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Search for electroweak production of supersymmetric particles in final states containing hadronic decays of WW, WZ, or WH and missing transverse momentum

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Abstract

Results are presented from a search for direct production of charginos and neutralinos via electroweak interactions. The results are based on a sample of $\sqrt{s} = 13\,\text{TeV}$ proton-proton collisions from the LHC, recorded with the CMS detector and corresponding to an integrated luminosity of $137\,\text{fb}^{-1}$. The search considers final states with large missing transverse momentum and pairs of hadronically decaying bosons WW, WZ, and WH, which are identified using novel algorithms. No significant excess of events is observed relative to the expectation from the standard model. Limits at the 95% confidence level are placed on the cross section for production of mass-degenerate wino-like supersymmetric particles $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$, and mass-degenerate higgsino-like supersymmetric particles $\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_2^0$, and $\widetilde{\chi}_3^0$. In the limit of a nearly-massless lightest supersymmetric particle $\widetilde{\chi}_1^0$, wino-like particles with masses up to 870 and 960 GeV are excluded in the cases of $\widetilde{\chi}_2^0 \to \text{Z}\widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0 \to \text{H}\widetilde{\chi}_1^0$, respectively, and higgsino-like particles are excluded between 300 and 620 GeV.

1 Introduction

Supersymmetry (SUSY) [1–10] proposes the addition of a new symmetry to the standard model (SM) of particle physics. This new symmetry requires that, for each boson (fermion) in the SM, there is also a fermionic (bosonic) superpartner (sparticle). Recent work [11, 12] suggests that strongly-interacting sparticles significantly heavier than current bounds [13–27] are consistent with a natural theory, but charginos and neutralinos are still expected to be lighter than ~ 1 TeV, with the lightest being close to the Higgs boson mass. This suggests the hunt for TeV-scale charginos and neutralinos is the next proving ground for natural SUSY.

In this Letter, we present a search for electroweak production of sparticles under the assumption that strongly-coupled sparticles are too massive to be produced at the LHC. The superpartners of the gauge bosons of the unbroken SU(2) and U(1) symmetries and the superpartners of the Higgs bosons (the winos, bino, and higgsinos, respectively) mix to form two chargino ($\widetilde{\chi}_i^{\pm}$ with $i = 1, 2$) and four neutralino ($\widetilde{\chi}_i^0$ with $i = 1, 2, 3, 4$) mass eigenstates, where i is in order of increasing mass.

We search for direct production of the wino-like charginos and neutralinos ($\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$) or higgsino-like charginos and neutralinos ($\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_2^0$, and $\widetilde{\chi}_3^0$). We assume that the superpartners of the SM leptons are much heavier than the charginos and neutralinos. As such, decays of wino-like or higgsino-like charginos and neutralinos proceed through W, Z, and Higgs (H) bosons.

In this search, we assume that R-parity [28] is conserved and that the lightest neutralino is a bino-like $\widetilde{\chi}_1^0$ which is stable and will escape the detector unobserved. We explore four signal regions, which target the most prominent final states when the scalar sparticles are very heavy: WW, WZ, or WH, together with a large transverse momentum imbalance.

At the LHC, several searches for direct chargino-neutralino and chargino-pair production in these final states have been performed by the ATLAS [29–36] and CMS [37–43] collaborations. Most of these searches have been performed in events with at least one lepton. This search is performed in fully hadronic final states, which feature larger branching fractions but larger backgrounds. Previous searches in fully hadronic final states have been performed for electroweak production of SUSY in the di-Higgs and other diboson final states by the ATLAS [36, 44] and CMS [45, 46] collaborations. In this search we utilize machine learning algorithms to identify hadronically decaying high transverse momentum (p_T) W, Z, and Higgs bosons reconstructed as large-radius jets [47]. The search uses a sample of LHC proton-proton collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment between 2016 and 2018, corresponding to an integrated luminosity of 137 fb^{-1}.

2 Simulated event samples

Simulations of SM processes are used for optimizing selection criteria and computing several correction factors. These factors are used to predict the rates of SM backgrounds based on observations in various control regions. The production of $\text{t}\bar{\text{t}}$ + jets, W + jets, Z + jets, Drell–Yan, and quantum chromodynamics (QCD) multijet events is simulated at leading-order (LO) precision using the MADGRAPH5_aMC@NLO (2.2.2 for 2016 and 2.4.2 for 2017–2018) generator [48]. Single-top-quark events for all channels are modeled at next-to-leading order (NLO). MADGRAPH5_aMC@NLO is used for s-channel production of single-top-quark events, while POWHEG v1.0 (v2.0) [49–53] is used to simulate t-channel and W-associated production for 2016 (2017–2018). Additional small backgrounds, such as $\text{t}\bar{\text{t}}$ produced in association with one

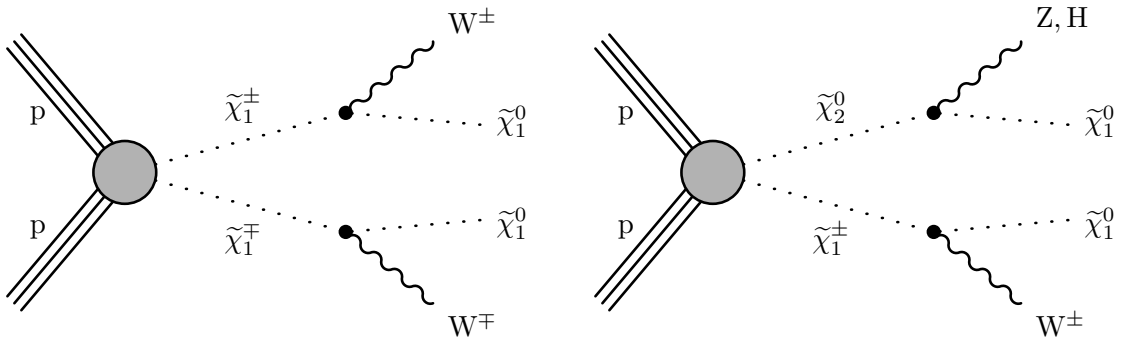

Figure 1: Production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ and $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ with the $\widetilde{\chi}_1^{\pm}$ decaying to a W boson and $\widetilde{\chi}_1^0$ and the $\widetilde{\chi}_2^0$ decaying to either a Z boson or a Higgs boson and $\widetilde{\chi}_1^0$.

or more SM bosons, are similarly produced at NLO with either MADGRAPH5_aMC@NLO or POWHEG [54–56]. Events for 2016 (2017–2018) are generated using the NNPDF 3.0 (3.1) [57, 58] set of parton distribution functions. Parton showering and fragmentation are performed using the PYTHIA 8.2 [59] program with the underlying event models detailed in Refs. [60, 61]. The detector simulation is performed with GEANT4 [62]. The cross sections used to normalize most of the SM samples correspond to next-to-next-to-leading-order precision in QCD.

Signal events are generated in a manner similar to that used for the SM backgrounds, with the MADGRAPH5_aMC@NLO generator at LO precision. The detector simulation of signal samples is performed with the CMS fast simulation package [63, 64]. The signal samples are corrected for differences with respect to the GEANT4-based simulation. Both the SM background samples and the signal samples are generated with nominal distributions of additional pp interactions per bunch crossing, referred to as pileup. The cross sections used for normalizing the signal yields are computed at NLO plus next-to-leading-logarithmic precision [65, 66].

We interpret our results in terms of simplified models [67–71] with the assumption that a chargino pair $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ or a chargino-neutralino pair $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ are produced. In the simplified model scenarios the chargino always decays to the W boson and the $\widetilde{\chi}_1^0$, while the neutralinos decay 100% of the time to either a Z or Higgs boson plus the $\widetilde{\chi}_1^0$, as depicted in Fig. 1. The simplified models are referred to as TChiWW, TChiWZ, and TChiWH, depending on the assumptions made about the decays of $\widetilde{\chi}_1^{\pm}/\widetilde{\chi}_2^0$. For the simplified model interpretations, we use the wino production cross sections for a mass-degenerate $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ pair. In the TChiWZ and TChiWH scenarios, the $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$ are the mass-degenerate next-to-lightest supersymmetric particles (NLSPs), while in the TChiWW scenario, the $\widetilde{\chi}_1^{\pm}$ is the NLSP.

We also consider cases where all winos or all higgsinos are mass degenerate, which we refer to as the wino-like and higgsino-like NLSP scenarios. For the wino-like NLSP scenario, we assume a mass-degenerate $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ pair with a lighter bino-like $\widetilde{\chi}_1^0$ as the lightest supersymmetric particle (LSP), and the production of both $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ and $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ are combined. We consider two options for the decay of the $\widetilde{\chi}_2^0$: either $\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0$ or $\widetilde{\chi}_2^0 \to H\widetilde{\chi}_1^0$, with 100% branching fraction in each case. For the higgsino-like NLSP scenario, we assume mass-degenerate $\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_2^0$, and $\widetilde{\chi}_3^0$ with a lighter bino-like $\widetilde{\chi}_1^0$. In this scenario, the production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_3^0$, and $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$ are combined. We assume 100% branching fractions of $\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0$ and $\widetilde{\chi}_3^0 \to H\widetilde{\chi}_1^0$ as expected for scenarios with $\tan\beta \sim 1$ [72, 73]. All the other sparticles are assumed to be too heavy to affect the production of charginos and neutralinos [65, 66].

3 The CMS detector and event reconstruction

A 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. [74]. Briefly, a superconducting solenoid of 6 m internal diameter provides a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity η coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

This analysis utilizes particle-flow (PF) jets, which are produced by clustering PF candidates into anti-k_T [75, 76] jets. The PF algorithm [77] combines all detector subsystems to identify and reconstruct charged hadrons, photons, neutral hadrons, muons, and electrons. We utilize two jet collections in which the clustering size is either 0.4 (AK4 jets) or 0.8 (AK8 jets). The latter is well-suited to reconstructing hadronic decays of W, Z, and Higgs bosons with p_T larger than roughly 200 GeV. We correct the jets for pileup effects [78, 79] and the jet energy scale [80]. The AK8 jet mass m_J is calculated using the softdrop algorithm [81]. We consider only AK4 jets with $p_T > 30$ GeV and $|\eta| < 2.4$ and AK8 jets with $p_T > 200$ GeV and $|\eta| < 2$ that satisfy a set of quality criteria to eliminate jets from spurious sources such as electronics noise [78].

The variable $\vec{p}_T^{\,miss}$ is defined as the negative vector sum of $\vec{p}_T$ for all PF candidates, and its magnitude is denoted by p_T^{miss}. Known detector effects are accounted for by adjusting p_T^{miss} for jet energy corrections [82]. A set of quality criteria is used to identify and eliminate events in which detector noise, dead calorimeter cells, beam halo, and other effects mimic p_T^{miss} [82].

The identification of jets originating from a b quark (b tagging) is performed by applying a version of the combined secondary vertex algorithm that utilizes deep-learning techniques [83]. For the medium working point utilized in this search, the efficiency of tagging b jets with $p_T > 30$ GeV in $t\bar{t}$ events is about 68%; the probability of misidentifying jets arising from the hadronization of a charm quark (light-flavor quark or gluon) is roughly 12% (1%).

The lepton content of events is used to define the signal and control samples. We require electron (muon) candidates [84, 85] to have $p_T > 10$ GeV and to lie within $|\eta| < 2.5$ (2.4). We also impose isolation requirements on electron and muon candidates to suppress those arising from jets erroneously identified as leptons, as well as genuine leptons from hadron decays, using the same criteria as in Refs. [21, 86]. To recover electrons or muons that fail the tighter identification requirements, as well as τ leptons via their one-prong hadronic decays, we make use of isolated charged tracks. Isolated tracks are required to satisfy $|\eta| < 2.4$ and $p_T > 5$ GeV for PF electrons and muons, and $p_T > 10$ GeV for PF hadrons [21].

Photon candidates are required to have $p_T > 100$ GeV and $|\eta| < 2.4$ and to be isolated from neutral hadrons, charged hadrons, and electromagnetic particles [87].

Candidate AK8 jets consistent with the decay and subsequent fragmentation and hadronization of heavy SM bosons are identified using a deep neural network (DNN). The DNN is designed to classify AK8 jets arising from hadronically decaying particles of five main categories: W, Z, H, t, and "other". Jets are further classified into subcategories according to their likelihood of originating from specific decays of these unstable particles, e.g., $Z(b\bar{b})$, $Z(c\bar{c})$, etc. The architecture of the DNN and details of its training can be found in Ref. [47]. Each classification has a corresponding score that is used to develop jet taggers.

In this analysis, AK8 jets are categorized using three jet taggers: the $b\bar{b}$ tagger, the W tagger,

and the V tagger. These taggers are non-exclusive, i.e., a single AK8 jet may be tagged by any, all, or none of the three taggers. Each tagger involves the DNN and the jet mass. The $\mathrm{b\bar{b}}$ tagger identifies AK8 jets consistent with a $\mathrm{Z(b\bar{b})}$ or $\mathrm{H(b\bar{b})}$ decay by their mass ($75 < m_{\mathrm{J}} < 140\,\mathrm{GeV}$) and a DNN score optimized for identifying boosted $\mathrm{b\bar{b}}$ topologies. The W tagger identifies jets consistent with a $\mathrm{W(q\bar{q}')}$ decay by their mass ($65 < m_{\mathrm{J}} < 105\,\mathrm{GeV}$) and a DNN score optimized for distinguishing between hadronic W boson decays and QCD jets. The V tagger identifies jets consistent with a $\mathrm{W(q\bar{q}')}$ or $\mathrm{Z(q\bar{q})}$ decay by their mass ($65 < m_{\mathrm{J}} < 105\,\mathrm{GeV}$) and a DNN score optimized in a similar manner to the W tagger, but utilizing adversarial training [88] to decorrelate the DNN score and the jet mass. The $\mathrm{b\bar{b}}$ tagger has an efficiency of about 54% for jets with $p_{\mathrm{T}} > 300\,\mathrm{GeV}$ originating from Higgs or Z bosons decaying into $\mathrm{b\bar{b}}$, and a misidentification rate of roughly 2.5% for QCD hadronic jets. Similarly, the W tagger has an efficiency of about 41% for jets arising from hadronic W boson decays and a misidentification rate of roughly 1%, and the V tagger has an efficiency of about 45% for tagging hadronic W and Z boson decays and a misidentification rate of roughly 2.5%.

4 Triggers and event selection

Candidate events are recorded based on a trigger [89] that requires $p_{\mathrm{T}}^{\mathrm{miss}}$ to be larger than a run-dependent threshold. The thresholds vary between 90 and 140 GeV. The efficiency of these triggers is measured using a separate data set in which events are recorded based on the requirement that a single electron or single muon is reconstructed. For $p_{\mathrm{T}}^{\mathrm{miss}}$ of about 200 GeV, which is the minimum $p_{\mathrm{T}}^{\mathrm{miss}}$ used in this search, the trigger efficiency is found to be 95%, 78%, and 74% for the 2016, 2017, and 2018 data-taking periods, respectively. The efficiency rises above 98% for $p_{\mathrm{T}}^{\mathrm{miss}} > 270\,\mathrm{GeV}$ for all years. When computing event yields, parameterizations of these efficiencies are used to correct simulations. For ancillary measurements of jet tagging rates in data, a combination of single-lepton and two-lepton triggers is used.

All events in our signal regions (SRs) are required to satisfy a common set of baseline selection criteria. Each event is required to have a primary vertex and no isolated leptons, photons, or isolated tracks. Leptons, in particular, typically arise from a W boson decay, which constitutes a major background. The requirement of no leptons in our SRs makes this analysis orthogonal to other searches targeting common signals in final states including leptons [37–41]. Events containing isolated tracks are only removed from the data set if the transverse mass of the track satisfies $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)} < 100\,\mathrm{GeV}$, where $\Delta\phi$ refers to the azimuthal separation between the track and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$. Low m_{T} is typical of tracks from $\mathrm{W} \to \ell\nu$ decays but less common in signal events with isolated tracks. Events are required to have $p_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$ and $H_{\mathrm{T}} > 300\,\mathrm{GeV}$, where H_{T} is defined as the scalar sum of p_{T} for all AK4 jets which satisfy the kinematic and quality criteria mentioned in Section 3. Large $p_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T} are typical of chargino and neutralino production when a high-momentum boson is present. Signal events typically have two AK8 jets and four AK4 jets; accordingly we require at least two AK8 jets and 2–6 (inclusive) AK4 jets. We also impose requirements on the azimuthal angle $\Delta\phi_{\mathrm{i}}$ between $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ and each of the four highest p_{T} AK4 jets, where the subscript i refers to the p_{T} ordering of the jets. Each event must satisfy $\Delta\phi_{1,2,3,4} > 1.5, 0.5, 0.3$, and 0.3. Events must satisfy $\Delta\Phi_{1,2} > 1.5$ and 0.5, where $\Delta\Phi_{\mathrm{i}}$ is defined analogously to $\Delta\phi_{\mathrm{i}}$ using the two highest p_{T} AK8 jets. These requirements on azimuthal angles suppress the background from QCD multijet events, for which $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is usually aligned along a jet direction. Within this baseline phase space, four SRs are defined. Three SRs require at least one b-tagged AK4 jet ($n_{\mathrm{b}} \geq 1$), which we refer to as the b-tag regions. The remaining SR requires zero b-tagged AK4 jets ($n_{\mathrm{b}} = 0$), which we refer to as the b-veto region. In addition to these SRs, we also define several control regions (CRs), which are used

to help constrain the background estimates as described in Section 5.

4.1 The b-veto search region

The b-veto SR seeks to isolate events that are consistent with the production of WW, WZ, or ZZ pairs of bosons plus large $p_{\mathrm{T}}^{\mathrm{miss}}$. In addition to the baseline event selection described above, the b-veto SR requires that at least two AK8 jets satisfy $65 < m_{\mathrm{J}} < 105\,\mathrm{GeV}$. At least one AK8 jet must be W tagged, and at least one other AK8 jet must be V tagged, as described in Section 3. A summary of the b-veto SR requirements is shown in Table 1. The b-veto SR is further subdivided into bins of $p_{\mathrm{T}}^{\mathrm{miss}}$. The $p_{\mathrm{T}}^{\mathrm{miss}}$ bin boundaries are 200, 250, 300, 350, 400, 450, 500, 600, 800 GeV, and infinity.

Table 1: Summary of tagging requirements for the b-veto SR and CRs. Each of these regions includes the baseline requirements described in Section 4, as well as requiring zero b-tagged AK4 jets and requiring at least two AK8 jets satisfying $65 < m_{\mathrm{J}} < 105\,\mathrm{GeV}$. The SR and CRs are described in detail in Sections 4.1 and 5.1, respectively. The W and V taggers are described in Section 3.

Region	Requirements
b-veto SR	$\geq$1 V-tagged jet $\geq$1 W-tagged jet $\geq$2 V- or W-tagged jets
b-veto zero-tag CR	0 V-tagged jets 0 W-tagged jets
b-veto one-tag CR	1 V-tagged jet 0 other W-tagged jets

The main background in the b-veto SR arises from $\mathrm{W/Z}+\mathrm{jets}$ production with $\mathrm{W} \to \ell\nu$ or $\mathrm{Z} \to \nu\bar{\nu}$. The $\mathrm{W} \to \ell\nu$ background is substantially reduced by requiring the number of reconstructed charged leptons, including isolated tracks, to be zero. These events still satisfy the event selection criteria when the charged lepton lies outside the lepton acceptance, is not reconstructed, or is not isolated, and thus is not counted even as an isolated track. In $\mathrm{W/Z}+\mathrm{jets}$ background events, both W- and V-tagged AK8 jets arise from misidentification of jets not originating from hadronic W or Z boson decays. These events together with background events arising from QCD multijet production are referred to as the "0-res" background.

The next largest background contributions come from $\mathrm{t\bar{t}}$, single top, and diboson production. These events typically have one leptonically decaying vector boson and one hadronically decaying vector boson. Therefore, one W- or V-tagged AK8 jet arises from a hadronic W or Z boson decay, and the other tag arises from misidentification. We refer to these backgrounds as the "1-res" backgrounds. The remaining minor background contributions, which constitute less than 10% of the expected event yield in any $p_{\mathrm{T}}^{\mathrm{miss}}$ bin of the SR, are expected from rare processes such as triboson production and $\mathrm{t\bar{t}}$ pairs produced in association with a W, Z, or Higgs boson.

The m_{J} distribution of V-tagged jets for signal, expected SM backgrounds, and observed event yields in the b-veto SR is shown in Fig. 2 (left), in which the mass requirement of the V tagger has been loosened. In some events, there are multiple V-tagged jets, some of which could also be W-tagged. In such events, the jet that is both W- and V-tagged and has the highest W-tagger DNN score is ignored, and the V-tagged jet with the highest V-tagger DNN score among the remaining jets is plotted. The simulated event yields are scaled such that the yield within the

SR matches our total predictions, which will be described in Section 5. Distributions for the TChiWZ and TChiWW signals show peaks in the region of 65–105 GeV, corresponding to the mass requirement of the V tagger.

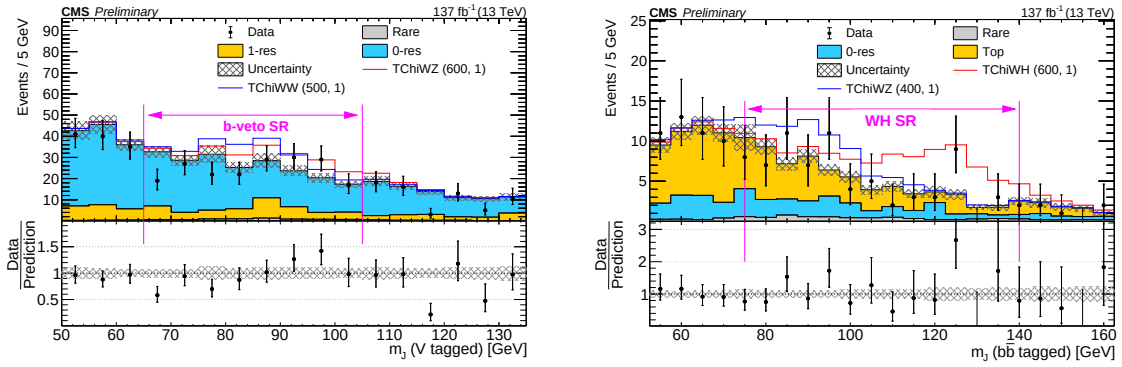

Figure 2: Distributions of the jet mass for V-tagged AK8 jets in the b-veto SR (left) and $\mathrm{b\bar{b}}$-tagged AK8 jets in the WH SR (right). The jet mass requirements for the V and $\mathrm{b\bar{b}}$ taggers have been loosened in these figures. The filled histograms show the SM background predictions. The open histograms show the SM background predictions plus the expectations for selected signal models, which are denoted in the legend by the name of the model followed by the assumed masses of the NLSP and LSP. The observed event yields are indicated by black markers. The hatched gray bands correspond to the statistical uncertainties in the SM predictions, but no systematic uncertainties are included.

4.2 The b-tag search regions

The SRs with b-tagged jets are referred to as the WH, W, and H SRs. These SRs isolate events in which either a WH or WZ pair of bosons is produced with large $p_{\mathrm{T}}^{\mathrm{miss}}$. In these SRs, AK8 jets may be classified as either Higgs boson candidates or W boson candidates based on their mass and their proximity to a b-tagged AK4 jet. AK8 jets that lie in the ZH mass window $75 < m_{\mathrm{J}} < 140\,\mathrm{GeV}$ and satisfy $\Delta R(\text{b jet, AK8 jet}) < 0.8$ for at least one b-tagged AK4 jet in the event are Higgs boson candidates. AK8 jets that lie in the WZ mass window $65 < m_{\mathrm{J}} < 105\,\mathrm{GeV}$ and are far from all b-tagged AK4 jets, i.e., $\Delta R(\text{b jet, AK8 jet}) > 0.8$ for all b-tagged AK4 jets in the event, are W boson candidates. These classes of AK8 jets do not overlap, but not every AK8 jet falls into either class.

The WH SR requires at least one W boson candidate that is W tagged and at least one Higgs boson candidate that is $\mathrm{b\bar{b}}$ tagged. The W SR requires at least one W boson candidate that is W tagged and no $\mathrm{b\bar{b}}$-tagged Higgs boson candidates, although Higgs boson candidates that are not $\mathrm{b\bar{b}}$-tagged are permitted. The H SR requires at least one Higgs boson candidate that is $\mathrm{b\bar{b}}$ tagged and no W boson candidates that are W tagged, but similarly imposes no requirement on untagged W boson candidates.

The SM backgrounds that contribute to the three b-tag SRs are top pair production, especially at low $p_{\mathrm{T}}^{\mathrm{miss}}$, and W/Z + jets events, especially at high $p_{\mathrm{T}}^{\mathrm{miss}}$. In all three b-tag SRs, there are small contributions from diboson, triboson, and $\mathrm{t\bar{t}}$ produced in association with a W, Z, or Higgs boson. Each of the three b-tag SRs is summarized in Table 2.

The b-tag SRs are also subdivided into bins of $p_{\mathrm{T}}^{\mathrm{miss}}$. The W and H SRs use the same $p_{\mathrm{T}}^{\mathrm{miss}}$ binning as the b-veto SR. For the WH SR, the last two $p_{\mathrm{T}}^{\mathrm{miss}}$ bins are merged because of to the small expected numbers of events in the corresponding CRs.

The distribution of the Higgs boson candidate m_{J} for events in the WH SR for signal, expected

Table 2: Summary of tagging requirements for the b-tag SRs and CRs. Each of these regions includes the baseline requirements described in Section 4, as well as requiring at least one b-tagged AK4 jet and at least two AK8 jets. The SRs and CRs are described in detail in Sections 4.2 and 5.2, respectively. The $\mathrm{b\bar{b}}$ and W taggers are described in Section 3, and the definitions of W and Higgs boson candidates are given in Section 4.2. In addition to the six regions described in this table, the b-tag predictions also use six single-lepton CRs that are identical except that exactly one charged lepton is required. A dash (—) indicates that no requirement is imposed.

	W boson candidate		Higgs boson candidate	
	W tagged	not W tagged	$\mathrm{b\bar{b}}$ tagged	not $\mathrm{b\bar{b}}$ tagged
WH SR	$\geq$1	—	$\geq$1	—
W SR	$\geq$1	—	0	—
H SR	0	—	$\geq$1	—
WH antitag CR	0	$\geq$1	0	$\geq$1
W antitag CR	0	$\geq$1	0	0
H antitag CR	0	0	0	$\geq$1

SM backgrounds, and observed event yields is shown in Fig. 2 (right). The Higgs boson candidate mass requirement has been loosened by $\sim$ 20 GeV on either side. The predicted yields from simulation are scaled such that the total SM background yields in the SR match the total prediction using the procedure described in Section 5. Distributions for the TChiWZ and TChiWH signals show peaks in the region of 75–140 GeV, corresponding to the mass requirement of the $\mathrm{b\bar{b}}$ tagger.

5 Background estimation

To constrain the contribution from the most dominant SM processes in each of our SRs, several CRs are defined. Each CR has reduced contributions from signal processes and enhanced contributions from SM background processes. Most of our CRs isolate different background components by inverting various tagging requirements to select events with a misidentified boson. For the b-tag SRs, where backgrounds involving top quarks are more prominent, a combination of CRs with inverted tagging requirements and with one charged lepton is used.

5.1 Background estimation for the b-veto search region

The sum of 0- and 1-res background events in the b-veto SR is estimated simultaneously from two mutually-exclusive CRs. Both CRs require at least two AK8 jets that satisfy the WZ mass requirements. The zero-tag CR is defined by requiring that all AK8 jets satisfying the WZ mass requirements are neither W tagged nor V tagged. This CR is dominated by the 0-res background. The one-tag CR requires exactly one V-tagged jet, and requires that all other AK8 jets that satisfy the WZ mass requirements are neither W tagged nor V tagged. The main contribution to the one-tag CR comes from the 0-res background, but this CR has increased contributions from the 1-res background compared to the zero-tag CR. Both b-veto CRs are summarized in Table 1.

The background yields in the b-veto SR are estimated using two sets of transfer factors derived from simulation, $\mathcal{R}_i$, defined as the ratio of the summed 0- and 1-res event yields in the SR divided by either the zero-tag ($\mathcal{R}_0$) or one-tag CR ($\mathcal{R}_1$). The values of $\mathcal{R}_i$ are computed separately for each p_T^{miss} bin and typically range between 0.2 and 0.3. The contributions of rare processes to the SRs and CRs are taken from simulation with appropriate data-to-simulation corrections

applied. The total background prediction is given by

$$N_{\mathrm{SR}}^{\mathrm{data}} = \mathcal{R}_{\mathrm{i}}(N_{\mathrm{CR_i}}^{\mathrm{data}} - N_{\mathrm{CR_i,rare}}^{\mathrm{MC}}) + N_{\mathrm{SR,rare}}^{\mathrm{MC}},$$

where $\mathcal{R}_{\mathrm{i}} = N_{\mathrm{SR,0\&1\text{-}res}}^{\mathrm{MC}} / N_{\mathrm{CR_i,0\&1\text{-}res}}^{\mathrm{MC}}$ and $\mathrm{CR_i}$ is either the zero-tag or one-tag CR. The final background predictions for the SR are determined by a simultaneous fit of the two CRs. The background composition of the one-tag CR is very similar to the b-veto SR, while the signal contamination is smaller in the zero-tag CR. Using both CRs allows us to benefit from these advantages.

The W- and V-tagging rates in simulation are corrected to match those measured in data. The corrections for jets matched to generator-level W bosons are obtained from a $\mathrm{t\bar{t}}$-enriched sample in which one of the W bosons from the top quark decays leptonically and the other decays hadronically [47]. The same corrections are also applied to jets matched to generator-level Z bosons. The corrections for misidentified jets are obtained from a sample of events with an $\ell^+\ell^-$ (ℓ = e, μ) pair plus at least one AK8 jet. The W- or V-tagged jets in these events are dominated by misidentification. Uncertainties associated with the determination of these corrections are propagated to the final predictions.

Our b-veto background prediction method relies on the modeling of the AK8 jet W- and V-tagging efficiencies in simulation after the corrections described above are applied. Several validation regions are defined to check how well the simulation models the tagging efficiencies in the phase space close to our SR and CRs. For one set of validation regions, events are required to satisfy the baseline event selection criteria except for the second AK8 jet requirement, and to have only one AK8 jet, which is W or V tagged. These validation regions are referred to as the one-jet W- and V-tag validation regions, respectively. The predicted SM backgrounds, with the exception of the rare backgrounds, in each validation region are based on an extrapolation from CRs defined by the inversion of the DNN requirement for the W or V tag. The predicted yields of the rare backgrounds are obtained directly from simulation, not via extrapolation from CRs. The predictions in these one-jet validation regions are found to be compatible with our observations.

Similar tests are also performed using events that satisfy the baseline event selection criteria including the requirement of having at least two AK8 jets. We then require that only one AK8 jet is W or V tagged. These validation regions are referred to as the two-jet W- and V-tag validation regions, respectively. Predictions of the background yields, with the exception of the rare backgrounds, are made by extrapolating from CRs defined by inversion of the tagging requirement. As before the rare backgrounds yields are taken directly from simulation.

In the two-jet W- and V-tag validation regions, the observed event yields are higher than the SM background predictions, primarily in the intermediate- to high-$p_{\mathrm{T}}^{\mathrm{miss}}$ region, which may be attributed to a dependence of the misidentification rate corrections on event topology or on AK8 jet multiplicity in this phase space. We correct the background predictions in the b-veto SR to account for these discrepancies. The correction from the W-tag validation region is applied to the extrapolation from the one-tag CR to the SR, and the corrections from the W- and V-tag CRs are both applied to the extrapolation from the zero-tag CR to the SR. The corrections obtained from the two-jet W-tag (V-tag) validation region range from 1.03 (1.01) at low $p_{\mathrm{T}}^{\mathrm{miss}}$ to 1.48 (1.27) in the highest $p_{\mathrm{T}}^{\mathrm{miss}}$ bin.

5.2 Background estimation for the b-tag search regions

For each of the b-tag SRs, we define three sets of CRs. The first set, the antitag CRs, inverts the tagging requirements of the corresponding SR. In the antitag CRs, every Higgs boson candidate

must not be $\mathrm{b\bar{b}}$ tagged, and every W boson candidate must not be W tagged. The WH antitag CR requires at least one Higgs boson candidate and at least one W boson candidate. The W antitag CR requires zero Higgs boson candidates and at least one W boson candidate, while the H antitag CR requires at least one Higgs boson candidate and zero W boson candidates. The antitag CRs are enhanced in $\mathrm{W}/\mathrm{Z}+$jets but still have contributions from events containing top quarks.

The remaining CRs are defined identically to the SRs and antitag CRs but require exactly one lepton, i.e., there is a set of three single-lepton (1ℓ) tagged CRs and a set of three 1ℓ antitag CRs. The 1ℓ CRs feature enhanced rates of top quark pair production. A summary of the selection for each SR and corresponding CR is given in Table 2.

Backgrounds with top quarks (top backgrounds), which typically involve at least one leptonically decaying W boson and one hadronically decaying W boson, are constrained using observations in the 1ℓ CRs. These CRs are dominated by top quark pair production, with small contributions from $\mathrm{W}+$jets and even smaller contributions from single top quark production (<18%) and $\mathrm{t\bar{t}H}$ (<1%). A transfer factor, $\mathcal{R}_{0\ell/1\ell}$, is used to provide an estimate of the number of top background events in either the SR or the 0ℓ antitag CR, where 0ℓ refers to the SRs and the antitag CRs with zero leptons. The values of $\mathcal{R}_{0\ell/1\ell}$ are computed from simulation, including all corrections to the lepton reconstruction efficiencies, b-tagging efficiencies, and AK8 jet tagging efficiencies.

The predicted number of top background events in either the SR or the 0ℓ antitag CR is given by

$$N_{\mathrm{i,top}}^{\mathrm{pred},0\ell} = \frac{N_{\mathrm{i,top}}^{\mathrm{MC},0\ell}}{N_{\mathrm{i,all}}^{\mathrm{MC},1\ell}} N_{\mathrm{i}}^{\mathrm{data},1\ell} = \mathcal{R}_{0\ell/1\ell} N_{\mathrm{i}}^{\mathrm{data},1\ell}, \tag{1}$$

where N^{MC} denotes the number of events expected from simulation, N^{data} denotes the number of observed events, and N^{pred} denotes the number of events predicted via this method. Additionally, the subscript i denotes the tagging region, tag or antitag. The subscript "all" refers to all of the SM backgrounds, while "top" refers to only the top backgrounds.

A transfer factor $\mathcal{R}_{\mathrm{p/f}}$ is used to constrain the 0-res event yields in the SR based on observations in the 0ℓ antitag CR. The value of $\mathcal{R}_{\mathrm{p/f}}$ is computed using simulation and is the ratio of the number of 0-res events in the SR to the number of 0-res events in the 0ℓ antitag CR. This transfer factor does not include the top backgrounds, which are constrained separately via the 1ℓ CRs. The transfer factor is corrected for differences in tagging rates between simulation and data. Corrections are derived separately for W-tagged and $\mathrm{b\bar{b}}$-tagged jets, and separately for misidentified and correctly-tagged jets [47]. Corrections for misidentified jets are derived in a similar manner to the corrections used for the b-veto regions, using samples of Drell–Yan events and requiring $n_{\mathrm{b}} = 1$. All uncertainties in these corrections are propagated to our final predictions.

Using $\mathcal{R}_{\mathrm{p/f}}$ and the prediction of the top backgrounds described above, the predicted 0-res background contribution to the SR is given by

$$N_{\text{0-res}}^{\mathrm{pred},0\ell} = \mathcal{R}_{\mathrm{p/f}} \left(N_{\mathrm{antitag}}^{\mathrm{data},0\ell} - N_{\mathrm{antitag,top}}^{\mathrm{pred},0\ell} - N_{\mathrm{antitag,rare}}^{\mathrm{MC},0\ell} \right), \tag{2}$$

where $N_{\mathrm{antitag}}^{\mathrm{data},0\ell}$ denotes the number of observed events in the 0ℓ antitag CR, $N_{\mathrm{antitag,top}}^{\mathrm{pred},0\ell}$ denotes the predicted number of top background events from Eq. (1), and $N_{\mathrm{antitag,rare}}^{\mathrm{MC},0\ell}$ denotes the number of rare background events, such as diboson and triboson events, expected from simulation.

The predictions of the top backgrounds and 0-res backgrounds are taken from from Eqs. (1) and (2), while the prediction of the rare backgrounds is taken from simulation. These predictions are produced in each $p_{\mathrm{T}}^{\mathrm{miss}}$ bin and in each SR independently. Each transfer factor is derived separately for each $p_{\mathrm{T}}^{\mathrm{miss}}$ bin except for $\mathcal{R}_{0\ell/1\ell}$, whose values above $p_{\mathrm{T}}^{\mathrm{miss}} > 450$ (400) GeV are averaged in the W and H (WH) SRs.

The predictions of the SM backgrounds are tested in data using an orthogonal validation region in which exactly one AK8 jet is required. This validation region is used to test the simulation-derived transfer factors, misidentification scale factors, and simulation-based contamination terms in the CRs. Within the validation region, two pseudo-SRs are defined in which the AK8 jet is W tagged or $\mathrm{b\bar{b}}$ tagged, respectively. For each pseudo-SR, a 0ℓ antitag CR and 1ℓ tag and antitag CRs are defined for the background estimation. All transfer factors are rederived in the validation region phase space. Predictions and observations in the pseudo-SRs are found to be statistically compatible.

6 Systematic uncertainties

For all SRs and CRs, the expected rate of signal and backgrounds is adjusted for known differences between data and simulation in the jet tagging rates (using the b, $\mathrm{b\bar{b}}$, W, and V taggers), lepton identification rates, and trigger efficiencies. Additional corrections are applied to the predicted signal yields to account for known differences between the GEANT4-based CMS detector simulation and the CMS fast simulation. These corrections depend on the AK8 jet mass, W tagging, V tagging, $\mathrm{b\bar{b}}$ tagging, and $p_{\mathrm{T}}^{\mathrm{miss}}$. Uncertainties associated with the determination of these correction factors are propagated to our final yield estimates, as is the uncertainty in the integrated luminosity. Uncertainties related to the determination of the trigger efficiency are dominated by the limited size of the data sets in which we measure the trigger efficiency at high $p_{\mathrm{T}}^{\mathrm{miss}}$ and by the differences between the efficiencies determined using two classes of events, namely events with one muon and events with one electron, at low $p_{\mathrm{T}}^{\mathrm{miss}}$. Uncertainties related to the corrections to the rates of jet misidentification are due to the limited size of our dilepton data sets. Uncertainties associated with the lepton identification efficiency corrections and jet tagging rate corrections are detailed in Refs. [84, 85] and Refs. [47, 83], respectively. Additional uncertainties associated with the choice of the QCD renormalization and factorization scales μ_{R} and μ_{F} were assessed by varying them up and down by a factor of 2. The corrections to the jet tagging rates in the b-veto SR and CRs derived from the validation regions described in Section 5.1 are treated as systematic uncertainties, and are referred to as the "non-closure" uncertainties in Table 3. All systematic uncertainties are modeled in the likelihood used to extract the results of the analysis as log-normal prior probability distributions except for the uncertainties due to the finite sizes of the MC samples and the CRs, for which we use the method described in Ref. [90]. Summaries of the dominant systematic uncertainties and their impacts on the yields of the various sources of background and the signal are presented in Table 3.

Among these uncertainties, except for those from the sizes of the CR data and MC samples, the two leading systematic uncertainties that affect the 95% confidence level upper limits on the signal production cross sections discussed in the next section are the W-tag non-closure and W-tag correction uncertainties. These degrade the cross section upper limits by up to about 15% and 10%, respectively, depending on the signal model and the SUSY particle masses. The others have much smaller impacts.

Table 3: Summary of the dominant systematic uncertainties (in %) in various analysis regions. For the 0- and 1-res backgrounds in the b-veto SR, uncertainties are presented separately depending on the CR region used for the estimation. A dash (—) indicates that the source of uncertainty is not applicable.

Source	b veto				b tag			
	0- and 1-res bkg.		Rare	Signal	Top	0-res	Rare	Signal
	0-tag CR	1-tag CR						
Luminosity	—	—	1.6	1.6	—	—	1.6	1.6
CR data size	6–71	5–50	—	—	3–100	2–35	—	—
MC sample size	8–25	8–30	14–24	2–5	2–28	3–40	4–27	2–5
μ_R, μ_F scales	1.2	0.4	8	<5	2–10	0.5	11	<5
Trigger efficiency	—	—	2–3	2–3	—	—	2–3	2–3
b-tag correction	<1	<1	<1	1	1	<3	<3	2–3
$b\bar{b}$-tag correction	—	—	—	—	—	4	2–7	4
W-tag correction	12–28	6–22	11–15	15	1	9	7	9
V-tag correction	7–15	2–10	1–4	2	—	—	—	—
W-tag non-closure	3–48	3–48	—	—	—	—	—	—
V-tag non-closure	1–27	—	—	—	—	—	—	—
Fast-simulation	—	—	—	5	—	—	—	8

7 Results

We perform simultaneous fits to our SRs and CRs using a statistical model of our SM background predictions. This fitting procedure further constrains the predictions and the uncertainties in the predictions. The predicted SM backgrounds based on this procedure, the observations, and the predicted signal yields in each of the SRs are shown in Fig. 3. No statistically significant excess of events is observed in the data with respect to the SM background predictions.

We place 95% confidence level (CL) upper limits on the production cross section of either pairs of charginos or a chargino and a neutralino together. A test statistic is used in conjunction with the CL_s criterion [91, 92] to set upper limits. The test statistic is defined as $q_\mu = -2\ln(\mathcal{L}_\mu/\mathcal{L}_{max})$, where $\mathcal{L}_\mu$ refers to the likelihood at a fixed value of the signal strength μ after minimizing with respect to all other parameters of the likelihood and $\mathcal{L}_{max}$ refers to the maximum value of the likelihood for any value of μ. We compute limits using the asymptotic approximation [93], and we compute expected limits by evaluating the test statistic using the predicted background yields varied within their Poisson uncertainties.

By comparing the upper limits on the production cross sections to the cross sections predicted for chargino-pair production and for chargino-neutralino production, 95% CL mass exclusion contours are derived. The 95% CL mass exclusion contours within the NLSP-LSP mass plane are shown in Fig. 4 (upper left and upper right) for the TChiWW and TChiWZ models. We exclude NLSP masses between 290 and 670 GeV assuming a pair of charginos are produced and result in a pair of W bosons and a pair of light LSPs in the final state. For low-mass LSPs, we exclude NLSP masses between 230 and 760 GeV assuming chargino-neutralino production resulting in W and Z bosons and a large p_T^{miss} in the final state. In the case of chargino-neutralino production with a W boson and a Higgs boson in the final state, for low-mass LSPs we exclude NLSP masses less than 970 GeV. Fig. 4 (bottom) shows 2-dimensional limits with varying LSP masses.

We also consider models including both $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production where the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$

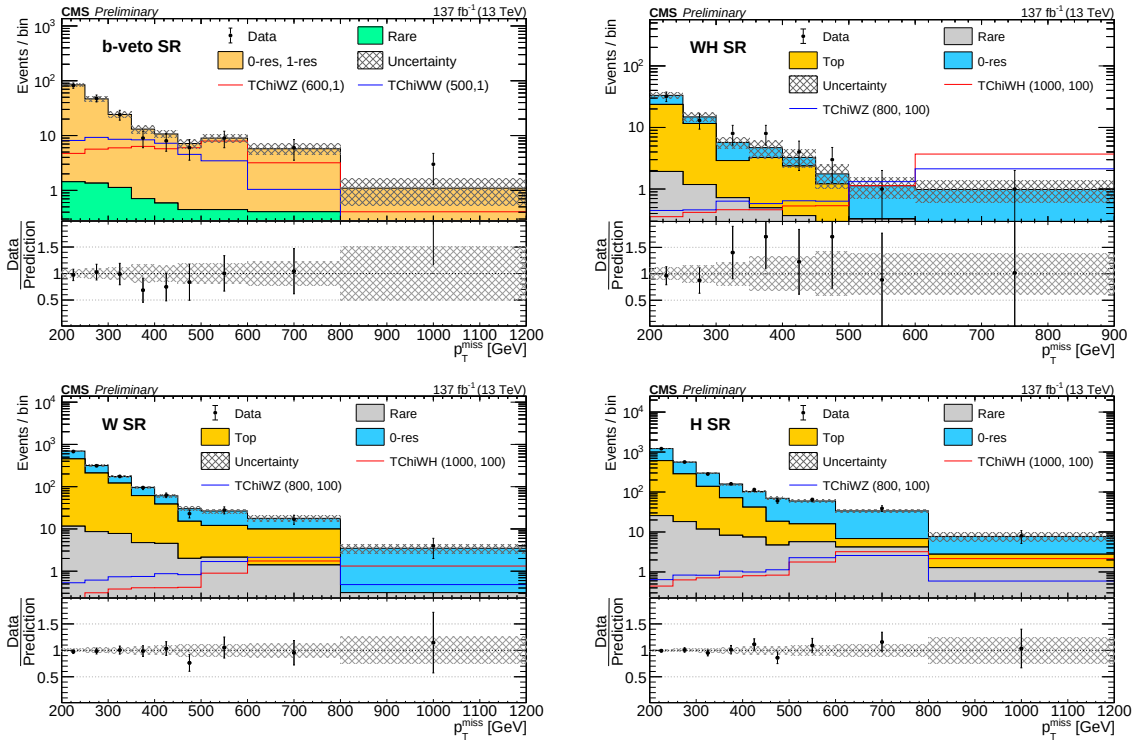

Figure 3: Prediction vs. observation in the b-veto SR (upper left), the WH SR (upper right), the W SR (lower left), and the H SR (lower right). The filled histograms show the SM background predictions, and the open histograms show the expectations for selected signal models, which are denoted in the legend by the name of the model followed by the assumed masses of the NLSP and LSP. The observed event yields are indicated by black markers. The hatched gray band corresponds to the total uncertainty in the prediction after the fit to the SRs and CRs under the background-only hypothesis.

are the mass-degenerate wino-like NLSPs. The expected and observed mass exclusions are presented in Fig. 5 (left). For the scenarios of $\widetilde{\chi}_2^0 \to \mathrm{Z}\widetilde{\chi}_1^0$ or $\widetilde{\chi}_2^0 \to \mathrm{H}\widetilde{\chi}_1^0$, wino-like NLSP masses up to 870 and 960 GeV are excluded, respectively, while exclusions up to 1010 and 1110 GeV are expected under the background-only hypothesis.

Figure 5 (right) shows the results for the mass-degenerate higgsino-like NLSP scenario including $\widetilde{\chi}_1^\pm\widetilde{\chi}_1^\mp$, $\widetilde{\chi}_1^\pm\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^\pm\widetilde{\chi}_3^0$, and $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$ production. Assuming $\widetilde{\chi}_2^0 \to \mathrm{Z}\widetilde{\chi}_1^0$ and $\widetilde{\chi}_3^0 \to \mathrm{H}\widetilde{\chi}_1^0$, we expect signal events with WW, WZ, WH, or ZH boson pairs and large $p_\mathrm{T}^\mathrm{miss}$ in the final state. In this scenario, higgsino-like NLSP masses from 300 to 620 GeV are excluded. The expected exclusion reaches from 320 to 810 GeV. The observed exclusion is weaker than expected mainly because of a modest excess in the data over the background prediction in the $300 < p_\mathrm{T}^\mathrm{miss} < 500$ GeV region of the WH SR.

8 Summary

A search is presented for signatures of electroweak production of charginos and neutralinos in fully hadronic final states. The charginos are assumed to decay to the W boson and the lightest neutralino $\widetilde{\chi}_1^0$, and the neutralinos (other than $\widetilde{\chi}_1^0$) are assumed to decay to either the Z or Higgs boson and $\widetilde{\chi}_1^0$. The decay products of W, Z, or Higgs bosons are clustered into large-radius jets. These jets are categorized based on their mass and a collection of novel jet-tagging algorithms

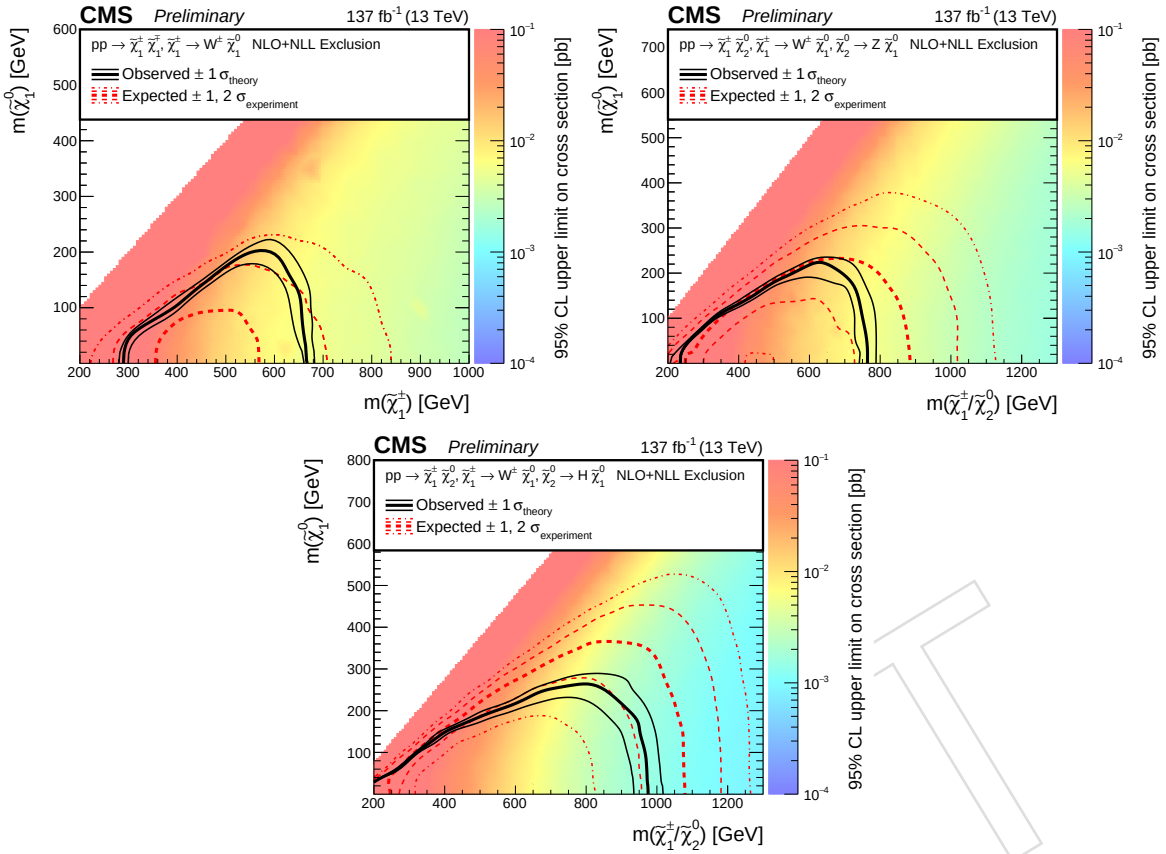

Figure 4: Expected and observed 95% CL upper limits on the production cross section for $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ production assuming they each decay to a W boson (upper left) and $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ production assuming they decay to a W boson and a Z boson (upper right) or to a W boson and a Higgs boson (lower). The red and black contours represent the expected and observed mass exclusion limits, respectively. The mass exclusion limits are computed assuming wino-like cross sections.

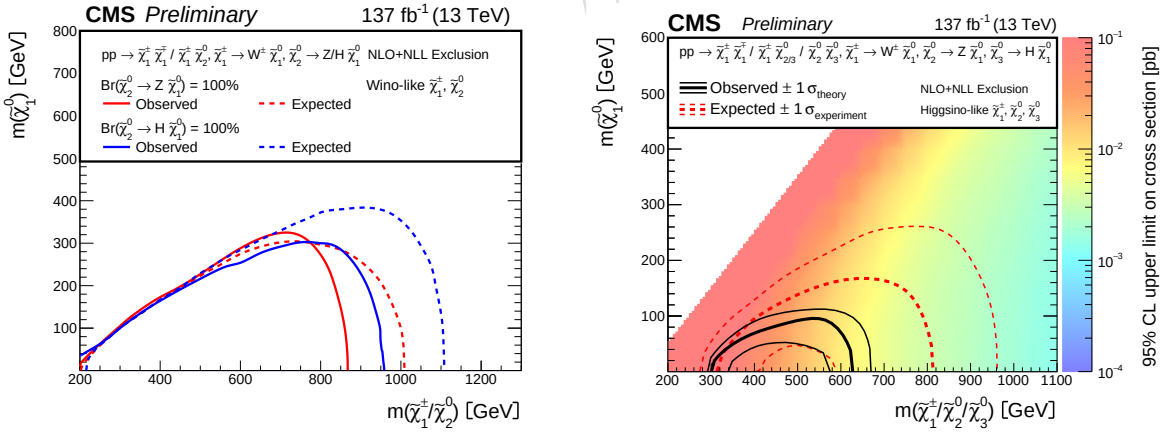

Figure 5: Expected and observed 95% CL exclusion for mass-degenerate wino-like $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ and $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ production (left) and higgsino-like $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_3^0$, and $\widetilde{\chi}_2^0\widetilde{\chi}_3^0$ production (right) as functions of the NLSP and LSP masses. The $\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_2^0$, and $\widetilde{\chi}_3^0$ are considered to be mass degenerate.

based on deep neural networks. Four search regions are constructed to look for chargino- and neutralino-mediated production of a pair of W bosons, a pair of W and Z bosons, or a pair of W

and Higgs bosons, together with a large transverse momentum imbalance in the final state. We consider simplified models in which the charginos $\widetilde{\chi}_1^{\pm}$ and the next-to-lightest neutralino $\widetilde{\chi}_2^0$ are assumed to be mass-degenerate next-to-lightest supersymmetric particles (NLSP), and the lightest neutralino $\widetilde{\chi}_1^0$ is assumed to be bino-like and to be the lightest supersymmetric particle (LSP). No statistically significant excess of events is observed in the data with respect to the expectation from the standard model.

Using wino-like pair production cross sections, 95% confidence level mass exclusions are derived. For signals with WW, WZ, or WH final states, the NLSP mass exclusion limit for low-mass LSPs extends up to 670, 760, and 970 GeV, respectively. When we consider models including both wino-like NLSP $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^{\mp}$ production under the assumption that either $\widetilde{\chi}_2^0 \to \mathrm{Z}\widetilde{\chi}_1^0$ or $\widetilde{\chi}_2^0 \to \mathrm{H}\widetilde{\chi}_1^0$, the NLSP mass exclusion extends up to 870 and 960 GeV, respectively. Alternatively, with higgsino-like NLSPs $\widetilde{\chi}_1^{\pm}$, $\widetilde{\chi}_2^0$, and $\widetilde{\chi}_3^0$, the higgsino mass exclusion extends up to 620 GeV. These mass exclusions are the most stringent constraints to date set by CMS at high NLSP masses.

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