

Combined search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13$ TeV



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ABSTRACT: A statistical combination of several searches for the electroweak production of charginos and neutralinos is presented. All searches use proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded with the CMS detector at the LHC in 2016 and corresponding to an integrated luminosity of 35.9 fb^{-1} . In addition to the combination of previous searches, a targeted analysis requiring three or more charged leptons (electrons or muons) is presented, focusing on the challenging scenario in which the difference in mass between the two least massive neutralinos is approximately equal to the mass of the Z boson. The results are interpreted in simplified models of chargino-neutralino or neutralino pair production. For chargino-neutralino production, in the case when the lightest neutralino is massless, the combination yields an observed (expected) limit at the 95% confidence level on the chargino mass of up to 650 (570) GeV, improving upon the individual analysis limits by up to 40 GeV. If the mass difference between the two least massive neutralinos is approximately equal to the mass of the Z boson in the chargino-neutralino model, the targeted search requiring three or more leptons obtains observed and expected exclusion limits of around 225 GeV on the second neutralino mass and 125 GeV on the lightest neutralino mass, improving the observed limit by about 60 GeV in both masses compared to the previous CMS result. In the neutralino pair production model, the combined observed (expected) exclusion limit on the neutralino mass extends up to 650–750 (550–750) GeV, depending on the branching fraction assumed. This extends the observed exclusion achieved in the individual analyses by up to 200 GeV. The combined result additionally excludes some intermediate gaps in the mass coverage of the individual analyses.

KEYWORDS: Hadron-Hadron scattering (experiments), Supersymmetry

ARXIV EPRINT: [1801.03957](https://arxiv.org/abs/1801.03957)

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1 Introduction

Supersymmetry (SUSY) [1–8] is an extension of the standard model (SM) of particle physics. It posits a new symmetry such that for each boson (fermion) in the SM, there exists a fermionic (bosonic) superpartner. Supersymmetry can potentially address several of the open questions in particle physics, including the hierarchy problem [9–11] and the unification of the gauge couplings at high energy scales [12, 13]. If R -parity [14] is conserved, the lightest SUSY particle (LSP) is stable and could be a potential dark matter candidate [15, 16].

This paper focuses on searches for electroweak production of SUSY particles, under the assumption that the strongly-coupled SUSY particles are too massive to be directly produced. The superpartners of the bosons from the SM $SU(2)$ and $U(1)$ gauge fields before electroweak symmetry breaking are denoted as the winos and bino, respectively. We consider SUSY models assuming two complex Higgs doublets, and the superpartners of the Higgs bosons are denoted as higgsinos. The bino, winos, and higgsinos form mass

eigenstates of two charginos ($\tilde{\chi}^\pm$) and four neutralinos ($\tilde{\chi}^0$) and in general can mix among one another. In this paper, we focus on the lightest neutralino ($\tilde{\chi}_1^0$), the next-to-lightest neutralino ($\tilde{\chi}_2^0$), and the lightest chargino ($\tilde{\chi}_1^\pm$). If the superpartners of the SM leptons, the sleptons, are much heavier than the charginos and neutralinos, decays of the charginos and neutralinos proceed through the W, Z, and Higgs bosons. The branching fractions of neutralinos to the Z and Higgs bosons depend on the mixing among the bino, winos, and higgsinos to form mass eigenstates.

Searches performed at LEP exclude promptly-decaying charginos below a mass of 103.5 GeV [17]. At the LHC, several searches have been performed by the ATLAS [18–29] and CMS [30–43] Collaborations looking for direct production of charginos and neutralinos. Given the various possible decay modes, a SUSY signal could simultaneously populate multiple final states. This paper implements a statistical combination of the searches performed by CMS in refs. [38–43] covering several final states to improve upon the sensitivity of the individual analyses, particularly in models where the neutralino has a nonzero branching fraction to both Z and Higgs bosons. In addition, we present an extension of a search selecting events with three or more charged leptons [38]. It targets the difficult region of phase space where the difference in mass between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is approximately equal to the Z boson mass, and the signal has similar kinematic properties to the dominant background of SM WZ production. All searches use a data sample of LHC proton-proton collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment in 2016, corresponding to an integrated luminosity of 35.9 fb $^{-1}$.

2 Signal models

Simplified models of SUSY [44–47] are used to interpret the combined search results presented below. In this paper, “H” refers to the 125 GeV scalar boson [48], interpreted as the lightest CP-even state of an extended Higgs sector. The H boson is expected to have SM-like properties if all of the other Higgs bosons are much heavier [49]. All signal models considered involve the production of two bosons (W, Z, or H) through SUSY decays, and we denote each model by the specific bosons produced. The W, Z, and H bosons are always assumed to decay according to their SM branching fractions. The sleptons are always assumed to have much higher masses than the charginos and neutralinos such that they do not contribute to the interactions.

The first class of models assumes $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production. The $\tilde{\chi}_1^0$ is assumed to be the LSP. The $\tilde{\chi}_1^\pm$ always decays to the W boson and the $\tilde{\chi}_1^0$, while the $\tilde{\chi}_2^0$ can decay to either of the Z or H bosons plus the $\tilde{\chi}_1^0$. We consider three choices for the $\tilde{\chi}_2^0$ decay: a branching fraction of 100% to $Z\tilde{\chi}_1^0$ (WZ topology), of 100% to $H\tilde{\chi}_1^0$ (WH topology), and of 50% to each of these two decays (mixed topology). This model is depicted in figure 1, showing the two possible decays. The production cross sections are computed in the limit of mass-degenerate winos $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, and light bino $\tilde{\chi}_1^0$, with all other sparticles assumed to be heavy and decoupled.

The second class of models assumes $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production. For bino- or wino-like neutralinos, the neutralino pair production cross section is very small, and thus we consider a specific gauge-mediated SUSY breaking (GMSB) model with quasidegenerate higgsi-

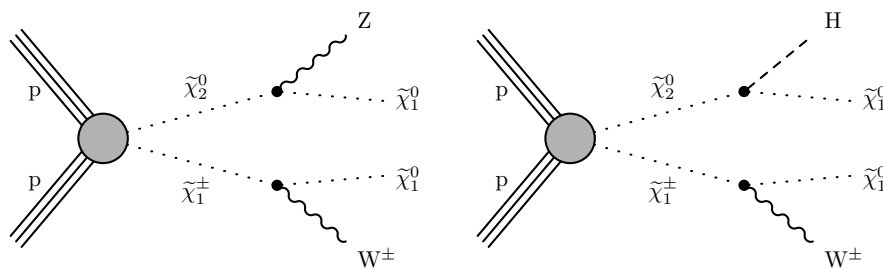


Figure 1. Production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ with the $\tilde{\chi}_1^\pm$ decaying to a W boson and the LSP, $\tilde{\chi}_1^0$, and the $\tilde{\chi}_2^0$ decaying to either (left) a Z boson and the $\tilde{\chi}_1^0$ or (right) a H boson and the $\tilde{\chi}_1^0$.

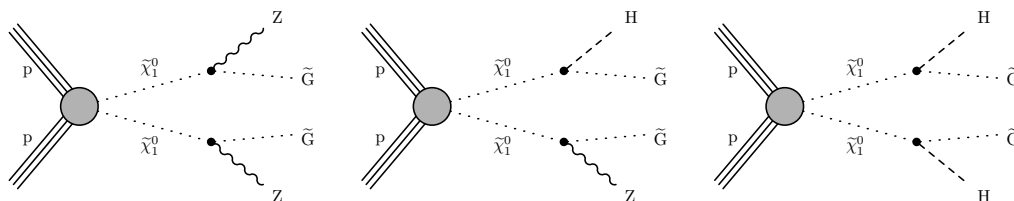


Figure 2. A GMSB model with $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ pair production. The two $\tilde{\chi}_1^0$ particles decay into the $\tilde{G}$ LSP and (left) both to Z bosons, (center) a Z and a H boson, or (right) both to H bosons.

nos as next-to-lightest SUSY particles and an effectively massless gravitino ($\tilde{G}$) as the LSP [50–52]. In the production of any two of these, $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$ decays immediately to $\tilde{\chi}_1^0$ and low-momentum particles that do not impact the analysis, effectively yielding pair production of $\tilde{\chi}_1^0 \tilde{\chi}_1^0$. The $\tilde{\chi}_1^0$ then decays to a $\tilde{G}$ and either a Z or H boson, and we consider varying branching fractions from 100% decay into the Z boson to 100% decay into the H boson including intermediate values. The possible decays in this model are shown in figure 2.

The production cross sections for the GMSB scenario are computed in a limit of mass-degenerate higgsino states $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^0$, with all the other sparticles assumed to be heavy and decoupled. Following the convention of real mixing matrices and signed neutralino masses [53], we set the sign of the mass of $\tilde{\chi}_1^\pm$ ($\tilde{\chi}_2^0$) to +1 (−1). The lightest two neutralino states are defined as symmetric (antisymmetric) combinations of higgsino states by setting the product of the elements N_{i3} and N_{i4} of the neutralino mixing matrix N to +0.5 (−0.5) for $i = 1$ (2). The elements U_{12} and V_{12} of the chargino mixing matrices U and V are set to 1.

Cross section calculations to next-to-leading order (NLO) plus next-to-leading-logarithmic (NLL) accuracy [54–59] in perturbative quantum chromodynamics (QCD) are used to normalize the signal samples for the results presented in sections 6 and 7. In this section, we present cross sections calculated to NLO accuracy [56] to demonstrate the dependence of the cross section values on assumptions made in decoupling other SUSY particles. The same qualitative conclusions also hold for the NLO+NLL calculations used in the final results.

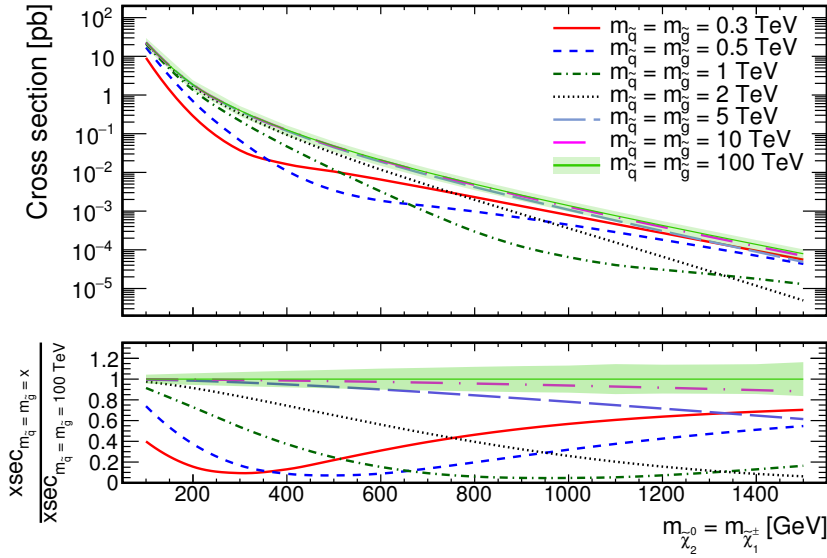


Figure 3. Cross section for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production at $\sqrt{s} = 13$ TeV versus the wino mass, calculated to NLO accuracy in QCD with RESUMMINO [56]. The $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are assumed to be mass-degenerate winos. The various curves show different assumptions on the masses of the squarks and gluinos, as described in the legend. The green band shows the theoretical uncertainty in the cross section calculation, from the variation of renormalization and factorization scales as well as parton density functions, for the 100 TeV squark and gluino mass assumption.

Figure 3 shows the NLO cross section for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production at $\sqrt{s} = 13$ TeV assuming mass-degenerate winos $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. The various curves show different assumptions on the masses of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), as described in the legend. The cross section depends significantly on the masses of the strongly coupled particles until they reach masses of at least 10 TeV. For the range of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses considered here, the reduction can make up to 90% in the cross section value. This is due to large destructive interference effects from t -channel diagrams involving squark exchange. The cross section calculation used in the interpretations of the analysis results assumes a mass of 100 TeV for the squarks and gluinos to have them fully decoupled. The obtained results would be less stringent if lower masses were assumed for the squarks and gluinos. We performed the same study for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$, and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ production with the assumption of mass-degenerate higgsinos $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^0$. The dependence of the production cross section on the decoupling mass assumption was found to be much smaller in the higgsino case, at most a few percent, and it is small compared to the uncertainty in the cross section calculation.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, that provides an axial magnetic field of 3.8 T. The bore of the solenoid is outfitted with various particle detection systems. Charged-particle trajectories are measured by silicon pixel and strip trackers, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$,

where the pseudorapidity η is defined as $-\log[\tan(\theta/2)]$, with θ being the polar angle of the trajectory of the particle with respect to the clockwise beam direction. A crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter (HCAL) surround the tracking volume. The calorimeters provide energy and direction measurements of electrons, photons, and hadronic jets. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing for energy balance measurements in the plane transverse to the clockwise beam direction. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. 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. [60].

4 Event reconstruction and Monte Carlo simulation

Event reconstruction is based on the particle-flow (PF) algorithm [61], which optimally combines information from the tracker, calorimeters, and muon systems to reconstruct and identify PF candidates, i.e., charged and neutral hadrons, photons, electrons, and muons. To select collision events, we require at least one reconstructed vertex. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex, where p_T is the transverse momentum with respect to the beam axis. The physics objects are the objects returned by a jet finding algorithm [62, 63] applied to all charged tracks associated with the vertex, plus the corresponding associated missing transverse momentum. The missing transverse momentum vector, $\vec{p}_T^{\text{miss}}$, is defined as the negative vector sum of the momenta of all reconstructed PF candidates projected onto the plane perpendicular to the proton beams. Its magnitude is referred to as p_T^{miss} . Events with possible contributions from beam halo processes or anomalous noise in the calorimeters can have large values of p_T^{miss} and are rejected using dedicated filters [64].

Electron candidates are reconstructed starting from a cluster of energy deposits in the ECAL. The cluster is then matched to a reconstructed track. The electron selection is based on the shower shape, the ratio of energy measured in the HCAL to that measured in the ECAL, track-cluster matching, and consistency between the cluster energy and the track momentum [65]. Muon candidates are reconstructed by performing a global fit that requires consistent hit patterns in the tracker and the muon system [66]. Photon candidates are reconstructed from a cluster of energy deposits in the ECAL, and they are required to pass criteria based on the shower shape and the ratio of energy measured in the HCAL to that measured in the ECAL [65]. Hadronically decaying tau lepton candidates (τ_h) are reconstructed from PF candidates with the “hadron-plus-strips” algorithm [67]. Electron, muon, photon, and τ_h candidates are required to be isolated from other particles, and electron, muon, and τ_h candidates must satisfy requirements on the transverse and longitudinal impact parameters relative to the primary vertex.

PF candidates are clustered to form jets using the anti- k_T clustering algorithm [62] with a distance parameter of 0.4, as implemented in the FASTJET package [63]. Identification

of jets originating from b quarks (b jets) is performed with either the combined secondary vertex (CSVv2) algorithm [68] or the DeepCSV algorithm [69]. Data events are selected using a variety of triggers requiring the presence of electrons, muons, photons, jets, or p_T^{miss} , depending on the final state targeted in each analysis.

Monte Carlo (MC) simulated samples are used in the various searches to estimate the background from some SM processes, to assess systematic uncertainties in prediction methods that rely on data, and to calculate the selection efficiency for signal models. Most SM background samples are produced with the MADGRAPH5_aMC@NLO v2.2.2 or v2.3.3 generator [70] at leading order (LO) or NLO accuracy in perturbative QCD, including up to four additional partons in the matrix element calculations, depending on the process and calculation order. Other samples are produced with the POWHEG v2 [71, 72] generator without additional partons in the matrix element calculations. Standard model WZ production in particular is modeled with MADGRAPH5_aMC@NLO v2.2.2 at NLO precision for the search described in section 6, which requires a precise description of initial-state radiation (ISR). In other cases, POWHEG v2 is used. The NNPDF3.0 LO or NLO [73] parton distribution functions (PDFs) are used in the event generation. Parton showering and fragmentation in all of these samples are performed using the PYTHIA v8.212 [74] generator and the CUETP8M1 tune [75]. A double counting of the partons generated with MADGRAPH5_aMC@NLO and those with PYTHIA is removed using the MLM [76] and the FxFx [77] matching schemes, in the LO and NLO samples, respectively. Cross section calculations at NLO or next-to-NLO [70, 78–82] are used to normalize the simulated background samples.

Signal samples are generated with MADGRAPH5_aMC@NLO at LO precision, including up to two additional partons in the matrix element calculations. Cross section calculations to NLO plus NLL accuracy [55, 56, 83] are used to normalize the signal samples. For these samples we improve on the modeling of ISR, which affects the total transverse momentum of the system of SUSY particles (p_T^{ISR}), by reweighting the p_T^{ISR} distribution in these events. This reweighting procedure is based on experimental studies of the p_T of Z bosons [84]. The reweighting factors range between 1.18 (at $p_T^{\text{ISR}} = 125$ GeV) and 0.78 (for $p_T^{\text{ISR}} > 600$ GeV). We take the deviation from 1.0 as the systematic uncertainty in the reweighting procedure.

For both signal and background events, additional simultaneous proton-proton interactions (pileup) are generated with PYTHIA and superimposed on the hard collisions. The response of the CMS detector for SM background samples is simulated using a GEANT4-based model [85], while that for new physics signals is performed using the CMS fast simulation package [86]. All simulated events are processed with the same chain of reconstruction programs as used for collision data. Corrections are applied to simulated samples to account for differences between the trigger, b tagging, and lepton and photon selection efficiencies measured in data and the GEANT4 simulation. Additional differences arising from the fast simulation modeling of selection efficiencies, as well as from the modeling of p_T^{miss} , are corrected in the fast simulation and included in the systematic uncertainties considered.

Search	Signal topology				
	WZ	WH	ZZ	ZH	HH
1 ℓ 2 b		✓			
4 b					✓
2 ℓ on-Z	✓		✓	✓	
2 ℓ soft	✓				
$\geq 3\ell$	✓	✓	✓	✓	✓
H($\gamma\gamma$)		✓		✓	✓

Table 1. Summary of all experimental searches considered in the combination (rows), and the signal topologies for which each search is used in the combined results (columns). The searches are described in sections 5.1 through 5.6 and section 6. The $\geq 3\ell$ search described in section 5.5 is used for all signal topologies except for WZ, where the reoptimized search strategy from section 6 is employed instead.

5 Individual searches

The experimental searches included in the combination are briefly described here. Table 1 lists which searches are used to place exclusion limits for each of the topologies introduced in section 2. The selections for all searches were checked to be mutually exclusive, such that no events fulfill the signal region requirements for more than one search. No significant deviations from the SM predictions were observed in any of these searches.

5.1 Search for one lepton, two b jets, and p_T^{miss}

The “1 ℓ 2 b ” search [43], targeting the WH topology, selects events with exactly one charged lepton (e or μ), exactly two b jets, and large p_T^{miss} . The invariant mass of the two b jets is required to be consistent with the mass of the H boson. Kinematic variables are used to suppress backgrounds, which predominantly come from dileptonic decays in $t\bar{t}$ production. Two exclusive signal regions are defined based on p_T^{miss} : $125 \leq p_T^{\text{miss}} < 200$ GeV and $p_T^{\text{miss}} \geq 200$ GeV. The SM backgrounds are predicted using MC simulation, with the predictions validated in data control regions distinct from the signal region.

5.2 Search for four b jets and p_T^{miss}

The “4 b ” search [41], targeting the HH topology, selects events with exactly four or five jets, with at least two of them identified as b jets, large p_T^{miss} , and no charged leptons. In each event, the four jets with the highest b tagging discriminator scores are considered to form dijet H candidates. There are three possible groupings to make two pairs of jets. The grouping is selected to minimize the difference between the invariant masses of the two dijet pairs, and the difference in masses is required to be less than 40 GeV. The average invariant mass of the two pairs is then required to be consistent with the mass of the H boson. Exclusive signal regions are defined based on the number of b jets (three or at least four) and multiple bins in p_T^{miss} . The primary background to this search comes from semileptonic decays in $t\bar{t}$ production, with smaller contributions from W or Z production in association with jets and from QCD multijet production. The backgrounds are predicted using data control samples that require either exactly two b jets or an average dijet invariant mass inconsistent with the H boson.

5.3 Search for two leptons consistent with a Z boson, jets, and p_T^{miss}

The “ 2ℓ on-Z” search [42], targeting the WZ, ZZ, and ZH topologies, selects events with exactly two opposite-sign, same-flavor (OSSF) leptons (e^+e^- or $\mu^+\mu^-$) consistent with the Z boson mass, at least two jets, and large p_T^{miss} . In the signal region targeting the WZ and ZZ topologies, two jets are required to have an invariant mass less than 110 GeV to be compatible with the W and Z boson masses, and events with b jets are rejected. To target the ZH topology, events are required to have two b jets with an invariant mass less than 150 GeV to be compatible with the H boson mass. Signal regions are defined with multiple exclusive bins in p_T^{miss} . The backgrounds fall into three categories. First, flavor symmetric backgrounds, such as $t\bar{t}$ production, yield $e^\pm\mu^\mp$ events at the same rate as e^+e^- and $\mu^+\mu^-$ events combined, and they are predicted from a data control sample of $e^\pm\mu^\mp$ events. Second, events with a Z boson and mismeasured jets give instrumental p_T^{miss} , and they are predicted from a data control sample of γ +jets events. Third, events with a Z boson and at least one prompt neutrino, arising from processes such as WZ, ZZ, and $t\bar{t}Z$ production, are estimated using simulation.

5.4 Search for two soft leptons and p_T^{miss}

The “ 2ℓ soft” search [39] selects events with exactly two low- p_T leptons (e^+e^- or $\mu^+\mu^-$ in the relevant selections), jets, and large p_T^{miss} . It targets the WZ topology where the mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is small such that the W and Z bosons are off-shell, and the observable decay products have low momentum. The leptons are required to satisfy $5 < p_T < 30$ GeV and have an invariant mass in the range $4 < m_{\ell\ell} < 50$ GeV, strongly suppressing SM backgrounds while retaining good acceptance for compressed signal scenarios. Additional kinematic requirements are applied to further reduce backgrounds, and the relevant signal regions are binned in $m_{\ell\ell}$ and p_T^{miss} . The largest backgrounds arise from Z/γ^* and $t\bar{t}$ production, as well as misidentification of nonprompt leptons. The first two are predicted from simulation with constraints from data control regions, while the latter is predicted entirely using data.

5.5 Search for three or more leptons, and p_T^{miss}

The “ $\geq 3\ell$ ” search [38] selects events with three or more leptons (e, μ , and up to two τ_h) and large p_T^{miss} . Several exclusive categories are defined based on the number of leptons, lepton flavor and charge, the presence of an OSSF pair, and kinematic variables such as the invariant mass of the OSSF pair and p_T^{miss} . Events with a b jet are rejected to reduce the background from $t\bar{t}$ production. The various categories are designed to give this search sensitivity for a wide range of new physics models, including all of the topologies introduced in section 2. The best performance is seen in the WZ and ZZ models, while the lower branching fraction of the H boson to leptons reduces the sensitivity to other models. The SM backgrounds in this search vary across the categories, and the most important for the relevant regions in these interpretations are SM WZ and ZZ production, and events with misidentified nonprompt leptons. The former are predicted using simulation, which in case of WZ is validated in a set of dedicated control regions, while the latter are predicted entirely from data.

A further optimization of this analysis has been performed for the WZ topology in the case where the difference in the masses of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is equal to the Z boson mass, focusing on a category selecting events with three light-flavor leptons (e, μ). This update is presented in section 6.

5.6 Search for a H boson decaying to diphotons and p_T^{miss}

The “H($\gamma\gamma$)” search [40] selects events with two photons consistent with the H boson mass, along with jets and large p_T^{miss} . Events are categorized based on the p_T of the diphoton system, the expected resolution on the diphoton mass, the presence of two b jets compatible with the H or Z boson masses, and the razor kinematic variables [87, 88]. It exhibits sensitivity to the WH, ZH, and HH topologies. The background arises either from γ +jets or SM H boson production. The former is estimated using a fit to the diphoton mass spectrum in a wider range than the signal window, while the latter is predicted using simulation.

6 Search for three light leptons consistent with WZ production and p_T^{miss}

The multilepton search described in section 5.5 contains a category selecting events with three light-flavor leptons (e, μ), two of which must form an OSSF pair. This final state aims to provide sensitivity for a variety of SUSY models, including the WZ topology depicted in figure 1 (left). The dominant background in this search category is SM WZ production.

Exclusion limits on the WZ topology were placed in ref. [38], and the sensitivity was found to be significantly reduced for $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx m_Z$, referred to here as the “WZ corridor.” In this case, SUSY signal is kinematically similar to the SM background. We present here a further optimization of the search for the WZ topology designed to target this challenging region of phase space. The search methodology remains the same as in ref. [38], but the event categorization has been updated as described below.

We require events to have three light-flavor leptons with two forming an OSSF pair. Events are categorized using the following kinematic variables: p_T^{miss} , the invariant mass $m_{\ell\ell}$ of the OSSF pair, and the transverse mass M_T of the third lepton computed with respect to p_T^{miss} . Three bins in $m_{\ell\ell}$ are defined to separate contributions from on- and off-shell Z boson decays, and three bins are defined in M_T to separate the SM W boson contribution.

To improve the separation between signal and background in the WZ corridor, we exploit ISR by further categorizing the events in H_T , the scalar p_T sum of the jets with $p_T > 30$ GeV. Due to the presence of the $\tilde{\chi}_1^0$ LSPs, signal model points in the WZ corridor will tend to have more events at high values of p_T^{miss} and M_T than the SM background for the same value of H_T , with the effect becoming relevant at $m_{\tilde{\chi}_1^0} \approx m_Z$ and more pronounced at higher H_T . This is demonstrated in figure 4, which shows the expected distributions of p_T^{miss} for background and two signal model points after requiring (left) $H_T < 100$ GeV and (right) ≥ 200 GeV. The H_T categorization is applied in the regions $m_{\ell\ell} < 75$ GeV and $75 \leq m_{\ell\ell} < 105$ GeV. The full set of search regions is summarized in table 2.

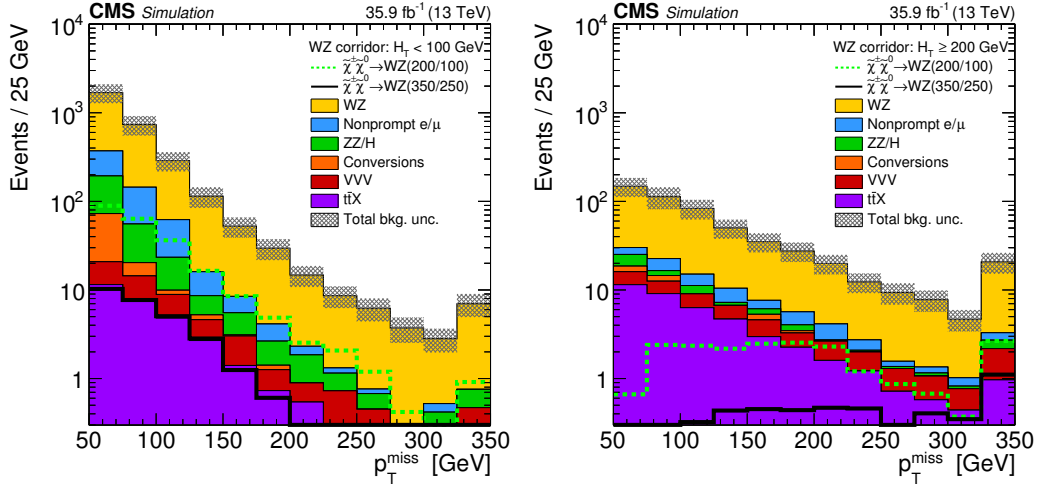


Figure 4. Distributions of p_T^{miss} for two representative signal points in the WZ corridor as well as the expected SM background for $H_T < 100$ (left) and ≥ 200 GeV (right). The mass values for the signal points are given as $(m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^0})$ in GeV. For larger values of H_T , the shape difference between signal and background becomes more pronounced due to the presence of $\tilde{\chi}_1^0$ LSPs with large Lorentz boost.

The dominant background in this search is SM WZ production, which provides a signature very similar to the signal process in the form of three isolated leptons and substantial p_T^{miss} due to the neutrino from the W boson decay. This background is estimated from simulation, while two control regions are used to assess the overall normalization and to validate the modeling of events at large values of p_T^{miss} , M_T , or both. Further backgrounds arise from misidentification of nonprompt leptons from processes like $t\bar{t}$ production, external and internal photon conversions, and rare SM processes such as triboson production, $t\bar{t}W$, and $t\bar{t}Z$. The contribution of the nonprompt lepton background is predicted using the “tight-to-loose” ratio method [89], which relies entirely on data. External and internal photon conversions as well as rare SM processes are predicted from simulation, and a dedicated data control region is used to constrain the normalization of the conversion background.

The SM WZ background normalization is constrained in a data control region requiring $75 \leq m_{\ell\ell} < 105$ GeV, $M_T < 100$ GeV, $35 < p_T^{\text{miss}} < 100$ GeV, and $H_T < 100$ GeV. The fraction of selected background events arising from SM WZ production in this region is approximately 86%. The validation of the p_T^{miss} and M_T shape modeling is done using a data control sample enriched in $W\gamma$ events, with the remainder of events coming mainly from W +jets production. A photon with $p_T > 40$ GeV is required together with a lepton and $p_T^{\text{miss}} \geq 50$ GeV, corresponding to a leptonic W boson decay. The minimum photon p_T threshold ensures that the photon does not arise from final-state radiation. The motivation behind this selection is that the W boson M_T distribution in both $W\gamma$ and W +jets events is found to be consistent with that of SM WZ production. A systematic uncertainty is assigned to the signal region bins with high M_T and p_T^{miss} based on the statistical precision of this control region.

$m_{\ell\ell}$ (GeV)	M_T (GeV)	p_T^{miss} (GeV)	$H_T < 100$ GeV	$100 \leq H_T < 200$ GeV	$H_T \geq 200$ GeV
0–75	0–100	50–100		SR 01	SR 12
		100–150		SR 02	
		150–200		SR 03	
		≥ 200		SR 04	
	100–160	50–100		SR 05	SR 13
		100–150		SR 06	
		≥ 150		SR 07	
	≥ 160	50–100		SR 08	SR 14
		100–150		SR 09	
		150–200		SR 10	
		≥ 200		SR 11	
75–105	0–100	50–100	(WZ CR)	SR 27	SR 40
		100–150	SR 15	SR 28	
		150–200	SR 16	SR 29	
		200–250	SR 17	SR 30	
		250–350	SR 18	SR 31	SR 42
		≥ 350			SR 43
	100–160	50–100	SR 19	SR 32	SR 44
		100–150	SR 20	SR 33	SR 45
		150–200	SR 21	SR 34	SR 46
		200–250	SR 22	SR 35	SR 47
		250–300			SR 48
		≥ 300			SR 49
	≥ 160	50–100	SR 23	SR 36	SR 50
		100–150	SR 24	SR 37	SR 51
		150–200	SR 25	SR 38	SR 52
		200–250	SR 26	SR 39	SR 53
		250–300			SR 54
		≥ 300			SR 55
≥ 105	0–100	≥ 50	SR 56		
	100–160	≥ 50	SR 57		
	≥ 160	≥ 50	SR 58		

Table 2. Definition of the search regions (SRs) optimized for the WZ corridor in the WZ signal topology. Events must have three leptons (e, μ) forming at least one OSSF pair and they are categorized in $m_{\ell\ell}$, M_T , p_T^{miss} and H_T . Where ranges of values are given, the lower bound is inclusive while the upper bound is exclusive, e.g., $75 \leq m_{\ell\ell} < 105$ GeV.

Distributions of key kinematic observables for the events entering the search regions are shown in figure 5 with two representative signal mass points included. The data agree with the prediction within systematic uncertainties, which are dominated at high M_T and p_T^{miss} by the WZ control region statistical precision as described above. This uncertainty is taken as correlated across signal region bins. The comparison between expected and observed yields in the search regions is shown in figure 6 and table 3. No significant deviations from the SM expectations are observed. The predicted background yields and uncertainties presented in this section are used as inputs to the likelihood fit for interpretation, described in section 7. The interpretation of the results in the WZ topology at 95% confidence level (CL) is presented in figure 7. Compared to ref. [38], the expected lower mass limit in the WZ corridor has improved from around $(m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}) = (200, 100)$ to around $(225, 125)$ GeV, while the observed limit has improved by around 60 GeV in both mass values. The expected

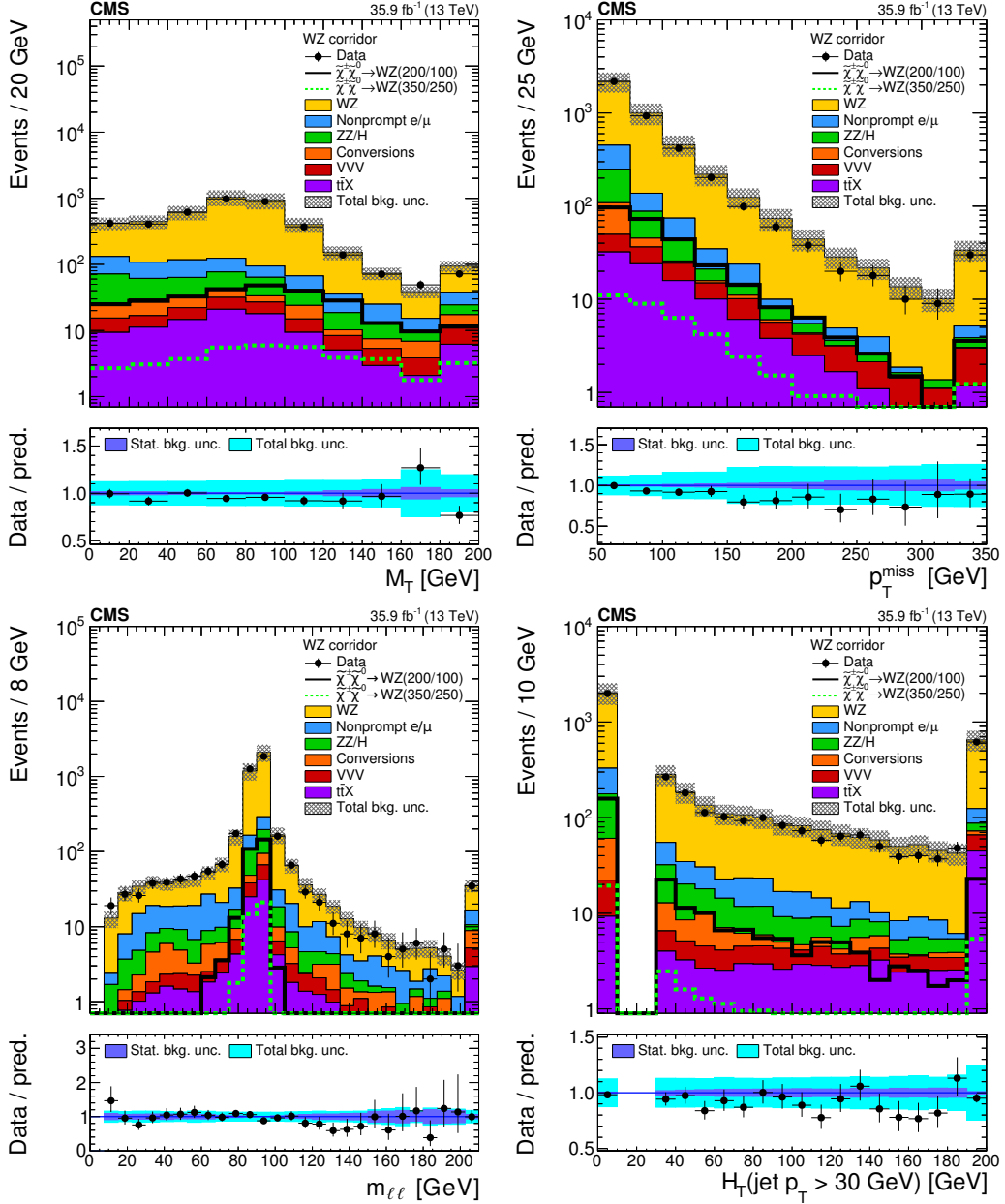


Figure 5. Distributions of the transverse mass of the third lepton with respect to p_T^{miss} (upper left), the p_T^{miss} (upper right), the $m_{\ell\ell}$ of the OSSF pair (lower left), and the H_T (lower right). Distributions for two signal mass points in the WZ corridor are overlaid for illustration. The mass values for the signal points are given as $(m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^0})$ in GeV. The bottom panel shows the ratio of observed data to predicted yields. The dark purple band shows the statistical uncertainty in the background prediction, while the light blue band shows the total uncertainty.

limit contour for signal points with $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > m_Z$ has also improved by as much as 25 GeV due to the new selections. The upper limit on the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production cross section has improved by a factor of 2.

The event selections listed in table 2 are used to replace the selections for category A

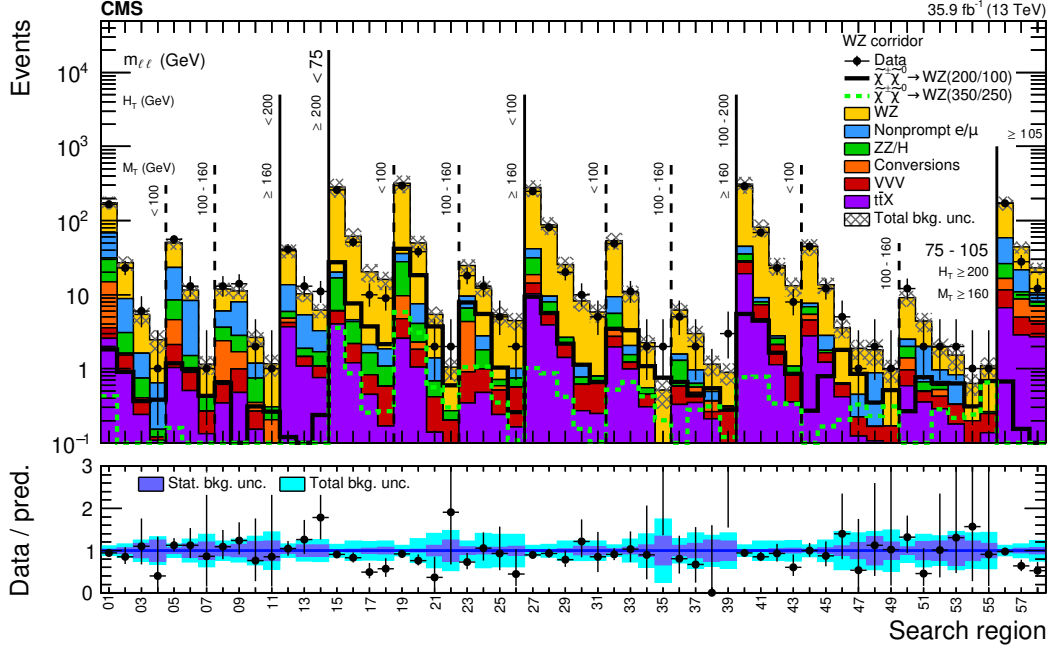


Figure 6. Expected and observed yield comparison in the search regions. Two example signal mass points along the WZ corridor are overlaid for illustration. The mass values for the signal points are given as $(m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^0})$ in GeV. The bottom panel shows the ratio of observed data to predicted yields. The dark purple band shows the statistical uncertainty in the background prediction, while the light blue band shows the total uncertainty.

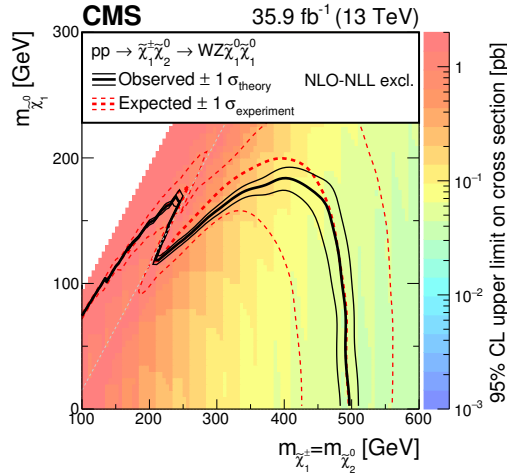


Figure 7. The 95% confidence level upper limit on the production cross section in the plane of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$ for the model of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with the WZ topology, using only the search requiring three or more leptons as described in section 6. The thick solid black (dashed red) curve represents the observed (expected) exclusion contour assuming the theory cross sections. The area below each curve is the excluded region. The thin dashed red lines indicate the $\pm 1\sigma_{\text{experiment}}$ uncertainty. The thin black lines show the effect of the theoretical uncertainties ($\pm 1\sigma_{\text{theory}}$) on the signal cross section. The color scale shows the observed limit at 95% CL on the signal production cross section.

$m_{\ell\ell}$ (GeV)	M_T (GeV)	p_T^{miss} (GeV)	$H_T < 100$ GeV		$100 \leq H_T < 200$ GeV		$H_T \geq 200$ GeV	
0–75	0–100	50–100	175 ± 20		166		39 ± 6	41
		100–150	27 ± 4		23			
		150–200	5 ± 1		6			
		≥200	2.5 ± 0.8		1			
	100–160	50–100	50 ± 8		56		10 ± 3	13
		100–150	12 ± 3		13			
		≥150	1.2 ± 0.4		1			
	≥160	50–100	12 ± 2		13		6 ± 2	11
		100–150	11 ± 3		14			
		150–200	2.6 ± 0.9		2			
≥200		1.2 ± 0.5		1				
75–105	0–100	50–100	(WZ CR)		279 ± 34	250	310 ± 40	292
		100–150	286 ± 44	260	87 ± 13	81		
		150–200	62 ± 14	51	26 ± 6	20	81 ± 18	69
		200–250	20 ± 5	10	8 ± 2	10		
		250–350	16 ± 4	9	6 ± 1	5	25 ± 6	23
		≥350					13 ± 3	8
	100–160	50–100	321 ± 42	297	54 ± 8	49	45 ± 6	45
		100–150	50 ± 14	38	11 ± 3	11	14 ± 3	12
		150–200	5 ± 2	2	2.2 ± 0.9	2	4 ± 2	5
		200–250	1.1 ± 0.5	2	0.5 ± 0.4	2	1.9 ± 0.8	1
		250–300					1.8 ± 0.8	2
		≥300					1.0 ± 0.5	1
	≥160	50–100	25 ± 6	18	6 ± 2	5	9 ± 3	12
		100–150	12 ± 5	13	3.0 ± 1.3	2	4 ± 2	2
		150–200	5 ± 2	5	1.1 ± 0.4	0	2.0 ± 0.7	2
		200–250	4 ± 2	2	0.9 ± 0.4	3	1.5 ± 0.7	2
		250–300					0.6 ± 0.3	1
		≥300					1.1 ± 0.5	1
	≥105	0–100	≥50	173 ± 21				170
		100–160	≥50	44 ± 7				28
≥160		≥50	23 ± 6				12	

Table 3. Expected and observed event yields in the search regions. For each bin, the first number corresponds to the expected yield and its total uncertainty while the second number gives the observation. Where ranges of values are given for the selections, the lower bound is inclusive while the upper bound is exclusive, e.g., $75 \leq m_{\ell\ell} < 105$ GeV.

in ref. [38] in the combination below with other analyses, when interpreting results in the models with either 100% or 50% branching fraction to the SUSY WZ topology. In this case, the systematic uncertainties in the background prediction are treated as being fully correlated with the other categories from ref. [38].

7 Interpretation

The results of the searches described in sections 5 and 6 are interpreted using the simplified models introduced in section 2. Cross section limits as a function of the SUSY particle masses are set using a modified frequentist approach, employing the CL_s criterion and an asymptotic formulation [90–93]. The uncertainties in the signal efficiency and acceptance and in the background predictions are incorporated as nuisance parameters. The observed data yields in control regions are typically incorporated either by a simultaneous maximum

likelihood fit of the signal and control regions or through parameterization using the gamma function. Other nuisance parameters are implemented using lognormal functions, whose widths reflect the size of the systematic uncertainty, or as alternate shapes of the relevant distributions. Within each signal model, the experimental and theoretical uncertainties affecting the signal prediction are treated as fully correlated for all analyses. The dominant uncertainties in the background predictions are not correlated among analyses as they tend to be either statistical in nature, arising from independent control regions, or uncertainties in the prediction methods, which are unique to each analysis. For each signal topology, the analyses with a check mark in table 1 are combined to place exclusion limits.

The following sources of uncertainty in the signal acceptance and efficiency are assumed to be fully correlated among analyses: determination of the integrated luminosity, lepton identification and isolation efficiency, lepton efficiency modeling in fast simulation, b tagging efficiency, jet energy scale, modeling of p_T^{miss} in fast simulation, modeling of ISR, simulation of pileup, and variations of the generator factorization and renormalization scales. Variations in the PDF set used are found to primarily affect the signal acceptance by changing the p_T distribution of the initially-produced sparticle pair, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ or $\tilde{\chi}_1^0 \tilde{\chi}_1^0$. This is already incorporated in the empirical uncertainty in the modeling of ISR as described in section 4, and we therefore do not apply a dedicated uncertainty in signal acceptance from PDF variations. All analyses also include the statistical uncertainty of the simulated signal samples, which is taken as being uncorrelated in every bin, and the uncertainty in the modeling of the trigger efficiency, which is also taken as uncorrelated given the different trigger requirements applied in each analysis. Some analyses have additional uncertainties beyond these, such as the uncertainty in the modeling of the diphoton mass resolution for the $H(\gamma\gamma)$ analysis, which are analysis-specific and treated as being uncorrelated.

For the models of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, 95% confidence level exclusion limits are presented in the plane of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$. Figure 8 shows the exclusion limits for the combination of analyses for the WZ topology, the WH topology, and the mixed topology with 50% branching fraction to each of the WZ and WH channels. Figure 9 shows the analysis with the best expected limit for each point in the plane for the same topologies. The on-Z dilepton analysis generally gives the best sensitivity for large values of $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. The search for three light-flavor leptons provides the best sensitivity at intermediate values of Δm , including the region where $\Delta m \approx m_Z$, while the soft-dilepton analysis provides unique sensitivity to the smallest values of Δm . Figure 10 (left) shows the observed and expected limit contours for each of the individual analyses considered in the combination, and figure 10 (right) shows the results from the combination for all three topologies considered. For a massless LSP $\tilde{\chi}_1^0$, the combined result gives an observed (expected) limit in $m_{\tilde{\chi}_1^\pm}$ of about 650 (570) GeV for the WZ topology, 480 (455) GeV for the WH topology, and 535 (440) GeV for the mixed topology. The combination also excludes intermediate mass values that were not excluded by individual analyses, including $m_{\tilde{\chi}_1^\pm}$ values between 180 and 240 GeV for a massless LSP in the WH topology.

For the models of $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production, the exclusion limits are presented in the plane of $m_{\tilde{\chi}_1^0}$ and the branching fraction $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$. The decay $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$ is assumed to make up the remainder of the branching fraction. Figure 11 shows the observed and expected limits

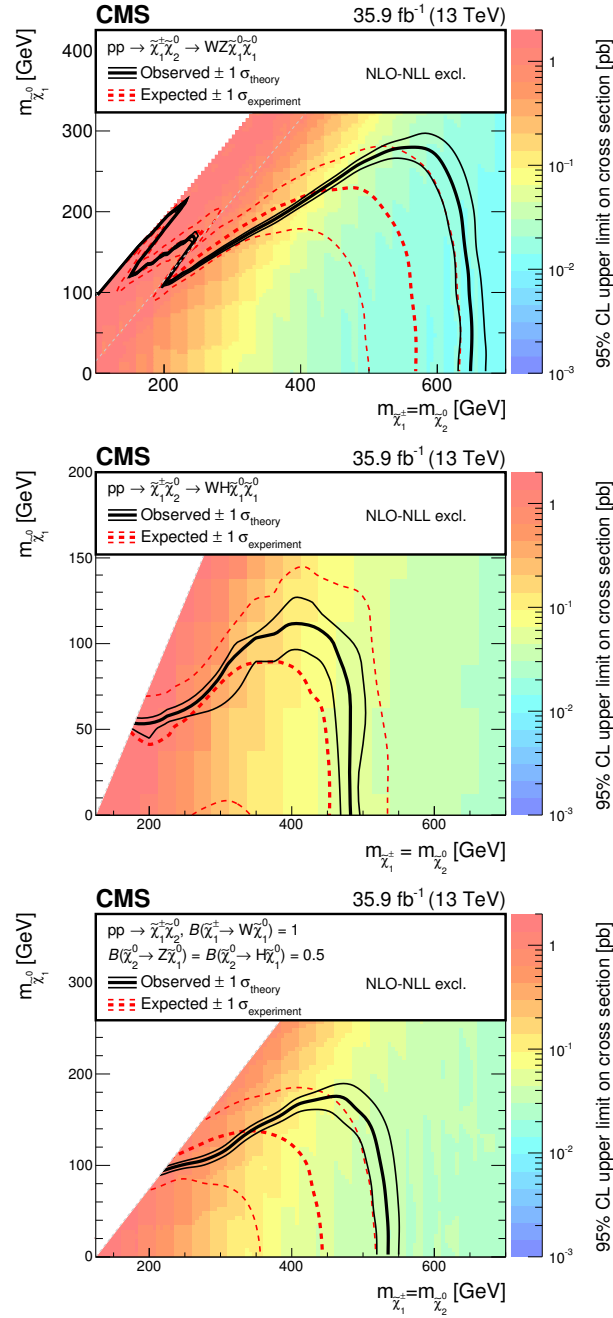


Figure 8. The 95% CL upper limits on the production cross sections in the plane of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$ for the models of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with (upper) the WZ topology, (middle) the WH topology, or (lower) the mixed topology with 50% branching fraction to each of WZ and WH. The thick solid black (dashed red) curve represents the observed (expected) exclusion contour assuming the theory cross sections. The area below each curve is the excluded region. The thin dashed red lines indicate the $\pm 1\sigma_{\text{experiment}}$ uncertainty. The thin black lines show the effect of the theoretical uncertainties ($\pm 1\sigma_{\text{theory}}$) on the signal cross section. The color scale shows the observed limit at 95% CL on the signal production cross section.

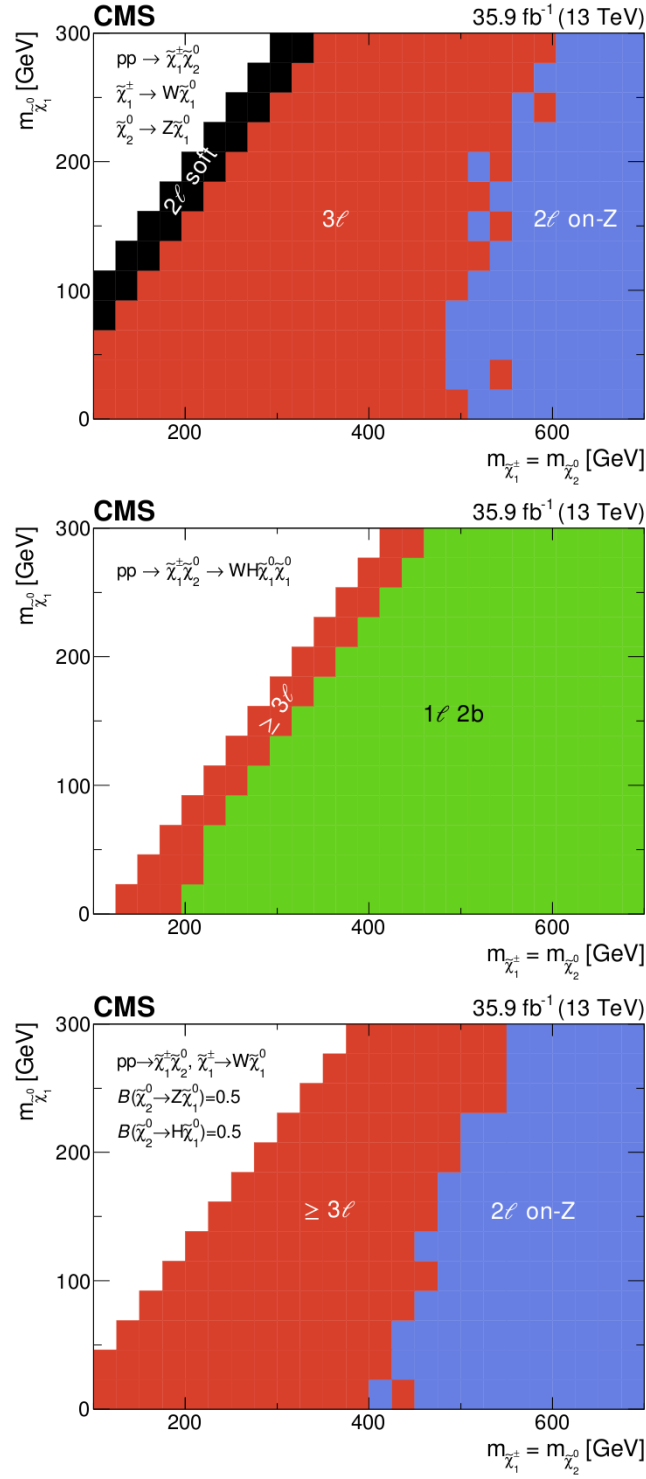


Figure 9. The analysis with the best expected exclusion limit at each point in the plane of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$ for the models of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with (upper) the WZ topology, (middle) the WH topology, and (lower) the mixed topology 50% branching fraction to each of WZ and WH.

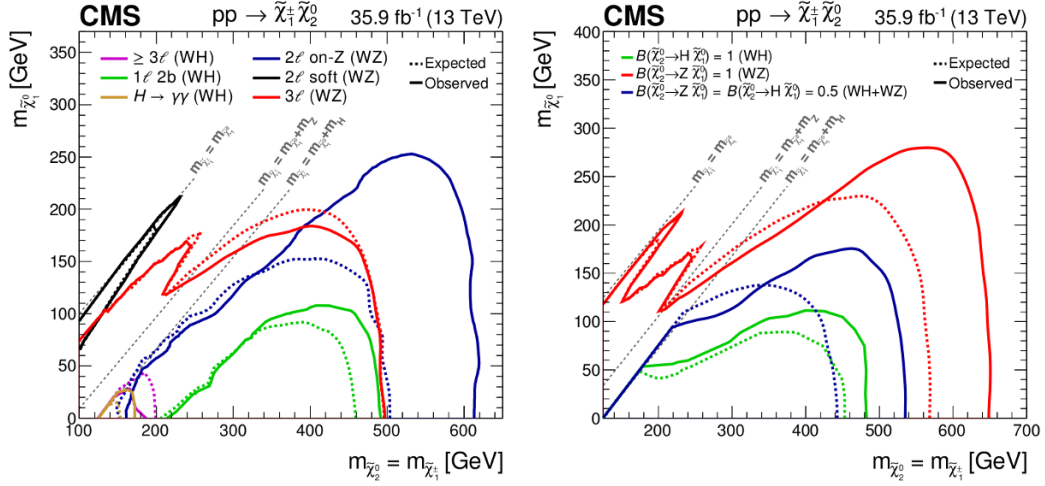


Figure 10. Exclusion contours at 95% CL in the plane of $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$ for the models of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production (left) for the individual analyses and (right) for the combination of analyses. The decay modes assumed for each contour are given in the legends.

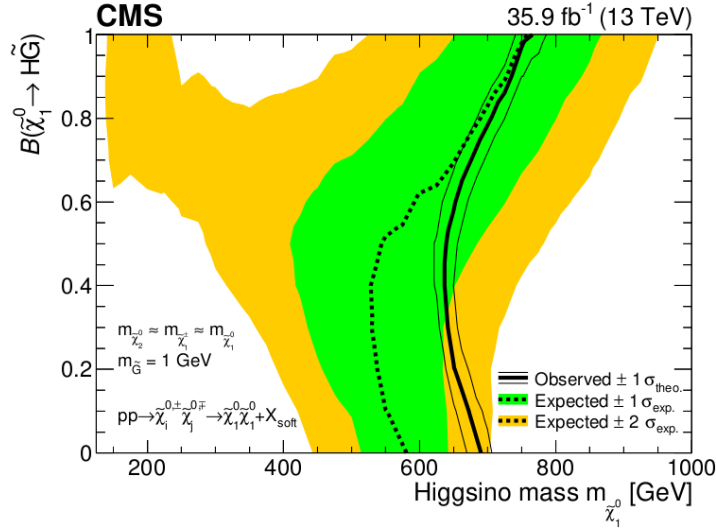


Figure 11. Combined exclusion contours at the 95% CL in the plane of $m_{\tilde{\chi}_1^0}$ and $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$ for the model of $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production. The area to the left of or below the solid (dashed) black curve represents the observed (expected) exclusion region. The green and yellow bands indicate the ± 1 and 2σ uncertainties in the expected limit. The thin black lines show the effect of the theoretical uncertainties ($\pm 1\sigma_{\text{theory}}$) on the signal cross section.

from the combination in this plane. The expected mass exclusion limit varies between about 550 and 750 GeV, being least stringent around $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G}) = 0.4$. The observed limit ranges between about 650 and 750 GeV, allowing us to exclude masses below 650 GeV independent of this branching fraction.

Figure 12 shows the observed limits from each analysis separately compared with the combined result. Figure 13 shows the analysis with the best expected exclusion limit

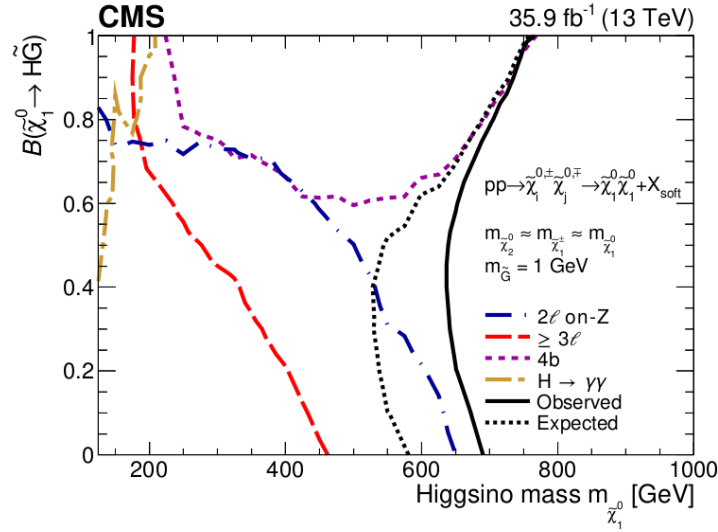


Figure 12. Observed exclusion contours at the 95% CL in the plane of $m_{\tilde{\chi}_1^0}$ and $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$ for the model of $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production for each individual analysis compared with the combination. For the $4b$ contour, the region above is excluded, while for all others, the region to the left is excluded. The $4b$ search drives the exclusion at large values of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$ while the on-Z dilepton and multilepton searches are competing at lower values of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$.

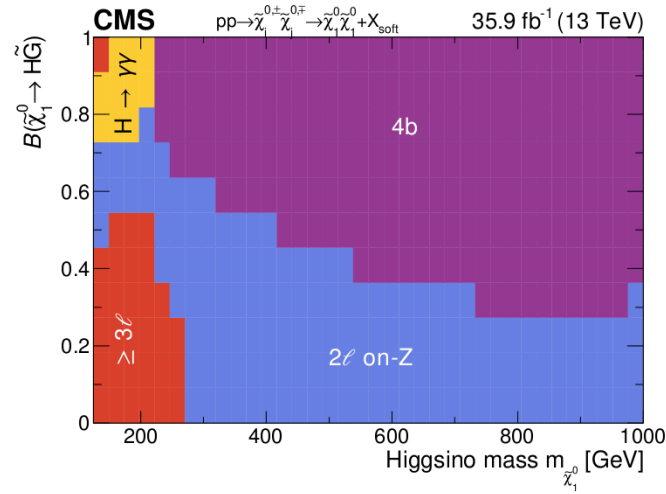


Figure 13. The analysis with the best expected exclusion limit at each point in the plane of $m_{\tilde{\chi}_1^0}$ and $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$ for the model of $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production.

for each point in the same plane. At higher values of $m_{\tilde{\chi}_1^0}$, the searches for at least one hadronically decaying boson provide the best sensitivity, the $4b$ search when $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$ is large and the on-Z dilepton search when it is smaller. At lower values of $m_{\tilde{\chi}_1^0}$, below around 200 GeV, the $H(\gamma\gamma)$ analysis is most sensitive when $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$ is large, while the three or more lepton search is dominant when it is small. Figure 14 then shows the exclusion limits as a function of $m_{\tilde{\chi}_1^0}$ for three choices of $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$: 0%, yielding the ZZ topology; 100%, yielding the HH topology; and 50%, yielding a mix of events from the

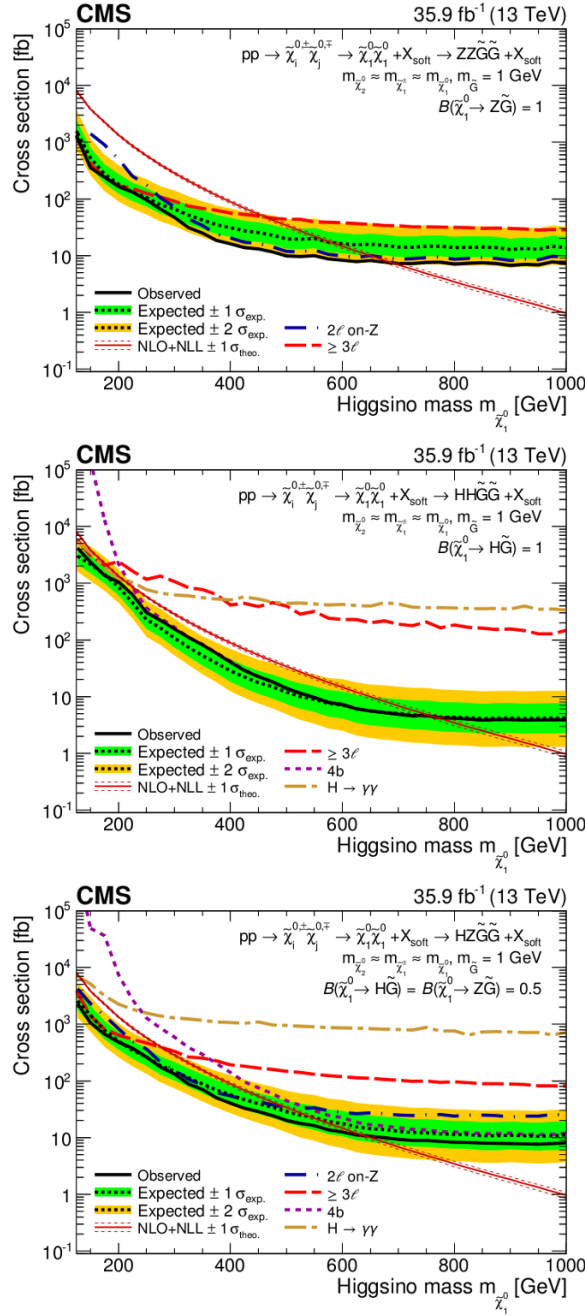


Figure 14. The 95% CL upper limits on the production cross sections as a function of $m_{\tilde{\chi}_1^0}$ for the model of $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production with three choices of $B(\tilde{\chi}_1^0 \rightarrow H\tilde{G})$: (upper) 0%, yielding the ZZ topology, (middle) 100%, yielding the HH topology, and (lower) 50%, yielding the ZH mixed topology. The solid black line represents the observed exclusion. The dashed black line represents the expected exclusion, while the green and yellow bands indicate the ± 1 and 2σ uncertainties in the expected limit. The red line shows the theoretical cross section with its uncertainty. The other lines in each plot show the observed exclusion for individual analyses.

ZZ, HH, and ZH topologies.

8 Summary

A number of searches for the electroweak production of charginos and neutralinos predicted in supersymmetry (SUSY) have been performed in different final states. All searches considered here use proton-proton collision data at $\sqrt{s} = 13$ TeV, recorded with the CMS detector at the LHC and corresponding to an integrated luminosity of 35.9 fb^{-1} . No significant deviations from the standard model expectations have been observed.

A targeted search requiring three or more charged leptons (electrons or muons) has been presented, focusing on chargino-neutralino production where the difference in mass between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is approximately equal to the mass of the Z boson, and no significant deviations from the standard model predictions are observed. This search is interpreted in a simplified model scenario of SUSY chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$) production with decays $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the lightest SUSY particle (LSP). In the targeted phase space, the expected and observed 95% confidence level exclusion limits extend to 225 GeV in the mass of $\tilde{\chi}_2^0$ and 125 GeV in the mass of $\tilde{\chi}_1^0$, improving the observed limits from the previous publication by up to 60 GeV [38].

A statistical combination of several searches is performed and interpreted in the context of simplified models of either chargino-neutralino production, or neutralino pair production in a gauge-mediated SUSY breaking (GMSB) scenario. For a massless LSP $\tilde{\chi}_1^0$ in the chargino-neutralino model, the combined result gives an observed (expected) limit in the $\tilde{\chi}_1^\pm$ mass of about 650 (570) GeV for the WZ topology, 480 (455) GeV for the WH topology, and 535 (440) GeV for the mixed topology. Compared to the results of individual analyses, the combination improves the observed exclusion limit by up to 40 GeV in the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ in the chargino-neutralino model. The combination also excludes intermediate mass values that were not excluded by individual analyses, including $\tilde{\chi}_1^\pm$ masses between 180 and 240 GeV in the WH topology. In the GMSB neutralino pair model, the combined result gives an observed (expected) limit in the $\tilde{\chi}_1^0$ mass of 650–750 (550–750) GeV. The combined result improves the observed limit by up to 200 GeV in the mass of $\tilde{\chi}_1^0$ in the GMSB neutralino pair model, depending on the branching fractions for the SUSY particle decays. These results represent the most stringent constraints to date for all models considered.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMFWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ,

and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, U.S.A.
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at California Institute of Technology, Pasadena, U.S.A.
- 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 46: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 47: Also at National and Kapodistrian University of Athens, Athens, Greece

- 48: Also at Riga Technical University, Riga, Latvia
- 49: Also at Universität Zürich, Zurich, Switzerland
- 50: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 51: Also at Gaziosmanpasa University, Tokat, Turkey
- 52: Also at Istanbul Aydin University, Istanbul, Turkey
- 53: Also at Mersin University, Mersin, Turkey
- 54: Also at Cag University, Mersin, Turkey
- 55: Also at Piri Reis University, Istanbul, Turkey
- 56: Also at Adiyaman University, Adiyaman, Turkey
- 57: Also at Izmir Institute of Technology, Izmir, Turkey
- 58: Also at Necmettin Erbakan University, Konya, Turkey
- 59: Also at Marmara University, Istanbul, Turkey
- 60: Also at Kafkas University, Kars, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Rutherford Appleton Laboratory, Didcot, U.K.
- 63: Also at School of Physics and Astronomy, University of Southampton, Southampton, U.K.
- 64: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 65: Also at Utah Valley University, Orem, U.S.A.
- 66: Also at Beykent University, Istanbul, Turkey
- 67: Also at Bingol University, Bingol, Turkey
- 68: Also at Erzincan University, Erzincan, Turkey
- 69: Also at Sinop University, Sinop, Turkey
- 70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 71: Also at Texas A&M University at Qatar, Doha, Qatar
- 72: Also at Kyungpook National University, Daegu, Koreae