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## **Part I**

**A search for highly ionising, short tracks at  
the CMS detector**



# 1 Motivation

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

In R-parity conserving Supersymmetry, compressed spectra can be realised if the lightest neutralino ( $\chi_1^0$ ) is almost mass-degenerate with the lightest chargino ( $\chi_1^\pm$ ). Such a mass-degeneracy naturally occurs in case of wino-like neutralinos and charginos, since the mass gap between  $W_3$  and  $W_{1/2}$  is fully determined by higher loop corrections (see Section ??). SUSY models with a wino-like lightest neutralino are especially interesting because they are able to explain the sources of the relic density [4,5]. While it is not possible to explain the full relic density with thermally produced neutralinos for  $m_{\chi_1^0} \lesssim 2.9$  TeV [6], 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 [7].

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

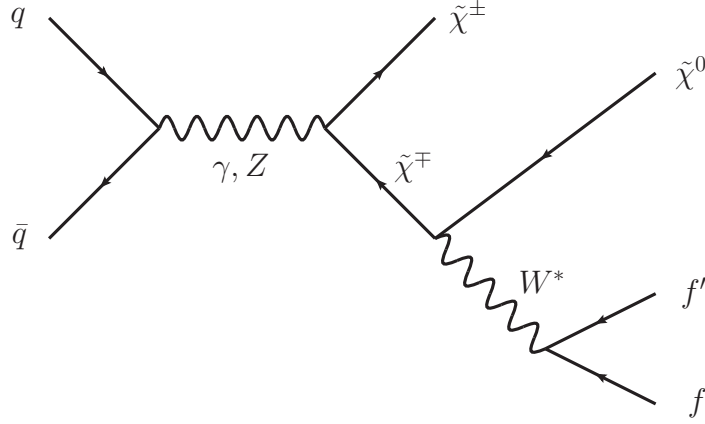


Figure 1.1: Feynman diagram of chargino pair production via gamma or  $Z$ -boson exchange and the subsequent decay via a virtual  $W$ -boson.

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

Apart from pair production, charginos can be produced via the chargino neutralino production channel. On tree-level, there exist two production mechanisms: the s-channel  $W$ -boson exchange and the t-channel squark exchange (Fig. 1.3).

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

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

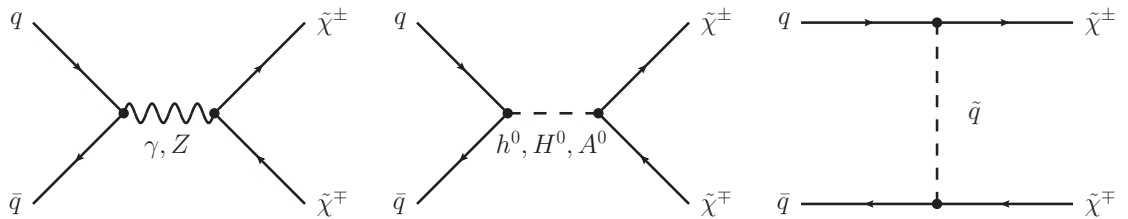


Figure 1.2: Main tree-level diagrams for chargino pair production.

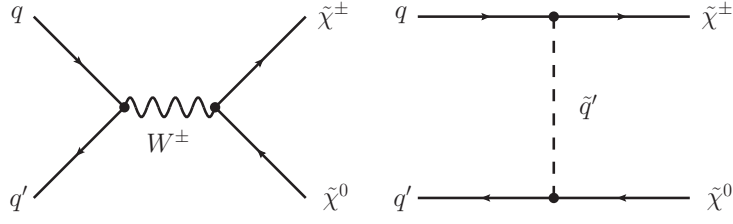


Figure 1.3: Main tree-level diagrams for chargino neutralino production.

introduction to the pMSSM). The results of such a study which has been performed in [8] are shown in Figure 1.4. It can be seen that general SUSY searches (blue area) are mostly sensitive to shorter chargino lifetimes ( $c\tau \lesssim 10 \text{ cm}$ )<sup>1</sup>. Two existing searches, the search for long-lived charged particles [9] and the search for disappearing tracks [8] focus on long and intermediate chargino lifetimes respectively. These two searches (purple and red areas) are sensitive to chargino lifetimes of  $\gtrsim 35 \text{ cm}$ . Taken together, the existing searches exclude a large fraction of pMSSM points at different chargino lifetimes. However, there is a gap between the general SUSY searches and the search for disappearing tracks where none of the existing searches show a high sensitivity.

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

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

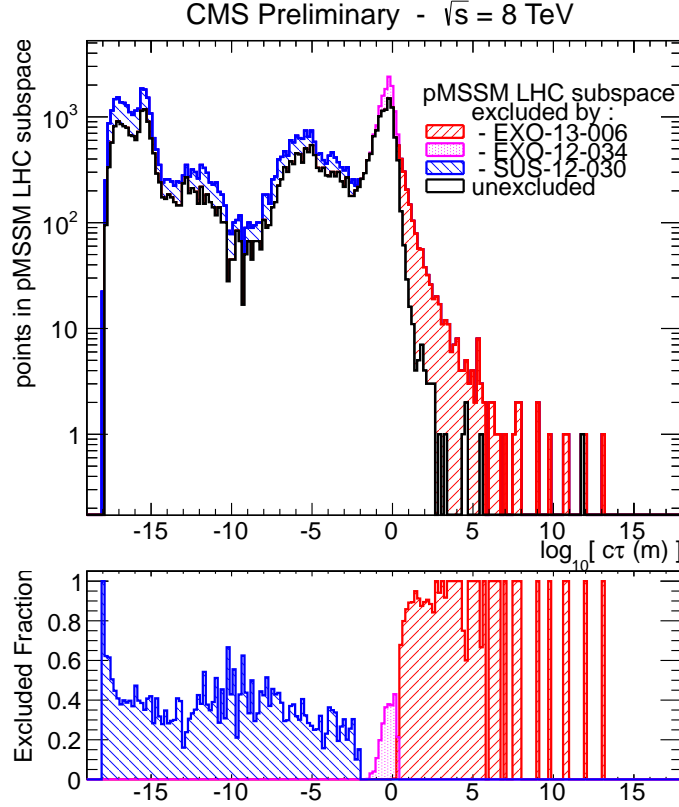


Figure 1.4: The number of excluded pMSSM points at 95% C.L. (upper part) and the fraction of excluded pMSSM points (bottom part) vs. the chargino lifetime for different CMS searches. Red area: the search for long-lived charged particles [9], Purple area: the search for disappearing tracks [8], Blue area: a collection of various general SUSY searches [10]. 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 [11] for further details). Taken from: [12].

## 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 [13]. For lower lifetimes, the chargino can already decay inside the detector



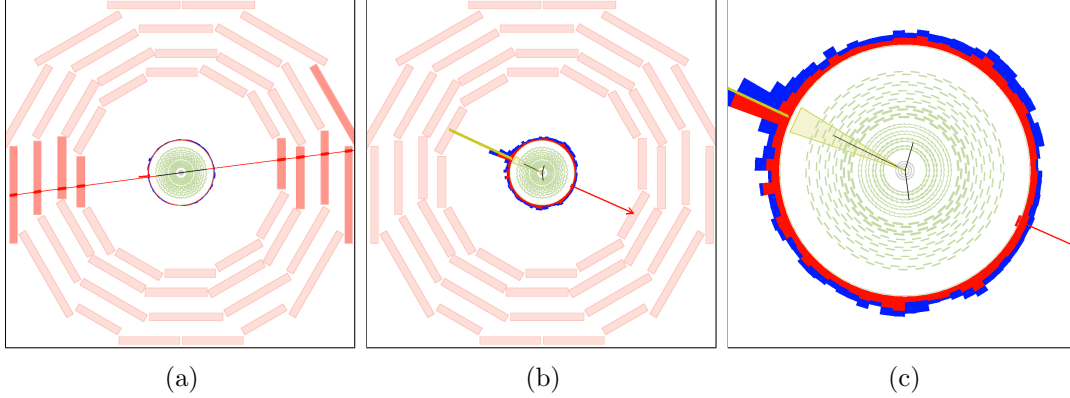


Figure 2.1: Visualisation of possible signatures of a chargino pair produced with a lifetime of  $c\tau = 10$  m (a) and a lifetime of  $c\tau = 0.5$  m (b and c). In the left picture, both charginos are reconstructed as muons, which can be seen in the energy deposition in the muon chambers (red boxes).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

(e. g. the tracker), and can hence not be reconstructed as a muon but leads to an isolated, potentially disappearing track in the tracker. The detector signatures of these two scenarios are visualised in Fig. 2.1, where simulated chargino-chargino events are shown in a cross-sectional view of the CMS detector.

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

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

First of all, the fermionic decay product (e. g. a pion) can hardly be reconstructed

because it does not origin from the primary vertex. Secondly, it is very low in momentum because of the mass-degeneracy between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ . The typical momentum of a pion originating from a chargino to neutralino decay in the  $\tilde{\chi}_1^\pm$  rest frame is of the order

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

For a mass gap between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  of  $\Delta m = 150$  MeV, the pt distribution of the resulting pion peaks at  $\sim 100$  MeV and ends at  $p_T \sim 400$  MeV (Fig. 2.2).

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 GeV decreases rapidly, reaching around 40% for isolated pions with a  $p_T$  of 100 MeV [14]. It is therefore impossible to rely on a reconstruction of the fermionic chargino decay products in this analysis.

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

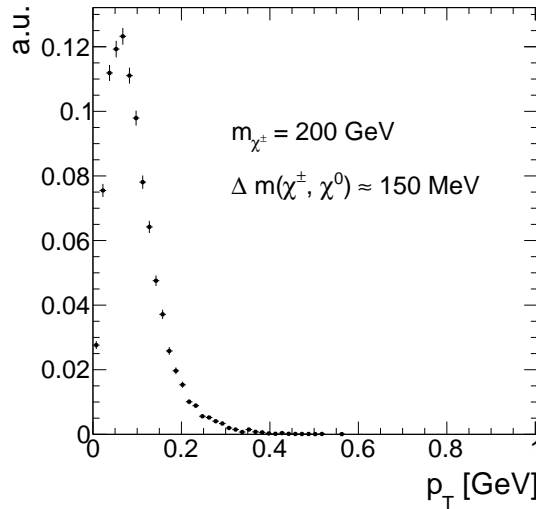


Figure 2.2: Transverse momentum distribution of pions coming from chargino decay into a neutralino with a mass gap of 150 MeV.

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 section (Figs. 1.2, 1.3), resulting in initial state radiation (ISR). If the initial quarks radiate a high  $p_T$  gluon, the resulting jet can be detected and can offer a possibility to search for events with nothing more than isolated tracks. Furthermore, the non-detection of the chargino's decay products plus a high  $p_T$  ISR jet lead to missing transverse energy (MET) in the event. Exploiting these two circumstances, it is possible to detect chargino-pair or chargino-neutralino events with the help of Jet+MET triggers.

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

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

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

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

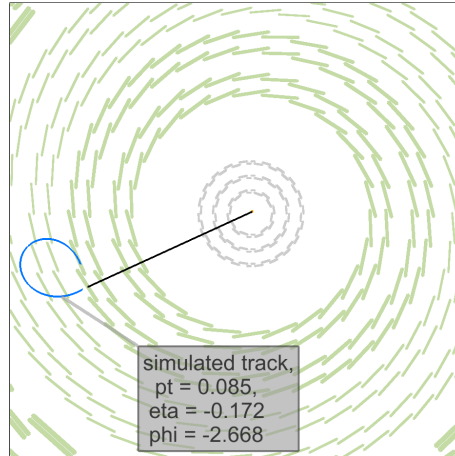


Figure 2.3: Cross-sectional view of the tracker (silicon strip (silicon pixel) tracker layers are illustrated with green (grey) lines) and a simulated chargino track (black line) decaying to a pion (bended blue line) with a  $p_T$  of  $\sim 85$  MeV and a neutralino (not visible).

sociated track is disappearing. For low lifetimes, the tracks can be very short and can have only a few hits in the detector. In order to reconstruct a particle's trajectory, a minimum of three hits are required since defining a helical path requires five parameters (see [14]). 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 [9] and the search for disappearing tracks [8]. 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 [8].

In [9], a minimum number of eight hits were required for every track, whereas [8] required a minimum of seven hits. This can be very inefficient for shorter lifetimes, where most of the charginos already decay shortly after the pixel tracker. In Fig. 2.4 (left), the normalised distribution of the number of measurements ( $N_{\text{hits}}$ ) of chargino tracks is shown. It can be seen, that  $N_{\text{hits}}$  peaks at the minimal possible value needed for track reconstruction of  $N_{\text{hits}} = 3$  for lower lifetimes. For higher lifetimes ( $c\tau = 50 \text{ cm}$ ) the distribution shifts to higher values with a second peak at  $N_{\text{hits}} \sim 17$ . However, a notable fraction of  $\sim 40\%$  of chargino tracks still has a number of measurements of  $N_{\text{hits}} < 8$ .

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

Additionally, the search for disappearing tracks which targets models with charginos decaying inside the tracker did not make use of the high energy deposition of heavy particles. Although this variable was indeed used in the search for long-lived charged particles,

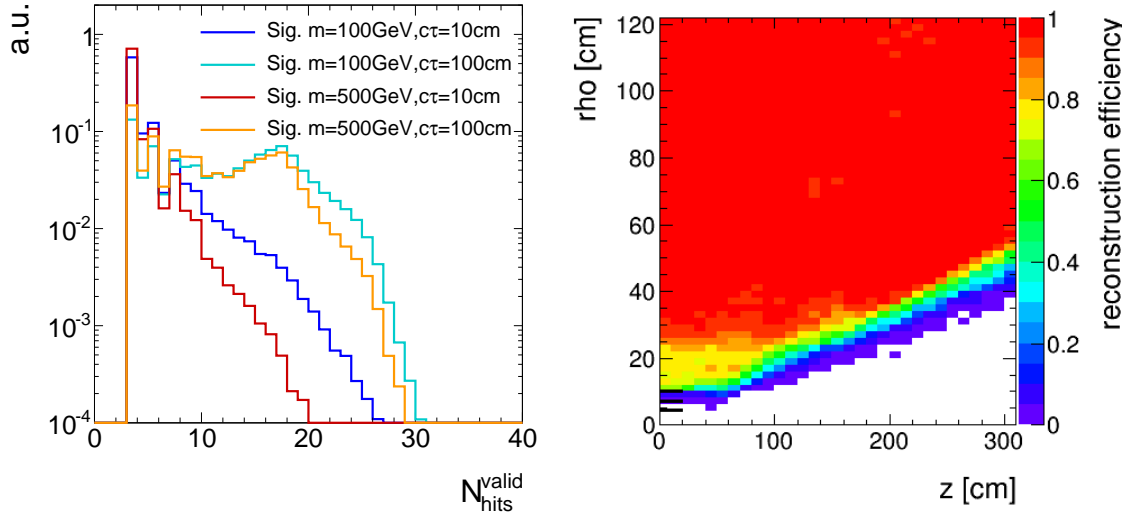


Figure 2.4: Left: Number of measurements in the tracker system  $N_{\text{hits}}$  for four different signal lifetimes. The low lifetime samples are rapidly falling and peaking at the lowest number of possible measurements of three. For a lifetime of  $c\tau = 50$  cm, a second peak at  $\sim 17$  hits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

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 [9] and [8] and to lower the strong selection on the number of hits in these analyses in order to get an optimised selection for lifetimes around  $10 \text{ cm} \lesssim c\tau \lesssim 40 \text{ cm}$ .

### 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 [9], 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 is 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 [15]:

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

It is valid 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 eV [16].  $T_{\max}$  represents the maximum energy transfer in a single collision. The relevant particle's properties are the velocity ( $\beta$ ), the Lorentz factor ( $\gamma$ ) and the charge ( $z$ ) of the incident particle. The density correction  $\delta(\beta\gamma)$  reduces the mean energy loss at high energies because of polarisation effects of the material. The constant factor  $K$  is  $4\pi N_A r_e^2 m_e^2 c^2$  with  $N_A$  being the Avogadro 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” [17]. 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 [18]

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

The Landau distribution has no free parameters. Its most probable value is around 0.222. However, it is possible to introduce artificially a different most probable value and a width with  $x \rightarrow \frac{x - \text{MPV}}{\sigma} - 0.222$ . 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 par-

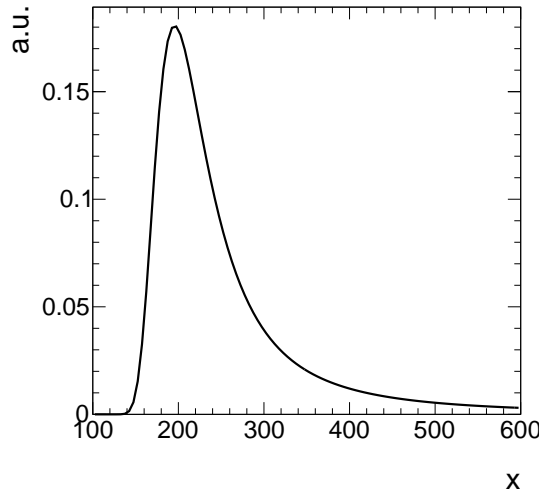


Figure 3.1: Illustration of the shape of a Landau distribution. Parameters were chosen as  $\mu = 200$  and  $\sigma = 20$ .

ticle'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 particle,  $\Delta_p$ , is defined by the Landau-Vavilov-Bichsel equation [19]:

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

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

However, 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 [20]. One of the estimators, also used in the next

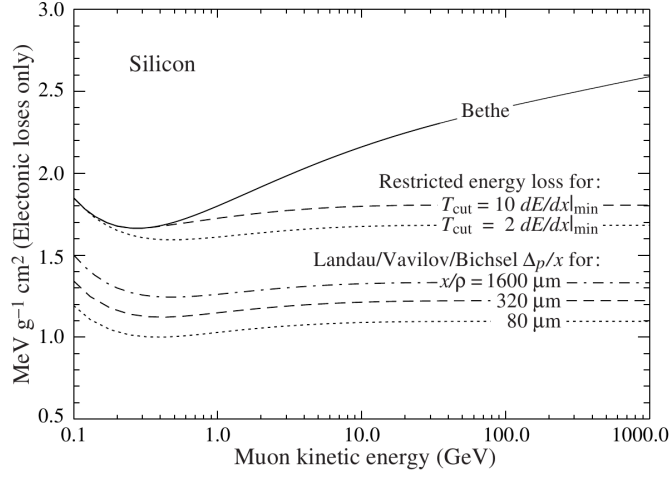


Figure 3.2: Comparison between the Bethe mean energy loss, restricted energy loss and the most probable energy loss described by the Landau-Vavilov-Bichsel function for muons for different values of absorber thickness. Taken from [17].

chapter, is the harmonic-2 estimator

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

where  $\Delta E / \Delta x$  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  $\beta\gamma \sim 3 - 4$  (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.



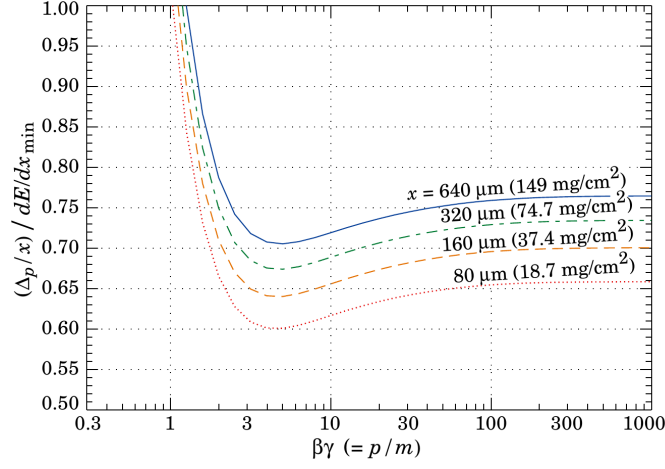


Figure 3.3: Most probable energy loss in silicon, scaled to the mean loss of a minimally ionising particle ( $388 \text{ eV}/\mu\text{m}$ ) for different absorber thicknesses. Taken from [17].

### 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. Every pixel was calibrated to the same response, so that the whole pixel tracker should have been well inter-calibrated [21]. Unfortunately, due to various reasons, such as the imperfect constancy of the reference signal, or radiation and temperature induced changes, the energy calibration could not ensure a fully calibrated pixel tracker. This imperfection of the gain calibration can be seen in Fig. 3.4, where the sum of the harmonic-2 estimator for all tracks  $\sum_{\text{all trks}} I_{h2}$  over the full data-taking period in 2012 is shown. Four different steps can be spotted. The first and the third steps correspond to changes in the settings of the tracker due to irradiation. The second and fourth step 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% are 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 is 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 ??.

### 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 is 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 is checked that all pixels and all ROCs (on one module) are well inter-calibrated, such that the inter-calibration is finally done module-wise.

The gain calibration of the pixel silicon tracker is 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  $\chi^2/\text{n.d.o.f.} < 3$  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

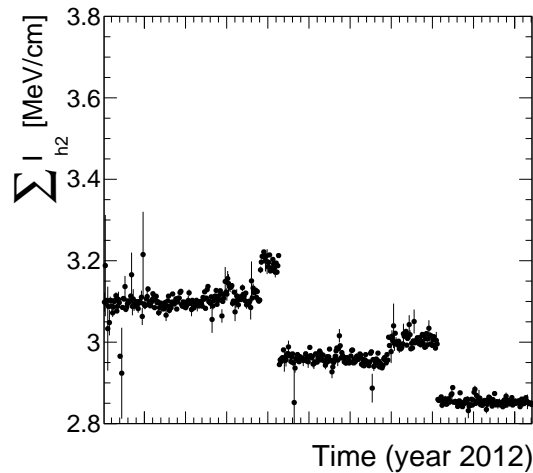


Figure 3.4: Sum of all track’s  $dE/dx$  (harmonic-2 estimator) over the full year 2012. Only pixel hits are taken into account. Every data point corresponds to one run.

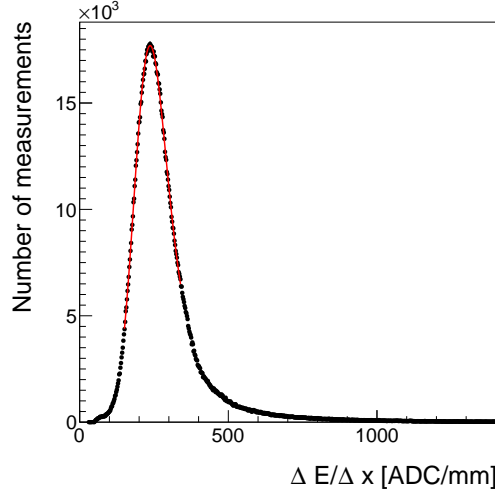


Figure 3.5: An example of the  $\Delta E/\Delta x$  distribution measured in ADC count per mm for one module of the CMS pixel tracker. A Landau convoluted with a Gaussian is fitted to the core of the distribution in an iterative procedure.

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  $\Delta x$  is calculated with

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

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

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

The factor  $300 \cdot 265 \text{ ADC/mm}$  is in principal an arbitrary number since the final response is adjusted by the absolute gain calibration described in the next section. However, it is 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

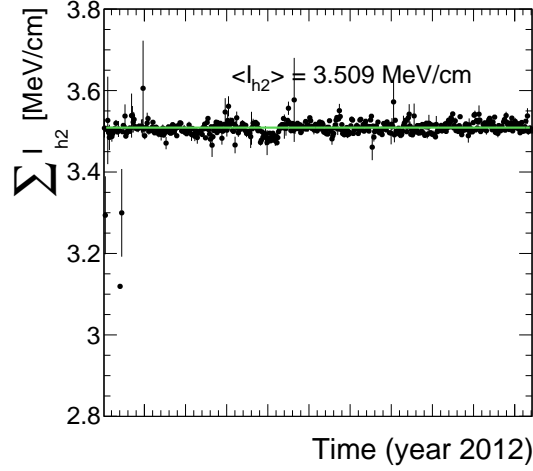


Figure 3.6: Sum of all track's  $dE/dx$  (harmonic-2 estimator) over the full year 2012 after applying the calibration factors, resulting in an average  $dE/dx$  of 3.51 MeV/cm. Only pixel hits are taken into account. Every data point corresponds to one run.

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 is 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  $\Delta E$  in ADC counts and the energy loss 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  $N_e/\text{ADC}$  is the number of electrons which correspond to one ADC count and 3.61 eV is the mean energy needed to create one electron-hole pair in silicon at  $-10^\circ\text{C}$ . Such an

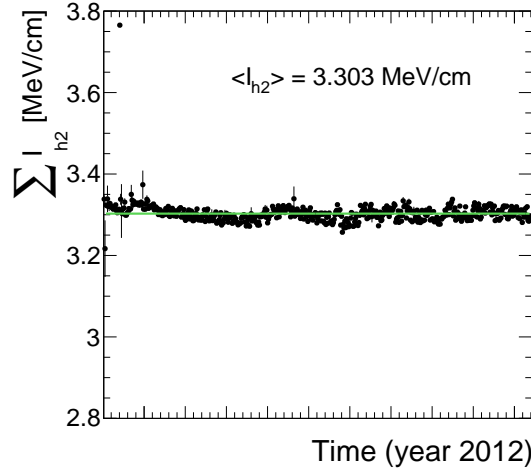


Figure 3.7: Sum of all track's  $dE/dx$  (harmonic-2 estimator) measured in the silicon strip detector over the full year 2012. The average most probable  $dE/dx$  is  $I_{h2} = 3.303$  MeV/cm. Every data point corresponds to one run.

absolute gain calibration can be done with the help of several methods (all explained in [20]). The absolute calibration of the silicon pixel tracker can rely on the already conducted absolute calibration of the silicon strip detector. In [20], the absolute gain calibration was done with the help of the most probable energy release per path length of muons, theoretically described by the Landau-Vavilov-Bichsel formula in Eq. 3.1. To calibrate the pixel tracker to the correct energy loss per path length it is therefore sufficient to determine one calibration factor to relate the average  $dE/dx$  of all tracks in the pixel tracker as shown in Fig. 3.6 to the average measured  $dE/dx$  in the strip tracker, shown in Fig. 3.7 by

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

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

Finally, 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.

### 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 [20] 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 [22, 23], which is deduced from the integral of the squared difference of the measured distribution  $P_N(x)$  to the hypothesis distribution  $P(x)$

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

leading to a test statistics of

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

where  $N$  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  $P_i$  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 [20] which is only sensitive to incompatibilities to the MIP hypothesis towards higher energy depositions

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

A value of  $I_{as}$  close to zero indicates good compatibility with the MIP hypothesis, whereas a value close to one indicates worse compatibility because of 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 [20].

A comparison between the energy release by MIPs ( $I_{as}$ ) in data and simulation for

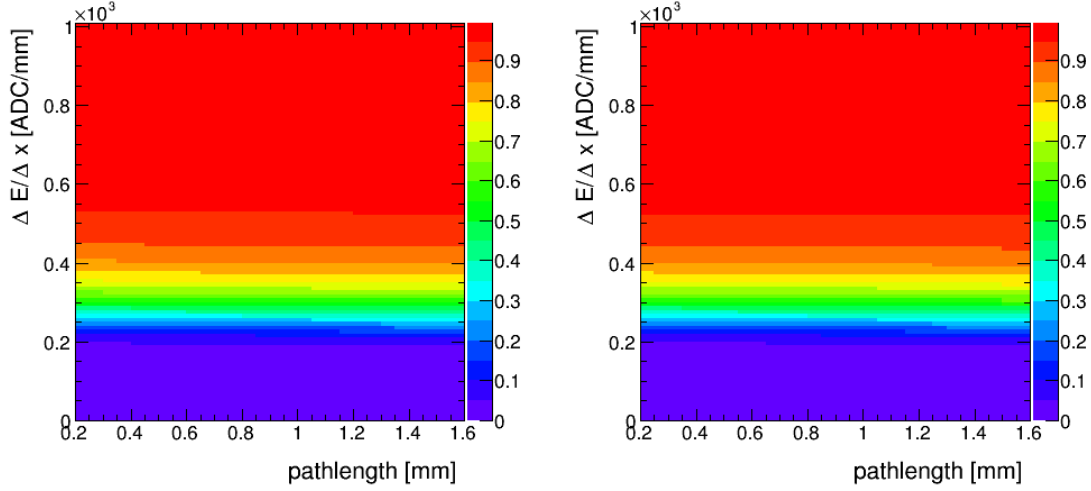


Figure 3.8: Cumulative probability for a MIP to release a  $\Delta E/\Delta x$  (y-axis) vs. the pathlength (x-axis) in data (left) and simulation (right) for the pixel tracker based on the “Minimum bias” sample.

high-quality tracks with  $p > 5$  GeV and  $|\eta| < 2.1$  can be found in Fig. 3.9.

$dE/dx$  shows good agreement in data and simulation for  $I_{as} < 0.1$ . For larger values,  $I_{as}$  shows a larger decrease in simulation than in measured data. That’s the reason why a data-based approach for analyses exploiting  $dE/dx$  information is needed.

### 3.4 Discrimination improvements

The goal of including the pixel energy information is to increase the discrimination power of  $I_{as}$  between background and signal tracks, especially for shorter lifetimes. In Fig. 3.10, a comparison of the shapes of the energy release by MIPs and by signal tracks in simulation is shown (details about the simulated samples can be found in the next section Section 4.2). It can be seen, that the  $I_{as}$  distributions of all signal models show a larger tail towards  $I_{as} = 1$ , whereas the  $I_{as}$  of the background is rapidly falling. The  $I_{as}$  distribution is not only influenced by the velocity ( $\beta$ ) of a particle but also by the number of hits of a track. The 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

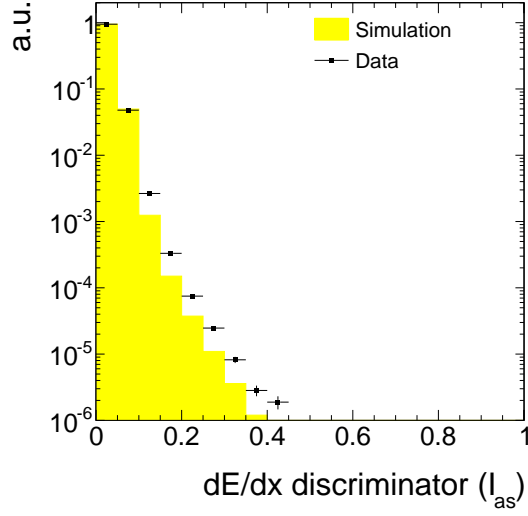


Figure 3.9: Normalised  $I_{\text{as}}$  distribution for MIPs from the minimum bias sample in data and simulation for high-quality (high purity as defined in [24], a minimum number of eight hits and no missing inner and middle hits) tracks with  $p > 5 \text{ GeV}$  and  $|\eta| < 2.1$ .

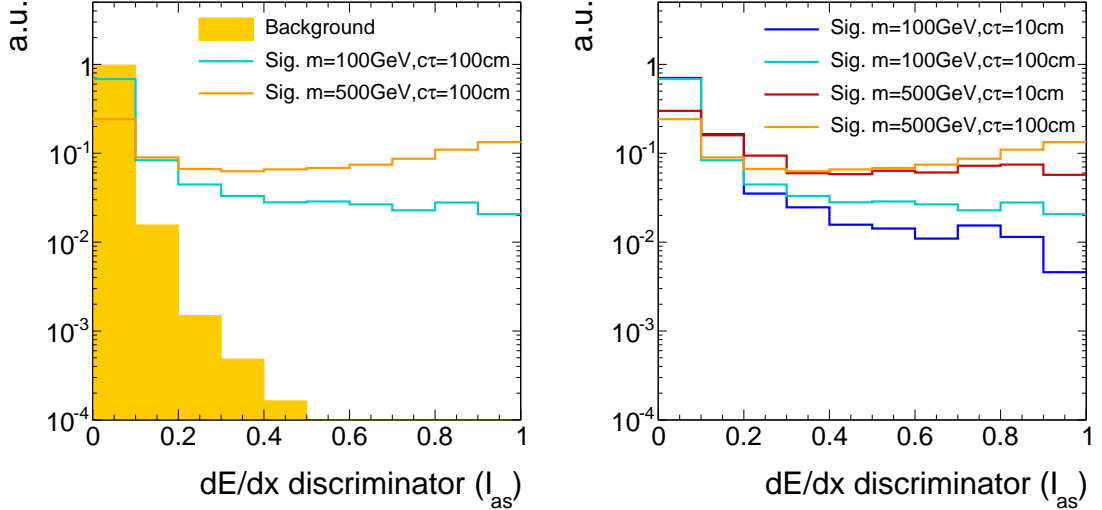


Figure 3.10: Normalised  $I_{\text{as}}$  distribution for simulated background and signal tracks (left) and for four different signal models (right) for high-purity tracks (as defined in [24]) with  $p_{\text{T}} > 10 \text{ GeV}$  and  $|\eta| < 2.1$ . For the illustration of the background tracks' spectrum simulated  $t\bar{t}$ +jets events are used (more information about this sample is given in Section 4).



shorter lifetimes (e. g.  $c\tau = 10$  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

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

This means that shorter lifetimes lead to higher average  $\beta$  which in turn lead to lower values of  $I_{\text{as}}$ .

The number of measurements in the tracker system defines the influence of single fluctuations in  $\Delta E/\Delta x$  on the  $I_{\text{as}}$  discriminator, because of the long right tail of the Landau distribution, A low number of hits lead therefore to higher  $I_{\text{as}}$  values.

Thus,  $I_{\text{as}}$  for charginos with lower lifetimes are affected by two things: First, due to the smaller number of measurements the chargino tends to higher  $I_{\text{as}}$  values. Second, low lifetimes charginos have in average a higher velocity leading to lower  $I_{\text{as}}$  values. Both effects can be seen in Fig. 3.10 (right). The large tail for longer lifetimes is caused by the lower velocities, but the small surplus between 0.1 and 0.2 is caused by the smaller number of measurements for lower lifetimes.

Finally, the impact of the additional  $\Delta E/\Delta x$  information from the pixel tracker on the selection efficiency of signal and background tracks is quantified. Figure 3.11 shows the signal selection efficiency against the background selection efficiency for different selection cuts in  $I_{\text{as}}$ , 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 samples can be found in the next section). No significant difference between these processes in the background selection efficiency was observed.

The signal selection efficiency and the background suppression depend on the mass and the lifetime of the charginos. The discrimination power of  $I_{\text{as}}$  is 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  $I_{\text{as}}$  (up to a factor of 20) and still considerable for looser selections with signal efficiencies of around 40% (factor of 10).

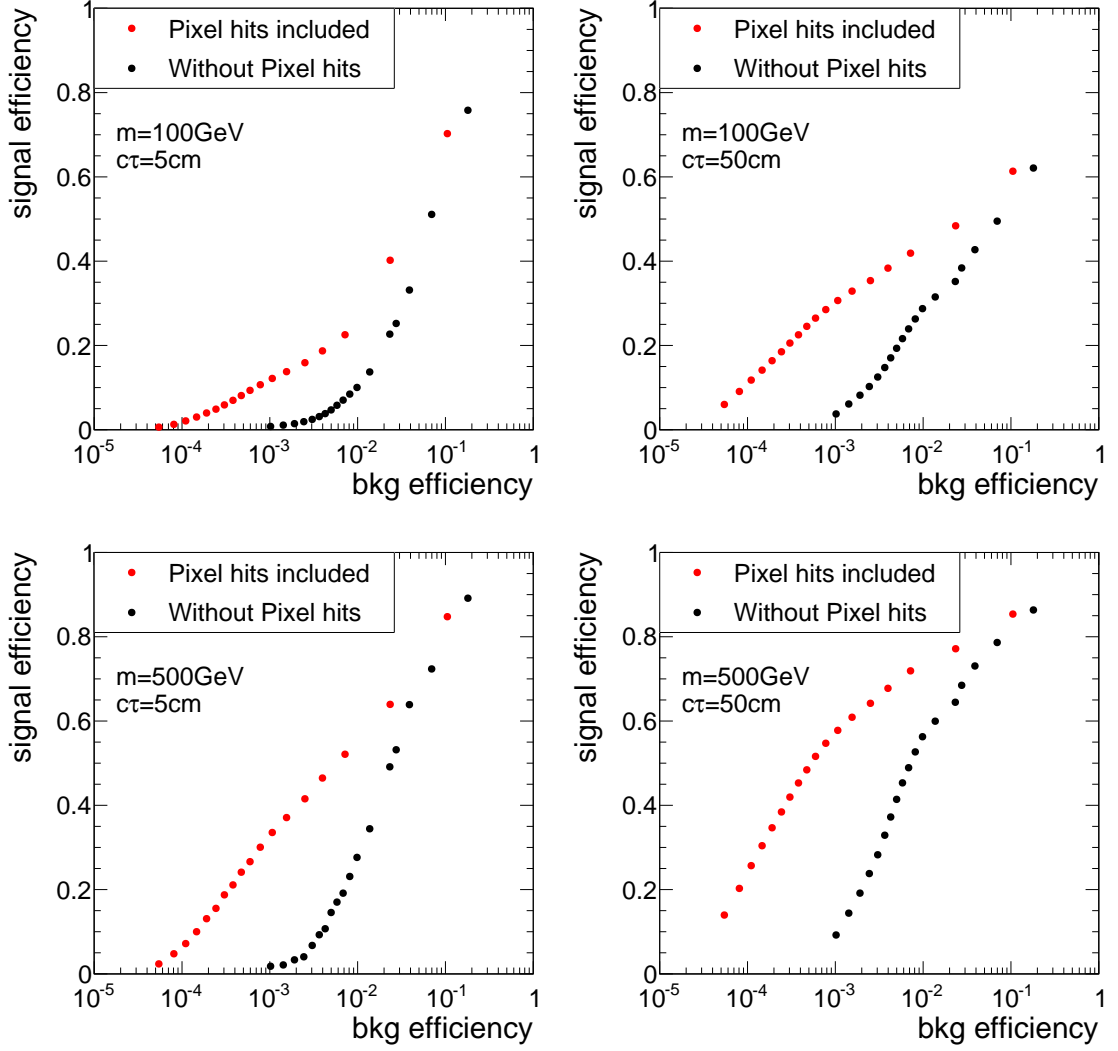


Figure 3.11: Signal selection efficiency vs. background selection efficiency with (red) and without (black) pixel information. Each point correspond to one selection cut in  $I_{\text{as}}$ . The figure is based on a simulated  $W + \text{jets}$  sample and a simulated signal sample with chargino-chargino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

## 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.<sup>1</sup>

In Table 4.1 all available SM samples used in this analysis are listed. Due to the size 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  $p_T > 60 \text{ GeV}$ .

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.

---

<sup>1</sup>For example, the simulated  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  sample that can contribute to the background 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  $W + \text{jets}$  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 [25]                          |
| $t\bar{t} + \text{jets}$   | 245.8              | NNLO [26]                          |
| $Z \rightarrow \ell\bar{\ell} + \text{jets}$ ( $\ell = e, \mu, \tau$ ) | 3531.9             | NNLO [25]                          |
| QCD ( $50 \text{ GeV} < \hat{p}_T < 1400 \text{ GeV}$ )                | 9374794.2          | LO                                 |

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 [25]                          |
| $Z \rightarrow \ell\bar{\ell} + \text{jets}$ ( $\ell = e, \mu, \tau$ ) | 3531.9             | NNLO [25]                          |

## 4.2 Signal samples

For the investigation of a possible SUSY signal, events containing either chargino pair production  $q\bar{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  or chargino neutralino production  $q\bar{q} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$  are simulated. The simulation is done with the matrix-element event generator MADGRAPH [27]. The parton showering and hadronisation processes are then simulated with PYTHIA [28]. Finally, the interactions of the generator-level particles with the detector material are simulated with GEANT4 [29, 30].

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 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 cm, 5 cm, 10 cm, 50 cm, 100 cm, 1 000 cm and 10 000 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

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

where  $n$  is the number of charginos in the event,  $\tau^{\text{gen}}$  is the generated mean lifetime in the particle's rest frame and  $t_i$  is the individual proper lifetime of the chargino. The targeted mean lifetime is given by  $\tau^{\text{target}}$ . A derivation of this formula can be found in Appendix A.1. Using this reweighting procedure a good coverage of the lifetime space can be achieved with lifetimes of  $c\tau = a \cdot 10^n$  for  $n = 0, 1, 2, 3$  and  $a = [1, 9]$ . Figure 4.1 shows the exponential distribution of the individual proper lifetime of the charginos after the reweighting of a simulated sample with  $c\tau^{\text{gen}} = 50$  cm to a lifetime of  $c\tau^{\text{target}} = 10$  cm. It can be seen that the reweighting procedure does indeed reproduce the targeted lifetime of 10 cm.

All samples are generated for different masses of the chargino, but always almost mass-degenerate to the lightest neutralino. The mass gap between chargino and neutralino is set to 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 to a total number of 42 signal samples. In Table 4.3 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 [31, 32]. The cross

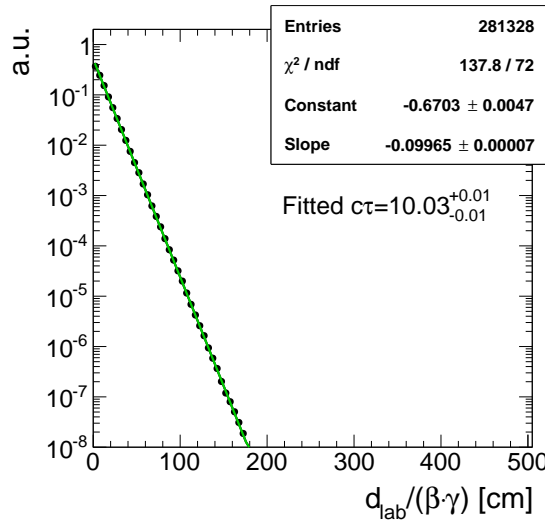


Figure 4.1: Normalised distribution of the proper individual lifetime  $d_{\text{lab}} / (\beta\gamma)$  of all charginos contained in a signal sample with a generated lifetime of  $c\tau^{\text{gen}} = 50$  cm reweighted to a lifetime of  $c\tau^{\text{target}} = 10$  cm. Fitting an exponential curve  $a \cdot \exp \left[ \frac{1}{c\tau} ct_i \right]$  yields  $c\tau = 1./\text{Slope} = 10$  cm.

section does not depend on the lifetime of the chargino.

Table 4.3: Simulated signal mass points with corresponding cross sections at NLO-NLL (NLO: next-to-leading order, NLL: next-to-leading logarithmic) accuracy for wino-like charginos.

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

## 5 Event selection

### 5.1 Datasets and triggers

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

As outlined in Section 2, the detection of chargino tracks is a challenging task already on trigger level. Direct triggering of events containing chargino-like tracks is not possible because in 2012 there was no information about the tracking system available on trigger level L1. Furthermore, there is no intrinsic missing transverse energy in the event if the chargino decays inside the tracker. Therefore, this analysis uses initial state radiation for the detection of chargino events. If ISR occurs, it is possible to trigger on a high- $p_T$  jet ( $p_T^{1,\text{jet}}$ ) and missing transverse energy ( $\cancel{E}_T$ ).

For this purpose, several triggers are utilised in this analysis. An event is selected, if at least one of the three triggers in Table 5.1 fired.

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

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

The HLTMonoCentralPFJet80\_PFMETnoMu95\_NHEF0p95 and HLTMonoCentralPFJet80\_PFMETnoMu105\_NHEF0p95 triggers both rely on the L1 ETM40 trigger which requires the missing energy to be larger than 40 GeV. On HLT level, they further require at least one particle-flow jet with  $p_T > 80$  GeV and a missing transverse momentum (not taking into account the  $p_T$  of muons) to be larger than 95 GeV or 105 GeV respectively. 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 active during Run A and Run B in 2012 data taking, whereas HLTMonoCentralPFJet80\_PFMETnoMu105\_NHEF0p95 was in place during Run C and Run D in 2012.

The HLT\_MET120\_HBHENoiseCleaned trigger is based on the two L1 triggers ETM40 and ETM36 that 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.

The events that were selected by the described triggers are available in the MET datasets listed in Table 5.2. Again, because of the size of the datasets ( $\sim 150$  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.

## 5.2 Selection of signal candidate events

In order to suppress events originating from Standard Model processes such as QCD-multijet events,  $W + \text{jets}$ , etc., a selection for signal-like tracks is applied. The signal candidate event selection closely follows the selection required in [33, 34]. It relies on event-based and track-based variables as described in the following two sections.

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                           |

### 5.2.1 Event-based selection

First a selection on the quality of the vertex is applied in order to suppress cosmic events and noise from the beam halo. This selection includes requirements on the position of the vertex with respect to the beam axes and the number of degrees of freedom of the vertex which is strongly correlated to the number of tracks originating from the vertex [35]:

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

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

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

- Charged hadron energy fraction (CHF)  $> 0.2$
- Charged electromagnetic energy fraction (CEF)  $< 0.5$
- Neutral hadron energy fraction (NHF)  $< 0.7$
- Neutral electromagnetic energy fraction (NEF)  $< 0.7$ .



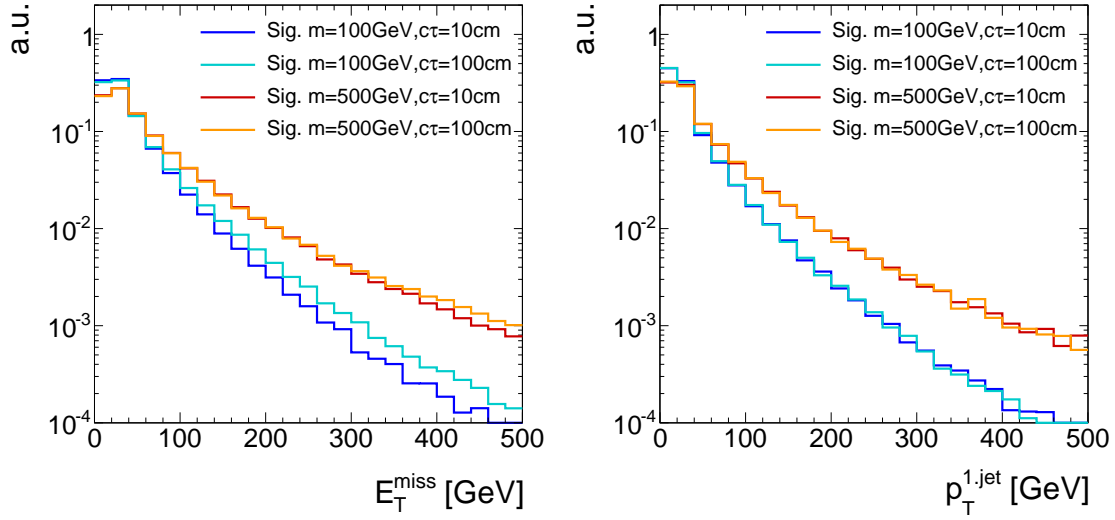


Figure 5.1: Normalised distributions of the missing transverse momentum (left) and the transverse momentum of the leading jet (right) for four different signal models.

These additional jet quality criteria ensure that noise from cosmic and beam halo muons and high- $p_T$  photons and electrons is suppressed [36].

The trigger efficiency as a function of  $\cancel{E}_T$  and  $p_T^{1,\text{jet}}$  was determined within [37] with a single-muon reference sample. The trigger paths become fully efficient for  $p_T^{1,\text{jet}} \gtrsim 110$  GeV and  $\cancel{E}_T \gtrsim 220$  GeV [36]. However, it can be seen in Fig. 5.1 that for a selection of  $\cancel{E}_T > 220$  GeV more than 99% of the signal events are rejected.

In order to achieve a reasonable signal acceptance, this search imposes a trigger selection closer to the intrinsic trigger thresholds. The trigger requirements are as follows:

- ❖ There is at least one jet within  $|\eta| < 2.4$  with transverse momentum larger than 110 GeV which fulfils the above mentioned jet noise cleaning criteria:  $p_T^{1,\text{jet}} > 110$  GeV.
- ❖ The missing transverse momentum must be larger than 100 GeV:  $\cancel{E}_T > 100$  GeV

These requirements result in a trigger efficiency of 100% in the variable  $p_T^{1,\text{jet}}$  and  $\sim 20\%$  in the variable  $\cancel{E}_T$  at the cut thresholds [36].

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

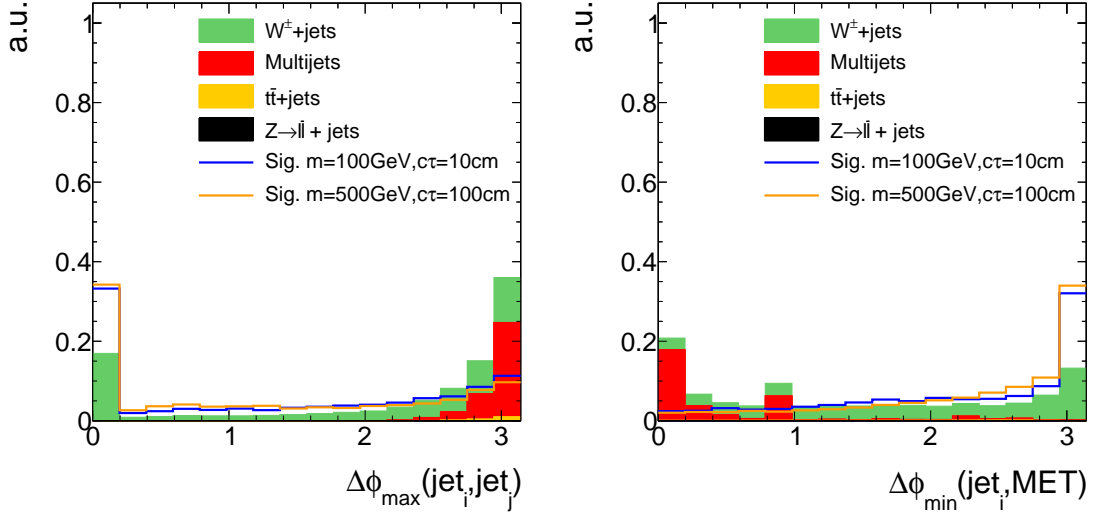


Figure 5.2: Maximum  $\Delta\phi$  between any of two jets (left) and the minimum  $\Delta\phi$  between the  $\cancel{E}_T$  vector and any of the two leading jets (right) normalised to unit area after the trigger selection. Only jets with  $p_T > 20$  GeV and  $|\eta| < 4.5$  are considered.

the event. Figure 5.2 shows the maximum  $\Delta\phi$  of any of two jets and the minimum  $\Delta\phi$  between the  $\cancel{E}_T$  vector and any of the two leading jets for the SM background and two different signal datasets.

The following two requirements are sufficient to suppress QCD-multijet events efficiently:

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

### 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 high-quality tracks is enforced:

- ❖ The track must be of “high purity” as defined in [24].
- ❖ 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 latter two quality selection cuts is shown.

Furthermore, a first kinematic preselection is applied:

- ❖ Only tracks in the central region are considered :  $|\eta| < 2.1$ .
- ❖ Only tracks with a minimum transverse momentum of 20 GeV are considered:  
 $p_T > 20 \text{ GeV}$ .

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

Unfortunately, the lepton veto selection cuts lack efficiency in some of the detector directions. For example, the reconstruction of an electron easily fails in the direction of a dead ECAL cell. This reduces the discrimination power of the electron veto. For this reason, tracks that point towards dead or noisy ECAL cells 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 [33,34] resulting in a total number of 1234 dead or noisy ECAL channels.

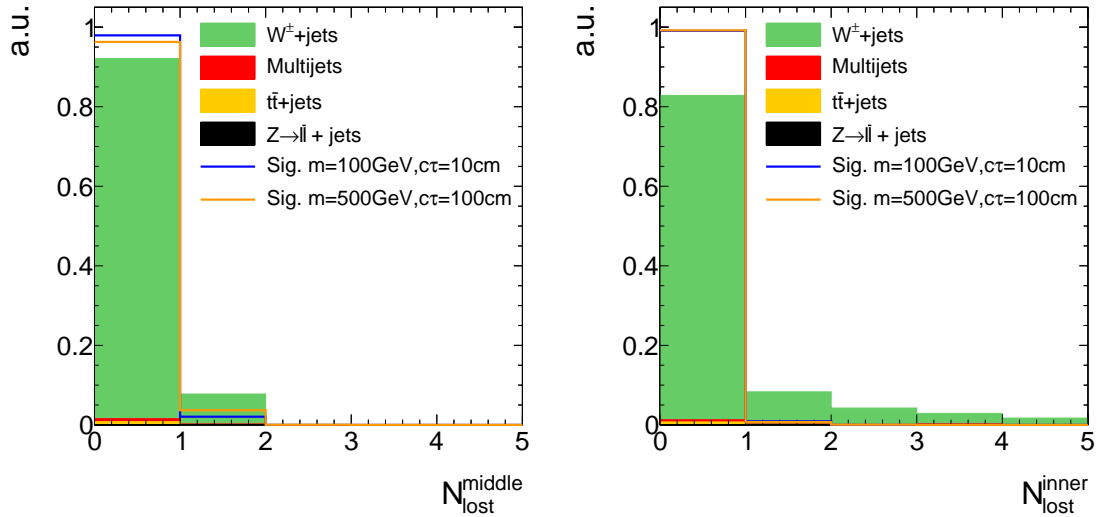


Figure 5.3: Number of missing middle (left) and inner (right) hits of background and signal tracks after trigger requirements and QCD suppression cuts.

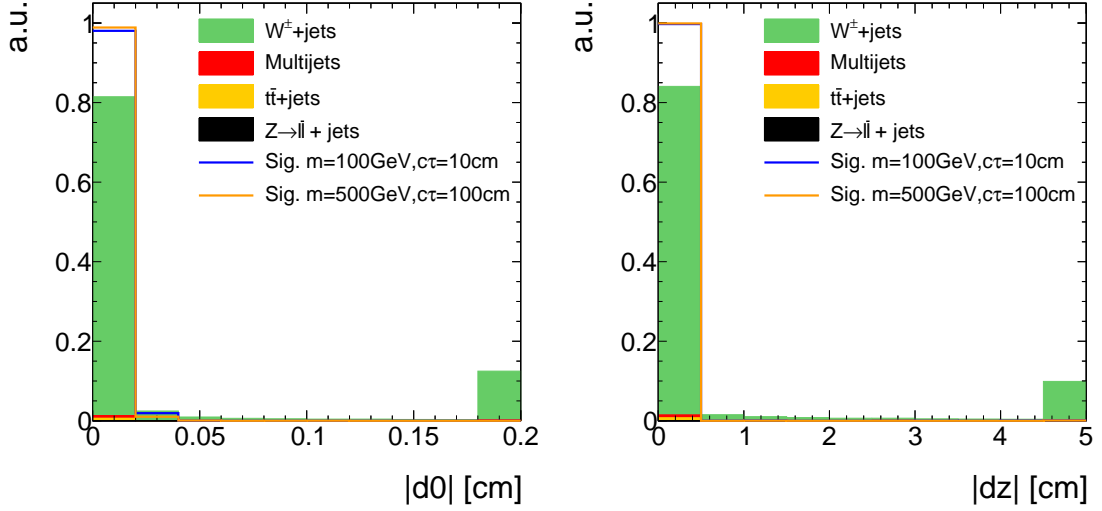


Figure 5.4: Absolute value of the radial (left) and longitudinal (right) distance between the track and the primary vertex after trigger requirements and multijet suppression cuts. All events with a candidate track with a radial (longitudinal) distance larger than 0.2 cm (5 cm) are contained in the last bin.

These are illustrated in Fig. 5.5 showing a map of all ECAL channels not considered in the search.

Additionally, tracks that 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, that is supplied centrally at CMS, is given in Table 5.3.

The muon reconstruction is less efficient for muons in detector regions with bad cathode strip chambers (CSC). These bad chambers are also identified centrally at CMS and their  $\eta$  and  $\phi$  values are visualised in Fig. 5.6. Thus, also tracks pointing towards 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 GeV (see Section ?? for details on the different muon definitions).
- ❖ The track must not be within a cone of  $\Delta R < 0.15$  to a reconstructed electron with a transverse momentum larger than 10 GeV (see Section ?? for details on the electron reconstruction).
- ❖ The track must not be within a cone of  $\Delta R < 0.15$  to a reconstructed tau with  $p_T > 20$  GeV and  $|\eta| < 2.3$  (see Section ?? for details on the tau reconstruction).

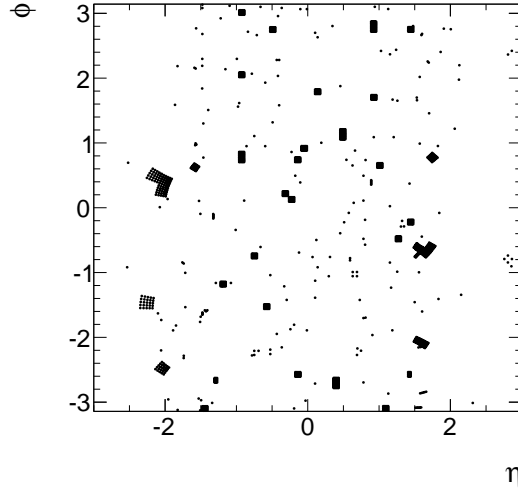


Figure 5.5: Visualisation of dead and noisy ECAL cells in the detector's  $\phi - \eta$  plane according to [33, 34].

Some loose isolation requirements are enforced to protect the tau reconstruction from jet contamination.

- ❖ The track must not be within a cone of  $\Delta R < 0.5$  to a reconstructed jet ( $p_T > 20$  GeV and  $|\eta| < 4.5$ ).
- ❖ Veto tracks within a cone of  $\Delta R < 0.05$  to a dead or noisy ECAL cell (visualised in Fig. 5.5).

Table 5.3: Intermodule ECAL gaps.

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

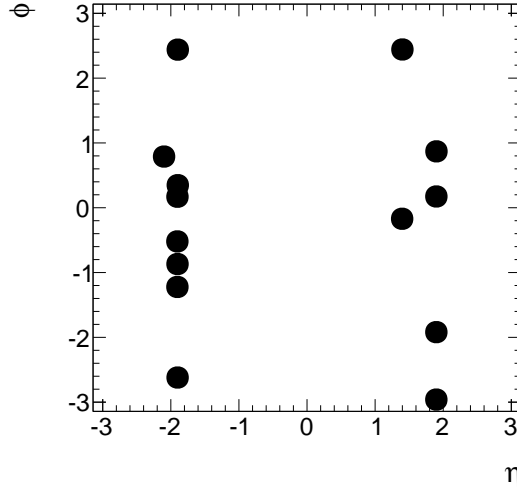


Figure 5.6: Visualisation of bad cathode strip chambers in the detector's  $\phi - \eta$ .

- ❖ Veto tracks that point towards the direction of the ECAL intermodule gap listed in Table 5.3.
- ❖ Veto tracks that point towards a bad CSC (visualised in Fig. 5.6).
- ❖ Veto tracks that point towards the region between ECAL barrel and endcap at  $1.42 < |\eta| < 1.65$

These lepton and jet veto selection requirements are of course highly suppressing the background emerging from real lepton/jet production like in  $W + \text{jets}$  events. The discrimination power of the lepton and jet vetos is shown in Fig. 5.7 where the minimum  $\Delta R$  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 characteristics of signal tracks.

The resulting selection cuts are as follows

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

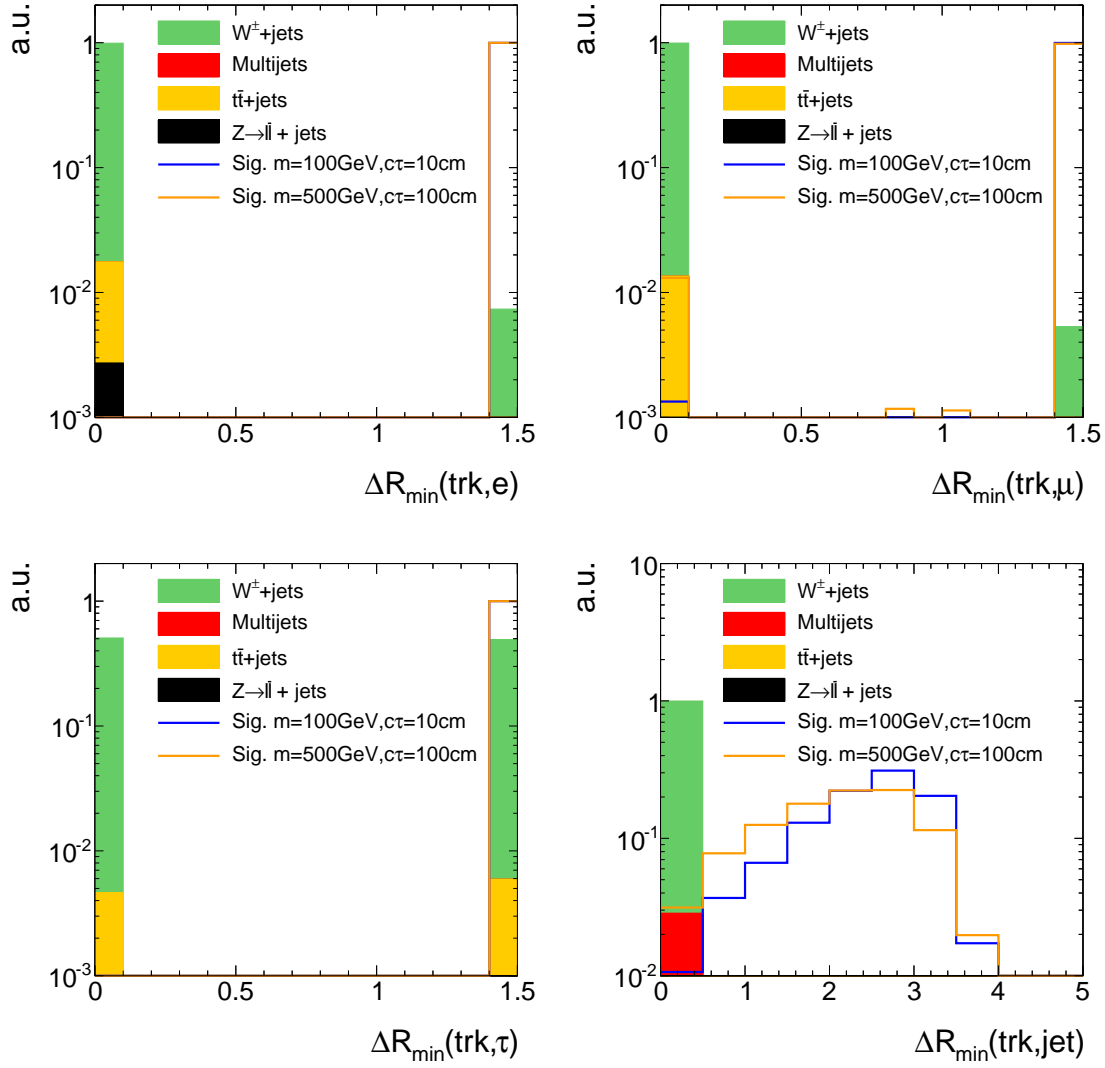


Figure 5.7: The minimum  $\Delta R$  between the candidate track and a reconstructed electron (top left), muon (top right), tau (bottom left) or jet (bottom right) after the full candidate track selection cuts besides the one shown in the corresponding plot. The last bin contains all events where the candidate track has a  $\Delta R_{\min}$  larger than 1.5 or 5.0 to the next lepton or jet respectively.

The discrimination power of these two variables is shown in Fig. 5.8.

As emphasised before, this analysis aims at being sensitive especially on shorter lifetimes. Still, in order to allow for charginos decaying at any layer of the tracker, no explicit selection cut on the number of missing outer hits is required.

An overview over the full analysis preselection is given in Table 5.4. A summary table

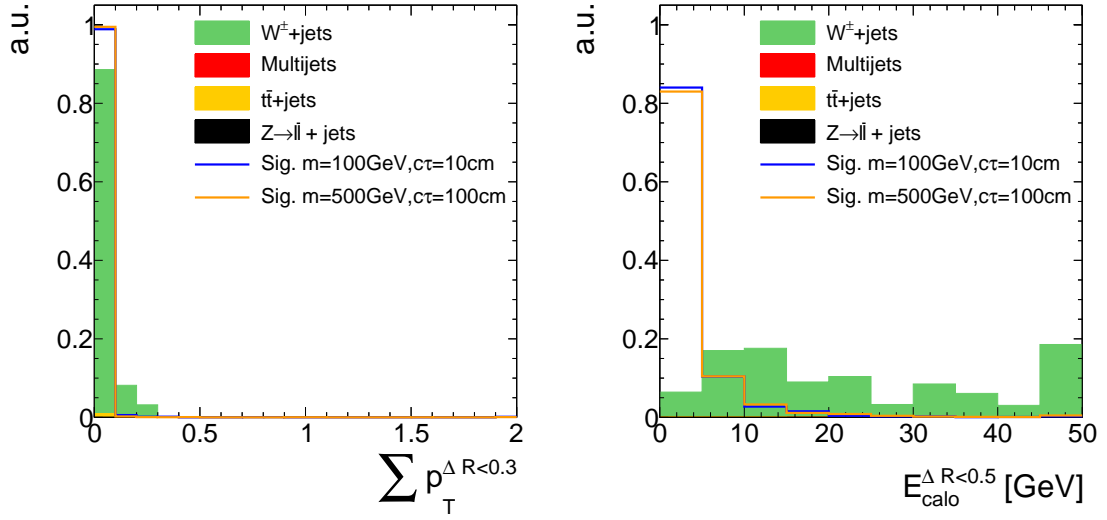


Figure 5.8: Track isolation (left) and calorimeter energy deposits (right) of the candidate track after the full previous selection.

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.2.

Given the presented signal candidate selection, a set of two variables remain that are highly discriminating: The transverse momentum  $p_T$  and the energy release per path length  $dE/dx$  of the candidate track. In this analysis, the Asymmetric Smirnov discriminator  $I_{\text{as}}$  is used to enhance the discriminating power of  $dE/dx$ . See Section 3.3 for the definition and a detailed explanation of  $I_{\text{as}}$ .

In Fig. 5.9, the distribution of the remaining two variables are shown after the application of the full signal candidate selection. These variables are used to optimise the sensitivity of the search. The optimisation process will be explained in Section 7. However, before the optimisation can be accomplished, a characterisation and estimation of the background is needed. This topic will be discussed in the following section.



Table 5.4: Summary and categorisation of the analysis selection.

|                           |  |   |
|---------------------------|--|---|
| Trigger                   | HLTMonoCentralPFJet80_PFMETnoMu95_NHEF0p95<br>HLTMonoCentralPFJet80_PFMETnoMu105_NHEF0p95<br>HLT_MET120_HBHENoiseCleaned |   |
| Event-based selection     | Trigger selection  | $p_T^{1.\text{jet}} > 100 \text{ GeV}$ with $ \eta_{1.\text{jet}}  < 2.4$ ,<br>$\text{CHF}_{1.\text{jet}} > 0.2$ ,<br>$\text{CEF}_{1.\text{jet}} < 0.5$ ,<br>$\text{NHF}_{1.\text{jet}} < 0.7$ ,<br>$\text{NEF}_{1.\text{jet}} < 0.7$<br>$\cancel{E}_T > 100 \text{ GeV}$   |
|                           | QCD suppression  | $\Delta\phi_{\text{max}}(\text{jet}_i, \text{jet}_j) < 2.7$ for all jets with<br>$p_T > 20 \text{ GeV}$ , $ \eta  < 4.5$<br>$\Delta\phi_{\text{max}}(\text{jet}_i, \cancel{E}_T) > 0.5$ for two leading jets  |
| Candidate track selection | $\geq 1$ track that fulfils the following criteria:  |   |
|                           | Good quality selection   | high-purity as defined in [24]<br>$N_{\text{miss}}^{\text{middle/inner}} = 0$<br>$ d0  < 0.02 \text{ cm}$<br>$ dz  < 0.5 \text{ cm}$  |
|                           | Kinematic selection  | $ \eta  < 2.1$<br>$p_T > 10 \text{ GeV}$  |
|                           | Lepton/jet veto  | No muon within $\Delta R < 0.15$<br>No electron within $\Delta R < 0.15$<br>No tau within $\Delta R < 0.15$<br>No jet within $\Delta R < 0.5$<br>No dead/noisy ECAL cell within $\Delta R < 0.05$<br>Not within an ECAL intermodule gap<br>Not within $1.42 <  \eta  < 1.65$<br>Not within $\Delta R < 0.25$ to a bad CSC |
|                           | Isolation selection  | $\sum_{\Delta R < 0.3} p_T / p_T^{\text{cand}} < 0.1$<br>$E_{\text{calo}}^{\Delta R < 0.5} < 5 \text{ GeV}$   |

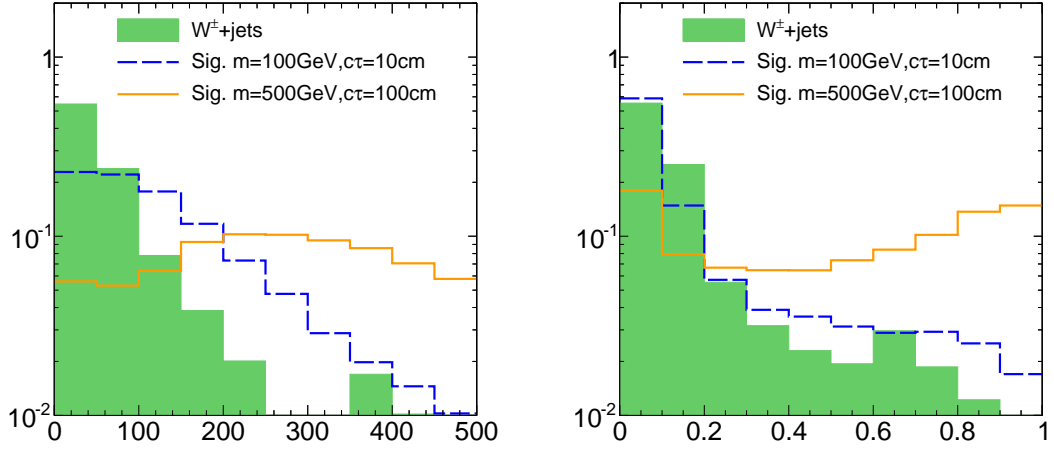


Figure 5.9: Candidate track  $p_T$  (left) and  $I_{as}$  (right) after the full signal candidate selection for signal and  $W + \text{jets}$  events. Because of the low statistical precision of the  $W + \text{jets}$  sample, the trigger requirements are not applied. This does not influence the shape of the distributions since  $\cancel{E}_T$  and  $p_T^{1,\text{jet}}$  are not expected to be correlated with the track characteristics.

## 6 Characterisation and estimation of the Standard Model backgrounds

After the application of the signal candidate selection, explained in the previous section, the background arising from Standard Model processes is dramatically reduced. Only two events in the simulated  $W + \text{jets}$  sample remain. One of these originates from an unreconstructed muon, the other one from an unreconstructed electron. This implies, that the electron, muon, and tau vetos cannot reject all leptons because some are not properly reconstructed. Due to the limited size of the simulated  $W + \text{jets}$  dataset (15 times smaller than the number of events expected from  $W + \text{jets}$  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 the non-reconstruction of a lepton and the corresponding methods to estimate the leptonic background will be explained in detail 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 a combination of unrelated hits will be explained in the following Section 6.1. It should be noted that the fake background is contributing through all SM processes, not only via  $W + \text{jets}$ . Still, as the characteristics of fake tracks are independent of the underlying process, this background can also be studied on simulation using  $W + \text{jets}$  events only.

## 6.1 Fake background

Fake tracks are tracks that are not reconstructed out of the trajectory of one single particle. The rate at which this wrong reconstruction occurs is highly restrained by the quality cuts on  $\chi^2$  and the vertex compatibility of the track reconstruction algorithm. Details on the reconstruction algorithm of tracks 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 normalised distribution of the number of hits from fake tracks is depicted. There are almost no fakes with a number of hits larger than seven. In simulation, fake tracks are defined as tracks that 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

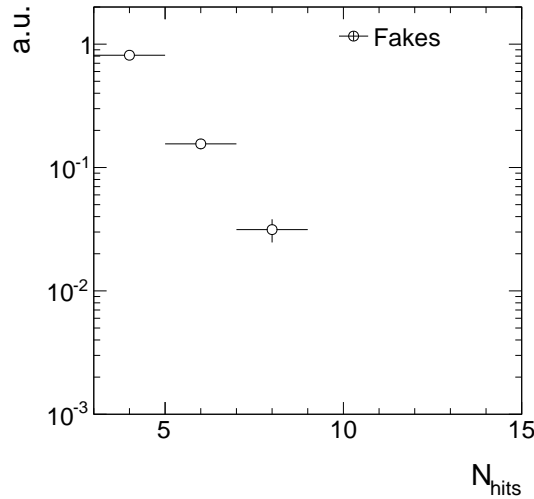


Figure 6.1: Normalised distribution of the number of hits for fake tracks after the signal candidate selection from Table 5.4. To increase the statistical precision, only track selection requirements are applied.

with high efficiency.

In this analysis, the estimation of the fake background is split into two parts. First, the background is determined inclusively in  $dE/dx$ . Second, the  $dE/dx$  ( $I_{\text{as}}$ ) distribution is estimated with the help of a fake enriched control region. This second step is needed to enable an optimisation in  $dE/dx$  (see Section 7).

### 6.1.1 Inclusive fake background estimation

The inclusive background estimation closely follows the background estimation method done in [33, 34]. It aims at determining the probability of having a fake track in an event that passes the full signal candidate selection (Table 5.4) plus a potential additional  $p_T$  selection cut that is determined in an optimisation procedure (Section 7). This probability will be called the fake rate  $\rho_{\text{fake}}$ .

The inclusive fake background is estimated with the help of  $Z \rightarrow \mu\bar{\mu}$  and  $Z \rightarrow e\bar{e}$  events from data.  $Z \rightarrow \ell\bar{\ell}$  events can be selected with high purity 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  $\sim 90$  GeV. As these events do not contain further leptons from the hard interaction, any additional track is either an ISR jet, a soft particle from the underlying event or is a fake, reconstructed out of a combination of several soft particles. Since the track-based signal candidate selection requires a track with a  $p_T > 20$  GeV that is no lepton or jet, it suppresses ISR jets and soft tracks from the underlying event. Thus, applying the track-based signal candidate selection on  $Z \rightarrow \ell\bar{\ell}$  events selects fake tracks with high purity.

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 is required to have two muons with  $p_T > 25$  GeV and  $|\eta| < 2.4$ . To suppress background from cosmic muons, the distance from the primary vertex must be less than  $|d0| < 0.2$  cm in radial and  $|dz| < 0.5$  cm in longitudinal direction. In order to suppress background arising from jets that fake muons, various quality criteria are applied: it is required that there is at least one hit in the muon detector that is considered in the global muon fit, and that at least two measurements are from different muon detector stations. 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 are required. An isolation criterion is applied that requires the sum of transverse momenta of all particle-flow particles in a cone of  $\Delta R < 0.4$  around the muon to be less than 12%. Finally, the muons are required to be opposite in charge and to have an invariant mass between 80 – 100 GeV. The  $Z \rightarrow \mu\bar{\mu} + \text{fake track}$  selection is summarised in Table 6.2.

In order to select  $Z \rightarrow e\bar{e}$  events in data, the two electrons are required to have

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                           |

$p_T > 25 \text{ GeV}$ ,  $|\eta| < 2.5$  and no missing hits in the inner layers of the tracker. Furthermore, the electrons need to pass a conversion veto as described in [38] in order to reduce background arising from photon conversions. An isolation requirement similar to the muon isolation criterion is applied with an increased threshold of 15%. The electron identification is further based on a multivariate technique developed within [39] that exploits electron characteristics about the track quality, the ECAL cluster shapes, and the combination of the measurements in the tracker and in the ECAL. Again, the two electrons must be opposite in charge and their invariant mass must be between  $80 - 100 \text{ GeV}$ . A summary of the  $Z \rightarrow e\bar{e} + \text{fake track}$  event selection can be found in Table 6.3.

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

As already mentioned, the fake rate is defined as the probability that an event contains a fake track that fulfils the candidate track selection. Thus, for the  $Z \rightarrow \ell\bar{\ell}$  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: Event selection cuts for the  $Z \rightarrow \mu\bar{\mu} + \text{fake}$  control sample to estimate the inclusive fake background.

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

Table 6.2 (Table 6.3)

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

Fake rates are determined independently for the  $Z \rightarrow \mu\bar{\mu} + \text{fake}$  and  $Z \rightarrow e\bar{e} + \text{fake}$  event selection and then averaged to obtain the final fake rate. The fake rate with the candidate track selection given in Table 5.4 is  $(6.86 \pm 0.25) \cdot 10^{-5}$ . This is not the final result as the optimisation in  $p_T$  will add an additional  $p_T$  selection cut to the candidate track selection.

Within [33,34], 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  $Z \rightarrow \ell\bar{\ell}$  dataset can be generalised for all SM background possibly contributing to this

Table 6.3: Event selection cuts for the  $Z \rightarrow e\bar{e} + \text{fake}$  control sample to estimate the inclusive fake background.

|                           |   |
|---------------------------|---|
| Event-based selection     | <p>Two Electrons with <math>p_T &gt; 25 \text{ GeV}</math></p> <p><math> \eta  &lt; 2.5</math></p> <p><math>\sum_{\Delta R &lt; 0.4} p_T^{\text{PF particle}} / p_T(e) &lt; 0.15</math></p> <p>pass conversion veto [38]</p> <p>no missing inner tracker hits</p> <p>good MVA electron as defined in [39]</p> <p>Electrons opposite in charge</p> <p><math>80 \text{ GeV} &lt; M_{\text{inv}}(e_1, e_2) &lt; 100 \text{ GeV}</math></p> |
| Candidate track selection | <p>Good quality selection</p> <p>Kinematic selection</p> <p>Lepton/jet veto</p> <p>Isolation selection</p>  |

search. Thus, the inclusive fake background can be estimated by multiplying the fake rate with the number of events selected from the MET dataset (Table 5.2) by applying the event-based signal candidate requirements from Table 5.4.

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

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  $94.7 \pm 3.4$  for the candidate track selection.

It should be noted again that the inclusive fake background estimation will be only inclusive in  $I_{\text{as}}$  not in  $p_T$ . That means that after the definition of the signal region,  $N_{\text{bkg}}^{\text{fake, inclusive in } I_{\text{as}}}$  is determined with the additional optimal  $p_T$  selection.

Possible differences between the fake rate in  $Z \rightarrow \ell\bar{\ell}$  events and other SM processes are estimated on simulated events and taken into account as a systematic uncertainty (see Section 6.4.1).

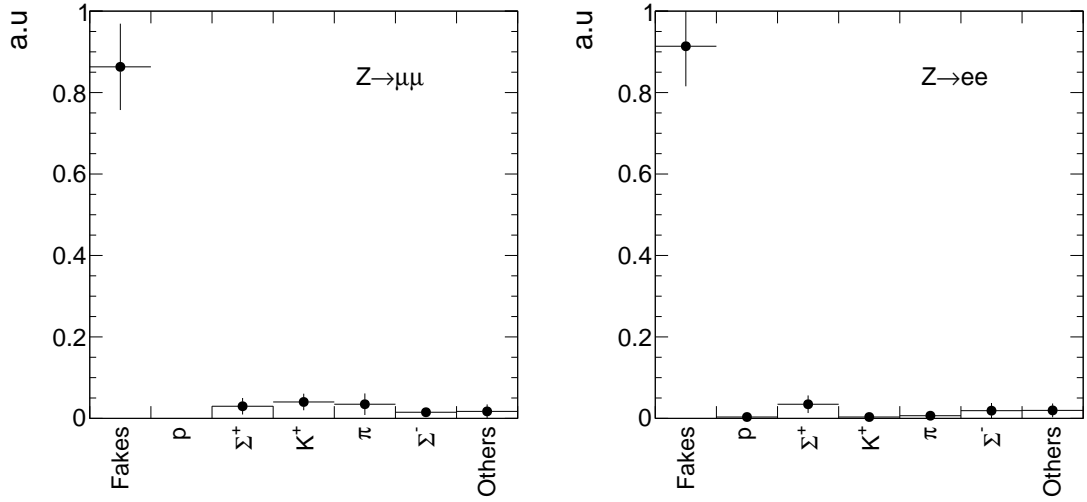


Figure 6.2: Corresponding generator-level particles of all tracks within  $Z \rightarrow \ell\bar{\ell} + \text{fake}$  that were selected according to the candidate track selection. The full selection for tracks in  $Z \rightarrow \mu\bar{\mu}$  events (left) is given in Table 6.2. The full selection for tracks in  $Z \rightarrow e\bar{e}$  events (right) is given in Table 6.3. “Fake” means that no corresponding generator-level particle is found.

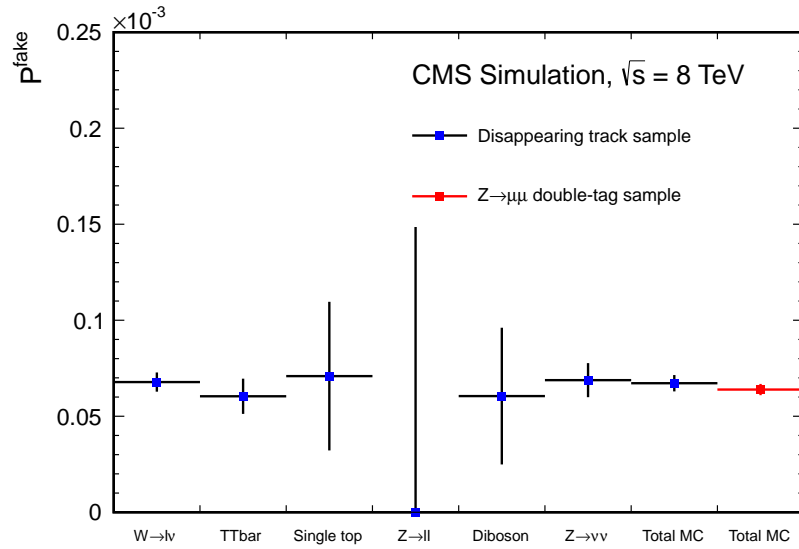


Figure 6.3: Fake track rate estimated in [33,34] for tracks with four hits. Taken from [34]



### 6.1.2 $dE/dx$ shape of fake background

The information about 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 (cf. Fig. 3.9). Within this analysis the Asymmetric Smirnov discriminator  $I_{\text{as}}$  is used to discriminate signal against background with respect to  $dE/dx$  (see Section 3.3). In order to estimate the  $I_{\text{as}}$  shape of fake tracks, a control region  $\text{CR}_{I_{\text{as}}}^{\text{fake}}$  is defined that is enriched with fakes and shows the same  $I_{\text{as}}$  distribution as fake tracks in the signal region.

To enrich fake tracks, it is possible to invert the selection cuts on the number of missing middle and inner hits, i.e. requiring at least one missing inner or middle hit ( $N_{\text{miss}}^{\text{inner}} + N_{\text{miss}}^{\text{middle}} > 0$ ). Figure 6.4 shows the distribution of the number of missing inner plus missing middle hits for fake and leptonic tracks in simulated  $W + \text{jets}$  events. It can be seen that the enrichment of fakes by this selection works. The resulting purity of fakes in  $\text{CR}_{I_{\text{as}}}^{\text{fake}}$  is about 98% (see Fig. 6.5).

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

The comparison of the  $I_{\text{as}}$  shape of fake tracks can only be done on simulation. Thus, simulated  $W + \text{jets}$  events are used to select fake tracks in both regions. A comparison of the shape for the candidate track selection and the  $\text{CR}_{I_{\text{as}}}^{\text{fake}}$  is shown in Fig. 6.5.

The  $I_{\text{as}}$  shape is almost identical in the signal and in the control region which makes the

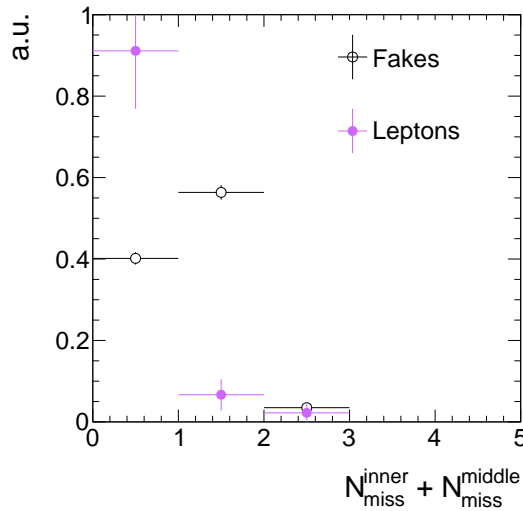


Figure 6.4: Normalised number of missing inner plus missing middle hits for fake and leptonic tracks for the full candidate track selection with the selection requirements on  $N_{\text{miss}}^{\text{inner}}$  and  $N_{\text{miss}}^{\text{middle}}$  removed. Trigger requirements and QCD suppression cuts were removed to enhance the statistical precision.

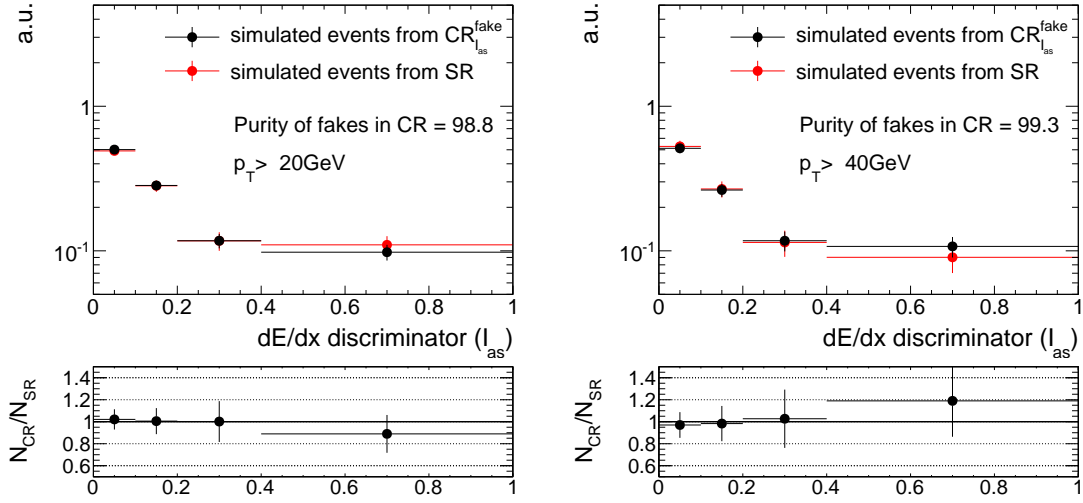


Figure 6.5: Comparison of the  $I_{as}$  shape between  $CR_{fake}$  and the signal region for two different track  $p_T$  selections of  $p_T > 20 \text{ GeV}$  (left) and  $p_T > 40 \text{ GeV}$  (right). To enhance the statistical precision only the track-based selection is applied.

definition of the control region perfectly suited for estimating the  $I_{as}$  shape from  $CR_{fake}$  in data. The remaining shape differences are taken into account as a systematic uncertainty (discussed in Section 6.4.2).

## 6.2 Leptonic background

The leptonic background of the here presented search is caused by non-reconstructed leptons that circumvent 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  $E_{calo}^{\Delta R < 0.5} < 5 \text{ GeV}$ . As muons don't deposit much energy in the calorimeters, this reasoning does not apply to them. In the following, the sources of the three different leptonic backgrounds are characterised.

### Electrons

To reject 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 endcap 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 passes all signal candidate 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 the

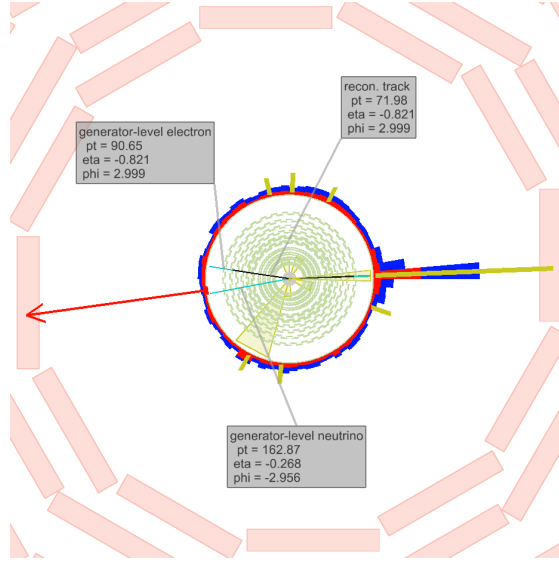


Figure 6.6: Visualisation of a  $W \rightarrow e\nu_e$  event contributing to the SM background. In light blue, generator-level particles including  $e$  and  $\nu_e$  of the  $W$ -boson decay are shown. The neutrino, only weakly interacting does not show any signature in the detector, whereas the electron ( $p_T \simeq 90$  GeV) leaves a track (black line) with  $p_T \simeq 70$  GeV in the tracker. No ECAL energy deposits in the direction of the electron are visible. This is caused by the fact that the corresponding ECAL energy deposits were not read out in this event. An ISR jet ( $p_T \simeq 230$  GeV) causes the  $\cancel{E}_T$  (read arrow) in the event.

corresponding ECAL tower was not 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  $\tau \rightarrow \pi^\pm \nu_\tau$ . Other decay modes of the tau lepton are suppressed by the track isolation criterion. Taus fail reconstruction if they don't deposit energy in the HCAL or ECAL. Unreconstructed taus 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  $p_T$ . Thus, taus can contribute to the background even if imposing a tight selection in the transverse momentum. Such an event is shown in Fig. 6.7.

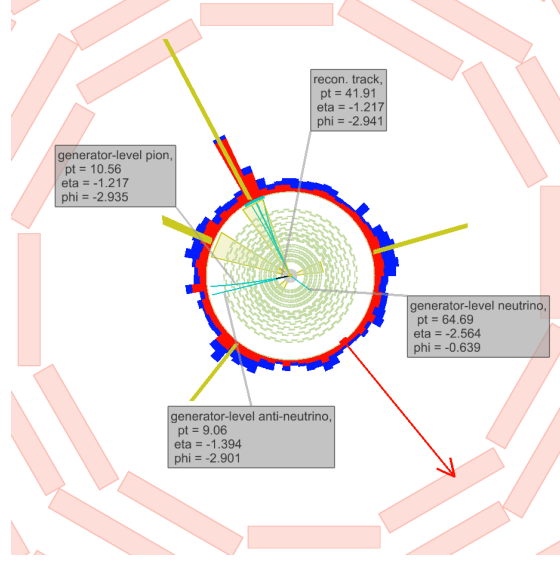


Figure 6.7: Visualisation of a  $W^+ \rightarrow \tau^+ \nu_\tau \rightarrow \pi^+ \bar{\nu}_\tau \nu_\tau$  event contributing to the SM background. In light blue, the generator-level particles including  $\pi^+$ ,  $\bar{\nu}_\tau$  and  $\nu_\tau$  are shown. The transverse momentum of the generator-level pion is only  $p_T \sim 10$  GeV, but because the reconstructed track (black line) is very short, it leads to a high mismeasurement of the track  $p_T$  of  $\sim 40$  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. The ISR jet causes the  $\cancel{E}_T$  (read arrow) in the event.

## Muons

Muons can fail reconstruction if they point towards a bad cathode strip chamber. This is taken into account in the candidate track selection. However, some of the muons still fail reconstruction if they fall within the gap between stations 0 and 1 of the drift tube system at  $|\eta| = 0.25$ . The muon reconstruction efficiency drops from around 99% to a value of around 94% as shown in [33, 34]. This possibility is illustrated in a simulated event shown in Fig. 6.8.

In [33, 34] events are rejected if 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 be efficiently suppressed. E.g. in the event shown in Fig. 6.8, the muon has an  $I_{as}$  value of about 0.007.

In general, all leptons are minimally ionising. However, as electrons are much lighter compared to muons or pions, they lose more energy also via radiative effects. Still, all three lepton types lose much less energy compared to hypothetical new heavy particles. To have the possibility to make an optimisation in the two main discriminating variables

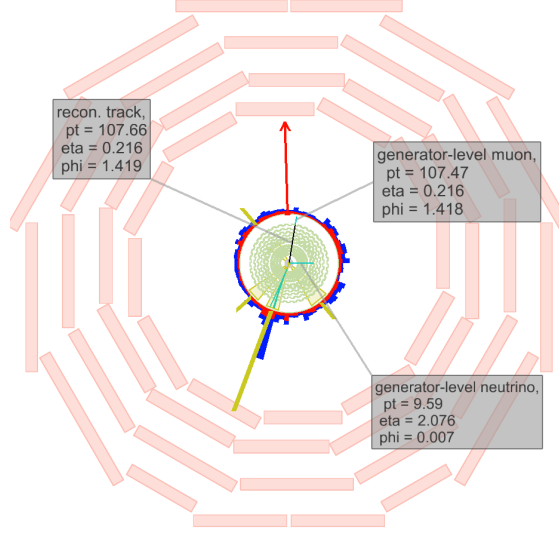


Figure 6.8: Visualisation of an  $W \rightarrow \mu\nu_\mu$  event contributing to the SM background. In light blue, the generator-level particles including  $\mu$  and  $\nu_\mu$  of the  $W$  decay are shown. The muon is pointing to the  $\eta$ -region between stations 0 and 1 of the DT system at  $|\eta| \sim 0.25$ . In this region the muon reconstruction is less efficient. No signal in the muon chambers is visible. Therefore the muon could not be reconstructed. The ISR jet causes the  $\cancel{E}_T$  (read arrow) in the event.

$p_T$  and  $I_{as}$ , the background estimation methods are designed to work for all different  $p_T$  and  $I_{as}$  selection cuts.

As for the fakes, the leptonic background estimation 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.

### 6.2.1 Inclusive leptonic background estimation

The inclusive (without  $dE/dx$  information) lepton background estimation method is similar to the background estimation method used in [33, 34].

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  $W + \text{jets}$  events, the ratio  $\rho_{MC}^{\text{lep}_i}$  between the number of events in the signal region with the selected track matched to a generator-level lepton  $N_{SR}^{\text{trk matched to lepton}_i}$  and the number of events in a control region  $N_{CR}^{\text{lepton}_i \text{ veto inverted}}$  with a inverted lepton veto is determined.

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 additionally 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 predicted background events can be estimated with

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

for muons, and

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

for electrons and taus.

This method relies on the simulation of the lepton reconstruction efficiencies which is expected to be reasonably accurate [40–42]. For electrons and taus the simulation of the calorimeter isolation is utilised as well. Possible discrepancies between simulation and data are taken into account as a systematic uncertainty via a comparison of the lepton reconstruction efficiencies in data and simulation in  $Z \rightarrow \ell\bar{\ell}$  events (see Section 6.4.3).

To reduce the statistical uncertainty, the scale factor is calculated without applying the QCD suppression cuts. After the signal candidate selection described in Section 5.2, only one event remains in the simulated  $W + \text{jets}$  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 matched to a pion. The statistical uncertainties are calculated as the 68% upper and lower limits on the inclusive background with the Neyman procedure [17, 43]. Table 6.4 gives the result for the prediction of the inclusive leptonic background for the signal candidate selection from Section 5.2.

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

|           | scaling factor $\rho_{MC}^{\text{lep}_i}$ | $N_{\text{CR,data}}$ | $N_{\text{predicted}}$   |
|-----------|---|----------------------|--------------------------|
| 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                  | $< 9.46$                 |

### 6.2.2 $dE/dx$ shape of leptonic background

In order to get information about the  $I_{\text{as}}$  (see Section 3.3) shape in the signal region of electrons, muons and taus, a control region must be found where the shape of the observable is at least 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  $I_{\text{as}}$  is highly correlated to the lepton reconstruction efficiency, as can be seen in Fig. 6.9. The discrepancies reach factors up to an order of magnitude.

Various other control regions were tested and could not be used because of too large  $I_{\text{as}}$  shape differences to the signal region.

As no suitable control region exists where the  $I_{\text{as}}$  shape of the leptons is at least similar to the shape in the signal region, it is decided to use the  $I_{\text{as}}$  information from simulation. This introduces a large systematic uncertainty since  $dE/dx$  (and therefore  $I_{\text{as}}$ ) is not

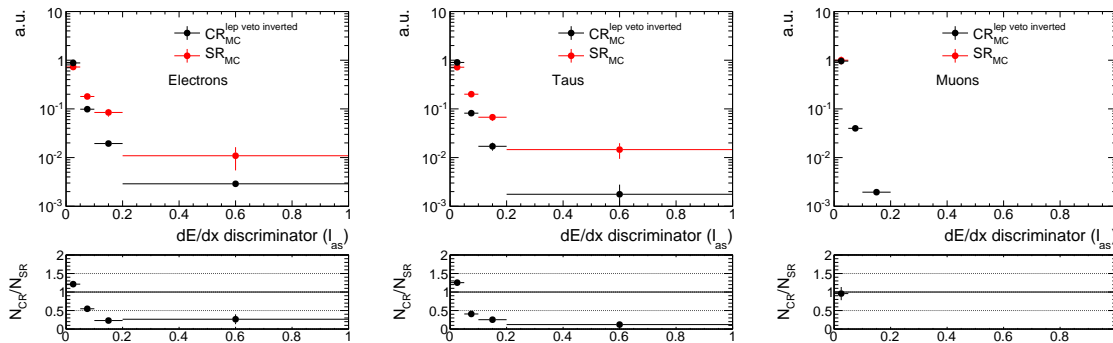


Figure 6.9: Normalised  $I_{\text{as}}$  distribution for electrons (left), pions from the tau decay (middle) and muons (right) in the signal region (red) and the lepton veto inverted control region (black).

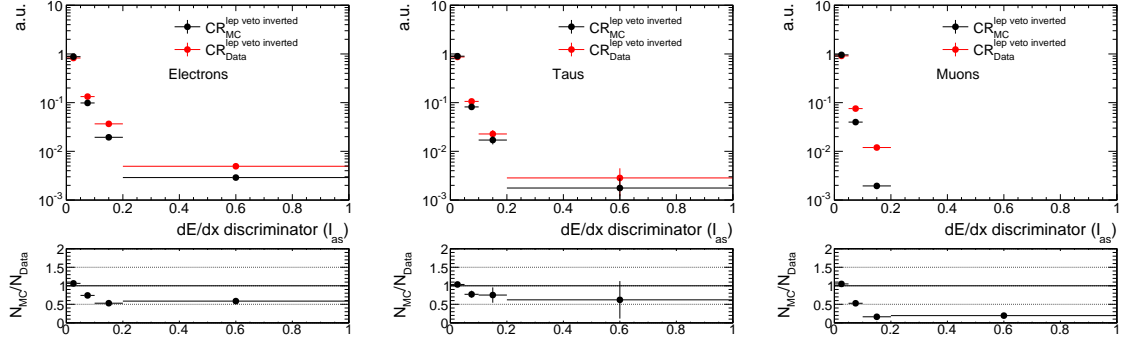


Figure 6.10: Normalised  $I_{as}$  distribution for electrons (left), pions from the tau decay (middle) and muons (right) in the lepton veto inverted control region from simulated (black) and real (red) events.

simulated well. However, the corresponding systematic uncertainty is still smaller than taking the  $I_{as}$  shape from a control region in data: compare Fig. 6.9 and Fig. 6.10.

In order to take into account the bias when using  $I_{as}$  from simulation, a systematic uncertainty is estimated that addresses 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 are used for validation. For each control region it has been checked that the signal contamination is less than the statistical uncertainty of the background prediction. For some of the models the expected number of events exceeds this limit. However, these models are already ruled out by the search for disappearing tracks [8] (see Appendix A.3).

First, to validate the estimation method of the leptonic background, a leptonic control region is defined by selecting only tracks with a minimum number of seven hits in the tracker. This reduces the fake contribution to a minimum (cf. Fig. 6.1). Additionally in order to minimise signal contamination, the calorimeter isolation requirement is inverted to  $E_{calo}^{\Delta R < 0.5} > 10 \text{ GeV}$ .

The validation test for the control region with  $E_{calo}^{\Delta R < 0.5} > 10 \text{ GeV}$  and  $N_{hits} > 6$  is shown in Table A.10. The predicted number of events by the leptonic background estimation is compatible with the observed data yield.

As the fake background can only be estimated within the low calorimeter isolation region ( $E_{calo}^{\Delta R < 0.5} < 10 \text{ GeV}$ ) to ensure high fake purity, the information about the num-



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

|           | Predicted Yield            | Data Yield |           | Predicted Yield      | Data Yield |
|-----------|----------------------------|------------|-----------|----------------------|------------|
| Total bkg | $131.70^{+26.30}_{-18.42}$ | 156        | Total bkg | $0.0^{+0.50}_{-0.0}$ | 1          |
| Electrons | $14.67^{+11.16}_{-6.29}$   |            | Electrons | $0.0^{+0.07}_{-0.0}$ |            |
| Muons     | $7.99^{+10.90}_{-5.00}$    |            | Muons     | $0.0^{+0.32}_{-0.0}$ |            |
| Taus      | $109.04^{+21.18}_{-16.58}$ |            | Taus      | $0.0^{+0.38}_{-0.0}$ |            |

ber of fake tracks in the high calorimeter isolation region is taken from the fake enriched control region  $\text{CR}_{I_{\text{as}}}^{\text{fake}}$  defined in Section 6.1. In this control region, the ratio of  $N_{E_{\text{calo}}^{\Delta R < 0.5} > 10 \text{ GeV}} / N_{E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}}$  is estimated and taken as a multiplicand to the number of events predicted from the  $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$  region. In Table 6.6, two different validation tests are shown, once an inclusive validation in  $I_{\text{as}}$  and once with an  $I_{\text{as}}$  selection of 0.2. Again, the predicted background events is in agreement with the number of observed events.

The whole validation is done for different selections in  $p_{\text{T}}$  and  $I_{\text{as}}$ . All validation tests

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

|           | Predicted Yield            | Data Yield |           | Predicted Yield         | Data Yield |
|-----------|----------------------------|------------|-----------|-------------------------|------------|
| Total bkg | $309.00^{+33.46}_{-26.62}$ | 324        | Total bkg | $14.80^{+2.92}_{-2.85}$ | 16         |
| 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     | $11.72^{+2.79}_{-2.79}$ |            |

show good agreement. A variety of validation tests with different  $p_T$  and  $I_{as}$  selections can be found in Appendix A.4.

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

Systematic uncertainties on the background estimation include:

- the uncertainty on the fake rate  $\rho_{\text{fake}}$ ;
- the uncertainty on the  $I_{as}$  shape of fake tracks predicted from a control region;
- the uncertainty on the leptonic scale factor  $\rho_{\text{MC}}^{\text{lep}_i}$  determined with simulated events;
- the uncertainty on the  $I_{as}$  shape of the leptonic background.

### 6.4.1 Uncertainty on the fake rate

The fake rate  $\rho_{\text{fake}}$  is determined with the help of observed  $Z \rightarrow \ell\bar{\ell}$  events. To estimate the uncertainty on this fake rate caused by differences in the fake rate between different underlying processes, a comparison between the fake rate in simulated  $Z \rightarrow \ell\bar{\ell} + \text{jets}$  and simulated  $W + \text{jets}$  events is done. The fake rate in the  $Z \rightarrow \ell\bar{\ell} + \text{fake track}$  control samples (see Tables 6.2 and 6.3) and the fake rate in the signal candidate selection from Table 5.4 in  $W + \text{jets}$  events are compared.

Unfortunately, the statistical precision of the simulated  $W + \text{jets}$  dataset is limited. Thus, the estimation of the systematic uncertainty is mainly driven by statistical uncertainties. In order to enhance the statistical precision of the estimation, the selection requirements on  $\cancel{E}_T$  and  $p_T^{1,\text{jet}}$  are loosened and the QCD suppression requirements are removed. As these variables are not expected to be correlated with the fake rate, the relative uncertainty of the fake rate should stay the same. That this is indeed the case, can be seen in Table 6.7.

The systematic uncertainty is estimated as the 1-sigma deviation of the ratio  $\rho_{\text{fake}}^{W+\text{jets}} / \rho_{\text{fake}}^{Z \rightarrow \ell\bar{\ell}}$  from 1. For the candidate track selection, this is estimated to  $\rho_{\text{fake}}^{W+\text{jets}} / \rho_{\text{fake}}^{Z \rightarrow \ell\bar{\ell}} = 0.96 \pm 0.16$  leading to a systematic uncertainty of 20%.

### 6.4.2 Uncertainty on the $dE/dx$ shape of fake tracks

The systematic uncertainty on the shape of the  $I_{as}$  distribution takes into account the differences between the  $I_{as}$  shape in the fake control region  $\text{CR}_{I_{as}}^{\text{fake}}$  and in the signal region. For the estimation, information from simulated  $W + \text{jets}$  events is used. A comparison between the simulated  $I_{as}$  shape in the signal and in the control region can be seen in Fig. 6.11. To enhance the statistical precision only track-based selection cuts are applied.

Table 6.7: Fake rates in simulated  $W + \text{jets}$  and  $Z \rightarrow \ell\bar{\ell} + \text{jets}$  events for different event-based selections of the  $W + \text{jets}$  sample. The track-based selection is the candidate track selection from Table 5.4.

| $W + \text{jets}$ selection   | $\rho_{\text{fake}}^{W+\text{jets}}$   | $\rho_{\text{fake}}^{Z \rightarrow \ell\bar{\ell}}$ |
|---|--|---|
| $\cancel{E}_T > 100 \text{ GeV}, p_T^{1.\text{jet}} > 110 \text{ GeV}$            | $(3.16^{+4.26}_{-1.94}) \cdot 10^{-5}$ | $(3.17 \pm 0.21) \cdot 10^{-5}$                     |
| $\cancel{E}_T > 0 \text{ GeV}, p_T^{1.\text{jet}} > 70 \text{ GeV}$               | $(3.03 \pm 0.68) \cdot 10^{-5}$        | $(3.17 \pm 0.21) \cdot 10^{-5}$                     |
| $\cancel{E}_T > 0 \text{ GeV}, p_T^{1.\text{jet}} > 70 \text{ GeV}$ , no QCD cuts | $(3.05 \pm 0.44) \cdot 10^{-5}$        | $(3.17 \pm 0.21) \cdot 10^{-5}$                     |

The 1-sigma difference of the ratio of the number of events in the signal region and the control region from one is taken as systematic uncertainty. For a signal region definition with  $p_T > 20 \text{ GeV}$  and  $I_{\text{as}} > 0.2$  this corresponds to an uncertainty of around 21% and for a definition with  $p_T > 40 \text{ GeV}$  and  $I_{\text{as}} > 0.2$  of around 25%.

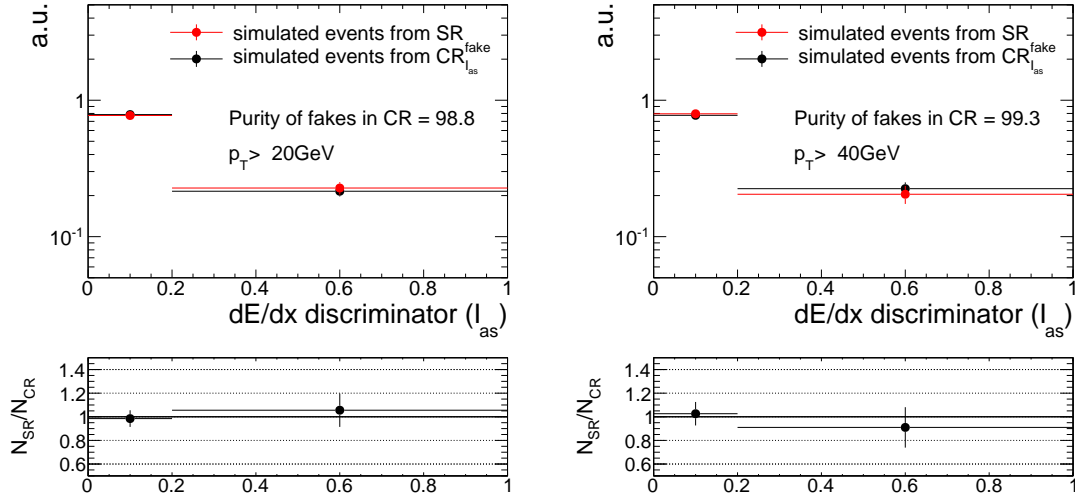


Figure 6.11: Underlying histograms to estimate the fake  $I_{\text{as}}$  systematic uncertainty. Normalised distributions of the  $I_{\text{as}}$  shape of fake tracks in the signal and control region of simulated  $W + \text{jets}$  events with a  $p_T$  selection of 20 GeV (left) and a 40 GeV (right).

### 6.4.3 Uncertainty on the leptonic scale factor

The leptonic scale factor  $\rho_{\text{MC}}^{\text{lep}_i}$  is estimated on simulated  $W$ +jets events. The corresponding systematic uncertainty that addresses the use of information from simulation is derived by a “tag-and-probe” method conducted on real data and simulated events.

For this method a selection of  $Z \rightarrow \ell\bar{\ell}$  events is done with one “tagged” well reconstructed lepton and one “probed” candidate track. To ensure a selection of  $Z \rightarrow \ell\bar{\ell}$  events, a selection on the invariant mass of the reconstructed lepton and the candidate track is applied with  $80 \text{ GeV} < M_{\text{inv}}(\text{lepton, cand. trk}) < 100 \text{ GeV}$  for muons and electrons. For taus, a muon from a  $\tau \rightarrow \mu\nu\nu$  decay is selected with  $40 \text{ GeV} < M_{\text{inv}}(\mu, \text{cand. trk}) < 75 \text{ GeV}$  and  $m_T(\mu, \cancel{E}_T) < 40 \text{ GeV}$  [33, 34]. Furthermore, the candidate track and the lepton are required to be opposite in charge. In order to reduce the contamination of fakes in the “tag-and-probe” samples an additional selection on the number of hits of  $N_{\text{hits}} > 5$  is required.

The “tag-and-probe” selection is done for each lepton type separately. In order to determine the leptonic scale factors, the number of events is once estimated for the candidate track selection including the corresponding lepton veto which gives the a number of events in the “tag-and-probe” signal region  $N_{\text{SR}}^{\text{T\&P}}$ , and once inverting the lepton veto selection requirement which gives the the number of events in the “tag-and-probe” lepton inverted control region  $N_{\text{CR, lepton veto inverted}}^{\text{T\&P}}$ . As for the determination of the tau and electron scale factor with simulated  $W$  + jets events, no requirement on the calorimeter isolation is applied in the lepton veto inverted control region for taus and electrons. This leads to the following expression of the lepton scale factor for muons

$$\rho^\mu = \frac{N_{\text{SR}}^{\text{T\&P}\mu}}{N_{\text{CR, } \mu \text{ veto inverted}}^{\text{T\&P}}}.$$

and for electrons and taus

$$\rho^{e,\tau} = \frac{N_{\text{SR}}^{\text{T\&P}e,\tau}}{N_{\text{CR, } e,\tau \text{ veto inverted}}^{\text{T\&P}}}.$$

The selection requirements for the three tag-and-probe samples are listed in Tables A.11, A.12 and A.13 in Appendix A.5.

The leptonic scale factors are calculated using simulated  $Z \rightarrow \ell\bar{\ell}$  events and real data from the single-muon and single-electron samples listed in Table 6.1. The 1-sigma difference of the ratio  $\rho_{\text{MC}}^{\text{lep}_i}/\rho_{\text{Data}}^{\text{lep}_i}$  from unity is taken as systematic uncertainty. This results for the signal candidate selection in an uncertainty of 69% for the electron, 39% for the muon and 79 % for the tau scale factor.

#### 6.4.4 Uncertainty on the leptonic $dE/dx$ shape

The uncertainty on lepton  $I_{as}$  shape is estimated by a comparison of the  $I_{as}$  shape in data and simulation in the lepton veto inverted control region. Figure 6.12 shows the leptonic  $I_{as}$  distributions for all three lepton types in the lepton veto inverted control region in data and simulation. The 1-sigma difference of the ratio of the number of events in the control region in data and simulation from 1 is taken as systematic uncertainty. This leads for example to uncertainties between 37% – 81% for the signal candidate selection plus a selection requirement of  $I_{as} > 0.2$ .

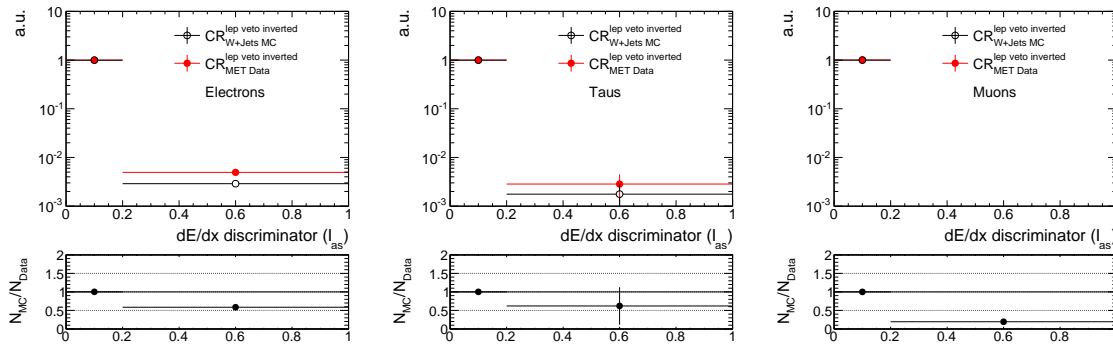


Figure 6.12: Underlying histograms to estimate the leptonic  $I_{as}$  systematic uncertainty. Normalised distributions of the lepton  $I_{as}$  distributions in the lepton veto inverted control region for data (red) and simulation (black) for all three lepton types. The event-based selection requirements and the calorimeter isolation requirement are removed to enhance the statistical precision.

## 7 Optimisation of the search sensitivity

Finally, having all background estimation methods in place, an optimisation procedure is conducted in order to increase the search sensitivity with respect to different signal models as introduced in Section 4.2. The optimisation is done in the most sensitive variables,  $p_T$  and  $I_{as}$  (see Section 3.3 for a definition and explanation of the Asymmetric Smirnov discriminator  $I_{as}$ ). A potential additional discriminating variable is the number of missing outer hits  $N_{lost}^{outer}$  in the tracker system. This variable is, however, not considered in this analysis because studies show that the discriminating potential is limited (see Appendix A.6).

SUSY models with different chargino lifetimes and masses are characterised by different  $p_T$  and  $I_{as}$  distributions as well as different theoretical cross sections. Therefore, the usual search optimisation strategy that maximises  $N_S/\Delta B$  ( $N_S$  = number of signal events of model  $S$ ,  $\Delta B$  = background uncertainty) implies a potential fine-tuning on the specific SUSY cross sections. In order to keep the search as general as possible, a cross section independent optimisation is performed. This is achieved by a minimisation of the cross section for which a  $5\sigma$ -discovery of the corresponding signal model is possible, i. e. finding the optimal selection cuts for  $p_T$  and  $I_{as}$  for which the lowest possible cross section,  $\sigma_{\min}$ , can be discovered

$$\frac{\alpha_{\min} \cdot N_S(\text{mass}, c\tau, p_T^{\text{cut}}, I_{as}^{\text{cut}})}{\Delta B(p_T^{\text{cut}}, I_{as}^{\text{cut}})} = 5. \quad \text{with } \alpha_{\min} = \frac{\sigma_{\min}}{\sigma_S}. \quad (7.1)$$

The number of expected events  $N_S$  of the signal model  $S$  depends on the  $p_T$  and  $I_{as}$  selection cut as well as the mass and the lifetime of the chargino. The uncertainty on the background  $\Delta B$  is dependent on the  $p_T$  and  $I_{as}$  cut, and takes into account the full systematic uncertainty as well as the statistical uncertainty on the background prediction which is the 68% one sided upper limit of a Poisson distribution with  $\mu = N_B$  estimated with the Neyman construction [17, 43]. The systematic uncertainty on the background prediction includes systematic uncertainties as described in Section 6.4, and statistical uncertainties arising from limited statistical precision of the control regions and simulated samples used in the background estimation. The factor  $\alpha_{\min}$  that is minimised is the ratio of the minimum cross section  $\sigma_{\min}$  divided by the nominal cross section  $\sigma_S$  of the signal model  $S$ .

As this analysis focuses on short tracks, rather low lifetimes are considered in the optimisation procedure:  $c\tau = 1$  cm, 10 cm, 50 cm. These lifetimes are further suitable as they lie at the edge of the sensitivity of the search for disappearing tracks [8]. To cover the full mass space, the optimisation is done for masses between 100 GeV and 500 GeV. The corresponding results are shown in Table 7.1.

It can be seen that the optimal selection is highly dependent on the signal models. The best sensitivity for low masses ( $\leq 200$  GeV) is mainly achieved by soft selection cuts in  $p_T$  between 20 – 30 GeV, while models with higher chargino masses require tighter  $p_T$  selections of around 50 GeV. The optimal  $I_{as}$  selection is mostly dependent on the mass of the chargino. For low masses and low lifetimes a soft selection in  $I_{as} > 0.05$  is preferred. Since for longer lifetimes more charginos are able to reach the tracking system, a tighter selection in  $I_{as}$  of 0.3 is preferable. For high masses the highest search sensitivity is always achieved by a high  $I_{as}$  selection cut of 0.3.

In order to visualise the mass and  $c\tau$  dependence of the optimal  $p_T$  and  $I_{as}$  selection, the

Table 7.1: Optimal  $p_T$  and  $I_{\text{as}}$  selection cuts and the corresponding minimum cross section  $\sigma_{\text{min}}$  that can be discovered with  $5\sigma$  significance for different signal models. For some signal samples, an optimisation result is not available due to the limited size of these samples.

| Mass [ GeV ] | Lifetime [ cm ] | Optimal $p_T$ cut | Optimal $I_{\text{as}}$ cut | $\sigma_{\text{min}}$ |
|--------------|-----------------|-------------------|-----------------------------|-----------------------|
| 100          | 1               | 30                | 0.05                        | 61.596                |
| 200          | 1               | 20                | 0.05                        | 43.414                |
| 300          | 1               | n/a               | n/a                         | n/a                   |
| 400          | 1               | n/a               | n/a                         | n/a                   |
| 500          | 1               | n/a               | n/a                         | n/a                   |
| 100          | 10              | 30                | 0.05                        | 1.531                 |
| 200          | 10              | 30                | 0.30                        | 0.561                 |
| 300          | 10              | 30                | 0.30                        | 0.354                 |
| 400          | 10              | 30                | 0.30                        | 0.238                 |
| 500          | 10              | 50                | 0.30                        | 0.201                 |
| 100          | 50              | 50                | 0.30                        | 0.435                 |
| 200          | 50              | 50                | 0.30                        | 0.110                 |
| 300          | 50              | 50                | 0.30                        | 0.063                 |
| 400          | 50              | 50                | 0.30                        | 0.045                 |
| 500          | 50              | 50                | 0.30                        | 0.037                 |

optimisation results for two very different lifetimes (5 cm and 50 cm) and masses (100 GeV and 500 GeV) are shown in Fig. 7.1, where the minimum cross section that is possible to discover is shown in the  $p_T - I_{\text{as}}$  plane. For the visualisation, general systematic uncertainties on the leptonic and the fake background of 100% and 20% respectively are imposed. Uncertainties arising from limited statistical precision of the samples used for the background estimation are propagated consistently into formula 7.1. Similar to the full optimisation, it can be seen that for low masses and low lifetimes, the highest search sensitivity is achieved by imposing rather soft selection cuts on  $I_{\text{as}}$  and  $p_T$ . Optimising for higher lifetime pushes the optimal selection in  $p_T$  and  $I_{\text{as}}$  to larger values, where signal

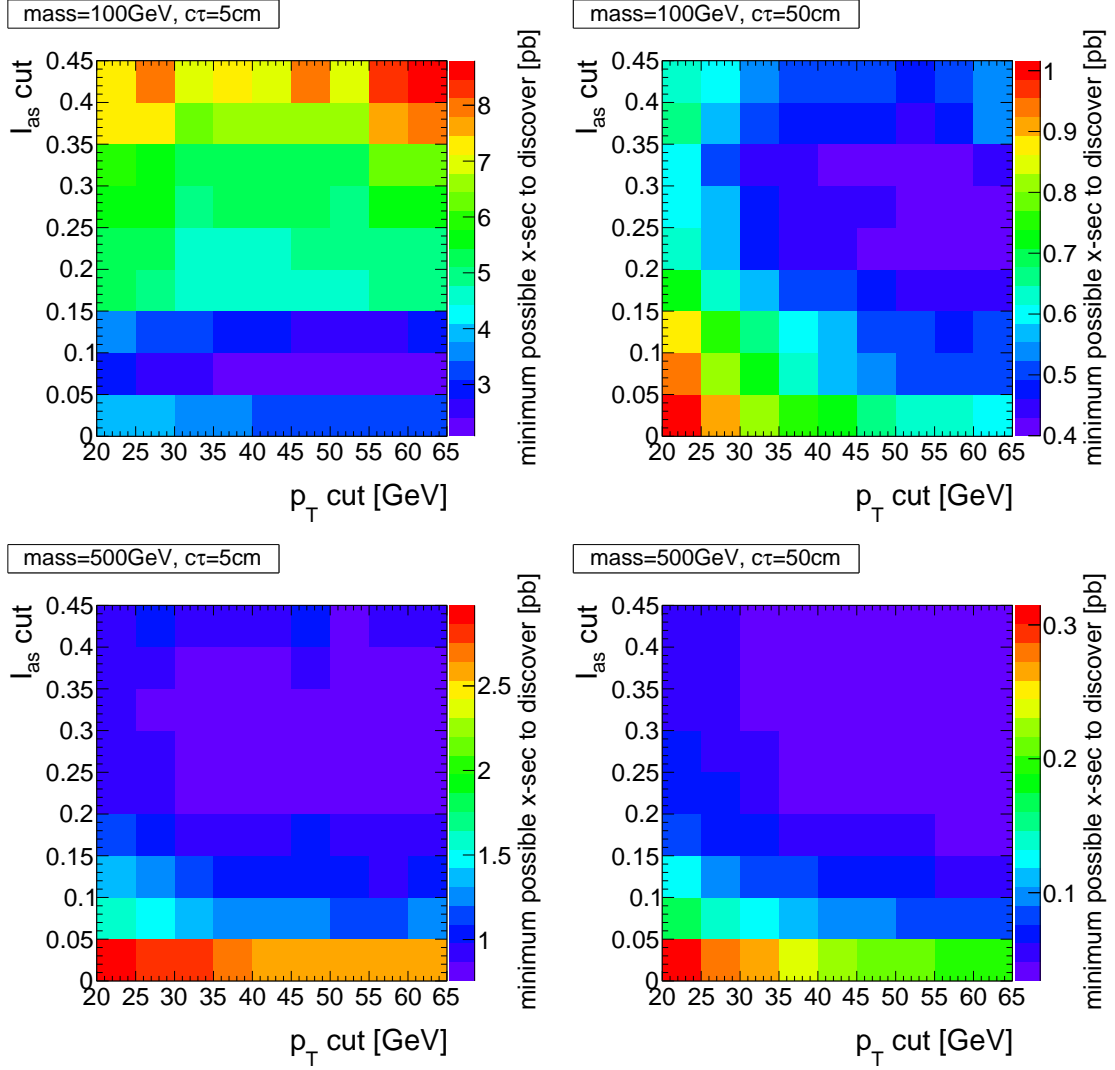


Figure 7.1: Minimum possible cross section that can be discovered with  $5\sigma$  significance in the  $I_{as} - p_T$  plane for four different signal models. The systematic uncertainties are taken to be 20% and 100% for the fake and the leptonic background respectively. The uncertainty on the background arising from the limited size of the used samples are propagated consistently to the search optimisation. In Table A.3 of Appendix A.7, the corresponding histograms of the background yield, the background uncertainty and the signal yield for the four signal models can be found.



models with higher masses prefer even tighter  $I_{\text{as}}$  selection cuts than the corresponding lower mass signal model. It can also be seen, that for low lifetimes, the  $p_{\text{T}}$  dependence of the search sensitivity is less pronounced than for long lifetimes.

Based on the optimisation, four different exclusive signal regions are defined in order to achieve an optimal coverage over a wide mass space and a high sensitivity for different lifetimes:

- 1.)  $30 \text{ GeV} < p_{\text{T}} < 50 \text{ GeV}$  and  $0.05 < I_{\text{as}} < 0.3$
- 2.)  $p_{\text{T}} > 50 \text{ GeV}$  and  $0.05 < I_{\text{as}} < 0.3$
- 3.)  $30 \text{ GeV} < p_{\text{T}} < 50 \text{ GeV}$  and  $I_{\text{as}} > 0.3$
- 4.)  $p_{\text{T}} > 50 \text{ GeV}$  and  $I_{\text{as}} > 0.3$ .

The unblinded results of the search for highly ionising, short tracks are presented in the following chapter.

## 8 Results

After developing the methods of the background estimation for all different background sources and their corresponding systematic uncertainties (all explained in Section 6), the search is performed in four exclusive signal regions with  $19.7 \text{ fb}^{-1}$  of data collected at a centre-of-mass energy of  $\sqrt{s} = 8 \text{ TeV}$  at the CMS experiment. The predicted number of events for the fake and the leptonic background in the four signal regions is depicted in Table 8.1. It can be seen, that fake tracks are by far the dominant background to this search. The leptonic background contributes only in one signal region to the total background with a share of about 10%.

Finally, the comparison between the predicted number of events and the number of observed events is shown in Fig. 8.1. Additionally, the corresponding numbers of predicted and observed events can be found in Table 8.2. The event yields observed in data after each selection requirement for the four signal regions are listed in Table A.3 in Appendix A.2.

The results are compatible with the Standard Model background within  $1\sigma$  uncertainties in all four signal regions. No excess above the SM prediction is observed in either of the four signal regions. Thus, no evidence for physics beyond the Standard Model could be found.

Table 8.1: Background prediction in the four exclusive signal regions for the fake and the leptonic background.

| Signal region  | Fake Bkg  | Leptonic Bkg   |
|--|---|--|
| $p_T : 30 - 50 \text{ GeV} / I_{as} : 0.05 - 0.30$     | $19.11^{+2.61}_{-2.61} \text{ (stat)} \pm 9.35 \text{ (sys)}$ | $0.00^{+2.58}_{-0.00} \text{ (stat)} \pm 0.00 \text{ (sys)}$ |
| $p_T : 50 - \infty \text{ GeV} / I_{as} : 0.05 - 0.30$ | $22.21^{+3.60}_{-3.60} \text{ (stat)} \pm 8.78 \text{ (sys)}$ | $2.17^{+2.99}_{-1.34} \text{ (stat)} \pm 1.65 \text{ (sys)}$ |
| $p_T : 30 - 50 \text{ GeV} / I_{as} : 0.30 - 1.00$     | $2.49^{+0.85}_{-0.85} \text{ (stat)} \pm 1.98 \text{ (sys)}$  | $0.00^{+0.22}_{-0.00} \text{ (stat)} \pm 0.00 \text{ (sys)}$ |
| $p_T : 50 - \infty \text{ GeV} / I_{as} : 0.30 - 1.00$ | $2.52^{+1.14}_{-1.14} \text{ (stat)} \pm 1.27 \text{ (sys)}$  | $0.04^{+0.30}_{-0.03} \text{ (stat)} \pm 0.03 \text{ (sys)}$ |

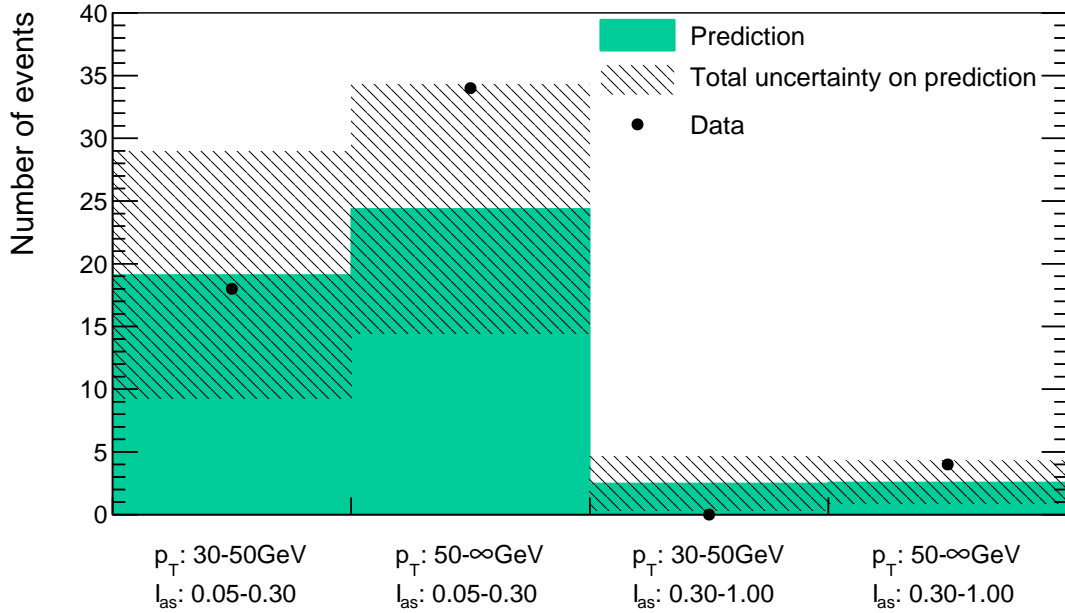


Figure 8.1: Number of predicted (green area) and observed (black dots) events for the four different signal regions. The hashed area represents the total uncertainty on the background prediction.

Table 8.2: Number of predicted and observed events for the four different signal regions.

| Signal region   | Prediction  | Observation |
|---|---|-------------|
| $p_T : 30 - 50 \text{ GeV} / I_{\text{as}} : 0.05 - 0.30$     | $19.11^{+3.67}_{-2.61} \text{ (stat)} \pm 9.35 \text{ (sys)}$ | 18          |
| $p_T : 50 - \infty \text{ GeV} / I_{\text{as}} : 0.05 - 0.30$ | $24.38^{+4.68}_{-3.84} \text{ (stat)} \pm 8.93 \text{ (sys)}$ | 34          |
| $p_T : 30 - 50 \text{ GeV} / I_{\text{as}} : 0.30 - 1.00$     | $2.49^{+0.87}_{-0.85} \text{ (stat)} \pm 1.98 \text{ (sys)}$  | 0           |
| $p_T : 50 - \infty \text{ GeV} / I_{\text{as}} : 0.30 - 1.00$ | $2.57^{+1.18}_{-1.14} \text{ (stat)} \pm 1.27 \text{ (sys)}$  | 4           |

Therefore, in the following section these results will be used to constrain the parameter space of supersymmetric models with almost mass degenerate charginos and neutralinos.

## 9 Interpretation

In order to interpret the result of the search in the context of supersymmetric models with almost mass degenerate charginos and neutralinos, sources of systematic uncertainties on the number of selected signal events must be identified and quantified. The interpretation will then be done with statistical methods that allow for the exclusion of parts of the supersymmetric parameter space on a 95% confidence level.

### 9.1 Systematic uncertainties of simulated signal samples

The systematic uncertainties on the number of signal events in the four signal regions are mainly caused by uncertainties on the quality of the simulation. This influences the signal efficiency of each selection requirement in this analysis. Furthermore, an uncertainty on the overall number of events is caused by the uncertainty on the integrated luminosity recorded in 2012 at CMS and the theoretical signal cross sections.

All systematic uncertainties are estimated for each signal model and each search bin separately. In the following, the sources of systematic uncertainties are discussed and the minimum and maximum value of the corresponding uncertainty is given.

### Uncertainty on the theoretical cross section

The theoretical cross sections of  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production at a centre-of-mass energy of 8 TeV are taken from [31, 32]. The corresponding theoretical uncertainties range between 4.5 – 12.1%.

### Luminosity uncertainty

The integrated luminosity recorded at CMS during the year 2012 is measured by counting of pixel clusters during the crossing of two bunches (zero-bias event). A detailed explanation of this method and the corresponding total uncertainty of 2.6% can be found in [44].

### Uncertainty on the simulation of initial state radiation

Initial state radiation affects the transverse momentum distribution of the 2-particle system,  $p_T(p_1^\mu + p_2^\mu)$ , in a 2-body decay. Differences between data and simulation of ISR are taken into account by reweighting the simulated events, such that the simulated transverse momentum distribution matches the measured distribution in data. The weights and associated systematic uncertainties are determined in [45] by comparing simulated and observed  $p_T$  distributions of  $Z$  and  $t\bar{t}$  events. These weights are applied to the simulated  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  events. To account for the systematic uncertainties on the reweighting procedure, the event weights are varied up and down by up to 25% according to [45] depending on the  $p_T^{\chi_1\chi_2}$ . The resulting uncertainty on the ISR simulation is between 9.2 – 12.6%.

### Uncertainty on the simulation of the trigger efficiency

The HLTMonoCentralPFJet80\_PFMETnoMu105\_NHEF0p95 trigger with the higher MET threshold of 105 GeV active in Run C and Run D during 2012 was not available in the simulated signal samples. It is therefore emulated using HLT trigger information. More details on the emulation of this trigger can be found in Appendix A.8.

The trigger uncertainty is assessed by comparing data-simulation differences of the trigger efficiency. This uncertainty has been quantified within [33, 34] by comparing simulated and measured trigger turn-on curves and determining weights for simulated events such that simulated and observed turn-on curves are compatible. These event weights are applied on the simulated signal samples in this analysis and lead to changes in the signal prediction of 1.9 – 4.4%.

### Uncertainty on the jet energy scale

The transverse momentum of all jets is corrected for non-uniformities in the energy response as a function of the jet  $\eta$  and  $p_T$  and for data-simulation differences [46]. The uncertainty on the jet energy scale (JES) is neatly described and quantified in [46]. It arises from uncertainties on the jet response in data including jet fragmentation, jet flavor composition, etc.. The JES correction is applied as a multiplicand on each jet's transverse momentum contained in an event. The corresponding systematic uncertainty is assessed by a up- and downward variation of the correction factor within  $1\sigma$ . The resulting uncertainties are of minor importance and range between  $0.4 - 3.1\%$ .

### Uncertainty on the jet energy resolution

The jet energy resolution (JER) is smaller in simulation than in measured data (see Part ??). In order to take these differences into account, the simulated jet energy response is smeared to match the measured response. The systematic uncertainty on the smearing factors is estimated in [46, 47]. It covers the uncertainty on JER in data, including the JES uncertainty, uncertainties arising from out-of-cone showering etc. [46, 47]. The resulting uncertainty on the signal efficiency in this study is between  $0.1 - 2.0\%$  and therefore almost negligible.

### Uncertainty on the simulation of the parton distribution functions

The parton distribution function (PDF) used for the simulation of proton-proton collisions is provided by the CTEQ group [48] (see Section ?? for more information about PDFs). In [48], a detailed description of the determination of a parton distribution function and its uncertainties is given. Practically, the estimation of the PDF uncertainty is done by the application of 44 different sets of event weights which take into account 22 different sources of uncertainties [49, 50] (up and down variations lead to a factor of 2). The sources correspond inter alia to uncertainties in the single distributions of gluons, up/down-quarks, etc, with the gluon distribution being by far the largest source of uncertainty.

The resulting uncertainties on the signal efficiency for this search are between  $2.6 - 6.8\%$ .

### Uncertainty of the pileup reweighting

The distribution of the number of primary vertices in simulation is reweighted to match the measured distribution in data. The number of primary vertices in data is determined by the luminosity of each bunch-crossing times the proton-proton inelastic cross section which is  $69.4\text{ mb}$  [51]. The uncertainty on the number of interactions thus consists of the uncertainty on the luminosity and the uncertainty on the cross section. To cover both

sources, a variation of the inelastic cross section by plus/minus 5% is done according to the recommendation by [52].

For most of the signal models and signal regions, the signal efficiency is only affected by less than 1% by the pileup reweighting uncertainty. If the statistical precision of the signal prediction in a specific search bin is low, the uncertainty can become significantly larger. However, the search sensitivity is always driven by search bins with high signal content so that large values of this uncertainty have no effect on the overall search sensitivity.

### Uncertainty on the simulation of the calorimeter isolation

The uncertainty on the simulation of the calorimeter isolation  $E_{\text{calo}}^{\Delta R < 0.5}$  is estimated by comparing simulated and measured selection efficiencies of  $E_{\text{calo}}^{\Delta R < 0.5} < 5 \text{ GeV}$  in the fake enriched control sample  $\text{CR}_{I_{\text{as}}}^{\text{fake}}$ . The fake enriched control region is well suited for this estimation, as fake tracks are also expected to deposit only a low amount of energy in the calorimeters. The selection efficiency in data is higher than in simulation in both  $p_{\text{T}}$  bins of  $30 - 50 \text{ GeV}$  and  $50 - \infty \text{ GeV}$ , resulting in an uncertainty of 12.1% and 3.0% respectively.

### Uncertainty on the simulation of missing middle/inner hits

The uncertainty on the simulation of the number of missing inner and middle hits is assessed by comparing the probability in simulation and data of passing the selection requirements of  $N_{\text{miss}}^{\text{middle/inner}} = 0$  of a candidate track in the muon-veto inverted control region. This control region is particularly suitable because muons are not expected to have intrinsic sources of missing hits, as e.g. pions or electrons have. Pions can interact nuclearly with the tracker material and electrons can have sizable radiative losses, such that both can change direction or don't deposit energy in a tracker layer. For muons, on the other hand, sources of missing inner and middle hits are mainly algorithmic [33, 34], making them very similar to the algorithmic sources of missing inner/middle hits for chargino tracks.

The uncertainty is estimated as the relative difference of the cut selection efficiency of  $N_{\text{miss}}^{\text{middle/inner}} = 0$  in data and simulation. The selection efficiency is always higher in simulation, resulting in systematic uncertainties of around 3.5% for the simulation of  $N_{\text{miss}}^{\text{inner}} = 0$  and around 2.2% for  $N_{\text{miss}}^{\text{middle}} = 0$ . The uncertainties are of very similar size in the signal regions with different  $p_{\text{T}}$ . No  $I_{\text{as}}$  dependence is considered.

### Uncertainty on the simulation of $I_{\text{as}}$

An uncertainty on the simulation of  $I_{\text{as}}$  needs to be estimated in order to account for possible data-simulation differences for highly ionising particles. The estimation of the  $I_{\text{as}}$  uncertainty is done following the methodology in [9, 53]. The  $I_{\text{as}}$  uncertainty can be

assessed by comparing data and simulation differences of slow protons. Slow protons are highly ionising and can thus be used to determine the uncertainty in the high  $I_{\text{as}}$  region.

In order to select slow protons, high quality tracks with a momentum smaller than 2.5 GeV are selected. The  $I_{\text{as}}$  versus momentum distribution for the selected tracks is shown in Fig. 9.1. The kaon, proton, and in data also the deuteron line is visible. Two

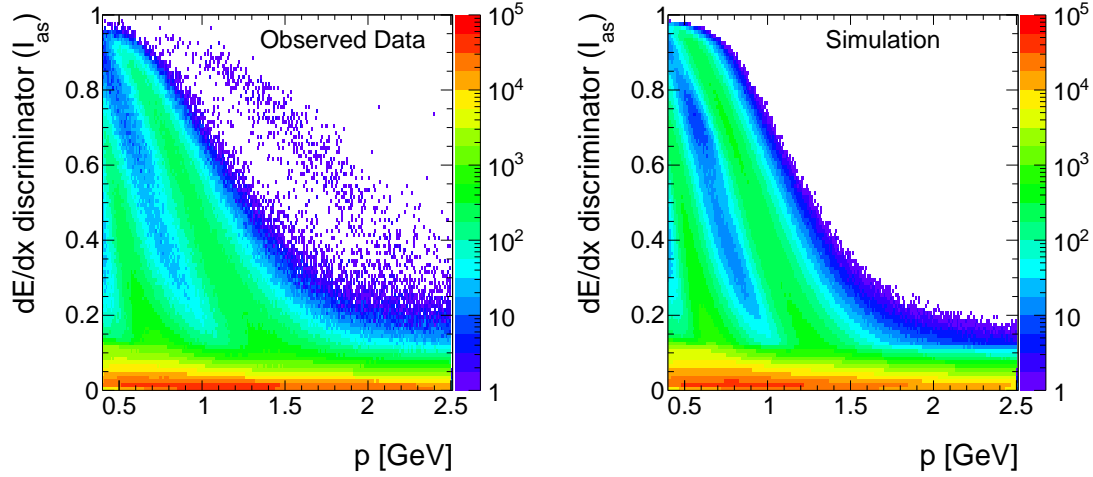


Figure 9.1:  $I_{\text{as}}$  versus momentum for good quality tracks with at least eight hits in observed data (left) and simulation (right). The kaon and proton line are visible in both datasets. The deuteron line is only visible in data, as deuteron's are not simulated.

different slices in the momentum are extracted where the proton line is contained:  $p$  between 0.80–0.85 and 0.95–1.00. A Gaussian function is fitted to the proton peak and the maximum difference of the mean of the fitted Gaussian between simulation and observed data is taken as systematic uncertainty. The  $I_{\text{as}}$  distribution for the two momentum ranges with the Gaussian fit is depicted in Fig. 9.2. The systematic uncertainty is estimated to a value of 6%.

### Uncertainty on the simulation of the track reconstruction efficiency

One final source of uncertainty is the simulation of the track reconstruction efficiency. Possible differences of the reconstruction efficiency in simulation and data can lead to a different signal acceptance. Differences in the track reconstruction efficiency are especially expected for short tracks. Therefore, a worst case estimation is done, comparing the track reconstruction efficiency in data and simulation for tracks with only three hits.

In simulation and observed data, well reconstructed muon tracks are selected and all hits after the third hit are removed. Afterwards the full track reconstruction is performed

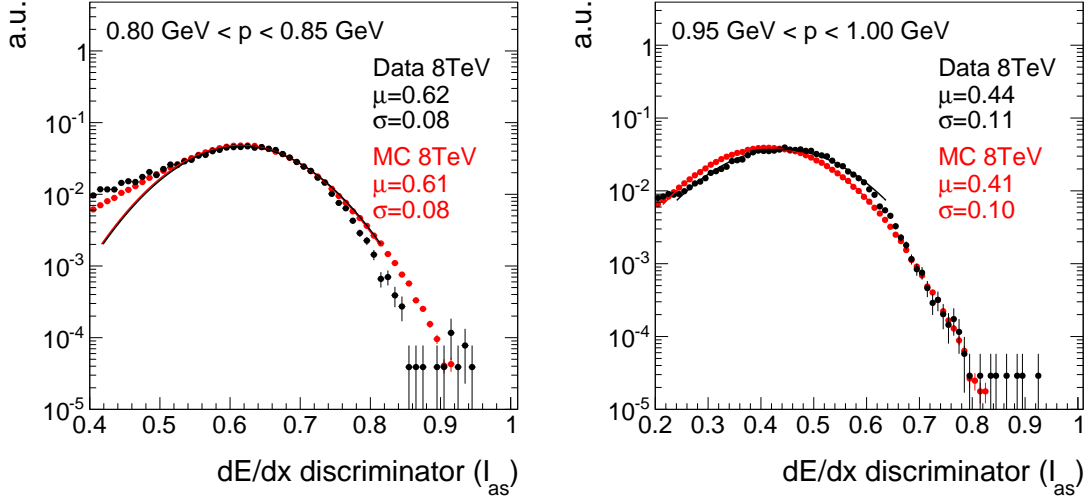


Figure 9.2:  $I_{\text{as}}$  distribution for slow protons in simulation and observed data for a momentum range of 0.80 – 0.85 GeV (left) and 0.95 – 1.00 GeV (left). For the momentum range of 0.80 – 0.85 GeV, the proton line is contained between  $I_{\text{as}}$  values of 0.4 – 0.8, whereas for the momentum range of 0.95 – 1.00 GeV, the proton line  $I_{\text{as}}$  lies between 0.2 – 0.6.

again. The relative difference of the track reconstruction efficiency in data and simulation ( $\epsilon = N_{\text{recon. trk matched to muon trk}}/N_{\text{selected muon trks}}$ ) is taken as systematic uncertainty. The track reconstruction efficiency is higher in simulation than in data and results in uncertainties between 4.6 – 6.0%.

### Summary of systematic uncertainties on the simulated signal samples

All systematic uncertainties are estimated for all simulated signal samples. An overview of the range of the uncertainties is given in Table 9.1.

In order to avoid an overestimation of the systematic uncertainties due to limited sizes of the samples (especially for low lifetimes like 1 cm), the corresponding signal sample with longer lifetime (100 cm) is used instead for determining the systematic uncertainty. This is possible for uncertainty sources, where the size is not affected by the lifetime of the chargino, including ISR, trigger efficiency, JES, JER, and PDF uncertainties.

It can be seen, that major uncertainties are the simulation of the initial state radiation, of the calorimeter isolation, and of  $I_{\text{as}}$ . The high maximum value of the pile-up uncertainty is caused by limited statistical precision.

The systematic uncertainties on the simulated signal samples are considered as fully correlated among the four signal regions.



Table 9.1: Ranges of systematic uncertainties on the simulated signal samples. Min and Max correspond to variations between different signal samples and search bins.

| Uncertainty                                   | Min [%] | Max [%] |
|---|---------|---------|
| Theoretical x-section                         | 4.5     | 12.1    |
| Luminosity                                    | 2.6     | 2.6     |
| Simulation of ISR                             | 9.2     | 12.6    |
| Simulation of trigger efficiency              | 1.9     | 4.4     |
| JES   | 0.4     | 3.1     |
| JER   | 0.1     | 2.0     |
| Simulation of PDF                             | 2.6     | 6.8     |
| Pile-up reweighting                           | 0.0     | 16.0    |
| Simulation of calorimeter isolation           | 3.0     | 12.1    |
| Simulation of missing middle hits             | 2.2     | 2.2     |
| Simulation of missing inner hits              | 3.3     | 3.7     |
| Simulation of $I_{\text{as}}$                 | 6.0     | 6.0     |
| Simulation of track reconstruction efficiency | 4.6     | 6.0     |

## 9.2 Statistical Methods/ Limit setting

This section is a small interlude to give a short introduction into the methods and techniques that are used to exclude theoretical models in this analysis. For a detailed and pedagogical introduction to the methods, the reader is referred to [54].

In this analysis, the exclusion of the underlying theoretical model is achieved with the  $\text{CL}_s$  method [55–57]. A model is considered as excluded at a 95% confidence level if  $\text{CL}_s$  is smaller than 5%. The  $\text{CL}_s$  method was developed for the Higgs searches at LEP in order not to overestimate the exclusion power of a result if an under-fluctuation of the background expectation occurs.  $\text{CL}_s$  is defined as the confidence level of the background plus signal hypothesis divided by the confidence level of the background only hypothesis

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b}.$$

The confidence level CL is defined as the probability of obtaining less than or equal the number of observed events  $P(n \leq n_{\text{obs}})$  for a given background (or background+signal) hypothesis. In general, the considered distribution can be any test statistics  $Q$  and is not necessarily the distribution of the number of events. However, For Poissonian statistics it leads to the following expressions for  $\text{CL}_{s+b}$  and  $\text{CL}_b$  for one signal region

$$\begin{aligned}\text{CL}_{s+b} &= \text{Poisson}(n \leq n_{\text{obs}} | \lambda = b + \mu \cdot s), \\ \text{CL}_b &= \text{Poisson}(n \leq n_{\text{obs}} | \lambda = b),\end{aligned}$$

where  $\lambda$  is the mean of the Poisson distribution and the signal strength  $\mu$  is the measure for the size of the signal cross section.

Systematic uncertainties are included by varying the background expectation  $b$  and the signal expectation  $\mu \cdot s$  according to a predefined probability density function (pdf). For one Gaussian distributed source of systematic uncertainty on the background, this leads to the following expressions for  $\text{CL}_{s+b}$  and  $\text{CL}_b$

$$\begin{aligned}\text{CL}_{s+b} &= \text{Poisson}(n \leq n_{\text{obs}} | \lambda = b \cdot (1 + \delta_b) + \mu \cdot s) \text{Gauss}(\delta_b | \text{mean} = 0, \sigma = \sigma_b), \\ \text{CL}_b &= \text{Poisson}(n \leq n_{\text{obs}} | \lambda = b \cdot (1 + \delta_b)) \text{Gauss}(\delta_b | \text{mean} = 0, \sigma = \sigma_b),\end{aligned}$$

These expressions can be generalised for more than one signal region and more than one systematic uncertainty [54]. In case of multiple signal regions, the distribution of the systematic uncertainties becomes a multi-dimensional probability density function that takes the covariance matrix of the systematic uncertainties in different signal regions into account. In order to get rid of the nuisance parameters  $\delta_s$  and  $\delta_b$ , the expression for  $\text{CL}_s$  is integrated over all possible values of  $\delta_{s/b}$ . This integration is generally not solvable analytically, but is calculated with pseudo data drawn from the pdf and inserted into the Poisson distribution.

In this search, the systematic uncertainties on the background and the signal yields as well as the statistical uncertainty on the fake background are modelled with log-normal distributions, whereas the statistical uncertainties on the leptonic background are modelled using gamma distributions. A log-normal distribution is used instead of a normal distribution to ensure that the prediction cannot become negative. The gamma distribution is well suited for statistical uncertainties arising from very limited statistical precision in control regions or in simulated samples that are used for the background estimation [58].

Correlations between systematic uncertainties on the background expectation in different search bins are assumed as shown in Table 9.2. The systematic uncertainties on the expected signal yields are considered fully correlated across search bins.

The exclusion limits are derived according to the above presented methodology using the *Combine* framework [58] which was developed for the Higgs searches at CMS.

Table 9.2: Correlation of systematic and statistical uncertainties between the four different signal regions.

|                                   | Fakes                                 | Taus                                  | Electrons                             | Muons                                 |
|-----------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| Statistical uncertainty           | 0% correlated                         | 100% for same bins in $I_{\text{as}}$ | 0% correlated                         | 100% for same bins in $I_{\text{as}}$ |
| Leptonic scale factor uncertainty | -                                     | 100% for same bins in $I_{\text{as}}$ | 100% for same bins in $I_{\text{as}}$ | 100% for same bins in $I_{\text{as}}$ |
| Fake rate uncertainty             | 100% for same bins in $I_{\text{as}}$ | -                                     | -                                     | -                                     |
| $I_{\text{as}}$ uncertainty       | 0% correlated                         | 100% for same bins in $p_{\text{T}}$  | 100% for same bins in $p_{\text{T}}$  | 100% for same bins in $p_{\text{T}}$  |

### 9.3 Exclusion limits

The presented search for highly ionising, short tracks is interpreted in the context of SUSY models with almost mass degenerate wino-like charginos and neutralinos. As explained in the previous section, the exclusion is done with the help of the  $\text{CL}_s$  method. Two direct production channels are taken into account: chargino pair production and chargino neutralino production. The corresponding cross sections can be found in Table 4.3.

In total, 37 different lifetimes from  $c\tau = 1 - 10000$  cm for each mass point (100–600 GeV) are considered, leading to 37 different exclusion limits. Four exemplary exclusion limits are shown in Fig. 9.3, the full set of exclusion limits can be found in Appendix A.9.

The upper 95% confidence level (CL) limit on the signal cross section is strongest for lifetimes between 10–100 cm. For lower lifetimes a sizable fraction of the charginos already decay before reaching the tracker. For longer lifetimes, the cross section upper limit gets weaker again because the charginos start to be reconstructed as muons and do not pass the muon veto. Also, the  $E_{\text{calo}}^{\Delta R < 0.5}$  requirement rejects these charginos with higher efficiency.

Due to the falling spectrum of the chargino production cross section, charginos with lower masses are more effectively excluded than charginos with a higher mass. A 2-dimensional exclusion limit in the chargino lifetime-mass parameter space is shown in Fig. 9.4.

Charginos with masses of 100 GeV can be excluded down to a lifetime of  $c\tau = 2$  cm.

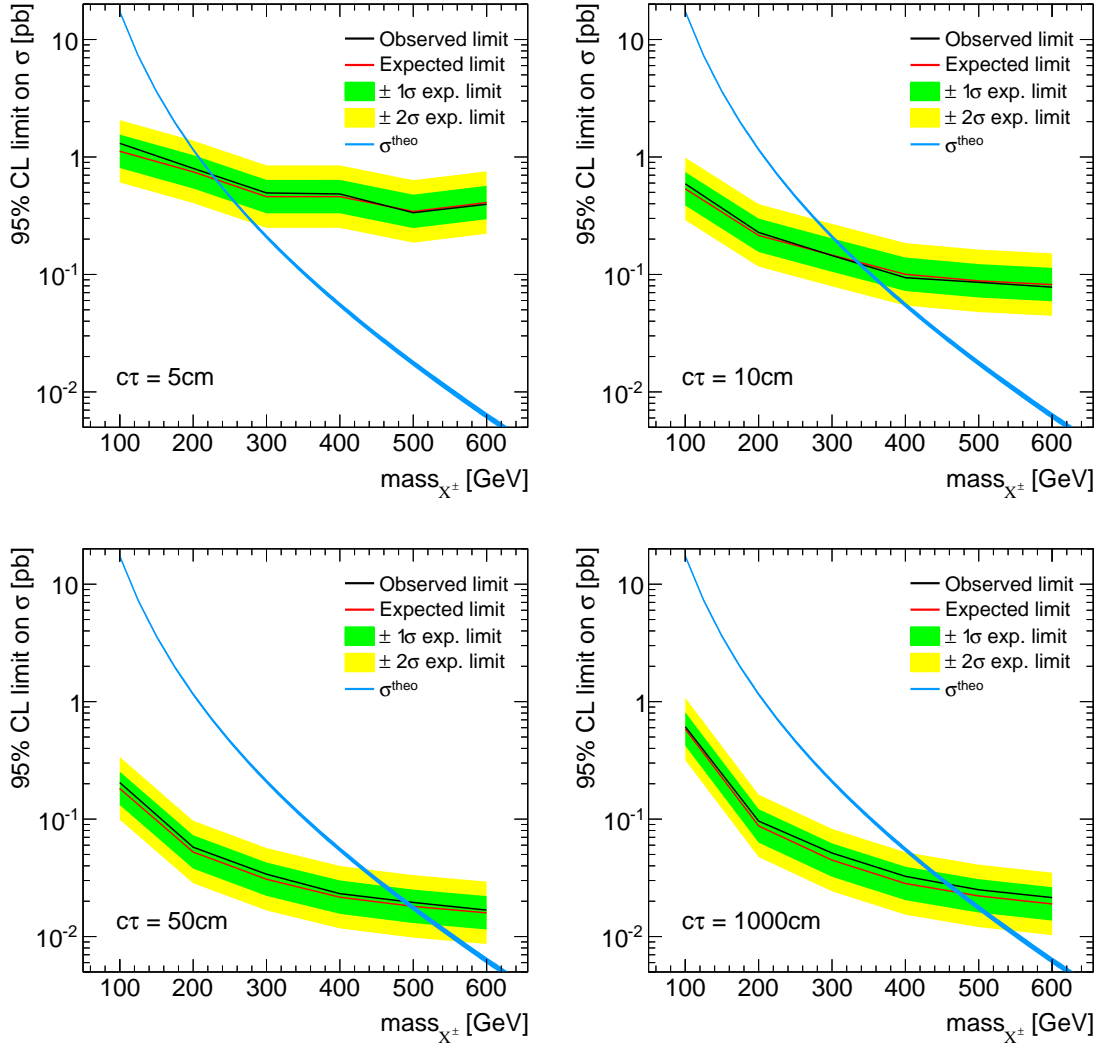


Figure 9.3: Four different  $CL_s$  exclusion limits for charginos with mean lifetimes of 5 cm (top left), 10 cm (top right), 50 cm (bottom left), 1000 cm (bottom right). The red line depicts the expected 95% confidence level (CL) upper cross-section limit with the  $1\text{-}\sigma$  (green band) and  $2\text{-}\sigma$  (yellow band) intervals. The black line is the observed limit. The signal cross section is depicted as a blue line. SUSY models can be excluded at 95% CL if the signal cross section is at least as large as the 95% CL observed upper limit on the cross section.

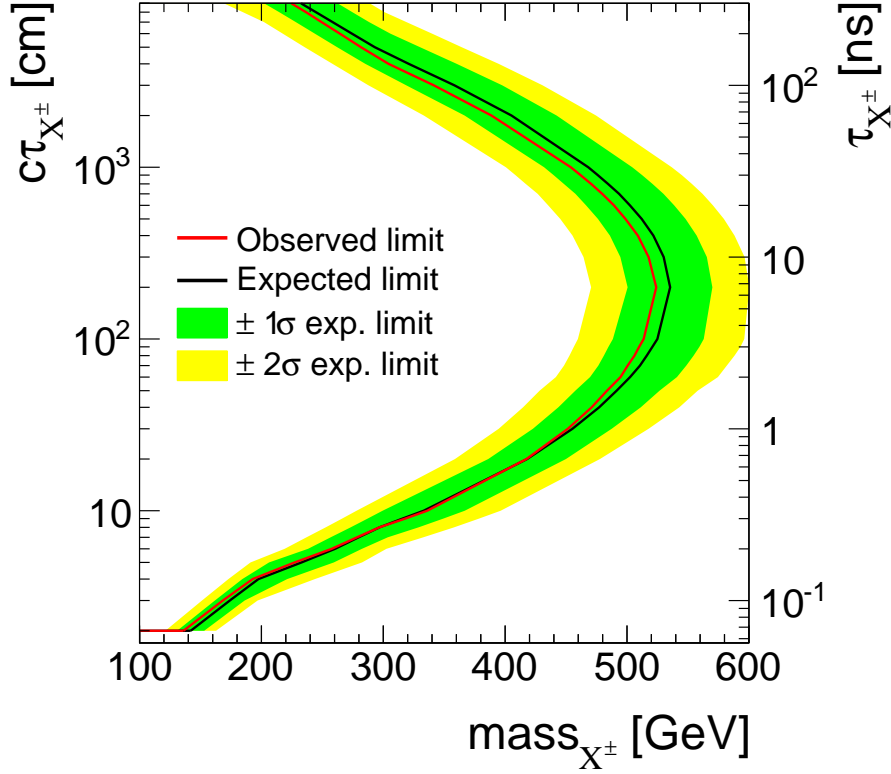


Figure 9.4: Excluded regions in the mass versus lifetime space. All excluded models are located left of the contour line. The red line depicts the expected 95% CL upper cross-section limit with the 1- $\sigma$  (green band) and 2- $\sigma$  (yellow band) intervals. The black line is the observed limit.

Charginos with a higher mass of 500 GeV are excluded for lifetimes between  $c\tau = 70 - 500$  cm.

Since the lifetime of a wino-like chargino is determined by the mass splitting between  $m_{\tilde{\chi}_1^\pm}$  and  $m_{\tilde{\chi}_1^0}$ , it is possible to express the lifetime of the chargino as a mass gap  $\Delta m_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0}$  between the chargino and the lightest neutralino. The correspondence between lifetime and mass gap is taken from [59], where the decay width of  $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$  is expressed in terms of chargino, neutralino, and pion mass. Thus, the mass gaps that are considered are bounded by the pion mass of  $\sim 140$  MeV. The corresponding 2d exclusion limit can be found in Fig. 9.5. It can be seen that this search is sensitive to mass splittings between  $\sim 140$  MeV – 210 MeV.

The presented exclusion limits confirm the exclusion from the search for disappearing tracks [8] with slight improvements in the low lifetime region. The comparison of the two

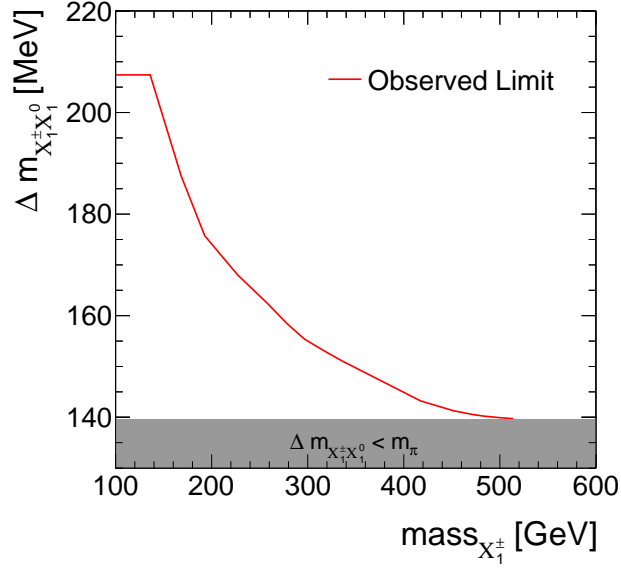


Figure 9.5: Excluded parameter region at 95% CL for wino-like charginos and neutralinos depending on the chargino mass and the mass splitting between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ ,  $\Delta m_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0}$ . All SUSY models between the red line and the grey area are excluded.

searches is shown in Fig 9.6.

For charginos with a lifetime of  $\tau = 0.07$  ns, the observed limit of this search improves the limits derived in [8] by  $\sim 35$  GeV in chargino mass, for a lifetime of  $\tau = 0.4$  ns by  $\sim 25$  GeV. For SUSY models with long chargino lifetimes the here presented search shows a higher exclusion power. The weaker exclusion for long lifetimes in [8] is caused by the additional selection cut on the number of missing outer hits,  $N_{\text{lost}}^{\text{outer}} \geq 3$ .

The confirmation of the excluded parameter space in [8] is especially interesting since the signal regions of the two searches are little correlated. The correlation between simulated signal events, that pass the selection from [8],  $N_A$ , and the selection used in this analysis,  $N_B$ , can be estimated by the event overlap  $\rho_{\text{corr}}$

$$\rho_{\text{corr}} = \frac{N_{A \cap B}}{N_{A \cup B}} = \frac{N_{A \cap B}}{N_A + N_B - N_{A \cap B}}.$$

In order to avoid an over- or underestimation of the event overlap, only the most sensitive signal region from this search is included in  $N_B$ . The degree of correlation is depicted in Fig. 9.7 which shows the event overlap for signal models with chargino masses between 100 – 600 GeV and lifetimes between 5 cm – 1000 cm. It can be seen that the event overlap for intermediate lifetimes of around 100 cm is around 60% and decreases for shorter lifetimes to small overlaps of around 15 – 20%. Thus, this analysis is able to confirm the

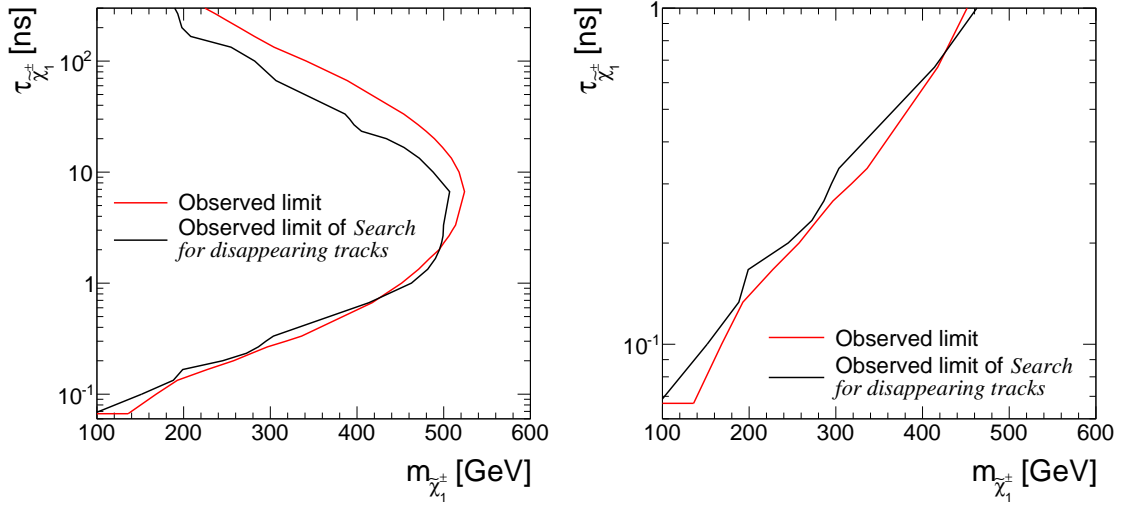


Figure 9.6: Comparison of the excluded regions in the mass versus lifetime space in this analysis (red line) and the search for disappearing tracks [8] (black line). The right figure is a zoom on the low lifetime region. All SUSY models left of the lines are excluded.

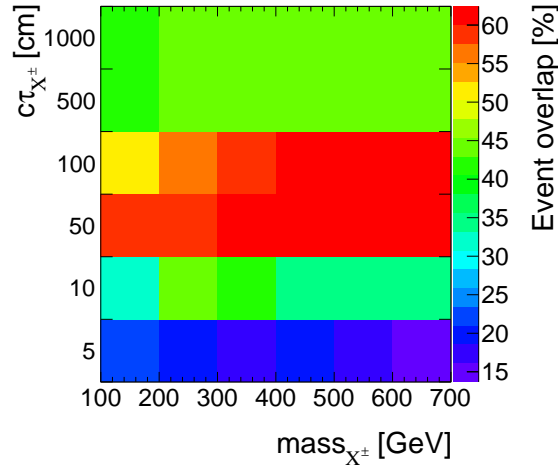


Figure 9.7: The event overlap between simulated signal events, that pass the selection from [8] and the selection used in this analysis for different signal models. The correlation is determined using only the signal region with the highest sensitivity of this analysis.

exclusion limits derived in [8] with an almost independent set of simulated signal events for low lifetimes. FIXME! observed data.

## 10 Discussion and conclusion

The here presented search for highly ionising, short tracks is motivated by supersymmetric models with almost mass-degenerate wino-like charginos  $\tilde{\chi}_1^\pm$  and neutralinos  $\tilde{\chi}_1^0$ . Such scenarios are well motivated by astrophysical observations that suggest the existence of large amounts of dark matter. It is possible to explain the relic density with wino-like neutralinos if they are non-thermally produced via the decay of long-lived particles, such as a wino-like chargino [7].

The presented analysis was designed to increase the search sensitivity on SUSY models with low chargino lifetimes. It extends the search for disappearing tracks [8] by the inclusion of the variable  $dE/dx$ . In order to increase the search sensitivity with respect to short lifetimes, energy information from the pixel silicon tracker is taken into account. For this purpose, a dedicated pixel energy calibration was carried out within this thesis to ensure stable energy measurements over time and across pixel modules. It is thus the first analysis at CMS that makes use of energy information from the pixel tracker. By this inclusion the discrimination power of  $dE/dx$  was increased significantly. Furthermore,  $dE/dx$  inclusion enabled to loosen the requirement on the number of hits in the tracker with respect to [8] that led to a strong suppression of signal events for low chargino lifetimes. The used  $dE/dx$  discriminator, the Asymmetric Smirnov discriminator  $I_{\text{as}}$ , shows good separation power and can lead to sensitivity increases up to 400% (cf. Fig. 7.1).

The Standard Model background is mainly estimated with data-based techniques. The main background to this search is arising from fake tracks, i. e. tracks that are reconstructed out of several particles' trajectories. Fake tracks are typically short and can have large values of  $I_{\text{as}}$ , thus showing a very signal-like signature in the detector. The uncertainty on the fake background is dominated by systematic uncertainties originating from low statistical precision in the simulated datasets. Simulating more events could therefore significantly improve the search sensitivity. This strategy is however technically challenging, since storage capacity limits were already reached within this analysis. Still, reducing the uncertainty will be one of the main tasks in order to increase the search sensitivity.

Even though this search already features low background, a further background suppression is desirable. However, the impact on the search sensitivity will be limited because



of the high relative Poisson error on low background predictions. For instance, a reduction of the number of background events by 75% from 4 to 1 event reduces the signal yield required for a  $5\sigma$ -discovery by around 30%, whereas a 75% reduction of expected background events from 400 to 100 reduces the required signal yield by 70%.

In the current analysis, the background was estimated between 19 – 24 events for the low  $I_{\text{as}}$  signal regions and 2.5 – 2.6 for the high  $I_{\text{as}}$  regions. This background estimate was confronted with collision data recorded during the year 2012 at the CMS experiment at a centre-of-mass energy of 8 TeV. No evidence for physics beyond the Standard Model was found since the observations are compatible with SM expectations within  $1\sigma$ . Thus, the absence of any deviation from the Standard Model prediction is used to constrain the supersymmetric parameter space. Wino-like charginos were excluded down to lifetimes of  $c\tau = 2$  cm for  $m_{\tilde{\chi}_1^\pm} = 100$  GeV. For high mass scenarios of  $m_{\tilde{\chi}_1^\pm} = 500$  GeV, the excluded lifetime ranges between  $c\tau = 70 - 500$  cm. This confirms the parameter exclusion limits of the search for disappearing tracks [8]. Interestingly, the signal regions of the here presented search and the search from [8] show little overlap. Therefore, this analysis serves as an independent cross check of [8]. Improvements of the exclusion of SUSY models with respect to existing searches of around 10 – 40 GeV in chargino mass were achieved in the low lifetime region.

Still, SUSY models with higher mass and low lifetimes could not be fully excluded by any search at the LHC. Therefore, it will stay interesting to further search for these phenomenological interesting scenarios. Combining a search for short tracks that are highly ionising is hereby a promising approach. As said before, further improvements can be achieved by the reduction of the large systematic uncertainties and a further suppression of the dominating fake background.

A similar study with 13 TeV collision data could be additionally very interesting as the signal production cross section would increase by around a factor of two for chargino masses of 500 GeV. As  $I_{\text{as}}$  is much more discriminating for high masses, a sensitivity increase by the inclusion of  $I_{\text{as}}$  is more pronounced for a high mass scenario. Thus, the increase of the search sensitivity by including  $I_{\text{as}}$  will become even stronger for  $\sqrt{s} = 13$  TeV.



## A A search for highly ionising, short tracks

### A.1 Lifetime reweighting

The probability density function of a particle's proper lifetime for a sample generated with a particle's mean lifetime  $\tau^{\text{gen}}$  is given by

$$p(t) = \frac{1}{\tau^{\text{gen}}} \cdot \exp\left[-\frac{t}{\tau^{\text{gen}}}\right].$$

After carrying out the lifetime reweighting procedure, the targeted p.d.f of the particle's new mean lifetime  $\tau^{\text{target}}$  is given by

$$p'(t) = \frac{1}{\tau^{\text{target}}} \cdot \exp\left[-\frac{t}{\tau^{\text{target}}}\right].$$

Thus, an event containing a particle with individual proper lifetime can be reweighted with the following weight

$$w = \frac{p'(t)}{p(t)} = \frac{\tau^{\text{gen}}}{\tau^{\text{target}}} \cdot \exp\left[\frac{t}{\tau^{\text{gen}}} - \frac{t}{\tau^{\text{target}}}\right].$$

For more than one non-stable particle, the event weight is calculated by multiplying the weights of the single reweighting procedures.

## A.2 Event yields for simulated samples and data

Table A.1: Event yields after each selection step for various background processes.

| Selection   | $W + \text{jets}$ | $t\bar{t} + \text{jets}$ | $Z \rightarrow \ell\bar{\ell}$ | Multijet             |
|---|-------------------|--------------------------|--------------------------------|----------------------|
| after skim  | $9.16 \cdot 10^7$ | $1.04 \cdot 10^6$        | $2.21 \cdot 10^7$              | $1.38 \cdot 10^{11}$ |
| trigger   | $4.31 \cdot 10^6$ | $1.15 \cdot 10^5$        | $4.23 \cdot 10^3$              | $4.32 \cdot 10^6$    |
| $p_{\text{T}}^{1,\text{jet}} > 100 \text{ GeV}$                       | $2.47 \cdot 10^6$ | $7.17 \cdot 10^4$        | $2.60 \cdot 10^3$              | $2.75 \cdot 10^6$    |
| $\cancel{E}_{\text{T}} > 100 \text{ GeV}$                             | $1.89 \cdot 10^6$ | $5.31 \cdot 10^4$        | $6.26 \cdot 10^2$              | $9.63 \cdot 10^5$    |
| $\Delta\phi_{\text{max}}(\text{jet}_i, \text{jet}_j) < 2.7$           | $1.11 \cdot 10^6$ | $6.81 \cdot 10^3$        | $1.32 \cdot 10^2$              | $2.01 \cdot 10^4$    |
| $\Delta\phi_{\text{max}}(\text{jet}_i, \cancel{E}_{\text{T}}) > 0.5$  | $1.11 \cdot 10^6$ | $6.76 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| $\geq 1$ track in the event with:                                     |                   |                          |                                |                      |
| reconstructed trk   | $1.10 \cdot 10^6$ | $6.75 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| high-purity   | $1.10 \cdot 10^6$ | $6.74 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| $N_{\text{miss}}^{\text{middle}} = 0$                                 | $1.09 \cdot 10^6$ | $6.72 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| $N_{\text{miss}}^{\text{inner}} = 0$                                  | $1.07 \cdot 10^6$ | $6.70 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| $ d0  < 0.02 \text{ cm}$  | $1.07 \cdot 10^6$ | $6.64 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| $ dz  < 0.5 \text{ cm}$   | $1.07 \cdot 10^6$ | $6.63 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| $ \eta  < 2.1$  | $1.03 \cdot 10^6$ | $6.58 \cdot 10^3$        | $1.32 \cdot 10^2$              | $9.55 \cdot 10^3$    |
| $p_{\text{T}} > 20 \text{ GeV}$                                       | $8.14 \cdot 10^5$ | $5.63 \cdot 10^3$        | $1.32 \cdot 10^2$              | $5.48 \cdot 10^3$    |
| No $\mu$ within $\Delta R < 0.15$                                     | $7.15 \cdot 10^5$ | $4.52 \cdot 10^3$        | $1.32 \cdot 10^2$              | $5.48 \cdot 10^3$    |
| No e within $\Delta R < 0.15$   | $6.69 \cdot 10^5$ | $3.67 \cdot 10^3$        | $7.86 \cdot 10^1$              | $5.48 \cdot 10^3$    |
| No $\tau$ within $\Delta R < 0.15$                                    | $6.62 \cdot 10^5$ | $3.61 \cdot 10^3$        | $7.86 \cdot 10^1$              | $5.47 \cdot 10^3$    |
| No jet within $\Delta R < 0.5$  | $1.18 \cdot 10^3$ | $1.44 \cdot 10^1$        | $1.09 \cdot 10^1$              | $0.00 \cdot 10^0$    |
| Not within $\Delta R < 0.05$ of<br>a dead/noisy ECAL cell             | $7.25 \cdot 10^2$ | $8.02 \cdot 10^0$        | $0.00 \cdot 10^0$              | $0.00 \cdot 10^0$    |
| Not within an ECAL intermodule gap                                    | $7.15 \cdot 10^2$ | $8.02 \cdot 10^0$        | $0.00 \cdot 10^0$              | $0.00 \cdot 10^0$    |
| Not within $1.42 <  \eta  < 1.65$                                     | $5.89 \cdot 10^2$ | $6.53 \cdot 10^0$        | $0.00 \cdot 10^0$              | $0.00 \cdot 10^0$    |
| Not within $\Delta R < 0.25$ to a bad CSC                             | $5.02 \cdot 10^2$ | $5.88 \cdot 10^0$        | $0.00 \cdot 10^0$              | $0.00 \cdot 10^0$    |
| $\sum_{\Delta R < 0.3} p_{\text{T}}/p_{\text{T}}^{\text{cand}} < 0.1$ | $4.46 \cdot 10^2$ | $4.78 \cdot 10^0$        | $0.00 \cdot 10^0$              | $0.00 \cdot 10^0$    |
| $E_{\text{calo}}^{\Delta R < 0.5} < 5 \text{ GeV}$                    | $3.19 \cdot 10^1$ | $0.67 \cdot 10^0$        | $0.00 \cdot 10^0$              | $0.00 \cdot 10^0$    |

Table A.2: Event yields after each selection step for various signal models.

| Selection   | m=100 GeV<br>$c\tau=10$ cm | m=100 GeV<br>$c\tau=100$ cm | m=500 GeV<br>$c\tau=10$ cm | m=500 GeV<br>$c\tau=100$ cm |
|---|----------------------------|-----------------------------|----------------------------|-----------------------------|
| total   | $3.41 \cdot 10^5$          | $3.41 \cdot 10^5$           | $3.46 \cdot 10^2$          | $3.46 \cdot 10^2$           |
| trigger   | $1.55 \cdot 10^4$          | $1.49 \cdot 10^4$           | $4.62 \cdot 10^1$          | $4.62 \cdot 10^1$           |
| $p_T^{1.\text{jet}} > 100$ GeV                            | $1.10 \cdot 10^4$          | $1.04 \cdot 10^4$           | $3.64 \cdot 10^1$          | $3.58 \cdot 10^1$           |
| $\cancel{E}_T > 100$ GeV                                  | $1.09 \cdot 10^4$          | $9.83 \cdot 10^3$           | $3.63 \cdot 10^1$          | $3.57 \cdot 10^1$           |
| $\Delta\phi_{\max}(\text{jet}_i, \text{jet}_j) < 2.7$     | $7.90 \cdot 10^3$          | $7.04 \cdot 10^3$           | $2.76 \cdot 10^1$          | $2.72 \cdot 10^1$           |
| $\Delta\phi_{\max}(\text{jet}_i, \cancel{E}_T) > 0.5$     | $7.90 \cdot 10^3$          | $6.98 \cdot 10^3$           | $2.76 \cdot 10^1$          | $2.71 \cdot 10^1$           |
| $\geq 1$ track in the event with:                         |                            |                             |                            |                             |
| reconstructed trk   | $3.13 \cdot 10^3$          | $5.74 \cdot 10^3$           | $5.74 \cdot 10^0$          | $2.13 \cdot 10^1$           |
| high-purity   | $2.91 \cdot 10^3$          | $5.65 \cdot 10^3$           | $5.25 \cdot 10^0$          | $2.08 \cdot 10^1$           |
| $N_{\text{miss}}^{\text{middle}} = 0$                     | $2.87 \cdot 10^3$          | $5.46 \cdot 10^3$           | $5.23 \cdot 10^0$          | $2.02 \cdot 10^1$           |
| $N_{\text{miss}}^{\text{inner}} = 0$                      | $2.86 \cdot 10^3$          | $5.40 \cdot 10^3$           | $5.22 \cdot 10^0$          | $2.01 \cdot 10^1$           |
| $ d0  < 0.02$ cm  | $2.81 \cdot 10^3$          | $5.39 \cdot 10^3$           | $5.07 \cdot 10^0$          | $2.00 \cdot 10^1$           |
| $ dz  < 0.5$ cm   | $2.80 \cdot 10^3$          | $5.38 \cdot 10^3$           | $5.07 \cdot 10^0$          | $2.00 \cdot 10^1$           |
| $ \eta  < 2.1$  | $2.63 \cdot 10^3$          | $4.97 \cdot 10^3$           | $5.01 \cdot 10^0$          | $1.91 \cdot 10^1$           |
| $p_T > 20$ GeV  | $2.54 \cdot 10^3$          | $4.93 \cdot 10^3$           | $4.73 \cdot 10^0$          | $1.89 \cdot 10^1$           |
| No $\mu$ within $\Delta R < 0.15$                         | $2.54 \cdot 10^3$          | $4.65 \cdot 10^3$           | $4.72 \cdot 10^0$          | $1.87 \cdot 10^1$           |
| No e within $\Delta R < 0.15$                             | $2.54 \cdot 10^3$          | $4.65 \cdot 10^3$           | $4.72 \cdot 10^0$          | $1.87 \cdot 10^1$           |
| No $\tau$ within $\Delta R < 0.15$                        | $2.54 \cdot 10^3$          | $4.64 \cdot 10^3$           | $4.72 \cdot 10^0$          | $1.87 \cdot 10^1$           |
| No jet within $\Delta R < 0.5$                            | $2.53 \cdot 10^3$          | $4.59 \cdot 10^3$           | $4.63 \cdot 10^0$          | $1.82 \cdot 10^1$           |
| Not within $\Delta R < 0.05$ of<br>a dead/noisy ECAL cell | $2.32 \cdot 10^3$          | $4.25 \cdot 10^3$           | $4.19 \cdot 10^0$          | $1.69 \cdot 10^1$           |
| Not within an ECAL intermodule gap                        | $2.31 \cdot 10^3$          | $4.23 \cdot 10^3$           | $4.17 \cdot 10^0$          | $1.68 \cdot 10^1$           |
| Not within $1.42 <  \eta  < 1.65$                         | $2.09 \cdot 10^3$          | $3.88 \cdot 10^3$           | $3.95 \cdot 10^0$          | $1.56 \cdot 10^1$           |
| Not within $\Delta R < 0.25$ to a bad CSC                 | $1.99 \cdot 10^3$          | $3.67 \cdot 10^3$           | $3.83 \cdot 10^0$          | $1.50 \cdot 10^1$           |
| $\sum_{\Delta R < 0.3} p_T/p_T^{\text{cand}} < 0.1$       | $1.97 \cdot 10^3$          | $3.64 \cdot 10^3$           | $3.78 \cdot 10^0$          | $1.49 \cdot 10^1$           |
| $E_{\text{calo}}^{\Delta R < 0.5} < 5$ GeV                | $1.67 \cdot 10^3$          | $3.04 \cdot 10^3$           | $3.39 \cdot 10^0$          | $1.26 \cdot 10^1$           |

Table A.3: Observed event yield after each selection step in data.

| Selection   | MET dataset       |
|---|-------------------|
| after skim  | $1.07 \cdot 10^7$ |
| trigger   | $1.07 \cdot 10^7$ |
| $p_{\text{T}}^{1.\text{jet}} > 100 \text{ GeV}$                       | $6.82 \cdot 10^6$ |
| $\cancel{E}_{\text{T}} > 100 \text{ GeV}$                             | $3.94 \cdot 10^6$ |
| $\Delta\phi_{\text{max}}(\text{jet}_i, \text{jet}_j) < 2.7$           | $1.39 \cdot 10^6$ |
| $\Delta\phi_{\text{max}}(\text{jet}_i, \cancel{E}_{\text{T}}) > 0.5$  | $1.38 \cdot 10^6$ |
| $\geq 1$ track in the event with:                                     |                   |
| reconstructed trk   | $1.37 \cdot 10^6$ |
| high-purity   | $1.36 \cdot 10^6$ |
| $N_{\text{miss}}^{\text{middle}} = 0$                                 | $1.34 \cdot 10^6$ |
| $N_{\text{miss}}^{\text{inner}} = 0$                                  | $1.31 \cdot 10^6$ |
| $ d0  < 0.02 \text{ cm}$  | $1.30 \cdot 10^6$ |
| $ dz  < 0.5 \text{ cm}$   | $1.30 \cdot 10^6$ |
| $ \eta  < 2.1$  | $1.26 \cdot 10^6$ |
| $p_{\text{T}} > 20 \text{ GeV}$                                       | $9.51 \cdot 10^5$ |
| No $\mu$ within $\Delta R < 0.15$                                     | $8.40 \cdot 10^5$ |
| No e within $\Delta R < 0.15$   | $8.01 \cdot 10^5$ |
| No $\tau$ within $\Delta R < 0.15$                                    | $7.95 \cdot 10^5$ |
| No jet within $\Delta R < 0.5$  | $1.75 \cdot 10^3$ |
| Not within $\Delta R < 0.05$ of<br>a dead/noisy ECAL cell             | $9.11 \cdot 10^2$ |
| Not within an ECAL intermodule gap                                    | $9.06 \cdot 10^2$ |
| Not within $1.42 <  \eta  < 1.65$                                     | $7.33 \cdot 10^2$ |
| Not within $\Delta R < 0.25$ to a bad CSC                             | $6.16 \cdot 10^2$ |
| $\sum_{\Delta R < 0.3} p_{\text{T}}/p_{\text{T}}^{\text{cand}} < 0.1$ | $5.26 \cdot 10^2$ |
| $E_{\text{calo}}^{\Delta R < 0.5} < 5 \text{ GeV}$                    | $1.19 \cdot 10^2$ |
| $p_{\text{T}} > 30 \text{ GeV}$                                       | $9.10 \cdot 10^1$ |
| $I_{\text{as}} > 0.05$  | $5.60 \cdot 10^1$ |

### A.3 Signal contamination in validation regions

Signal contamination in the four validation regions from Section 6.3. The highest signal contamination is visible for a lifetime of 100 cm for all signal masses. For higher lifetimes the signal contamination is again reduced due to the muon veto selection requirement. The most extreme values (from  $c\tau = 100$  cm) of expected signal events and some other selected signal models are shown in the following tables. The signal contamination is rapidly falling towards lower lifetimes and higher masses.

Table A.4: Signal contamination in leptonic control region:  $E_{\text{calo}}^{\Delta R < 0.5} > 10$  GeV and  $N_{\text{hits}} > 6$ .  $N_S$  is the number of expected signal events and  $\Delta B$  is the statistical uncertainty on the background prediction.

| Signal model                   | $N_S$  | $N_S/\Delta B$ | Excluded by [8] |
|--------------------------------|--------|----------------|-----------------|
| mass=100 GeV, $c\tau = 100$ cm | 211.93 | 8.06           | yes             |
| mass=100 GeV, $c\tau = 10$ cm  | 27.83  | 1.06           | yes             |
| mass=100 GeV, $c\tau = 5$ cm   | 7.39   | 0.28           | yes             |
| mass=100 GeV, $c\tau = 1$ cm   | 0      | 0              | no              |
| mass=300 GeV, $c\tau = 100$ cm | 6.97   | 0.26           | yes             |
| mass=300 GeV, $c\tau = 10$ cm  | 0.33   | 0.01           | yes             |
| mass=300 GeV, $c\tau = 5$ cm   | 0.0    | 0.0            | no              |
| mass=500 GeV, $c\tau = 100$ cm | 0.72   | 0.03           | yes             |
| mass=500 GeV, $c\tau = 10$ cm  | 0.00   | 0.00           | no              |

Table A.5: Signal contamination in leptonic control region:  $E_{\text{calo}}^{\Delta R < 0.5} > 10 \text{ GeV}$ ,  $N_{\text{hits}} > 6$  and  $I_{\text{as}} > 0.2$ .  $N_S$  is the number of expected signal events and  $\Delta B$  is the statistical uncertainty on the background prediction.

| Signal model                           | $N_S$ | $N_S/\Delta B$ | Excluded by [8] |
|--|-------|----------------|-----------------|
| mass=100 GeV, $c\tau = 100 \text{ cm}$ | 24.11 | 48.21          | yes             |
| mass=100 GeV, $c\tau = 10 \text{ cm}$  | 0.00  | 0.00           | yes             |
| mass=300 GeV, $c\tau = 100 \text{ cm}$ | 2.03  | 4.06           | yes             |
| mass=300 GeV, $c\tau = 10 \text{ cm}$  | 0.03  | 0.07           | yes             |
| mass=300 GeV, $c\tau = 5 \text{ cm}$   | 0.0   | 0.0            | no              |
| mass=500 GeV, $c\tau = 100 \text{ cm}$ | 0.38  | 0.75           | yes             |
| mass=500 GeV, $c\tau = 10 \text{ cm}$  | 0.00  | 0.00           | no              |

Table A.6: Signal contamination in fake+lepton control region:  $E_{\text{calo}}^{\Delta R < 0.5} > 10 \text{ GeV}$ .  $N_S$  is the number of expected signal events and  $\Delta B$  is the statistical uncertainty on the background prediction.

| Signal model                           | $N_S$  | $N_S/\Delta B$ | Excluded by [8] |
|--|--------|----------------|-----------------|
| mass=100 GeV, $c\tau = 100 \text{ cm}$ | 257.33 | 7.69           | yes             |
| mass=100 GeV, $c\tau = 10 \text{ cm}$  | 116.21 | 3.47           | yes             |
| mass=100 GeV, $c\tau = 5 \text{ cm}$   | 48.07  | 1.44           | yes             |
| mass=100 GeV, $c\tau = 1 \text{ cm}$   | 1.26   | 0.04           | no              |
| mass=300 GeV, $c\tau = 100 \text{ cm}$ | 9.35   | 0.28           | yes             |
| mass=300 GeV, $c\tau = 10 \text{ cm}$  | 2.20   | 0.07           | yes             |
| mass=300 GeV, $c\tau = 5 \text{ cm}$   | 0.85   | 0.03           | no              |
| mass=500 GeV, $c\tau = 100 \text{ cm}$ | 1.10   | 0.03           | yes             |
| mass=500 GeV, $c\tau = 10 \text{ cm}$  | 0.15   | 0.00           | no              |



Table A.7: Signal contamination in fake+lepton control region:  $E_{\text{calo}}^{\Delta R < 0.5} > 10 \text{ GeV}$ , and  $I_{\text{as}} > 0.2$ .  $N_S$  is the number of expected signal events and  $\Delta B$  is the statistical uncertainty on the background prediction.

| Signal model                           | $N_S$ | $N_S/\Delta B$ | Excluded by [8] |
|--|-------|----------------|-----------------|
| mass=100 GeV, $c\tau = 100 \text{ cm}$ | 36.40 | 12.47          | yes             |
| mass=100 GeV, $c\tau = 10 \text{ cm}$  | 5.22  | 1.79           | yes             |
| mass=100 GeV, $c\tau = 5 \text{ cm}$   | 1.76  | 0.60           | yes             |
| mass=300 GeV, $c\tau = 100 \text{ cm}$ | 3.20  | 1.10           | yes             |
| mass=300 GeV, $c\tau = 10 \text{ cm}$  | 0.58  | 0.20           | yes             |
| mass=300 GeV, $c\tau = 5 \text{ cm}$   | 0.12  | 0.04           | no              |
| mass=500 GeV, $c\tau = 100 \text{ cm}$ | 0.63  | 0.22           | yes             |
| mass=500 GeV, $c\tau = 10 \text{ cm}$  | 0.07  | 0.02           | no              |

## A.4 Validation tests of the background estimation methods

Table A.8: Validation tests of the background estimation methods in the calorimeter isolation control region  $E_{\text{calo}}^{\Delta R < 0.5} > 10 \text{ GeV}$  for two different  $p_T$  selection requirements:  $p_T > 40 \text{ GeV}$  (left) and  $p_T > 60 \text{ GeV}$  (right). Only statistical uncertainties are included.

|           | Predicted Yield           | Data Yield |           | Predicted Yield          | Data Yield |
|-----------|---------------------------|------------|-----------|--------------------------|------------|
| Total bkg | $84.36^{+16.47}_{-10.88}$ | 94         | Total bkg | $35.56^{+11.95}_{-6.20}$ | 53         |
| Electrons | $15.69^{+11.92}_{-6.72}$  |            | Electrons | $0.00^{+9.14}_{-0.00}$   |            |
| Muons     | $5.67^{+7.74}_{-3.55}$    |            | Muons     | $3.65^{+4.98}_{-2.28}$   |            |
| Taus      | $35.78^{+5.09}_{-4.18}$   |            | Taus      | $13.22^{+1.88}_{-1.55}$  |            |
| Fakes     | $27.23^{+6.57}_{-6.57}$   |            | Fakes     | $18.70^{+5.55}_{-5.55}$  |            |

Table A.9: Validation tests of the background estimation methods in the calorimeter isolation control region  $E_{\text{calo}}^{\Delta R < 0.5} > 10 \text{ GeV}$  with an additional  $I_{\text{as}}$  selection of  $I_{\text{as}} > 0.2$  for two different  $p_{\text{T}}$  selection requirements:  $p_{\text{T}} > 40 \text{ GeV}$  (left) and  $p_{\text{T}} > 60 \text{ GeV}$  (right). Only statistical uncertainties are included.

|           | Predicted Yield        | Data Yield |           | Predicted Yield        | Data Yield |
|-----------|------------------------|------------|-----------|------------------------|------------|
| Total bkg | $4.76^{+1.42}_{-1.39}$ | 8          | Total bkg | $2.31^{+0.97}_{-0.95}$ | 3          |
| Electrons | $0.20^{+0.17}_{-0.10}$ |            | Electrons | $0.00^{+0.11}_{-0.00}$ |            |
| Muons     | $0.00^{+0.22}_{-0.00}$ |            | Muons     | $0.00^{+0.14}_{-0.00}$ |            |
| Taus      | $0.48^{+0.15}_{-0.11}$ |            | Taus      | $0.18^{+0.06}_{-0.04}$ |            |
| Fakes     | $4.08^{+1.38}_{-1.38}$ |            | Fakes     | $2.14^{+0.95}_{-0.95}$ |            |

Table A.10: Validation tests of the background estimation methods in the calorimeter isolation control region  $E_{\text{calo}}^{\Delta R < 0.5} > 10 \text{ GeV}$  with an additional  $I_{\text{as}}$  selection of  $I_{\text{as}} > 0.4$  for two different  $p_{\text{T}}$  selection requirements:  $p_{\text{T}} > 40 \text{ GeV}$  (left) and  $p_{\text{T}} > 60 \text{ GeV}$  (right). Only statistical uncertainties are included.

|           | Predicted Yield        | Data Yield |           | Predicted Yield        | Data Yield |
|-----------|------------------------|------------|-----------|------------------------|------------|
| Total bkg | $1.98^{+0.87}_{-0.83}$ | 2          | Total bkg | $1.10^{+0.63}_{-0.61}$ | 1          |
| Electrons | $0.00^{+0.05}_{-0.00}$ |            | Electrons | $0.00^{+0.00}_{-0.00}$ |            |
| Muons     | $0.00^{+0.22}_{-0.00}$ |            | Muons     | $0.00^{+0.14}_{-0.00}$ |            |
| Taus      | $0.08^{+0.09}_{-0.04}$ |            | Taus      | $0.03^{+0.03}_{-0.02}$ |            |
| Fakes     | $1.91^{+0.83}_{-0.83}$ |            | Fakes     | $1.07^{+0.61}_{-0.61}$ |            |

The underprediction in the control regions with  $I_{\text{as}} > 0.2$  is caused by the prediction of the leptonic  $I_{\text{as}}$  shape from simulation. This leads to a bias as the  $I_{\text{as}}$  distribution in simulation is softer than in data. However, this bias is taken into account as systematic uncertainty (see Section 6.4.4).

## A.5 Selection requirements of the “tag-and-probe” samples

Table A.11: Event selection cuts for the muon “tag-and-probe” samples (T&P signal region sample and T&P lepton veto inverted control region sample) that are used to estimate the uncertainty on the muon scale factor  $\rho_{\text{MC}}^\mu$ .

|                           |  |
|---------------------------|--|
| Muon selection            | $p_{\text{T}} > 25 \text{ GeV}$<br>$ \eta  < 2.4$<br>$\sum_{\Delta R < 0.4} p_{\text{T}}^{\text{PF particle}} / p_{\text{T}}(\mu) < 0.12$<br>$\frac{\chi^2}{ndof} \Big _{\text{global track}} < 10$<br>$ d0  < 0.2 \text{ cm}$<br>$ dz  < 0.5 \text{ cm}$<br>$\geq 1 \text{ hit in the muon detector}$<br>$\geq 2 \text{ hits in different muon detector planes}$<br>$\geq 1 \text{ hit in the pixel detector}$<br>$\geq 6 \text{ hits in the tracker system}$ |
| Candidate track selection | Good quality selection<br>Kinematic selection<br>Lepton/jet veto ( $\mu$ veto inverted for the “tag-and-probe” control region)<br>Isolation selection<br>$N_{\text{hits}} > 5$   |
| Event-based selection     | Muon and candidate track opposite in charge<br>$80 \text{ GeV} < M_{\text{inv}}(\mu, \text{can. trk}) < 100 \text{ GeV}$   |

Table A.12: Event selection cuts for the tau “tag-and-probe” samples (T&P signal region sample and T&P lepton veto inverted control region sample) that are used to estimate the uncertainty on the tau scale factor  $\rho_{\text{MC}}^\tau$ .

|   |  |
|---|--|
| <p>Muon selection<br/>that is compatible with a<br/><math>\tau \rightarrow \mu\nu\nu</math> decay</p> | <p><math>p_{\text{T}} &gt; 25 \text{ GeV}</math><br/> <math> \eta  &lt; 2.4</math><br/> <math>\sum_{\Delta R &lt; 0.4} p_{\text{T}}^{\text{PF particle}} / p_{\text{T}}(\mu) &lt; 0.12</math><br/> <math>\frac{\chi^2}{ndof} \Big _{\text{global track}} &lt; 10</math><br/> <math> d0  &lt; 0.2 \text{ cm}</math><br/> <math> dz  &lt; 0.5 \text{ cm}</math><br/> <math>\geq 1</math> hit in the muon detector<br/> <math>\geq 2</math> hits in different muon detector planes<br/> <math>\geq 1</math> hit in the pixel detector<br/> <math>\geq 6</math> hits in the tracker system</p> |
| <p>Candidate track selection</p>  | <p>Good quality selection<br/> Kinematic selection<br/> Lepton/jet veto (<math>\tau</math> veto inverted for the<br/> “tag-and-probe” control region)<br/> <math>\sum_{\Delta R &lt; 0.3} p_{\text{T}} / p_{\text{T}}^{\text{cand}} &lt; 0.1</math><br/> <math>N_{\text{hits}} &gt; 5</math></p>   |
| <p>Event-based selection</p>  | <p>Muon and candidate track opposite in charge<br/> <math>40 \text{ GeV} &lt; M_{\text{inv}}(\mu, \text{cand. trk}) &lt; 75 \text{ GeV}</math><br/> <math>m_{\text{T}}(\mu, \cancel{E}_{\text{T}}) &lt; 40 \text{ GeV}</math></p>  |

Table A.13: Event selection cuts for the electron “tag-and-probe” samples (T&P signal region sample and T&P lepton veto inverted control region sample) that are used to estimate the uncertainty on the electron scale factor  $\rho_{\text{MC}}^e$ .

|                           |   |
|---------------------------|---|
| Electron selection        | $p_{\text{T}} > 25 \text{ GeV}$<br>$ \eta  < 2.5$<br>$\sum_{\Delta R < 0.4} p_{\text{T}}^{\text{PF particle}} / p_{\text{T}}(e) < 0.15$<br>pass conversion veto<br>no missing tracker hits<br>good MVA electron as defined in [39]  |
| Candidate track selection | Good quality selection<br>Kinematic selection<br>Lepton/jet veto ( $e$ veto inverted for the<br>“tag-and-probe” control region)<br>$\sum_{\Delta R < 0.3} p_{\text{T}} / p_{\text{T}}^{\text{cand}} < 0.1$<br>$N_{\text{hits}} > 5$ |
| Event-based selection     | Electron and candidate track opposite in charge<br>$80 \text{ GeV} < M_{\text{inv}}(e, \text{cand. trk}) < 100 \text{ GeV}$   |

## A.6 Optimisation results with the number of missing outer hits

Also an optimisation in the number of missing outer hits is performed. No significant improvement is visible in the search sensitivity for different selection requirements of  $N_{\text{lost}}^{\text{outer}}$ , see Fig A.1. This is caused by the fact, that the main background, the fake background,

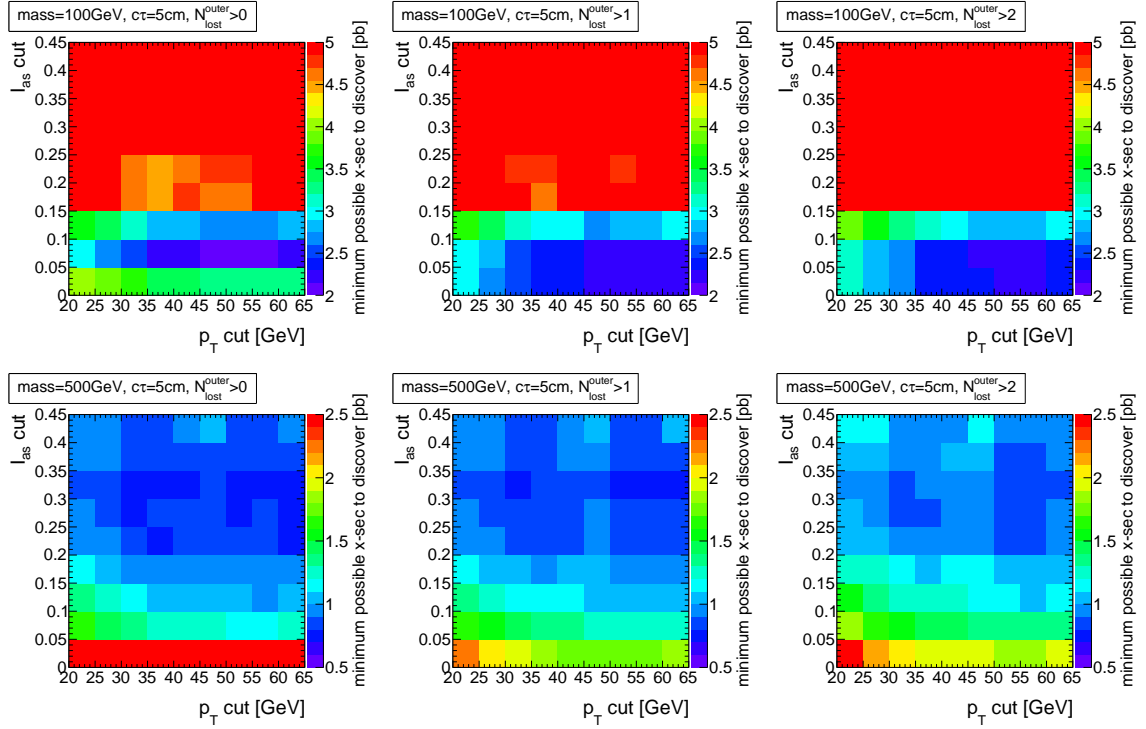


Figure A.1: Minimum possible cross section that can be discovered with  $5\sigma$  significance in the  $I_{\text{as}}p_{\text{T}}$  plane for two different signal models with a chargino lifetime of 5 cm and a mass of 100 GeV (top) and 500 GeV (bottom). The requirement on the number of missing outer hits is varied between  $N_{\text{lost}}^{\text{outer}} > 0$  (left),  $N_{\text{lost}}^{\text{outer}} > 1$  (middle),  $N_{\text{lost}}^{\text{outer}} > 2$  (right). A difference in the sensitivity can be spotted when looking at the lowest value of the minimum cross section that occurs. No sizable discrimination improvement is visible for a tighter selection in  $N_{\text{lost}}^{\text{outer}}$ .

also shows missing outer hits. A comparison between the number of missing outer hits for the fake background and two signal models is shown in Fig. A.2.

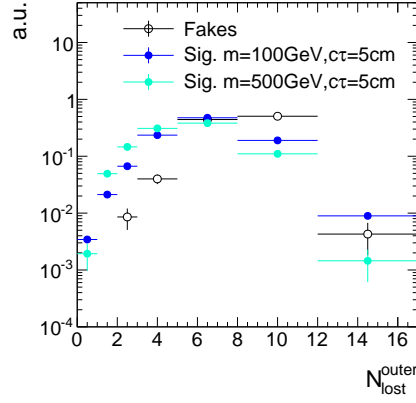


Figure A.2: Normalised distribution of the number of missing outer hits for fake tracks and two different signal models.

## A.7 Underlying distributions for the qualitative search sensitivity optimisation

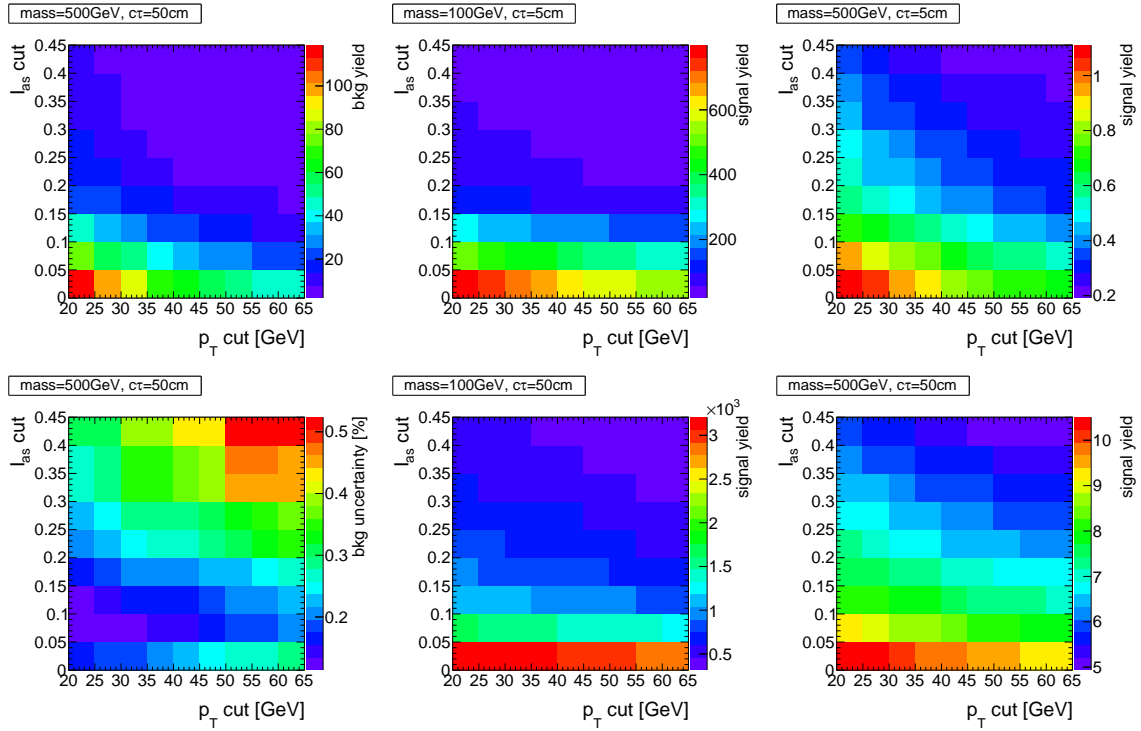


Figure A.3: Background yield, background uncertainty and signal yield for different  $p_T$  and  $I_{as}$  selection requirements and four different signal models.

## A.8 Trigger emulation

As the HLTMonoCentralPFJet80\_PFMETnoMu105\_NHEF0p95 trigger is not available in the simulated signal samples, this trigger is emulated in these samples. Since HLT trigger information is stored in the samples, it is possible to rebuild the trigger afterwards.

The following requirements must be fulfilled in order to consider the trigger firing [33,34]:

- $p_T$  of hltL1sL1ETM40  $> 40$  GeV
- $p_T$  of hltCentralJet65L1FastJet  $> 65$  GeV
- $p_T$  of hltMET65  $> 65$  GeV
- $p_T$  of hltCentralPFJet80  $> 80$  GeV
- $p_T$  of hltPFMETWOM95  $> 105$  GeV

As a cross check, also the HLTMonoCentralPFJet80\_PFMETnoMu95\_NHEF0p95 is rebuild with the looser selection of  $p_T$  of hltPFMETWOM95  $> 95$  GeV. The correct implementation could be verified with this test.



## A.9 Exclusion limits for all simulated lifetimes

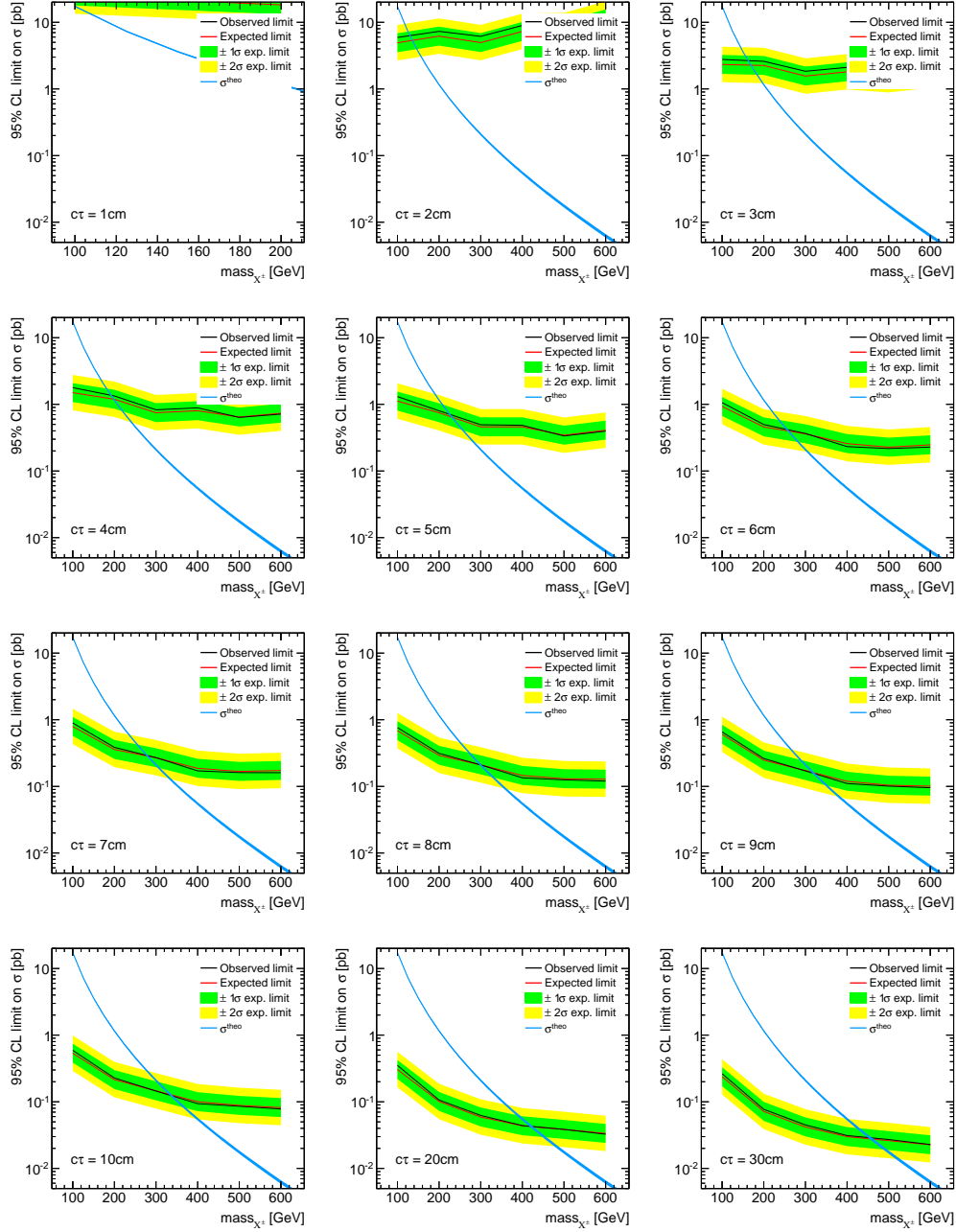
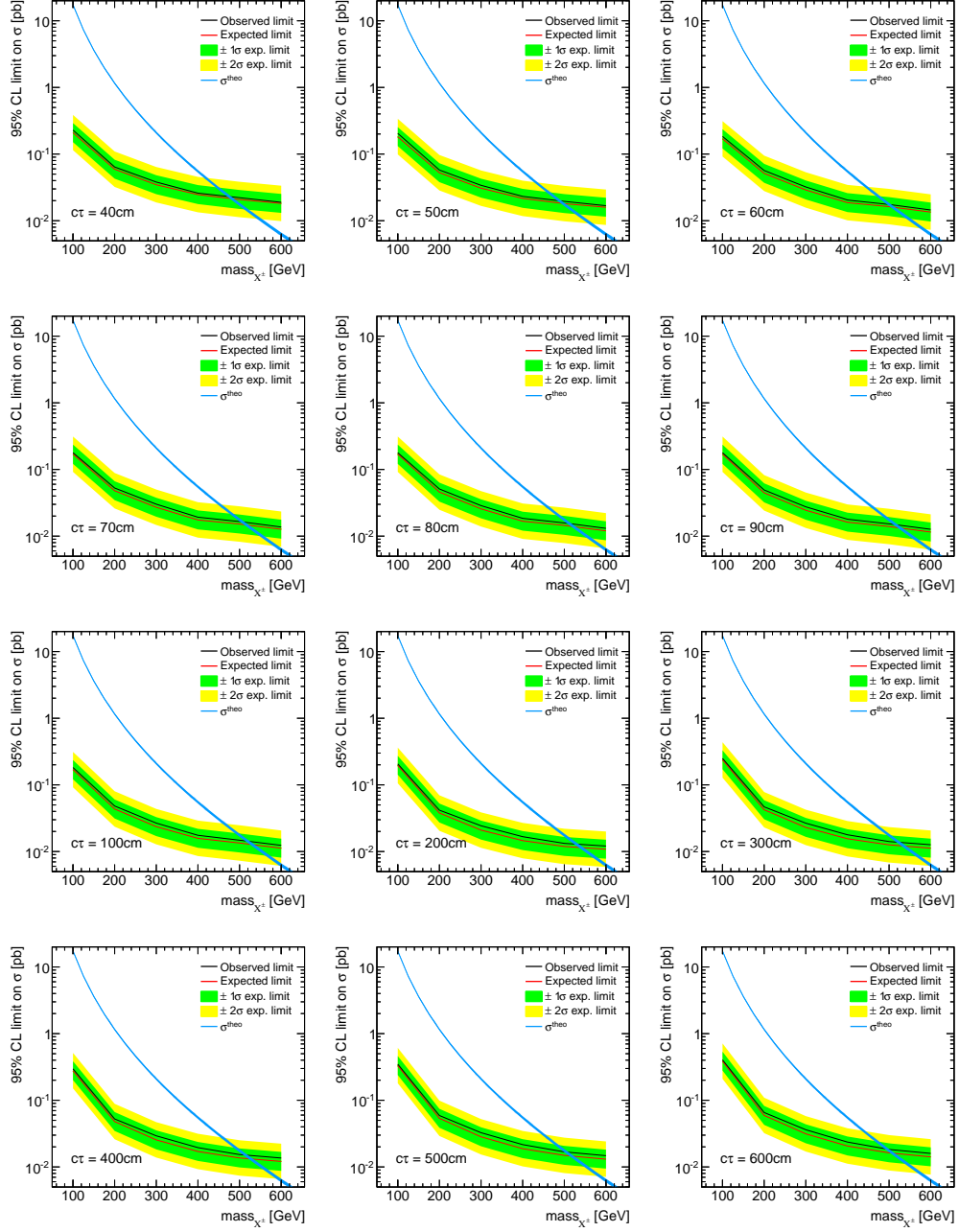
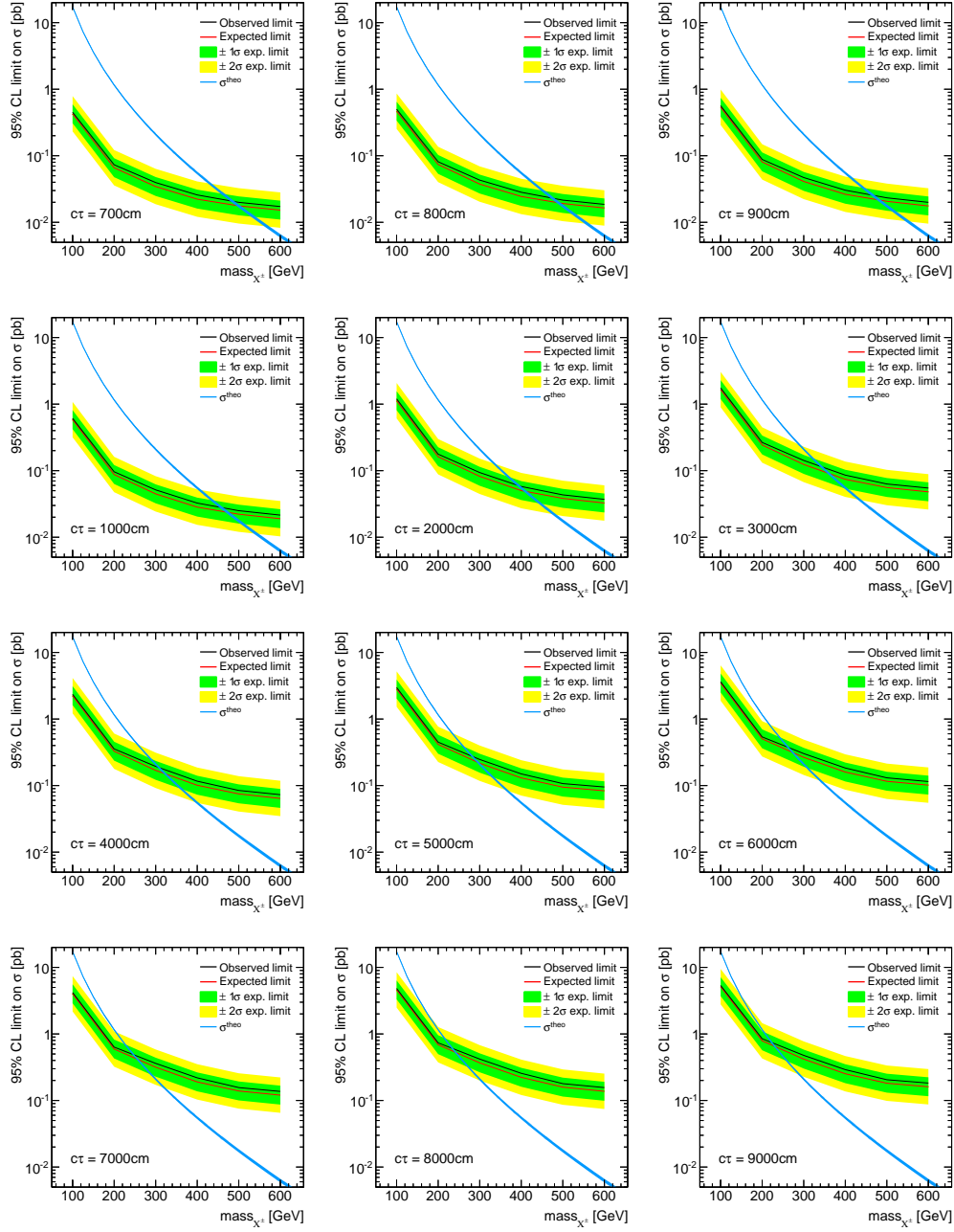


Figure A.4: 95% CL exclusion limits for signal models with  $c\tau = 1 - 30$  cm.

Figure A.5: 95% CL exclusion limits for signal models with  $c\tau = 40 - 600$  cm.

Figure A.6: 95% CL exclusion limits for signal models with  $c\tau = 700 - 9000$  cm.



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