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 (χ_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 FIXME []. 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).
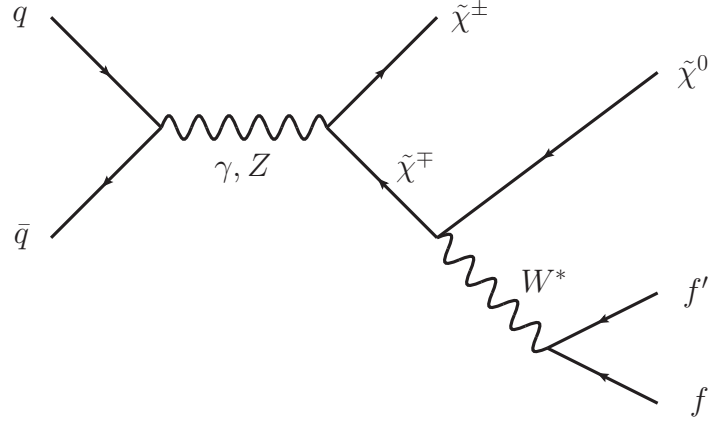

Figure 1.1: Feynman diagram of chargino pair production via gamma or Z-boson exchange and the subsequent decay via a virtual W-boson.
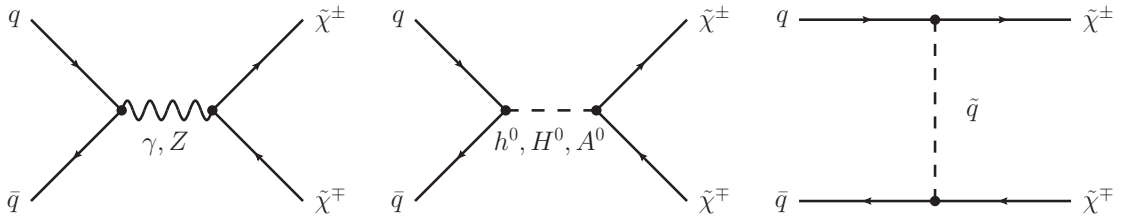

Figure 1.2: Main tree-level diagrams for chargino pair production.

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.

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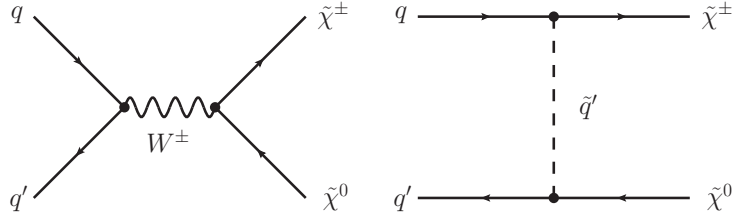
Figure 1.3: Main tree-level diagrams for chargino neutralino production.

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 $(c\tau \lesssim 10\,\mathrm{cm})$[1]. Two existing searches, the search for long-lived charged particles [7] and the search for disappearing tracks [6] focus on long and intermediate chargino lifetimes respectively. These two searches (purple and red areas) are sensitive to chargino lifetimes of $\gtrsim 35\,\mathrm{cm}$. 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 $10\,\mathrm{cm} \lesssim c\tau \lesssim 40\,\mathrm{cm}$. 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 sce-

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[1]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 $c\tau > 1\,\mathrm{cm}$. It could therefore not be tested to which exact upper lifetime the searches combined in the blue area are sensitive to.
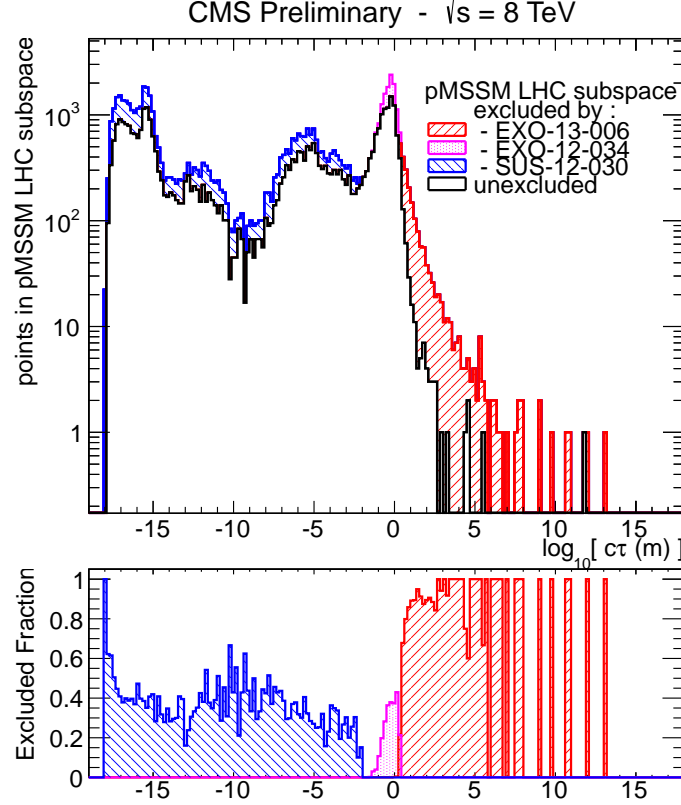
Figure 1.4: The number of excluded pMSSM points at 95% C.L. (upper part) and the fraction of excluded pMSSM points (bottom part) vs. the chargino lifetime for different CMS searches. Red area: the search for long-lived charged particles [7], Purple area: the search for disappearing tracks [6], Blue area: 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].

narios 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 $10\,\mathrm{cm} \lesssim c\tau \lesssim 40\,\mathrm{cm}$, 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
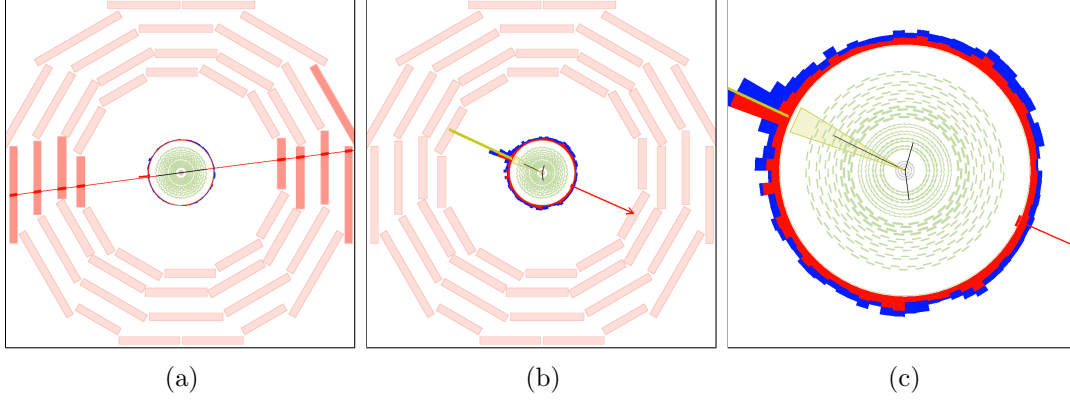
Figure 2.1: Visualisation of possible signatures of a chargino pair produced with a lifetime of $c\tau = 10\,\mathrm{m}$ (a) and a lifetime of $c\tau = 0.5\,\mathrm{m}$ (b and c). In the left picture, both charginos are reconstructed as muons, which can be seen in the energy deposition in the muon chambers (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).

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

$$p_\pi \sim \sqrt{m_{\chi_1^\pm} - m_{\chi_1^0} - m_\pi}.$$

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 ~ 100 MeV and ends at $p_\mathrm{T} \sim 400$ MeV (Fig. 2.2).

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 bending, the track reconstruction efficiency of particles with a transverse momentum below $1\,\mathrm{GeV}$ decreases rapidly, reaching around 40% for isolated pions with a p_T of $100\,\mathrm{MeV}$ [12]. It is therefore impossible to rely on a reconstruction of the fermionic chargino decay
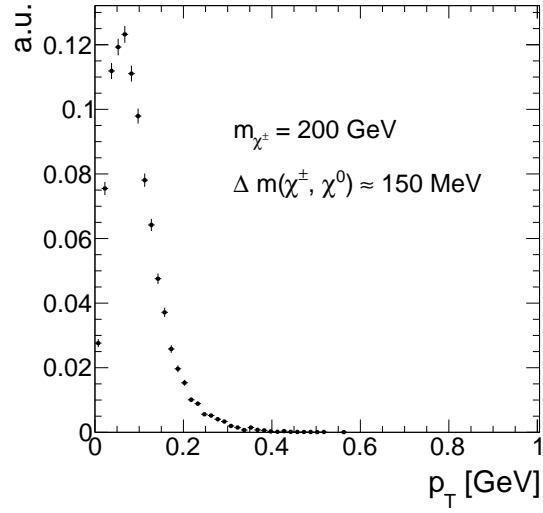
Figure 2.2: Transverse momentum distribution of pions coming from chargino decay into a neutralino with a mass gap of $150\,\mathrm{MeV}$.
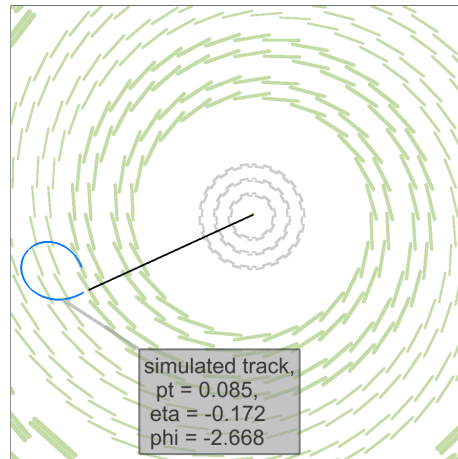

Figure 2.3: Cross-sectional view of the tracker (silicon strip (silicon pixel) tracker layers are illustrated with green (grey) lines) and a simulated chargino track (black line) decaying to a pion (bended blue line) with a p_T of $\sim\!85\,\mathrm{MeV}$ and a neutralino (not visible).

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 associated 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_{hits}) of chargino tracks is shown. It can be seen, that N_{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_{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 (e.g. no explicit 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 $10\,\text{cm} \lesssim c\tau \lesssim 40\,\text{cm}$.
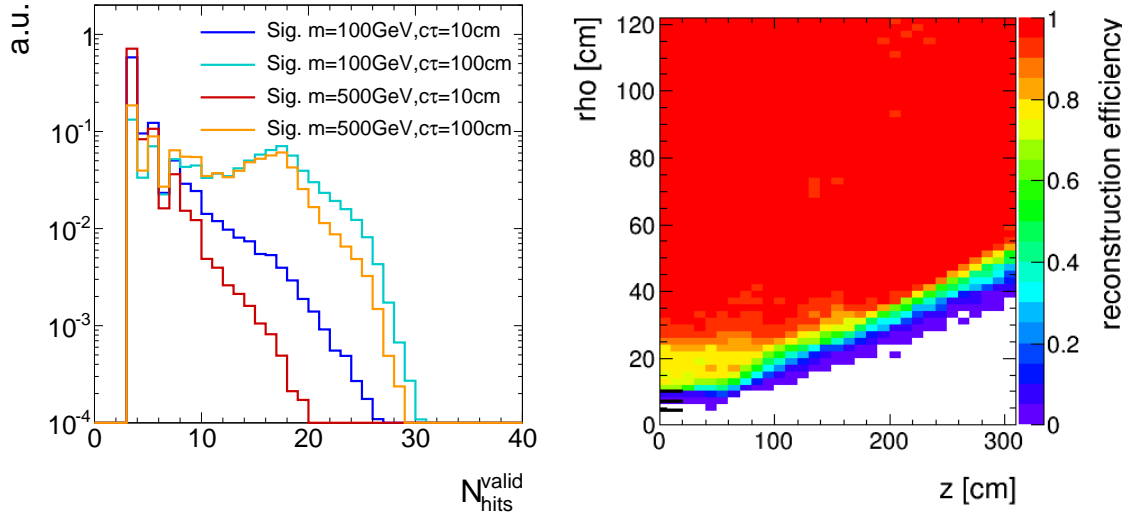
Figure 2.4: Left: Number of measurements in the tracker system N_{hits} for four different signal lifetimes. The low lifetime samples are rapidly falling and peaking at the lowest number of possible measurements of three. For a lifetime of $c\tau = 50\,\text{cm}$, a second peak at $\sim$17 hits appears 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

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3 Improved dE/dx measurement of short tracks

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 to the CMS tracker system and the energy measurement can be found in Section **??**.

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], no

offline calibration has been done for the pixel silicon tracker so far. To increase the discrimination power of dE/dx for short tracks, such a 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]:

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

It is valid if 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 (A) of the absorber. The mean excitation energy (I) for silicon is $173\,\text{eV}$ [14]. $T_{\max}$ represents 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 polarisation effects of the material. The constant factor K is $4\pi N_A r_e^2 m_e^2 c^2$ with N_A being the Avogadros number.

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 $\Delta E/\Delta x$ 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 has no free parameters. Its most probable value is around 0.222. However, it is possible to introduce artificaly a different most probable value and a width with $x \to \frac{x - \text{MPV}}{\sigma} - 0.222$. 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 strong asymmetry, 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 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
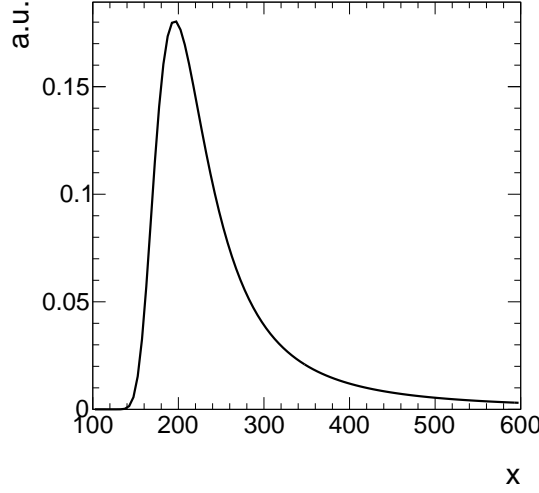
Figure 3.1: Illustration of the shape of a Landau distribution. Parameters were chosen as $\mu = 200$ and $\sigma = 20$.

particle, Δ_p, is defined by the Landau-Vavilov-Bichsel equation [17]:

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

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 Δ_p/dx logarithmically dependent on x. A comparison between the Bethe mean energy loss $\langle dE/dx \rangle$ and the most probable energy loss Δ_p/dx is shown in Fig. 3.2.

However, it is difficult to determine the most probable value for tracks with only $\sim$15 energy measurements available. Large fluctuations can still lead to a bias towards higher value of the most probable dE/dx.

Several "estimators" exist that suppress a potential bias towards the high end without introducing a bias towards lower values [18]. One of the estimators, also used in the next chapter, is the harmonic-2 estimator

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

where $\Delta E/\Delta x$ corresponds to one measurement in one tracker module. The harmonic mean of all N measurements to the power of two is the estimated most probable dE/dx.

SM particles such as pions and muons are minimally ionising in silicon for $\beta\gamma \sim 3 -$
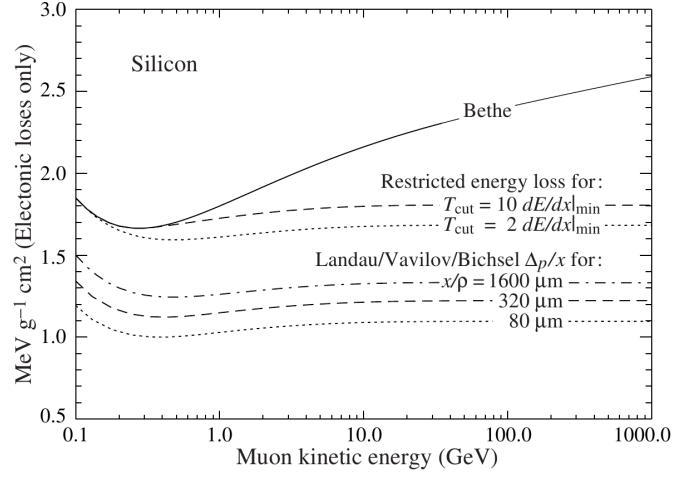
Figure 3.2: Comparison between the Bethe mean energy loss, restricted energy loss and the most probable energy loss described by the Landau-Vavilov-Bichsel function for muons for different values of absorber thickness. Taken from [15].

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.
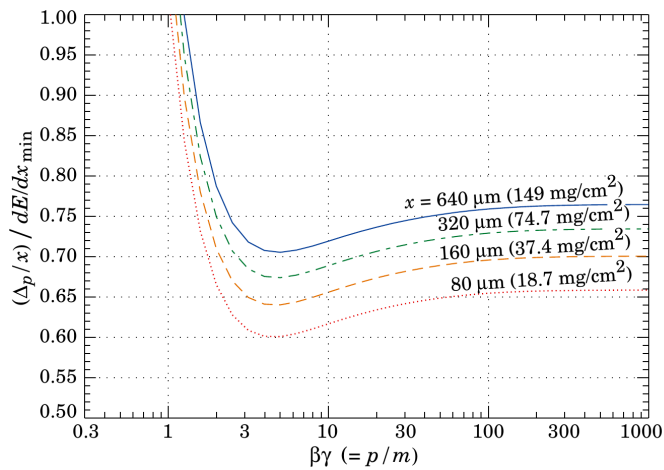

Figure 3.3: Most probable energy loss in silicon, scaled to the mean loss of a minimally ionising particle (388 eV/μm) for different absorber thicknesses. Taken from [15].

3.2 Energy calibration of the silicon pixel tracker

During Run I in 2012, the pixel silicon detector was continuously subjected to an energy calibration, a so-called gain calibration [19]. Every pixel was calibrated to the same response, so 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 $\sum\limits_{\text{all trks}} I_{\text{h2}}$ 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 are induced by associated adjustments in the online gain calibration. Unfortunately, although the gain calibration was adjusted (even with some delay), it was not able to ensure a constant energy response of the pixel tracker over time. The variations of the dE/dx measurement over time of around 15% is too large to use dE/dx without a further calibration.

The following sections explain the method of the gain calibration of the pixel silicon tracker which was conducted for this analysis. It is splitted into a section about the inter-calibration of gain and the absolute calibration of gain) Detailed technical information about the pixel tracker can be found in Section **??**.
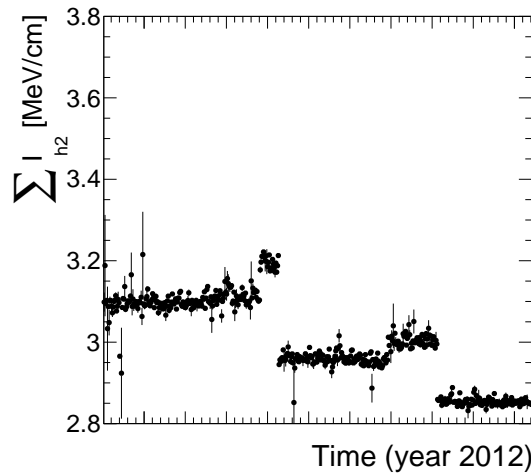

Figure 3.4: Sum of all track's dE/dx (harmonic-2 estimator) over the full year 2012. Only pixel hits are taken into account. Every data point corresponds to one run.

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 also ensure a uniform response of all modules within one time step, an additional inter-calibration on module level was carried out. The inter-calibration can in principle be done on various levels: the highest granularity would be a calibration on pixel level, followed by a calibration on read-out-chip (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 gain calibration of the pixel silicon tracker has been carried out with the help of minimally 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). This approach ensures that all particles deposit similar amount of energy so that the variation due to different momenta is minimised. MIPs are selected by a momentum selection of p > 2 GeV. Additionally, only tracks with at least eight hits and a χ^2/n.d.o.f. < 3 are used to ensure a high-quality track reconstruction. A sample containing around 50 million "minimum bias" events is used for calibration. The "minimum bias" sample was specifically recorded for tracker calibration purposes. Its distinctive property is 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. 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. 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 path length Δx is calculated with

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

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

$$c_{\mathrm{inter}} = \frac{\mathrm{MPV}_{\mathrm{target}}\,[\mathrm{ADC/mm}]}{\mathrm{MPV}\,[\mathrm{ADC/mm}]} = \frac{300 \cdot 265\,\mathrm{ADC/mm}}{\mathrm{MPV}\,[\mathrm{ADC/mm}]}.$$
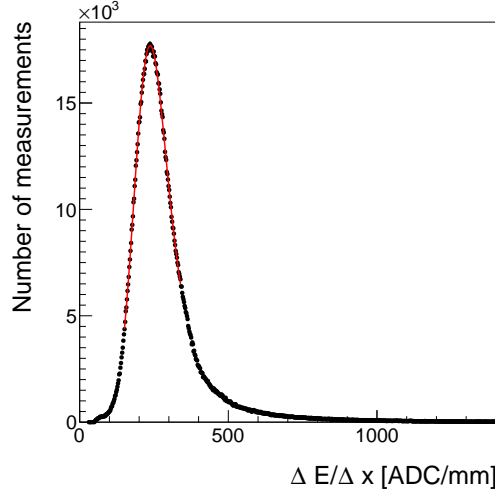
Figure 3.5: An example of the $\Delta E/\Delta x$ distribution measured in ADC count per mm for one module of the CMS pixel tracker. A Landau convoluted with a Gaussian is fitted to the core of the distribution in an iterative procedure.

The factor $300 \cdot 265$ ADC/mm is in principal an arbitrary number since the final response is adjusted by the absolute gain calibration described in the next section. 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 single measurement in a module to a calibrated $\Delta E/\Delta x$ measurement

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

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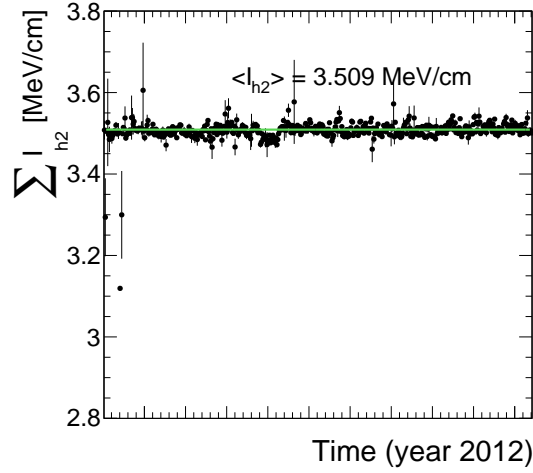
Figure 3.6: Sum of all track's dE/dx (harmonic-2 estimator) over the full year 2012 after applying the calibration factors, resulting in an average dE/dx of 3.51 MeV/cm. Only pixel hits are taken into account. Every data point corresponds to one run.

in eV is given by

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

where N_e/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°C. Such an absolute gain calibration can be done with the help of several methods (all explained in [18]). The absolute calibration of the silicon pixel tracker can rely on 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_{inter} for all pixel modules.

Finally, an absolute calibration factor needs to be determined for the simulated samples, where the simulated pixel tracker is calibrated to the average dE/dx of the silicon strip measured in data.
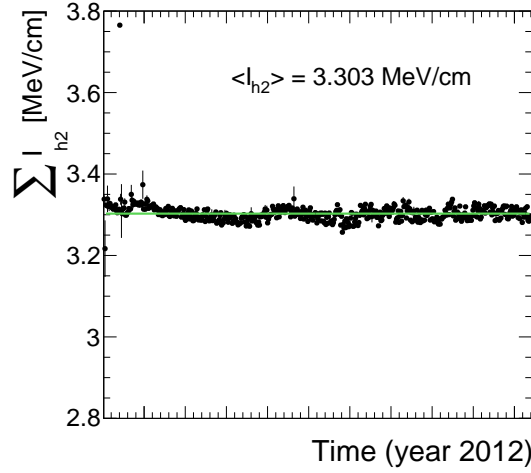
Figure 3.7: Sum of all track's dE/dx (harmonic-2 estimator) measured in the silicon strip detector over the full year 2012. The average most probable dE/dx is $I_{h2} = 3.303$ MeV/cm. Every data point corresponds to one run.

3.3 Discrimination of highly-ionising particles

As mentioned before, it is difficult to find a robust estimator for the MPV of the Landau distribution, if only a few single measurements of $\Delta E/\Delta x$ are available. The harmonic-2 estimator I_{h2} was already introduced in Section 3.1 in Eq. 3.2. It is known to be a robust estimator not easily biased by large fluctuation in $\Delta E/\Delta x$ because of the suppression by a factor of two.

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. determining 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 [20, 21], which is deduced from the integral of the squared difference of the measured distribution $P_N(x)$ to the hypothesis distribution $P(x)$

$$I_s = \int\limits_{-\infty}^{\infty} \left[P_N(x) - P(x)\right]^2 dP(x)$$

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 N is the total number of energy measurements and 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 the sign of the difference between the measured and the theoretical distribution. It can therefore not distinguish between incompatibilities due to variations towards higher or lower energy deposits compared to the hypothesis distribution. Thus it is not 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

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

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 unexpectedly high energy losses.

The underlying probability P_i 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. In Fig. 3.8 the probability distribution template for the pixel tracker in data and simulation is shown. The corresponding templates for the energy release in the silicon strip detector were already built by [18].

A comparison between the energy release by MIPs (I_{as}) in data and simulation for good quality tracks with $p > 5\,\mathrm{GeV}$ and $|\eta| < 2.1$ can be found in Fig. 3.9. dE/dx shows good agreement in data and simulation for $I_{\mathrm{as}} < 0.1$. 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). It can be seen, that the I_{as} distributions of all signal models show a larger tail towards $I_{\mathrm{as}} = 1$, whereas the I_{as} of the background is rapidly falling. The I_{as} distribution is not only influenced by the velocity (β) of a particle but also by the number of hits of a track. The
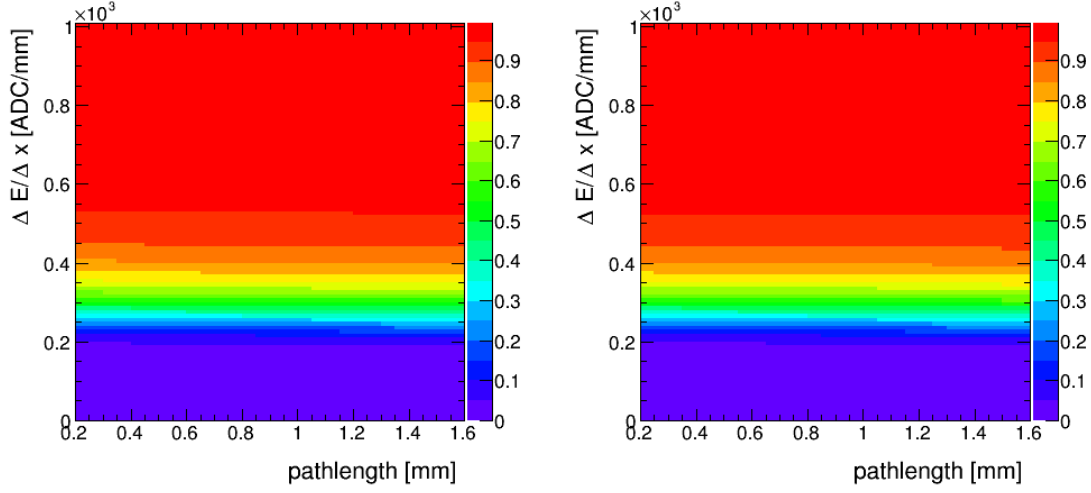
Figure 3.8: Cumulative probability for a MIP to release a $\Delta E/\Delta x$ (y-axis) vs. the path length (x-axis) in data (left) and simulation (right) for the pixel tracker based on the "Minimum bias" sample.
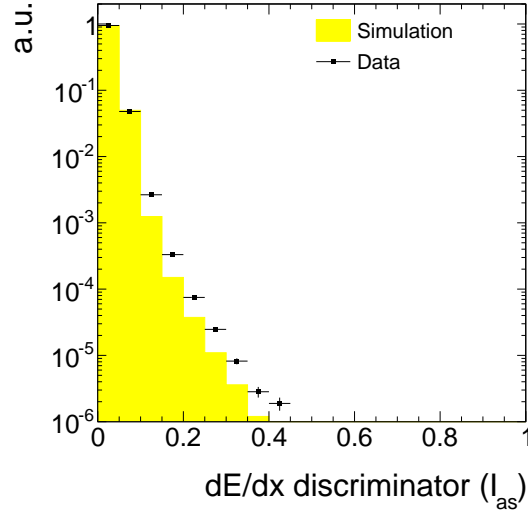

Figure 3.9: Normalised I_{as} distribution for MIPs from the minimum bias sample in data and simulation for good quality (high-purity as defined in [22] and minimum number of eight hits) tracks with $p > 5\,\text{GeV}$ and $|\eta| < 2.1$.

influence of the velocity can be easily seen in Eq. 3.1. This in turn results in a dependency of I_{as} on the mass of the incident particle. However, also for charginos with 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 of the charginos decay before reaching the tracker system. The probability of reaching the detector increases for higher velocities because of the boost, which can be clearly seen at the survival probability

$$P\left(t\right) = e^{-\frac{t}{\gamma\tau}}. \tag{3.3}$$

This means that shorter lifetimes lead to higher average β which in turn lead to lower values of 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 long right tail of the Landau distribution, A low number of hits lead therefore to higher I_{as} values.

Thus, I_{as} for charginos with lower lifetimes are affected by two things: First, due to the smaller number of measurements the chargino tends to higher I_{as} values. Second, low lifetimes charginos have in average a higher velocity leading 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.

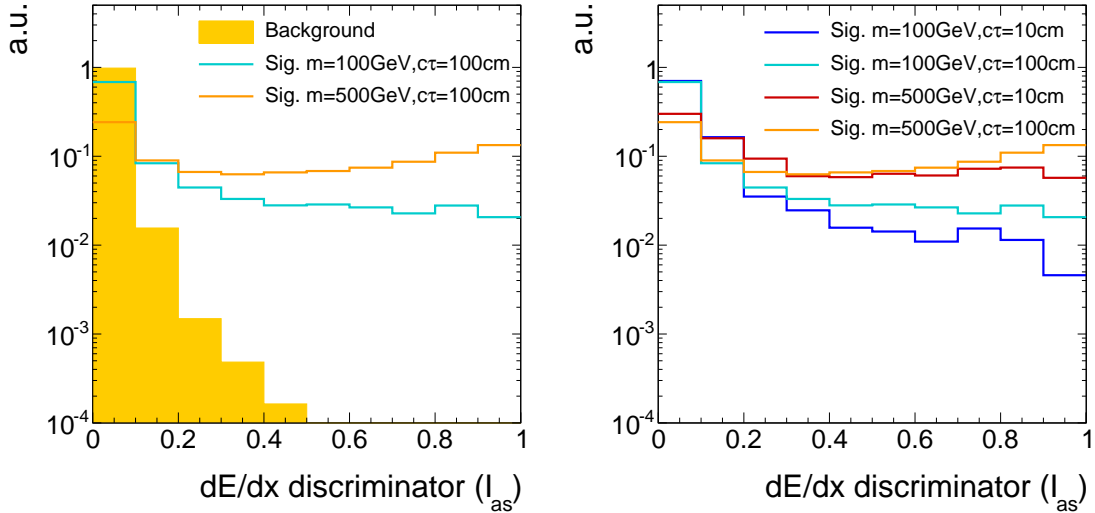Figure 3.10: Normalised I_{as} distribution for simulated background and signal tracks (left) and for four different signal models (right) for high-purity tracks (as defined in [22]) with $p_{\text{T}} > 10\,\text{GeV}$ and $|\eta| < 2.1$. For the illustration of the background tracks' spectrum simulated $t\bar{t}$+jets events are used (more information about this sample is given in Section 4).

Finally, the impact of the additional $\Delta E/\Delta x$ information from the pixel tracker on the selection efficiency of signal and background tracks is 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. 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

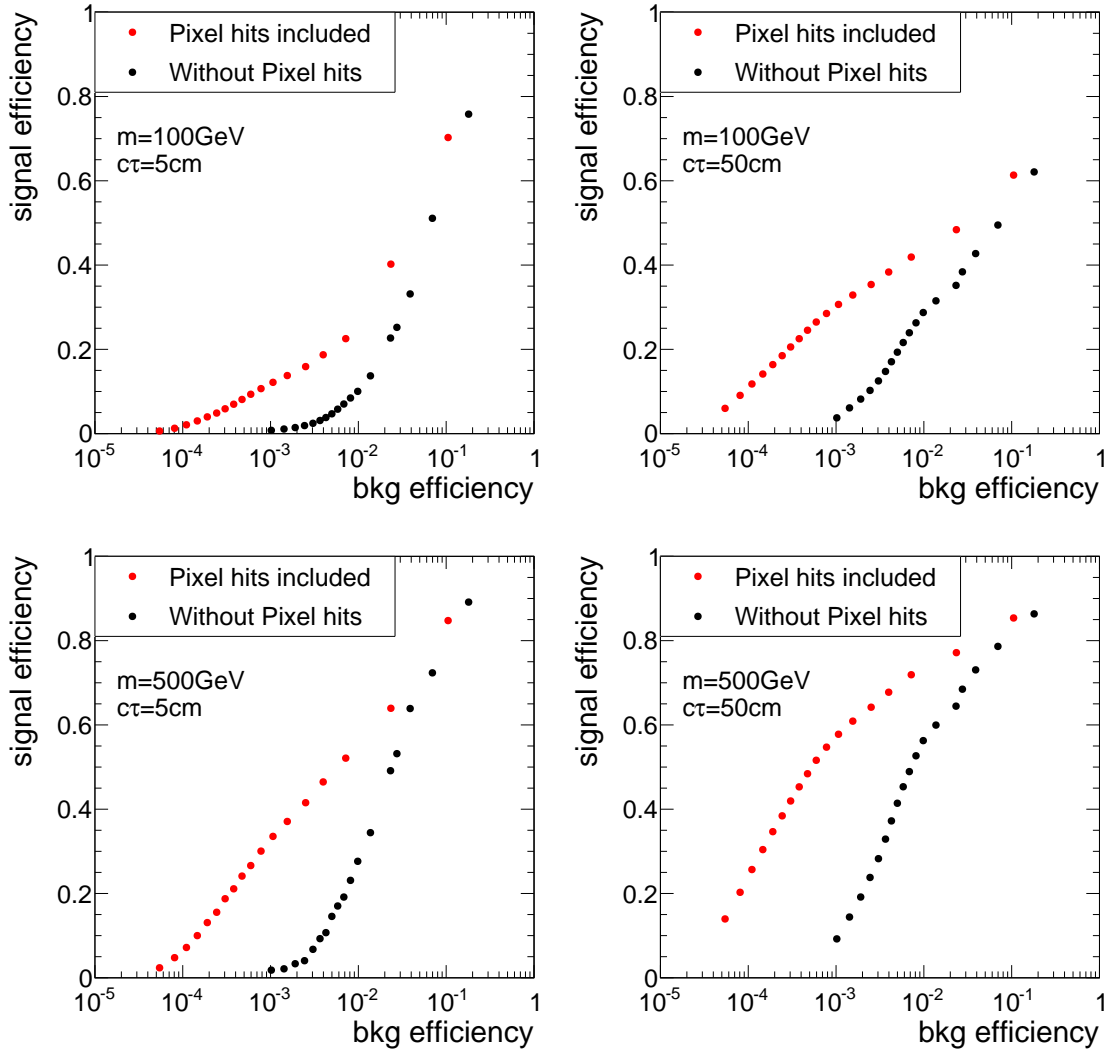

Figure 3.11: Signal selection efficiency vs. background selection efficiency with (red) and without (black) pixel information. Each point correspond to one selection cut in I_{as}. The figure is based on a simulated $W+$ jets sample and a simulated signal sample with chargino-chargino production, both subject to a selection of good quality tracks with $p_{\text{T}} > 10\,\text{GeV}$.

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_{as} is much better for higher masses as expected.

It can be seen that the inclusion of the pixel information increases the background suppression for a given signal efficiency throughout the investigated signal models. This background suppression improvement is most pronounced for very tight cuts on I_{as} (up to a factor of 20) and still considerable for looser selections with signal efficiencies of around 40% (factor of 10).

4 Simulated samples

In order to design the search and to study background and signal characteristics, this analysis relies on simulated SM and SUSY datasets. An extensive introduction to the techniques and tools required for the simulation of SM and beyond SM processes can be found in Section **??**.

The following two sections present an overview of the SM (Section 4.1) and SUSY samples (Section 4.2) used in this 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. Since this analysis aims at making use of dE/dx, a special data format of the simulated samples, the so-called RECO format, is required. Unfortunately, not all SM processes are available in this specific format making it impossible to compare the total number of events in simulation and real data. This, however, does not constitute a serious problem since this analysis will finally use data-based background estimation methods. The simulated SM datasets can still be used to compare the shapes of important distributions in simulation and data.[1]

In Table 4.1 all available SM samples used in this analysis are listed. Due to the size

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[1]For example, the simulated $Z \to \nu\bar{\nu}$ + jets sample that can contribute to the backround of this search via fake tracks is not available in RECO format. However, as the shape of important observables of fake tracks is independent of the underlying process, this background can be studied with a simulated W + jets sample.

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

Process	Cross section [pb]	$\mathcal{O}_{\text{calculation}}$
$W + \text{jets}$	36703.2	NNLO [23]
$t\bar{t} + \text{jets}$	245.8	NNLO [24]
$Z \to \ell\bar{\ell} + \text{jets} \ (\ell = e, \mu, \tau)$	3531.9	NNLO [23]
QCD $(50\,\text{GeV} < \hat{p}_{\text{T}} < 1400\,\text{GeV})$	9374794.2	LO

of the samples (between 5 and 70 TB) a reduction needs to be done in order to limit the storage space requirements. This is achieved by selecting only events which contain at least one 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 dE/dx. They are listed in Table 4.2.

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 [23]
$Z \to \ell\bar{\ell} + \text{jets} \ (\ell = e, \mu, \tau)$	3531.9	NNLO [23]

4.2 Signal samples

For the investigation of a possible SUSY signal, events containing either chargino pair production $q\bar{q} \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ or chargino neutralino production $q\bar{q} \to \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ are simulated. The simulation is done with the matrix-element event generator MADGRAPH [25] The parton showering and hadronisation processes are then simulated with PYTHIA [26]. Finally, the interactions of the generator-level particles with the detector material are simulated with GEANT4 [27, 28].

Furthermore, a special treatment for long-lived particles is required. In order to get a correct detector simulation of the energy loss of long-lived particles that decay after the
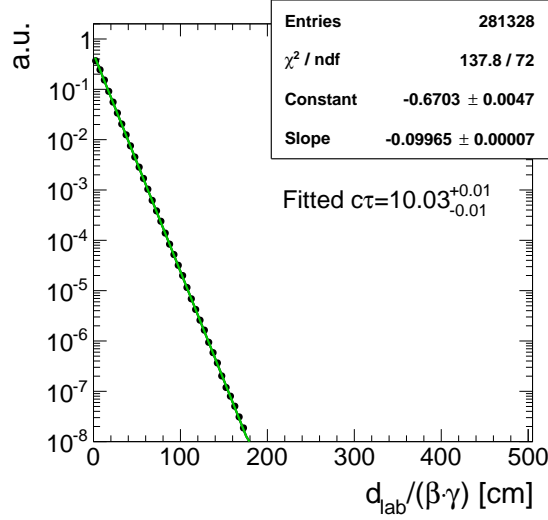
Figure 4.1: Normalised distribution of the proper individual lifetime $d_{\mathrm{lab}}/\left(\beta\gamma\right)$ of all charginos contained in a signal sample with a generated lifetime of $c\tau^{\mathrm{gen}} = 50\,\mathrm{cm}$ reweighted to a lifetime of $c\tau^{\mathrm{target}} = 10\,\mathrm{cm}$. Fitting an expotential curve $a \cdot \exp\left[\frac{1}{c\tau}ct_i\right]$ yields $c\tau = 1./\mathrm{Slope} = 10\,\mathrm{cm}$.

beam pipe, the decay of the chargino cannot be simulated in the matrix-element generator but needs to be simulated within GEANT4.

To narrow down the required computing sources, the simulation is only done for a few lifetimes ($1\,\mathrm{cm}$, $5\,\mathrm{cm}$, $10\,\mathrm{cm}$, $50\,\mathrm{cm}$, $100\,\mathrm{cm}$, $1\,000\,\mathrm{cm}$ and $10\,000\,\mathrm{cm}$). In order to scan in a high resolution over the lifetime space, other lifetimes are generated using lifetime reweighting. The weight for each event depends on the individual proper lifetime of the chargino and is given by

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

where n is the number of charginos in the event, τ^{gen} is the generated mean lifetime in the particle's rest frame and t_i is the individual proper lifetime of the chargino. The targeted mean lifetime is given by τ^{target}. A derivation of this formula can be found in Appendix ??. Using this reweighting procedure a good coverage 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 $c\tau^{\mathrm{gen}} = 50\,\mathrm{cm}$ to a lifetime of $c\tau^{\mathrm{target}} = 10\,\mathrm{cm}$. The reweighting procedure does indeed reproduce the targeted lifetime of $10\,\mathrm{cm}$.

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 150 MeV. 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[2] 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 for wino-like charginos and neutralinos are listed [29, 30]. The cross section does not dependent on the lifetime of the chargino.

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

$m_{\tilde{\chi}_1^{\pm}}\,[\,\mathrm{GeV}]$	$\sigma_{\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}}\,[\,\mathrm{pb}]$	$\sigma_{\tilde{\chi}_1^{0}\tilde{\chi}_1^{\mp}}\,[\,\mathrm{pb}]$
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

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 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 the chargino (or both charginos) decay inside the tracker. Therefore, the detection of

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[2]NLO: next-to-leading order, NLL: next-to-leading logarithmic accuracy

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 $\not{E}_T$ 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: $\not{E}_T$ and $\not{E}_T$ + jet triggers used in the analysis together with the corresponding recorded integrated luminosity in the time when they were in place.

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

The HLTMonoCentralPFJet80_PFMETnoMu95_NHEF0p95 and HLTMonoCentralPF-Jet80_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 $\not{E}_T$ (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 (~ 150 TB in total), a reduction of the size is achieved by selecting only events where one of the used triggers fired and that contain at least one jet with a minimum p_T of 50 GeV.

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

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 analysis selection follows closely the selection required in [31, 32].

5.2.1 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) [33]:

❖ The vertex must have at least four degrees of freedom: vtx with ≥ 4 d.o.f.

❖ The position of the vertex along the beam line must be within $24\,\text{cm}$ from the beam origin: $|dz| \leq 24\,\text{cm}$.

❖ The position in the transverse direction must be within $2\,\text{cm}$ from the beam origin: $|d0| \leq 2\,\text{cm}$.

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 $\not{E}_{\text{T}}$ and the transverse momentum of the leading jet $p_{\text{T}}^{1.\,\text{jet}}$ 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 [34]. In can be seen in Fig. 5.1 that already for a selection of $\not{E}_T > 100\,\text{GeV}$ 80% of the signal events are rejected.

The trigger efficiency as a function of $\not{E}_T$ and $p_T^{1.\,\text{jet}}$ was determined within [35] with a single-muon reference sample. The trigger paths become fully efficient for $p_T^{1.\,\text{jet}} \gtrsim 110\,\text{GeV}$ and $\not{E}_T \gtrsim 220\,\text{GeV}$ [34].

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

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

❖ The missing transverse momentum must be larger than $100\,\text{GeV}$: $\not{E}_T > 100\,\text{GeV}$

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
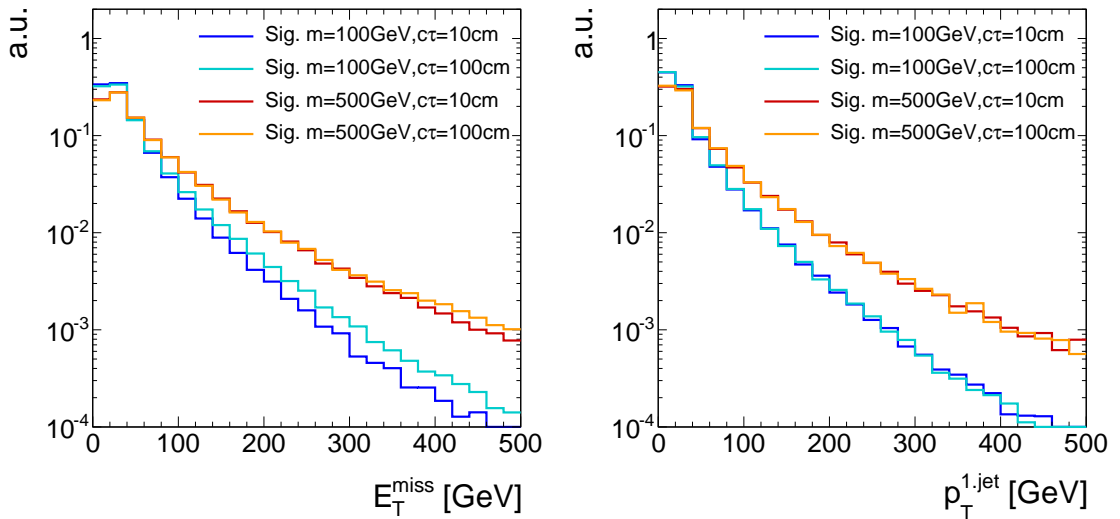

Figure 5.1: Normalised distributions of the missing transverse momentum (left) and the transverse momentum of the leading jet (right) for four different signal models.
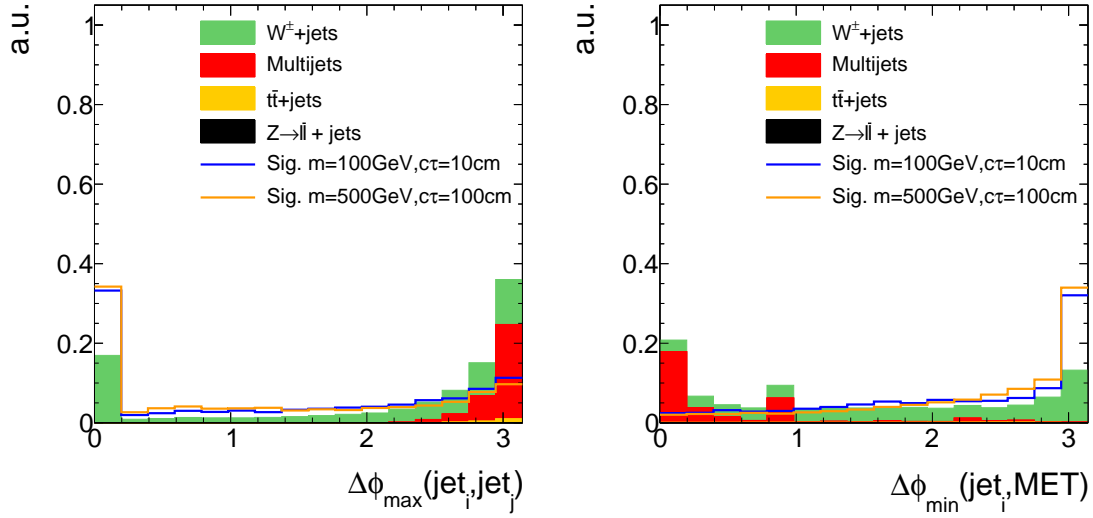
Figure 5.2: Maximal $\Delta\phi$ between any of two subleading jets (left) and the minimal $\Delta\phi$ between the $\not{E}_T$ vector and the first two jets (right) normalised to unit area after the trigger selection.

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 were 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 $\not{E}_T$ 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 $\not{E}_T$ vector and the first two subleading jets for the SM background and two different signal datasets.

5.2.2 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:

❖ The track must be of "high purity" as defined in [22].

❖ 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 selection of tracks in the transverse momentum is applied: $p_{\text{T}} > 20\,\text{GeV}$.

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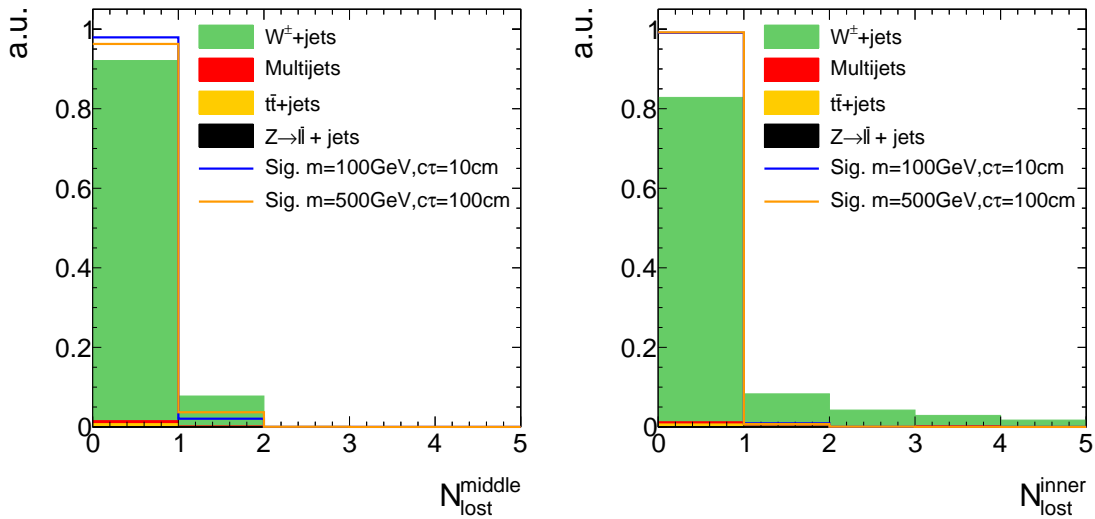

Figure 5.3: Number of missing middle (left) and inner (right) hits of background and signal tracks after trigger requirements and QCD suppression cuts.
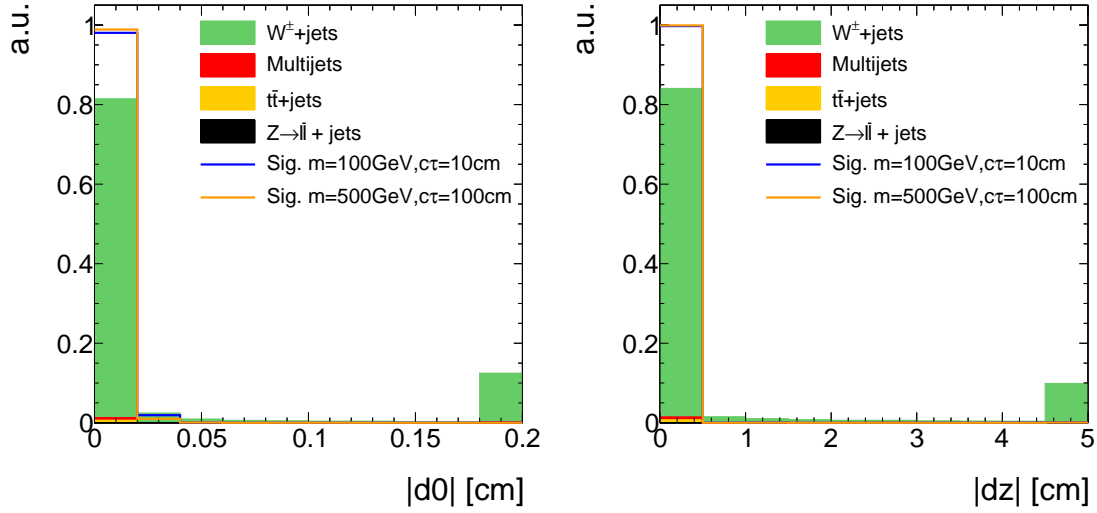
Figure 5.4: Absolute value of the radial (left) and longitudinal (right) distance between the track and the primary vertex after trigger requirements and multijet suppression cuts. Overflow entries are added to the last bin.
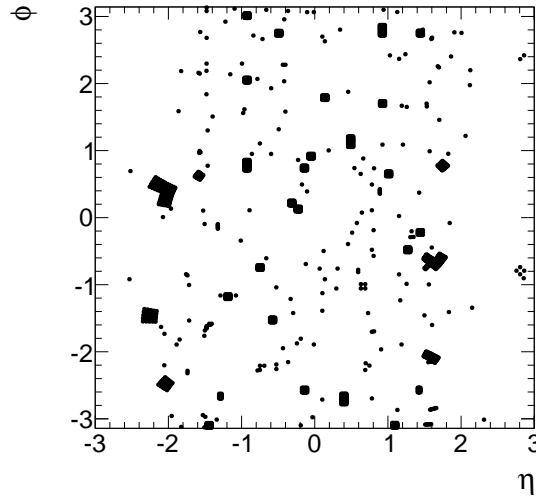
Figure 5.5: Visualisation of dead and noisy ECAL cells in the detector's $\phi - \eta$ plane.

a dead ECAL cell. This reduces the discrimination power of the electron veto. For this reason, tracks that 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.

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 5.3.

Table 5.3: Intermodule ECAL gaps.

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

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 $\Delta R < 0.25$ 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 $10\,\text{GeV}$.

❖ Veto all tracks within a cone of $\Delta R < 0.15$ to a reconstructed electron with a transverse momentum larger than $10\,\text{GeV}$.

❖ The track must not be within a cone of $\Delta R < 0.15$ to a reconstructed tau with $p_{\text{T}} > 20\,\text{GeV}$ and $|\eta| < 2.3$.

❖ No subleading jet ($p_{\text{T}} < 20\,\text{GeV}$ 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 5.3.

❖ 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 $1.42 < |\eta| < 1.65$

These lepton veto selection requirements are of course highly suppressing the background emerging from real lepton production like in $W+$jets events. The discrimination power of the lepton vetos is shown in Fig. 5.6 where the minimal ΔR between the candidate track and a reconstructed electron, muon, tau or jet is shown.

Finally, two further characteristics of chargino tracks are exploited. As the chargino is produced in a very clean environment, the isolation of the 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
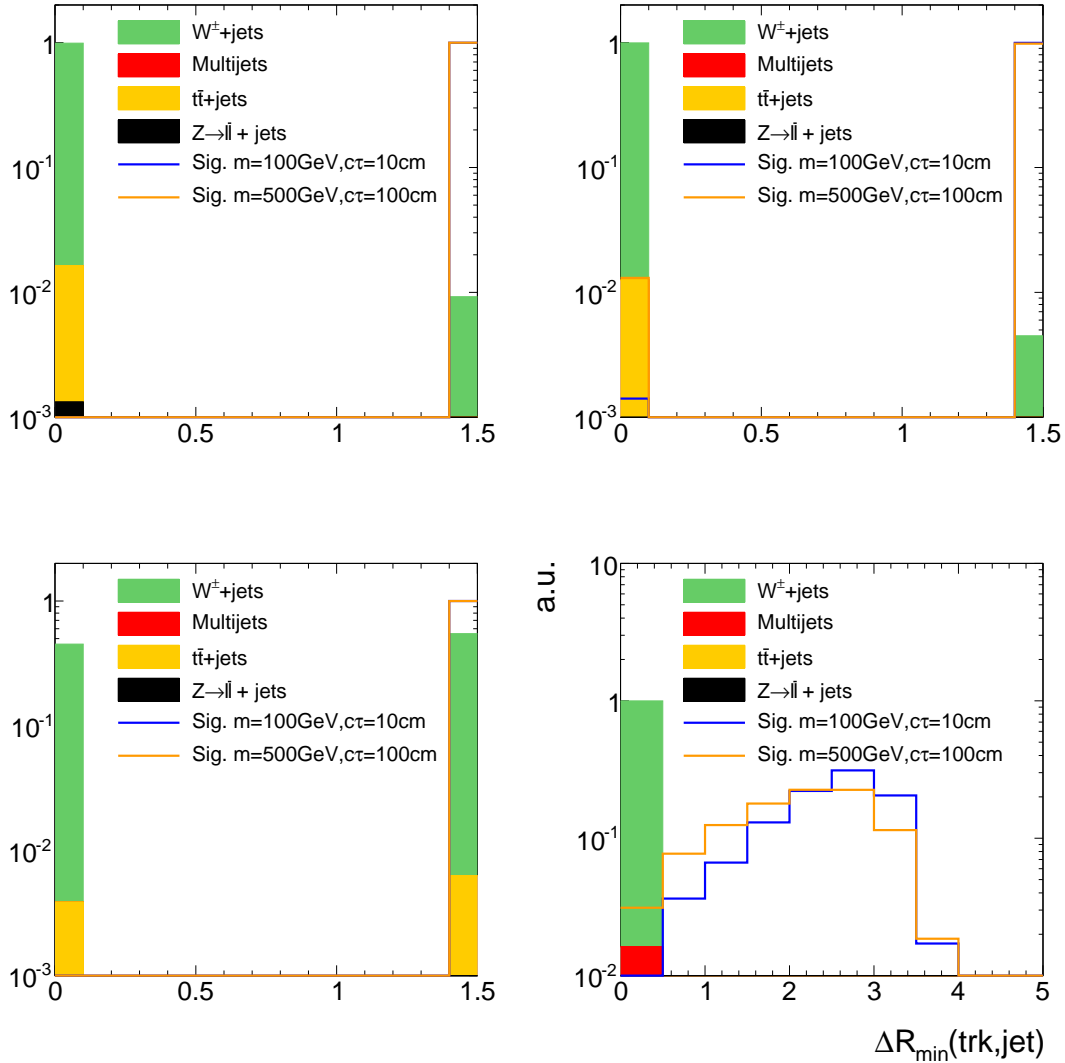

Figure 5.6: The minimal dr betweenn

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: $\sum\limits_{\Delta R < 0.3} p_{\mathrm{T}}/p_{\mathrm{T}}^{\mathrm{cand}} < 0.1$

❖ Little calorimeter energy deposits (ECAL+HCAL) in a cone of $\Delta R < 0.5$ around the track: $E_{\mathrm{calo}}^{\Delta R < 0.5} < 5\,\mathrm{GeV}$.

The discrimination power of these two variables is shown in Fig. 5.7.

As emphasised before, this analysis aims to be as general as possible to search for charginos with different lifetimes. To allow for charginos decaying at any layer of the tracker, no explicit selection cut is required in the number of missing outer hits.

An overview over the analysis preselection is given in Table 5.4. A summary table of the event yields after each selection step for the simulated background datasets and for some of the signal models can be found in Appendix A.

Given the presented analysis 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. 5.8, the distribution of the remaining two variables are shown after the application of the full analysis selection. These variables are used to optimise the sensitivity of the search in the variable $S/(S + B)$ (S=number of signal
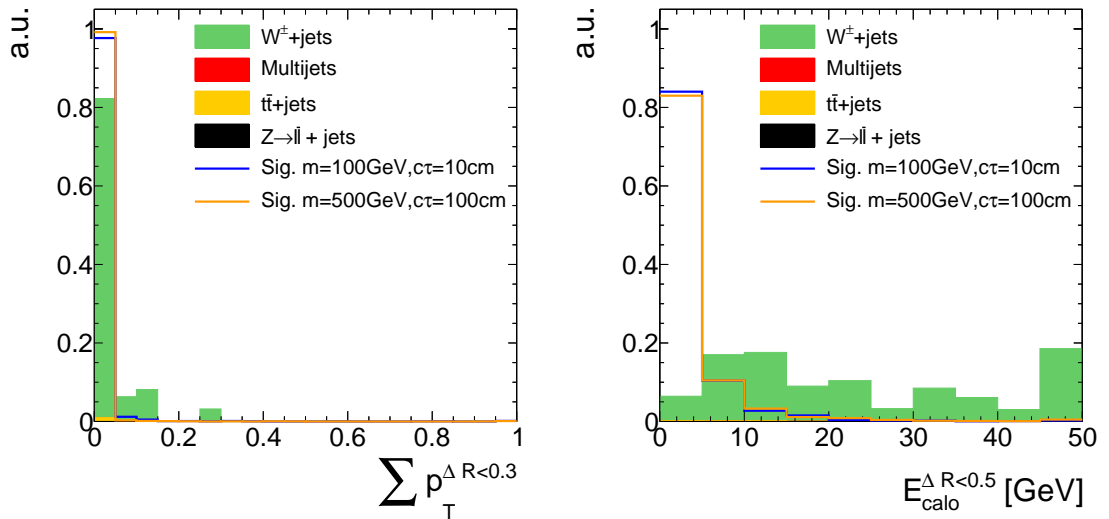

Figure 5.7: Track isolation (left) and calorimeter energy deposits (right) of the candidate track after the full previous selection.

Table 5.4: 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 $|\eta_{1.\text{jet}}| < 2.4$, $\text{CHF}_{1.\text{jet}} > 0.2$, $\text{CEF}_{1.\text{jet}} < 0.5$, $\text{NHF}_{1.\text{jet}} < 0.7$, $\text{NEF}_{1.\text{jet}} < 0.7$ $\not{E}_T > 100\,\text{GeV}$
	QCD suppression	$\Delta\phi_{\max}\left(\text{jet}_i, \text{jet}_j\right) < 2.7$ for all jets with $p_T > 20\,\text{GeV}$, $|\eta| < 4.5$ $\Delta\phi_{\max}\left(\text{jet}_i, \not{E}_T\right) > 0.5$ for two leading jets
Candidate track selection	Good quality selection	≥ 1 high-purity track ≥ 1 track with $N_{\text{miss}}^{\text{middle/inner}} = 0$ ≥ 1 track with $|d0| < 0.02\,\text{cm}$ ≥ 1 track with $|dz| < 0.5\,\text{cm}$
	Kinematic selection	≥ 1 track with $|\eta| < 2.1$ ≥ 1 track with $p_T > 10\,\text{GeV}$
	Lepton/jet veto	≥ 1 track without a muon within $\Delta R < 0.15$ ≥ 1 track without an electron within $\Delta R < 0.15$ ≥ 1 track without a tau within $\Delta R < 0.15$ ≥ 1 track without a jet within $\Delta R < 0.5$ ≥ 1 track not within $\Delta R < 0.05$ of a dead/noisy ECAL cell ≥ 1 track not within an ECAL intermodule gap ≥ 1 track not within $1.42 < |\eta| < 1.65$ ≥ 1 track not within $\Delta R < 0.25$ to a bad CSC
	Isolation selection	≥ 1 isolated track $\sum_{\Delta R < 0.3} p_T / p_T^{\text{cand}} < 0.1$ ≥ 1 track with $E_{\text{calo}}^{\Delta R < 0.5} < 5\,\text{GeV}$

events, B=number of background events). The optimisation process will be explained in Section 7. However, before the optimisation can be accomplished, the characterisation end estimation of the background is needed. This topic will be discussed 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. Only two events in the simulated $W +$ jets sample remain. One of these originates from an unreconstructed muon, and one from an unreconstructed electron. That means, it can still happen sometimes that an electron, muon or tau fails reconstruction. Due to the limited size of the simulated $W +$ jets dataset (15 times smaller than the number of events expected from $W +$ jets processes during 2012 data taking), it is not possible to rely on a full simulation-based estimation of the leptonic background. The underlying mechanism of

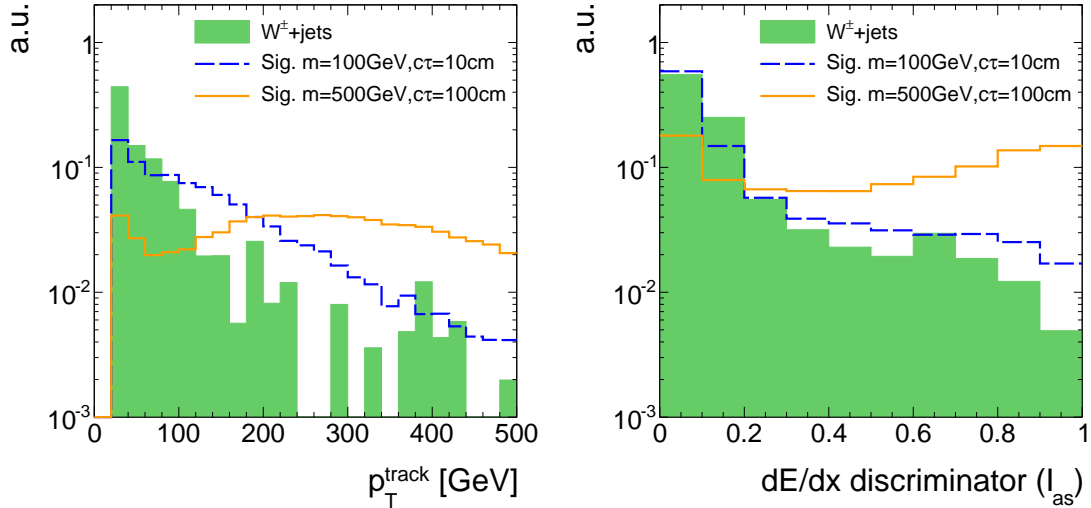

Figure 5.8: Candidate track p_T (left) and I_{as} (right) after the full candidate track selection for signal and $W +$ jets events. Because of high event weights of the $W +$ jets sample, the trigger requirements are not applied. As $\not{E}_T$ and $p_T^{1.\,jet}$ are not expected to be correlated with the track characteristics it does not influences the shape of the shown distributions.
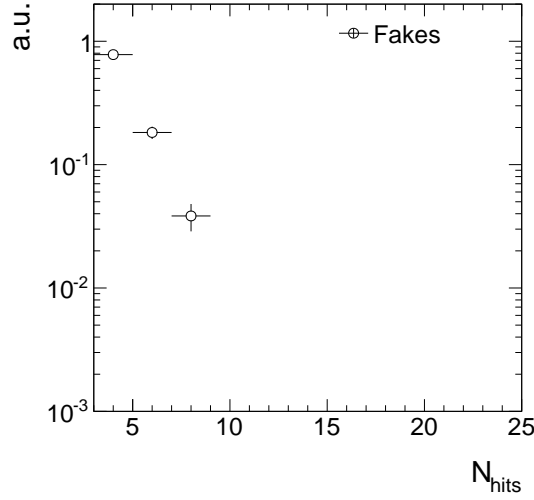
Figure 6.1: Normalised distribution of the number of hits for fake tracks after the candidate track selection from Section 5.2.2.

the non-reconstruction of a lepton and the corresponding methods to estimate the leptonic background will be in detail explained in Section 6.2.

Furthermore, there is the possibility that a track is reconstructed out of a set of hits that 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. It needs to be mentioned that the fake background is contributing through all SM processes, not only via $W+$jets processes. Still, the characteristics of fake tracks can be studied using only $W+$jets. The limited quality of the dE/dx simulation enforces anyways a data-based background estimation method.

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 χ^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 6.1, where the distribution of 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_{as}. Second, to be able to optimise later in the variable I_{as}, the I_{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 [31, 32]. It aims to determine the probability of having a fake track in an event that pass the full track selection (besides the I_{as} criterium). This probability will be called the fake rate.

The inclusive fake background is estimated with the help of $Z \rightarrow \mu\bar{\mu}$ and $Z \rightarrow e\bar{e}$ events from data. 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 5.2.2, the selected track must be a fake.

The selection of two well reconstructed muons and electrons is done with the single-muon and single-electron datasets listed in Table 6.1. For the $Z \rightarrow \mu\bar{\mu}$ selection an event

Table 6.1: Datasets used for the determination of the fake rate.

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

is required to have two muons with $p_{\text{T}} > 25\,\text{GeV}$ and $|\eta| < 2.4$. To supress background

from cosmic muons, the distance from the primary vertex must be less than $|d0| < 0.2\,\text{cm}$ in radial and $|dz| < 0.5\,\text{cm}$ in longitudinal direction. To supress background arising from jets that fake muons, various quality criteria are apllied. Thus, it is required that there is at least one hit in the muon detector and at least two hits in different detector planes. Concerning the track of the muon in the tracker system, at minimum one hit in the pixel tracker and at least six hits in the full tracker system is required. An isolation criterium is applied that requires the sum of transverse momenta in a cone of $\Delta R < 0.4$ of all PF particles to be less than 12%. Finally, the muons are required to be opposite in charge and that their invariant mass is between $80 - 100\,\text{GeV}$. The $Z \to \mu\bar{\mu} +$ fake track selection is summarised in Table 6.2.

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

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

In order to select $Z \to e\bar{e}$ events in data, the two electrons are required to have $p_\text{T} > 25\,\text{GeV}$, $|\eta| < 2.5$ and no missing hits in the inner layers of the tracker. Furthermore, the electrons need to pass a conversion veto to reduce background arising from photon

conversions (as described in [36]). An isolation requirement is applied similar to the muon isolation criterium with a reduced cut of 15%. The electron identification is further based on a multivariate technique developed within [37] that exploits electron characteristics about the track quality, the ECAL cluster shapes, and the combination about the measurements in the tracker and in the ECAL. Again, also the two electrons must be opposite in charge and their invariant mass must be between $80 - 100 \, \text{GeV}$. A summary of the $Z \to e\bar{e} +$ fake track event selection can be found in Table 6.3.

Table 6.3: Event selection cuts for the electrons + fake control sample to estimate the inclusive fake background.

Event-based selection	Two Electrons with	$p_\text{T} > 25 \, \text{GeV}$
		$|\eta| < 2.5$
		$\sum_{\Delta R < 0.4} p_\text{T}^{\text{PF particle}} / p_\text{T}(e) < 0.15$
		pass conversion veto
		no missing tracker hits
		good MVA electron as defined in [37]
	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	

When applying a $Z \to \ell\bar{\ell}$ selection plus the candidate track selection, the selected track should be a fake. If this is indeed the case can be tested on simulated $Z \to \ell\bar{\ell}$ events. As can be seen in Fig. 6.2, a reasonable purity in fake tracks can be achieved by applying the candidate track selection on top of the $Z \to \ell\bar{\ell}$ selection. In simulated $Z \to \mu\bar{\mu}$ events, a purity of 88%, whereas in simulated $Z \to e\bar{e}$ events a purity of 92% of fake tracks can be achieved.

As already mentioned, the fake rate is defined as the probability that an event contains a fake track that fulfils the candidate track selection criteria listed in Section 5.2.2. Thus, for the $Z \to \ell\bar{\ell}$ datasets it is defined as the number of events passing the full selection described in Table 6.2 (Table 6.3) divided by the number of events that pass only the

event-based selection in Table 6.2 (Table 6.3)

$$\rho_{\text{fake}} = \frac{N_{Z \to ll}^{\text{cand trk selection}}}{N_{Z \to ll}}$$

The fake rate for the candidate track selection is e.g. $(6.86 \pm 0.25) \cdot 10^{-5}$. This is of course not the final result as the optimisation in p_{T} will add an additional p_{T} selection cut to the candidate track selection.

Within [31,32], it was checked that the fake rate is constant for different processes. This is shown in Fig. 6.3 where the fake rate is depicted for the most important SM processes. Since the fake rate is constant for different SM processes, the fake rate determined on the $Z \to \ell\bar{\ell}$ dataset can be generalised for all SM background possibily contributing to this search. Thus, the inclusive fake background can be estimated by multiplying the fake rate with the number of events selected in the MET dataset after the event-based selection from Section 5.2.1

$$N_{\text{bkg}}^{\text{fake, inclusive in I}_{\text{as}}} = \rho_{\text{fake}} \cdot N_{\text{event-based selection}}^{\text{MET}} \cdot$$

Given the number of events after the event-based selection of $N_{\text{event-based selection}}^{\text{MET}} = 1.38 \cdot 10^6$ and the fake rate cited above, the inclusive fake background can be estimated to 94.7 ± 3.4 for the candidate track selection.

It should again be mentioned that the inclusive fake background estimation will be
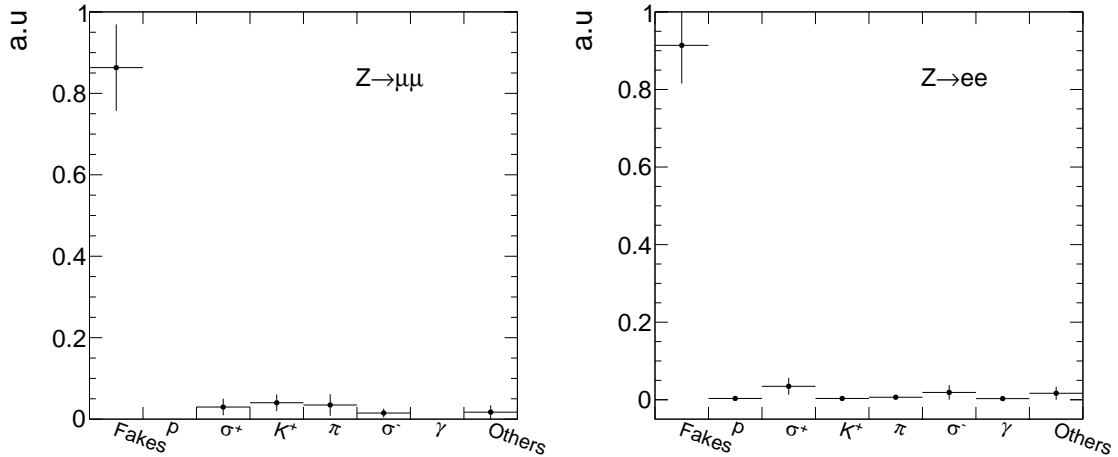

Figure 6.2: Generator-level particle matched to the selected track with the selection described in Table 6.2 (left) and Table 6.3 (right). "Fake" mean that no corresponding generator-level particle could be found.

only inclusive in I_{as} not in p_T. That means that after the definition of the signal region, $N_{bkg}^{\text{fake, inclusive in } I_{as}}$ is determined with the additional optimal p_T selection. Possible differences between the fake rate in $Z \to \ell\bar{\ell}$ events and other SM processes will be estimated with simulated events and taken as systematic uncertainty into account (see Section 6.4.1).

To receive information about the selection efficiency of an I_{as} selection criterium, information about the I_{as} shape of fake tracks is needed. How to receive this information will be explained in the next section.

I_{as} shape of fake background

Information of the energy release per path length for fake tracks should not be taken from simulated samples as the simulation of dE/dx is not reliable (see Fig. 3.9). To get still knowledge about the I_{as} shape of fake tracks, a control region $\text{CR}_{I_{as}}^{\text{fake}}$ is defined that is enriched with fakes and shows the same I_{as} distribution as fake tracks in the signal region.

To enrich fake tracks, it is possible to invert the selection cuts of the number of missing middle and inner hits, i.e. requiring at least one missing inner or middle hit $\left(N_{\text{miss}}^{\text{inner}} + N_{\text{miss}}^{\text{middle}} > 0 \right)$. This can be seen in Fig 6.4, where the distribution of the number of missing inner plus missing middle hits is shown for fakes compared to the leptonic background for simulated $W + \text{jets}$ events.

Of course, it needs also to be checked wether the I_{as} shape in $\text{CR}_{I_{as}}^{\text{fake}}$ is comparable to the I_{as} shape in the signal region. As the exact definition of the signal region will be addressed during optimisation, this test is be done for various p_T selection cuts.
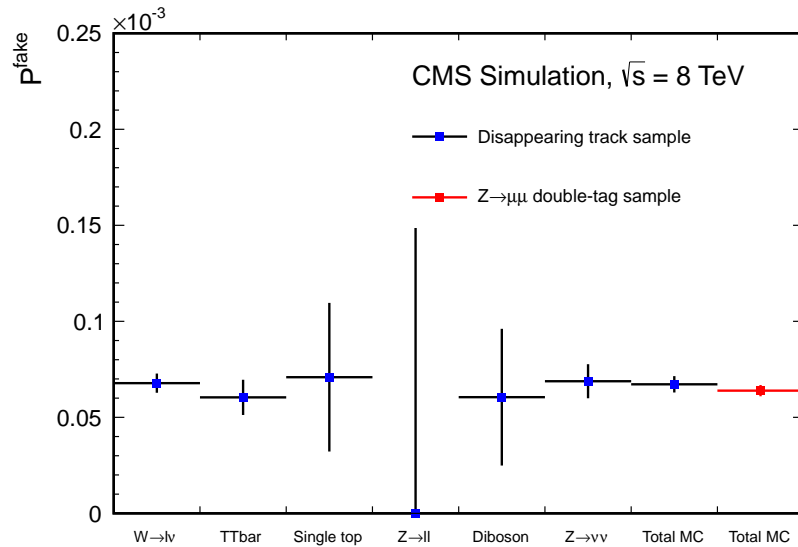

Figure 6.3: Fake track rate estimated in [31,32] for tracks with four hits. Taken from [32]

The comparison of the I_{as} shape of fake tracks can of course only be done on simulation. Thus, simulated $W+$jets events are used to select fake tracks in both region. A compariosn of the shape for the candidate track selection and the $\mathrm{CR}^{fake}_{I_{as}}$ is shown in Fig 6.5. It can be seen that indeed an excellent purity of around 99% of fakes can be achieved in the I_{as} fake control region $\mathrm{CR}^{fake}_{I_{as}}$.

The I_{as} shape is almost identical in the signal and in the control region which makes the definition of the control region perfectly suited for the purpose to estimate the I_{as} shape from $\mathrm{CR}^{fake}_{I_{as}}$ in data. The differences between the both region will be taken as systematic uncertainty into account (discussed in Section 6.4.2).

6.2 Leptonic background

The leptonic background of the here 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.
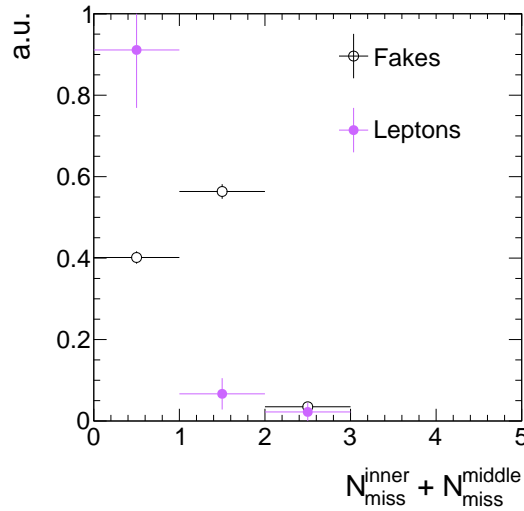

Figure 6.4: Normalised number of missing inner plus missing middle hits for fake and leptonic tracks for the full candidate track selection with the selection requirements on N^{inner}_{miss} and N^{middle}_{miss} removed. The trigger requirements and QCD supression cuts were removed to enhance the statistical precisison.
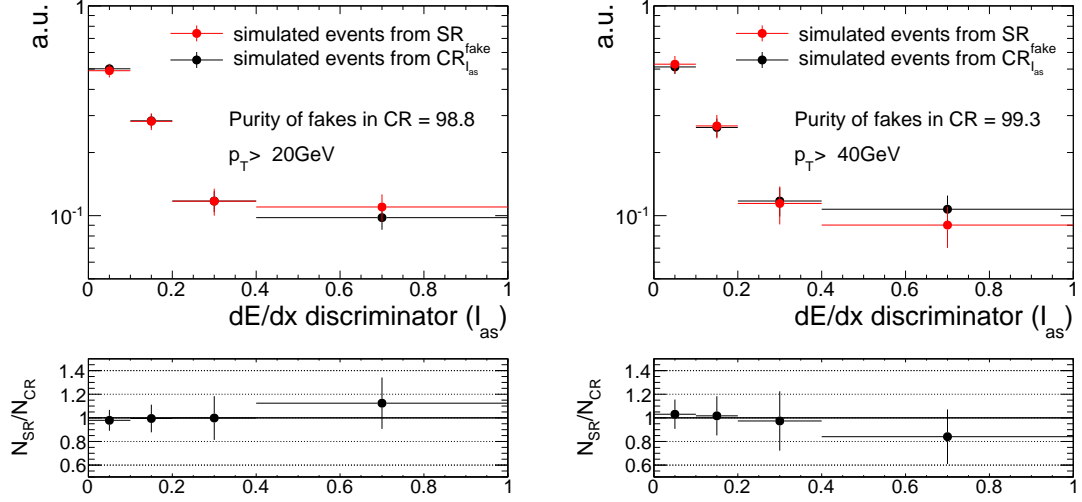
Figure 6.5: Comparison of the I_{as} shape between $\text{CR}_{I_{as}}^{\text{fake}}$ and the signal region for two different track p_T cuts of $20\,\text{GeV}$ (left) and $40\,\text{GeV}$ (right). To enhance the statistical precision only the track selection is applied.

Electrons

To avoid the background source from unreconstructed electrons, all tracks pointing to a dead or noisy ECAL cell, to an ECAL intermodule gap, or to the region between ECAL barrel and encap at $1.42 < |\eta| < 1.65$ are vetoed, as described in Section 5.2. By this selection, almost all electrons are efficiently rejected. In the simulated $W +$ jets sample only one simulated event remains that pass all candidate track selection criteria and for which the candidate track can be matched to a generator-level electron. This event is visualised in Fig 6.6.

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

Taus are contributing to the leptonic background through the hadronic decay of a tau lepton to one charged pion $\tau \to \pi^{\pm}\nu$. Other decay modes of the tau lepton are suppressed by the track isolation criterion. Unreconstructed taus typically don't deposit energy in the HCAL or ECAL, thus fail reconstruction. They can therefore also easily bypass the calorimeter isolation criterion. Because of nuclear interactions in the tracker, pions often result in short reconstructed tracks that can easily be highly mismeasured in p_T.

Figure 6.6: Visualisation of an $W \to e\nu_e$ event contributing to the SM background. In light blue the generator-level particles e and ν_e of the W decay are shown. The ν_e, only weakly interacting does not show any signature in the detector, whereas the electron ($p_T \simeq 90\,\text{GeV}$) leaves a track (black line) with $p_T \simeq 70\,\text{GeV}$ 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 ($p_T \simeq 230\,\text{GeV}$) causes the $\not{E}_T$ (read arrow) in the event.

Thus, taus can also contribute even when imposing a tighter selection in the transverse momentum. Such an event is shown in Fig. 6.7.

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 [31, 32]. This possibility is illustrated in a simulated event shown in Fig 6.8.

In [31, 32] 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_{as}, muons can easily be efficiently suppressed. E.g. in the event example shown in Fig 6.8, the muon has an I_{as} value of about 0.007.

In general, all leptons are minimal ionising. However, as electrons are much lighter

Figure 6.7: Visualisation of a $W^+ \to \tau^+ \nu_\tau \to \pi^+ \bar{\nu}_\tau \nu_\tau$ event contributing to the SM background. In light blue the generator-level particles π^+, $\bar{\nu}_\tau$ and ν_τ are shown. The transverse momentum of the generator-level pion is only $p_{\mathrm{T}} \sim 10\,\mathrm{GeV}$, but because the reconstructed track (black line) is very short, it leads to a high mismeasurement of the track p_{T} of $\sim 40\,\mathrm{GeV}$. The shortness of the track is caused by nuclear interactions of the pion. As no corresponding ECAL or HCAL energy deposits are measured the reconstruction of the pion fails.

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.

Also for the leptonic background the estimation method is splitted into two parts. First, the estimation of the inclusive background without I_{as} information. Second, the estimation of the I_{as} shape for all three leptonic background sources.

Inclusive leptonic background estimation

The inclusive (without I_{as} information) lepton background estimation method follows closely the background estimation method used in [31, 32].

In order to estimate the number of events in the signal region originating from unreconstructed leptons, information from simulated events is used. With the help of simulated $W + \mathrm{jets}$ events, the ratio between the number of events in the signal region with the selected track matched to a generator-level lepton $N_{SR}^{\mathrm{trk\ matched\ to\ lepton}_i}$ and the number of events in the control region $N_{CR}^{\mathrm{lepton}_i\ \mathrm{veto\ inverted}}$ with the lepton veto inverted is determined.
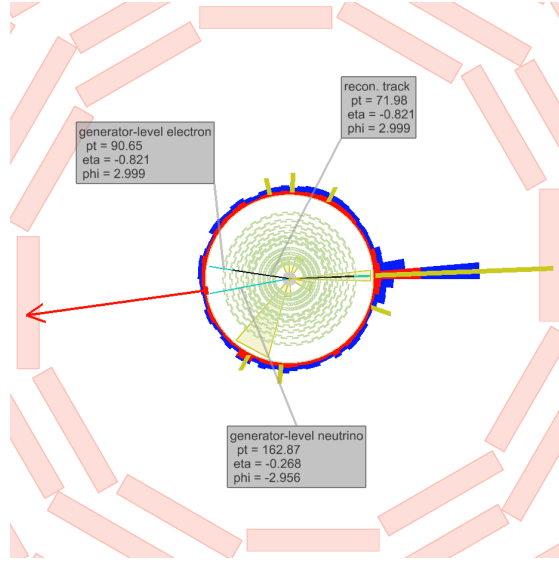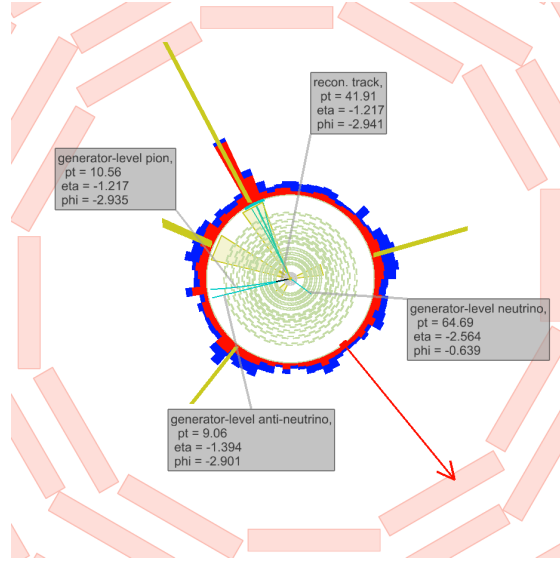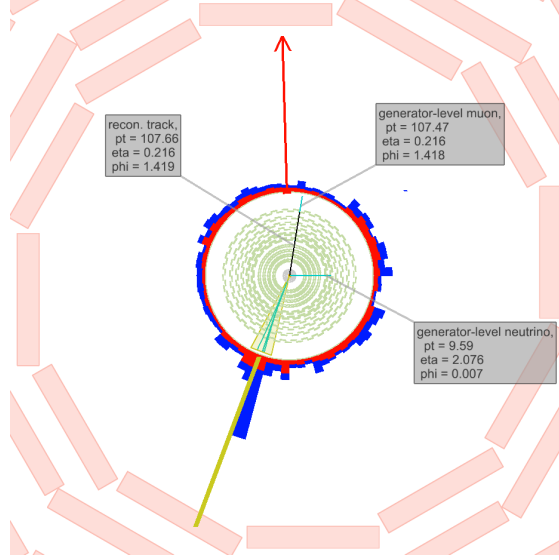
Figure 6.8: Visualisation of an $W \to \mu\nu_\mu$ event contributing to the SM background. In light blue the generator-level particles μ and ν_μ of the W decay are shown. The muon is pointing to the η-region between stations 0 and 1 of the DT system at $|\eta| \sim 0.25$. In this region the muon reconstruction is less effcient. No signal in the muon chambers are visible. Therefore the muon could not be reconstructed.

For muons, this lead to the following expression

$$\rho_{\text{MC}}^\mu = \frac{N_{\text{SR,MC}}^{\text{trk matched to } \mu}}{N_{\text{CR,MC}}^{\mu \text{ veto inverted}}}.$$

Since for electrons and taus the reconstruction efficiency is highly correlated with the $E_{\text{calo}}^{\Delta R < 0.5}$ selection requirement, the $E_{\text{calo}}^{\Delta R < 0.5}$ requirement is additionnaly removed in the control regions for these two lepton types

$$\rho_{\text{MC}}^{e,\tau} = \frac{N_{\text{SR,MC}}^{\text{trk matched to } e,\tau}}{N_{\text{CR,MC}}^{e,\tau \text{ veto inverted}, \cancel{E_{\text{calo}}^{\Delta R < 0.5} < 5\,\text{GeV}}}}.$$

In order to estimate the inclusive background for all three lepton types, the scaling factor $\rho_{\text{MC}}^{\text{lep}_i}$ is applied to the number of events in the lepton veto inverted control region measured in data. Also in data the control region for electrons and taus is defined with the $E_{\text{calo}}^{\Delta R < 0.5}$ requirement removed. Thus the inclusive number of background events is

$$N_{\text{bkg}}^{\mu, \text{ inclusive in I}_{\text{as}}} = \rho_{\text{MC}}^\mu \cdot N_{\text{CR,data}}^{\mu \text{ veto inverted}}.$$

for muons, and

$$N_{\text{bkg}}^{e,\tau, \text{ inclusive in I}_{as}} = \rho_{\text{MC}}^{e,\tau} \cdot N_{\text{CR,data}}^{e,\tau \text{ veto inverted,} \cancel{E_{\text{calo}}^{\Delta R < 0.5} < 5\,\text{GeV}}}.$$

for electrons and taus.

This method relies on the simulation of the lepton reconstruction inefficiencies. A possible wrong simulation is taken into account via a comparison of the lepton reconstruction efficiencies in data and simulation in $Z \rightarrow \ell\bar{\ell}$ events which will be later explained in Section 6.4.3.

To reduce the statistical uncertainty, the scale factor is calculated without applying the QCD suppression cuts. After the candidate track selection described in Section 5.2 (without QCD selection cuts), only one event remains in the simulated $W + $ jets sample where the candidate track can be matched to an electron. There are five track candidates that can be matched to a muon, and zero selected tracks that can be mactched to a pion. The 68% upper and lower limits on the inclusive background are estimated with the Neyman procedure [15]. Table 6.4 gives the result for the prediction of the inclusive leptonic background estimation for the candidate track selection from Section 5.2.

Table 6.4: Scaling factor ρ_{MC}, number of events in the control region in data $N_{\text{CR,data}}$ and the resulting inclusive estimation $N_{\text{predicted}}$ after the candidate track selection.

	scaling factor ρ_{MC}	$N_{\text{CR,data}}$	$N_{\text{predicted}}$
electrons	$1.25^{+1.70}_{-0.77} \cdot 10^{-4}$	60067	$7.49^{+10.19}_{-4.63}$
muons	$2.17^{+1.65}_{-0.93} \cdot 10^{-4}$	76664	$16.64^{+12.64}_{-7.12}$
taus	$< 2.13 \cdot 10^{-2}$	445	< 9.46

I_{as} shape of leptonic background

In order to get information about the I_{as} shape of electrons, muons and taus in the signal region, one need to find a control region where the shape is similar to that in the signal region. The most natural control region, being the lepton veto inverted control region, cannot be used because the variable I_{as} is highly correlated to the lepton recontruction efficiency, as can be seen in Fig. **??**. Various other control regions were tested. Unfortunately, the energy deposition is not only correlated to the reconstruction probability of the leptons but also to $E_{\text{calo}}^{\Delta R < 0.5}$, p_{T} and various other observables that were tested. As no suitable control region exists where the I_{as} shape of the leptons is at least similar to the shape in the signal region, it is therefore decided to use the I_{as} information from

simulation. This introduces of course a large systematic uncertainty. However, the corresponding systematic uncertainty is still smaller than taking the I_{as} shape from a control region in data.

In order to take into account the bias when taking I_{as} from simulation, a systematic uncertainty is estimated that address simulation-data differences of the I_{as} distributions. This systematic uncertainty is discussed in Section 6.4.4.

6.3 Background estimation validation

The background estimation methods are exhaustively validated with the help of signal depleted control regions. Various control regions were used for the validation.

First, to validate the estimation method of the leptonic background, a leptonic control region is defined by selecting only tracks with $N_{hits} > 6$. This reduces the fake contribution to a minimum. Additionally in order to minimise signal contamination, the $E_{calo}^{\Delta R < 0.5}$ requirement is inverted to $E_{calo}^{\Delta R < 0.5} > 10\,\text{GeV}$. The validation test for the candidate track selection with $E_{calo}^{\Delta R < 0.5} > 10\,\text{GeV}$ and $N_{hits} > 6$ is shown in Table 6.7.

Table 6.5: Validation test of leptonic background estimation. Left: $E_{calo}^{\Delta R < 0.5} > 10\,\text{GeV}$ and $N_{hits} > 6$ (only statistical uncertainties are included). Right: $E_{calo}^{\Delta R < 0.5} > 10\,\text{GeV}$, $N_{hits} > 6$ and $I_{as} > 0.2$

	Predicted Yield	Data Yield
electrons	$14.67^{+11.16}_{-6.29}$	
muons	$7.99^{+10.90}_{-5.00}$	
taus	$109.04^{+21.18}_{-16.58}$	
Total bkg	$132.68^{+26.31}_{-18.43}$	156

	Predicted Yield	Data Yield
electrons	$0.0^{+0.07}_{-0.0}$	
muons	$0.0^{+0.32}_{-0.0}$	
taus	$0.0^{+0.38}_{-0.0}$	
Total bkg	$0.0^{+0.50}_{-0.0}$	1

In order to validate the fake background, the N_{hits} selection cut is again removed. As the inclusive fake background can only be estimated within the low calorimeter isolation region $E_{calo}^{\Delta R < 0.5} < 5\,\text{GeV}$ or $E_{calo}^{\Delta R < 0.5} < 10\,\text{GeV}$, the information about the number of fake tracks in the high $E_{calo}^{\Delta R < 0.5}$ region is taken from the fake enriched control region. In this control region, the ratio of $N_{E_{calo}^{\Delta R < 0.5} > 10\,\text{GeV}} / N_{E_{calo}^{\Delta R < 0.5} < 10\,\text{GeV}}$ is estimated and taken as a multiplicator to the number of events predicted from the $E_{calo}^{\Delta R < 0.5} < 10\,\text{GeV}$ region. In Table 6.6, two different validation tests are shown, once an inclusive validation in I_{as} and once with an I_{as} selection of 0.2.

Table 6.6: Validation test of fake and leptonic background estimation methods (only statistical uncertainties are included). Left: $E_{\text{calo}}^{\Delta R<0.5} > 10\,\text{GeV}$. Right: $E_{\text{calo}}^{\Delta R<0.5} > 10\,\text{GeV}$ and $I_{\text{as}} > 0.2$

	Predicted Yield	Data Yield		Predicted Yield	Data Yield
Electrons	$59.92^{+16.11}_{-11.85}$		Electrons	$0.75^{+0.36}_{-0.25}$	
Muons	$8.04^{+10.97}_{-5.03}$		Muons	$0.00^{+0.32}_{-0.00}$	
Taus	$173.06^{+24.62}_{-20.23}$		Taus	$2.33^{+0.74}_{-0.55}$	
Fakes	$67.98^{+11.57}_{-11.57}$		Fakes	$11.72^{+2.79}_{-2.79}$	
Total bkg	$309.00^{+33.46}_{-26.62}$	324	Total bkg	$14.80^{+2.92}_{-2.85}$	16

The validation is done for different selections in p_{T} and I_{as}. All validation tests show good agreement.

Still, systematic uncertainties need to be estimated. The sources of systematic uncertainties and how they are estimated will be explained in the following section.

6.4 Systematic uncertainties

The corresponding systematic uncertainties on the background estimation methods, are the uncertainty on the fake rate ρ_{fake}, the uncertainty of shape differences in the I_{as} distribution between the signal region and the fake control region $\text{CR}_{I_{\text{as}}}^{\text{fake}}$, the uncertainty on the leptonic scale factor $\rho_{\text{MC}}^{\text{lep}_i}$ determined with simulated events, and the uncertainty of the shape differences between simulation and real data of the leptonic background.

6.4.1 Uncertainty on the fake rate

The uncertainty on the fake rate ρ_{fake} is determined with a comparison of the fake rate in $W + \text{jets}$ and $Z \to \ell\bar{\ell}$ events in simulation (datasets listed in Table 4.2 were used.) Unfortunately, the statistical precision of this comparison is limited. Therefore, the estimation of this systematic uncertainty is again introducing large uncertainties due to the statistical limitation of the simulated $W + \text{jets}$ sample. As the fake rate is not expected to be correlated to the $\not{E}_{\text{T}}$ and $p_{\text{T}}^{1.\text{jet}}$ selections, these selections requirements are removed/loosend for the fake rate comparison in order to enhance the statistical precision of the systemactic uncertainty. This can be seen in Table **??**. There, the results of the fake rate can be seen for different event-based selections. All are compatible within the statistcial uncertainty.

Table 6.7: Fake rates in simulated $W + \text{jets}$ and $Z \to \ell\bar{\ell}$ events for different event-based selections). Right: $E_{\text{calo}}^{\Delta R<0.5} > 10\,\text{GeV}$, $N_{\text{hits}} > 6$ and $I_{\text{as}} > 0.2$

Selections	$\rho_{\text{fake}}^{W+\text{jets}}$	$\rho_{\text{fake}}^{Z\to\ell\bar{\ell}}$
	$14.67^{+11.16}_{-6.29}$	
	$7.99^{+10.90}_{-5.00}$	
	$109.04^{+21.18}_{-16.58}$	

The systematic uncertainty is estimated with the largest 1-sigma deviation from one, being 25%.

6.4.2 Uncertainty on the fake track I_{as} shape

The uncertainty on the I_{as} shape from the fake control region $\rho_{\text{MC}}^{\text{lep}_i}$ is estimated using simulated $W + \text{jets}$ events. A comparison is done between the I_{as} shape in the signal region and the control region in simulation. Figure ?? shows the I_{as} distribution fore different p_{T} selection cuts. The ratio in the second bin between the signal region and the control region is calculated. Again, the largest 1-sigma difference fromone is taken as systematic ucnertainty.

6.4.3 Uncertainty on the leptonic scale factor

6.4.4 Uncertainty on the leptonic I_{as} shape

7 Optimisation of search sensitivity

- Show plots

- show table

- Include NlostOuter here, too

8 Results

- Data cutflowtable

- 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

A Detailed event yield tables for simulated samples and data

Table A.1: Event yields after each selection step for various background processes. FIXME update this table with correct ttjets sample!!

Selection	W + jets	$t\bar{t}$ + jets	$Z \to \ell\bar{\ell}$	Multijet
after skim ($p_{\mathrm{T}}^{1.\mathrm{jets}} > 60\,\mathrm{GeV}$)	$9.16 \cdot 10^7$	$1.04 \cdot 10^6$	$2.21 \cdot 10^7$	$1.38 \cdot 10^{11}$
trigger	$4.31 \cdot 10^6$	$1.12 \cdot 10^5$	$4.23 \cdot 10^3$	$4.32 \cdot 10^6$
$p_{\mathrm{T}}^{1.\mathrm{jet}} > 100\,\mathrm{GeV}$	$3.07 \cdot 10^6$	$7.89 \cdot 10^4$	$1.02 \cdot 10^3$	$1.15 \cdot 10^6$
$\not{E}_{\mathrm{T}} > 100\,\mathrm{GeV}$	$1.89 \cdot 10^6$	$5.17 \cdot 10^4$	$6.26 \cdot 10^2$	$9.63 \cdot 10^5$
$\Delta\phi_{\mathrm{max}}\left(\mathrm{jet}_i, \mathrm{jet}_j\right) < 2.7$	$1.11 \cdot 10^6$	$6.58 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
$\Delta\phi_{\mathrm{max}}\left(\mathrm{jet}_i, \not{E}_{\mathrm{T}}\right) > 0.5$	$1.11 \cdot 10^6$	$6.64 \cdot 10^3$	$1.32 \cdot 10^2$	$2.01 \cdot 10^4$
≥ 1 reconstructed trk	$1.10 \cdot 10^6$	$6.57 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 high-purity trk	$1.10 \cdot 10^6$	$6.57 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk with $N_{\mathrm{miss}}^{\mathrm{middle}} = 0$	$1.09 \cdot 10^6$	$6.55 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk with $N_{\mathrm{miss}}^{\mathrm{inner}} = 0$	$1.07 \cdot 10^6$	$6.53 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk with $|d0| < 0.02\,\mathrm{cm}$	$1.07 \cdot 10^6$	$6.47 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk with $|dz| < 0.5\,\mathrm{cm}$	$1.07 \cdot 10^6$	$6.46 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk with $|\eta| < 2.1$	$1.03 \cdot 10^6$	$6.41 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$	$1.03 \cdot 10^6$	$6.41 \cdot 10^3$	$1.32 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk without a μ within $\Delta R < 0.15$	$9.85 \cdot 10^5$	$6.32 \cdot 10^3$	$1.14 \cdot 10^2$	$9.55 \cdot 10^3$
≥ 1 trk without an e within $\Delta R < 0.15$	$9.55 \cdot 10^5$	$6.22 \cdot 10^3$	$8.53 \cdot 10^1$	$9.55 \cdot 10^3$
≥ 1 trk without a τ within $\Delta R < 0.15$	$9.53 \cdot 10^5$	$6.21 \cdot 10^3$	$8.53 \cdot 10^1$	$9.55 \cdot 10^3$
≥ 1 trk without a jet within $\Delta R < 0.5$	$9.15 \cdot 10^5$	$6.13 \cdot 10^3$	$8.53 \cdot 10^1$	$9.55 \cdot 10^3$
≥ 1 trk ! within $\Delta R < 0.05$ of a dead/noisy ECAL cell	$3.70 \cdot 10^5$	$3.78 \cdot 10^3$	$8.53 \cdot 10^1$	$0.00 \cdot 10^0$
≥ 1 trk ! within an ECAL intermodule gap	$3.52 \cdot 10^5$	$3.61 \cdot 10^3$	$8.53 \cdot 10^1$	$0.00 \cdot 10^0$
≥ 1 trk ! within $1.42 < |\eta| < 1.65$	$2.21 \cdot 10^5$	$2.30 \cdot 10^3$	$0.00 \cdot 10^0$	$0.00 \cdot 10^0$
≥ 1 trk ! within $\Delta R < 0.25$ to a bad CSC	$1.04 \cdot 10^4$	$1.20 \cdot 10^2$	$0.00 \cdot 10^0$	$0.00 \cdot 10^0$
≥ 1 trk with $\sum\limits_{\Delta R < 0.3} p_{\mathrm{T}}/p_{\mathrm{T}}^{\mathrm{cand}} < 0.1$	$8.14 \cdot 10^3$	$7.96 \cdot 10^1$	$0.00 \cdot 10^0$	$0.00 \cdot 10^0$

Table A.2: Event yields after each selection step for various signal models. FIXME update this table with other signal samples!!

Selection	m=100 GeV $c\tau$=10 cm	m=100 GeV $c\tau$=100 cm	m=500 GeV $c\tau$=10 cm	m=500 GeV $c\tau$=100 cm
before selection	$3.41 \cdot 10^5$	$3.41 \cdot 10^5$	$3.46 \cdot 10^2$	$3.46 \cdot 10^2$
trigger	$1.56 \cdot 10^4$	$1.49 \cdot 10^4$	$4.63 \cdot 10^1$	$4.61 \cdot 10^1$
$p_\mathrm{T}^{1.\,\mathrm{jet}} > 100\,\mathrm{GeV}$	$1.10 \cdot 10^4$	$1.05 \cdot 10^4$	$3.65 \cdot 10^1$	$3.58 \cdot 10^1$
$\not{E}_\mathrm{T} > 100\,\mathrm{GeV}$	$1.09 \cdot 10^4$	$9.84 \cdot 10^3$	$3.63 \cdot 10^1$	$3.56 \cdot 10^1$
$\Delta\phi_\mathrm{max}\left(\mathrm{jet}_i, \mathrm{jet}_j\right) < 2.7$	$7.91 \cdot 10^3$	$6.99 \cdot 10^3$	$2.76 \cdot 10^1$	$2.70 \cdot 10^1$
$\Delta\phi_\mathrm{max}\left(\mathrm{jet}_i, \not{E}_\mathrm{T}\right) > 0.5$	$7.91 \cdot 10^3$	$7.04 \cdot 10^3$	$2.77 \cdot 10^1$	$2.71 \cdot 10^1$
≥ 1 reconstructed trk	$3.13 \cdot 10^3$	$5.75 \cdot 10^3$	$5.74 \cdot 10^0$	$2.13 \cdot 10^1$
≥ 1 high-purity trk	$2.91 \cdot 10^3$	$5.66 \cdot 10^3$	$5.25 \cdot 10^0$	$2.08 \cdot 10^1$
≥ 1 trk with $N_\mathrm{miss}^\mathrm{middle} = 0$	$2.87 \cdot 10^3$	$5.46 \cdot 10^3$	$5.23 \cdot 10^0$	$2.02 \cdot 10^1$
≥ 1 trk with $N_\mathrm{miss}^\mathrm{inner} = 0$	$2.86 \cdot 10^3$	$5.41 \cdot 10^3$	$5.22 \cdot 10^0$	$2.01 \cdot 10^1$
≥ 1 trk with $|d0| < 0.02\,\mathrm{cm}$	$2.81 \cdot 10^3$	$5.39 \cdot 10^3$	$5.08 \cdot 10^0$	$1.99 \cdot 10^1$
≥ 1 trk with $|dz| < 0.5\,\mathrm{cm}$	$2.80 \cdot 10^3$	$5.39 \cdot 10^3$	$5.08 \cdot 10^0$	$1.99 \cdot 10^1$
≥ 1 trk with $|\eta| < 2.1$	$2.63 \cdot 10^3$	$4.98 \cdot 10^3$	$5.01 \cdot 10^0$	$1.91 \cdot 10^1$
≥ 1 trk with $p_\mathrm{T} > 10\,\mathrm{GeV}$	$2.63 \cdot 10^3$	$4.98 \cdot 10^3$	$5.01 \cdot 10^0$	$1.91 \cdot 10^1$
≥ 1 trk without a μ within $\Delta R < 0.15$	$2.63 \cdot 10^3$	$4.70 \cdot 10^3$	$5.01 \cdot 10^0$	$1.89 \cdot 10^1$
≥ 1 trk without an e within $\Delta R < 0.15$	$2.63 \cdot 10^3$	$4.70 \cdot 10^3$	$5.01 \cdot 10^0$	$1.89 \cdot 10^1$
≥ 1 trk without a τ within $\Delta R < 0.15$	$2.63 \cdot 10^3$	$4.68 \cdot 10^3$	$5.01 \cdot 10^0$	$1.89 \cdot 10^1$
≥ 1 trk without a jet within $\Delta R < 0.5$	$2.61 \cdot 10^3$	$4.64 \cdot 10^3$	$4.89 \cdot 10^0$	$1.84 \cdot 10^1$
≥ 1 trk !within $\Delta R < 0.05$ of a dead/noisy ECAL cell	$2.40 \cdot 10^3$	$4.30 \cdot 10^3$	$4.44 \cdot 10^0$	$1.71 \cdot 10^1$
≥ 1 trk !within an ECAL intermodule gap	$2.38 \cdot 10^3$	$4.27 \cdot 10^3$	$4.41 \cdot 10^0$	$1.70 \cdot 10^1$
≥ 1 trk !within $1.42 < |\eta| < 1.65$	$2.16 \cdot 10^3$	$3.92 \cdot 10^3$	$4.19 \cdot 10^0$	$1.58 \cdot 10^1$
≥ 1 trk !within $\Delta R < 0.25$ to a bad CSC	$2.06 \cdot 10^3$	$3.71 \cdot 10^3$	$4.06 \cdot 10^0$	$1.52 \cdot 10^1$
≥ 1 trk with $\sum\limits_{\Delta R < 0.3} p_\mathrm{T}/p_\mathrm{T}^\mathrm{cand} < 0.1$	$2.03 \cdot 10^3$	$3.67 \cdot 10^3$	$4.00 \cdot 10^0$	$1.51 \cdot 10^1$

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