

# 1 Motivation

Supersymmetry is able to offer solutions to unexplained phenomena in astrophysics and can solve the shortcomings of the Standard Model of particle physics (see Section ??). Unfortunately, due to the unknown mechanism of supersymmetry breaking, the most general parametrisation of Supersymmetry introduces over 100 new parameters and thus opens up an incredibly large phenomenological space, leading to very different possible signatures at particle colliders. A variety of searches were hunting for SUSY during the Phase I run at the LHC in 2012. Proton-proton collision data from the CMS and ATLAS experiments were analysed with a strong focus on the search for SUSY in the strong production sector (e.g. [1–3]). As a consequence, wide regions of SUSY parameter space are already excluded and the search for SUSY in more "exotic" regions gains more and more attention. Typical SUSY scenarios that are not easily excluded by the general SUSY searches consist of so-called compressed spectra where two or more particles are nearly mass-degenerate. Such scenarios can have two very distinctive phenomenological properties. First, if mother and daughter particles in a two body decay are almost mass-degenerate, the remaining decay product can be very soft in  $p_T$ , making them very hard to detect. Second, the mother particle can be long-lived due to phase space suppression (see Section ??). Because of these two properties, scenarios with compressed spectra can be challenging to search for and are in general much weaker constrained.

In R-parity conserving Supersymmetry, compressed spectra can be realised if the lightest neutralino ( $\chi_1^0$ ) is almost mass-degenerate with the lightest chargino ( $\chi_1^\pm$ ). Such a mass-degeneracy naturally occurs in case of wino-like neutralinos and charginos, since the mass gap between  $W_3$  and  $W_{1/2}$  is fully determined by higher loop corrections (see Section ??). SUSY models with a wino-like lightest neutralino are especially interesting because they are able to explain the sources of the relic density  $\Omega_{\text{CDM}} h^2$ . While it is not possible to explain the full relic density with thermally produced neutralinos for  $m_{\chi_1^0} \lesssim 2.9$  TeV [4], neutralinos can still be the dominant part if they are non-thermally produced via the decay of a long-lived particle such as a wino-like chargino [5].

At the LHC, there are several possible chargino production channels. Chargino pairs can be produced through a photon or a  $Z$ -boson exchange. The chargino then decays via a virtual  $W$ -boson to the lightest neutralino and a fermion pair (e.g. a pion). This process is illustrated in the Feynman diagram in Fig. 1.1.

Other possible chargino pair production channels include the exchange of a supersymmetric Higgs boson or a  $t$ -channel squark exchange (Fig. 1.2).

Apart from pair production, charginos can be produced via 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 (Fig. 1.3).

Thus, the LHC offers the potential to search for charginos and due to its high centre-of-mass energy it is the first collider that can access SUSY models with charginos of several hundreds GeV.

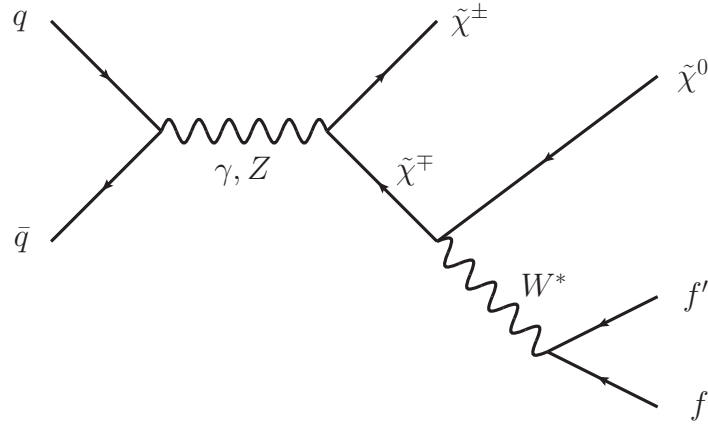


Figure 1.1: Feynman diagram of chargino pair production via gamma or  $Z$ -boson exchange and the subsequent decay via a virtual  $W$ -boson.

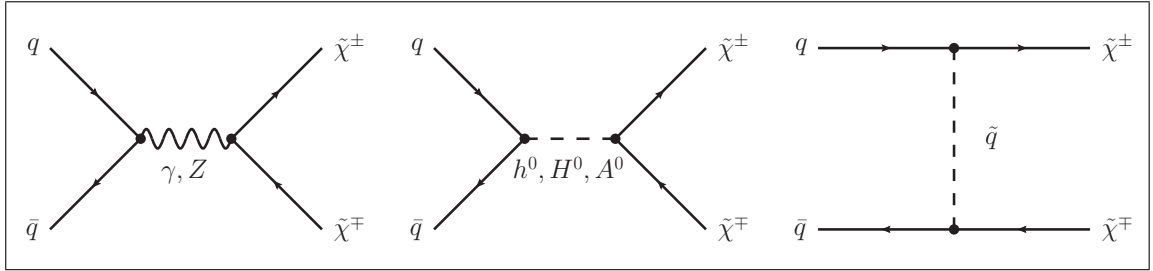


Figure 1.2: Main tree-level diagrams for chargino pair production.

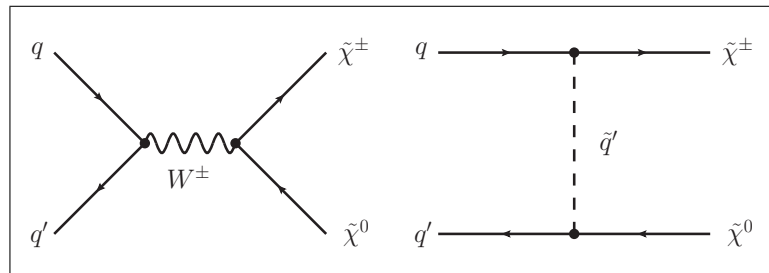


Figure 1.3: Main tree-level diagrams for chargino neutralino production.

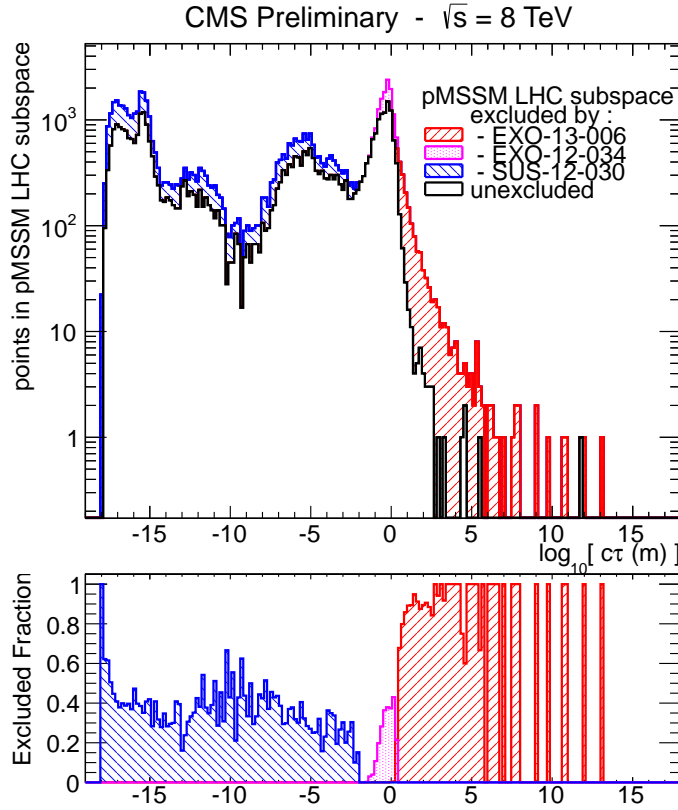


Figure 1.4: The number of excluded pMSSM points at 95% C.L. (upper part) and the fraction of excluded pMSSM points (bottom part) vs. the chargino lifetime for different CMS searches. Red area: the search for long-lived charged particles [7], Purple area: the search for disappearing tracks [6], Blue area: a collection of various general SUSY searches [8]. The black line indicates the unexcluded pMSSM parameter points. The sampling of the parameter space points was done according to a prior probability density function which takes pre-LHC data and results from indirect SUSY searches into account (see [9] for further details). Taken from: [10].

Although supersymmetric models with nearly mass-degenerate  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  lead to exotic signatures with long lived charginos and soft decay products, existing SUSY searches at CMS can in principle be sensitive to these models. The exclusion power of existing SUSY searches can be assessed by interpreting their results in terms of the fraction of excluded parameter points in the phenomenological MSSM (see Section ?? for a detailed introduction to the pMSSM). The results of such a study which has been performed in [6] are shown in Figure 1.4. It can be seen that general SUSY searches (blue area) are mostly sensitive to shorter chargino lifetimes ( $c\tau \lesssim 10$  cm)<sup>1</sup>. Two existing searches, the search for long-lived charged particles [7] and the search for disappearing tracks [6] focus on long and

<sup>1</sup>It should be mentioned, that the pMSSM interpretation relied on the use of fast simulation techniques which are not capable of simulating charginos with lifetimes  $c\tau > 1$  cm. It could therefore not be tested to which exact upper lifetime the searches combined in the blue area are sensitive to.

intermediate chargino lifetimes respectively. These two searches (purple and red areas) are sensitive to chargino lifetimes of  $\gtrsim 35$  cm. Taken together, the existing searches exclude a large fraction of pMSSM points at different chargino lifetimes. However, there is a gap between the general SUSY searches and the search for disappearing tracks where none of the existing searches show a high sensitivity.

The here presented analysis aims at targeting this gap by focusing on charginos with intermediate lifetimes of  $10 \text{ cm} \lesssim c\tau \lesssim 40 \text{ cm}$ . The main idea is to make use of the variable  $dE/dx$  which can be very discriminating for massive particles such as charginos. The associated challenges and the general strategy of this analysis will be presented in the next section.

## 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 despite a longer time-of-flight [11]. For lower lifetimes, the chargino can already decay inside the detector (e.g. the tracker), and can hence not be reconstructed as a muon but leads to an isolated, potentially disappearing track in the tracker. The detector signatures of these two scenarios are visualised in Fig. 2.1, where simulated chargino-chargino events are shown in a cross-sectional view of the CMS detector.

Since this analysis targets a search for Supersymmetry with charginos of lifetimes between  $10 \text{ cm} \lesssim c\tau \lesssim 40 \text{ cm}$ , the charginos decay rather early in the detector, even in the inner layers of the tracker. Thus, the signature of the chargino consists of an isolated track and the signatures of the decay products, i.e. of a neutralino and a fermion pair. In case of R-parity conservation the neutralino is stable and weakly interacting, thus traversing the detector without leaving any further signature. The missing transverse energy of the neutralino is balanced by the missing transverse energy of the second produced SUSY particle. This is either a neutralino or the decay products of the chargino in events with chargino pairs.

The signature of the fermion pair can in principle be used to select chargino events. However, for mass-degenerate charginos, it can be very hard or even impossible to detect these fermions as will be explained in detail in the next paragraph.

First of all, the fermionic decay product (e.g. a pion) can hardly be reconstructed because it does not origin from the primary vertex. Secondly, it is very low in momentum because of the mass-degeneracy between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ . The typical momentum of a pion originating from a chargino to neutralino decay in the  $\tilde{\chi}_1^\pm$  rest frame is of the order

$$p_\pi \sim \sqrt{m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} - m_\pi}.$$

For a mass gap between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  of  $\Delta m = 150$  MeV, the pt distribution of the resulting pion peaks at  $\sim 100$  MeV and ends at  $p_T \sim 400$  MeV (Fig. 2.3).

If 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. 2.3 for illustration). Due to this

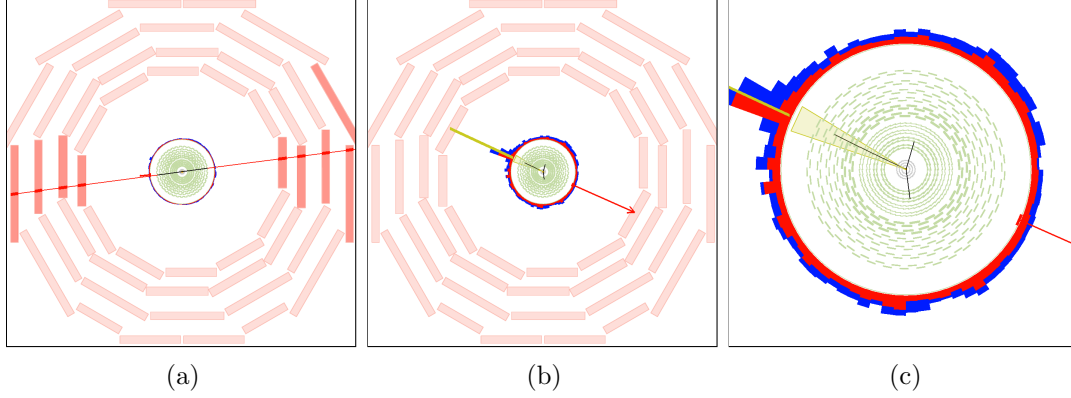


Figure 2.1: Visualisation of possible signatures of a chargino pair produced with a lifetime of  $c\tau = 10$  m (a) and a lifetime of  $c\tau = 0.5$  m (b and c). In the left picture, both charginos are reconstructed as muons, which can be seen in the energy deposition in the muon chambers (red boxes). In the middle picture both charginos are only visible as tracks in the tracker (black lines), where both trajectories end inside the silicon strip tracker, showing the decay 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 for the strip and grey lines for the pixel) is displayed. The red arrow shows the missing transverse energy in the event. The red (blue) towers correspond to the energy deposition in the ECAL (HCAL).

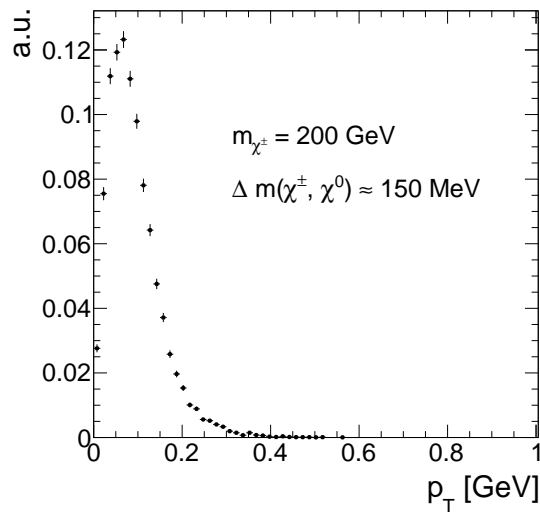


Figure 2.2: Transverse momentum distribution of pions coming from chargino decay into a neutralino with a mass gap of 150 MeV.

bending, the track reconstruction efficiency of particles with a transverse momentum below 1 GeV decreases rapidly, reaching around 40% for isolated pions with a  $p_T$  of 100 MeV [12]. It is therefore impossible to rely on a reconstruction of the fermionic chargino decay products in this analysis.

In summary, the signature of chargino events in mass-degenerate SUSY models consists only of a potentially disappearing- track. Such a signature is very difficult to detect, especially since CMS doesn't offer a dedicated track trigger so that triggering on the chargino track is impossible.

In order to search for such signatures, one therefore needs to trigger on other, less obvious properties of chargino events. This analysis takes 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). If the initial quarks radiate a high  $p_T$  gluon, the resulting jet can be detected and can offer a possibility to search for events with nothing more than isolated tracks. Furthermore, the non-detection of the chargino's decay products plus a high  $p_T$  ISR jet lead 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.

Since Jet+MET triggers are not very specific for chargino events, it is important to identify further track properties that can be used to select chargino candidates. One distinctive property of charginos compared to SM particles is their high mass. Therefore, charginos can be identified by selecting high  $p_T$  tracks. Furthermore, the energy loss per path length ( $dE/dx$ ) depends quadratically on the particle's mass for low velocities ( $0.2 < \beta\gamma < 0.9$ ):

$$\langle \frac{dE}{dx} \rangle = K \frac{m^2}{p^2} + C$$

Therefore,  $dE/dx$  constitutes a very nice discriminating variable for massive particles like charginos against SM particles. The selection of chargino events in this analysis thus relies on the selection of isolated high  $p_T$  tracks with high  $dE/dx$  values.

If the chargino decays before it has crossed the full pixel and strip detector, the as-

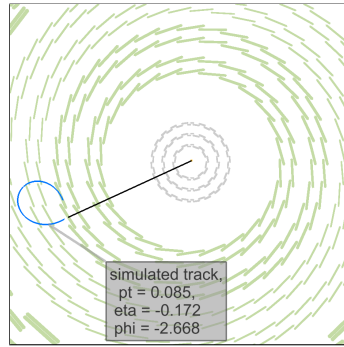


Figure 2.3: Cross-sectional view of the tracker (silicon strip (silicon pixel) tracker layers are illustrated with green (grey) lines) and a simulated chargino track (black line) decaying to a pion (bended blue line) with a  $p_T$  of  $\sim 85$  MeV and a neutralino (not visible).

sociated track is disappearing. For low lifetimes, the tracks can be very short and can have only a few hits in the detector. In order to reconstruct a particle's trajectory, a minimum of three hits are required since defining a helical path requires five parameters (see [12]). A specific challenge for this analysis is hence the combination of searching for short tracks and utilising the measurement of the energy deposition of the chargino. For very short tracks, eventually only passing the first couple of layers of the whole tracker system, the pixel tracker information becomes very important. Therefore, an accurate energy measurement in the pixel system is of great importance to this analysis. However, no other CMS analysis has used the energy information of the pixel tracker so far. This analysis thus requires a thorough study of the quality of the pixel energy calibration and, potentially, a recalibration in case the pixel energy calibration is not sufficient.

## 2.1 Comparison to existing searches

As already mentioned before, there are several analyses at CMS at  $\sqrt{s} = 8$  TeV with  $20 \text{ fb}^{-1}$  data, that are sensitive to intermediate lifetime charginos, most notably the search for long-lived charged particles [7] and the search for disappearing tracks [6]. The here presented analysis aims at achieving an increase in sensitivity towards shorter lifetimes compared to the existing analyses in a twofold way. First, the selection is optimised for the inclusion of very short tracks. Second, the inclusion of the variable  $dE/dx$  is used to increase the search sensitivity compared to [6].

In [7], a minimum number of eight hits were required for every track, whereas [6] required a minimum of seven hits. This can be very inefficient for shorter lifetimes, where most of the charginos already decay shortly after the pixel tracker. In Fig. 2.4 (left), the normalised distribution of the number of measurements ( $N_{\text{hits}}$ ) of chargino tracks is shown. It can be seen, that  $N_{\text{hits}}$  peaks at the minimal possible value needed for track reconstruction of  $N_{\text{hits}} = 3$  for lower lifetimes. For higher lifetimes ( $c\tau = 50 \text{ cm}$ ) the distribution shifts to higher values with a second peak at  $N_{\text{hits}} \sim 17$ . However, a notable fraction of  $\sim 40\%$  of chargino tracks still has a number of measurements of  $N_{\text{hits}} < 8$ .

It should be also mentioned, that the track reconstruction efficiency is sufficient for short chargino tracks, such that a loosening of the  $N_{\text{hits}}$  requirement is expected to be really improving the signal acceptance. The track reconstruction efficiency for different chargino decay points is depicted in Fig. 2.4 (right). For very short tracks ( $N_{\text{hits}} = 3$ ) the efficiency is still around 20%.

Additionally, the search for disappearing tracks which targets models with charginos decaying inside the tracker did not make use of the high energy deposition of heavy particles. Although this variable was indeed used in the search for long-lived charged particles, this search was not optimised for intermediate lifetimes (FIXME e.g. no muon veto on the selected tracks was required). Thus, it shows less sensitivity compared to the disappearing track search in the lifetime region between  $35 \text{ cm} \lesssim c\tau \lesssim 100 \text{ cm}$  (see Fig. 1.4).

To conclude, the general search strategy of the here presented analysis is to unite the strategies of [7] and [6] and to lower the strong selection on the number of hits in these analyses in order to get an optimised selection for lifetimes around  $10 \text{ cm} \lesssim c\tau \lesssim 40 \text{ cm}$ .

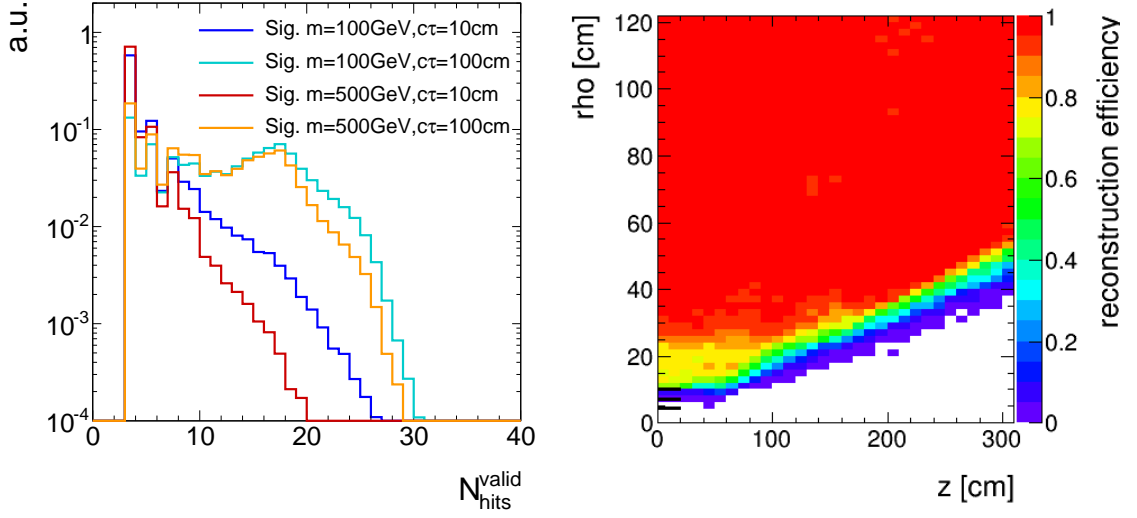


Figure 2.4: Left: Number of measurements in the tracker system  $N_{\text{hits}}$  for four different signal lifetimes. The low lifetime samples are rapidly falling and peaking at the lowest number of possible measurements of three. For a lifetime of  $c\tau = 50$  cm, a second peak at  $\sim 17$  hits appears corresponding to the number of measurements when crossing all pixel barrel (3) and strip inner and outer barrel (6 from stereo and 8 from normal) layers. Right: Probability to reconstruct a track ( $z$ ) in dependency of the chargino's decay point ( $x$  and  $y$ ). More information on the generation of the simulated signal samples can be found in Section 4.2

### 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 for short tracks. While the silicon strip detector has already been calibrated as part of the search for long-lived charged particles [7], there was never an offline calibration done for the pixel silicon tracker. To increase the discrimination power of  $dE/dx$ , such an calibration procedure was therefore conducted within this PHD thesis.



### 3.1 Ionisation loss of charged particles

The mean energy loss per path length of particles travelling through a layer of material can be described with the Bethe formula [13]:

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

It is valid, where the main energy loss originates from ionisation effects, i.e. 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 eV [14].  $T_{\max}$  stands for the maximum energy transfer in a single collision. The relevant particle's properties are the velocity ( $\beta$ ), the Lorentz factor ( $\gamma$ ) and the charge ( $z$ ) of the incident particle. The density correction  $\delta(\beta\gamma)$  reduces the mean energy loss at high energies because of polarisation 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” [15]. The problem is caused by the underlying probability distribution of one single  $dE/dx$  measurement (this will be named by  $\Delta E/\Delta x$  throughout the following sections), which can be parametrised by a Landau distribution [16]

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

The Landau distribution is a highly asymmetric distribution with a long tail towards the right end (see Fig. 3.1). 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 asymmetry,

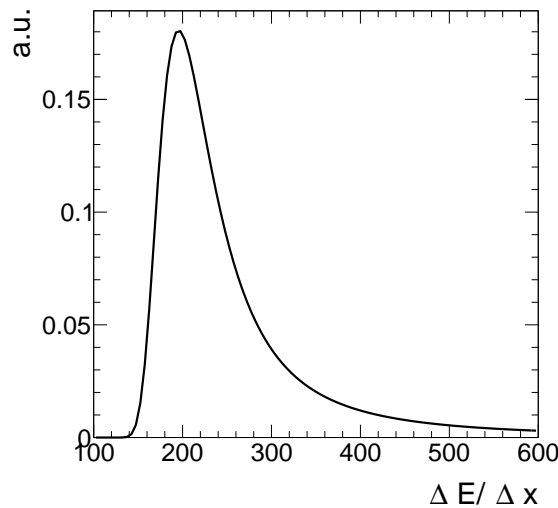


Figure 3.1: Illustration of the shape of a Landau distribution. Parameters were arbitrarily chosen for this figure.

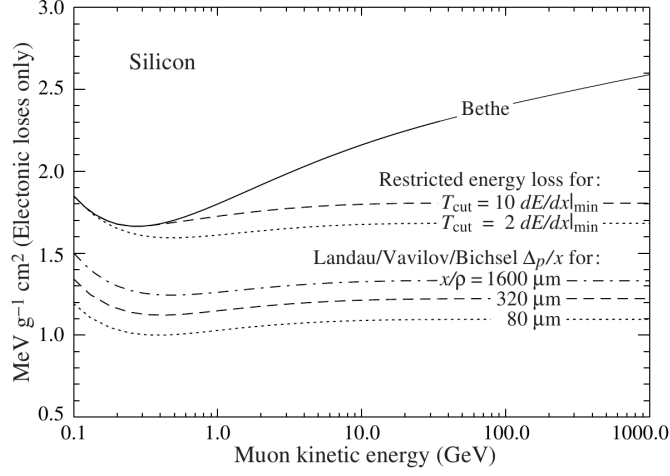


Figure 3.2: Comparison between the Bethe mean energy loss with and without restricted energy loss and the most probable energy loss described by the Landau-Vavilov-Bichsel function for different sizes of thickness. Taken from [15].

measurements of  $\langle dE/dx \rangle$  with only a few single measurements 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 probable value (MPV): the maximum of the Landau distribution. The MPV is much more stable compared to the mean and is not as easily biased towards higher  $dE/dx$  values. The most probable energy loss of a charged particle is defined by the Landau-Vavilov-Bichsel equation [17]:

$$\Delta_p = \xi \left[ \ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right], \quad (3.1)$$

with  $\xi = (K/Z)\langle Z/A \rangle(x/\beta^2)$ . The thickness of the absorber  $x$  appears explicitly in the Landau-Vavilov-Bichsel equation making the most probable energy loss per path length  $\Delta_p/dx$  logarithmically dependent on  $x$ . A comparison between the Bethe mean energy loss  $\langle dE/dx \rangle$  and the most probable energy loss  $\Delta_p/dx$  is shown in Fig. 3.2. However, when measuring tracks with around  $\sim 15$  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  $dE/dx$ .

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

$$I_{h2} = \left( \frac{1}{N} \sum_{i=1}^N (\Delta E/\Delta x)_i^2 \right)^{-1/2}, \quad (3.2)$$

where  $\Delta E/\Delta x$  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  $dE/dx$ .

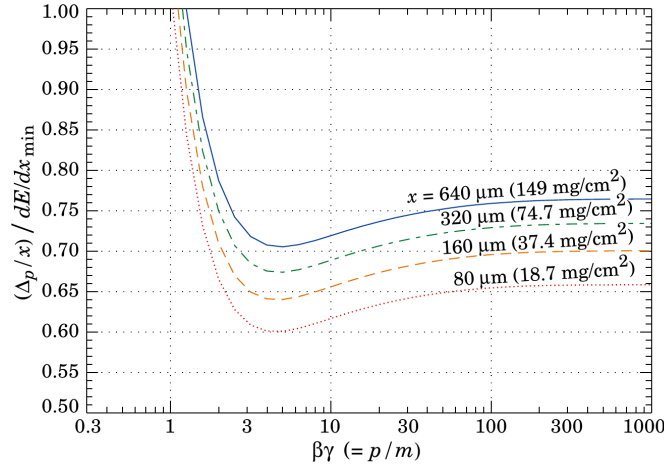


Figure 3.3: Most probable energy loss in silicon, scaled to the mean loss of a minimal ionising particle ( $388 \text{ eV}/\mu\text{m}$ ). Taken from [15].

SM particles as pions and muons are minimal ionising in silicon for  $\beta\gamma \sim 4$  (see Fig. 3.3). 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  $dE/dx$  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 high mass.

### 3.2 Energy calibration of the silicon pixel tracker

The CMS tracker system does not only allow for the precise measurement of particle's tracks and primary and secondary vertices but also the measurement of a particle's energy loss within the tracker material. This is done by the detection of the number of electrons produced by the ionisation of the particle during its passage through the silicon tracker. A detailed introduction about the CMS tracker system and the energy measurement can be found in Section ??.

During Run I in 2012, the pixel silicon detector was continuously subjected to an energy calibration, a so-called gain calibration. Every pixel was calibrated to the same response, such that the whole pixel tracker should have been 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 could not ensure a fully calibrated pixel tracker. This imperfection of the gain calibration can be seen in Fig. 3.4, where the sum of the harmonic-2 estimator for all tracks  $\sum_{\text{all trks}} I_{h2}$  over the full data-taking period in 2012 is shown. Four different steps can be spotted. The first and the third steps correspond to changes in the settings of the tracker due to irradiation. 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 changes in the settings 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 sections the method of the gain calibration (splitted into an section about the inter-calibration of gain and the absolute calibration of gain) of the pixel silicon tracker is explained. Detailed technical information about the pixel tracker can be found in Section ??.

### Inter-calibration of gain

The main goal of the gain calibration is to get a uniform response in the ionisation energy loss  $dE/dx$  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 all ROCs (on one module) are well inter-calibrated, such that the inter-calibration was finally done module-wise. The applied method for the gain calibration of the pixel tracker follows closely the method in [18].

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 generally a small amount of energy. This denotes all particles located at the plateau of the  $dE/dx$  distribution vs. momentum (see Fig. 3.3). It 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  $p > 2$  GeV. Additionally, only tracks

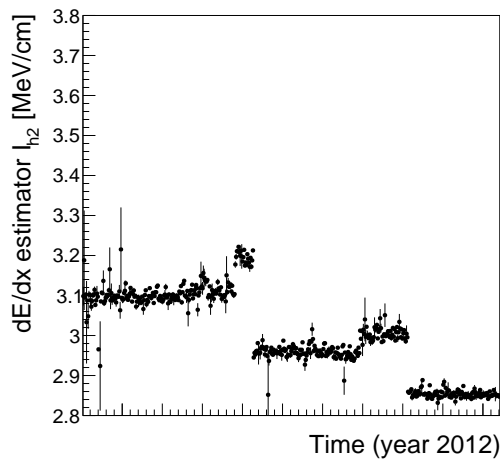


Figure 3.4: Sum of all track's  $dE/dx$  (harmonic-2 estimator) over the full year 2012. Only pixel hits are taken into account. Every data point corresponds to one run.

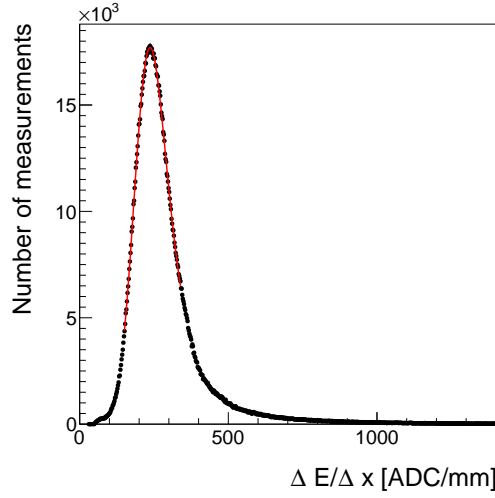


Figure 3.5: An example of the  $\Delta E/\Delta x$  distribution measured in ADC count per mm for one module of the CMS pixel tracker. A Landau convoluted with a Gaussian is fitted to the core of the distribution in an iterative procedure.

with at least eight hits and a  $\chi^2/n.d.o.f. < 3$  to ensure a good reconstruction were used. For the calibration a sample containing around 50 million “minimum bias” events is used which is specifically recorded for tracker calibration purposes. “Minimum bias” means that neither an online nor offline selection was applied.

For every module in the pixel tracker (there are 1440 modules in total), a distribution of the energy loss per path length  $\Delta E/\Delta x$  is built. Figure 3.5 shows an example distribution for one module. The underlying Landau distribution can be nicely seen. To extract the MPV for every module a fit to the core distribution is performed. The fit is done with a Landau convoluted with a Gaussian function to be closer to the experimentally observed energy spectrum. This also increases 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 digitisation. It consists out of a unsigned 16-bit integer (ranging from 0 to 65 535). The path length  $\Delta x$  is calculated with

$$\Delta x = d_{\text{module}_i} \cdot \cos(\phi_{\text{track}}),$$

where  $d_{\text{module}_i}$  is the thickness of module  $i$  and  $\phi_{\text{track}}$  is the relative angle of the particle’s trajectory to the axis normal of the module. With the measured MPV extracted from the fit, an inter-calibration factor is calculated for every module

$$c_{\text{inter}} = \frac{\text{MPV} [\text{ADC/mm}]}{\text{MPV}_{\text{target}} [\text{ADC/mm}]} = \frac{\text{MPV} [\text{ADC/mm}]}{300 \cdot 265 \text{ ADC/mm}}.$$

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

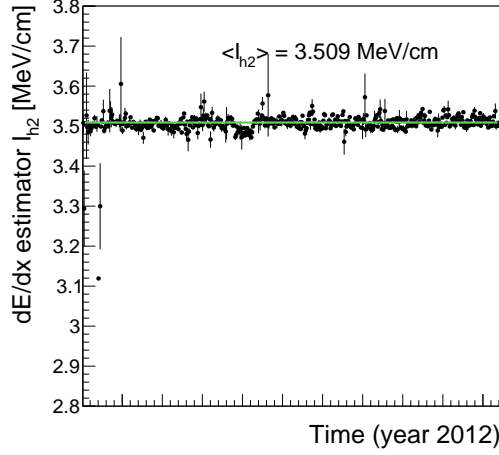


Figure 3.6: Sum of all track's  $dE/dx$  (harmonic-2 estimator) over the full year 2012 after applying the calibration factors, resulting in an average  $dE/dx$  of 3.51 MeV/cm. Only pixel hits are taken into account. Every data point corresponds to one run.

a calibrated  $\Delta E/\Delta x$  measurement

$$\frac{\Delta E}{\Delta x_{\text{calibrated}}} = \frac{\Delta E}{\Delta x_{\text{uncalibrated}}} \cdot c_{\text{inter}}$$

The determination of the calibration factor needs to be done for every of the five time steps, shown in Fig. 3.4 independently, in order to get rid of the time dependency. The result of the inter-calibration can be seen in Fig. 3.6. The variation over time was indeed eradicated, resulting in a maximal time variation of less than  $\sim 1\%$ .

Additionally, the same procedure is carried out for a corresponding simulated data sample to ensure also the inter-calibration of the pixel modules on all simulated samples.

### Absolute calibration of gain

As a final step, the targeted MPV being  $\text{MPV}_{\text{target}} = 300 \cdot 265 \text{ ADC/mm}$  needs to be translated to a meaningful physical quantity given in physical units (e.g. MeV/cm). That means, that the charge measurement in ADC counts needs to be converted to the real energy release of a particle. The relation between  $\Delta E$  in ADC counts and the energy loss in eV is given by

$$\Delta E [\text{eV}] = \frac{\Delta E [\text{ADC}]}{c_{\text{inter}}} \cdot \frac{N_e}{\text{ADC}} \cdot 3.61 \text{ eV},$$

where  $N_e/\text{ADC}$  is the number of electrons which correspond to one ADC count and 3.61 eV is the mean energy needed to create one electron-hole pair in silicon at  $-10^\circ\text{C}$ . Such an absolute gain calibration can be done with the help of several methods (all explained in [18]). For the absolute calibration of the silicon pixel tracker, it can be taken advantage

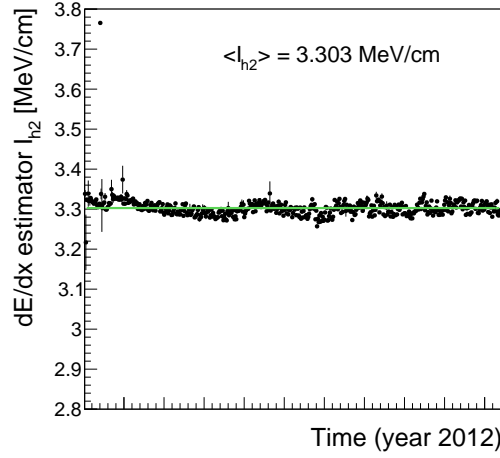


Figure 3.7: Sum of all track's  $dE/dx$  (harmonic-2 estimator) measured in the silicon strip detector over the full year 2012. The average most probable  $dE/dx$  is  $I_{h2} = 3.303$  MeV/cm. Every data point corresponds to one run.

of the already conducted absolute calibration of the silicon strip detector. In [18], the absolute gain calibration was done with the help of the most probable energy release per path length of muons, theoretically described by the Landau-Vavilov-Bichsel formula in Eq. 3.1. To calibrate the pixel tracker to the correct energy loss per path length it is therefore sufficient to determine one calibration factor to relate the average  $dE/dx$  of all tracks in the pixel tracker as shown in Fig. 3.6 to the average measured  $dE/dx$  in the strip tracker, shown in Fig. 3.7 by

$$c_{\text{absolute}} = \frac{dE/dx_{\text{strip}}}{dE/dx_{\text{pixel}}} = \frac{3.303}{3.509} = 0.941.$$

This factor is then applied on top of  $c_{\text{inter}}$  for all pixel modules.

Finally, also for the simulated samples an absolute calibration factor needs to be determined, where the simulated pixel tracker is calibrated to the average  $dE/dx$  of the silicon strip measured in data.

### 3.3 Discrimination of highly-ionising particles

As mentioned before, a difficult task when measuring the energy deposition of a particle consists in finding a robust estimator for the MPV of the underlying Landau, i.e combining eventually only a few single measurements of  $\Delta E/\Delta x$  to one single  $dE/dx$  estimator. The harmonic-2 estimator  $I_{h2}$  was already introduced in Section 3.1 in Eq. 3.2. It is known as a robust estimator not easily biased by large fluctuation in  $\Delta E/\Delta x$  because of the suppression by a factor of 2.

However, it was shown in [18] that a better discrimination between SM particles and possible new heavy particles can be achieved when using likelihood techniques, i.e. de-

termining the probability that the set of all  $\Delta E/\Delta x$  belonging to one track is actually compatible with the hypothetical probability distribution of a MIP.

Testing that a measured sample has been drawn from a specific distribution is known as the Smirnov-Cramér-von Mises test [19, 20], which is deduced from the integral of the squared difference of the measured distribution  $P_N(x)$  to the hypothesis distribution  $P(x)$

$$I_s = \int_{-\infty}^{\infty} [P_N(x) - P(x)]^2 dP(x)$$

leading to a test statistics of

$$I_s = \frac{3}{N} \cdot \left( \frac{1}{12N} + \sum_{i=1}^N \left[ P_i - \frac{2i-1}{2N} \right]^2 \right),$$

where  $P_i$  is the cumulative probability that a MIP would release a  $\Delta E/\Delta x$  equal or smaller than the measured  $\Delta E/\Delta x$  with all  $P_i$  are arranged in increasing order.

However, this test statistics is not sensitive to whether there are incompatibilities because of higher or lower variations compared to the hypothesis distribution. It is therefore not really suitable for the discrimination between MIPs and heavy new particles by  $dE/dx$ . A so-called Asymmetric Smirnov-Cramér-von Mises discriminator was developed in [18] which is only sensitive to incompatibilities to the MIP hypothesis towards higher energy depositions

$$I_{as} = \frac{3}{N} \cdot \left( \frac{1}{12N} + \sum_{i=1}^N \left[ P_i \cdot \left( P_i - \frac{2i-1}{2N} \right)^2 \right] \right).$$

A value of  $I_{as}$  close to zero indicates good compatibility with the MIP hypothesis, whereas a value close to one indicates worse compatibility because of too large energy loss.

The underlying probability distribution of the energy release for a given path length in the pixel tracker is extracted from the same “Minimum bias” sample used for the pixel energy calibration. In total 28 different templates each for a different given path length are created. The corresponding templates for the energy release in the silicon strip detector were already built by [18]. In Fig. 3.8 the probability distribution template for the pixel tracker in data and simulation is shown. A comparison between the energy release by MIPs ( $I_{as}$ ) in data and simulation for good quality tracks (high-purity as defined in [21] and minimum number of eight hits) with  $p > 5$  GeV and  $|\eta| < 2.1$  can be found in Fig. 3.9.  $dE/dx$  shows good agreement in data and simulation for  $I_{as} < 0.1$ . For larger values,  $I_{as}$  shows a larger decrease in simulation than in measured data. That’s the reason why a data-based approach for analyses exploiting  $dE/dx$  information is needed.

### 3.4 Discrimination improvements

The goal of including the pixel energy information is to increase the discrimination power of  $I_{as}$  between background and signal tracks, especially for shorter lifetimes. In Fig. 3.10, a comparison of the shapes of the energy release by MIPs and by signal tracks in simulation is shown (details about the simulated samples can be found in the next section Section 4.2).



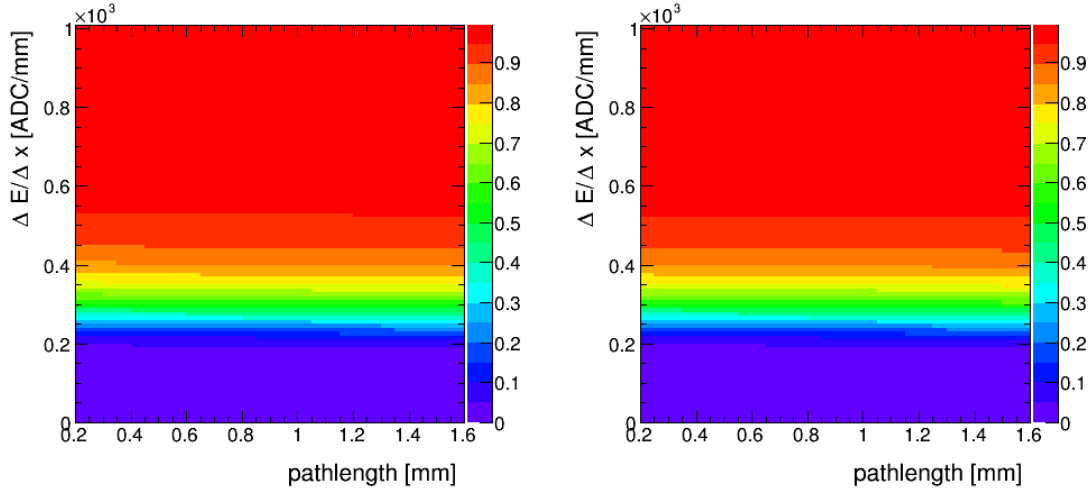


Figure 3.8: Cumulative probability for a MIP to release a  $\Delta E/\Delta x$  (y-axis) vs. the pathlength (x-axis) in data (left) and simulation (right) for the pixel tracker.

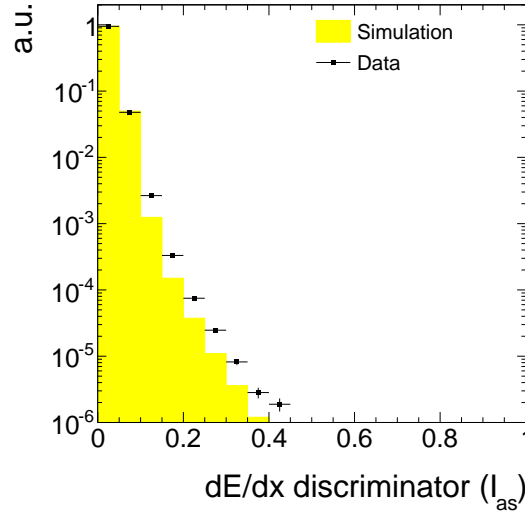


Figure 3.9: Normalised  $I_{as}$  distribution for MIPs from the minimum bias sample in data and simulation for good quality tracks with  $p > 5 \text{ GeV}$  and  $|\eta| < 2.1$ .

It can be seen, that the  $I_{as}$  distributions of the all signal models show a much longer tail toward  $I_{as} = 1$ , whereas the background is rapidly falling. Not only the mass of the signal track influences the  $I_{as}$  distribution but also the number of hits and the velocity ( $\beta$ ) distribution of a signal model. The influence of the velocity can be easily seen in Eq. 3.1. This in turn results in the dependency of  $I_{as}$  on the mass of the chargino. But also for models with the same mass, the velocity is higher in average for shorter lifetimes. This is caused by the fact, that for shorter lifetimes (e.g.  $c\tau = 10 \text{ cm}$ ), already a sizable fraction

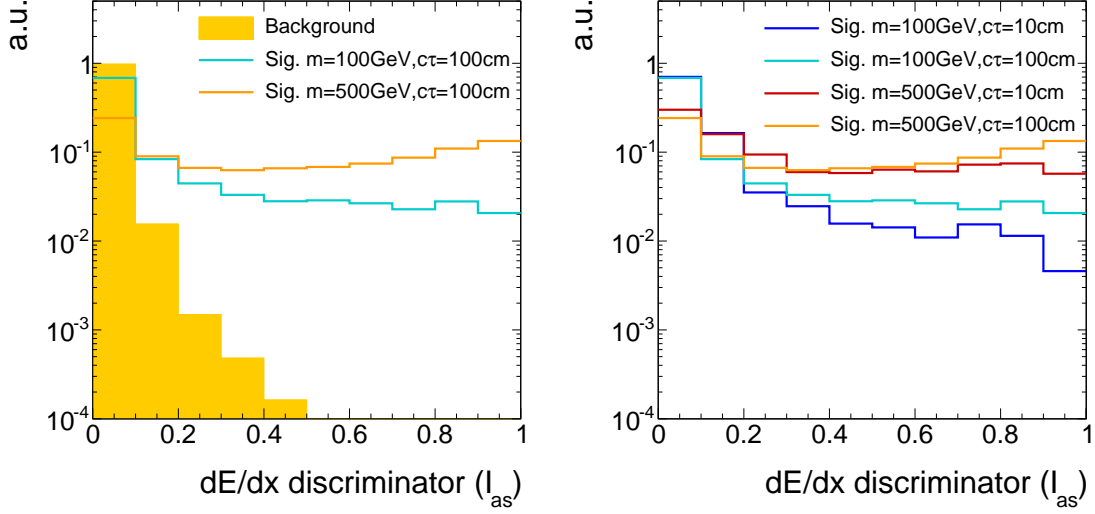


Figure 3.10: Normalised  $I_{as}$  distribution for simulated background and signal tracks (left) and for four different signal models (right) for high-purity tracks (as defined in [21]) with  $p_T > 10$  GeV and  $|\eta| < 2.1$ . For the illustration of the background tracks' spectrum simulated  $t\bar{t}$ +jets events are used (more information about this sample is given in Section 4).

of the charginos decay before reaching the tracker system. The probability of reaching the detector increases for higher velocities, which can be clearly seen at the survival probability

$$P(t) = e^{-\frac{t}{\gamma\tau}}, \quad (3.3)$$

which shows that the survival probability is increasing for increasing  $\beta$ . That means shorter lifetimes lead to higher average  $\beta$  which in turn lead to lower  $I_{as}$ .

The number of measurements in the tracker system defines the influence of single fluctuations in  $\Delta E/\Delta x$  on the  $I_{as}$  discriminator. Because of the large right tail of the Landau distribution, for tracks with a low number of hits this leads to higher  $I_{as}$  due to the fluctuations in the energy release.

That means that for models with lower lifetimes of the chargino there are two different effects: first, due to the smaller number of measurements the chargino tends to higher  $I_{as}$  values, second for low lifetime, the velocity distribution of those charginos reaching the detector is in average higher, which in turn leads to lower  $I_{as}$  values. Both effects can be seen in Fig. 3.10 (right). The large tail for longer lifetimes is caused by the lower velocities, but the small surplus between 0.1 and 0.2 is caused by the smaller number of measurements for lower lifetimes.

Finally, the impact of the additional  $\Delta E/\Delta x$  information from the pixel tracker on the selection efficiency of signal and background tracks shall be quantified. Figure 3.11 shows the signal selection efficiency against the background selection efficiency for different selection cuts in  $I_{as}$ , once including the pixel information and once without it. A previous selection of good quality tracks and  $p_T > 10$  GeV is applied. The background selection

efficiency is estimated with simulated  $W$ +jets events but was additionally checked on simulated  $t\bar{t}$ +jets and QCD-multijet events (further information about the simulated samples can be found in the next section). No significant difference between these processes in the background selection efficiency was observed.

The signal selection efficiency and the background suppression depend on the mass and the lifetime of the charginos. The discrimination power of  $I_{\text{as}}$  is as expected much better for higher masses. In addition, the impact of the inclusion of the pixel energy information is already for looser selections in  $I_{\text{as}}$  visible in the higher mass case. However, the additional energy information shows similar impact for very strong selections for all lifetimes and masses.

For high chargino masses and small signal selection efficiencies, the background suppression can be improved up to a factor of 20. For looser selections leading to higher signal efficiency of 40%, the gain in the suppression reduces to a factor of 10.

## 4 Simulated samples

For the investigation of the various backgrounds, the analysis relies also on simulated samples. An extensive introduction to the techniques and tools required for the simulation of SM and beyond SM processes can be found in Section ??.

In the following two sections an overview is given about the SM (Section 4.1) and SUSY samples (Section 4.2) used to design the search. All samples are reweighted to match the measured distribution of primary vertices in data.

### 4.1 Standard Model background samples

To investigate the sources of background, various simulated SM samples are used. In order to have the possibility to make use of the  $dE/dx$  variables, a special data format of the simulated samples is required (called RECO format). Unfortunately, not all SM processes were available in this specific format. However, as this analysis needs to rely anyways on a data-based background estimation method, because of the limited quality of the  $dE/dx$  simulation, it does not constitute a serious problem. It only limits the possibility of a comparison between data and simulation going beyond shape comparisons.<sup>1</sup>

In Table 4.1 all available SM samples used in this analysis are listed. Due to the immense size of the samples (between 5 and 70 TB) and in order to match a reasonable storage space a reduction is done by selecting only events which contain at least one leading jet with a minimum transverse momentum of  $p_{\text{T}} > 60 \text{ GeV}$ .

In addition, further simulated samples not containing the energy information are used. These are needed to study the background inclusively in the variable  $I_{\text{as}}$ . They are listed in Table 4.2.

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<sup>1</sup>E.g. the background process  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  sample is not available, which can possibly contribute via the fake background to the search. However, as the rate of fakes is independent of the underlying process, this background can be studied with the same quality with a  $W + \text{jets}$  sample.

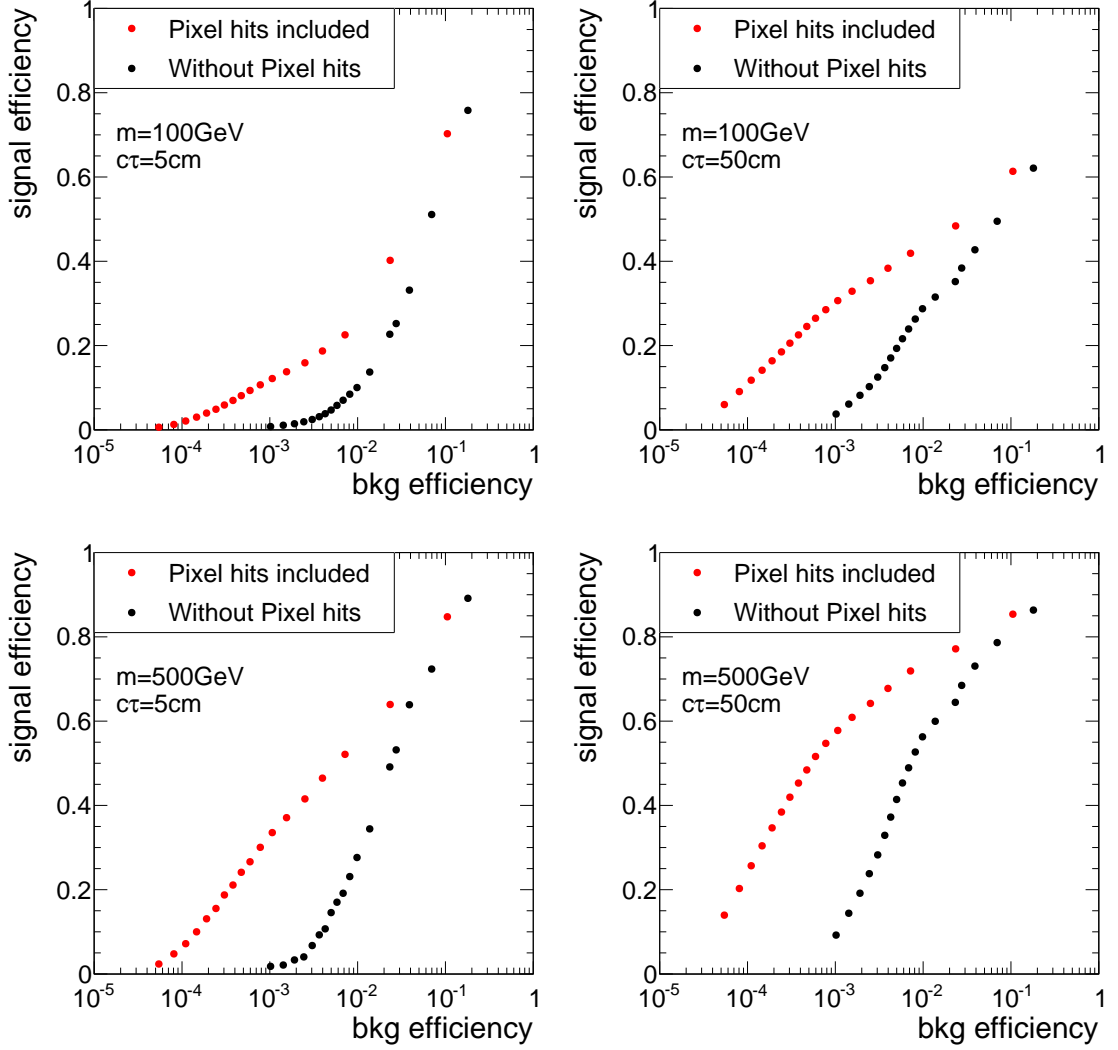


Figure 3.11: Signal selection efficiency vs. background selection efficiency when scanning through different selections in  $I_{\text{as}}$  for four different signal models.

## 4.2 Signal samples

For the investigation of a possible signal, events containing either chargino pair production  $q\bar{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  or chargino neutralino production  $q\bar{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$  are simulated. The simulation is done with the matrix-element event generator MADGRAPH [24]. The parton showering and hadronisation processes are then simulated with PYTHIA [25]. A last step is needed to simulate the interactions of the generated particles with the detector material, which is done with GEANT4 [26, 27].

Furthermore, a special treatment for long-lived particles is required. In order to get the right detector simulation of the energy loss of the long-lived particles which decay after the beam pipe, the lifetime of the chargino cannot be set in the matrix-element generator but needs to be specified within GEANT4.

To narrow down the required computing sources, the simulation is only done for a few lifetimes (1 cm, 5 cm, 10 cm, 50 cm, 100 cm, 1 000 cm and 10 000 cm). In order to get yet a tight scan over the lifetime space, other lifetimes are generated using lifetime reweighting. This can be done by determining a weight for every event. The weight depends on the individual proper lifetime of the chargino (in case of chargino pair production it depends on the individual lifetime of the two charginos). It is given by

$$w = \prod_{i=1}^n \frac{\tau^{\text{gen}}}{\tau^{\text{target}}} \cdot \exp \left[ t_i \cdot \left( \frac{1}{\tau^{\text{target}}} - \frac{1}{\tau^{\text{gen}}} \right) \right],$$

where  $n$  is the number of charginos in the event,  $\tau^{\text{gen}}$  is the generated mean lifetime in the particle's rest frame and  $t_i$  is the individual proper lifetime of the chargino. The resulting mean lifetime is then given by  $\tau^{\text{target}}$ . A derivation of this formula can be found in Appendix ???. With the reweighting procedure a tight covering of the lifetime space can be achieved with lifetimes of  $c\tau = a \cdot 10^n$  for  $n = 0, 1, 2, 3, 4$  and  $a = [1, 9]$ . Figure 4.1 shows the exponential distribution of the individual proper lifetime of the charginos after the reweighting of a simulated sample with  $c\tau^{\text{gen}} = 50$  cm to a lifetime of  $c\tau^{\text{target}} = 10$  cm. Fitting the exponential spectrum should result in the correct mean proper lifetime as parameter of the fit. It can be seen, that the reweighting procedure can reproduce the targeted lifetime of 10 cm.

All samples are generated for different masses of the chargino, but always almost mass-degenerate to the lightest neutralino. The mass gap between chargino and neutralino is set to 5 GeV. However, as this analysis does not make use of the decay products of the chargino and the lifetime is independently set within GEANT4, the mass gap does not play any role. Six different masses from 100 GeV to 600 GeV are simulated. This leads then to a total number of 42 signal samples. In Table 4.3 the NLO-NLL<sup>2</sup> cross sections at  $\sqrt{s} = 8$  TeV for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production with wino-like charginos are listed [28, 29]. The cross section does not dependent on the lifetime of the chargino.

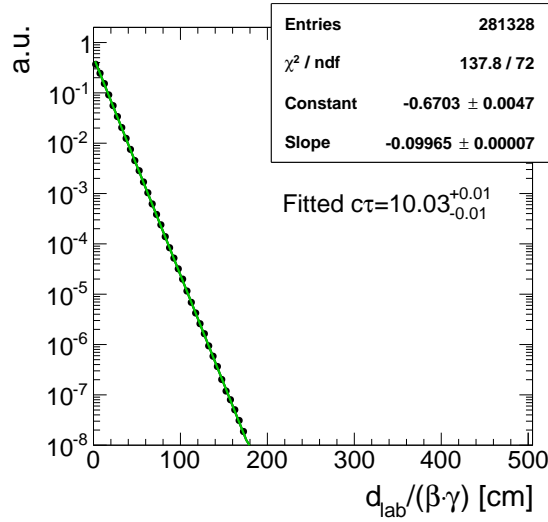
Table 4.1: Available Standard Model background samples containing  $\Delta E/\Delta x$  information which are used for background estimation studies.

Process	Cross section [pb]	$\mathcal{O}_{\text{calculation}}$
$W + \text{jets}$	36703.2	NNLO [22]
$t\bar{t} + \text{jets}$	245.8	NNLO [23]
$Z \rightarrow \ell\bar{\ell} + \text{jets}$ ( $\ell = e, \mu, \tau$ )	3531.9	NNLO [22]
QCD ( $50 \text{ GeV} < \hat{p}_T < 1400 \text{ GeV}$ )	9374794.2	LO

<sup>2</sup>NLO: next-to-leading order, NLL: next-to-leading logarithmic accuracy

Table 4.2: Standard Model background samples without  $\Delta E/\Delta x$  information.

Process	Cross section [pb]	$\mathcal{O}_{\text{calculation}}$
$W + \text{jets}$	36703.2	NNLO [22]
$Z \rightarrow \ell\bar{\ell} + \text{jets} (\ell = e, \mu, \tau)$	3531.9	NNLO [22]

Figure 4.1: Normalised distribution of the proper lifetime  $d_{\text{lab}}/(\beta\gamma)$  of all charginos contained in a signal sample with a generated lifetime of  $c\tau^{\text{gen}} = 50$  cm reweighted to a lifetime of  $c\tau^{\text{target}} = 10$  cm.

## 5 Event selection

### 5.1 Datasets and triggers

The analysis is performed on pp collision data recorded in the year 2012 at the CMS experiment for a centre-of mass energy of  $\sqrt{s} = 8$  TeV. In total an integrated luminosity of  $19.7 \text{ fb}^{-1}$  was recorded in 2012.

As outlined in Section 2, the detection of chargino tracks is a challenging task already on trigger level. The direct triggering of events containing chargino-like tracks is not possible because in 2012 there was no information about the tracking system on L1 level available. Furthermore, there is no intrinsic missing transverse energy in the event, when

Table 4.3: Simulated signal mass points with corresponding cross sections for wino-like charginos.

$m_{\tilde{\chi}_1^\pm}$ [GeV]	$\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp}$ [pb]	$\sigma_{\tilde{\chi}_1^0 \tilde{\chi}_1^\mp}$ [pb]
100	5.8234	11.5132
200	0.37924	0.77661
300	0.06751	0.14176
400	0.01751	0.03758
500	0.00553	0.01205
600	0.00196	0.00431

the chargino (or both charginos) decay inside the tracker. Therefore, the detection of these events shall be achieved with the help of initial state radiation. When initial state radiation occurs, it is possible to trigger on a high- $p_T$  jet and also on  $\cancel{E}_T$  in the event.

For this purpose, several triggers are exploited. To consider the event in the analysis, at least one of them must have fired. In Table 5.1 the three triggers are listed together with the corresponding recorded integrated luminosity in the time when they were active.

Table 5.1:  $\cancel{E}_T$  and  $\cancel{E}_T$  + jet triggers used in the analysis together with the corresponding recorded integrated luminosity in the time when they were in place.

Trigger	Luminosity [ $\text{fb}^{-1}$ ]
HLTMonoCentralPFJet80_PFMETnoMu95_NHEF0p95	5.3
HLTMonoCentralPFJet80_PFMETnoMu105_NHEF0p95	14.4
HLT_MET120_HBHENoiseCleaned	19.7

The HLTMonoCentralPFJet80\_PFMETnoMu95\_NHEF0p95 and HLTMonoCentralPFJet80\_PFMETnoMu105\_NHEF0p95 triggers exploit both the L1 ETM40 trigger, which requires the missing energy to be larger than 40 GeV. On HLT level, they require further at least one PF jet with  $p_T > 80$  GeV and the missing transverse momentum  $\cancel{E}_T$  (not taken into account the  $p_T$  of any muon in the event) to be larger than 95 GeV (or 105 GeV). Finally, the energy release by neutral hadrons must not be larger than 95% for all jets in the event. The HLTMonoCentralPFJet80\_PFMETnoMu95\_NHEF0p95 trigger was in place during Run A and Run B in 2012 data taking, whereas HLTMonoCentralPF-

Jet80\_PFMETnoMu105\_NHEF0p95 was set during Run C and Run D in 2012.

The HLT\_MET120\_HBHENoiseCleaned trigger is based on the two L1 triggers ETM40 and ETM36 which are combined by a logical OR. On HLT level, the trigger requires that the missing energy measured in the calorimeter is larger than 120 GeV. The HBHENoise-filter reduces background from electronic noise in the HCAL.

Table 5.2 lists the datasets in which the triggers used in the analysis are comprised. Again, because of the size of the datasets ( $\sim 150$  TB in total), a reduction of the size is

Table 5.2: MET data samples used in the search with the contained integrated luminosity.

Dataset	Luminosity [ $\text{fb}^{-1}$ ]
/MET/Run2012A-22Jan2013-v1/RECO	0.876
/MET/Run2012B-22Jan2013-v1/RECO	4.412
/MET/Run2012C-22Jan2013-v1/RECO	7.055
/METParked/Run2012D-22Jan2013-v1/RECO	7.354

achieved by selecting only events with at least one jet with a minimum  $p_T$  of 50 GeV.

In addition, the analysis makes use of the datasets listed in Table 5.3. These datasets are used for background estimation purposes and the estimation of their associated systematic uncertainties.

Table 5.3: Further datasets used for background estimation.

Dataset	Luminosity [ $\text{fb}^{-1}$ ]
/SingleMu/Run2012A-22Jan2013-v1/AOD	0.876
/SingleMu/Run2012B-22Jan2013-v1/AOD	4.405
/SingleMu/Run2012C-22Jan2013-v1/AOD	7.040
/SingleMu/Run2012D-22Jan2013-v1/AOD	7.369
/SingleElectron/Run2012A-22Jan2013-v1/AOD	0.876
/SingleElectron/Run2012B-22Jan2013-v1/AOD	4.412
/SingleElectron/Run2012C-22Jan2013-v1/AOD	7.050
/SingleElectron/Run2012D-22Jan2013-v1/AOD	7.368



## 5.2 Analysis selection

In order to suppress events originating from SM processes (such as QCD-multijet events,  $W + \text{jets}$ , etc.), a selection for signal-like tracks is applied which shall be described in the following sections. The candidate track selection follows closely the selection required in [30, 31].

### Event based selection

First, to suppress cosmic events and noise from the beam halo a selection on the quality of the vertex can be applied. This selection includes requirements of the position of the vertex with respect to the beam axes and the number of degrees of freedom (which is strongly correlated to the number of tracks originating from the vertex) [32]:

- ❖ The vertex must have at least four degrees of freedom:  $vtx$  with  $\geq 4$  d.o.f.
- ❖ The position of the vertex along the beam line must be within 24 cm from the beam origin:  $|dz| \leq 24$  cm.
- ❖ The position in the transverse direction must be within 2 cm from the beam origin:  $|d0| \leq 2$  cm.

After these selection cuts are applied the remaining events are subjected to a further pre-selection.

To maximise the signal acceptance, the trigger related selection cuts are chosen as close as possible to the trigger thresholds (see Section 5.1). In Fig. 5.1, the distributions of  $\cancel{E}_T$  and the transverse momentum of the leading jet  $p_T^{1.\text{jet}}$  are shown for different signal models. Only jets are taken into account with  $|\eta| < 2.4$  and which fulfil several further criteria:

- Charged hadron energy fraction  $> 0.2$
- Charged electromagnetic energy fraction  $< 0.5$
- Neutral hadron energy fraction  $< 0.7$
- Neutral electromagnetic energy fraction  $< 0.7$ .

These additional jet quality criteria ensure that noise from cosmic and beam halo muons and high- $p_T$  photons and electrons is suppressed [33]. It can be seen in Fig. 5.1 that already for a selection of  $\cancel{E}_T > 100$  GeV 80% of the signal events are rejected.

The trigger efficiency as a function of  $\cancel{E}_T$  and  $p_T^{1.\text{jet}}$  was determined within [34] with a single-muon reference sample. The trigger paths become fully efficient for  $p_T^{1.\text{jet}} \gtrsim 110$  GeV and  $\cancel{E}_T \gtrsim 220$  GeV [33].

However, as said before, this search imposes a trigger selection to maximise the signal acceptance. The trigger requirements are as follows:

- ❖ There is at least one jet within  $|\eta| < 2.4$  with transverse momentum larger than 110 GeV which fulfils the above mentioned jet noise cleaning criteria:  $p_T^{1.\text{jet}} > 110$  GeV.

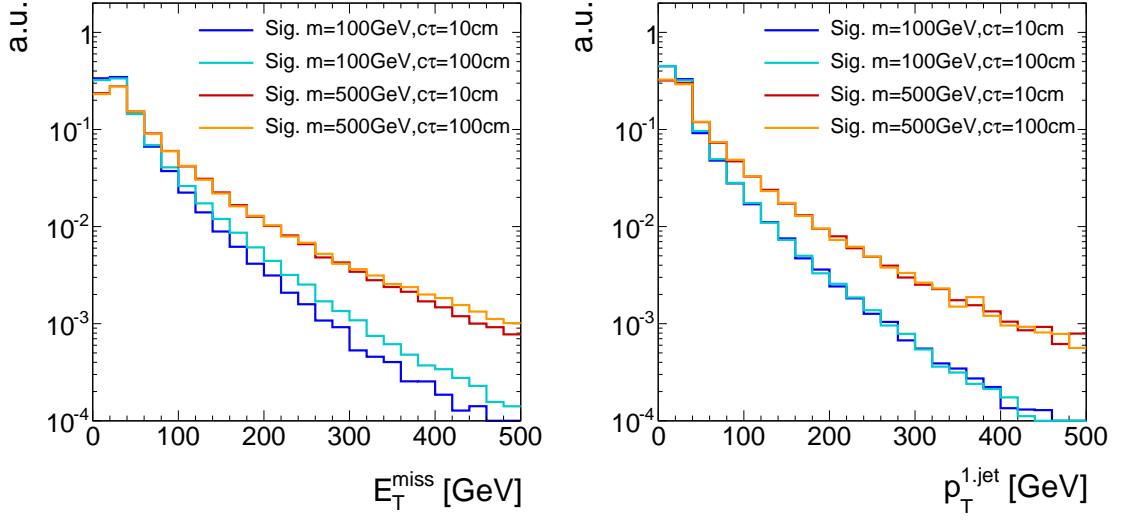


Figure 5.1: Normalised distributions of the missing transverse momentum (left) and the transverse momentum of the leading jet (right) for four different signal models.

- ❖ The missing transverse momentum must be larger than 100 GeV:  $\cancel{E}_T > 100 \text{ GeV}$

Because of the huge cross section, QCD-multijet events are frequently produced at the LHC. Due to jet energy mismeasurements, they can also contribute to data samples recorded with MET triggers. Therefore, some special requirements to suppress events emerging from strong production processes are enforced. QCD-multijet events can be characterised by topologies where two jets are almost back-to-back. Additionally, in QCD-multijet events the missing energy is usually aligned with one of the leading jets in the event. Therefore the following two requirements are sufficient to suppress QCD-multijet events efficiently:

- ❖  $\Delta\phi$  between any of two subleading jets (with  $p_T < 20 \text{ GeV}$  and  $|\eta| < 4.5$ ) in the event must be smaller than 2.5.
- ❖  $\Delta\phi$  between any of the two leading jets (with  $p_T < 20 \text{ GeV}$  and  $|\eta| < 4.5$ ) and the  $\cancel{E}_T$  must be larger than 0.5.

Figure 5.2 shows the maximal  $\Delta\phi$  of any of two subleading jets and the minimal  $\Delta\phi$  between the  $\cancel{E}_T$  vector and the first two subleading jets for the SM background and two different signal datasets.

### Candidate track selection

After the reduction of background processes with event based variables, a track based selection is carried out. To get an optimised selection for possible chargino tracks several signal track characteristics are exploited.

First a selection of tracks of good quality is enforced:

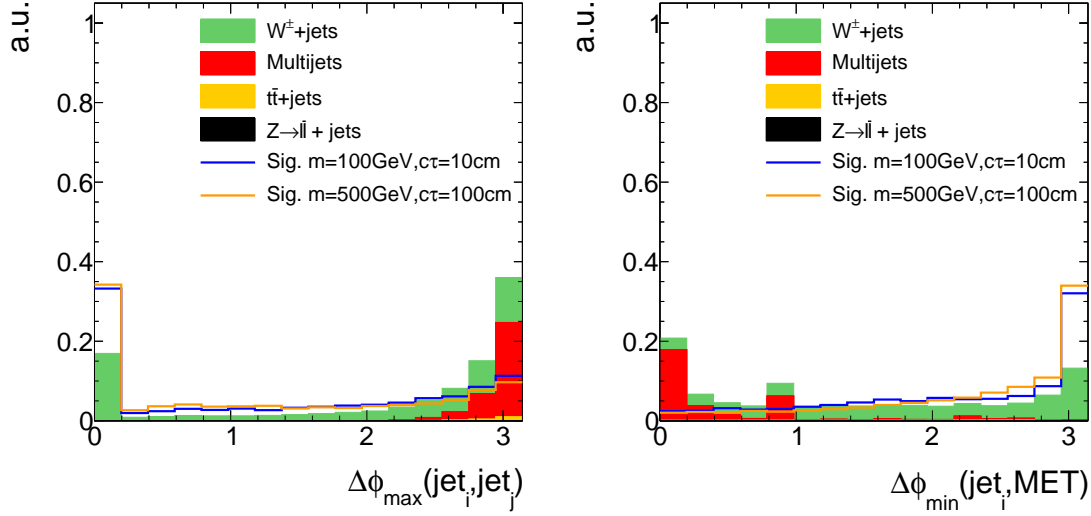


Figure 5.2: Maximal  $\Delta\phi$  between any of two subleading jets (left) and the minimal  $\Delta\phi$  between the  $\cancel{E}_T$  vector and the first two jets (right) normalised to unit area after the trigger selection.

- ❖ The track must be of “high purity” as defined in [21].
- ❖ The track is required to have no missing middle or inner hits:  $N_{\text{miss}}^{\text{middle/inner}} = 0$
- ❖ The radial and longitudinal distance of the track to the primary vertex must be small:  $|d0| < 0.02 \text{ cm}$ ,  $|dz| < 0.5 \text{ cm}$ .

In Figs ??, 5.3 and 5.4, the power of the quality selection cuts are shown.

Furthermore, a first kinematic preselection is applied:

- ❖ Only tracks are considered which are within the tracker acceptance taken an isolation cone into account:  $|\eta| < 2.1$ .
- ❖ A first loose selection of tracks in the transverse momentum is applied:  $p_T > 10 \text{ GeV}$ .

In order to suppress background tracks emerging from SM processes, an electron, muon and tau veto is applied. That means events containing a candidate tracks close to a reconstructed electron, muon or tau are rejected. Additionally, the candidate track must not be close to a subleading jet ( $p_T < 20 \text{ GeV}$  and  $|\eta| < 4.5$ ).

Unfortunately, the lepton veto selection cuts lack efficiency in some of the detector directions. For example, the reconstruction of an electron easily fails in the direction of a dead ECAL cell. This reduces the discrimination power of the electron veto. For this reason, tracks which point to a dead ECAL cell are rejected. A general list of dead and noisy ECAL cells is provided centrally at CMS. Further dead cells were identified within a study in [6] resulting in a total number of 1234 dead or noisy ECAL channels. These are illustrated in Fig. 5.5 showing a map of all ECAL channels not considered in the search.

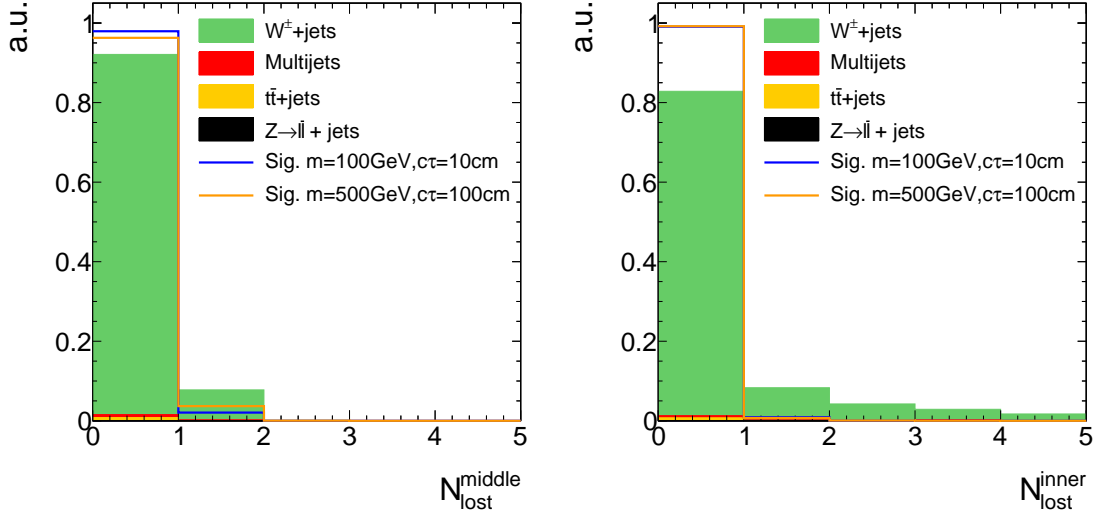


Figure 5.3: Number of missing middle (left) and inner (right) hits of background and signal tracks after trigger requirements and QCD suppression cuts.

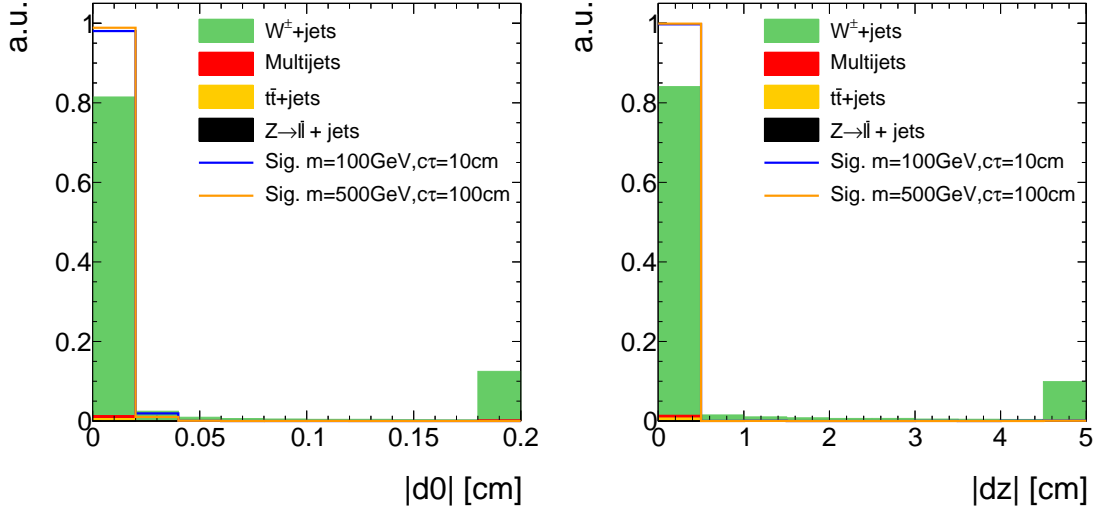


Figure 5.4: Absolute value of the radial (left) and longitudinal (right) distance between the track and the primary vertex after trigger requirements and multijet suppression cuts. Overflow entries are added to the last bin.

Additionally, also tracks which point towards intermodule gaps of ECAL cells or to the ECAL barrel endcap gap at  $1.42 < |\eta| < 1.65$  are rejected. A list of the ECAL intermodule gaps is given in Table 5.4.

The muon reconstruction is less efficient for muons in detector regions with bad cathode strip chambers (CSC). Thus, also tracks pointing in these regions within a distance of

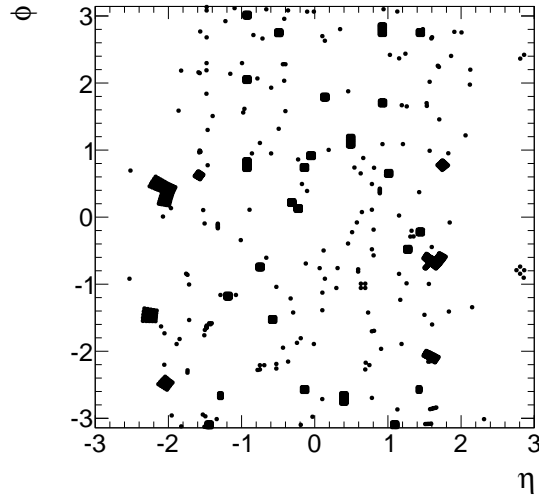


Figure 5.5: Visualisation of dead and noisy ECAL cells in the detector's  $\phi - \eta$  plane.

Table 5.4: Intermodule ECAL gaps.

$\eta$ -ranges
$-1.14018 < \eta < -1.1439$
$-0.791884 < \eta < -0.796051$
$-0.44356 < \eta < -0.447911$
$0.00238527 < \eta < -0.00330793$
$0.446183 < \eta < 0.441949$
$0.793955 < \eta < 0.789963$
$1.14164 < \eta < 1.13812$

$\Delta R < 0.25$  are rejected.

To summarise, the candidate track must fulfil the following selection criteria:

- ❖ The track must not be within a cone of  $\Delta R < 0.15$  to a reconstructed standalone, tracker or global muon with a transverse momentum larger than 10 GeV.
- ❖ Veto all tracks within a cone of  $\Delta R < 0.15$  to a reconstructed electron with a transverse momentum larger than 10 GeV.
- ❖ The track must not be within a cone of  $\Delta R < 0.15$  to a reconstructed tau with  $p_T > 20$  GeV and  $|\eta| < 2.3$ .

- ❖ No subleading jet ( $p_T < 20 \text{ GeV}$  and  $|\eta| < 4.5$ ) is allowed around the track in a cone of  $\Delta R < 0.5$
- ❖ Veto tracks within a cone of  $\Delta R < 0.05$  to a dead or noisy ECAL cell.
- ❖ The track must not point in the direction of the ECAL intermodule gap listed in Table 5.4.
- ❖ The track must not be within a cone of  $\Delta R < 0.25$  to a bad CSC.
- ❖ Veto any track pointing to the region between ECAL barrel and endcap at  $1.42 < |\eta| < 1.65$

Figure ?? shows a the minimal  $\Delta R$  between the candidate track and a reconstructed electron, muon or tau. As can be seen, these selection cuts can efficiently reduce the  $W + \text{jets}$  background.

Finally, two further pronounced characteristics of chargino tracks are exploited. As the chargino is produced in a very clean environment, the isolation of the track (defined as the sum of all track's transverse momentum in a cone of  $\Delta R < 0.3$  around the candidate track) can discriminate signal against background events.

Furthermore, for charginos decaying inside the tracker there is no associated energy deposition in the calorimeters in the direction of the track. This is a very pronounced characteristics of signal tracks.

The concrete selection cuts are as follows

- ❖ No further substantial track activity (less than 10%) is allowed in a cone of  $\Delta R < 0.3$  around the candidate track:  $\sum_{\Delta R < 0.3} p_T / p_T^{\text{cand}} < 0.1$
- ❖ Little calorimeter energy deposits (ECAL+HCAL) in a cone of  $\Delta R < 0.5$  around the track:  $E_{\text{calo}}^{\Delta R < 0.5} < 5 \text{ GeV}$ .

The discrimination power of these two variables is shown in Fig. 5.6.

As emphasised before, this analysis aims to be as general as possible to search for charginos with different lifetimes. Although the search is designed with a focus on charginos which decay inside the tracker, no explicit selection cut is required in the number of missing outer hits. For charginos with very short mean lifetimes it was checked, whether a sensitivity increase can be achieved by imposing a cut on  $N_{\text{miss}}^{\text{outer}}$ . However, this is not the case and therefore a selection in  $N_{\text{miss}}^{\text{outer}}$  is not considered.

An overview over the analysis preselection is given in Table 5.5.

A cutflow of the simulated background datasets and for some of the signal models can be found in Appendix ??.

Given the presented candidate selection requirements, a set of two variables remain, which are highly discriminating: The transverse momentum and the energy release per path length of the candidate track. In Fig. 5.7, the distribution of the remaining two variables are shown after the application of the full candidate track selection. These variables are used to optimise the sensitivity of the search in the variable  $S/(S + B)$  ( $S$ =number of signal events,  $B$ =number of background events). The optimisation process

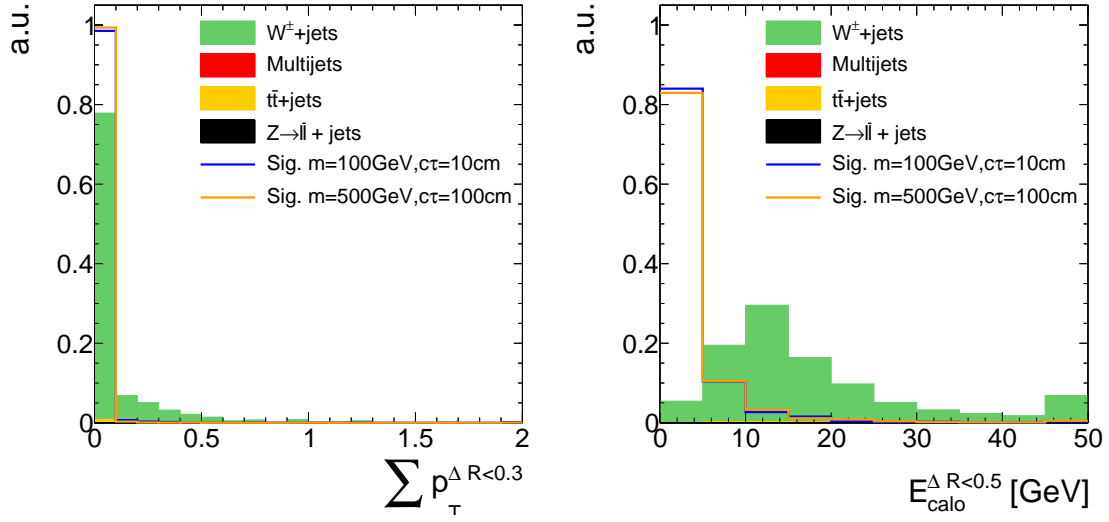


Figure 5.6: Track isolation (left) and calorimeter isolation (right) of the candidate track after the full previous selection (after all other selection cuts of the candidate track selection).

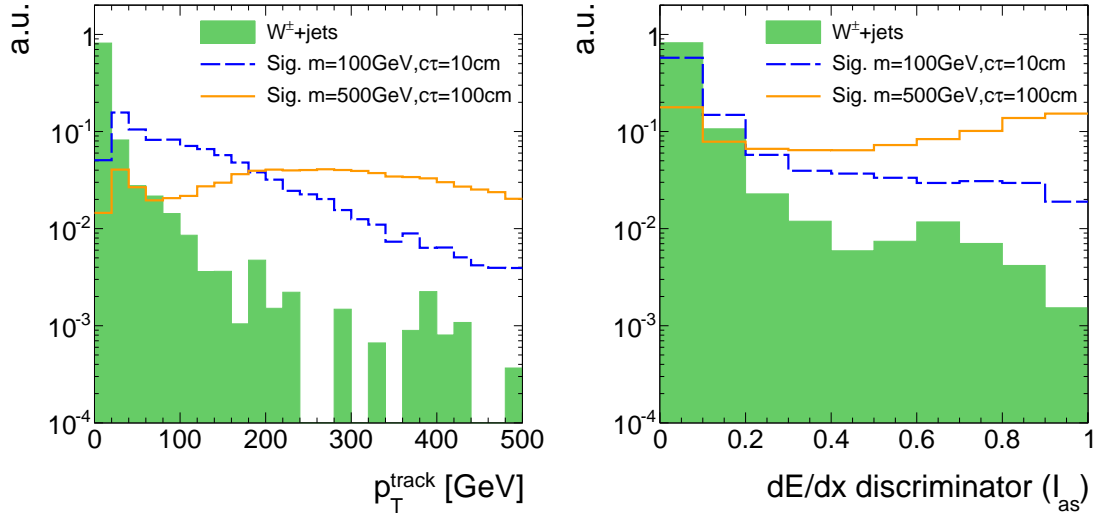


Figure 5.7: Candidate track  $p_T$  (left) and  $I_{\text{as}}$  (right) after the full candidate track selection for signal and  $W + \text{jets}$  events. Because of high event weights of the  $W + \text{jets}$  sample, the trigger requirements are not applied. As  $\cancel{E}_T$  and  $p_T^{1.\text{jet}}$  are not expected to be correlated with the track characteristics it does not influence the shape of the shown distributions.

will be explained in Sec ???. However, before the optimisation can be accomplished, the characterisation and estimation of the background is needed. This topic will be discussed

Table 5.5: Summary and categorisation of the analysis selection.

Trigger	HLTMonoCentralPFJet80_PFMETnoMu95_NHEF0p95	
	HLTMonoCentralPFJet80_PFMETnoMu105_NHEF0p95	
	HLT_MET120_HBHENoiseCleaned	
Event based selection	Trigger selection	$p_T^{1,\text{jet}} > 100 \text{ GeV}$ with $ \eta_{1,\text{jet}}  < 2.4$ , $\text{CHF}_{1,\text{jet}} > 0.2$ , $\text{CEF}_{1,\text{jet}} < 0.5$ , $\text{NHF}_{1,\text{jet}} < 0.7$ , $\text{NEF}_{1,\text{jet}} < 0.7$ $\cancel{E}_T > 100 \text{ GeV}$
	QCD supression	$\Delta\phi_{\text{max}}(\text{jet}_i, \text{jet}_j) < 2.7$ for all jets with $p_T > 20 \text{ GeV}$ , $ \eta  < 4.5$ $\Delta\phi_{\text{max}}(\text{jet}_i, \cancel{E}_T) > 0.5$ for two leading jets
Candidate track selection	Good quality selection	$\geq 1$ high-purity track $\geq 1$ track with $N_{\text{miss}}^{\text{middle/inner}} = 0$ $\geq 1$ track with $ d0  < 0.02 \text{ cm}$ $\geq 1$ track with $ dz  < 0.5 \text{ cm}$
	Kinematic selection	$\geq 1$ track with $ \eta  < 2.1$ $\geq 1$ track with $p_T > 10 \text{ GeV}$
	Lepton/jet veto	$\geq 1$ track without a muon within $\Delta R < 0.15$ $\geq 1$ track without an electron within $\Delta R < 0.15$ $\geq 1$ track without a tau within $\Delta R < 0.15$ $\geq 1$ track without a jet within $\Delta R < 0.5$ $\geq 1$ track not within $\Delta R < 0.05$ of a dead/noisy ECAL cell $\geq 1$ track not within an ECAL intermodule gap $\geq 1$ track not within $1.42 <  \eta  < 1.65$ $\geq 1$ track not within $\Delta R < 0.25$ to a bad CSC
	Isolation selection	$\geq 1$ isolated track $\sum_{\Delta R < 0.3} p_T/p_T^{\text{cand}} < 0.1$ $\geq 1$ track with $E_{\text{calo}}^{\Delta R < 0.5} < 5 \text{ GeV}$



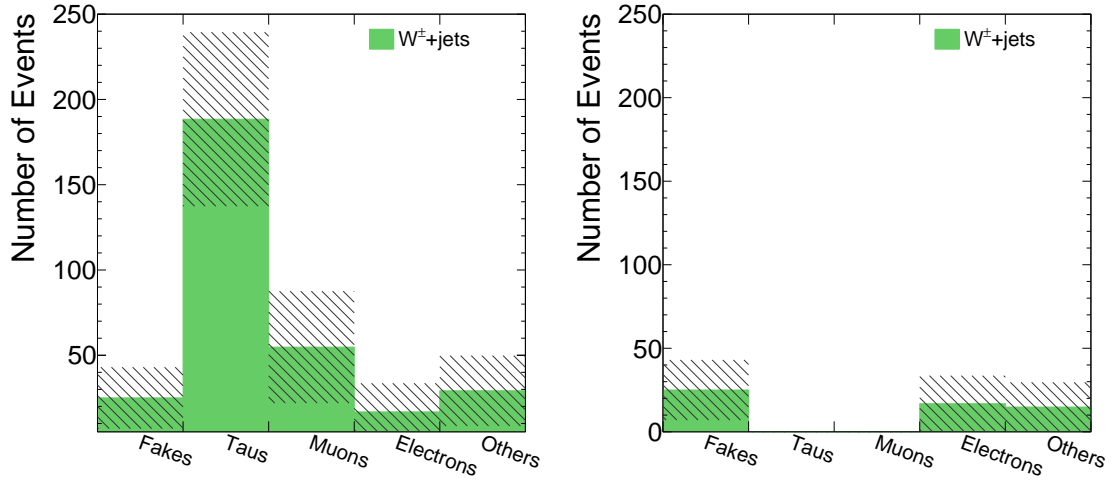


Figure 6.1: Background composition after the full candidate track selection (left) and after the full candidate track selection plus an additional selection cut of  $I_{as} > 0.05$  (right). The statistical uncertainty is depicted by the hashed grey area. Given the limited size of the simulated  $W + \text{jets}$  dataset, the uncertainty of the composition is accordingly large.

in the following section.

## 6 Characterisation and estimation of the Standard Model backgrounds

After the application of the candidate track selection explained in the previous section the background arising from Standard Model processes is dramatically reduced. However, it still happens sometimes that an electron, muon or tau fails reconstruction. The underlying mechanism and the methods to estimate the leptonic background will be in detail explained in Section ???. Furthermore, there is the possibility that a track is reconstructed out of a set of hits which do not origin from only one single particle. Such tracks are called “fake tracks”. Background tracks arising from the wrong combination of hits will be explained in the following Section 6.1

The composition of the background after the candidate track selection is shown in Fig. 6.3. This composition can change significantly when imposing further selection cuts on  $p_T$  and  $I_{as}$ . This, however, will be addressed during the optimisation procedure. To get a feeling how the composition of the background is affected by further cuts on one of the main variables, the background composition is also shown with the candidate track selection plus an additional  $I_{as}$  cut of 0.05. It can be seen that the fake background is less reduced by an additional selection cut on  $I_{as}$ . This gains even more in importance when

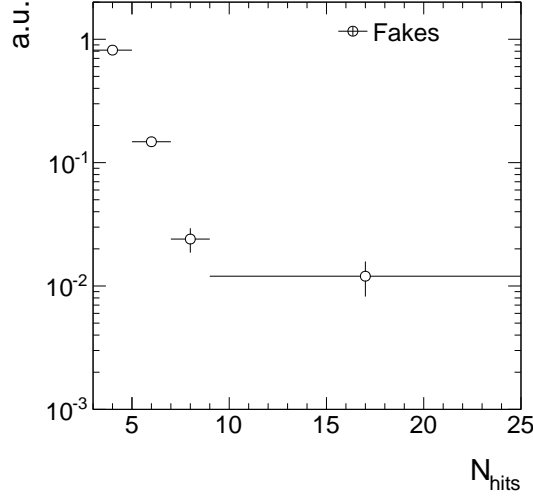


Figure 6.2: Normalised distribution of the number of hits for fake tracks.

considering all sources of fake tracks. The fake background is not only present in  $W + \text{jets}$  events but essentially in all Standard Model processes.

Still, also the leptonic background can be important. Unfortunately, because of the limited size of the simulated  $W + \text{jets}$  dataset, it is not possible to study the leptonic contribution to the background with simulated events. Furthermore, when the simulation of the operativeness of every single detector module is not fully correct, the simulation could highly underestimate the leptonic background.

Therefore, a data-based approach is needed for either of the two background sources: the fake and the leptonic background.

## 6.1 Fake background

Fake tracks are tracks which are not reconstructed out of the trajectory of one single particle. The rate with which this wrong reconstruction occurs is of course highly restrained by the quality cuts on  $\chi^2$  and the vertex compatibility of the track reconstruction algorithm. Details on the reconstruction algorithm at CMS can be found in Section ???. The probability of reconstructing a fake track is strongly correlated with the number of hits in the tracker system. This can be seen in Fig 6.2, where the distribution in the number of hits of fakes is depicted. There are almost no fakes with a number of hits larger than six. In simulation, fake tracks are defined as tracks which cannot be matched to a generator-level particle within a distance of  $\Delta R < 0.01$ .

Fakes are efficiently suppressed by the requirements of no missing middle or inner hits and the compatibility with the primary vertex. Unfortunately, wrongly reconstructed tracks which pass these criteria, do also easily pass the  $E_{\text{calo}}^{\Delta R < 0.5} < 5 \text{ GeV}$  requirement with high efficiency.

In this analysis, the estimation of the fake background is split into two parts. First, the background is estimated inclusively in  $I_{\text{as}}$ . Second, to be able to optimise later in the variable  $I_{\text{as}}$ , the  $I_{\text{as}}$  distribution is taken from a fake enriched control region.

### Inclusive fake background estimation

The inclusive background estimation follows closely the background estimation method done in [30, 31]. The inclusive fake background is estimated with the help of  $Z \rightarrow \mu\bar{\mu}$  and  $Z \rightarrow e\bar{e}$  events. Selecting clean  $Z \rightarrow \ell\bar{\ell}$  events can be done with high efficiency by requiring two well reconstructed muons or electrons, that are opposite in charge and for which the invariant mass is around the  $Z$ -boson mass of  $\sim 90 \text{ GeV}$ . Putting on top the candidate track selection described in Section 5.2, the selected track must be a fake. The event selection in full detail for the muon and electron control sample is given in Table 6.1 and Table 6.2 respectively.

Table 6.1: Event selection cuts for the muon control sample to estimate the inclusive fake background.

Event based selection	<p>Two global muons with <math>p_{\text{T}} &gt; 25 \text{ GeV}</math></p> <p><math> \eta  &lt; 2.4</math></p> <p><math>\sum_{\Delta R &lt; 0.4} p_{\text{T}}^{\text{PF particle}} / p_{\text{T}}(\mu) &lt; 0.12</math></p> <p><math>\frac{\chi^2}{ndof} \Big _{\text{global track}} &lt; 10</math></p> <p><math> d0  &lt; 0.2 \text{ cm}</math></p> <p><math> dz  &lt; 0.5 \text{ cm}</math></p> <p><math>\geq 1</math> hit in the muon detector</p> <p><math>\geq 2</math> hits in different muon detector planes</p> <p><math>\geq 1</math> hit in the pixel detector</p> <p><math>\geq 6</math> hits in the tracker system</p> <p>Muons opposite in charge</p> <p><math>80 \text{ GeV} &lt; M_{\text{inv}}(\mu_1, \mu_2) &lt; 100 \text{ GeV}</math></p>
Candidate track selection	<p>Good quality selection</p> <p>Kinematic selection</p> <p>Lepton/jet veto</p> <p>Isolation selection</p>

Table 6.2: Event selection cuts for the electron control sample to estimate the inclusive fake background.

Event based selection	Two Electrons with $p_T > 25 \text{ GeV}$ $ \eta  < 2.5$ $\sum_{\Delta R < 0.4} p_T^{\text{PF particle}} / p_T(e) < 0.15$ pass conversion veto no missing tracker hits good MVA electron as defined in [35]
	Electrons opposite in charge $80 \text{ GeV} < M_{\text{inv}}(e_1, e_2) < 100 \text{ GeV}$
Candidate track selection	Good quality selection
	Kinematic selection
	Lepton/jet veto
	Isolation selection

Indeed, when testing this procedure in a simulated  $Z \rightarrow \ell\bar{\ell} + \text{jets}$  sample, a selection of fake tracks can be achieved with a reasonable purity. This is illustrated in Fig. 6.3, where the generator-level particle matched to the candidate track is shown. As can be seen, in simulated  $Z \rightarrow \mu\bar{\mu}$  events, a purity of 88%, whereas in simulated  $Z \rightarrow e\bar{e}$  events a purity of 92% of fake tracks can be achieved.

The fake rate is defined as the number of events passing the full selection described in Table 6.1 (Table 6.2) divided by the number of events that pass only the event based selection in Table 6.1 (Table 6.2)

$$\rho_{\text{fake}} = \frac{N_{Z \rightarrow \ell\ell}^{\text{cand trk selection}}}{N_{Z \rightarrow \ell\ell}}$$

It was checked in [30,31] that the fake rate is constant for different processes. In Fig. 6.4 the fake rate for the most important SM processes is shown.

Since the fake rate is constant for different SM processes the inclusive fake background can be estimated with

$$N_{\text{bkg}}^{\text{fake, inclusive in } I_{\text{as}}} = \rho_{\text{fake}} \cdot N_{\text{kinematic selection}},$$

where  $N_{\text{kinematic selection}}$  is defined as the number of events after the event based selection in Table 5.5. After the inclusive estimation of the fake track background, an estimation of the  $I_{\text{as}}$  for fake tracks is needed.

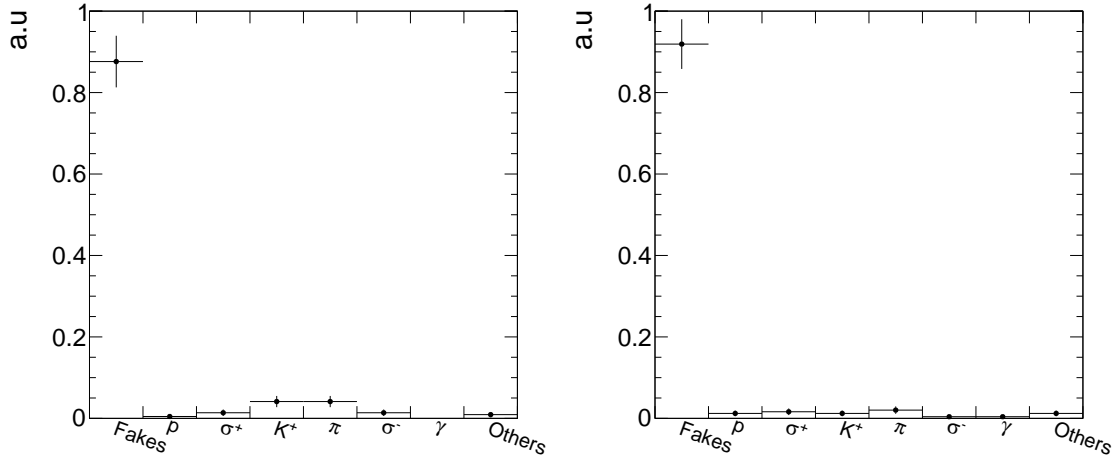


Figure 6.3: Generator-level particle matched to the selected track with the selection described in Table 6.1 (left) and Table 6.2 (right). “Fake” mean that no corresponding generator-level particle could be found.

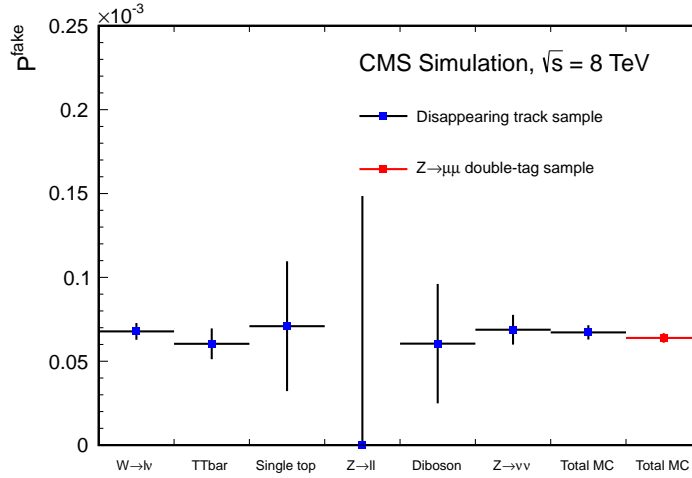


Figure 6.4: Fake track rate estimated in [30,31] for tracks with four hits. Taken from [31]

### $I_{as}$ shape of fake background

To be able to optimise the sensitivity of the search, the  $I_{as}$  distribution of fake tracks is needed. This can be done with the definition of a fake enriched control region.

To enrich fake tracks, it is possible to invert the selection cuts of the number of missing middle and inner hits. As fakes tend to have missing middle and inner hits, shown in fig. ??, This is not the case for the other backgrounds sources.

The  $I_{as}$  distribution can then be estimated from data in the fake CR. That the purity

is high was checked on simulated samples. The  $I_{\text{as}}$  distribution is shown in Fig ??.

In the optimisation process, the  $p_{\text{T}}$  selection will be applied on the inclusive background estimation as a second step the  $I_{\text{as}}$  distribution will be taken from the fake cr with all selection cuts applied (including  $p_{\text{T}}$ ).

## 6.2 Leptonic background

The leptonic background of the presented search is caused by non-reconstructed leptons which undergo hence the lepton veto selection. However, at least non-reconstructed electrons or taus should in principle deposit enough energy in the calorimeters such that they can still be vetoed by the calorimeter isolation requirement. As muons don't deposit much energy in the calorimeters, this reason does not hold for them. In the following, the sources of the three different leptonic backgrounds shall be characterised.

### Electrons

To avoid the background source from unreconstructed electrons, all tracks pointing to a dead or noisy ECAL cells are vetoed, as described in the previous section. By this selection, almost all electrons are efficiently rejected. In the simulated  $W + \text{jets}$  sample only one simulated event remains which pass all candidate track selection criteria and where the candidate track can be matched to a generator-level electron. This event is visualised in Fig 6.5. In this event no energy deposits in the ECAL are read out, which suggests, that this ECAL tower was neither working properly in 2012. Additionally, electrons can do bremsstrahlung which can change the direction of the electron significantly. Thus, the energy deposits in the ECAL can possibly not be matched to the original electron.

### Taus

The tau background is contributing through the hadronic decay of a tau lepton to one charged pion  $\tau \rightarrow \pi^{\pm}\nu$ . Unreconstructed taus are typically low energetic and can therefore bypass the calorimeter isolation criterion. Because of nuclear interactions in the tracker, they can result in short reconstructed tracks which can easily be highly mismeasured in  $p_{\text{T}}$ . Thus, pions can also contribute even when imposing a tighter selection in the transverse momentum. Such an event is shown in Fig. 6.6.

### Muons

Muons can fail reconstruction when they are pointing towards a bad cathode strip chamber. This is taken into account in the candidate track selection. However, some of the muons still fail reconstruction when they fall within the gap between stations 0 and 1 of the DT system at  $\eta = 0.25$ . The muon reconstruction efficiency drops from around 99% to a value of around 94% as shown in [30,31]. This possibility is illustrated in a simulated event shown in Fig 6.7. In [30,31] events are rejected when the track is pointing in a region of  $0.15 < |\eta| < 0.35$ . In this search, this cut was omitted to maximise signal acceptance. Due to the additional selection in  $I_{\text{as}}$ , muons can easily be efficiently suppressed. E.g. in the event example shown in Fig 6.7, the muon has an  $I_{\text{as}}$  value of about 0.02.

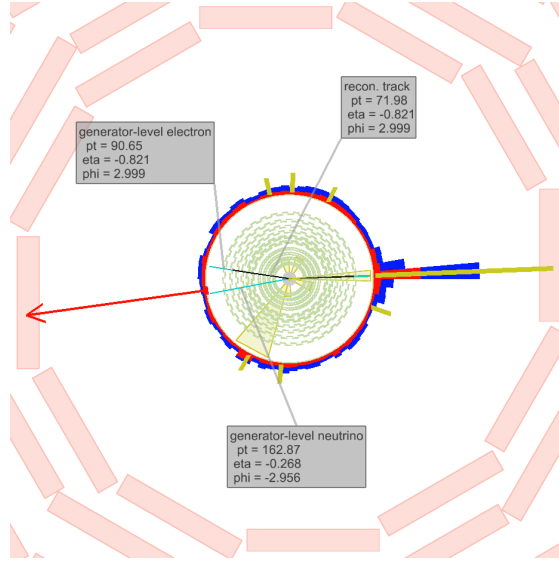


Figure 6.5: Visualisation of an  $W \rightarrow e\nu_e$  event contributing to the SM background. In light blue the generator-level particles  $e$  and  $\nu_e$  of the  $W$  decay are shown. The  $\nu_e$ , only weakly interacting does not show any signature in the detector, whereas the electron ( $p_T \simeq 90$  GeV) leaves a track (black line) with  $p_T \simeq 70$  GeV in the tracker. No ECAL energy deposits in the direction of the electron are visible. This is caused by the fact that the corresponding ECAL energy deposits were not read out in this event. An ISR jet ( $p_T \simeq 230$  GeV) causes the  $\cancel{E}_T$  (read arrow) in the event.

In general, all leptons are minimal ionising. However, as electrons are much lighter compared to muons or pions, they loose more energy also via radiative effects. Still, all three lepton types loose much less energy compared to hypothetical new heavy particles. To have the possibility to make an optimisation in the two main discriminating variables  $p_T$  and  $I_{as}$ , the background estimation methods are designed to work for all different  $p_T$  and  $I_{as}$  selection cuts. A comparison of the  $I_{as}$  distribution for all four different background sources is shown in Fig 6.8.

### 6.3 Systematic uncertainties

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

## 7 Optimisation of search sensitivity

- Show plots

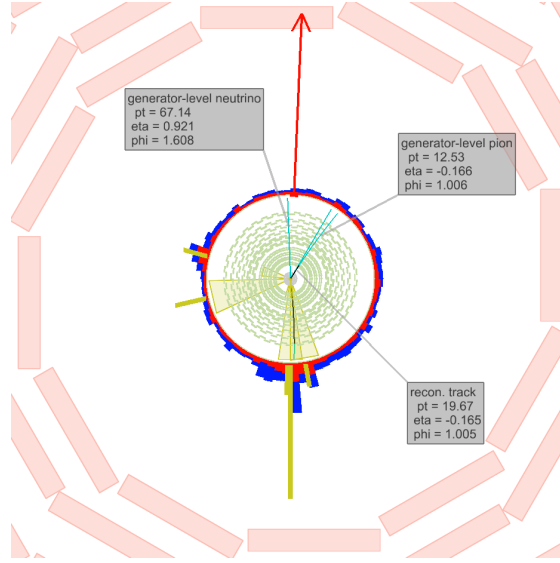


Figure 6.6: Visualisation of a  $W^+ \rightarrow \tau^+ \nu_\tau \rightarrow \pi^+ \nu_\tau$  event contributing to the SM background. In light blue the generator-level particles  $\pi^+$  and  $\nu_\tau$  are shown. The reconstructed track (black line) is very short because the pion interacts with the tracker material via the strong force.

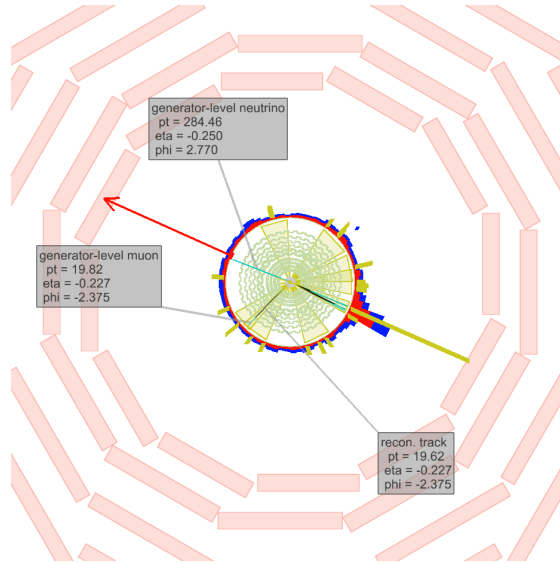


Figure 6.7: Visualisation of an  $W \rightarrow \mu \nu_\mu$  event contributing to the SM background. In light blue the generator-level particles  $\mu$  and  $\nu_\mu$  of the  $W$  decay are shown.

- show table
- Include NlostOuter here, too



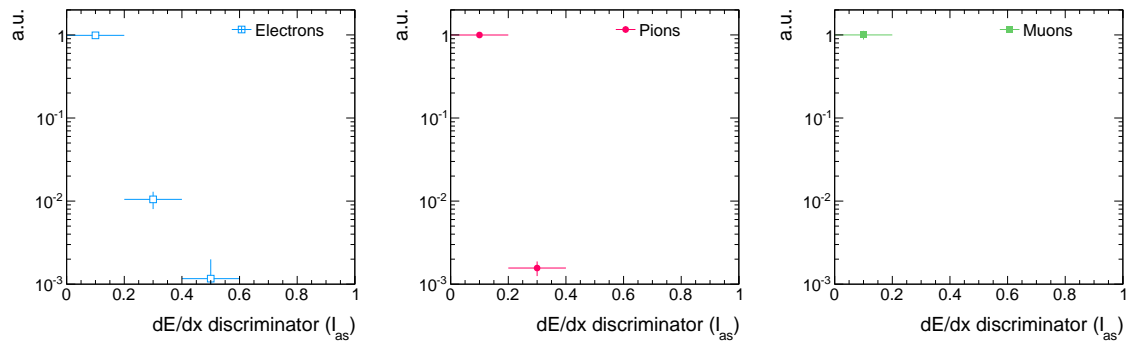


Figure 6.8: Normalised  $I_{as}$  distribution for electrons (left), pions (middle) and muons (right). For all leptons the  $I_{as}$  distribution is rapidly falling.

## 8 Results

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

## 9 Interpretation

### 9.1 Systematic uncertainties of simulated signal samples

### 9.2 Statistical Methods/ Limit setting

### 9.3 Exclusion limits

- 1-d limits
- 2-d limits

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