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Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

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Abstract

A search is presented for long-lived charged particles that decay within the CMS detector and produce the signature of a disappearing track. A disappearing track is an isolated track with missing hits in the outer layers of the silicon tracker, little or no energy in associated calorimeter deposits, and no associated hits in the muon detectors. This search uses data collected with the CMS detector in 2015 and 2016 from proton-proton collisions at a center-of-mass energy of 13 TeV at the LHC, corresponding to an integrated luminosity of $38.4\,\mathrm{fb}^{-1}$. The results of the search are interpreted in the context of the anomaly-mediated supersymmetry breaking model. The data are consistent with the background-only hypothesis. Limits are set on the product of the cross section for direct production of charginos and their branching fraction to a neutralino and a pion, as a function of the chargino mass and lifetime. At 95% confidence level, charginos with masses below 715 (695) GeV are excluded for a lifetime of 3 (7) ns, as are charginos with lifetimes from 0.5 to 60 ns for a mass of 505 GeV. These are the most stringent limits using a disappearing track signature on this signal model for chargino lifetimes above ≈0.7 ns.

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[*] See Appendix A for the list of collaboration members

1 Introduction

This paper presents a search for long-lived, charged particles that decay within the volume of the silicon tracker of the CMS detector at the CERN LHC and produce the signature of a “disappearing track.” A disappearing track occurs when the decay products of a charged particle are undetected because they either have too little momentum to be reconstructed or interact only weakly, such that they do not produce hits in the tracker and do not deposit significant energy in the calorimeters.

Anomaly-mediated supersymmetry breaking (AMSB) [1, 2] is one of the many beyond-the-standard-model (BSM) scenarios in which such a disappearing track would be produced, and one that has been widely used to interpret the results of searches for disappearing tracks. In AMSB, a particle mass spectrum is predicted with a small mass difference between the lightest chargino ($\widetilde{\chi}_1^{\pm}$) and neutralino ($\widetilde{\chi}_1^0$), where the latter is the lightest supersymmetric particle [3–6]. The chargino decays to a neutralino and a pion: $\widetilde{\chi}_1^{\pm} \to \widetilde{\chi}_1^0\pi^{\pm}$. Because of the small chargino-neutralino mass difference, the phase space for this decay is limited, and as a consequence the chargino has a lifetime on the order of 1 ns. The pion from this decay has low momentum ($\approx$100 MeV), generally too low for it to be observable as a reconstructed track. If the chargino decays inside the tracker volume, it thus will often leave a disappearing track. We present the search in terms of the chargino mass and lifetime in AMSB, although other BSM scenarios that produce a disappearing track signature have also been proposed [3, 7–11].

Previous analyses performed by the CMS and ATLAS Collaborations have searched for disappearing tracks in proton-proton (pp) collision data at $\sqrt{s} = 8$ TeV [12, 13], and a recent analysis by the ATLAS Collaboration searched for short disappearing tracks in 13 TeV data [14]. The previous CMS search excluded at 95% confidence level (CL) direct electroweak production of charginos with a mass less than 505 GeV for a mean proper lifetime of 7 ns, while the ATLAS search at 13 TeV extended the exclusion limits on chargino mass to 460 GeV for a lifetime of 0.2 ns. These searches are complementary to searches for heavy stable charged particles, which are able to exclude charginos with much longer lifetimes [15, 16]. Two significant improvements with respect to the 8 TeV search for disappearing tracks have been implemented for this search at 13 TeV: a new dedicated trigger developed specifically for this search, and an estimation of the background from standard model (SM) leptons entirely based on control samples in data.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T field of the solenoid. For particles that are not explicitly required to be isolated from other event activity, and that have transverse momentum $1 < p_{\mathrm{T}} < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter. These particles represent the bulk of those produced in collisions. For comparison, isolated particles of $p_{\mathrm{T}} = 100$ GeV emitted at $|\eta| < 1.4$ have track resolutions of 2.8% in p_{T} and

10 (30) μm in the transverse (longitudinal) impact parameter [17].

Events of interest are selected using a two-tier trigger system [18]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [19].

3 Data sets

This search uses pp collision data corresponding to an integrated luminosity of 38.4 fb^{-1} [20, 21], collected with the CMS detector at $\sqrt{s} = 13$ TeV during 2015 and 2016. We analyze separately the data collected during each of the two years. Further, because of changes to the trigger configuration during the 2016 run, we also consider the earlier and later data-taking periods, designated as 2016A and 2016B, separately. The three running periods, which we analyze independently, and the corresponding integrated luminosities are presented in Table 1.

Table 1: The data-taking periods and the corresponding integrated luminosities.

Run period	Integrated luminosity [fb^{-1}]
2015	2.7
2016A	8.3
2016B	27.4

Simulated signal events of pp $\rightarrow \widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ and pp $\rightarrow \widetilde{\chi}_1^{0}\widetilde{\chi}_1^{\pm}$ are generated at leading order (LO) precision with PYTHIA 6.4.26 [22] with the CTEQ6L1 [23] parton distribution function (PDF) set for $\widetilde{\chi}_1^{\pm}$ masses from 100 to 900 GeV and lifetimes from 0.33 ns to 330 ns, using sparticle mass spectra produced by ISAJET 7.80 [24]. The branching fraction for $\widetilde{\chi}_1^{\pm} \rightarrow \widetilde{\chi}_1^{0}\pi^{\pm}$ is set to 100%, and $\tan\beta$ is fixed to 5 with $\mu > 0$, where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets and μ is the higgsino mass parameter. In practice the $\widetilde{\chi}_1^{\pm}$-$\widetilde{\chi}_1^{0}$ mass difference has little dependence on $\tan\beta$ and the sign of μ [25]. These events are normalized using chargino production cross sections calculated at next-to-leading order (NLO) plus next-to-leading-logarithmic (NLL) precision using RESUMMINO 1.0.9 [26, 27] with CTEQ6.6 [28] and MSTW2008nlo90cl [29] PDF sets. The final cross sections and uncertainties are calculated using the PDF4LHC recommendations for the two sets of cross sections [30]. The ratio of $\widetilde{\chi}_1^{0}\widetilde{\chi}_1^{\pm}$ to $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ production is estimated to be roughly 2:1 for all chargino masses considered. Scale factors are applied as a function of the p_{T} of the sparticle pair (either $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ or $\widetilde{\chi}_1^{0}\widetilde{\chi}_1^{\pm}$) to correct for mismodeling of initial state radiation (ISR) in PYTHIA; they are derived by comparing experimental and simulated data in a control region populated mainly by $\mathrm{Z} \rightarrow \mu\mu$ decays as a function of the p_{T} of the Z boson candidate, similar to the method used in Ref. [31]. These events were chosen because the production modes of the Z boson and the $\widetilde{\chi}_1^{\pm}$ are similar. The scale factors typically result in a correction of order +25% in the kinematic region relevant to this search.

Although the methods used to estimate backgrounds in this search are based on experimental data, samples of simulated SM processes are used to validate them and calculate systematic uncertainties. Drell–Yan events, single top quark production via the s and t channels, $\mathrm{Z}\gamma$, $\mathrm{W}\gamma$, and $\mathrm{W} \rightarrow \ell\nu$ events, where ℓ can be an electron, muon, or tau lepton, are generated at NLO precision using the MADGRAPH5_aMC@NLO 2.3.3 generator [32]. The WZ, ZZ, and quantum chromodynamics (QCD) multijet events, with the last composed of jets produced solely through the strong interaction, are generated at LO precision with PYTHIA 8.205 [33]. The WW, $\mathrm{t\bar{t}}$, tW, and $\mathrm{\bar{t}W}$ events are generated at NLO precision using POWHEG v2.0 [34–40]. The fragmentation and hadronization for all simulated background processes are provided by PYTHIA 8.205. The NNPDF3.0 [41] PDF set is used for all simulated backgrounds, and the CUETP8M1 [42, 43] tune is used for the underlying event.

For both simulated signal and background events, the detector response is described by a full model of the CMS detector based on GEANT4 [44] and reconstructed with the same software that is used for collision data. Simulated minimum bias events are superimposed on the hard interaction to describe the effect of overlapping inelastic pp interactions within the same or neighboring bunch crossings, known as pileup, and the samples are reweighted to match the reconstructed vertex multiplicity observed in data.

4 Event reconstruction and selection

The particle-flow (PF) event algorithm [45] is designed to reconstruct and identify each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

This search is performed on events that pass one or more of several triggers with requirements on missing transverse momentum, a characteristic of signal events where the missing transverse momentum is generated by an ISR jet recoiling off the sparticle pair. For this specific analysis we define the vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, with magnitude $p_{\mathrm{T}}^{\mathrm{miss}}$, as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF candidates in an event, with the exception of muons, or, in the case of the L1 trigger, of all calorimeter energy deposits. The triggers require $p_{\mathrm{T}}^{\mathrm{miss}}$ at L1, with the specific requirement varying throughout data taking with changes in the instantaneous luminosity. At the HLT, events with either $p_{\mathrm{T}}^{\mathrm{miss}}$ or $p_{\mathrm{T}}^{\mathrm{miss},\mu}$, which is defined similarly to $p_{\mathrm{T}}^{\mathrm{miss}}$ but with muons included in its calculation, are selected. The lowest-threshold trigger, which was developed specifically for this search, requires $p_{\mathrm{T}}^{\mathrm{miss}} > 75\,\mathrm{GeV}$ as well as an isolated track with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ at the HLT. The higher-threshold triggers require either $p_{\mathrm{T}}^{\mathrm{miss}}$ or $p_{\mathrm{T}}^{\mathrm{miss},\mu}$ to be greater than 90 (120) GeV for the 2015 (2016) data. For signal events, which typically have no reconstructed muons, $p_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{\mathrm{miss},\mu}$ are usually identical, and both are used at the HLT to mitigate any inefficiency in the isolated track requirement for events with higher $p_{\mathrm{T}}^{\mathrm{miss}}$ or $p_{\mathrm{T}}^{\mathrm{miss},\mu}$. In the offline selection, only $p_{\mathrm{T}}^{\mathrm{miss}}$ is used, in order to mirror the requirements in the L1 trigger and lowest-threshold HLT path. Events are required to have $p_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$ offline, where $p_{\mathrm{T}}^{\mathrm{miss}}$ is calculated from the full PF reconstruction.

Jets are clustered from PF candidates using FASTJET 3.10 [46] with the anti-k_{T} algorithm [47] with a distance parameter of 0.4, and only jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$ are considered in the analysis. Additional criteria are imposed on these jets to remove those originating from calorimeter noise and misidentified leptons [48]. Events are required to have at least one jet with $p_{\mathrm{T}} > 110\,\mathrm{GeV}$ in order to be consistent with the ISR recoil topology.

We require the difference in azimuthal angle, ϕ, between the $\vec{p}_{\mathrm{T}}$ of the leading (highest energy) jet and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ to be greater than 0.5, and for events with at least two jets, we require the maximum difference in ϕ between any two jets, $\Delta\phi_{\mathrm{max}}$, to be less than 2.5. These requirements are designed to remove the large, reducible background originating from QCD multijet events. In these events, a dijet topology with back-to-back jets dominates and mismeasurement of the jet energy may result in a significant measured $p_{\mathrm{T}}^{\mathrm{miss}}$. We refer to the selection up to this point, before any track-related criteria are imposed, as the "basic selection." Events passing this selection are expected to have minimal signal contamination and are dominated by the $\mathrm{W} \to \ell\nu$ process. The effect of the two angular requirements of the basic selection on the 2016 data and on simulated signal and background events is shown in Fig. 1. For signal events, the shapes of these distributions are largely independent of chargino mass and lifetime, and a single representative signal point is shown. The combination of these two requirements is sufficient to remove most of the large QCD multijet background that would otherwise pass the basic selection, while the majority of the remaining background is removed by the track criteria described below.

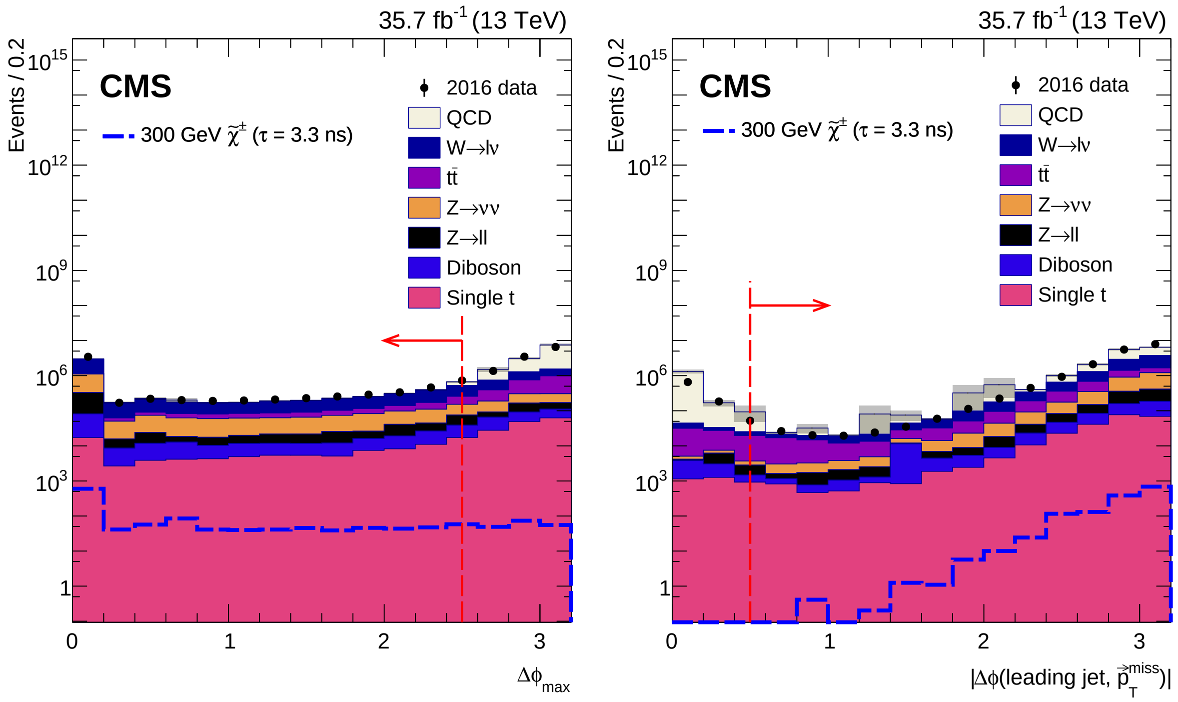

Figure 1: Distributions of the maximum difference in ϕ between any two jets (left) and the difference in ϕ between the $\vec{p}_{\mathrm{T}}$ of the leading jet and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ (right) for events passing the basic selection, before either of the requirements on these two variables is imposed. The data is from the 2016 data-taking period, and the blue dashed lines show the distributions for simulated signal events with a chargino that has a lifetime of 3.3 ns and mass of 300 GeV, with a corresponding production cross section of 0.58 pb. The gray shaded area indicates the statistical uncertainty in the SM background, and the leftmost bin of the left plot includes events with only one selected jet. The vertical dashed lines indicate the chosen value for the requirement on each variable, and the arrows indicate which events are selected.

After the basic selection, tracks are selected that have $p_{\mathrm{T}} > 55\,\mathrm{GeV}$ and $|\eta| < 2.1$. The track p_{T} requirement is chosen such that the corresponding requirement in the HLT path is fully efficient. We ensure that selected tracks are isolated from other activity in the tracker by requiring the scalar sum of the p_{T} of other tracks within a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ around the momentum vector of the selected track be less than 5% of the p_{T} of the track. Selected tracks are also required to be well-separated from jets with $\Delta R(\text{track, jet}) > 0.5$.

One source of background for this search arises from "spurious tracks," i.e., pattern recognition errors that do not correspond to actual charged particles. Spurious tracks can have missing hits in the outer layers of the silicon tracker and muon detectors, and are not generally associated with large energy deposits in the calorimeters, thus mimicking a disappearing track. This background is suppressed by requiring that selected tracks have at least three hits in the pixel detector and at least seven hits overall in the tracker, a typical non-disappearing track leaving twice that number of hits on average. A missing hit in a layer of the tracker between the interaction point and the first actual hit on the track is called a missing inner hit, while a missing hit between the first and last hits on the track is called a missing middle hit. We require selected tracks to have no missing inner or middle hits. In other words, there must be a consecutive pattern of hits originating in the tracker layers closest to the interaction point. Since spurious tracks often appear displaced from the interaction point, we also require all tracks to have a transverse impact parameter $|d_0| < 0.02\,\mathrm{cm}$ and a longitudinal impact parameter $|z_0| < 0.5\,\mathrm{cm}$, both with respect to the primary vertex, chosen as the reconstructed vertex with the largest value of summed physics object p_{T}^2. The physics objects are the jets, clustered using the jet finding algorithm [46, 47] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets. More details are given in Section 9.4.1 of Ref. [49].

Besides spurious tracks, most isolated, high-p_{T} tracks from SM processes come from charged leptons produced in the decays of W or Z bosons or virtual photons. Thus, the other main source of background for this search arises from isolated charged leptons that are not correctly reconstructed by the PF algorithm. Leptons can have missing hits in the tracker for several reasons: for example, energetic bremsstrahlung in the case of electrons, or nuclear interactions with the tracker material in the case of hadronically decaying tau leptons (τ_{h}). Leptons may also have small associated calorimeter energy deposits because of nonoperational or noisy channels. To mitigate this background, events where selected tracks are close to reconstructed leptons ($\Delta R(\text{track, lepton}) < 0.15$) are vetoed. To avoid selecting leptons that fail to be reconstructed because of detector inefficiencies, we impose the following fiducial track criteria. We avoid regions of muon reconstruction inefficiency by vetoing tracks within gaps in the coverage of the muon chambers at $0.15 < |\eta| < 0.35$ and $1.55 < |\eta| < 1.85$. Similarly, we avoid regions of electron reconstruction inefficiency by rejecting tracks within the overlap region between the barrel and endcap sections of the ECAL at $1.42 < |\eta| < 1.65$, as well as tracks within $\Delta R < 0.05$ of a nonoperational or noisy ECAL channel, where ΔR is calculated with respect to the track at the point of closest approach to the center of CMS.

Additional areas of inefficiency are identified using electron and muon tag-and-probe (T&P) studies [50], where $\mathrm{Z} \to \ell\ell$ candidates are selected in data with $m_{\ell\ell} \approx m_{\mathrm{Z}}$, where m_{Z} is the world-average mass of the Z boson [51], and the Z resonance is exploited to obtain a sample of tracks that have a high probability of being leptons, without explicitly requiring them to be reconstructed as leptons. The fraction of these tracks that are not explicitly identified as leptons passing a loose set of identification criteria is a measure of the inefficiency for identifying leptons and is grouped in bins in the η-ϕ plane. Tracks in bins with an anomalously high inefficiency are rejected from the selection. This procedure removes ≈4% of tracks in simulated signal events that would otherwise be selected.

Two additional requirements define the criteria for a track to "disappear." First, we require the selected tracks to have at least three missing outer hits, which are missing hits in the tracker layers outside of the last layer containing a hit on the track. Second, the associated calorimeter energy within $\Delta R < 0.5$ of the track, E_{calo}, is required to be less than 10 GeV, where ΔR is calculated using the track coordinates at the point of closest approach to the center of CMS. This requirement removes a negligible amount of signal, while E_{calo} is much larger, typically over 100 GeV, for background events passing the other selection criteria, according to the simulation. The number of missing outer hits is shown in Fig. 2 for simulated signal and background events that pass the full selection, except for the requirement on that variable. The tracks selected in the simulated background events are predominantly from electrons and τ_{h}, since events with muons have a smaller $p_{\text{T}}^{\text{miss}}$ on average. As can be seen, the number of missing outer hits is very effective at isolating the signal because tracks from background events typically have no missing outer hits. The efficiency of the full selection for simulated signal events is limited mostly by the requirements targeting events with ISR and the relatively narrow range of chargino decay lengths that yield a disappearing track that passes the criterion on the number of missing outer hits. This efficiency varies with the chargino mass and lifetime, peaking at $\approx$2% for a 700 GeV chargino with a lifetime of 3 ns.

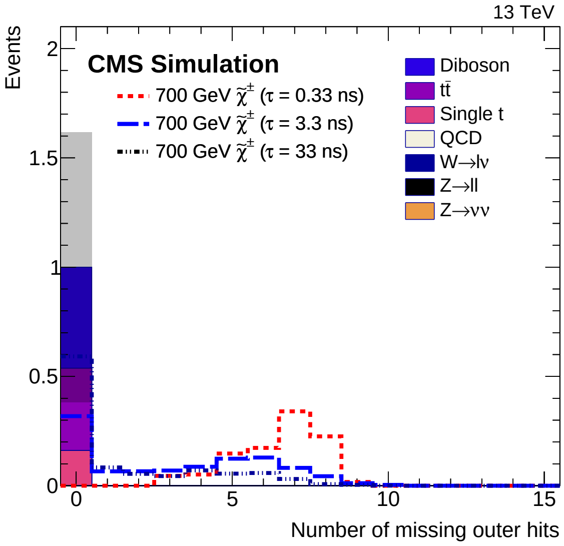

Figure 2: Distributions of the number of missing outer hits for tracks in simulation that pass the full selection, except for the requirement on that variable. Each signal distribution and the sum of the SM background distributions are scaled to have unit area. The gray shaded area indicates the statistical uncertainty in the SM background.

5 Background estimation

5.1 Charged leptons

The dominant source of high-p_{T}, isolated tracks from SM processes arises from charged leptons (electrons and muons, produced promptly or via the decay of tau leptons, or τ_{h}) from the decay of W or Z bosons or virtual photons. In order for events with such tracks to appear in the search region, three things must happen: (1) the lepton must fail to be explicitly identified as a lepton, while still leaving a track in the silicon tracker but less than 10 GeV of energy in the calorimeters;

(2) the resulting $p_{\mathrm{T}}^{\mathrm{miss},\mu}$ and $p_{\mathrm{T}}^{\mathrm{miss}}$ must be large enough for the event to pass the triggers; and (3) the resulting $p_{\mathrm{T}}^{\mathrm{miss}}$ must be large enough for the event to pass the offline $p_{\mathrm{T}}^{\mathrm{miss}}$ requirements.

The key point is that $p_{\mathrm{T}}^{\mathrm{miss},\mu}$ and $p_{\mathrm{T}}^{\mathrm{miss}}$ are affected by whether the lepton is explicitly identified as a lepton or not. If it is not, but still leaves a track in the silicon tracker and less than 10 GeV of energy in the calorimeters, its energy does not typically contribute to the visible energy of the event. The method used to estimate the background from charged leptons is based on calculating the probability in data of the three conditions listed above, with each lepton flavor treated independently.

The first probability we consider is P_{veto}, the probability that the lepton in a single-lepton event is not explicitly identified as a lepton. For each flavor of charged lepton, we estimate P_{veto} using a T&P study. The electron (muon) T&P selections utilize $\mathrm{Z} \to \mathrm{ee}$ $(\mu\mu)$ candidates. For this study we select events passing a single-electron (single-muon) trigger and containing a reconstructed electron (muon) that passes tight identification and isolation criteria. This lepton serves as the tag. A probe track is required to pass the disappearing track criteria, except for those defining the electron (muon) veto in Table 2. The tag lepton and the probe track are required to have an invariant mass within 10 GeV of the Z boson mass and to have opposite signs of electric charge.

Table 2: Definitions of the lepton vetoes used in the T&P studies to estimate P_{veto}, for each flavor of charged lepton. The criteria listed are the subset of the search criteria that are the most efficient at rejecting each flavor.

Selection	Electron	Muon	Tau lepton
Min $\Delta R_{\mathrm{track,\,electron}} > 0.15$	✓		
Min $\Delta R_{\mathrm{track,\,muon}} > 0.15$		✓	
Min $\Delta R_{\mathrm{track},\,\tau_{\mathrm{h}}} > 0.15$			✓
$E_{\mathrm{calo}} < 10\,\mathrm{GeV}$	✓		✓
Missing outer hits ≥ 3	✓	✓	✓
$\Delta R_{\mathrm{track,\,jet}} > 0.5$			✓

For the τ_{h} T&P study, we define two selections using $\mathrm{Z} \to \tau\tau$ events that are combined for the calculation of P_{veto}: one where the electron from a $\tau \to \mathrm{e}\nu\nu$ candidate is selected as the tag, and one where the muon from a $\tau \to \mu\nu\nu$ candidate is selected as the tag. These two selections are identical to the electron and muon T&P selections defined above, respectively, except for two modifications. First, we require the transverse mass $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\mathrm{miss},\mu}(1-\cos\Delta\phi)}$ to be less than 40 GeV, where p_{T}^{ℓ} is the magnitude of the transverse momentum of the tag lepton and $\Delta\phi$ is the difference in ϕ between the $\vec{p}_{\mathrm{T}}$ of the tag lepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss},\mu}$. This m_{T} requirement is made to reduce contamination from $\mathrm{W} \to \ell\nu$ events. Second, because the τ leptons from the Z decay are not fully reconstructed, the dilepton invariant mass requirement is $m_{\mathrm{Z}} - 50 < m < m_{\mathrm{Z}} - 15\,\mathrm{GeV}$.

For each of these selections, we also define a version in which the tag lepton and the probe track are required to have the same sign of electric charge instead of opposite signs. This requirement makes it unlikely that the selected probe track candidates are genuine tracks, and these selections are used to subtract the background from spurious tracks in the calculation of P_{veto}.

For each of the three T&P channels (electrons, muons, and τ_{h}), the quantities $N_{\mathrm{T\&P}}$ ($N_{\mathrm{T\&P}}^{\mathrm{veto}}$) and $N_{\mathrm{SS\,T\&P}}$ ($N_{\mathrm{SS\,T\&P}}^{\mathrm{veto}}$) are the numbers of selected T&P pairs before (after) the final lepton veto is applied to the probe tracks, for the opposite-sign and same-sign selection, respectively. From this, the veto probability is calculated as:

$$P_{\text{veto}} = \frac{N^{\text{veto}}_{\text{T\&P}} - N^{\text{veto}}_{\text{SS T\&P}}}{N_{\text{T\&P}} - N_{\text{SS T\&P}}}. \tag{1}$$

We define P_{offline} as the conditional probability of a single-lepton event to pass the offline requirements of $p_{\mathrm{T}}^{\text{miss}} > 100\,\text{GeV}$ and $|\Delta\phi(\text{leading jet}, \vec{p}_{\mathrm{T}}^{\text{miss}})| > 0.5$ given that the lepton candidate is not explicitly identified as a lepton. Using events in single-lepton control regions in data, we introduce a modified $\vec{p}_{\mathrm{T}}^{\text{miss}}$ variable that represents what $\vec{p}_{\mathrm{T}}^{\text{miss}}$ would look like if the lepton in these events were not explicitly identified as such, assuming that if a lepton is not explicitly identified it contributes no visible energy to the event. In the single-electron and single τ_{h} control regions, we use $\vec{p}_{\mathrm{T}}^{\text{miss}} + \vec{p}_{\mathrm{T}}^{\text{lepton}}$. For the single-muon control region, we simply use $\vec{p}_{\mathrm{T}}^{\text{miss}}$ since the p_{T} of all reconstructed muons is already excluded from its calculation. We then estimate P_{offline} by counting the fraction of events with $p_{\mathrm{T}}^{\text{miss}} > 100\,\text{GeV}$ and $|\Delta\phi(\text{leading jet}, \vec{p}_{\mathrm{T}}^{\text{miss}})| > 0.5$ after modifying $\vec{p}_{\mathrm{T}}^{\text{miss}}$ in this way.

We define P_{trigger} as the conditional probability of a single-lepton event to pass the $p_{\mathrm{T}}^{\text{miss},\mu}$ or $p_{\mathrm{T}}^{\text{miss}}$ triggers, given that the lepton candidate is not explicitly identified as a lepton and that the event passes the offline requirements of $p_{\mathrm{T}}^{\text{miss}} > 100\,\text{GeV}$ and $|\Delta\phi(\text{leading jet}, \vec{p}_{\mathrm{T}}^{\text{miss}})| > 0.5$. The estimation of P_{trigger} is made in a similar way to the estimation of P_{offline} in the single-lepton control regions, assuming that a lepton that is not explicitly identified as such contributes no visible energy to the event and constructing the modified $\vec{p}_{\mathrm{T}}^{\text{miss}} + \vec{p}_{\mathrm{T}}^{\text{lepton}}$ for electrons and τ_{h}, using $\vec{p}_{\mathrm{T}}^{\text{miss}}$ for muons. The exception for P_{trigger} is that instead of constructing these quantities with offline reconstructed leptons, online objects are used from both the L1 trigger and the HLT. For each lepton selected in each of the single-lepton control regions in data, we find the closest L1 trigger object and closest HLT object within $\Delta R < 0.1$ of the offline object. The $\vec{p}_{\mathrm{T}}$ of these objects is then added to the nominal $\vec{p}_{\mathrm{T}}^{\text{miss}}$, as calculated by the L1 trigger and HLT, respectively, and to the nominal $\vec{p}_{\mathrm{T}}^{\text{miss},\mu}$ in the case of the HLT. This way, we can test, event by event, if the L1 trigger and HLT would have passed, given these modifications to the online $\vec{p}_{\mathrm{T}}^{\text{miss},\mu}$ and $\vec{p}_{\mathrm{T}}^{\text{miss}}$. The number of events passing the offline $p_{\mathrm{T}}^{\text{miss}}$ requirements is calculated following the procedure used to calculate P_{offline}, and the fraction of these events that also pass the $p_{\mathrm{T}}^{\text{miss},\mu}$ and $p_{\mathrm{T}}^{\text{miss}}$ triggers according to the above procedure is then the estimate of P_{trigger}.

The product of the three probabilities defined above (P_{veto}, P_{offline}, and P_{trigger}) gives the probability of an event with a charged lepton to enter the search region. We use the single-lepton control regions to estimate the total numbers of events in data containing each flavor of lepton, N^{ℓ}_{ctrl}, and obtain the estimated number of background events from charged leptons as

$$N^{\ell}_{\text{est}} = N^{\ell}_{\text{ctrl}} P_{\text{veto}} P_{\text{offline}} P_{\text{trigger}}. \tag{2}$$

Closure tests were performed with samples of simulated background events and with the early 13 TeV data taken in 2015. Both tests proved the validity of the background estimation method, with agreement within $1.2\,\sigma$ observed in all cases.

5.2 Spurious tracks

The contribution of spurious tracks to the background is largely suppressed by the requirement that the impact parameters of the tracks with respect to the primary vertex are small and by the requirement that the tracks are missing no inner or middle hits in the tracker. We estimate the residual contribution from this background using a control region of $\mathrm{Z} \to \mu\mu$ events as a representative sample of SM events. Within this sample, we additionally require a track, separate from the muons coming from the Z boson candidate, that passes the track requirements of the search region except for the transverse impact parameter criterion, which we replace with a sideband selection, $0.02 < |d_0| < 0.10\,\mathrm{cm}$, designed to enhance the likelihood that the tracks we select are spurious. In this way, we can estimate the probability for there to be spurious tracks that satisfy these requirements. This probability is multiplied by a transfer factor to obtain the probability of spurious tracks passing the nominal impact parameter requirement, P_{spurious}. This transfer factor is obtained from a sample of tracks with only three hits in the pixel detector and no hits in the strip detector, which is dominated by spurious tracks. The estimated background from spurious tracks is the number of events in data passing the basic selection, $N^{\text{basic}}_{\text{ctrl}}$, multiplied by P_{spurious}:

$$N^{\text{spurious}}_{\text{est}} = N^{\text{basic}}_{\text{ctrl}} P_{\text{spurious}}. \tag{3}$$

6 Systematic uncertainties

6.1 Background estimates

The lepton background estimates rely on the assumption that when a lepton is not explicitly identified as a lepton, while still leaving a track in the silicon tracker but less than 10 GeV of energy in the calorimeters, it contributes no visible energy to the event. We test the impact of this assumption for electrons and τ_{h} by replacing the nominal $\vec{p}_{\mathrm{T}}^{\,\text{miss}} + \vec{p}_{\mathrm{T}}^{\,\text{lepton}}$ variable used to calculate P_{offline} and P_{trigger} with a “scaled down” version,

$$\vec{p}_{\mathrm{T}}^{\,\text{miss}} + \frac{p_{\mathrm{T}}^{\text{lepton}} - 10\,\mathrm{GeV}}{p_{\mathrm{T}}^{\text{lepton}}} \vec{p}_{\mathrm{T}}^{\,\text{lepton}}, \tag{4}$$

and recalculating P_{offline} and P_{trigger}. In other words, we assume that unreconstructed leptons contribute 10 GeV of visible energy to the event. The value of 10 GeV is chosen because selected tracks are required to have $E_{\text{calo}} < 10\,\mathrm{GeV}$ in the disappearing track search region. The difference from unity of the ratio

$$\frac{(P_{\text{offline}} P_{\text{trigger}})_{\text{scaled down}}}{(P_{\text{offline}} P_{\text{trigger}})_{\text{nominal}}} \tag{5}$$

is taken as the systematic uncertainty. This uncertainty is approximately 12 (17)% for electrons (τ_{h}) and is not calculated for muons, since even successfully reconstructed muons are not expected to contribute substantial visible calorimeter energy to an event.

For the spurious track background estimate, it is assumed that the particular choice of the d_0 sideband region results in predominantly spurious tracks being selected. To test the impact of this assumption, we examine the variations in the background estimate as the lower bound on the sideband is increased from 0.02 to 0.10 cm. These variations are indeed consistent with the nominal estimate within statistical uncertainties, with maximum variations of 100% down and 45% up for the 2016 data, which are assigned as systematic uncertainties. For the 2015 data, since the estimate is zero and there is no indication of behavior different from 2016 data, we assign a systematic uncertainty of 50% for this data. To apply systematic uncertainties to estimates of zero events, the recommendations of Ref. [52] are followed.

A systematic uncertainty associated with the evaluation of the sideband transfer factor using tracks with three hits is determined. This systematic uncertainty is evaluated by examining the variation in the d_0 distribution from tracks with three consecutive hits to at least seven consecutive hits using tracks in simulated events that are not associated with a generated particle. In this way, we can see how much the true distribution of d_0 for spurious tracks varies with the number of hits, and constrain the impact this variation has on the background estimate. This procedure yields an uncertainty of approximately -50% and $+100\%$ in the spurious-track background estimate.

The spurious-track background estimate rests on the assumption that the spurious-track probability is similar for events in the $\mathrm{Z} \to \mu\mu$ control region and events passing the basic selection. However, there is nothing about the method used to calculate this probability that prevents us from calculating it for events passing the basic selection, and we are able to compare the estimates we obtain from these two independent control regions. This comparison serves to validate the method for estimating the spurious-track background, and the relative difference between the estimates is assigned as a systematic uncertainty. Excellent agreement is seen between the two control regions in both the spurious-track probability and the spurious-track estimate itself, with the estimates agreeing to within $\approx$8% for the 2016 data, and this is taken as a systematic uncertainty. Again, both estimates are zero in the 2015 data, but without any indication that their behaviors are different from 2016 data, we assign a 20% systematic uncertainty for this period and implement this as in Ref. [52].

6.2 Signal efficiencies

Theoretical uncertainties of 3–9% (depending on the chargino mass), which include factorization and renormalization scale uncertainties as well as the PDF uncertainties, are assigned to the chargino production cross sections. Additional sources of systematic uncertainty in the signal yields include those in the integrated luminosity, 2.3 (2.5)% for 2015 (2016) data [20, 21], and those related to the modeling of pileup (2–3%), ISR (8–9%), jet energy scale and resolution (2–6%), and $p_{\mathrm{T}}^{\mathrm{miss}}$ (0.4%), with the values of these uncertainties depending on chargino mass and lifetime. We also estimate uncertainties in the efficiency of the selection criteria on missing inner, middle, and outer hits (1–3, 0.3–3, and 0–3%, respectively), and E_{calo} (0.6–1%), with values that depend on the run period being considered. We evaluate uncertainties to account for potential mismodeling of the trigger efficiency (4–6%, depending on chargino mass and lifetime) and track reconstruction efficiency, namely, 1.5 (4.5)% for 2015 (2016) data. The systematic uncertainties in the signal yields are summarized in Table 3.

7 Results

The numbers of expected events from background sources compared with the observation in the search sample are shown in Table 4. The observation agrees with the expected background. We set 95% CL upper limits on the product of the cross section for direct production of charginos (σ) and their branching fraction to $\widetilde{\chi}_1^0\pi^{\pm}$ ($\mathcal{B}$) for various chargino masses and lifetimes.

These limits are calculated using the LHC-type [53] modified frequentist $\mathrm{CL_s}$ criterion [54, 55]. This method uses a test statistic based on a profile likelihood ratio [56] and treats nuisance parameters in a frequentist context. Nuisance parameters for the theoretical uncertainties in the signal cross sections, and systematic uncertainties in the integrated luminosity and in the signal selection efficiency, are constrained with log-normal distributions. There are two types of nuisance parameters for the uncertainties in the background estimates, and they are specified separately for each of the four background contributions (three arising from the three flavors of charged leptons and one from spurious tracks). Those that result from the limited size of the

Table 3: Summary of the systematic uncertainties in the signal yields. The ranges represent either the variation with chargino mass and lifetime or with the data-taking period used to calculate the uncertainty, depending on the source of each uncertainty as described in the text.

Source of uncertainty	Range [%]
Theory	3–9
Integrated luminosity	2.3–2.5
Pileup	2–3
ISR	8–9
Jet energy scale/resolution	2–6
$p_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.4
Missing inner hits	1–3
Missing middle hits	0.3–3
Missing outer hits	0–3
E_{calo} selection	0.6–1
Trigger efficiency	4–6
Track reconstruction efficiency	1.5–4.5
Total	10–18

Table 4: Summary of numbers of events for the estimated backgrounds and the observed data. The uncertainties include those from statistical and systematic sources. In categories where the systematic uncertainty is negligible, it is not shown.

Run period	Estimated number of background events			Observed events
	Leptons	Spurious tracks	Total	
2015	0.1 ± 0.1	$0^{+0.1}_{-0}$	0.1 ± 0.1	1
2016A	$2.0 \pm 0.4 \pm 0.1$	$0.4 \pm 0.2 \pm 0.4$	$2.4 \pm 0.5 \pm 0.4$	2
2016B	$3.1 \pm 0.6 \pm 0.2$	$0.9 \pm 0.4 \pm 0.9$	$4.0 \pm 0.7 \pm 0.9$	4
Total	$5.2 \pm 0.8 \pm 0.3$	$1.3 \pm 0.4 \pm 1.0$	$6.5 \pm 0.9 \pm 1.0$	7

control samples are constrained with gamma distributions, while those that are associated with statistical uncertainties in multiplicative factors and the systematic uncertainties discussed in Section 6 are constrained with log-normal distributions.

The expected and observed limits on the product of σ and $\mathcal{B}$ are shown in Fig. 3 as a function of chargino mass, for three different chargino lifetimes. Both $\widetilde{\chi}_1^0\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_1^\pm\widetilde{\chi}_1^\mp$ production are included in σ as a function of chargino mass as given in theory, which predicts a ratio of roughly 2:1 over the masses considered. The intersection of the theoretical prediction and the upper limit on the cross section is used to set a constraint on the mass of the chargino, for a given chargino lifetime. This procedure is repeated for a large number of chargino lifetimes, in order to produce a two-dimensional constraint on the chargino mass and mean proper lifetime, which is shown in Fig. 4. Charginos with a lifetime of 3 (7) ns are excluded up to a mass of 715 (695) GeV. Conversely, charginos with a mass of 505 GeV are excluded for lifetimes from 0.5 to 60 ns. Figure 5 shows the observed limits on the product of the cross section for direct production of charginos and their branching fraction to $\widetilde{\chi}_1^0\pi^\pm$.

8 Summary

A search has been presented for long-lived charged particles that decay within the CMS detector and produce the signature of a disappearing track. In a sample of proton-proton data recorded in 2015 and 2016 at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 38.4 fb^{-1}, seven events are observed, compared with the estimated background from standard model processes of $6.5 \pm 0.9\,(\text{stat}) \pm 1.0\,(\text{syst})$ events. The observation is consistent with the background-only hypothesis. The results are interpreted in the context of the anomaly-mediated supersymmetry breaking model, which predicts a small mass difference between the lightest chargino ($\widetilde{\chi}_1^\pm$) and neutralino ($\widetilde{\chi}_1^0$). The chargino decays via $\widetilde{\chi}_1^\pm \to \widetilde{\chi}_1^0\pi^\pm$, and because of the limited phase space available for the decay, the chargino has a lifetime on the order of 1 ns and the pion generally has too low momentum to yield a reconstructed track. If the chargino decays inside the tracker volume, it can thus produce a disappearing track. We place constraints on the mass of charginos from direct electroweak production, for chargino mean proper lifetimes between 0.1 and 100 ns. Charginos with masses up to 715 (695) GeV for a lifetime of 3 (7) ns are excluded at 95% confidence level, as are charginos with lifetimes from 0.5 to 60 ns for a mass of 505 GeV. These constraints extend the limits set by a previous search for disappearing tracks performed by the CMS Collaboration [12] and are complementary to the limits set by searches for heavy stable charged particles, which exclude charginos with much longer lifetimes [15, 16]. For chargino lifetimes above ≈0.7 ns, the present search places the most stringent constraints using a disappearing track signature on direct chargino production.

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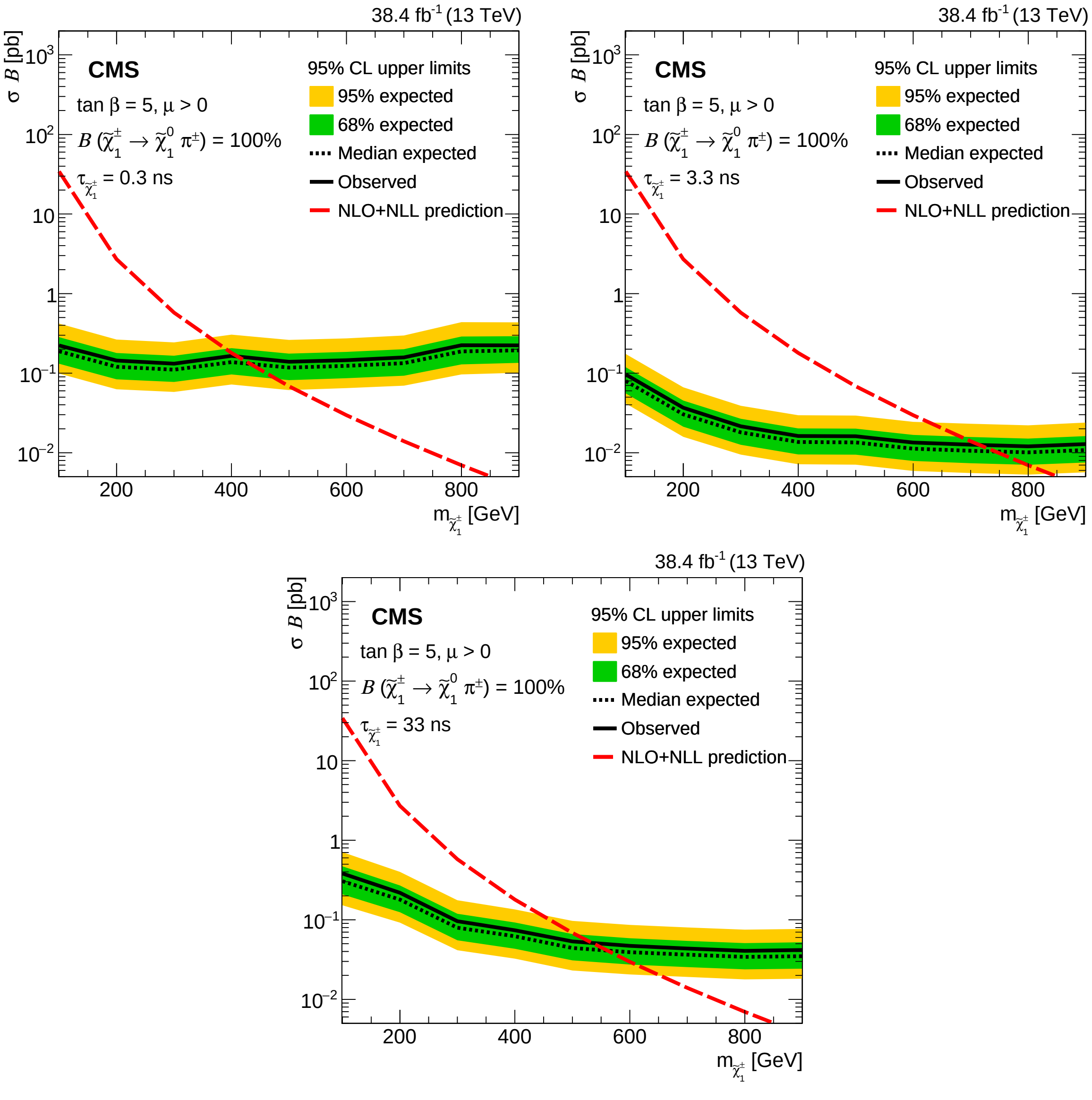

Figure 3: The expected and observed 95% CL upper limits on the product of the cross section for direct production of charginos and their branching fraction to $\widetilde{\chi}^0_1\pi^{\pm}$ as a function of chargino mass for chargino lifetimes of 0.33, 3.3, and 33 ns. The direct chargino production cross section includes both $\widetilde{\chi}^0_1\widetilde{\chi}^{\pm}_1$ and $\widetilde{\chi}^{\pm}_1\widetilde{\chi}^{\mp}_1$ production in roughly a 2:1 ratio for all chargino masses considered. The dashed red line indicates the theoretical prediction for the AMSB model.

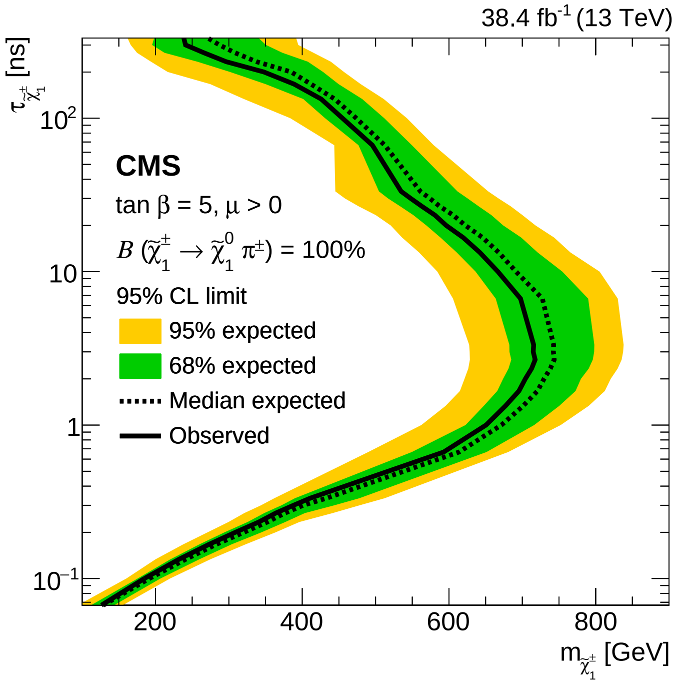

Figure 4: The expected and observed constraints on chargino lifetime and mass. The region to the left of the curve is excluded at 95% CL.

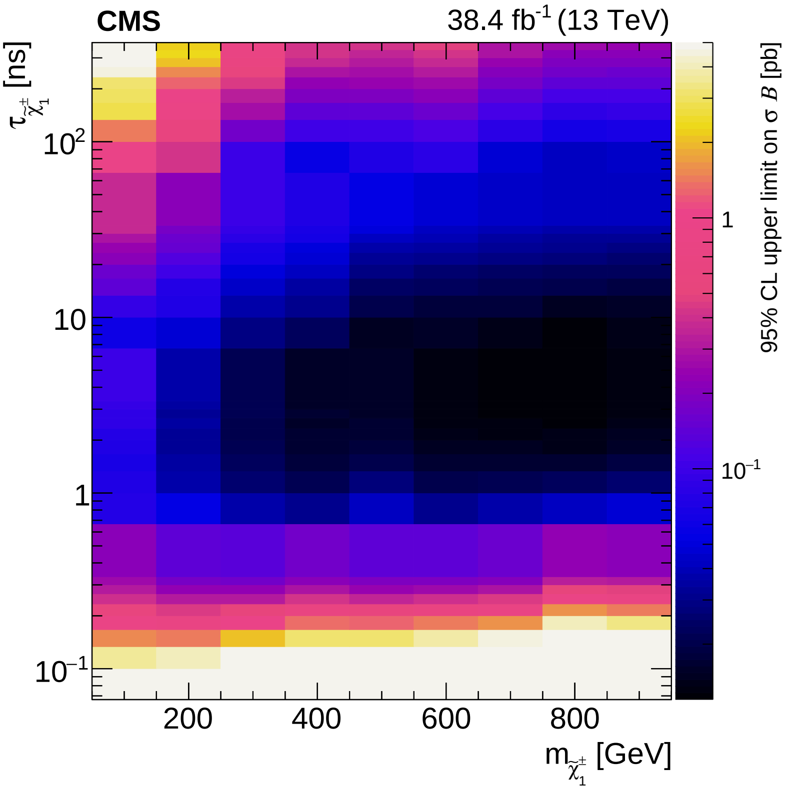

Figure 5: The observed 95% CL upper limits on the product of the cross section for direct production of charginos and their branching fraction to $\tilde{\chi}_1^0 \pi^{\pm}$ as a function of chargino mass and lifetime. The direct chargino production cross section includes both $\tilde{\chi}_1^0 \tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ production in roughly a 2:1 ratio for all chargino masses considered.

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