The following full text is a publisher's version.

For additional information about this publication click this link.
https://hdl.handle.net/2066/217304

Please be advised that this information was generated on 2020-04-29 and may be subject to change.
Searches for electroweak production of supersymmetric particles with compressed mass spectra in \( \sqrt{s} = 13 \) TeV \( pp \) collisions with the ATLAS detector

G. Aad et al.*
(ATLAS Collaboration)

(Received 2 December 2019; accepted 30 January 2020; published 11 March 2020)

This paper presents results of searches for the electroweak production of supersymmetric particles in models with compressed mass spectra. The searches use 139 fb\(^{-1}\) of \( \sqrt{s} = 13 \) TeV proton-proton collision data collected by the ATLAS experiment at the Large Hadron Collider. Events with missing transverse momentum and two same-flavor, oppositely charged, low-transverse-momentum leptons are selected, and are further categorized by the presence of hadronic activity from initial-state radiation or a topology compatible with vector-boson fusion processes. The data are found to be consistent with predictions from the Standard Model. The results are interpreted using simplified models of \( R \)-parity-conserving supersymmetry in which the lightest supersymmetric partner is a neutralino with a mass similar to the lightest chargino, the second-to-lightest neutralino, or the slepton. Lower limits on the masses of charginos in different simplified models range from 193 to 240 GeV for moderate mass splittings, and extend down to mass splittings of 1.5 to 2.4 GeV at the LEP chargino bounds (92.4 GeV). Similar lower limits on degenerate light-flavor sleptons extend up to masses of 251 GeV and down to mass splittings of 550 MeV. Constraints on vector-boson fusion production of electroweak SUSY states are also presented.

DOI: 10.1103/PhysRevD.101.052005

I. INTRODUCTION

Extensions of the Standard Model (SM) that include new states with nearly degenerate masses can help to resolve open issues in particle physics while evading constraints from experiments at high-energy colliders. The mass spectra of such new states are referred to in this paper as “compressed.” Supersymmetry (SUSY) [1–6] predicts new particles that have identical quantum numbers to their SM partners with the exception of spin, with SM fermions having bosonic partners and SM bosons having fermionic partners. The neutralinos \( \tilde{\chi}_1^{0,2,3,4} \) and charginos \( \tilde{\chi}_1^{\pm} \) are collectively referred to as electroweakinos, where the subscripts indicate increasing electroweakino mass. If the \( \tilde{\chi}_1^{0} \) is stable, e.g., as the lightest SUSY partner (LSP) in \( R \)-parity-conserving SUSY models [7], then it is a viable dark-matter candidate [8,9]. In the compressed SUSY models considered in this paper, the \( \tilde{\chi}_1^{0} \) is close in mass to a heavier SUSY partner such as a chargino (\( \tilde{\chi}_1^{\pm} \)), second-lightest neutralino (\( \tilde{\chi}_2^{0} \)), or slepton (\( \tilde{\ell} \), the SM lepton partner).

This paper presents searches for physics beyond the SM in signatures sensitive to models with compressed mass spectra. Simplified SUSY models [10–12] are used to optimize the searches and interpret the results. The searches use 13 TeV \( pp \) collision data corresponding to 139 fb\(^{-1}\) of integrated luminosity, collected by the ATLAS experiment [13] from 2015 to 2018 at the CERN Large Hadron Collider (LHC).

All searches assume pair production of SUSY particles via electroweak interactions, with subsequent decays into the \( \tilde{\chi}_1^{0} \) and SM particles. The electroweakino mass eigenstates are a mixture of wino, bino, and Higgsino fields,\(^1\) which form the SUSY partners of the SM \( W, \gamma/Z, \) and Higgs fields, respectively. In the minimal supersymmetric extension of the SM (MSSM) [14,15], the masses of the bino, wino, and Higgsino states are parametrized in terms of \( M_1, M_2, \) and \( \mu \), respectively. For large values of \( \tan(\beta) \), these three parameters drive the phenomenology of the electroweakinos.

Four SUSY scenarios are considered in the interpretation of the searches. In the first scenario, the lightest SUSY partners are assumed to be a triplet of Higgsino-like states

---

\(^1\)In the minimal supersymmetric extension of the SM, the Higgs sector is extended to contain two Higgs doublets, and \( \tan(\beta) \) is the ratio of the vacuum expectation values of the two Higgs doublets.
(χ_{1}^0, \tilde{\chi}_1^+, \tilde{\chi}_2^0), in which the mass splitting between the states is partially determined by the magnitude of M_1 or M_2 relative to |μ|. Such a scenario, referred to here as Higgsino models, is motivated by naturalness arguments [16,17], which suggest that |μ| should be near the weak scale [18–21], while M_1 and/or M_2 can be larger.

The second scenario features a similar particle spectrum to the first, except with |M_1| < |M_2| << |μ|, so that the produced electroweakinos have a wino and/or bino nature. In such wino/bino scenarios, the LSP can be a thermal-relic dark-matter candidate that was depleted in the early Universe through coannihilation processes to match the observed dark-matter density [22,23]. The production cross section in such scenarios is typically larger than in the first scenario. They are also poorly constrained by dark-matter direct-detection experiments, and collider searches constitute the only direct probe for |μ| > 800 GeV [24]. Diagrams representing the production mode for the first two scenarios are shown in Fig. 1(a). A \tilde{\chi}_2^0 produced in either scenario can decay into a dilepton pair via an off-shell Z boson (Z’), such that the dilepton invariant mass m_{\ell\ell} is kinematically restricted to be smaller than the mass splitting between the \tilde{\chi}_2^0 and \tilde{\chi}_1^0. Hadronic initial-state radiation (ISR) is also required to boost the system as a way of enhancing the sensitivity of the search.

The third scenario is similar to the previous two, but it instead assumes that the pair production of the electroweakinos proceeds via vector-boson fusion (VBF) processes, in which SM weak bosons exchange an electroweakino in a t-channel process to produce two electroweakinos and a pair of forward jets. Such scenarios typically have very low cross sections, but they can complement the sensitivity of gg annihilation modes that dominate the inclusive Higgsino and wino/bino cross sections, especially for LSP masses above a few hundred GeV [25]. An example of such a process is illustrated in Fig. 1(b). The kinematic cutoff of the m_{\ell\ell} distribution is also used as the primary discriminant in this scenario, along with the presence of two forward jets consistent with a VBF production mode.

The fourth scenario assumes the presence of scalar partners of the SM leptons (sleptons, \tilde{e}) that are slightly heavier than a bino-like LSP. Such models can explain dark-matter thermal-relic densities through coannihilation channels, as well as the muon g – 2 anomaly [26,27]. This process is illustrated in Fig. 1(c). This scenario exploits the relationship between the lepton momenta and the missing transverse momentum through the transverse mass, m_{T2} [28,29], which exhibits a kinematic end point similar to that for m_{\ell\ell} in electroweakino decays.

Events with two same-flavor opposite-charge leptons (electrons or muons), significant missing transverse momentum of size E_T^{miss}, and hadronic activity are selected for all scenarios. Signal regions (SRs) are defined by placing additional requirements on a number of kinematic variables. The dominant SM backgrounds are either estimated with in situ techniques or constrained using data control regions (CRs) that enter into a simultaneous likelihood fit with the SRs. The fit is performed in bins of either the m_{\ell\ell} distribution (for electroweakinos) or the m_{T2} distribution (for sleptons).

Constraints on these compressed scenarios were first established at LEP [30–40]. The lower bounds on direct chargino production from these results correspond to m(\tilde{\chi}_1^+) > 103.5 GeV for \Delta m(\tilde{\chi}_1^+, \tilde{\chi}_1^0) > 3 GeV and m(\tilde{\chi}_1^0) > 92.4 GeV for smaller mass differences, although the lower bound on the chargino mass weakens to around 75 GeV for models with additional new scalars and Higgsino-like cross sections [41]. For sleptons, conservative lower limits on the mass of the scalar partner of the right-handed muon, denoted \tilde{\mu}_R, are approximately m(\tilde{\mu}_R) > 94.6 GeV for mass splittings down to m(\tilde{\mu}_R) – m(\tilde{\chi}_1^0) > 2 GeV. For the scalar partner of the right-handed electron, denoted \tilde{e}_R, LEP established a universal lower bound of m(\tilde{e}_R) > 73 GeV that is independent of \Delta m(\tilde{e}_R, \tilde{\chi}_1^0) [34]. Recent papers from the CMS [42–44] and ATLAS [45] Collaborations have extended the LEP limits for a range of mass splittings.

This paper extends previous LHC results by increasing the integrated luminosity, extending the search with additional channels, and exploiting improvements in detector calibration and performance. The dedicated search for production via VBF is also added, and the event selection is reoptimized and uses techniques based on recursive jigsaw reconstruction [46], which improve the separation of the SUSY signal from the SM backgrounds.

II. ATLAS DETECTOR

The ATLAS experiment is a general-purpose particle detector that surrounds the interaction point with nearly 4π solid angle coverage.² It comprises an inner detector, calorimeter systems, and a muon spectrometer. The inner detector provides precision tracking of charged particles in the pseudorapidity region |η| < 2.5, consisting of pixel and microstrip silicon subsystems within a transition radiation tracker. The innermost pixel detector layer, the insertable B-layer [47,48], was added for \sqrt{s} = 13 TeV data-taking to improve tracking performance. The inner detector is immersed in a 2 T axial magnetic field provided by a superconducting solenoid. High-granularity lead/liquid-argon

²ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates (r, \phi) are used in the transverse plane, \phi being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle \theta as \eta = -\ln \tan(\theta/2). Angular distance is measured in units of \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. Rapidity is defined by y = \frac{1}{2} \ln((E + p_T)/(E - p_T)), where E is the energy and p_T is the longitudinal component of the momentum along the beam direction.
FIG. 1. Diagrams representing the two-lepton final state of (a) the production of electroweakinos $\tilde{\chi}^0_2 \tilde{\chi}^+_1$ with initial-state radiation ($j$), (b) the VBF production of electroweakinos $\tilde{\chi}^0_2 \tilde{\chi}^+_1$, and (c) slepton pair ($\tilde{\ell} \tilde{\ell}$) production in association with initial-state radiation ($j$). The Higgsino simplified model also considers $\tilde{\chi}^0_2 \tilde{\chi}^0_1$ and $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ production.

electromagnetic sampling calorimeters are used for $|\eta| < 3.2$. Hadronic energy deposits are measured in a steel/scintillator tile barrel calorimeter in the $|\eta| < 1.7$ region. Forward calorimeters cover the region $3.2 < |\eta| < 4.9$ for both electromagnetic and hadronic measurements. The muon spectrometer comprises trigger and high-precision tracking chambers spanning $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively, with a magnetic field provided by three large superconducting toroidal magnets. Events of interest are selected using a two-level trigger system [49], consisting of a first-level trigger implemented in hardware, which is followed by a software-based high-level trigger.

III. DATA AND SIMULATED EVENT SAMPLES

Events were selected with a $E_{T}^{\text{miss}}$ trigger, employing varied trigger thresholds as a function of the data-taking periods. The trigger is $>95\%$ efficient for offline $E_{T}^{\text{miss}}$ values above 200 GeV for all periods. The dataset used corresponds to 139 fb$^{-1}$ of $\sqrt{s} = 13$ TeV $pp$ collision data, where the uncertainty in the integrated luminosity is 1.7% [50], obtained using the LUCID-2 detector [51] for the primary luminosity measurements. The average number of interactions per bunch crossing was 33.7.

Samples of Monte Carlo (MC) simulated events are used to estimate the signal yields, and for estimating the background from processes with prompt leptons, as well as in the determination of systematic uncertainties.

For the first signal scenario introduced in Sec. I, samples were generated for a simplified model of Higgsino LSPs, including the production of $\tilde{\chi}^+_1 \tilde{\chi}^-_1$, $\tilde{\chi}^0_1 \tilde{\chi}^+_1$, and $\tilde{\chi}^0_2 \tilde{\chi}^-_1$. The masses of the neutralinos ($\tilde{\chi}^0_{1,2}$) were varied, while the chargino mass was set to $\tilde{\chi}^\pm_1 = \frac{1}{2} [m(\tilde{\chi}^0_1) + m(\tilde{\chi}^0_2)]$. Mass splittings in the case of pure Higgsinos are generated by radiative corrections, and are of the order of hundreds of MeV [52]. Mass splittings of the order of tens of GeV can be obtained by introducing mixing with wino or bino states. In this simplified model, mass differences ranging from 1 to 60 GeV are considered, but the calculated cross sections assume electroweakino mixing matrices corresponding to pure Higgsino $\tilde{\chi}^0_2$, $\tilde{\chi}^+_1$, and $\tilde{\chi}^0_1$ states, and all other SUSY particles are decoupled. Typical values of cross sections for $m(\tilde{\chi}^0_2) = 110$ GeV and $m(\tilde{\chi}^+_1) = 100$ GeV are 4.3 ± 0.1 pb for $\tilde{\chi}^0_2 \tilde{\chi}^+_1$ production, 2.73 ± 0.07 pb for $\tilde{\chi}^0_1 \tilde{\chi}^+_1$ production, and 2.52 ± 0.08 pb for $\tilde{\chi}^0_1 \tilde{\chi}^-_1$ production. The samples were generated at leading order (LO) with MG5_aMC@NLO [53] using the NNPDF23LO [54] parton distribution function (PDF) set and included up to two extra partons in the matrix element (ME). The electroweakinos were decayed with MADSPIN [55]. The events were then interfaced with PYTHIA8.212 [56] to model the parton shower (PS), hadronization, and underlying event (UE) using the A14 set of tuned parameters (tune) [57]. The ME-PS matching was performed using the CKKW-L scheme [58] with the merging scale set to 15 GeV. To enforce an ISR topology, at least one parton in the final state was required to have a transverse momentum ($p_T$) greater than 50 GeV. Possible diagrams including colored SUSY particles were excluded from the generation.

In the wino/bino scenario, the generated process is $pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^+_1$. The $\tilde{\chi}^+_1$ is a pure bino state, with the $\tilde{\chi}^0_2$ and $\tilde{\chi}^+_1$ states forming degenerate pure wino states. The generator configurations are consistent with those used for the Higgsino samples. A typical value of the $\tilde{\chi}^0_2 \tilde{\chi}^+_1$ production cross section is $16.0 \pm 0.5$ pb for $m(\tilde{\chi}^0_2) = m(\tilde{\chi}^+_1) = 110$ GeV.

Additional samples were generated for the third scenario of pair production of electroweakinos produced via VBF. These were generated with the same decay, PS, hadronization, and UE configuration as the Higgsino simplified model samples. The ME generation was the same as in the Higgsino case, but it used an updated version of MG5_aMC@NLO (version 2.6.2). In order to select uniquely the VBF topologies, the number of QCD vertices was set to zero. An additional filter was applied to select events with exactly two parton emissions in the ME. The invariant mass of the two partons is required to be at least 200 GeV, while the minimum transverse momentum of each parton is 12 GeV. Typical values of LO cross sections with these requirements for $m(\tilde{\chi}^0_2) = 100$ GeV and $m(\tilde{\chi}^+_1) = 90$ GeV...
are $16 \pm 1$ fb and $47 \pm 4$ fb, for the Higgsino and wino/bino models, respectively. For Higgsino masses smaller than half of the Higgs boson mass, the cross sections include contributions from VBF Higgs production with decays $h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0_1$.

The electroweakino searches exploit the kinematic endpoint in the dilepton invariant mass spectrum from the decay chain $\tilde{\chi}^0_2 \rightarrow Z \tilde{\chi}^0_1$, $Z \rightarrow \ell \ell'$. Therefore, processes that involve the production of a $\tilde{\chi}^0_2$ neutralino dominate the sensitivity of the search. The branching ratios for the processes $\tilde{\chi}^0_2 \rightarrow Z \tilde{\chi}^0_1$ and $\tilde{\chi}^0_1 \rightarrow W \tilde{\chi}^0_0$ were fixed to 100% for all the scenarios given above. The branching ratios of $Z \rightarrow \ell \ell'$ and $W\rightarrow\ell\nu$ depend on the invariant mass of the off-shell vector boson. For both the Higgsino and wino/bino models, the branching ratios were computed with SUSY-HIT1.5a [59], which accounts for finite $b$-quark and $\tau$-lepton masses. At $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) = 40$ GeV, the $Z \rightarrow \ell \ell'$ branching ratio to electrons or muons is 3.5%. This increases to 5.3% and 5.0%, respectively, at $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) = 1$ GeV, as decays into heavier quarks or $\tau$ leptons become kinematically inaccessible. Similarly, for $W \rightarrow \ell \nu$, the branching ratios to electrons or muons are both 11% at a mass splitting of 40 GeV, but they increase to 20% and 17%, respectively, for $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) = 1$ GeV.

The distribution of the dilepton invariant mass from the decay of the virtual $Z'$ [60] depends on the relative sign of the $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ mass parameters. In a pure Higgsino model, the product of the signed mass eigenvalues $(m(\tilde{\chi}^0_2) \times m(\tilde{\chi}^0_1))$ can only be negative, while for the wino/bino case either positive or negative products are allowed. The generated wino/bino process assumes the product of the signed mass eigenvalues is positive, and the analytical description of the expected line shape is used to reweight the $m_{\ell\ell}$ distribution to the case of the product being negative. The difference between wino/bino and Higgsino line shapes, as well as the level of agreement between the reweighted distribution and the expected line shape, is shown in Fig. 2. The two possible wino/bino $m_{\ell\ell}$ distributions are used to provide two separate model-dependent interpretations of the results. With the exception of the signal modeling, the interpretations for Higgsino and both wino/bino samples are otherwise conducted identically and use the same search regions as defined in Sec. V.

For the fourth scenario, samples with direct production of selectrons $\tilde{e}_{L,R}$ or smuons $\tilde{\mu}_{L,R}$ were generated. The $L, R$ subscripts denote left- or right-handed chirality of the corresponding SM lepton partners. All slepton flavors and chirality contributions are assumed to be degenerate.

The mixing matrix used to diagonalize the neutral electroweakino states is forced to be a real matrix in the SLHA2 format [61]. A consequence of this choice is a negative sign given to one or more mass eigenvalues, determined in part by the relative fractions of wino, bino, or Higgsino content of the physical states. For additional discussion of this, see Ref. [62].

FIG. 2. Dilepton invariant mass for Higgsino and wino/bino simplified models. The end point of the distribution is determined by the difference between the masses of the $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$. The results from simulation (histograms) are compared with analytic calculations of the expected line shape (dashed lines) presented in Ref. [60]. The product of the signed mass eigenvalues $(m(\tilde{\chi}^0_2) \times m(\tilde{\chi}^0_1))$ is negative for the Higgsino model and can be either negative or positive for wino/bino scenarios.

in mass. A typical value of the splet production cross section is $0.55 \pm 0.01$ pb for $m(\tilde{\ell}_{L,R}) = 110$ GeV. These particles decay with a 100% branching ratio into their corresponding SM partner lepton and a pure bino neutralino, $\tilde{\chi}^0_1 \times \tilde{\chi}^0_1$. The slepton samples were generated with MG5_aMC@NLO2.6.1 and interfaced with PYTHIA8.230. The PDF set used was NNPDF23LO with the A14 tune. Similarly to the Higgsino and wino/bino samples, CKKW-L merging [58] was used for the ME-PS matching, with the merging scale set to a quarter of the slepton mass. Cross sections for all but the VBF signal scenarios are calculated with RESUMMINO2.01 at NLO + NLL precision [63–70]. The VBF cross sections are computed at LO precision with MG5_aMC@NLO2.6.2. The evaluation of the cross sections and corresponding uncertainty are taken from an envelope of cross-section predictions using different PDF sets, and varied factorization and renormalization scales. This procedure is described in Ref. [71] and is the same procedure as used in the previous search [45].

The SM background processes are estimated from a combination of MC simulation as well as data-driven approaches. The latter are described in Sec. VI. The programs SHERPA2.2.1 and SHERPA2.2.2 [72] were used to model the $V + \text{jets}$ ($V = W, Z, \gamma^*$) samples involving leptonically decaying vector bosons, as well as diboson ($WW, ZZ, \text{and} WZ$, collectively referred to as $VV$) and fully leptonic triboson processes. The $Z^{(*)}/\gamma^*$ + jets and $VV$ samples provide coverage of dilepton invariant masses down to 0.5 GeV for $Z^{(*)}/\gamma^* \rightarrow e^+e^-/\mu^+\mu^-$, and 3.8 GeV for $Z^{(*)}/\gamma^* \rightarrow \tau^+\tau^-$. A separate set of $Z(\rightarrow \mu\mu) + \text{jets}$
samples were generated using MG5_aMC@NLO using the same configuration as for the signal samples described above in order to evaluate initial- and final-state radiation modeling in signal samples. Gluon-gluon fusion (ggF) and VBF single-Higgs production were generated with POWHEG-BOX [73], while Higgs production in association with a massive vector boson was generated with PYTHIA8.186, and $t\bar{t}$ production was generated with MG5_aMC@NLO2.2.3. POWHEG-BOX was used to generate $t\bar{t}$ [73–76], single top [77], and top quarks produced in association with $W$ bosons [78]. Rarer top-quark processes all used MG5_aMC@NLO (versions 2.2.2/2.3.3). Matrix elements, excluding those generated with PYTHIA or SHERPA, were then interfaced with PYTHIA8 using the ME + PS prescription. Further details on the configuration of the simulation of SM processes can be found in Refs. [79–83].

A summary of the generator configurations, including the PDF sets and the order of the cross-section calculations associated with

Events are required to have at least one reconstructed $pp$ interaction vertex with a minimum of two associated tracks with $p_T > 500$ MeV. In events with multiple vertices, the primary vertex is defined as the one with the highest $\sum p_T^2$ of associated tracks. To reject events with detector noise or noncollision backgrounds, a set of basic quality criteria [101] are applied.

Leptons, jets, and tracks are “preselected” using loose identification criteria, and must survive tighter “signal” identification requirements in order to be selected for the search regions. Preselected leptons and jets are used in fake/nonprompt (FNP) lepton background estimates, as well as in resolving ambiguities between tracks and clusters associated with multiple lepton and jet candidates.

Isolation criteria are used in the definition of signal leptons and are based on tracking information, calorimeter clusters, or both. Isolation energies are computed as a sum of energy in the hadronic showers of nearby activity, excluding the contributions from nearby leptons, and are effective in reducing contributions from semileptonic heavy-flavor hadron decays and jets faking prompt leptons. The isolation requirements used in this analysis are based on those described in Refs. [102,103], with updates to improve their performance under the increased pileup conditions encountered in the 2017 and 2018 data samples.

Electrons are required to have $p_T > 4.5$ GeV and $|\eta| < 2.47$. Preselected electrons are further required to
pass the calorimeter- and tracking-based VeryLoose likelihood identification [103], and to have a longitudinal impact parameter $z_0$ relative to the primary vertex that satisfies $|z_0 \sin \theta| < 0.5 \text{ mm}$. Signal electrons must satisfy the Medium isolation criterion [103], and be compatible with originating from the primary vertex, with the significance of the transverse impact parameter defined relative to the beam position satisfying $|d_0|/\sigma(d_0) < 5$. Signal electrons are further refined using the Gradient isolation working point [103], which uses both tracking and calorimeter information.

Muons are required to satisfy $p_T > 3 \text{ GeV}$ and $|\eta| < 2.5$. Preselected muons are identified using the LowPt criterion [104], a reoptimized selection similar to those defined in Ref. [102] but with improved signal efficiency and background rejection for $p_T < 10 \text{ GeV}$ muon candidates. The LowPt working point has improved efficiency for muons with $p_T < 4 \text{ GeV}$ traversing the central detector region, which can lose enough energy in the calorimeters that they do not reach the second station of precision muon tracking chambers. The LowPt selection accepts candidates composed of track segments in the inner detector matched to track segments from a single station of the muon spectrometer. Misidentified muon candidates originating from in-flight hadron decays are rejected by requirements on the significance of a change in trajectory along the track, and by requiring that the momentum measurements in the inner tracker and in the muon spectrometer be compatible with each other. For prompt muons with $3 < p_T < 6 \text{ GeV}$, the LowPt criterion recovers approximately 20% of the identification efficiency in the $|\eta| < 1.2$ region, while maintaining an average misidentification probability comparable to the Medium selection described in Ref. [102].

Preselected muons must also satisfy $|z_0 \sin \theta| < 0.5 \text{ mm}$. From the remaining preselected muons, signal muons must satisfy $|d_0|/\sigma(d_0) < 3$. Finally, signal muons are required to pass the FCTightTrackOnly isolation working point [102], which uses only tracking information.

Preselected jets are reconstructed from calorimeter topological energy clusters [105] in the region $|\eta| < 4.5$ using the anti-$k_t$ algorithm [106,107] with radius parameter $R = 0.4$. The jets are required to have $p_T > 20 \text{ GeV}$ after being calibrated in accord with Ref. [108] and having the expected energy contribution from pileup subtracted according to the jet area [109]. In order to suppress jets due to pileup, jets with $p_T < 120 \text{ GeV}$ and $|\eta| < 2.5$ are required to satisfy the Medium working point of the jet vertex tagger [109], which uses information from the tracks associated with the jet. The Loose working point of the forward jet vertex tagger [110] is in turn used to suppress pileup in jets with $p_T < 50 \text{ GeV}$ and $|\eta| > 2.5$. From the sample of preselected jets, signal jets are selected if they satisfy $p_T > 30 \text{ GeV}$ and $|\eta| < 2.8$. The VBF search uses a modified version of signal jets, labeled VBF jets, satisfying $p_T > 30 \text{ GeV}$ and $|\eta| < 4.5$.

Jets identified as containing $b$-hadron decays, referred to as $b$-tagged jets, are identified from preselected jets within $|\eta| < 2.5$ using the MV2c10 algorithm [111]. The $p_T > 20 \text{ GeV}$ requirement is maintained to maximize the rejection of the $t\bar{t}$ background. The $b$-tagging algorithm working point is chosen so that $b$-jets from simulated $t\bar{t}$ events are identified with an 85% efficiency, with rejection factors of 2.7 for charm-quark jets and 25 for light-quark and gluon jets.

The following procedure is used to resolve ambiguities between the reconstructed leptons and jets. It employs the distance measure $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$, where $y$ is the rapidity. Electrons that share an inner detector track with a muon candidate are discarded to remove bremsstrahlung from muons followed by a photon conversion. Non-$b$-tagged jets that are separated from the remaining electrons by $\Delta R > 0.2$ are removed. Jets containing a muon candidate within $\Delta R < 0.4$ and with fewer than three tracks with $p_T > 500 \text{ MeV}$ are removed to suppress muon bremsstrahlung. Electrons or muons with $\Delta R < 0.4$ from surviving jet candidates are removed to suppress bottom- and charm-hadron decays.

Signal regions based on a signal lepton and an isolated low-$p_T$ track are used to increase the efficiency for electroweakino signals with the lowest mass splittings, where the lepton $p_T$ can be very low. For these regions, the track is selected to be matched to a reconstructed electron or muon candidate with no identification requirements, including muons reconstructed with the CaloTagged and SegmentTagged algorithms described in Ref. [102]. Preselected tracks with $p_T > 500 \text{ MeV}$ and $\eta < 2.5$ are selected using the Tight-Primary working point defined in Ref. [112]. Signal tracks are required to be within $\Delta R = 0.01$ of a reconstructed electron or muon candidate. Electron (muon) candidates can be reconstructed with transverse momenta as low as 1 (2) $\text{ GeV}$, and are required to fail the signal lepton requirements defined above to avoid any overlap. Signal tracks with a $p_T$ that differs from the transverse momentum of the matched lepton by more than 20% are rejected. The track–lepton matching allows the tracks to be identified as electron or muon tracks, reducing backgrounds from tracks not originating from the leptonic decay of a SUSY particle. Signal tracks must also satisfy dedicated isolation criteria: they are required to be separated from preselected jets by at least $\Delta R > 0.5$, and the $\sum_j p_T$ of preselected tracks within $\Delta R = 0.3$ of signal tracks, excluding the contributions from nearby leptons, is required to be smaller than 0.5 GeV. Finally, signal tracks must satisfy $p_T > 1 \text{ GeV}$, $|z_0 \sin \theta| < 0.5 \text{ mm}$, and $|d_0|/\sigma(d_0) < 3$.

The missing transverse momentum $p_T^{\text{miss}}$, with magnitude $E_T^{\text{miss}}$, is defined as the negative vector sum of the transverse momenta of all preselected objects (electrons,
muons, jets, and photons [103]), and an additional soft term that is constructed from all tracks that are not associated with any lepton or jet, but that are associated with the primary vertex. A dedicated overlap removal procedure is used to resolve ambiguities between the reconstructed objects [113]. In this way, $E_T^{\text{miss}}$ is adjusted for the best calibration of jets and leptons, while maintaining pileup independence in the soft term [114].

Small scale factors are applied to the efficiencies of reconstructed electrons, muons, $b$-tagged jets, and tracks in the simulated samples to match the reconstruction efficiencies in data. The scale factors for $b$-tagged jets account for the differences between data and simulated samples in the identification efficiencies for jets, including $b$-hadron decays, as well as misidentification rates of jets initiated from charm quarks, light-flavor quarks, or gluons. The scale factors for low-momentum leptons are obtained from $J/\psi \rightarrow e^+e^-$ events with the same tag-and-probe methods as used for higher-$p_T$ electrons [103] and muons [102]. The scale factors used to account for track–lepton matching efficiency differences between data and simulation are derived from events with a $J/\psi$ meson decaying into a low-$p_T$ signal electron and a preselected track. The track–isolation scale factors are measured using events with a $Z$ boson decaying into a signal lepton and a track matched to a reconstructed lepton candidate. All track scale factors are found to be compatible with 1.

After all lepton selection criteria and efficiency scale factors are applied, the efficiency for reconstructing and identifying signal electrons within the detector acceptance in the Higgsino and slepton signal samples ranges from 20% for $p_T = 4.5$ GeV to over 75% for $p_T > 30$ GeV. The corresponding efficiency for signal muons ranges from approximately 50% at $p_T = 3$ GeV to 90% for $p_T > 30$ GeV. The efficiency of selecting signal tracks for electroweakino events peaks at 78% for tracks with $p_T = 2.5$ GeV, with lower efficiencies at lower $p_T$ due to track selection criteria and at higher $p_T$ due to increasing electron and muon efficiencies. The efficiency for signal electrons, muons, and isolated tracks in a mix of slepton and Higgsino samples is shown in Fig. 3 as a function of lepton $p_T$.

Dedicated scale factors are also used to reweight MC events to properly model the trigger efficiency observed in data. These scale factors are measured in events selected with single-muon triggers, passing kinematic selections similar to the ones used to define the SRs. They are parametrized as a function of $E_T^{\text{miss}}$ and found to vary between 0.85 and 1 in the $E_T^{\text{miss}}$ range of interest. The uncertainty in the parametrization of the scale factors is negligible. An uncertainty of 5% is assigned to the scale factors to cover their dependence on other kinematic quantities of interest, such as $m_{\ell\ell}$ and $m_{\ell\gamma}$. Additional uncertainties of at most 4% are assigned due to differences between the trigger efficiencies determined with MC events for the different signal and background processes.

V. SIGNAL REGIONS

Events entering into all SRs share a common preselection, with requirements listed in Table II. The $2\ell$ channels require exactly two opposite-charge (OS) signal leptons of the same flavor, while the $1\ell/1T$ channel requires exactly one signal lepton and at least one OS signal track of the same flavor. In events where more than one OS same-flavor signal track is present, the candidate with the highest $p_T$ is used to define the $1\ell/1T$ system. In regions with two leptons, the higher-$p_T$ lepton is referred to as the “leading” lepton ($\ell_1$), while the lower-$p_T$ lepton is the “subleading” lepton ($\ell_2$).

Preselection requirements are employed to reduce backgrounds and form a basis for SRs and CRs used in the simultaneous fit. The leading lepton is required to have $p_T > 5$ GeV, which reduces backgrounds from FNP leptons. Pairs of muons are required to be separated by $\Delta R_{\mu\mu} > 0.05$, while pairs of electrons are required to be separated by $\Delta R_{ee} > 0.3$ to avoid reconstruction inefficiencies due to overlapping electron showers in the EM

![FIG. 3. Signal lepton efficiencies for electrons, muons, and isolated tracks in a mix of slepton and Higgsino samples. Combined reconstruction, identification, isolation, and vertex association efficiencies are shown for leptons within detector acceptance, and with lepton $p_T$ within a factor of 3 of $\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^0)$ for sleptons or of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)/2$ for Higgsinos. The efficiencies for isolated tracks include track reconstruction and vertex association efficiencies [112], as well as the efficiencies for track–lepton matching and track isolation, which are specific to this search. Scale factors are applied to match reconstruction efficiencies in data. The average number of interactions per crossing in the MC samples is 33.7; the number of pileup interactions match the distribution in data in spread and mean value. Uncertainty bands represent the range of efficiencies observed across all signal samples used for the given $p_T$ bin.](052005-7)
TABLE II. Preselection requirements applied to all events entering into electroweakino, slepton, and VBF search regions. Requirements marked with ∗ are not applied to VBF search regions. Requirements on jets are applied to VBF jets (satisfying |η| < 4.5) in the VBF channel.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$2\ell$</th>
<th>$1\ell/1T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons (tracks)</td>
<td>2 leptons</td>
<td>1 lepton and ≥1 track</td>
</tr>
<tr>
<td>Lepton $p_T$ [GeV]</td>
<td>$p_T^\ell &gt; 5$</td>
<td>$p_T^\ell &lt; 10$</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell}$</td>
<td>$\Delta R_{ee} &gt; 0.30$, $\Delta R_{\mu\mu} &gt; 0.05$, $\Delta R_{e\mu} &gt; 0.2$</td>
<td>0.05 &lt; $\Delta R_{\text{track}} &lt; 1.5$</td>
</tr>
<tr>
<td>Lepton (track) charge and flavor</td>
<td>$e^+e^-$ or $\mu^+\mu^-$</td>
<td>$e^+e^-$ or $\mu^+\mu^-$</td>
</tr>
<tr>
<td>Lepton (track) invariant mass [GeV]</td>
<td>$3 &lt; m_{\ell\ell} &lt; 60$, $1 &lt; m_{\mu\mu} &lt; 60$</td>
<td>$0.5 &lt; m_{\text{track}} &lt; 5$</td>
</tr>
<tr>
<td>$J/\psi$ invariant mass [GeV]</td>
<td>veto 3 &lt; $m_{e\ell} &lt; 3.2$</td>
<td>veto 3 &lt; $m_{\text{track}} &lt; 3.2$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>&lt;0 or &gt;160</td>
<td>no requirement</td>
</tr>
<tr>
<td>Number of jets</td>
<td>≥1</td>
<td>≥1</td>
</tr>
<tr>
<td>Number of $b$-tagged jets</td>
<td>0</td>
<td>no requirement</td>
</tr>
<tr>
<td>Leading jet $p_T$ [GeV]</td>
<td>≥100</td>
<td>≥100</td>
</tr>
<tr>
<td>$\min(\Delta \phi(\text{any jet}, p_T^{\text{miss}}))$</td>
<td>&gt;0.4</td>
<td>&gt;0.4</td>
</tr>
<tr>
<td>$\Delta \phi(j_1, p_T^{\text{miss}})$</td>
<td>≥2.0</td>
<td>≥2.0</td>
</tr>
</tbody>
</table>

calorimeter. Electrons and muons are likewise required to be separated by $\Delta R_{\mu\mu} > 0.2$ to avoid energy deposits from muons spoiling electron shower shapes. An additional requirement that $m_{\ell\ell}$ be outside of $[3.0, 3.2]$ GeV removes contributions from $J/\psi$ decays, while requiring $m_{\ell\ell} < 60$ GeV reduces contributions from on-shell $Z$-boson decays. Contributions from other hadronic resonances, e.g., $T$ states, are expected to be negligible in the search regions and are not explicitly vetoed. Requirements on the minimum angular separation between the lepton candidates ($\Delta R_{\ell\ell}$) and invariant mass ($m_{\ell\ell}$) remove events in which an energetic photon produces collinear lepton pairs.

The $m_{\tau\tau}$ variable [115–117] approximates the invariant mass of a leptonically decaying $\tau$-lepton pair if both $\tau$ leptons are sufficiently boosted so that the neutrinos from each $\tau$ decay are collinear with the visible lepton momentum. It is defined as $m_{\tau\tau} = \text{sign}(m_{\tau\tau}) \sqrt{|m_{\tau\tau}|}$, which is the signed square root of $m_{\tau\tau}^2 = 2p_{\tau_1} \cdot p_{\tau_2} (1 + \xi_1)(1 + \xi_2)$, where $p_{\tau_1}$ and $p_{\tau_2}$ are the lepton four-momenta, while the parameters $\xi_1$ and $\xi_2$ are determined by solving $p_T^{\text{miss}} = \xi_1 p_T^{\ell_1} + \xi_2 p_T^{\ell_2}$. It can be less than zero in events where one of the lepton momenta has a smaller magnitude than the $E_T^{\text{miss}}$ and points in the hemisphere opposite to the $p_T^{\text{miss}}$ vector. Events with $0 < m_{\tau\tau} < 160$ GeV are rejected, which reduces backgrounds from $Z \rightarrow \tau\tau$ and has an efficiency greater than 80% for the signals considered.

The reconstructed $E_T^{\text{miss}}$ is required to be greater than 120 GeV in preselection, with higher thresholds applied in some SRs. For SUSY events in which much of the invisible momentum is carried by the $Z^0$ pair, these requirements on $E_T^{\text{miss}}$ suggest that the SUSY system is recoiling against additional hadronic activity, in the form of either ISR or the forward jets in VBF processes. All events are therefore required to have at least one jet with $p_T > 100$ GeV. Additional jets in the event are also required to be separated from the $p_T^{\text{miss}}$ by $\min(\Delta \phi(\text{any jet}, p_T^{\text{miss}})) > 0.4$ in order to suppress the impact of jet energy mismeasurement on $E_T^{\text{miss}}$. For searches involving ISR, the leading jet is required to be separated from the $p_T^{\text{miss}}$ by at least 2.0 radians in $\phi$. In the $2\ell$ channel, events with one or more $b$-tagged jets with $p_T > 20$ GeV ($N_{b\text{-jet}}^{20}$) are vetoed to reduce backgrounds from $t\bar{t}$ production.

After applying the preselection requirements above, SRs are further optimized for specific SUSY scenarios. Three categories of SRs, labeled “SR-E,” “SR-VBF,” and “SR-S,” are constructed: the first for electroweakinos recoiling against ISR (or simply electroweakinos), the second for electroweakinos produced through VBF, and the last targeting sleptons recoiling against ISR.

The SRs designed for optimal sensitivity to electroweakinos are defined in Table III. High-$E_T^{\text{miss}}$ regions, labeled “SR-E-high” and “SR-E-1\ell/1T,” require $E_T^{\text{miss}} > 200$ GeV, where the online $E_T^{\text{miss}}$ triggers are fully efficient for the SUSY signal. Low-$E_T^{\text{miss}}$ regions are constructed using events with $120$ GeV < $E_T^{\text{miss}} < 200$ GeV: “SR-E-med” targets electroweakinos with small mass splittings, and “SR-E-low” targets mass splittings larger than ~10 GeV.

The $p_T$ threshold for the subleading lepton is defined with sliding cuts that retain efficiency for soft leptons from low-$\Delta m$ signals, while reducing backgrounds from FNP leptons in events with larger values of $m_{\ell\ell}$. The sliding requirement was optimized using a significance metric separately in each SR, considering signal models with a variety of masses and mass splittings. The significance was calculated following the profile likelihood method of
TABLE III. Requirements applied to events entering into the four signal regions used for electroweakino searches. The $1\ell^+1\ell^-$ preselection requirements from Table II are applied for SR-E-1$\ell^+1\ell^-$, while the $2\ell^+$ ones are applied for the other SRs.

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR-E-low</th>
<th>SR-E-med</th>
<th>SR-E-high</th>
<th>SR-E-1$\ell^+1\ell^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>[120, 200]</td>
<td>[120, 200]</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/H_T^{lep}$</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>&lt;30</td>
<td>&lt;30</td>
</tr>
<tr>
<td>$\Delta \phi(\text{lep}, p_T^{\text{miss}})$</td>
<td>...</td>
<td>...</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Lepton or track $p_T$ [GeV]</td>
<td>$p_T^{\ell^+} &gt; 5 + m_{\ell\ell}/4$</td>
<td>$p_T^{\ell^+} &gt; \min(10, 2 + m_{\ell\ell}/3)$</td>
<td>$p_T^{\ell^+} &lt; 5$</td>
<td>$p_T^{\ell^+} &lt; 5$</td>
</tr>
<tr>
<td>$M_S^S$ [GeV]</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>$m_T^{\ell\ell}$ [GeV]</td>
<td>[10, 60]</td>
<td>[10, 60]</td>
<td>&lt;60</td>
<td>&lt;60</td>
</tr>
<tr>
<td>$R_{\text{ISR}}$</td>
<td>[0.8, 1.0]</td>
<td>[0.8, 1.0]</td>
<td>[max(0.85, 0.98 - 0.02 \times m_{\ell\ell}), 1.0]</td>
<td>[max(0.85, 0.98 - 0.02 \times m_{\ell\ell}), 1.0]</td>
</tr>
</tbody>
</table>

Ref. [118], under the assumption that the observation in each SR matches the expected number of signal plus background events.

The transverse mass of the leading lepton and $E_T^{\text{miss}}$ is defined as $m^{T\ell} = \sqrt{2(E_T^{\text{miss}} E_T^{\ell} - p_T^{\ell} \cdot p_T^{\text{miss}})}$ and is used in the SR-E-low and SR-E-high regions to reduce contributions from fake and nonprompt leptons.

In events with high-$p_T$ ISR jets, the axis of maximum back-to-back $p_T$, referred to here as the thrust axis, approximates the direction of the recoil of the ISR activity against the sparticle pair. The recursive jigsaw reconstruction (RJR) technique [46] is used to divide each event into two hemispheres perpendicular to the thrust axis: a supersymmetric-particles hemisphere $S$, expected to contain the decay products of the electroweakinos or slepton pair and therefore the $E_T^{\text{miss}}$; and an ISR hemisphere, containing hadronic activity. This bisection allows the calculation of two discriminating variables that are useful in isolating events with ISR-induced $E_T^{\text{miss}}$ topologies: $R_{\text{ISR}}$, the ratio of the $E_T^{\text{miss}}$ to the transverse momentum of the ISR system, and $M_S^S$, the transverse mass of the $S$ system. The $R_{\text{ISR}}$ variable in particular is sensitive to the mass splitting, with values near 1.0 for the most compressed SUSY events. Figure 4 shows the relationship between $R_{\text{ISR}}$ and $m_{\ell\ell}$ and $m_T^{100}$, which is exploited in SR-E-high and SR-S-high ($m_T^{100}$ and SR-S-high are defined below) through sliding requirements on $R_{\text{ISR}}$.

The $E_T^{\text{miss}}/H_T^{lep}$ variable, where $H_T^{lep}$ is the scalar sum of the $p_T$ of the two leptons, has been shown to be an effective discriminant for SUSY signals [45]. The two low-$E_T^{\text{miss}}$ electroweakino SRs are made orthogonal by requiring $E_T^{\text{miss}}/H_T^{lep} > 10$ for SR-E-med, where $H_T^{lep}$ is typically

FIG. 4. Distributions of $R_{\text{ISR}}$, the ratio of the $E_T^{\text{miss}}$ to the transverse momentum of the hadronic ISR activity, for the electroweakino (left) and slepton (right) high-$E_T^{\text{miss}}$ SRs. Distributions are shown after applying all signal selection criteria except those on $R_{\text{ISR}}$. The solid red line indicates the requirement applied in the signal region; events in the region below the red line are rejected. Representative benchmark signals for the Higgsino (left) and slepton (right) simplified models are shown as circles. The gray rectangular boxes show the distribution of the total background prediction, which is primarily composed of top-like processes, diboson processes, and events with fake/nonprompt leptons. Regions at larger $m_{\ell\ell}$ and $m_T^{100}$ are not populated by the representative signals shown here, but are useful probes of less-compressed signal models.
smaller for the SUSY signal, and $E_{T}^{\text{miss}}/H_{T}^{\text{lep}} < 10$ for SR-E-low, where $H_{T}^{\text{lep}}$ increases due to the larger mass splitting.

The 1/$\ell$T channel targets SUSY signals with especially low values of $\Delta m$, which produce decay products with very low momentum. The signal region “SR-E-1/$\ell$T” therefore requires that the identified lepton have $p_{T} < 10$ GeV and that the track have $p_{T} < 5$ GeV. The lepton is also required to be within 1.0 radians of the $p_{T}^{\text{miss}}$ in $\phi$, to reduce backgrounds with tracks associated with nonprompt leptons or hadrons. Finally, the SR-E-1/$\ell$T region requires $E_{T}^{\text{miss}}/H_{T}^{\text{lep}} > 30$, where in this case $H_{T}^{\text{lep}}$ is the scalar sum of lepton and track $p_{T}$, again exploiting the low values of $H_{T}^{\text{lep}}$ expected for signal models with small mass splittings.

After all selection criteria are applied, the Higgsino model with $m(\tilde{\chi}_{1}^{0}) = 110$ GeV and $m(\tilde{\chi}_{2}^{0}) = 100$ GeV has an acceptance times efficiency of $1.1 \times 10^{-4}$ in the union of all SR-E regions.

Signal regions designed for sensitivity to electroweakinos produced through VBF are defined in Table IV and denoted SR-VBF. VBF production is commonly characterized by the presence of two energetic jets with a large dijet invariant mass and large separation in pseudorapidity. Two regions are constructed, distinguished by the pseudorapidity gap between the two leading jets: events with $2 < \Delta \eta_{jj} < 4$ are tested in “SR-VBF-low,” while events with $\Delta \eta_{jj} > 4$ are tested in “SR-VBF-high.” The $E_{T}^{\text{miss}}$ is required to be greater than 150 GeV, which increases the acceptance relative to an $E_{T}^{\text{miss}} > 200$ GeV requirement while not introducing significant additional backgrounds. Additional requirements on $p_{T}^{\ell}$, $m_{\ell}$, and $E_{T}^{\text{miss}}/H_{T}^{\text{lep}}$ similarly reduce backgrounds for small losses in signal efficiency. The $R_{\text{VBF}}$ variable is constructed similarly to $R_{\text{ISR}}$ with the vector sum of the two leading VBF jets in $R_{\text{VBF}}$ taking the place of the ISR system in $R_{\text{ISR}}$. Additionally, in the case that an energetic jet is well separated from the two leading VBF jets, this jet is added to the decay tree. This forms an effective third-jet veto by altering the decay hemisphere, spoiling the back-to-back configuration in QCD-initiated events, while in signal events the central hadronic activity is expected to be suppressed. The $R_{\text{VBF}}$ variable is also sensitive to the mass splitting, so sliding requirements on $R_{\text{VBF}}$ are used in both VBF SRs. The acceptance times efficiency of Higgsinos with $m(\tilde{\chi}_{1}^{0}) = 100$ GeV and $m(\tilde{\chi}_{2}^{0}) = 95$ GeV produced through VBF in the SR-VBF is $2.9 \times 10^{-4}$.

The SRs designed to provide sensitivity for slepton production, denoted SR-S, are defined in Table V. The slepton search exploits the relationship between the mass splitting and the lepton and $E_{T}^{\text{miss}}$ kinematics via the transverse mass ($m_{T}$) variable [28,29]. The transverse mass is defined as

$$m_{T} = \sqrt{m_{\ell}^{2} + (p_{T}^{\ell} \cdot p_{T}^{miss})^{2}} = \min(m_{T}(p_{T}^{\ell}, q_{\ell}), m_{T}(p_{T}^{\ell}, q_{T}), m_{T}(p_{T}^{\ell}, p_{T}^{\text{miss}} - q_{T}, m_{\ell}^{2})).$$

where $m_{\ell}$ is the hypothesized mass of the invisible particles, and the transverse momentum vector $q_{\ell}$ with magnitude $q_{T}$ is chosen to minimize the larger of the two transverse masses, defined by

$$m_{T}(p_{T}^{\ell}, q_{\ell}) = \min(m_{T}(p_{T}^{\ell}, q_{\ell})) = \min(m_{T}(p_{T}^{\ell}, q_{\ell}), m_{T}(p_{T}^{\ell}, q_{T})) = \min(max(0.85, 0.98 - 0.02 \times (m_{T} - 100)), 1.0)$$

**TABLE IV.** Requirements applied to all events entering into signal regions used for searches for electroweakinos produced through VBF. The 2/$\ell$ preselection requirements from Table II are implied.

<table>
<thead>
<tr>
<th>Variable</th>
<th>VBF SR requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\ell}$ [GeV]</td>
<td>$&lt;40$</td>
</tr>
<tr>
<td>Number of jets</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$p_{T}^{\ell}$ [GeV]</td>
<td>$&gt;40$</td>
</tr>
<tr>
<td>$E_{T}^{\text{miss}}$ [GeV]</td>
<td>$&gt;150$</td>
</tr>
<tr>
<td>$E_{T}^{\text{miss}}/H_{T}^{\text{lep}}$</td>
<td>$&gt;2$</td>
</tr>
<tr>
<td>$p_{T}^{\ell}$ [GeV]</td>
<td>$&gt;\min(10, 2 + m_{\ell}/3)$</td>
</tr>
<tr>
<td>$m_{\ell}$ [GeV]</td>
<td>$&lt;60$</td>
</tr>
<tr>
<td>$R_{\text{VBF}}$</td>
<td>$[\max(0.6, 0.92 - m_{\ell}/60), 1.0]$</td>
</tr>
<tr>
<td>$\Delta \eta_{jj}$</td>
<td>$&lt;4$</td>
</tr>
<tr>
<td>$\Delta \eta_{jj}$</td>
<td>$&gt;4$</td>
</tr>
</tbody>
</table>

**TABLE V.** Requirements applied to all events entering into signal regions used for slepton searches. The 2/$\ell$ preselection requirements from Table II are implied.

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR-S-low</th>
<th>SR-S-high</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{T}^{\text{miss}}$ [GeV]</td>
<td>[150, 200]</td>
<td>&gt;200</td>
</tr>
<tr>
<td>$m_{T}^{100}$ [GeV]</td>
<td>$&lt;140$</td>
<td>$&lt;140$</td>
</tr>
<tr>
<td>$p_{T}^{\ell}$ [GeV]</td>
<td>$&gt;\min(15.75 + 0.75 \times (m_{T} - 100))$</td>
<td>$&gt;\min(20, 2.5 + 2.5 \times (m_{T} - 100))$</td>
</tr>
<tr>
<td>$R_{\text{ISR}}$</td>
<td>[0.8, 1.0]</td>
<td>$[\max(0.85, 0.98 - 0.02 \times (m_{T} - 100)), 1.0]$</td>
</tr>
</tbody>
</table>
For signal events with slepton mass $m(\tilde{e})$ and LSP mass $m(\tilde{\chi}_1^0)$, the values of $m_{t_2}^{\tilde{e}}$ are bounded from above by $m(\tilde{e})$ when $m(\tilde{e})$ is equal to $m(\tilde{\chi}_1^0)$. The transverse mass with $m(\tilde{e}) = 100$ GeV, denoted $m_{t_2}^{100}$, is used in this paper. The chosen value of 100 GeV is based on the expected LSP masses of the signals studied. The distribution of $m_{t_2}^{100}$ does not vary significantly for the signals considered in which $m(\tilde{\chi}_1^0) \neq 100$ GeV.

The “SR-S-low” slepton region requires events with $150 \text{ GeV} < E_T^{\text{miss}} < 200 \text{ GeV}$, while the “SR-S-high” region requires events with $E_T^{\text{miss}} > 200 \text{ GeV}$. The SR-S-low region contributes most significantly for signals with $\Delta m \gtrsim 10 \text{ GeV}$, where the leptons satisfy the $p_T$ thresholds without needing a significant additional boost from ISR jets. Both regions are constructed with sliding requirements on $p_T^\ell$, following the strategy for the electroweakino regions above. The requirements on $R_{\text{ISR}}$ are looser in the SR-S-low region, targeting less compressed scenarios. The SR-S-high region uses a sliding requirement on $R_{\text{ISR}}$ to maintain sensitivity to the most compressed scenarios while reducing backgrounds for events with larger $m_{t_2}^{100}$. After all selection criteria are applied, the slepton model with $m(\tilde{e}) = 100$ GeV and $m(\tilde{\chi}_1^0) = 90$ GeV has an acceptance times efficiency of $2.5 \times 10^{-3}$ when considering both SR-S regions. Acceptances and efficiencies for left- and right-handed sleptons are consistent with each other for all slepton scenarios under study.

After all selection requirements are applied, the SR-E and the SR-VBF regions are binned in $m_{T\ell}$, with bin boundaries at $m_{T\ell} = 1, 2, 3, 5, 10, 20, 30, 40,$ and $60 \text{ GeV}$ for the $2\ell$ channels, and at $m_{T\ell} = 0.5, 1, 1.5, 2, 3, 4,$ and $5 \text{ GeV}$ for the $1\ell/1T$ channel. Events in the SR-E-med region with $m_{T\ell} > 30 \text{ GeV}$ have minimal sensitivity to the electroweakino signals studied and are not considered. Similarly, events in the SR-E-1$\ell/1T$ region with $m_{T\ell} > 5 \text{ GeV}$ are discarded. The slepton SR-S regions are instead binned in $m_{t_2}^{100}$, with bin boundaries at $m_{t_2}^{100} = 100, 100.5, 101, 102, 105, 110, 120, 130,$ and $140 \text{ GeV}$. Events with $m_{t_2}^{100}$ above 140 GeV have minimal sensitivity to compressed sleptons and are not considered in any of the regions. Events with $m_{T\ell}$ above 60 GeV are rejected in preselection for all channels.

The binned $m_{T\ell}$ and $m_{t_2}^{100}$ distributions are used in two different types of statistical tests. The first test is a search for excesses with minimal model dependence, in which any given fit considers a single inclusive SR. An inclusive electroweakino SR is constructed by merging all SR-E-high, SR-E-med, SR-E-low, and SR-E-1$\ell/1T$ bins below a $m_{T\ell}$ bin boundary listed above, with each $2\ell$ electroweakino bin boundary corresponding to an inclusive SR. Similarly, the inclusive slepton regions are constructed by merging all SR-S-high and SR-S-low bins below the $m_{t_2}^{100}$ bin boundaries. The inclusive VBF SRs are also constructed by merging the SR-VBF-low and SR-VBF-high bins below the $m_{T\ell}$ boundaries. Additional inclusive VBF SRs are defined using events in SR-VBF-high only.

<table>
<thead>
<tr>
<th>Region</th>
<th>SR orthogonality</th>
<th>Lepton flavor</th>
<th>Additional requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRtop-E-high</td>
<td>$N_\text{jet}^{20}$ $\geq 1$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$R_{\text{ISR}} \in [0.7, 1.0], m_{T\ell}^{\tilde{e}}$ removed, $E_T^{\text{miss}}/H_T^{\text{lep}}$ and $m_{T\ell}^{\tilde{e}}$ removed</td>
</tr>
<tr>
<td>CRtop-E-low</td>
<td>$N_\text{jet}^{10}$ $\geq 1$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$R_{\text{ISR}} \in [0.7, 1.0], m_{T\ell}^{\tilde{e}}$ removed</td>
</tr>
<tr>
<td>CRTau-E-high</td>
<td>$m_{T\ell} \in [60, 120] \text{ GeV}$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$R_{\text{ISR}} \in [0.6, 1.0], m_{T\ell}^{\tilde{e}}$ removed</td>
</tr>
<tr>
<td>CRTau-E-low</td>
<td>$m_{T\ell} \in [60, 120] \text{ GeV}$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$m_{T\ell}^{\tilde{e}}$ removed</td>
</tr>
<tr>
<td>VRVSS-E-med</td>
<td>$R_{\text{ISR}} \in [0.7, 0.85]$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$R_{\text{ISR}} \in [0.7, 1.0], m_{T\ell}^{\tilde{e}}$ and $p_T^{\tilde{e}}$ removed, $E_T^{\text{miss}}/H_T^{\text{lep}}$, $m_{T\ell}^{\tilde{e}}$ and $p_T^{\tilde{e}}$ removed</td>
</tr>
<tr>
<td>VRSS-E-low</td>
<td>$R_{\text{ISR}} \in [0.6, 0.8]$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$R_{\text{ISR}} \in [0.7, 1.0], m_{T\ell}^{\tilde{e}}$ and $p_T^{\tilde{e}}$ removed, $E_T^{\text{miss}}/H_T^{\text{lep}}$, $m_{T\ell}^{\tilde{e}}$ and $p_T^{\tilde{e}}$ removed</td>
</tr>
<tr>
<td>VRDF-E-high</td>
<td>Same sign $e^\pm e^\pm$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td></td>
</tr>
<tr>
<td>VRDF-E-low</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td></td>
</tr>
<tr>
<td>VRDF-E-med</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td>$ee + \mu\mu + \mu\mu$</td>
<td></td>
</tr>
</tbody>
</table>
VI. BACKGROUND ESTIMATION

The sources of SM background in regions with two leptons can be subdivided into two categories: reducible backgrounds from events where at least one of the candidate leptons is FNP, and irreducible backgrounds from events that contain two prompt leptons. Since MC simulation is not expected to model processes with FNP leptons accurately, a data-driven method, referred to as the fake factor method [119,120], is employed to estimate these backgrounds. The yields obtained from this procedure are cross-checked in validation regions (VRs), which are not used to constrain the fit and are orthogonal in selection to the CRs and SRs.

The dominant sources of irreducible background are $t\bar{t}/tW$, $WW/WZ$, and $Z^{(*)}/Z^\rightarrow (\tau\tau)$ + jets. These backgrounds are estimated using MC simulations normalized to data in dedicated CRs. Events originating from the production of a Drell-Yan lepton pair, a triboson, a Higgs boson, or top quarks in association with gauge bosons constitute a small fraction of the total background. Their contributions in the regions with two leptons are estimated using the MC samples listed in Table I. Additional VRs are used to validate the extrapolation of background in the fitting procedure within the same kinematic regime as the SRs.

The definitions of the CRs and VRs used in the electroweakino, VBF, and slepton searches are summarized in Tables VI, VII, and VIII, respectively. The VRSS regions are further described in Sec. VI A, in the context of the FNP background estimation, while the remaining CRs and VRs are explained in Sec. VI B.

The dominant source of background in the $1\ell'1T$ channel is combinatorial, from events containing one prompt lepton and one random track, and is collectively estimated using data, as described in Sec. VIC.

A. Reducible background in regions with two leptons

The FNP lepton background arises from jets misidentified as leptons, photon conversions, or semileptonic decays.

<table>
<thead>
<tr>
<th>Region</th>
<th>SR orthogonality</th>
<th>Lepton flavor</th>
<th>Additional requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRtop-VBF</td>
<td>$N_{R_{b-jet}}^{20} \geq 1$</td>
<td>$e\mu + \mu\mu + \mu\mu + \mu\mu$</td>
<td>$R_{ISR} \in [0.7, 1.0]$</td>
</tr>
<tr>
<td>CRtau-VBF</td>
<td>$m_{\ell\ell} \in [60, 120]$ GeV</td>
<td>$e\mu + \mu\mu + \mu\mu + \mu\mu$</td>
<td>$R_{ISR} \in [0.7, 1.0]$</td>
</tr>
<tr>
<td>VRSS-VBF</td>
<td>$R_{ISR} \in [0.7, 0.8]$</td>
<td>$e\mu + \mu\mu + \mu\mu + \mu\mu$</td>
<td>$m_{T}^{\ell\ell} &gt; 30$, $N_{jets} \in [1.2]$</td>
</tr>
<tr>
<td>VRDF-VBF-low</td>
<td>Same sign $\ell^{+}\ell^{-}$</td>
<td>$e\mu + \mu\mu + \mu\mu + \mu\mu$</td>
<td>$R_{ISR} \in [0.7, 1.0]$, $p_{T}^{\ell\ell}$ removed</td>
</tr>
<tr>
<td>VRDF-VBF-high</td>
<td>$e\mu + \mu\mu + \mu\mu + \mu\mu$</td>
<td>$e\mu + \mu\mu + \mu\mu + \mu\mu$</td>
<td>$p_{T}^{\ell\ell}$ removed</td>
</tr>
</tbody>
</table>

TABLE VIII. Definition of control (“CR” prefix) and validation (“VR” prefix) regions used for background estimation in the search for electroweakinos produced through VBF, presented relative to the definitions of the corresponding signal regions SR-VBF-high and SR-VBF-low. The $2\ell$ preselection criteria from Table II and selection criteria from Table V are implied, unless specified otherwise.
of heavy-flavor hadrons. Studies based on simulated samples indicate that the last is the dominant component in the SRs with two leptons. The contamination of the SRs by the FNP lepton background is large at low values of $m_{T2}$ and $m_{T1}^{100}$, and it decreases at the upper end of the distributions.

In the fake factor method, a two-lepton control sample is defined in data using leptons with modified signal lepton requirements. At least one of the leptons, labeled as “anti-ID,” is required to fail one or more of the requirements applied to signal leptons, but is required to satisfy less restrictive requirements. The other lepton can either meet all signal lepton requirements, in which case it is labeled as ID, or satisfy the anti-ID requirements. This sample is enriched in FNP lepton backgrounds, while backgrounds, labeled cross-checked in dedicated VRs enriched in FNP lepton requirements. At least one of the leptons, labeled as $l^-$, is defined in data using leptons with modified signal lepton requirements. The fake factor is measured in a data sample collected with prescaled low-$p_T$ single-lepton triggers. This sample is dominated by multijet events with FNP leptons and is referred to as the measurement sample. A selection of $m_{T1}^{100} < 40$ GeV is applied to reduce the contributions from processes with prompt leptons in the measurement sample. The contributions from these processes are subtracted using MC simulation, with negligible impact on the measured fake factors.

To enrich the sample in FNP leptons similar to those contaminating the SRs, the leading-jet $p_T$ is required to be greater than 100 GeV. The fake factors are calculated as the ratio of ID to anti-ID leptons in the measurement sample, measured in bins of lepton $p_T$, separately for electrons and muons. The fake factors are also found to have a dependence on the number of $b$-tagged jets in the events. Different fake factors are therefore computed in events with and without $b$-tagged jets.

The yields predicted by the fake factor method are cross-checked in dedicated VRs enriched in FNP lepton backgrounds, labeled “VRSS.” As summarized in Tables VI, VII, and VIII, a dedicated VRSS is constructed for each SR by selecting events with two leptons with the same electric charge. The kinematic requirements applied

![Figure 5](image_url)

**FIG. 5.** The relative systematic uncertainties in the fitted SM background as obtained from CR + SR background-only fits for the electroweakino SRs (top), VBF SRs (middle), and slepton SRs (bottom). The uncertainty in the “SS data” includes a statistical component due to the size of the SS data sample used to estimate the background in the SR-E-1/17 region, and a systematic component from the SS–OS extrapolation. The “MC Statistics” uncertainty originates from the limited size of the MC samples used to model the irreducible background contributions. The “Normalization” uncertainty arises from the use of CRs to normalize the contributions from processes with prompt leptons in the measurement sample. The “Background modeling” includes the different sources of theoretical modeling uncertainties in the $m_{T2}$ or $m_{T1}^{100}$ line shapes for the irreducible backgrounds. All sources of uncertainty affecting the FNP background estimate are included under “Fake/nonprompt.” The uncertainties arising from the reconstruction and selection of signal leptons, jets, and $E_T^{miss}$ are included under the “Experimental” category. The individual uncertainties can be correlated and do not necessarily add up in quadrature to the total uncertainty.
to each VRSS are mostly the same as the ones used in the corresponding SR, ensuring that the FNP lepton processes are similar in the two regions. To guarantee high purity in FNP lepton background, the selection criteria designed to suppress these processes in the SRs, such as the sliding cut on the $p_T$ threshold of the subleading lepton, are loosened or removed in each VRSS. The contribution of the FNP background in the VRSS regions is typically above 91%, with the remaining backgrounds originating from VV processes with two prompt leptons of the same electric charge. The signal contamination is at most 14%.

**B. Irreducible background in regions with two leptons**

Several CRs are defined for the electroweakino, VBF, and slepton searches and are used to normalize the MC simulations of $\bar{t}t/Wt$ and $Z^{(*)}/\gamma^* (\rightarrow \tau \tau) +$ jets background processes to the data in a simultaneous fit also including the SRs, as described in Sec. VIII. In searches for electroweakinos and sleptons recoiling against ISR, CRs are also constructed to normalize the WW/WZ background. The event rates in the SRs are predicted by extrapolating from the CRs using the simulated MC distributions. This extrapolation is validated using events in dedicated VRs.

The CRs are designed to be statistically disjoint from the SRs, to be enriched in a particular background process, to have minimal contamination from the signals considered, and to exhibit kinematic properties similar to the SRs. The CRs labeled as “CRtop” are defined by selecting events with at least one $b$-tagged jet. The CRtop regions have purities ranging from 83% to 94% in processes with top quarks and are used to constrain the normalization of the $\bar{t}t$ and $tW$ processes with dilepton final states. The “CRtau” regions, which are enriched in the $Z^{(*)}/\gamma^* (\rightarrow \tau \tau) +$ jets process with purities of at least 75%, are constructed by selecting events satisfying $m_{\tau\tau} \in [60, 120]$ GeV. Finally, the $R_{ISR}$ selection used to define the CRs is modified to construct CRs enriched in WW and WZ processes, denoted “CRVV.” In these CRs, 41%–45% of the events are VV events.

The $\bar{t}t/Wt$, $WW/WZ$, and $Z^{(*)}/\gamma^* (\rightarrow \tau \tau) +$ jets processes containing two prompt leptons all yield same-flavor lepton pairs (ee and $\mu\mu$) at the same rate as for different-flavor pairs ($e\mu$ and $\mu e$), where the first lepton is the leading lepton). This feature is used to enhance the statistical constraining power of the CRs, by selecting events with all possible flavor assignments ($e\mu$, $\mu e$, and $e\mu$). It is also used to define additional VRs, denoted “VRDF.” One VRDF is defined for each $Z$/SR by requiring two different-flavor leptons ($e\mu$ and $\mu e$), but otherwise keeping the same kinematic selections as the corresponding SR. The relative fractions of each background process are similar in the SR and the corresponding VRDF. The signal contamination in the VRDF regions is at most 16%, originating from $\tilde{\chi}^0_1\tilde{\chi}^0_2$ or $\tilde{\chi}^0_2\tilde{\chi}^0_2$ Higgsino events decaying fully leptonically.

In the search for electroweakinos recoiling against ISR, six single-bin CRs are defined as summarized in Table VI. Three CRs, labeled “CR-E-high,” employ a $E_T^{\text{miss}} > 200$ GeV selection and are used to constrain the normalization of $\bar{t}t/Wt$, $WW/WZ$, and $Z^{(*)}/\gamma^* (\rightarrow \tau \tau) +$ jets backgrounds in SR-E-high. To minimize the impact of the mismodeling of the trigger efficiency in the simulation, three additional CRs, labeled “CR-E-low,” are defined by selecting events with $E_T^{\text{miss}} \in [120, 200]$ GeV. These CRs are used to normalize the same background processes in SR-E-low. Events with FNP leptons entering the CRs are suppressed using the same sliding cut on $p_T^{\ell}$ as the corresponding SRs.

The dominant source of irreducible background in the SR-E-med region is the $Z^{(*)}/\gamma^* (\rightarrow \tau \tau) +$ jets process. It is difficult to construct a dedicated CR with enough events to constrain the normalization of the $Z^{(*)}/\gamma^* (\rightarrow \tau \tau) +$ jets background in the SR-E-med region. The “CRtau-E-low” region is therefore used for this purpose. The extrapolation from CRtau-E-low to SR-E-med is tested in an additional VR, labeled “VRtau-E-med,” defined by selecting events with $m_{\tau\tau} \in [60, 120]$ GeV, but otherwise applying the same kinematic selections as in the SR-E-med region, as summarized in Table VI.

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>$E_T^{\text{miss}}$ region</th>
<th>Normalization parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Electroweakino</td>
</tr>
<tr>
<td>$\bar{t}t/Wt$</td>
<td>high</td>
<td>1.08 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>1.08 ± 0.18</td>
</tr>
<tr>
<td>$Z^{(<em>)}/\gamma^</em> (\rightarrow \tau \tau) +$ jets</td>
<td>high</td>
<td>0.96 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>1.02 ± 0.15</td>
</tr>
<tr>
<td>$VV$</td>
<td>high</td>
<td>0.89 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>0.69 ± 0.22</td>
</tr>
</tbody>
</table>

TABLE IX. Normalization factors obtained from a background-only fit of the CRs defined for electroweakino, slepton, and VBF searches. The uncertainties include statistical and systematic contributions combined.
Two control regions are defined for the VBF search, as summarized in Table VII. The “CRtop-VBF” and the “CRTtau-VBF” regions are designed with a Δη_{jj} > 2 requirement, and are used to constrain the normalizations of the ττ/W and Z^{(*)}/γ^{*} (→ ττ) + jets processes in both the SR-VBF-low and the SR-VBF-high regions. The number of events in the VBF CRs is increased by removing the m_{T}^{ll} and R_{VBF} selections used in the SRs.

Six CRs are used to normalize the ττ/W, WW/WZ, and Z^{(*)}/γ^{*} (→ ττ) + jets background processes entering the SR-S-low and SR-S-high regions, as summarized in Table VIII. The CRs used in the search for sleptons are designed similarly to the CRs used in the search for electroweakinos. One notable difference is the sliding cut on the p_{T}^{miss} threshold, which is chosen to match the requirements used in the slepton SRs and therefore depends on m_{T2}^{100}.

C. Background in the 1ℓ1T signal region

The background in the SR-E-1ℓ1T region is suppressed by requiring that the selected track be associated with a reconstructed lepton candidate. Simulation studies show that this background is dominated by events with one prompt lepton and one track from hadrons or nonprompt leptons. The MC samples used to model SM processes with two prompt leptons contribute negligibly in the 1ℓ1T SR.

The amount of background in the 1ℓ1T channel is estimated using a data-driven procedure. A control sample is defined in data with events that satisfy the same selection criteria as the SR-E-1ℓ1T region. Instead of selecting OS events with one lepton and one track, the lepton and the track in the control sample are required to have the same electric charge (SS). The contamination of the SS control sample by signal is negligible. The data in the SS sample are directly used as the estimate of the background in SR-E-1ℓ1T. The background estimate assumes that the background events are produced with equal rates for OS and SS events. This is expected to be the case because the track is randomly selected and its electric charge is not correlated with the charge of the prompt lepton.

The assumption that OS and SS background events are produced with equal rates in the 1ℓ1T signal region is tested in simulation using W + jets events. The ratio of OS to SS W + jets events was found to be compatible with 1, with a statistical uncertainty of 12% determined by the size of the MC sample. A VR, denoted “VR-1ℓ1T,” is constructed to test the assumption using data. The VR-1ℓ1T is designed using the same kinematic selections as the 1ℓ1T SR, except that Δφ(lep, p_{T}^{miss}) > 1.5 is required to ensure that the samples are disjoint. The upper bound on ΔR_{track} used in SR-E-1ℓ1T is removed to reduce the signal contamination, and the p_{T}^{miss}/H_{T}^{lep} requirement is loosened to p_{T}^{miss}/H_{T}^{lep} > 15 to increase the number of events in the

FIG. 6. Comparison of observed and expected event yields in the VRDF regions after a background-only fit of the CRs. The three VRDF-E regions are shown at the top, binned in m_{T} as the corresponding electroweakino SRs. The two VRDF-VBF regions are shown in the middle, also binned in m_{T}. The bin 1 GeV < m_{T} < 2 GeV is omitted from the VRDF-VBF-high region because both the expected and observed event yields are zero. Finally, the two VRDF-S regions are shown at the bottom, binned in m_{T} as the corresponding slepton SRs. Uncertainties in the background estimates include both the statistical and systematic uncertainties. The bottom panel in all three plots shows the significance of the difference between the expected and observed yields, computed following the profile likelihood method of Ref. [118] in the case where the observed yield exceeds the prediction, and using the same expression with an overall minus sign if the yield is below the prediction.
VR. The kinematic distributions of the SS and OS data events in the VR-1/1T are compared and found to agree.

VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are evaluated for all background processes and signal samples. As the predictions for the main SM background processes modeled via MC simulation are normalized to data in dedicated control regions, the systematic uncertainties only affect the extrapolation to the signal regions in these cases.

Figure 5 illustrates the dominant classes of uncertainties in the expected background yields in the electroweakino, VBF, and slepton SRs. The main sources of experimental
uncertainty affect the FNP background predictions obtained with the fake factor method. These systematic uncertainties stem from the size of the FNP control samples, as well as from the size of the measurement sample used to compute the fake factors. The uncertainties associated with the subtraction of processes involving prompt leptons in the FNP control samples and in the measurement sample are estimated from simulation and found to be negligible. Uncertainties are also assigned to cover the differences in the event and lepton kinematics between the measurement region and the signal regions. Moreover, additional uncertainties are computed as the differences between the FNP background predictions and observed data in the VRSS regions.

Other sources of significant experimental systematic uncertainties are the jet energy scale (JES) and resolution (JER). The jet uncertainties are derived as a function of $p_T$ and $\eta$ of the jet, as well as of the pileup conditions and the jet flavor composition of the selected jet sample. They are determined using a combination of simulated samples and studies of data, such as measurements of the jet $p_T$ balance in dijet, $Z +$ jet, and $\gamma +$ jet events [108]. The systematic uncertainties related to the modeling of $E_T^{miss}$ in the simulation are estimated by propagating the uncertainties in the energy and momentum scale of each of the objects entering the calculation, as well as the uncertainties in the soft-term resolution and scale [113].

The reconstruction, identification, and isolation efficiencies for low-$p_T$ leptons, as well as the momentum resolution and scale, are measured and calibrated following methods similar to those employed for higher-$p_T$ electrons [103] and muons [102]. The associated systematic uncertainties are in general found to be small.

The MC samples simulating the dominant background processes, $t\bar{t}W$, $Z^{(*)}/\gamma^* (\rightarrow \tau\tau) +$ jets and $VV$, are also affected by different sources of theoretical modeling uncertainty. The uncertainties related to the choice of QCD renormalization and factorization scales are assessed by varying the corresponding generator parameters up and
down by a factor of 2 around their nominal values. Uncertainties in the resummation scale and the matching scale between matrix elements and parton showers for the $Z^{(*)}/\gamma^{*}\rightarrow \tau\tau + \text{jets}$ samples are evaluated by varying up and down by a factor of 2 the corresponding parameters in SHERPA. The uncertainties associated with the choice of PDF set, NNPDF [54,84], and uncertainty in the strong coupling constant, $\alpha_s$, are also considered.

As discussed in Sec. VI, the background predictions in the 1/$\ell$/$1T$ SR, selecting OS lepton–track pairs, are extracted from a SS data control sample. Two different types of
TABLE X.  *Left to right:* The first column indicates the inclusive signal region under study, defined as the union of the individual SRs defined in Sec. V and by upper bounds on $m_{ee}$ or $m_{T^2}^{100}$ in GeV. The $m_{ee}$ regions include events in both the $2\ell e$ and $1\ell 1\tau$ channels, while the $m_{T^2}^{100}$ regions only include $2\ell e$ events. The next two columns present observed ($N_{\text{obs}}$) and expected ($N_{\text{exp}}$) event yields in the inclusive signal regions. The latter are obtained by the background-only fit of the CRs, and the errors include both the statistical and systematic uncertainties. The next two columns show the observed 95% C.L. upper limits on the visible cross section ($<\sigma_{\text{obs}}^{95}$) and on the number of signal events ($N_{\text{obs}}^{95}$). The next column ($N_{\text{exp}}^{95}$) shows the 95% C.L. upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ deviations from the expectation) of background events. The last column indicates the discovery $p(s = 0)$.

<table>
<thead>
<tr>
<th>Signal region</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{exp}}$</th>
<th>$&lt;\sigma_{\text{obs}}^{95}$ [fb]</th>
<th>$N_{\text{obs}}^{95}$</th>
<th>$N_{\text{exp}}^{95}$</th>
<th>$p(s = 0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{ee} &lt; 1$</td>
<td>0</td>
<td>1.0 ± 1.0</td>
<td>0.022</td>
<td>3.0</td>
<td>3.0 ± 1.3</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 2$</td>
<td>46</td>
<td>44 ± 6.8</td>
<td>0.15</td>
<td>21</td>
<td>19 ± 7</td>
<td>0.38</td>
</tr>
<tr>
<td>$m_{ee} &lt; 3$</td>
<td>90</td>
<td>77 ± 12</td>
<td>0.29</td>
<td>41</td>
<td>31 ± 11</td>
<td>0.18</td>
</tr>
<tr>
<td>$m_{ee} &lt; 5$</td>
<td>151</td>
<td>138 ± 18</td>
<td>0.38</td>
<td>52</td>
<td>43 ± 16</td>
<td>0.24</td>
</tr>
<tr>
<td>$m_{ee} &lt; 10$</td>
<td>244</td>
<td>200 ± 19</td>
<td>0.62</td>
<td>86</td>
<td>49 ± 26</td>
<td>0.034</td>
</tr>
<tr>
<td>$m_{ee} &lt; 20$</td>
<td>383</td>
<td>301 ± 23</td>
<td>0.95</td>
<td>132</td>
<td>61 ± 22</td>
<td>0.0034</td>
</tr>
<tr>
<td>$m_{ee} &lt; 30$</td>
<td>453</td>
<td>366 ± 27</td>
<td>1.04</td>
<td>144</td>
<td>70 ± 26</td>
<td>0.0065</td>
</tr>
<tr>
<td>$m_{ee} &lt; 40$</td>
<td>492</td>
<td>420 ± 30</td>
<td>0.96</td>
<td>134</td>
<td>74 ± 29</td>
<td>0.026</td>
</tr>
<tr>
<td>$m_{ee} &lt; 60$</td>
<td>583</td>
<td>520 ± 35</td>
<td>0.97</td>
<td>135</td>
<td>84 ± 32</td>
<td>0.063</td>
</tr>
<tr>
<td>SR-VBF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{ee} &lt; 2$</td>
<td>0</td>
<td>2.8 ± 1.6</td>
<td>0.022</td>
<td>3.0</td>
<td>3.9 ± 1.6</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 3$</td>
<td>1</td>
<td>3.1 ± 1.7</td>
<td>0.030</td>
<td>3.6</td>
<td>4.4 ± 2.0</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 5$</td>
<td>2</td>
<td>3.3 ± 1.7</td>
<td>0.035</td>
<td>4.8</td>
<td>5.2 ± 2.1</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 10$</td>
<td>9</td>
<td>8.4 ± 2.7</td>
<td>0.068</td>
<td>9.5</td>
<td>8.8 ± 3.2</td>
<td>0.43</td>
</tr>
<tr>
<td>$m_{ee} &lt; 20$</td>
<td>36</td>
<td>32 ± 5</td>
<td>0.14</td>
<td>20</td>
<td>16 ± 6</td>
<td>0.27</td>
</tr>
<tr>
<td>$m_{ee} &lt; 30$</td>
<td>58</td>
<td>52 ± 7</td>
<td>0.19</td>
<td>26</td>
<td>21 ± 8</td>
<td>0.28</td>
</tr>
<tr>
<td>$m_{ee} &lt; 40$</td>
<td>82</td>
<td>74 ± 10</td>
<td>0.24</td>
<td>23</td>
<td>27 ± 10</td>
<td>0.27</td>
</tr>
<tr>
<td>SR-VBF-high</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{ee} &lt; 2$</td>
<td>0</td>
<td>2.4 ± 1.1</td>
<td>0.022</td>
<td>3.0</td>
<td>4.0 ± 1.6</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 3$</td>
<td>1</td>
<td>3.0 ± 1.4</td>
<td>0.025</td>
<td>3.5</td>
<td>4.6 ± 1.8</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 5$</td>
<td>2</td>
<td>3.0 ± 1.4</td>
<td>0.034</td>
<td>4.7</td>
<td>5.1 ± 2.0</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 10$</td>
<td>3</td>
<td>3.8 ± 1.7</td>
<td>0.041</td>
<td>5.6</td>
<td>5.8 ± 2.1</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 20$</td>
<td>9</td>
<td>11.7 ± 2.8</td>
<td>0.055</td>
<td>8</td>
<td>9 ± 4</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 30$</td>
<td>17</td>
<td>20 ± 5</td>
<td>0.079</td>
<td>11</td>
<td>13 ± 5</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{ee} &lt; 40$</td>
<td>26</td>
<td>28 ± 6</td>
<td>0.10</td>
<td>14</td>
<td>15 ± 6</td>
<td>0.50</td>
</tr>
<tr>
<td>SR-S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 100.5$</td>
<td>24</td>
<td>27 ± 4.8</td>
<td>0.09</td>
<td>13</td>
<td>14 ± 5</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 101$</td>
<td>41</td>
<td>46 ± 6.5</td>
<td>0.11</td>
<td>16</td>
<td>18 ± 7</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 102$</td>
<td>91</td>
<td>82 ± 10</td>
<td>0.25</td>
<td>35</td>
<td>28 ± 8</td>
<td>0.25</td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 105$</td>
<td>158</td>
<td>158 ± 17</td>
<td>0.30</td>
<td>41</td>
<td>41 ± 6</td>
<td>0.50</td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 110$</td>
<td>243</td>
<td>242 ± 21</td>
<td>0.38</td>
<td>52</td>
<td>52 ± 9</td>
<td>0.36</td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 120$</td>
<td>328</td>
<td>312 ± 24</td>
<td>0.51</td>
<td>71</td>
<td>60 ± 17</td>
<td>0.26</td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 130$</td>
<td>419</td>
<td>388 ± 28</td>
<td>0.66</td>
<td>92</td>
<td>68 ± 27</td>
<td>0.17</td>
</tr>
<tr>
<td>$m_{T^2}^{100} &lt; 140$</td>
<td>472</td>
<td>443 ± 31</td>
<td>0.69</td>
<td>95</td>
<td>74 ± 28</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Systematic uncertainties are associated with the OS–SS extrapolation. For $m_{\text{track}} < 2$ GeV, low-mass resonances can cause higher production rates for OS events than for SS events. A 30% uncertainty is assigned, based on an exponential fit to the OS/SS ratio as a function of $E_T^{\text{miss}}$ in the $\Delta\phi(\text{lep}, \mathbf{p}_T^{\text{miss}}) > 1.5$ region. This OS/SS ratio was found to be constant and equal to 1 for $E_T^{\text{miss}} > 200$ GeV, indicating that low-mass resonances do not contribute significantly to the OS sample in the SR-E-$1\ell 1\tau$ region. The uncertainty is computed as the value of the fitting function at $E_T^{\text{miss}} = 200$ GeV, where the deviation from unity is largest, summed linearly with the corresponding fit uncertainty. The $m_{\text{track}} > 2$ GeV region is instead mainly populated by $W + \text{jets}$ events, in which the correlation between the lepton and the track charge may introduce differences between the SS and OS expectations. A 12% uncertainty, extracted from $W + \text{jets}$ simulated events, is assigned.

The $m_{\text{track}} > 2$ GeV region is instead mainly populated by $W + \text{jets}$ events, in which the correlation between the
lepton and the track charge may introduce differences between the SS and OS expectations. A 12% uncertainty, extracted from $W + \text{jets}$ simulated events, is assigned.

Uncertainties in the expected yields for non-VBF SUSY samples arising from generator modeling are determined in situ by comparing the yields from $Z \rightarrow \mu\mu$ events in data with those from $Z(\rightarrow \mu\mu) + \text{jets}$ events generated using the same MG5_aMC@NLO configuration as the signal samples. The muon four-momenta are added to the $E_T^{\text{miss}}$ to emulate the $p_T$ of the SUSY system in signal events, and uncertainties are derived from observed differences in $E_T^{\text{miss}}$ between data and simulation. The largest modeling uncertainties are approximately 20% for samples with the most compressed mass spectrum and in high-$E_T^{\text{miss}}$ channels, while low-$E_T^{\text{miss}}$ channels and noncompressed signal points have uncertainties ranging from 1% to 10%. Uncertainties in the signal acceptance due to PDF uncertainties are evaluated following the PDF4LHC15 recommendations [121] and amount to at most 15% for large $\tilde{t}$ or $\tilde{c}$ masses. Uncertainties in the shape of the $m_{\ell\ell}$ or $m_{1\ell}$ signal distributions due to the sources above are found to be small, and are neglected.

Uncertainties due to generator modeling in the acceptance of the VBF signal samples are evaluated by varying by a factor of 2 the MG5_aMC@NLO parameters corresponding to the renormalization, factorization and CKKW-L matching scales, as well as the PYTHIA8 shower tune parameters and $a_s$. The largest uncertainties arise from renormalization and factorization scale variations (13%–22%), with smaller contributions from matching and $a_s$ variations (0.5%–5%).

Additional uncertainties are assigned to the predictions from signal simulation in the $\ell\ell\tau$ SR. An uncertainty in the modeling of the rate for reconstructed tracks that do not match a generated charged particle is accounted for. It is estimated by comparing the nonlinear component of the per-event track multiplicity as a function of pileup, in data and simulation. Furthermore, the calibration procedure applied to MC events to match the track impact parameter resolution in different data-taking periods is also a source of systematic uncertainty. Finally, uncertainties are assigned to the track–lepton matching efficiency and the track–isolation efficiency, as derived from the studies of events with a $J/\psi$ meson or $Z$ boson decaying into a lepton and a track, described in Sec. IV.

VIII. RESULTS

Data in the control regions, validation regions, and signal regions are compared with SM predictions using a profile likelihood method [122] implemented in the HISTFITTER package [123]. Most systematic uncertainties are treated as nuisance parameters with Gaussian constraints in the likelihood, apart from those of a statistical nature, for which Poisson constraints are used. Experimental systematic

FIG. 10. Comparison of observed and expected event yields in the SRs after the CR + SR background-only fits. The SRs used in searches for electroweakinos recoiling against ISR are shown at the top, and the SRs used for the VBF electroweakino search are shown in the middle, all binned in $m_{\tau^\pm}$. The SRs used in searches for sleptons recoiling against ISR are shown at the bottom, binned in $m_{1\ell}$. Uncertainties in the background estimates include both the statistical and systematic uncertainties. The bottom panel in all three plots shows the significance of the difference between the observed and expected yields, computed following the profile likelihood method of Ref. [118] in the case where the observed yield exceeds the prediction, and using the same expression with an overall minus sign if the yield is below the prediction.
FIG. 11. Examples of kinematic distributions after the background-only fit of the CRs showing the data as well as the expected background in the signal regions sensitive to electroweakinos. The full event selection of the corresponding regions is applied, except for distributions showing blue arrows, where the requirement on the variable being plotted is removed and indicated by the arrows in the distributions instead. The first (last) bin includes underflow (overflow). The uncertainty bands plotted include all statistical and systematic uncertainties.
uncertainties are correlated between signal and backgrounds for all regions.

A. Control and validation regions

A background-only fit of the CRs is constructed using only the control regions to constrain the fit parameters. The data in the control regions CRTop, CRtau, and CRVV are fit simultaneously in each search to constrain overall normalization factors for the $t\bar{t}/Wt$, $Z(\ell\ell)/\gamma^* (\rightarrow \tau\tau)$ + jets, and VV background predictions. The resulting normalization parameters are presented in Table IX.

The background prediction as obtained from the background-only fit of the CRs is then compared with data in the validation regions to verify the accuracy of the background modeling. Figure 6 shows a comparison of the data yields with background predictions in the VRDF regions, binned in $m_{\ell\ell}$ and $m_{100}$ using the same intervals as defined for the corresponding SRs. Good agreement is observed in all event selection categories, with deviations below 2σ. Examples of kinematic distributions in control and validation regions are presented in Figs. 7, 8, and 9, where good agreement between data and MC simulation is seen in both the shape and normalization of the discriminating variables.

B. Inclusive signal regions

The inclusive signal regions defined in Sec. V are used to test for excesses of events above the SM predictions. Each fit only considers one single-bin inclusive signal region, and includes a signal model with an unconstrained normalization parameter to estimate the contributions of any phenomena beyond those predicted by the Standard Model. The signal region is fit simultaneously with the control regions, which are assumed to contain no signal, resulting in background estimates constrained by the background-only fit of the CRs.

To quantify the probability under the background-only hypothesis to produce event yields greater than or
equal to the observed data, the discovery $p$-values are calculated for each inclusive signal region. The results for the electroweakino, VBF, and slepton regions are shown in Table X. Several electroweakino regions have low $p$-values, with the lowest observed in the $m_{\ell\ell} < 20$ GeV bin corresponding to a local significance of 2.7$\sigma$. The CL$_S$ prescription [124] is used to perform a hypothesis test that sets upper limits at the 95% confidence level (C.L.) on the visible cross sections in each inclusive signal region. Dividing $S^{95}_{\text{obs}}$ by the integrated luminosity defines the upper limits on the visible cross sections $S^{95}_{\text{obs}}$.

C. Exclusive signal regions and model-dependent interpretations

The exclusive signal regions are used to constrain specific SUSY models. An exclusion fit extends a background-only fit of the CRs to include signal regions relevant for the model under study. All regions are fit simultaneously with a parameter of interest corresponding to the signal strength, a factor that coherently scales the signal yield across all regions. In order to assess the stability of the exclusion fit, a "CR + SR background-only fit" of the CRs and the exclusive signal regions is performed in which the signal strength is fixed to zero. Comparisons of the data yields with the background prediction in each inclusive signal region are shown in Figs. 11, 12, and 13, where good agreement between data and the background predictions is seen in both the shape and the normalization of the discriminating variables.

The CL$_S$ prescription is used to perform hypothesis tests of specific SUSY models. The SRs defined using $m_{\ell\ell}$ are used for electroweakino models, while regions defined using $m_{T2}^{100}$ are used for slepton models. Exclusions at...
<table>
<thead>
<tr>
<th>SR bin [GeV]</th>
<th>[1, 2]</th>
<th>[2, 3]</th>
<th>[3, 2, 5]</th>
<th>[5, 10]</th>
<th>[10, 20]</th>
<th>[20, 30]</th>
<th>[30, 40]</th>
<th>[40, 60]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-E-high ee</td>
<td>Observed</td>
<td>Fitted SM events</td>
<td>0.7 ± 0.4</td>
<td>10.3 ± 2.5</td>
<td>12.1 ± 2.2</td>
<td>10.1 ± 1.7</td>
<td>10.4 ± 1.7</td>
<td>19.3 ± 2.5</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>0.03^{+0.10}_{-0.09}</td>
<td>6.6 ± 2.7</td>
<td>4.6 ± 2.0</td>
<td>4.0 ± 1.5</td>
<td>4.4 ± 1.6</td>
<td>6.7 ± 2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z(→ ττ) + jets</td>
<td>0.06^{+0.10}_{-0.09}</td>
<td>1.7 ± 0.7</td>
<td>2.6 ± 1.2</td>
<td>0.93 ± 0.24</td>
<td>0.04 ± 0.04</td>
<td>0.62 ± 0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>0.000^{+0.004}_{-0.004}</td>
<td>0.12 ± 0.05</td>
<td>0.74 ± 0.18</td>
<td>1.14 ± 0.19</td>
<td>0.29 ± 0.07</td>
<td>0.27 ± 0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-E-high μμ</td>
<td>Observed</td>
<td>Fitted SM events</td>
<td>3.4 ± 1.2</td>
<td>3.5 ± 1.3</td>
<td>3.9 ± 1.3</td>
<td>11.0 ± 2.0</td>
<td>17.8 ± 2.7</td>
<td>8.3 ± 1.4</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>2.4 ± 1.2</td>
<td>2.6 ± 1.4</td>
<td>1.9 ± 1.0</td>
<td>3.1 ± 1.7</td>
<td>6.0 ± 2.8</td>
<td>1.3 ± 0.8</td>
<td>2.0 ± 0.9</td>
<td>1.4 ± 1.3</td>
</tr>
<tr>
<td>Z(→ ττ) + jets</td>
<td>0.07^{+0.34}_{-0.07}</td>
<td>0.06^{+0.34}_{-0.06}</td>
<td>1.0 ± 0.4</td>
<td>3.9 ± 0.9</td>
<td>5.7 ± 1.6</td>
<td>0.31 ± 0.25</td>
<td>0.060^{+0.04}_{-0.04}</td>
<td>0.31 ± 0.16</td>
</tr>
<tr>
<td>Others</td>
<td>0.032^{+0.035}_{-0.032}</td>
<td>0.025 ± 0.018</td>
<td>0.66 ± 0.33</td>
<td>0.91 ± 0.14</td>
<td>1.10 ± 0.18</td>
<td>0.75 ± 0.16</td>
<td>1.06 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>SR-E-med ee</td>
<td>Observed</td>
<td>Fitted SM events</td>
<td>0.11 ± 0.08</td>
<td>5.1 ± 1.6</td>
<td>7.3 ± 1.9</td>
<td>2.2 ± 0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>0.000^{+0.016}_{-0.006}</td>
<td>3.8 ± 1.3</td>
<td>6.9 ± 2.0</td>
<td>1.6 ± 1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z(→ ττ) + jets</td>
<td>0.000^{+0.006}_{-0.003}</td>
<td>0.12 ± 0.05</td>
<td>0.28 ± 0.26</td>
<td>0.02 ± 0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>0.000^{+0.010}_{-0.002}</td>
<td>0.12 ± 0.12</td>
<td>0.3 ± 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-E-med μμ</td>
<td>Observed</td>
<td>Fitted SM events</td>
<td>14.6 ± 2.9</td>
<td>6.9 ± 2.1</td>
<td>6.2 ± 1.9</td>
<td>34 ± 4</td>
<td>52 ± 6</td>
<td>18.5 ± 3.2</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>7.9 ± 3.2</td>
<td>4.8 ± 2.1</td>
<td>5.1 ± 2.0</td>
<td>27 ± 5</td>
<td>44 ± 6</td>
<td>18.2 ± 3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z(→ ττ) + jets</td>
<td>0.01^{+0.06}_{-0.01}</td>
<td>0.01^{+0.06}_{-0.01}</td>
<td>0.00^{+0.05}_{-0.01}</td>
<td>0.12^{+0.13}_{-0.12}</td>
<td>0.24 ± 0.08</td>
<td>0.14^{+0.19}_{-0.14}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>0.000^{+0.002}_{-0.001}</td>
<td>0.036 ± 0.015</td>
<td>0.019 ± 0.017</td>
<td>0.9 ± 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-E-low ee</td>
<td>Observed</td>
<td>Fitted SM events</td>
<td>5.3 ± 1.5</td>
<td>8.6 ± 1.8</td>
<td>16.7 ± 2.5</td>
<td>15.5 ± 2.6</td>
<td>12.9 ± 2.1</td>
<td>18.8 ± 2.2</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>1.6 ± 1.1</td>
<td>3.8 ± 1.8</td>
<td>6.2 ± 2.2</td>
<td>5.8 ± 2.3</td>
<td>4.2 ± 1.8</td>
<td>2.8 ± 1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z(→ ττ) + jets</td>
<td>0.015 ± 0.006</td>
<td>0.32 ± 0.30</td>
<td>2.8 ± 0.6</td>
<td>3.4 ± 1.1</td>
<td>4.5 ± 0.9</td>
<td>9.7 ± 1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>1.3 ± 0.6</td>
<td>2.4 ± 0.8</td>
<td>3.0 ± 0.7</td>
<td>2.1 ± 0.7</td>
<td>2.4 ± 0.7</td>
<td>4.2 ± 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-E-low μμ</td>
<td>Observed</td>
<td>Fitted SM events</td>
<td>15.4 ± 2.4</td>
<td>8.0 ± 1.7</td>
<td>6.5 ± 1.6</td>
<td>11.3 ± 1.9</td>
<td>15.6 ± 2.3</td>
<td>16.7 ± 2.3</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>7.7 ± 1.9</td>
<td>0.3 ± 0.6</td>
<td>0.01^{+0.22}_{-0.01}</td>
<td>2.6 ± 1.3</td>
<td>4.7 ± 1.9</td>
<td>2.8 ± 1.6</td>
<td>2.8 ± 1.6</td>
<td>4.9 ± 2.3</td>
</tr>
<tr>
<td>Z(→ ττ) + jets</td>
<td>0.000^{+0.004}_{-0.004}</td>
<td>0.26 ± 0.07</td>
<td>1.2 ± 0.5</td>
<td>3.4 ± 0.7</td>
<td>5.1 ± 1.5</td>
<td>7.8 ± 1.3</td>
<td>18.9 ± 2.7</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>0.01^{+0.05}_{-0.01}</td>
<td>0.20 ± 0.05</td>
<td>0.79 ± 0.23</td>
<td>1.3 ± 0.8</td>
<td>0.54 ± 0.09</td>
<td>2.10 ± 0.34</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table XI. Observed event yields and fit results using a CR + SR background-only fit for the exclusive electroweakino signal regions. Background processes containing fewer than two prompt leptons are categorized as “Fake/nonprompt.” The category “Others” contains rare backgrounds from triboson, Higgs-boson, and the remaining top-quark production processes listed in Table I. Uncertainties in the fitted background estimates combine statistical and systematic uncertainties.
TABLE XII. Observed event yields and fit results using a CR + SR background-only fit for the exclusive electroweakino $1\ell 1\ell$T regions. All backgrounds are determined from the same-sign method. Uncertainties in the fitted background estimates combine statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>SR bin [GeV]</th>
<th>[0.5, 1.0]</th>
<th>[1.0, 1.5]</th>
<th>[1.5, 2.0]</th>
<th>[2.0, 3.0]</th>
<th>[3.2, 4.0]</th>
<th>[4.0, 5.0]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>0</td>
<td>8</td>
<td>8</td>
<td>24</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Fitted SM events</td>
<td>0.5 ± 0.5</td>
<td>6.0 ± 1.9</td>
<td>7.6 ± 2.1</td>
<td>20.7 ± 3.4</td>
<td>24 ± 4</td>
<td>18.1 ± 3.1</td>
</tr>
</tbody>
</table>

TABLE XIII. Observed event yields and fit results using a CR + SR background-only fit for the exclusive VBF signal regions. Background processes containing fewer than two prompt leptons are categorized as “Fake/nonprompt.” The category “Others” contains rare backgrounds from triboson, Higgs-boson, and the remaining top-quark production processes listed in Table I. Uncertainties in the fitted background estimates combine statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>SR bin [GeV]</th>
<th>[1, 2]</th>
<th>[2, 3]</th>
<th>[3, 5]</th>
<th>[5, 10]</th>
<th>[10, 20]</th>
<th>[20, 30]</th>
<th>[30, 40]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Fitted SM events</td>
<td>0.7 ± 0.4</td>
<td>0.47 ± 0.25</td>
<td>0.64 ± 0.32</td>
<td>4.9 ± 1.2</td>
<td>17.3 ± 2.6</td>
<td>12.5 ± 1.8</td>
<td>15.2 ± 2.7</td>
</tr>
<tr>
<td>$Z(\rightarrow \tau\tau) +\text{jets}$</td>
<td>0.11$^{+0.22}_{-0.11}$</td>
<td>0.17 ± 0.12</td>
<td>0.009$^{+0.016}_{-0.009}$</td>
<td>1.8 ± 0.7</td>
<td>6.4 ± 1.4</td>
<td>5.7 ± 1.3</td>
<td>2.6 ± 1.0</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>0.01$^{+0.05}_{-0.01}$</td>
<td>0.01$^{+0.05}_{-0.01}$</td>
<td>0.01$^{+0.05}_{-0.01}$</td>
<td>1.5 ± 1.0</td>
<td>3.4 ± 2.0</td>
<td>0.01$^{+0.06}_{-0.01}$</td>
<td>1.8$^{+2.5}_{-1.8}$</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.57 ± 0.29</td>
<td>0.28 ± 0.17</td>
<td>0.35 ± 0.20</td>
<td>1.0 ± 0.4</td>
<td>2.8 ± 1.1</td>
<td>2.7 ± 1.004</td>
<td>4.0 ± 1.4</td>
</tr>
<tr>
<td>$t\bar{t}$, single top</td>
<td>0.01$^{+0.04}_{-0.01}$</td>
<td>0.01$^{+0.05}_{-0.01}$</td>
<td>0.26 ± 0.18</td>
<td>0.55 ± 0.27</td>
<td>3.6 ± 1.3</td>
<td>3.1 ± 0.7</td>
<td>6.4 ± 1.1</td>
</tr>
<tr>
<td>Others</td>
<td>0.007 ± 0.007</td>
<td>0.007 ± 0.004</td>
<td>0.01$^{+0.05}_{-0.01}$</td>
<td>0.056 ± 0.026</td>
<td>1.0 ± 0.4</td>
<td>1.03 ± 0.32</td>
<td>0.37 ± 0.13</td>
</tr>
</tbody>
</table>

TABLE XIV. Observed event yields and fit results using a CR + SR background-only fit for the exclusive slepton signal regions. Background processes containing fewer than two prompt leptons are categorized as “Fake/nonprompt.” The category “Others” contains rare backgrounds from triboson, Higgs-boson, and the remaining top-quark production processes listed in Table I. Uncertainties in the fitted background estimates combine statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>SR bin [GeV]</th>
<th>[100, 100.5]</th>
<th>[100.5, 101]</th>
<th>[101, 102]</th>
<th>[102, 105]</th>
<th>[105, 110]</th>
<th>[110, 120]</th>
<th>[120, 130]</th>
<th>[130, 140]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>13</td>
<td>9</td>
<td>6</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Fitted SM events</td>
<td>4.0 ± 1.1</td>
<td>3.6 ± 1.0</td>
<td>7.9 ± 1.9</td>
<td>13.2 ± 2.1</td>
<td>8.6 ± 1.4</td>
<td>5.7 ± 1.0</td>
<td>7.0 ± 1.2</td>
<td>6.8 ± 1.1</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>2.7 ± 1.1</td>
<td>2.1 ± 1.0</td>
<td>5.6 ± 1.9</td>
<td>4.7 ± 1.9</td>
<td>0.2±0.3</td>
<td>0.01$^{+0.17}_{-0.01}$</td>
<td>0.01$^{+0.17}_{-0.01}$</td>
<td>0.00$^{+0.15}_{-0.05}$</td>
</tr>
<tr>
<td>$t\bar{t}$, single top</td>
<td>0.8 ± 0.4</td>
<td>0.8 ± 0.5</td>
<td>0.8 ± 0.4</td>
<td>3.5 ± 0.7</td>
<td>4.5 ± 1.2</td>
<td>3.0 ± 0.7</td>
<td>3.9 ± 0.9</td>
<td>3.9 ± 0.9</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.42 ± 0.16</td>
<td>0.68 ± 0.23</td>
<td>1.4 ± 0.4</td>
<td>4.2 ± 1.1</td>
<td>2.4 ± 0.7</td>
<td>2.5 ± 0.7</td>
<td>3.0 ± 0.8</td>
<td>2.8 ± 0.7</td>
</tr>
<tr>
<td>$Z(\rightarrow \tau\tau) +\text{jets}$</td>
<td>0.00$^{+0.02}_{-0.00}$</td>
<td>0.00$^{+0.01}_{-0.00}$</td>
<td>0.027 ± 0.012</td>
<td>0.38 ± 0.16</td>
<td>1.32 ± 0.31</td>
<td>0.00$^{+0.12}_{-0.00}$</td>
<td>0.02$^{+0.08}_{-0.02}$</td>
<td>0.00$^{+0.19}_{-0.00}$</td>
</tr>
<tr>
<td>Others</td>
<td>0.0 ± 0.0</td>
<td>0.06$^{+0.01}_{-0.00}$</td>
<td>0.09 ± 0.05</td>
<td>0.43 ± 0.32</td>
<td>0.26 ± 0.14</td>
<td>0.5$^{+0.15}_{-0.05}$</td>
<td>0.06$^{+0.03}_{-0.00}$</td>
<td>0.05 ± 0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SR bin [GeV]</th>
<th>[130, 140]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>10</td>
</tr>
<tr>
<td>Fitted SM events</td>
<td>11.0 ± 2.2</td>
</tr>
<tr>
<td>Fake/nonprompt</td>
<td>9.1 ± 2.2</td>
</tr>
<tr>
<td>$t\bar{t}$, single top</td>
<td>0.8 ± 0.5</td>
</tr>
<tr>
<td>Diboson</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>$Z(\rightarrow \tau\tau) +\text{jets}$</td>
<td>0.00$^{+0.19}_{-0.00}$</td>
</tr>
<tr>
<td>Others</td>
<td>0.000$^{+0.19}_{-0.000}$</td>
</tr>
</tbody>
</table>

(Table continued)
FIG. 14. Expected 95% C.L. exclusion sensitivity (blue dashed line), with ±1σ_{exp} (yellow band) from experimental systematic uncertainties and statistical uncertainties on the data yields, and observed limits (red solid line) with ±1σ_{theory} (dotted red line) from signal cross-section uncertainties for simplified models of direct Higgsino (top) and wino (bottom) production. A fit to the m_{ετ} spectrum is used to derive the limit, which is projected into the Δm(χ_2^0,χ_1^0) vs m(χ_2^0) plane. For Higgsino production, the chargino \tilde{χ}^±_1 mass is assumed to be halfway between the \tilde{χ}^0_2 and \tilde{χ}^0_1 masses, while m(χ_2^0) = m(χ_1^±) is assumed for the wino/bino model. Following the discussion in Sec. III, the m_{ετ} shape in the wino/bino model depends on the relative sign of the \tilde{χ}^0_2 and \tilde{χ}^0_1 masses parameters. The bottom-left plot assumes m(\tilde{χ}^0_2) × m(\tilde{χ}^0_1) < 0, while m(\tilde{χ}^0_2) × m(\tilde{χ}^0_1) > 0 is assumed on the bottom right. The gray regions denote the lower chargino mass limit from LEP [30]. The blue regions indicate the limits from ATLAS searches at 8 TeV [125,126] and at 13 TeV with 36 fb^{-1} [45].
95% confidence level are presented in a two-dimensional plane with the horizontal axis given by the mass of the \(\tilde{\chi}_0^2\) and the vertical axis defined by the difference in mass between the \(\tilde{\chi}_0^2\) or slepton and the \(\tilde{\chi}_0^1\).

Exclusion contours for both wino and Higgsino production are shown in Fig. 14. Most of the exclusion power originates from the high-\(E_T\)miss channel, with added sensitivity provided by the 1\(l\)1\(T\) search at small mass splittings and by the low-\(E_T\)miss channels at higher mass splittings. The behavior of the observed exclusion contours at large \(\Delta m(\tilde{\chi}_0^2, \tilde{\chi}_0^1)\) is due to the SM background expectation underestimating the data for events...
with $10 < m_{\mu\mu} < 20$ GeV in SR-E-high, while it overestimates for events with $20 < m_{\mu\mu} < 40$ GeV in the same signal region. This is also visible in Fig. 10, which shows the results of a CR + SR background-only fit assuming that no signal is present. The lack of allowed contributions from signal processes in the SR-constrained fit reduces the significance of bin-by-bin deviations, while the presence of a signal normalization parameter in the exclusion fit allows for larger deviations from the background constraints. When assuming wino production with $m(\tilde{\chi}^0_1) \times m(\tilde{\chi}^0_1) > 0$, electroweakino masses of up to 240 GeV for mass splittings of 7 GeV are excluded. For electroweakino masses at the edge of LEP exclusions, mass splittings from 1.5 GeV to 46 GeV are excluded. Assuming Higgsino production, $\tilde{\chi}^0_2$ masses below 193 GeV are excluded for mass splittings of 9.3 GeV. At the LEP bounds on $m(\tilde{\chi}^0_1)$, mass splittings from 2.4 GeV to 55 GeV are excluded. All observed limits are within $2\sigma$ of the median expected limit.

Models containing electroweakinos produced through VBF processes are constrained using the VBF signal regions. These constraints are shown in Fig. 15. The limits on VBF Higgsino production cross sections have a weak dependence on the mass splittings and are shown assuming $\Delta m = 5$ GeV. Higgsinos with masses below 55 GeV are excluded for mass splittings of 5 GeV. Assuming VBF production of winos, electroweakino masses up to 76 GeV for mass splittings of 5 GeV are excluded. Assuming Higgsino production, $\tilde{\chi}^0_2$ masses below 193 GeV are excluded for mass splittings of 9.3 GeV. At the LEP bounds on $m(\tilde{\chi}^0_1)$, mass splittings from 2.4 GeV to 55 GeV are excluded. All observed limits are within $2\sigma$ of the median expected limit.

Exclusion contours for light-flavor sleptons are shown in Fig. 16. Assuming mass-degenerate selectrons and smuons, slepton masses below 251 GeV are excluded for mass splittings of 10 GeV. For sleptons with masses just above the LEP limits, mass splittings from 550 MeV to 30 GeV are excluded. Figure 16 also shows results where only the right-/left-handed selectron or smuon is produced. When producing these results, only $ee$ or $\mu\mu$ events in the SRs are considered. Right-handed sleptons have smaller cross sections than their left-handed counterparts, due to their different couplings to the weak gauge fields [127]. Right-handed smuons are excluded up to 150 GeV for mass splittings of 8.2 GeV, while left-handed smuons are excluded up to 216 GeV for mass splittings of 10 GeV. Left-handed selectrons are excluded up to 169 GeV for mass splittings of 7.1 GeV. Right-handed selectrons are excluded up to 101 GeV for mass splittings of 7.5 GeV.

**IX. CONCLUSION**

Results of searches for the electroweak production of supersymmetric particles in models with compressed mass spectra are presented, using $\sqrt{s} = 13$ TeV proton-proton collision data corresponding to 139 fb$^{-1}$ collected by the ATLAS experiment at the CERN Large Hadron Collider. Events with missing transverse momentum, two same-flavor, opposite-charge, low-transverse-momentum leptons, and hadronic activity from initial-state radiation or characteristic of vector-boson fusion production are selected. The data are found to be consistent with predictions from the Standard Model. Assuming wino production, constraints at a 95% confidence level are placed on the minimum mass of the $\tilde{\chi}^0_2$ at 240 GeV for a mass splitting of 7 GeV and extend down to a mass splitting of 1.5 GeV at the LEP chargino mass limit of 92.4 GeV. For Higgsino production, the corresponding lower limits are at 193 GeV at a mass splitting of 9.3 GeV and extend down to a mass splitting of 2.4 GeV at the LEP chargino mass limit. Events consistent with the production of electroweak SUSY states through vector-boson fusion processes are used to constrain wino/bino and Higgsino models while assuming a vanishing $q\bar{q}$ fusion production cross section. Light-flavor sleptons are constrained to have masses above 251 GeV for a mass splitting of 10 GeV, with constraints extending down to mass splittings of 550 MeV at the LEP slepton limits (73 GeV).

**ACKNOWLEDGMENTS**

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions, without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IFRF, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNISW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KiI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada, and CRC, Canada; ERC, ERDF, Horizon 2020, Marie Skłodowska-Curie Actions and COST, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex, and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales, and Aristeia programs cofinanced by EU-ESF and the Greek NSRF.
Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya and PROMETEO Programme Generalitat Valenciana, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [128].

[29] A. Barr, C. Laster, and P. Stephens, A variable for measuring masses at hadron colliders when missing energy is expected; $m_{T2}$: The truth behind the glamour, J. Phys. G 29, 2343 (2003).


[37] L3 Collaboration, Search for charginos with a small mass difference with the lightest supersymmetric particle at $\sqrt{s} = 189$ GeV, Phys. Lett. B 482, 31 (2000).


(ATLAS Collaboration)
SEARCHES FOR ELECTROWEAK PRODUCTION OF …  

PHYS. REV. D 101, 052005 (2020)

79 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
80 Joint Institute for Nuclear Research, Dubna, Russia

81 Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
81 Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
81 Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil
81 Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
82 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
83 Graduate School of Science, Kobe University, Kobe, Japan
84 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
84 Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
85 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
86 Faculty of Science, Kyoto University, Kyoto, Japan
87 Kyoto University of Education, Kyoto, Japan
88 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
89 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
90 Physics Department, Lancaster University, Lancaster, United Kingdom
91 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
92 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
93 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
94 Department of Physics, Royal Holloway University of London, Egham, United Kingdom
95 Department of Physics and Astronomy, University College London, London, United Kingdom
96 Louisiana Tech University, Ruston, Louisiana, USA
97 Fysiska institutionen, Lunds universitet, Lund, Sweden
98 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
99 Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
100 Institut für Physik, Universität Mainz, Mainz, Germany
101 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
102 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
103 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
104 Department of Physics, McGill University, Montreal, Quebec, Canada
105 School of Physics, University of Melbourne, Victoria, Australia
106 Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
107 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
108 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
109 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
110 Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
111 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
112 National Research Nuclear University MEPhI, Moscow, Russia
113 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
114 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
115 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
116 Nagasaki Institute of Applied Science, Nagasaki, Japan
117 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
118 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
119 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
120 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
121 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
122 Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia
122 Novosibirsk State University, Novosibirsk, Russia
123 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
124 Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre “Kurchatov Institute”, Moscow, Russia
125 Department of Physics, New York University, New York, New York, USA
126 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
127 Ohio State University, Columbus, Ohio, USA
128 Faculty of Science, Okayama University, Okayama, Japan
129 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
130 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
131 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
132 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
133 Graduate School of Science, Osaka University, Osaka, Japan
134 Department of Physics, University of Oslo, Oslo, Norway
135 Department of Physics, Oxford University, Oxford, United Kingdom
136 LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France
137 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
138 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
139 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
140 Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
141 Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
142 Departamento de Física, Universidad de Coimbra, Coimbra, Portugal
143 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
144 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
145 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
146 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
147a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
147b Universidad Andres Bello, Department of Physics, Santiago, Chile
147c Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
148 Department of Physics, University of Washington, Seattle, Washington, USA
149 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
150 Department of Physics, Shinshu University, Nagano, Japan
151 Department Physik, Universität Siegen, Siegen, Germany
152 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
153 SLAC National Accelerator Laboratory, Stanford, California, USA
154 Physics Department, Royal Institute of Technology, Stockholm, Sweden
155 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
156 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
157 School of Physics, University of Sydney, Sydney, Australia
158 Institute of Physics, Academia Sinica, Taipei, Taiwan
159a E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
159b High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
160 Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
161 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
162 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
163 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
164 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
165 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
166 Tomsk State University, Tomsk, Russia
167 Department of Physics, University of Toronto, Toronto, Ontario, Canada
168a TRIUMF, Vancouver, British Columbia, Canada
168b Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA

Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Department of Physics, University of Illinois, Urbana, Illinois, USA

Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, Connecticut, USA

Deceased.

Also at Department of Physics, King’s College London, London, United Kingdom.

Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.

Also at TRIUMF, Vancouver BC, Canada.

Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

Also at Physics Department, An-Najah National University, Nablus, Palestine.

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at Physics Dept, University of South Africa, Pretoria, South Africa.

Also at Departamento de Física de la Universidad Autonoma de Barcelona, Barcelona, Spain.

Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Vancouver, Canada.

Also at Department of Physics, University of Adelaide, Adelaide, Australia.

Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.

Also at Department of Physics, California State University, Fresno, USA.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Department of Physics, California State University, East Bay, USA.

Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Université Paris-Saclay, CNRS/IN2P3, JICLab, 91405, Orsay, France.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at CERN, Geneva, Switzerland.

Also at Department of Physics, Stanford University, Stanford, California, USA.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Hellenic Open University, Patras, Greece.

Also at The City College of New York, New York, New York, USA.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

Also at Louisiana Tech University, Ruston, Louisiana, USA.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

Also at Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA.