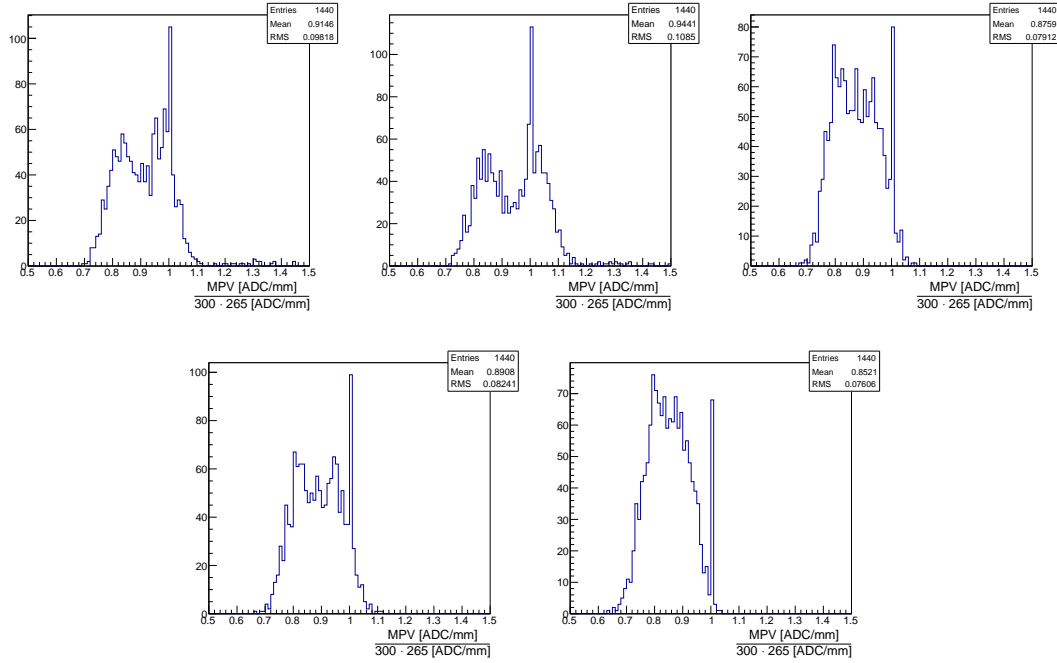


Figure 1.13: The resulting calibration factors for all five time step (from left top to bottom right in increasing time).

1.3.3 Asymmetric Smirnov discriminator

1.3.4 Efficiency improvements

1.4 Simulated samples

1.4.1 SM samples

1.4.2 Signal samples

1.5 Event selection

1.5.1 Datasets and triggers

- Datasets and triggers used in the analysis
- signal samples generated with Madgraph and pythia
- They are decayed in Geant to only pions. Around ten different lifetimes were simulated
- For other lifetimes: lifetime reweighting is done PLOT
- For five different masses (100-500 GeV)

1.5.2 Preselection

- Motivate different selection cuts
- Reference DT search for most of them

1.5.3 Main discriminating variables

- dE/dx
- p_t
- Show some MC signal bkg comparison plots (only Wjets?)

1.6 Sources of backgrounds

- Background consist of particles which make high energy deposits and are high p_t
- In general: Low background search

1.6.1 Fake tracks

- Definition of fake tracks
- How can they fake the signal

1.6.2 Muons

- How can muons fake the signal

1.6.3 Pions

- How can pions fake the signal

1.6.4 Electrons

- How can electrons fake the signal

1.7 Background estimation methods

1.7.1 Fake background

1.7.2 Leptonic background

1.7.3 Systematic uncertainties

1.8 Optimization of search sensitivity

- Show plots
- show table
- Include NlostOuter here, too

1.9 Statistical Methods/ Limit setting

1.10 Results

- Data cutflowtable
- Tables with results
- One plot (4 bins: Prediction and data)

1.11 Interpretation

1.11.1 Systematic uncertainties of simulated signal samples

1.11.2 Exclusion limits

- 1-d limits
- 2-d limits

Bibliography

- [1] CMS Collaboration, “Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s}=8$ TeV”, *JHEP* **06** (2014) 055, [arXiv:1402.4770](#). doi:10.1007/JHEP06(2014)055.
- [2] CMS Collaboration, “Searches for Supersymmetry using the M_{T2} Variable in Hadronic Events Produced in pp Collisions at 8 TeV”, *JHEP* **05** (2015) 078, [arXiv:1502.04358](#). doi:10.1007/JHEP05(2015)078.
- [3] ATLAS Collaboration, “Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s}=8$ TeV proton-proton collision data”, *JHEP* **09** (2014) 176, [arXiv:1405.7875](#). doi:10.1007/JHEP09(2014)176.
- [4] CMS Collaboration, “Searches for long-lived charged particles in pp collisions at $\sqrt{s}=7$ and 8 TeV”, *JHEP* **07** (2013) 122, [arXiv:1305.0491](#). doi:10.1007/JHEP07(2013)122.
- [5] CMS Collaboration, “Search for disappearing tracks in proton-proton collisions at $\sqrt{s}=8$ TeV”, *JHEP* **01** (2015) 096, [arXiv:1411.6006](#). doi:10.1007/JHEP01(2015)096.
- [6] CMS Collaboration, “Reinterpreting the results of the search for long-lived charged particles in the pMSSM and other BSM scenarios”, *CMS Physics Analysis Summary CMS-PAS-EXO-13-006* (2014).
- [7] CMS Collaboration, “Phenomenological MSSM interpretation of the CMS 2011 5fb-1 results”, *CMS Physics Analysis Summary CMS-PAS-SUS-12-030* (2013).
- [8] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014), no. 10, P10009, [arXiv:1405.6569](#). doi:10.1088/1748-0221/9/10/P10009.
- [9] H. Bethe, “Theory of the Passage of Fast Corpuscular Rays Through Matter”, *Annalen Phys.* **5** (1930) 325–400. [Annalen Phys.397,325(1930)]. doi:10.1002/andp.19303970303.
- [10] Particle Data Group Collaboration, “Review of Particle Physics”, *Chin. Phys.* **C38** (2014) 090001. doi:10.1088/1674-1137/38/9/090001.
- [11] L. Landau, “On the energy loss of fast particles by ionization”, *J. Phys.(USSR)* **8** (1944) 201–205.
- [12] L. Quertenmont, “Search for Heavy Stable Charged Particles with the CMS detector at the LHC”. PhD thesis, Louvain, U., 2010.

