Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 13$ TeV pp collisions with ATLAS

Aaboud, M.; The ATLAS Collaboration

DOI
10.1103/PhysRevD.98.032009

Publication date
2018

Document Version
Final published version

Published in
Physical Review D. Particles and Fields

License
CC BY

Citation for published version (APA):
Search for supersymmetry in events with four or more leptons in \( \sqrt{s} = 13 \) TeV pp collisions with ATLAS

M. Aaboud et al.*
(ATLAS Collaboration)

(Received 11 April 2018; published 15 August 2018)

Results from a search for supersymmetry in events with four or more charged leptons (electrons, muons and taus) are presented. The analysis uses a data sample corresponding to 36.1 fb\(^{-1}\) of proton–proton collisions delivered by the Large Hadron Collider at \( \sqrt{s} = 13 \) TeV and recorded by the ATLAS detector. Four-lepton signal regions with up to two hadronically decaying taus are designed to target a range of supersymmetric scenarios that can be either enriched in or depleted of events involving the production and decay of a Z boson. Data yields are consistent with Standard Model expectations and results are used to set upper limits on the event yields from processes beyond the Standard Model. Exclusion limits are set at the 95% confidence level in simplified models of general gauge mediated supersymmetry, where Higgsino masses are excluded up to 295 GeV. In R-parity-violating simplified models with decays of the lightest supersymmetric particle to charged leptons, lower limits of 1.46, 1.06, and 2.25 TeV are placed on wino, slepton and gluino masses, respectively.

DOI: 10.1103/PhysRevD.98.032009

I. INTRODUCTION

Supersymmetry (SUSY) [1–6] is a space-time symmetry that postulates the existence of new particles with spin differing by one half-unit from their Standard Model (SM) partners. In supersymmetric extensions of the SM, each SM fermion (boson) is associated with a SUSY boson (fermion), having the same quantum numbers as its partner except for spin. The introduction of these new SUSY particles provides a potential solution to the hierarchy problem [7–10].

The scalar superpartners of the SM fermions are called sfermions (comprising the charged sleptons, \( \tilde{e} \), the sneutrinos, \( \tilde{\nu} \), and the squarks, \( \tilde{q} \)), while the gluons have fermionic superpartners called gluinos (\( \tilde{g} \)). The bino, wino and Higgsino fields are fermionic superpartners of the SU(2) × U(1) gauge fields of the SM, and the two complex scalar doublets of a minimally extended Higgs sector, respectively. Their mass eigenstates are referred to as chargedinos \( \tilde{\chi}^\pm_i \) (\( i = 1, 2 \)) and neutralinos \( \tilde{\chi}^0_j \) (\( j = 1, 2, 3, 4 \)), numbered in order of increasing mass.

In the absence of a protective symmetry, SUSY processes not conserving lepton number (L) and baryon number (B) could result in proton decay at a rate that is in conflict with the tight experimental constraints on the proton lifetime [11]. This conflict can be avoided by imposing the conservation of R-parity [12], defined as \((-1)^{3(B-L)+2S}\), where S is spin, or by explicitly conserving either B or L in the Lagrangian in R-parity-violating (RPV) scenarios. In RPV models, the lightest SUSY particle (LSP) is unstable and decays to SM particles, including charged leptons and neutrinos when violating L but not B. In R-parity-conserving (RPC) models, the LSP is stable and leptons can originate from unstable weakly interacting sparticles decaying into the LSP. Both the RPV and RPC SUSY scenarios can therefore result in signatures with high lepton multiplicities and substantial missing transverse momentum, selections on which can be used to suppress SM background processes effectively.

This paper presents a search for new physics in final states with at least four isolated, charged leptons (electrons, muons or taus) where up to two hadronically decaying taus are considered. The analysis exploits the full proton–proton data set collected by the ATLAS experiment during the 2015 and 2016 data-taking periods, corresponding to an integrated luminosity of 36.1 fb\(^{-1}\) at a center-of-mass energy of 13 TeV. The search itself is optimized using several signal models but is generally model independent, using selections on the presence or absence of Z bosons in the event and loose requirements on effective mass or missing transverse momentum. Results are presented in terms of the number of events from new physics processes with a four charged lepton signature, and also in terms of RPV and RPC SUSY models.

Previous searches for SUSY particles using signatures with three or more leptons were carried out at the Tevatron...
collider [13–18], and at the LHC by the ATLAS experiment [19–22] and the CMS experiment [23–27]. This analysis closely follows the 7 TeV [19] and 8 TeV [22] ATLAS analyses.

II. SUSY SCENARIOS

SUSY models are used for signal region optimization and to interpret the results of this analysis. Models of both RPV SUSY and RPC SUSY are considered here, as they each require a different approach for signal selection, as discussed in Sec. V.

In all scenarios, the light CP-even Higgs boson, $h$, of the minimal supersymmetric extension of the SM [28,29] Higgs sector is assumed to be practically identical to the minimal supersymmetric extension of the SM [31] where the LSP is used, which is defined by $\lambda_{ij} = \frac{m_i}{m_j}$ measured at the LHC [30], with the same mass and couplings as measured at the LHC [31–33]. In addition, the decoupling limit is used, which is defined by $m_A > m_Z$, while the CP-odd ($A$), the neutral CP-even ($H$), and the two charged ($H^\pm$) Higgs bosons are considered to be very heavy and thus considerably beyond the kinematic reach of the LHC.

A. RPV SUSY scenarios

In generic SUSY models with minimal particle content, the superpotential includes terms that violate conservation of $L$ and $B$ [34,35]:

$$\frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda_{ijk}' L_i Q_j \bar{D}_k + \frac{1}{2} \lambda_{ijk}'' \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2,$$

where $L_i$ and $Q_i$ indicate the lepton and quark SU(2)-doublet superfields, respectively, and $\bar{E}_i$, $\bar{U}_i$, and $\bar{D}_i$ are the corresponding singlet superfields. Quark and lepton generations are referred to by the indices $i$, $j$, and $k$, while the Higgs field that couples to up-type quarks is represented by the Higgs SU(2)-doublet superfield $H_2$. The $\lambda_{ijk}$, $\lambda_{ijk}'$, and $\lambda_{ijk}''$ parameters are three sets of new Yukawa couplings, while the $\kappa_i$ parameters have dimensions of mass.

Simplified models of RPV scenarios are considered, where the LSP is a bino-like neutralino ($\tilde{\chi}^0_1$) and decays via an RPV interaction. The LSP decay is mediated by the following lepton-number-violating superpotential term:

$$W_{LLE} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k.$$

This RPV interaction allows the following decay of the neutralino LSP:

$$\tilde{\chi}^0_1 \rightarrow \ell_k^\pm \ell_j^\mp \ell_i^\pm,$$

through a virtual slepton or sneutrino, with the allowed lepton flavors depending on the indices of the associated $\lambda_{ijk}$ couplings [36]. The complex conjugate of the decay in Eq. (1) is also allowed. Thus, in the case of pair production, every signal event contains a minimum of four charged leptons and two neutrinos.

In principle, the nine $\lambda_{ijk}$ RPV couplings allow the $\tilde{\chi}^0_1$ to decay to every possible combination of charged lepton pairs, where the branching ratio for each combination differs for each $\lambda_{ijk}$. For example, for $\lambda_{121} \neq 0$ the branching ratios for $\tilde{\chi}^0_1 \rightarrow e\nu, \tilde{\chi}^0_1 \rightarrow \mu\nu$ and $\tilde{\chi}^0_1 \rightarrow \mu\nu$ are 50%, 50% and 0% respectively, whereas for $\lambda_{122} \neq 0$ the corresponding branching ratios are 50%, 0% and 50%. In Ref. [22], it was found that the four-charged-lepton search sensitivity is comparable in the cases of $\lambda_{121} \neq 0$ or $\lambda_{122} \neq 0$, and for $\lambda_{133} \neq 0$ or $\lambda_{233} \neq 0$. Since the analysis reported here uses similar techniques, the number of $L$-violating RPV scenarios studied is reduced by making no distinction between the electron and muon decay modes of the $\tilde{\chi}^0_1$. Two extremes of the $\lambda_{ijk}$ RPV couplings are considered:

(i) $LLE12k$ ($k \in 1, 2$) scenarios, where $\lambda_{12k} \neq 0$ and only decays to electrons and muons are included,

(ii) $LLE133$ ($i \in 1, 2$) scenarios, where $\lambda_{133} \neq 0$ and only decays to taus and either electrons or muons are included.

In both cases, all other RPV couplings are assumed to be zero. The branching ratios for the $\tilde{\chi}^0_1$ decay in the $LLE12k$ and $LLE133$ are shown in Table I. The sensitivity to $L$ couplings not considered here (e.g., $\lambda_{123}$) is expected to be between that achieved in the $LLE12k$ and $LLE133$ scenarios.

For the pure-bino $\tilde{\chi}^0_1$ considered here, the $\tilde{\chi}^0_1$ production cross section is found to be vanishingly small, thus models that include one or more next-to-lightest SUSY particles (NLSP) are considered in order to obtain a reasonably large cross section. The choice of NLSP in the $LLE12k$ and $LLE133$ scenarios determines the cross section of the SUSY scenario, and can impact the signal acceptance to a lesser extent. In all cases, the NLSP is pair produced in an RPC interaction, and decays to the LSP (which itself undergoes an RPV decay). Three different possibilities are considered for the NLSP in the $LLE12k$ and $LLE133$ scenarios:

(i) Wino NLSP: Mass-degenerate wino-like charginos and neutralinos are produced in association ($\tilde{\chi}^+_1\tilde{\chi}^-_1$ or $\tilde{\chi}^0_2\tilde{\chi}^0_2$). The $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ decays to the LSP while emitting a $W$ ($Z$ or $h$) boson, as shown in Figs. 1(a) and 1(b).

(ii) $\tilde{\ell}_L/\tilde{\nu}$ NLSP: Mass-degenerate left-handed sleptons and sneutrinos of all three generations are produced

TABLE I. Decay modes and branching ratios for the $\tilde{\chi}^0_1$ LSP in the RPV models, where $\nu$ denotes neutrinos or antineutrinos of any lepton generation.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\tilde{\chi}^0_1$ branching ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LLE12k$</td>
<td>$e^+ e^- \nu \left(1/4\right)$, $e^+ \mu^- \nu \left(1/2\right)$, $\mu^+ \mu^- \nu \left(1/4\right)$</td>
</tr>
<tr>
<td>$LLE133$</td>
<td>$e^\pm \tau^\mp \nu \left(1/4\right)$, $\tau^\pm \tau^\mp \nu \left(1/2\right)$, $\mu^\pm \tau^\mp \nu \left(1/4\right)$</td>
</tr>
</tbody>
</table>

The 27 $\lambda_{ijk}$ RPV couplings are reduced to 9 by the antisymmetry requirement $\lambda_{ijk} = -\lambda_{jik}$.  

032009-2
in association ($\tilde{e}_L$, $\tilde{e}_L$, $\tilde{\nu}_L$, $\tilde{\nu}_L$). The $\tilde{e}_L$ ($\tilde{\nu}_L$) decays to the LSP while emitting a charged lepton (neutrino) as seen in Fig. 1(c).

(iii) $\tilde{g}$ NLSP: Gluino pair production, where the gluino decays to the LSP while emitting a quark-antiquark pair ($u$, $d$, $s$, $c$, $b$ only, with equal branching ratios), as seen in Fig. 1(d).

For the RPV models, the LSP mass is restricted to the range $10$ GeV $\leq m(\text{LSP}) \leq m(\text{NLSP}) - 10$ GeV to ensure that both the RPC cascade decay and the RPV LSP decay are prompt. Nonprompt decays of the $\tilde{\chi}_1^0$ in similar models were previously studied in Ref. [37].

### B. RPC SUSY scenarios

RPC scenarios with light $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+$. Higgsino states are well motivated by naturalness [38,39]. However, they can be experimentally challenging, as members of the Higgsino triplet are close in mass and decays of the $\tilde{\chi}_2^0/\tilde{\chi}_1^+$ to a $\tilde{\chi}_1^0$ LSP result in low-momentum decay products that are difficult to reconstruct efficiently. Searches for Higgsino-like $\tilde{\chi}_1^+$ in approximately mass-degenerate scenarios were performed by the LEP experiments, where chargino masses below 103.5 GeV were excluded [40] (reduced to 92 GeV for chargino-LSP mass differences between 0.1 and 3 GeV). Recently, the ATLAS experiment has excluded Higgsino-like $\tilde{\chi}_1^+$ up to masses $\sim 145$ GeV and down to $\tilde{\chi}_2^0$-LSP mass differences of 2.5 GeV [41] for scenarios where the $\tilde{\chi}_1^+$ mass is assumed to be halfway between the two lightest neutralino masses. In the

Planck-scale-mediated SUSY breaking scenario the gravitino $\tilde{G}$ is the fermionic superpartner of the graviton, and its mass is comparable to the masses of the other SUSY particles, $m \sim 100$ GeV [42,43]. General gauge mediated (GGM) SUSY models [44] predict the $\tilde{G}$ is nearly massless and offer an opportunity to study light Higgsinos. The decays of the Higgsinos to the LSP $\tilde{G}$ would lead to on-shell $Z/h$, and the decay products can be reconstructed.

Simplified RPC models inspired by GGM are considered here, where the only SUSY particles within reach of the LHC are an almost mass-degenerate Higgsino triplet $\tilde{\chi}_1^+$, $\tilde{\chi}_2^0$ and a massless $\tilde{G}$. To ensure the SUSY decays are prompt, the $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ masses are set to 1 GeV above the $\tilde{\chi}_1^0$ mass, and due to their weak coupling with the gravitino always decay to the $\tilde{\chi}_1^0$ via virtual $Z/W$ bosons (which in turn decay to very soft final states that are not reconstructed). The $\tilde{\chi}_1^0$ decays promptly to a gravitino plus a $Z$ or $h$ boson, $\tilde{\chi}_1^0 \rightarrow Z/h + \tilde{G}$, where the leptonic decays of the $Z/h$ are targeted in this analysis. Four production processes are included in this Higgsino GGM model: $\tilde{\chi}_1^+\tilde{\chi}_1^+$, $\tilde{\chi}_1^+\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$, as shown in Fig. 2, and the total SUSY cross section is dominated by $\tilde{\chi}_1^+\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0\tilde{\chi}_2^0$ production. The $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$ branching ratio is a free parameter of the GGM Higgsino scenarios, and so offers an opportunity to study 4$\ell$ signatures with one or more $Z$ candidates.

### III. THE ATLAS DETECTOR

The ATLAS detector [45] is a multipurpose particle physics detector with forward-backward symmetric cylindrical geometry. The inner tracking detector (ID) covers...
|$\eta|$ < 2.5 and consists of a silicon pixel detector, a semiconductor microstrip detector, and a transition radiation tracker. The innermost pixel layer, the insertable B-layer [46], was added for the $\sqrt{s} = 13$ TeV running period of the LHC. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. A high-granularity lead/liquid-argon sampling calorimeter measures the energy and the position of electromagnetic showers within $|\eta| < 3.2$. Sampling calorimeters with liquid argon as the active medium are also used to measure hadronic showers in the end cap (1.5 < $|\eta|$ < 3.2) and forward (3.1 < $|\eta|$ < 4.9) regions, while a steel/scintillator tile calorimeter measures hadronic showers in the central region ($|\eta|$ < 1.7). The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting air-core toroid magnets, each with eight coils, a system of precision tracking chambers ($|\eta|$ < 2.7), and fast trigger chambers ($|\eta|$ < 2.4). A two-level trigger system [47] selects events to be recorded for off-line analysis.

IV. MONTE CARLO SIMULATION

Monte Carlo (MC) generators were used to simulate SM processes and new physics signals. The SM processes considered are those that can lead to signatures with at least four reconstructed charged leptons. Details of the signal and background MC simulation samples used in this analysis, as well as the order of cross section calculations in perturbative QCD used for yield normalization, are shown in Table II. Signal cross sections were calculated to next-to-leading order in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO + NNLL) [48–55]. The nominal signal cross section and its uncertainty were taken from an envelope of cross section predictions using different parton distribution function (PDF) sets and factorization and renormalization scales, as described in Ref. [56].

The dominant irreducible background processes that can produce four prompt and isolated charged leptons are $ZZ$, $t\bar{t}Z$, $VVV$ and Higgs production (where $V = W$, $Z$, and includes off-shell contributions). For the simulated $ZZ$ production, the matrix elements contain all diagrams with four electroweak vertices, and they were calculated for up to one extra parton at NLO, and up to three extra partons at LO. The production of top quark pairs with an additional $Z$ boson was simulated with the cross section normalized to NLO. Simulated triboson ($VVV$) production includes the processes $ZZZ$, $WZZ$ and $WWZ$ with four to six charged leptons, and was generated at NLO with additional LO matrix elements for up to two extra partons. The simulation of Higgs processes includes Higgs production via gluon-gluon fusion (ggH) and vector-boson fusion (VBF), and associated production with a boson (WH, ZH) or a top-antitop pair ($t\bar{t}H$). Other irreducible background processes with small cross sections are grouped into a category labeled “Other,” which contains the $tWZ$, $t\bar{W}W$, $t\bar{t}W$ and $t\bar{t}\bar{t}$ processes.

TABLE II. Summary of the simulated SM background samples used in this analysis, where $V = W$, $Z$, and includes off-shell contributions. “Tune” refers to the set of tuned parameters used by the generator. The sample marked with a $\dagger$ is used for a cross-check of yields and for studies of systematic uncertainties.

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator(s)</th>
<th>Simulation</th>
<th>Cross-section calculation</th>
<th>Tune</th>
<th>PDF set</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WZ$, $WW$</td>
<td>SHERPA 2.2.1 [57]</td>
<td>Full</td>
<td>NLO [58]</td>
<td>SHERPA default</td>
<td>NNPDF30NNLO [59]</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>SHERPA 2.2.2 [57]</td>
<td>Full</td>
<td>NLO [58]</td>
<td>SHERPA default</td>
<td>NNPDF30NNLO [59]</td>
</tr>
<tr>
<td>$VVV$</td>
<td>SHERPA 2.2.1</td>
<td>Full</td>
<td>NLO [58]</td>
<td>SHERPA default</td>
<td>NNPDF30NNLO</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>MadGraph5_AMC@NLO 2.3.2 [66] + PYTHIA 8.186</td>
<td>Full</td>
<td>NLO [67]</td>
<td>A14</td>
<td>NNPDF23LO</td>
</tr>
<tr>
<td>$t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}WW$</td>
<td>MadGraph5_AMC@NLO 2.2.2 [69] + PYTHIA 8.186</td>
<td>Full</td>
<td>NLO [67]</td>
<td>A14</td>
<td>NNPDF23LO</td>
</tr>
<tr>
<td>$t\bar{t}Z^\dagger$</td>
<td>SHERPA 2.2.1</td>
<td>Fast</td>
<td>NLO [67]</td>
<td>SHERPA default</td>
<td>NNPDF30NNLO</td>
</tr>
<tr>
<td>$tWZ$</td>
<td>aMC@NLO 2.3.2 + PYTHIA 8.186</td>
<td>Full</td>
<td>NLO [67]</td>
<td>A14</td>
<td>NNPDF23LO</td>
</tr>
<tr>
<td>$ttW$, $t\bar{t}\bar{t}$</td>
<td>MadGraph5_AMC@NLO 2.2.2 + PYTHIA 8.186</td>
<td>Full</td>
<td>NLO [69]</td>
<td>A14</td>
<td>NNPDF23LO</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>POWHEG v2 + PYTHIA 6.428 [70]</td>
<td>Full</td>
<td>NNLO + NNLL [71]</td>
<td>Perugia2012 [72]</td>
<td>CT10</td>
</tr>
<tr>
<td>$Z$ + jets, $W$ + jets</td>
<td>MadGraph5_AMC@NLO 2.2.2 + PYTHIA 8.186</td>
<td>Full</td>
<td>NNLO [73]</td>
<td>A14</td>
<td>NNPDF23LO</td>
</tr>
<tr>
<td>SUSY signal</td>
<td>MadGraph5_AMC@NLO 2.2.2 + PYTHIA 8.186</td>
<td>Fast</td>
<td>NLO + NLL [48–55]</td>
<td>A14</td>
<td>NNPDF23LO</td>
</tr>
</tbody>
</table>
For all MC simulation samples, the propagation of particles through the ATLAS detector was modeled with GEANT4 [74] using the full ATLAS detector simulation [75], or a fast simulation using a parametrization of the response of the electromagnetic and hadronic calorimeters [75] and GEANT4 elsewhere. The effect of multiple proton-proton collisions in the same or nearby bunch crossings, in-time and out-of-time pileup, is incorporated into the simulation by overlaying additional minimum-bias events generated with PYTHIA8 [61] onto hard-scatter events. Simulated events are reconstructed in the same manner as data, and are weighted to match the distribution of the expected mean number of interactions per bunch crossing in data. The simulated MC samples are corrected to account for differences from the data in the triggering efficiencies, lepton reconstruction efficiencies, and the energy and momentum measurements of leptons and jets.

V. EVENT SELECTION

After the application of beam, detector and data-quality requirements, the total integrated luminosity considered in this analysis corresponds to 36.1 ± 1.2 fb⁻¹. Events recorded during stable data-taking conditions are used in the analysis if the reconstructed primary vertex has at least two tracks with transverse momentum \( p_T > 400 \) MeV associated with it. The primary vertex of an event is identified as the vertex with the highest \( \Sigma p_T^2 \) of associated tracks.

Preselected electrons are required to have \( |\eta| < 2.47 \) and \( p_T > 7 \) GeV, where the \( p_T \) and \( \eta \) are determined from the calibrated clustered energy deposits in the electromagnetic calorimeter and the matched ID track, respectively. Electrons must satisfy “loose” criteria of the likelihood-based identification algorithm [76], with additional track requirements based on the innermost pixel layer. Preselected muons are reconstructed by combining tracks in the ID with tracks in the MS [77], and are required to have \( |\eta| < 2.7 \) and \( p_T > 5 \) GeV. Muons must satisfy “medium” identification requirements based on the number of hits in the different ID and MS subsystems, and the significance of the charge-to-momentum ratio, defined in Ref. [77]. Events containing one or more muons that have a transverse impact parameter relative to the primary vertex \( |d_0| > 0.2 \) mm or a longitudinal impact parameter relative to the primary vertex \( |z_0| > 1 \) mm are rejected to suppress the cosmic-ray muon background.

Jets are reconstructed with the anti-\( k_T \) algorithm [78] with a radius parameter of \( R = 0.4 \). Three-dimensional calorimeter energy clusters are used as input to the jet reconstruction, and jets are calibrated following Ref. [79]. Jets must have \( |\eta| < 2.8 \) and \( p_T > 20 \) GeV. To reduce pileup effects, jets with \( p_T < 60 \) GeV and \( |\eta| < 2.4 \) must satisfy additional criteria using the jet vertex tagging algorithm described in Ref. [80]. Events containing jets failing to satisfy the quality criteria described in Ref. [81] are rejected to suppress events with large calorimeter noise or noncollision backgrounds.

The visible part of hadronically decaying tau leptons, denoted as \( \tau_{\text{had-vis}} \) and conventionally referred to as taus throughout this paper, is reconstructed [82] using jets as described above with \( |\eta| < 2.47 \) and \( p_T > 10 \) GeV. The \( \tau_{\text{had-vis}} \) reconstruction algorithm uses information about the tracks within \( \Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2 \) of the jet direction, in addition to the electromagnetic and hadronic shower shapes in the calorimeters. Preselected \( \tau_{\text{had-vis}} \) candidates are required to have one or three associated tracks (prongs), because taus predominantly decay to either one or three charged hadrons together with a neutrino and often additional neutral hadrons. The preselected \( \tau_{\text{had-vis}} \) candidates are required to have \( p_T > 20 \) GeV and unit total charge of their constituent tracks. In order to suppress electrons misidentified as preselected \( \tau_{\text{had-vis}} \), taus are vetoed using transition radiation and calorimeter information. The preselected \( \tau_{\text{had-vis}} \) candidates are corrected to the replica energy scale using an \( \eta \) and \( p_T \)-dependent calibration. A boosted decision tree algorithm (BDT) uses discriminating track and cluster variables to optimize \( \tau_{\text{had-vis}} \) identification, where “loose,” “medium” and “tight” working points are defined [83], but not used to preselect tau leptons. In this analysis, kinematic variables built with hadronically decaying taus use only their visible decay products.

The missing transverse momentum, \( E_T^{\text{miss}} \), is the magnitude of the negative vector sum of the transverse momenta of all identified physics objects (electrons, photons, muons and jets) and an additional soft term [84]. Taus are included as jets in the \( E_T^{\text{miss}} \). The soft term is constructed from the tracks matched to the primary vertex, but not associated with identified physics objects, which allows the soft term to be nearly independent of pileup.

To avoid potential ambiguities among identified physics objects, preselected charged leptons and jets must survive “overlap removal,” applied in the following order:

1. Any tau within \( \Delta R = 0.2 \) of an electron or muon is removed.
2. Any electron sharing an ID track with a muon is removed.
3. Jets within \( \Delta R = 0.2 \) of a preselected electron are discarded.
4. Electrons within \( \Delta R = 0.4 \) of a preselected jet are discarded, to suppress electrons from semileptonic decays of \( c \)- and \( b \)-hadrons.
5. Jets with fewer than three associated tracks are discarded either if a preselected muon is within \( \Delta R = 0.2 \) or if the muon can be matched to a track associated with the jet.
6. Muons within \( \Delta R = 0.4 \) of a preselected jet are discarded to suppress muons from semileptonic decays of \( c \)- and \( b \)-hadrons.
7. Jets within \( \Delta R = 0.4 \) of a preselected tau passing medium identification requirements are discarded.
VI. SIGNAL REGIONS

Events with four or more signal leptons ($e, \mu, \tau_{\text{had-vis}}$) are selected and are classified according to the number of light signal leptons ($L = e, \mu$) and signal taus ($T$) required: at least four light leptons and exactly zero taus 4LO7T, exactly three light leptons and at least one tau 3L1T, or exactly two light leptons and at least two taus 2L2T.

Events are further classified according to whether they are consistent with a leptonic Z boson decay or not. The $Z$ requirement selects events where any SFOS $LL$ pair combination has an invariant mass close to the $Z$ boson mass, in the range $81.2–101.2$ GeV. A second $Z$ candidate may be identified if a second SFOS $LL$ pair is present and satisfies $61.2 < m(LL) < 101.2$ GeV. Widening the low-mass side of the $m(LL)$ window used for the selection of a second $Z$ candidate increases GGM signal acceptance. The $Z$ veto rejects events where any SFOS lepton pair combination has an invariant mass close to the $Z$ boson mass, in the range $81.2–101.2$ GeV. To suppress radiative $Z$ boson decays into four leptons (where a photon radiated from a $Z \rightarrow \ell^+ \ell^-$ decay converts to a second SFOS lepton pair) the $Z$ veto also considers combinations of any SFOS $LL$ pair with an additional lepton (SFOS + $L$), or with a second SFOS $LL$ pair (SFOS + SFOS), and rejects events where either the SFOS + $L$ or SFOS + SFOS invariant mass lies in the range $81.2–101.2$ GeV.

In order to separate the SM background from SUSY signal, the $E_T^{\text{miss}}$ and the effective mass of the event, $m_{\text{eff}}$, are both used. The $m_{\text{eff}}$ is defined as the scalar sum of the $E_T^{\text{miss}}$, the $p_T$ of signal leptons and the $p_T$ of all jets with $p_T > 40$ GeV. The $p_T > 40$ GeV requirement for jets aims to suppress contributions from pileup and the underlying event. A selection using the $m_{\text{eff}}$ rather than the $E_T^{\text{miss}}$ is particularly effective for the RPV SUSY scenarios, which produce multiple high-energy leptons (and in some cases jets), but only low to moderate $E_T^{\text{miss}}$ from neutrinos in the final state. The chosen $m_{\text{eff}}$ thresholds are found to be close to optimal for the RPV scenarios with different NLSPs considered in this paper.

Two signal regions (SR) are defined with 4LO7T and a $Z$ veto: a general, model-independent signal region (SROA) with $m_{\text{eff}} > 600$ GeV, and a tighter signal region (SR0B) with $m_{\text{eff}} > 1100$ GeV, optimized for the RPV $LLE12k$ scenarios. Two further SRs are defined with 4LO7T, a first and second $Z$ requirement as described above, and different selections on $E_T^{\text{miss}}$: a loose signal region (SR0C) with $E_T^{\text{miss}} > 50$ GeV, and a tighter signal region (SR0D) with $E_T^{\text{miss}} > 100$ GeV, optimized for the low-mass and high-mass Higgsino GGM scenarios, respectively. Finally, two SRs are optimized for the tau-rich RPV $LLE133$ scenarios: one with $3L1T$ where the tau has $p_T > 30$ GeV, a $Z$ veto and $m_{\text{eff}} > 700$ GeV (SR1), and a second with 2L2T where the taus have $p_T > 30$ GeV, a $Z$ veto and $m_{\text{eff}} > 650$ GeV (SR2). The signal region definitions are summarized in Table IV.
Several SM processes can result in signatures resembling SUSY signals with four reconstructed charged leptons, including both the “real” and “fake” lepton contributions. Here, a real charged lepton is defined to be a prompt and genuinely isolated lepton, while a fake charged lepton is defined to be a nonprompt or nonisolated lepton that could originate from semileptonic decays of $b$- and $c$-hadrons, or from in-flight decays of light mesons, or from misidentification of particles within light-flavor or gluon-initiated jets, or from photon conversions. The SM processes are classified into two categories:

**Irreducible background:** Hard-scattering processes giving rise to events with four or more real leptons, $ZZ$, $t\bar{t}Z$, $t\bar{t}WW$, $t\bar{t}WZ$, $VVV$ ($V = W, Z$), Higgs ($ggH, WH, ZH, t\bar{t}H$), $t\bar{t}t$, $t\bar{t}W$.

**Reducible background:** Processes leading to events with at least one fake lepton, $t\bar{t}$, $Z +$ jets, $WZ$, $WW$, $WWW$, $t\bar{t}W$, $t\bar{t}t$. Processes listed under irreducible that do not undergo a decay to four real leptons (e.g., $ZZ \rightarrow q\bar{q}^{\ell}\ell'$) are also included in the reducible background.

Backgrounds with three or more fake leptons (e.g., $W +$ jets) are found to be very small for this analysis, and the systematic uncertainty on the reducible background is increased to cover any effect from them (discussed in Sec. VII A).

In the signal regions, the irreducible background is dominated by $t\bar{t}Z$, $VVV$ ($V = W, Z$), and $ZZ$, while the reducible background is dominated by the two-fake-lepton backgrounds $t\bar{t}$ and $Z +$ jets. The irreducible backgrounds are estimated from MC simulation, while the reducible backgrounds are derived from data with the fake-factor method. Signal regions with $4L0T$ are dominated by irreducible background processes, whereas the reducible background processes dominate the $3L1T$ and $2L2T$ signal regions. The predictions for irreducible and reducible backgrounds are tested in validation regions (Sec. VII B).

In the fake-factor method, the number of reducible background events in a given region is estimated from data using probabilities for a fake preselected lepton to pass or fail the signal lepton selection. The ratio $F = f/\bar{f}$ for fake leptons is the “fake factor,” where $f$ ($\bar{f}$) is the probability that a fake lepton is misidentified as a signal (loose) lepton. The probabilities used in the fake-factor calculations are based on simulation and corrected to data where possible. Loose leptons are preselected leptons surviving overlap removal that do not satisfy signal lepton criteria. For this fake-factor

<table>
<thead>
<tr>
<th>Region</th>
<th>$N(e, \mu)$</th>
<th>$N(\tau_{\text{had-vis}})$</th>
<th>$p_T(\tau_{\text{had-vis}})$</th>
<th>$Z$ boson</th>
<th>Selection</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR0A</td>
<td>4</td>
<td>0</td>
<td>$&gt;20$ GeV</td>
<td>Veto</td>
<td>$m_{\text{eff}} &gt; 600$ GeV</td>
<td>General</td>
</tr>
<tr>
<td>SR0B</td>
<td>4</td>
<td>0</td>
<td>$&gt;20$ GeV</td>
<td>Veto</td>
<td>$m_{\text{eff}} &gt; 1100$ GeV</td>
<td>RPV LLÉ12k</td>
</tr>
<tr>
<td>SR0C</td>
<td>4</td>
<td>0</td>
<td>$&gt;20$ GeV</td>
<td>Require first and second</td>
<td>$E_T^{\text{miss}} &gt; 50$ GeV</td>
<td>Higgsino GGM</td>
</tr>
<tr>
<td>SR0D</td>
<td>4</td>
<td>0</td>
<td>$&gt;20$ GeV</td>
<td>Require first and second</td>
<td>$E_T^{\text{miss}} &gt; 100$ GeV</td>
<td>Higgsino GGM</td>
</tr>
<tr>
<td>SR1</td>
<td>3</td>
<td>1</td>
<td>$&gt;30$ GeV</td>
<td>Veto</td>
<td>$m_{\text{eff}} &gt; 700$ GeV</td>
<td>RPV LLÉi33</td>
</tr>
<tr>
<td>SR2</td>
<td>2</td>
<td>2</td>
<td>$&gt;30$ GeV</td>
<td>Veto</td>
<td>$m_{\text{eff}} &gt; 650$ GeV</td>
<td>RPV LLÉi33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>$N(e, \mu)$</th>
<th>$N(\tau_{\text{had-vis}})$</th>
<th>$Z$ boson</th>
<th>Selection</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1_LLLl</td>
<td>3</td>
<td>0</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td></td>
</tr>
<tr>
<td>CR2_Lll</td>
<td>2</td>
<td>2</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td></td>
</tr>
<tr>
<td>CR1_LLLl</td>
<td>3</td>
<td>0</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td></td>
</tr>
<tr>
<td>CR1_LLLl</td>
<td>2</td>
<td>1</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td></td>
</tr>
<tr>
<td>CR2_LLLl</td>
<td>2</td>
<td>1</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td></td>
</tr>
<tr>
<td>CR1_LLLl</td>
<td>2</td>
<td>0</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td></td>
</tr>
<tr>
<td>CR2_LLLl</td>
<td>2</td>
<td>0</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td></td>
</tr>
</tbody>
</table>
evaluation, a very loose selection on the identification BDT is also applied to the preselected taus, since candidates with very low BDT scores are typically gluon-induced jets and jets arising from pileup, which is not the case for the signal tau candidates.

The reducible background prediction is extracted by applying fake factors to control regions (CR) in data. The CR definition only differs from that of the associated SR in the quality of the required leptons; here exactly one (CR1) or two (CR2) of the four leptons must be identified as a loose lepton, as shown in Table V. In 3L1T events, the contribution from events with two fake light leptons is negligible, as is the contribution from one and two fake light leptons in 2L2T events.

Fake factors are calculated separately for fake electrons, muons, and taus, from light-flavor jets, heavy-flavor jets, gluon-initiated jets (taus only) and photon conversions (electrons and taus only). These categories are referred to as fake-lepton “types.” The fake factor for each fake-lepton type is computed for each background process due to a dependence on the hard process (e.g., $t\bar{t}$, $Z +$ jets). The fake factor per fake-lepton type and per process is binned in lepton $p_T$, $\eta$ and number of prongs for taus.

To account correctly for the relative abundances of fake-lepton types and production processes, a weighted average $F_w$ of fake factors is computed in each CR, as

$$F_w = \sum_{i,j} (R^{ij} \times s^i \times F^{ij}).$$

The factors $R^{ij}$ are "process fractions" that depend on the fraction of fake leptons of type $i$ from process $j$, determined from MC simulation in the corresponding CR2, and are similar to the process fractions obtained in the signal regions from MC simulation, which suffer from having few events. The term $F^{ij}$ is the corresponding fake factor calculated using MC simulation. The "scale factors" $s^i$ are corrections that depend on the fake-lepton type, and are applied to the fake factors to account for possible differences between data and MC simulation. These are assumed to be independent of the physical process, and are determined from data in dedicated regions enriched in objects of a given fake-lepton type.

For fake light leptons from heavy-flavor jets, the scale factor is measured in a $t\bar{t}$-dominated control sample. The heavy-flavor scale factors are seen to have a modest $p_T$ dependence, decreasing for muons from 1.00 ± 0.07 to 0.73 ± 0.18 as the muon $p_T$ increases from 5 to 20 GeV. For electrons, the heavy-flavor scale factor is seen to increase from 1.16 ± 0.11 to 1.35 ± 0.29 across the same $p_T$ range. For taus, the heavy-flavor, gluon-initiated and conversion scale factors cannot be reliably measured using data. Instead, they are assumed to be the same as the light-flavor jet scale factor described below.

The scale factor for fake taus originating from light-flavor jets is measured separately for one- and three-prong taus in a control sample dominated by $Z +$ jets events. The scale factors are seen to be $p_T$-dependent, decreasing from 1.30 ± 0.05 to 0.96 ± 0.06 (1.42 ± 0.11 to 1.23 ± 0.13) as the one-prong (three-prong) tau $p_T$ increases from 20 to 60 GeV. The contribution to the signal regions from fake light leptons originating from light-flavor jets is very small (less than 1.8% of all $e$, $\mu$ and the scale factor cannot be reliably measured using data. Therefore, values of 1.00 ± 0.25 are used instead, motivated by similar uncertainties in the other scale factor measurements.

For fake electrons from conversions, the scale factor is determined in a sample of photons from final-state radiation of $Z$ boson decays to muon pairs. The electron conversion scale factor is seen to have a small $p_T$ dependence, increasing from 1.38 ± 0.17 to 1.53 ± 0.20 as the electron $p_T$ increases from 7 to 25 GeV.

The number $N^{\text{SR}}_{\text{red}}$ of background events with one or two fake leptons from reducible sources in each SR is determined from the number of events in data in the corresponding CRs, $N^{\text{CR1}}_{\text{data}}$ and $N^{\text{CR2}}_{\text{data}}$, according to

$$N^{\text{SR}}_{\text{red}} = [N^{\text{CR1}}_{\text{data}} - N^{\text{CR1}}_{\text{irr}}] \times F_{w,1} - [N^{\text{CR2}}_{\text{data}} - N^{\text{CR2}}_{\text{irr}}] \times F_{w,1} \times F_{w,2}.$$

where $F_{w,1}$ and $F_{w,2}$ are the two weighted fake factors that are constructed using the leading and subleading in $p_T$ loose leptons in the CRs, respectively. The small contributions from irreducible background processes in the CRs, $N^{\text{CR1,CR2}}_{\text{irr}}$, are evaluated using MC simulation and subtracted from the corresponding number of events seen in data. The second term removes the double counting of events with two fake leptons in the first term. Both CR1 and CR2 are dominated by the two-fake-lepton processes $t\bar{t}$ and $Z +$ jets, thus the first term is roughly double the second term. Higher-order terms in $F_w$ describing three- and four-fake-lepton backgrounds are neglected, as are some terms with a very small contribution; e.g., in 3L1T events, the contribution from events with two fake light leptons is negligible. A systematic uncertainty is applied to account for these neglected terms, as described in the following section.

A. Systematic uncertainties

Several sources of systematic uncertainty are considered for the SM background estimates and signal yield predictions. The systematic uncertainties affecting the simulation-based estimate can be divided into three components: MC statistical uncertainty, sources of experimental uncertainty (from identified physics objects $e$, $\mu$, $\tau$ and jets, and also $E^{\text{miss}}_T$), and sources of theoretical uncertainty. The reducible background is affected by different sources of uncertainty associated with data counts in control regions and uncertainties in the weighted fake factors. The primary
sources of systematic uncertainty, described below, are summarized in Fig. 3. The MC statistical uncertainty for the simulation-based background estimate is small and less than 7% of the total background estimate in all signal regions. Systematic uncertainties in the SUSY signal yields from experimental and theoretical sources are typically of the order of 10% each. The experimental uncertainties include the uncertainties associated with electrons, muons, taus, jets, and \( E_{T}^{miss} \), as well as the uncertainty associated with the simulation of pileup, and uncertainty in the luminosity (2.1%, following a methodology similar to that detailed in Ref. [85]). The uncertainties associated with pileup and luminosity are included in the total uncertainty in Fig. 3. The experimental uncertainties pertaining to electrons, muons and taus include the uncertainties due to the lepton identification efficiencies, lepton energy scale and energy resolution, isolation and trigger efficiencies. Systematic uncertainties from electron, muon, and tau sources are generally low in all signal regions, at about 5% relative to the total expected background. The uncertainties associated with jets are due to the jet energy scale, jet energy resolution and jet vertex tagging. Uncertainties in the object momenta are propagated to the \( E_{T}^{miss} \) measurement, and additional uncertainties in \( E_{T}^{miss} \) arising from energy deposits not associated with any reconstructed objects are also considered. The jet and \( E_{T}^{miss} \) uncertainties are generally of the order of a few percent in the signal regions, but this rises to 21% (7%) in SR0C (SR0D), where a selection on \( E_{T}^{miss} \) is made.

Theoretical uncertainties in the simulation-based estimates include the theoretical cross section uncertainties due to the choice of renormalization and factorization scales and PDFs, the acceptance uncertainty due to PDF and scale variations, and the choice of MC generator. The theoretical cross section uncertainties for the irreducible backgrounds used in this analysis are 12% for \( t\bar{t}Z \) [67], 6% for \( ZZ \) [58], and 20% for the triboson samples [58], where the order of the cross section calculations is shown in Table II. For the Higgs boson samples, an uncertainty of 20% is used for \( WH, ZH \) and VBF [62], while uncertainties of 100% are assumed to \( t\bar{t}H \) and \( ggH \) [86]. The uncertainties in the \( t\bar{t}H \) and \( ggH \) estimates are assumed to be large to account for uncertainties in the acceptance, while the inclusive cross sections are known to better precision. Uncertainties arising from the choice of generator are determined by comparing the MadGraph5_AMC@NLO and Sherpa generators for \( t\bar{t}Z \). Finally, the uncertainty in the \( ZZ \) and \( t\bar{t}Z \) acceptance due to PDF variations, and due to varying the renormalization and factorization scales by factors of 1/2 and 2, is also taken into account. In SR0A and SR0B, the theoretical uncertainties dominate the total uncertainty, mainly due to the 20% uncertainty from the \( t\bar{t}Z \) MC generator choice, and the 10% uncertainty from the \( t\bar{t}Z \) PDF/scale variations (25% for \( ZZ \)).

The uncertainty in the reducible background is dominated by the statistical uncertainty of the data events in the corresponding CR1 and CR2. The uncertainty in the weighted fake factors includes the MC statistical uncertainty in the process fractions, the uncertainty in the fake lepton scale factors, and the statistical uncertainty from the fake factors measured in simulation. The uncertainties for the fake factors from each fake-lepton type are treated as correlated across processes. Thus, since both CR1 and CR2 are dominated by two-fake-lepton processes with the same type of fake lepton, correlations in the fake factors applied to CR1 and CR2 result in a close cancellation of the uncertainties from the weighted fake factors between the first and second terms in Eq. (2). Finally, a conservative uncertainty is applied to account for the neglected terms in Eq. (2). For example, in 4L0T events the three- and

![Graph showing breakdown of dominant systematic uncertainties in background estimates for signal regions.](attachment:graph.png)

**FIG. 3.** Breakdown of the dominant systematic uncertainties in the background estimates for the signal regions. The individual uncertainties can be correlated, and do not necessarily sum in quadrature to the total background uncertainty. The text provides category details.

<table>
<thead>
<tr>
<th>Validation region</th>
<th>( N(e,\mu) )</th>
<th>( N(\tau_{had-vis}) )</th>
<th>( p_{T}(\tau_{had-vis}) )</th>
<th>( Z ) boson</th>
<th>Selection</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR0</td>
<td>( \geq 4 )</td>
<td>( = 0 )</td>
<td>( &gt; 20 \text{ GeV} )</td>
<td>Veto</td>
<td>( m_{eff} &lt; 600 \text{ GeV} )</td>
<td>( t\bar{t}, Z ) + jets, ( ZZ )</td>
</tr>
<tr>
<td>VR0Z</td>
<td>( \geq 4 )</td>
<td>( = 0 )</td>
<td>( &gt; 20 \text{ GeV} )</td>
<td>Require first and veto second</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>VR1</td>
<td>( = 3 )</td>
<td>( \geq 1 )</td>
<td>( &gt; 30 \text{ GeV} )</td>
<td>Veto</td>
<td>( m_{eff} &lt; 700 \text{ GeV} )</td>
<td>( t\bar{t}, Z ) + jets</td>
</tr>
<tr>
<td>VR2</td>
<td>( = 2 )</td>
<td>( \geq 2 )</td>
<td>( &gt; 30 \text{ GeV} )</td>
<td>Veto</td>
<td>( m_{eff} &lt; 650 \text{ GeV} )</td>
<td>( t\bar{t}, Z ) + jets</td>
</tr>
</tbody>
</table>

TABLE VI. Validation region definitions. The \( p_{T}(\tau_{had-vis}) \) column denotes the \( p_{T} \) threshold used for the tau selection or veto.
four-fake-lepton terms are neglected. Weighted fake factors are applied to data events with one signal and three loose light leptons to estimate an upper limit on this neglected contribution for each 4LO process. The calculated upper limit plus 1σ statistical uncertainty is added to the reducible background uncertainty, adding an absolute uncertainty of 0.14 events in SR0A. This is repeated for the 3L1T and 2L2T regions, accounting for the neglected terms with one or two fake light leptons as necessary, adding an absolute uncertainty of 0.07 events in SR1, and 0.20 events in SR2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>VR0</th>
<th>VR0Z</th>
<th>VR1</th>
<th>VR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>132</td>
<td>365</td>
<td>116</td>
<td>32</td>
</tr>
<tr>
<td>SM total</td>
<td>123 ± 11</td>
<td>334 ± 52</td>
<td>91 ± 19</td>
<td>28 ± 6</td>
</tr>
<tr>
<td>ZZ</td>
<td>65 ± 7</td>
<td>234 ± 23</td>
<td>8.8 ± 1.0</td>
<td>3.4 ± 0.5</td>
</tr>
<tr>
<td>t\bar{t}Z</td>
<td>3.9 ± 0.6</td>
<td>10.5 ± 1.5</td>
<td>1.76 ± 0.25</td>
<td>0.60 ± 0.10</td>
</tr>
<tr>
<td>Higgs</td>
<td>5 ± 4</td>
<td>43 ± 37</td>
<td>3.2 ± 2.9</td>
<td>1.3 ± 1.2</td>
</tr>
<tr>
<td>VVV</td>
<td>2.9 ± 0.6</td>
<td>16.1 ± 3.4</td>
<td>1.23 ± 0.27</td>
<td>0.29 ± 0.07</td>
</tr>
<tr>
<td>Reducible</td>
<td>46 ± 7</td>
<td>28 ± 26</td>
<td>76 ± 19</td>
<td>22 ± 6</td>
</tr>
<tr>
<td>Other</td>
<td>0.40 ± 0.07</td>
<td>2.7 ± 0.5</td>
<td>0.34 ± 0.06</td>
<td>0.16 ± 0.04</td>
</tr>
</tbody>
</table>

TABLE VII. Expected and observed yields for 36.1 fb\(^{-1}\) in the validation regions. “Other” is the sum of the tWZ, t\bar{t}WW, and t\bar{t}t\bar{t} backgrounds. Both the statistical and systematic uncertainties in the SM background are included in the uncertainties shown.

FIG. 4. The distributions for data and the estimated SM backgrounds in VR0 and VR0Z for (a) and (c) the electron and muon \(p_T\), (b) the SFOS invariant mass, and (d) the \(E_T^\text{miss}\). “Other” is the sum of the tWZ, t\bar{t}WW, and t\bar{t}t\bar{t} backgrounds. The last bin includes the overflow. Both the statistical and systematic uncertainties in the SM background are included in the shaded band.
B. Background modeling validation

The general modeling of both the irreducible and reducible backgrounds is tested in VRs that are defined to be adjacent to, yet disjoint from, the signal regions, as shown in Table VI. For signal regions that veto $Z$ boson candidates, three VRs are defined by reversing the $m_{\text{eff}}$ requirement, while for signal regions requiring two $Z$ boson candidates, one VR is defined by vetoing the presence of a second $Z$ boson candidate. The background model adopted in the VRs is the same as in the SRs, with the irreducible backgrounds obtained from MC simulation and the reducible background estimated from data using the fake-factor method with process fractions and loose lepton control regions corresponding to the VRs. The systematic uncertainties on the SM backgrounds in the VRs are evaluated as in Sec. VII A. The SM background in the VRs is dominated by $ZZ$, $t\bar{t}$ and $Z$ + jets.

Observed and expected event yields in the VRs are shown in Table VII, where good agreement is seen in general within statistical and systematic uncertainties. No significant excesses above the SM expectations are observed in any VR.

The lepton $p_T$, $m_{\text{SFOS}}$ and $E_T^{\text{miss}}$ distributions in the VRs are shown in Figs. 4 and 5. Figure 4(a) shows that VR0 has a slight downward trend in the ratio of the

FIG. 5. The distributions for data and the estimated SM backgrounds in VR1 and VR2 for (a) and (c) the light lepton $p_T$, and (b) and (d) the tau $p_T$. “Other” is the sum of the $tWZ$, $t\bar{t}WW$, and $t\bar{t}t\bar{t}$ backgrounds. The last bin includes the overflow. Both the statistical and systematic uncertainties in the SM background are included in the shaded band.
data to estimated SM background as the $p_T$ of the leptons increases, which was found to be most noticeable in the $p_T$ of the leading electron in the event. However, since the corresponding signal regions (SR0A and SR0B) require high $m_{\text{eff}}$, the potential impact of a small mismodeling of one electron in the event was found to be insignificant.

The $m_{\text{eff}}$ distributions in VR0, VR1 and VR2 can be seen in the lower $m_{\text{eff}}$ bins in Fig. 6.

**VIII. RESULTS**

The expected and observed yields in each signal region are reported in Table VIII, together with the statistical and systematic uncertainties in the background predictions. The observations are consistent with the SM expectations within a local significance of at most $2.3\sigma$. The $m_{\text{eff}}$ and $E_{\text{T}}^{\text{miss}}$ distributions for all events passing signal region requirements, except the $m_{\text{eff}}$ or $E_{\text{T}}^{\text{miss}}$ requirement itself, are shown in Fig. 6.
TABLE VIII. Expected and observed yields for 36.1 fb$^{-1}$ in the signal regions. “Other” is the sum of the $tWZ$, $t\bar{t}WW$, and $t\bar{t}t$ backgrounds. Both the statistical and systematic uncertainties in the SM background are included in the uncertainties shown. Also shown are the model-independent limits calculated from the signal region observations; the 95% C.L. upper limit on the visible cross section times efficiency ($\langle e\sigma \rangle_{\text{obs}}^{95}$), the observed number of signal events ($S_{\text{obs}}^{95}$), and the signal events given the expected number of background events ($S_{\text{exp}}^{95}$, ±1σ variations of the expected number) calculated by performing pseudoexperiments for each signal region. The last three rows report the CL$_b$ value for the background-only hypothesis, and finally the one-sided $p_0$-value and the local significance $Z$ (the number of equivalent Gaussian standard deviations).

<table>
<thead>
<tr>
<th>Sample</th>
<th>SR0A</th>
<th>SR0B</th>
<th>SR0C</th>
<th>SR0D</th>
<th>SR1</th>
<th>SR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>13</td>
<td>2</td>
<td>47</td>
<td>10</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>SM total</td>
<td>10.2 ± 2.1</td>
<td>1.31 ± 0.24</td>
<td>37 ± 9</td>
<td>4.1 ± 0.7</td>
<td>4.9 ± 1.6</td>
<td>2.3 ± 0.8</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.7 ± 0.7</td>
<td>0.33 ± 0.10</td>
<td>28 ± 9</td>
<td>0.84 ± 0.34</td>
<td>0.35 ± 0.09</td>
<td>0.33 ± 0.08</td>
</tr>
<tr>
<td>$t\bar{t}$Z</td>
<td>2.5 ± 0.6</td>
<td>0.47 ± 0.13</td>
<td>3.2 ± 0.4</td>
<td>1.62 ± 0.23</td>
<td>0.54 ± 0.11</td>
<td>0.31 ± 0.08</td>
</tr>
<tr>
<td>Higgs</td>
<td>1.2 ± 1.2</td>
<td>0.13 ± 0.13</td>
<td>0.9 ± 0.8</td>
<td>0.28 ± 0.25</td>
<td>0.5 ± 0.5</td>
<td>0.32 ± 0.32</td>
</tr>
<tr>
<td>VVV</td>
<td>0.79 ± 0.17</td>
<td>0.22 ± 0.05</td>
<td>2.7 ± 0.6</td>
<td>0.64 ± 0.14</td>
<td>0.18 ± 0.04</td>
<td>0.20 ± 0.06</td>
</tr>
<tr>
<td>Reducible</td>
<td>2.4 ± 1.4</td>
<td>0.000$^{+0.005}_{-0.000}$</td>
<td>0.9$^{+1.4}_{-0.9}$</td>
<td>0.23$^{+0.38}_{-0.23}$</td>
<td>3.1 ± 1.5</td>
<td>1.1 ± 0.7</td>
</tr>
<tr>
<td>Other</td>
<td>0.53 ± 0.06</td>
<td>0.165 ± 0.018</td>
<td>0.85 ± 0.19</td>
<td>0.45 ± 0.10</td>
<td>0.181 ± 0.022</td>
<td>0.055 ± 0.012</td>
</tr>
<tr>
<td>$\langle e\sigma \rangle_{\text{obs}}^{95}$, fb</td>
<td>0.32</td>
<td>0.14</td>
<td>0.87</td>
<td>0.36</td>
<td>0.28</td>
<td>0.13</td>
</tr>
<tr>
<td>$S_{\text{obs}}^{95}$</td>
<td>12</td>
<td>4.9</td>
<td>31</td>
<td>13</td>
<td>10</td>
<td>4.6</td>
</tr>
<tr>
<td>$S_{\text{exp}}^{95}$</td>
<td>9.3$^{+3.6}_{-2.3}$</td>
<td>3.9$^{+1.6}_{-0.8}$</td>
<td>23$^{+2}_{-1}$</td>
<td>6.1$^{+2.1}_{-1.0}$</td>
<td>6.5$^{+3.5}_{-1.3}$</td>
<td>4.7$^{+2.0}_{-1.3}$</td>
</tr>
<tr>
<td>CL$_b$</td>
<td>0.76</td>
<td>0.74</td>
<td>0.83</td>
<td>0.99</td>
<td>0.86</td>
<td>0.47</td>
</tr>
<tr>
<td>$p_0$</td>
<td>0.23</td>
<td>0.25</td>
<td>0.15</td>
<td>0.011</td>
<td>0.13</td>
<td>0.61</td>
</tr>
<tr>
<td>$Z$</td>
<td>0.75</td>
<td>0.69</td>
<td>1.0</td>
<td>2.3</td>
<td>1.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The HistFitter [87] software framework is used for the statistical interpretation of the results. In order to quantify the probability for the background-only hypothesis to fluctuate to the observed number of events or higher, a one-sided $p_0$-value is calculated using pseudoexperiments, where the profile likelihood ratio is used as a test statistic [88] to exclude the signal-plus-background hypothesis. A signal model can be excluded at 95% confidence level (C.L.) if the CL$_b$ [89] of the signal-plus-background hypothesis is below 0.05. For each signal region, the expected and observed upper limits at 95% C.L. on the number of beyond-the-SM events ($S_{\text{exp}}^{95}$ and $S_{\text{obs}}^{95}$) are calculated using the model-independent signal fit. The 95% C.L. upper limits on the signal cross section times efficiency ($\langle e\sigma \rangle_{\text{obs}}^{95}$) and the CL$_b$ value for the background-only hypothesis are also calculated for each signal region. The number of observed events in each signal region is used to set exclusion limits in the SUSY models, where the statistical combination of all disjoint signal regions is used. For overlapping signal regions, specifically SR0A and SR0B, and also SR0C and SR0D, the signal region with the better expected exclusion is used in the combination. Experimental uncertainties affecting irreducible backgrounds, as well as the simulation-based estimate of the weighted fake factors, are treated as correlated between regions and processes. Uncertainties associated to the data-driven estimate of the reducible background are correlated between regions only. Theoretical uncertainties in the irreducible background and signal are treated as correlated between regions, while statistical uncertainties from MC simulation and data in the CR are treated as uncorrelated between regions and processes. For the exclusion limits, the observed and expected 95% C.L. limits are calculated by performing pseudoexperiments for each SUSY model point, taking into account the theoretical and experimental uncertainties in the SM background and the experimental uncertainties in the signal. For all expected and observed exclusion limit contours, the ±1σ$_{\text{exp}}$ uncertainty band indicates the impact on the expected limit of the systematic and statistical uncertainties included in the fit. The ±1σ$_{\text{SUSY}}$ uncertainty lines around the observed limit illustrate the change in the observed limit as the nominal signal cross section is scaled up and down by the theoretical cross section uncertainty.

Figures 7 and 8 show the exclusion contours for the RPV models considered here, where SR0B dominates the exclusion for $LL\bar{E}12k$ models, and the combination of SR1 and SR2 is important for the $LL\bar{E}i33$ models. The exclusion limits in the RPV models extend to high masses, due to the high lepton multiplicity in these scenarios (\(\ell^+\ell^-\ell^+\ell^-\) with 100% branching ratio) and the high efficiency of the M$_{dil}$ selections. In the RPV wino NLSP $LL\bar{E}12k$ models shown in Figs. 7(a) and 7(b), $\tilde{\chi}^+_1/\tilde{\chi}^0_2$ masses up to $\sim$1.46 TeV are excluded for $m(\tilde{\chi}^0_1) > 500$ GeV. The sensitivity is reduced for large mass splittings between the $\tilde{\chi}^+_1/\tilde{\chi}^0_2$ and the $\tilde{\chi}^0_1$, where the decay products are strongly boosted, and $\tilde{\chi}^+_1/\tilde{\chi}^0_1$ masses
FIG. 7. Expected (dashed) and observed (solid) 95% C.L. exclusion limits on (a) wino NLSP, and (b) wino NLSP pair production with RPV \( \tilde{\chi}^0_1 \) decays via \( \lambda_{123} \) or \( \lambda_{133} \) where \( i, k \in 1, 2 \). The limits are set using the statistical combination of disjoint signal regions. Where the signal regions are not mutually exclusive, the observed CLs value is taken from the signal region with the better expected CLs value.

FIG. 8. Expected (dashed) and observed (solid) 95% C.L. exclusion limits on (a) \( \tilde{\ell} \)/\( \ell \) NLSP, and (b) gluino NLSP pair production with RPV \( \tilde{\chi}^0_1 \) decays via \( \lambda_{123} \) or \( \lambda_{133} \) where \( i, k \in 1, 2 \). The limits are set using the statistical combination of disjoint signal regions. Where the signal regions are not mutually exclusive, the observed CLs value is taken from the signal region with the better expected CLs value.

up to \( \sim 1.32 \) TeV are excluded for \( m(\tilde{\chi}^0_1) > 50 \) GeV. Figures 7(a) and 7(b) also show exclusion contours for the RPV wino NLSP \( LLEi33 \) models, where \( \tilde{\chi}^+_1/\tilde{\chi}^0_2 \) masses up to \( \sim 980 \) GeV are excluded for \( 400 \) GeV < \( m(\tilde{\chi}^+_1) < 700 \) GeV. The sensitivity is also reduced for large mass differences between the \( \tilde{\chi}^+_1/\tilde{\chi}^0_2 \) and the \( \tilde{\chi}^0_1 \), where the tau leptons, in particular, are collimated. These results extend the limits set in a similar model considering only \( \tilde{\chi}^+_1 \) production in Ref. [22] by around 400–750 GeV.

Figure 8(a) shows exclusion contours for the RPV \( \tilde{\ell} / \ell \) NLSP model, where left-handed slepton/sneutrino masses are excluded up to \( \sim 1.06 \) TeV for \( m(\tilde{\chi}^0_1) \approx 600 \) GeV for \( LLE12k \) models, and up to 780 GeV for \( m(\tilde{\chi}^0_1) \approx 300 \) GeV for \( LLEi33 \) models. These results extend the limits set in a similar model considering only \( \tilde{\ell} \) production in Ref. [22] by around 200–400 GeV.

The exclusion contours for the RPV \( \tilde{\chi}^0_1 \) NLSP model are shown in Fig. 8(b), where gluino masses are excluded up to \( \sim 2.25 \) TeV for \( m(\tilde{\chi}^0_1) > 1 \) TeV for \( LLE12k \) models, and up to \( \sim 1.65 \) TeV for \( m(\tilde{\chi}^0_1) > 500 \) GeV for \( LLEi33 \) models. These results significantly improve upon limits set in a similar model in Ref. [22] by around 500–700 GeV.

Figure 9 shows the exclusion contours for the Higgsino GGM models considered here. The exclusion is dominated by SR0C and SR0D for low and high Higgsino masses,
is not sensitive to scenarios with Higgsino GGM models, where Higgsino-like respectively. The results are also interpreted in simplified to 1.46 TeV, 1.06 GeV, and 2.25 TeV are excluded, for scenarios with taus), using final state with four or more leptons (electrons, muons or"

\[ \chi_0^0 \rightarrow Z + \tilde{\chi}_1^0 \]

FIG. 9. Expected (dashed) and observed (solid) 95% C.L. exclusion limits on the Higgsino GGM models. The limits are set using the statistical combination of disjoint signal regions. Where the signal regions are not mutually exclusive, the observed CLs value is taken from the signal region with the better expected CLs value.

respectively. Higgsino-like \( \tilde{\chi}_1^+/\chi_0^0/\tilde{\chi}_1^0 \) with masses up to 295 GeV are excluded in scenarios with a branching ratio \( B(\tilde{\chi}_1^0 \rightarrow Z + \tilde{\tilde{\chi}}_1) = 100\% \), while the exclusion is weakened for scenarios with \( B(\tilde{\chi}_1^0 \rightarrow Z + \tilde{\tilde{\chi}}_1) < 100\% \). This analysis is not sensitive to scenarios with \( B(\tilde{\chi}_1^0 \rightarrow h + \tilde{\tilde{\chi}}_1) = 100\% \), where final states with lower lepton multiplicity may be more successful. The expected limit is comparable to those set using the combination of multiple analysis channels in Ref. [90], but the observed limit is not as strong.

IX. CONCLUSION

Results are reported from a search for new physics in the final state with four or more leptons (electrons, muons or taus), using 36.1 fb\(^{-1}\) of \( \sqrt{s} = 13 \) TeV proton-proton collision data collected by the ATLAS detector at the LHC in 2015 and 2016. Six signal regions are defined with up to two hadronically decaying taus, and target lepton-rich RPV and RPC SUSY signals with selections requiring large effective mass or missing transverse momentum, and the presence or absence of reconstructed Z boson candidates. Data yields in the signal regions are consistent with Standard Model expectations. The results are interpreted in simplified models of NLSP pair production with RPV LSP decays, where wino-like \( \tilde{\chi}_1^+/\chi_2^0/\tilde{\chi}_1^0/\tilde{\tilde{\chi}} \), and \( \check{g} \) masses up to 1.46 TeV, 1.06 GeV, and 2.25 TeV are excluded, respectively. The results are also interpreted in simplified Higgsino GGM models, where Higgsino-like \( \tilde{\chi}_1^+/\chi_2^0/\tilde{\chi}_1^0 \) masses up to 295 GeV are excluded in scenarios with a 100% branching ratio for \( \tilde{\chi}_1^0 \) decay to a Z boson and a gravitino.

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; BMWF 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 DSNRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE 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 KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, USA. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Sklodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, 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 (United Kingdom) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [91].

032009-15


[22] ATLAS Collaboration, Search for supersymmetry in events with four or more leptons in √s = 8 TeV pp collisions with the ATLAS detector, Phys. Rev. D 90, 052001 (2014).


[40] The LEP SUSY Working Group and the ALEPH, DELPHI, L3 and OPAL experiments, Notes No. LEPUSYWG/01-03 and No. 04-01.1 [http://lepsusy.web.cern.ch/lepsusy/Welcome.html].


[67] ATLAS Collaboration, Modeling of the $t\bar{t}H$ and $t\bar{t}V(V= W, Z)$ processes for $\sqrt{s} = 13$ TeV ATLAS analyses, Report No. ATL-PHYS-PUB-2016-005, 2016 [https://cds.cern.ch/record/2120826].


SEARCH FOR SUPERSYMMETRY IN EVENTS WITH FOUR ...

PHYS. REV. D 98, 032009 (2018)
SEARCH FOR SUPERSYMMETRY IN EVENTS WITH FOUR ...

PHYS. REV. D 98, 032009 (2018)
SEARCH FOR SUPERSYMMETRY IN EVENTS WITH FOUR …

PHYS. REV. D 98, 032009 (2018)

23b INFN Sezione di Bologna, Italy
24 Physikalisches Institut, University of Bonn, Bonn, Germany
25 Department of Physics, Boston University, Boston Massachusetts, USA
26 Department of Physics, Brandeis University, Waltham Massachusetts, USA
27a Transilvania University of Brasov, Brasov, Romania
27b Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania
27c Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
27d National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
27e University Politehnica Bucharest, Bucharest, Romania
27f West University in Timisoara, Timisoara, Romania
28a Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
28b Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
29 Physics Department, Brookhaven National Laboratory, Upton New York, USA
30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
32a Department of Physics, University of Cape Town, Cape Town, South Africa
32b Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
32c School of Physics, University of the Witwatersrand, Johannesburg, South Africa
33 Department of Physics, Carleton University, Ottawa Ontario, Canada
34a Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco
34b Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
34c Faculté des Sciences Semlalia, Université Cadi Ayyad, LPPTPM, Oujda, Morocco
34d Faculté des sciences, Université Mohammed V, Rabat, Morocco
35 CERN, Geneva, Switzerland
36 Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA
37 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
38 Nevis Laboratory, Columbia University, Irvington New York, USA
39 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
40 Dipartimento di Fisica, Università della Calabria, Rende, Italy
40b INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
41a AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
41b Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
41c Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
41d Physics Department, Southern Methodist University, Dallas Texas, USA
41e Physics Department, University of Texas at Dallas, Richardson Texas, USA
41f Department of Physics, Stockholm University, Stockholm, Sweden
41g The Oskar Klein Centre, Stockholm, Sweden
41h DESY, Hamburg and Zeuthen, Germany
42 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern-und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham North Carolina, USA
45 SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
45 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
45b INFN e Laboratori Nazionali di Frascati, Frascati, Italy
45c II Physikalisches Institut, Justus-Liebig-Universität Göttingen, Germany
45d Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
45e Dipartimento di Fisica, Università di Genova, Genova, Italy
45f INFN Sezione di Genova, Italy
50 SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
51 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
52 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
53 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
56a Dipartimento di Fisica, Università di Genova, Genova, Italy
56b INFN Sezione di Genova, Italy
57 II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
58 SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
59 LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
60 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge Massachusetts, USA
<table>
<thead>
<tr>
<th>Department</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China</td>
<td>Department of Physics, Shandong University, Shandong, China</td>
</tr>
<tr>
<td>School of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, China</td>
<td>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany</td>
</tr>
<tr>
<td>Department of Physics, Shandong University, Shandong, China</td>
<td>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany</td>
</tr>
<tr>
<td>Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan</td>
<td>Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China</td>
</tr>
<tr>
<td>Department of Physics, The University of Hong Kong, Hong Kong, China</td>
<td>Department of Physics for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China</td>
</tr>
<tr>
<td>Department of Physics, National Tsing Hua University, Hsinchu, Taiwan</td>
<td>Department of Physics, Indiana University, Bloomington Indiana, USA</td>
</tr>
<tr>
<td>Department of Physics, Indiana University, Bloomington Indiana, USA</td>
<td>INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Lecce, Lecce, Italy</td>
<td>ICTP, Trieste, Italy</td>
</tr>
<tr>
<td>Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy</td>
<td>INFN Sezione di Milano, Milano, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Milano, Milano, Italy</td>
<td>INFN Sezione di Napoli, Napoli, Italy</td>
</tr>
<tr>
<td>Dipartimento di Fisica, Università di Milano, Milano, Italy</td>
<td>INFN Sezione di Pavia, Pavia, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Napoli, Napoli, Italy</td>
<td>INFN Sezione di Pavia, Pavia, Italy</td>
</tr>
<tr>
<td>Dipartimento di Fisica, Università di Napoli, Napoli, Italy</td>
<td>Dipartimento di Fisica, Università di Pavia, Pavia, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Pavia, Pavia, Italy</td>
<td>INFN Sezione di Pisa, Pisa, Italy</td>
</tr>
<tr>
<td>Dipartimento di Fisica, Università di Pisa, Pisa, Italy</td>
<td>INFN Sezione di Roma, Roma, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Roma, Roma, Italy</td>
<td>INFN Sezione di Roma Tor Vergata, Roma, Italy</td>
</tr>
<tr>
<td>Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy</td>
<td>INFN Sezione di Roma Tor Vergata, Roma, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Roma Tor Vergata, Roma, Italy</td>
<td>INFN Sezione di Roma Tre, Roma, Italy</td>
</tr>
<tr>
<td>Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy</td>
<td>INFN-TIFPA, Trento, Italy</td>
</tr>
<tr>
<td>INFN-TIFPA, Trento, Italy</td>
<td>University of Trento, Trento, Italy</td>
</tr>
<tr>
<td>Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria</td>
<td>University of Iowa, Iowa City Iowa, USA</td>
</tr>
<tr>
<td>University of Iowa, Iowa City Iowa, USA</td>
<td>Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA</td>
<td>KEK, High Energy Accelerator Research Organization, Tsukuba, Japan</td>
</tr>
<tr>
<td>Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia</td>
<td>Graduate School of Science, Kobe University, Kobe, Japan</td>
</tr>
<tr>
<td>KEK, High Energy Accelerator Research Organization, Tsukuba, Japan</td>
<td>Faculty of Science, Kyoto University, Kyoto, Japan</td>
</tr>
<tr>
<td>Graduate School of Science, Kobe University, Kobe, Japan</td>
<td>Kyoto University of Education, Kyoto, Japan</td>
</tr>
<tr>
<td>Faculty of Science, Kyoto University, Kyoto, Japan</td>
<td>Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan</td>
</tr>
<tr>
<td>Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan</td>
<td>Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina</td>
</tr>
<tr>
<td>Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina</td>
<td>Physics Department, Lancaster University, Lancaster, United Kingdom</td>
</tr>
<tr>
<td>Physics Department, Lancaster University, Lancaster, United Kingdom</td>
<td>Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom</td>
</tr>
<tr>
<td>Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom</td>
<td>Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia</td>
</tr>
<tr>
<td>Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia</td>
<td>School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom</td>
</tr>
<tr>
<td>School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom</td>
<td>Department of Physics, Royal Holloway University of London, Surrey, United Kingdom</td>
</tr>
<tr>
<td>Department of Physics, Royal Holloway University of London, Surrey, United Kingdom</td>
<td>Department of Physics and Astronomy, University College London, London, United Kingdom</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University College London, London, United Kingdom</td>
<td>Louisiana Tech University, Ruston Los Angeles, USA</td>
</tr>
<tr>
<td>Louisiana Tech University, Ruston Los Angeles, USA</td>
<td>Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France</td>
</tr>
<tr>
<td>Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France</td>
<td>Fysiska institutionen, Lunds universitet, Lund, Sweden</td>
</tr>
<tr>
<td>Fysiska institutionen, Lunds universitet, Lund, Sweden</td>
<td>Departamento de Física Teorica C-15 and CIAFF, Universidad Autonoma de Madrid, Madrid, Spain</td>
</tr>
<tr>
<td>Departamento de Física Teorica C-15 and CIAFF, Universidad Autonoma de Madrid, Madrid, Spain</td>
<td>032009-28</td>
</tr>
</tbody>
</table>
SEARCH FOR SUPERSYMMETRY IN EVENTS WITH FOUR ...

PHYS. REV. D 98, 032009 (2018)

97 Institut für Physik, Universität Mainz, Mainz, Germany
98 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
99 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
100 Department of Physics, University of Massachusetts, Amherst Massachusetts, USA
101 Department of Physics, McGill University, Montreal Québec, Canada
102 School of Physics, University of Melbourne, Victoria, Australia
103 Department of Physics, The University of Michigan, Ann Arbor Michigan, USA
104 Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, USA
105 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
106 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
107 Group of Particle Physics, University of Montreal, Montreal Québec, Canada
108 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
109 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
110 National Research Nuclear University MEPhI, Moscow, Russia
111 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
112 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
113 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
114 Nagasaki Institute of Applied Science, Nagasaki, Japan
115 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
116 Department of Physics and Astronomy, University of New Mexico, Albuquerque New Mexico, USA
117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
118 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
119 Department of Physics, Northern Illinois University, DeKalb Illinois, USA
120 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
121 Novosibirsk State University Novosibirsk, Russia
122 Department of Physics, New York University, New York New York, USA
123 Ohio State University, Columbus Ohio, USA
124 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA
125 Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA
126 Palacký University, RCPTM, Olomouc, Czech Republic
127 Center for High Energy Physics, University of Oregon, Eugene Oklahoma, USA
128 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
129 Graduate School of Science, Osaka University, Osaka, Japan
130 Department of Physics, University of Oslo, Oslo, Norway
131 Department of Physics, Oxford University, Oxford, United Kingdom
132 Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA
133 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
134 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA
135 Laboratório de Instrumentação e Física Experimental de Partículas-LIP, Lisboa, Portugal
136 Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Portugal
137 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
138 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
139 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
140 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
141 Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Juiz de Fora, Brazil
142 Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
143 Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
144 Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
145 Electric Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
146 Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
147 Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
032009-29
Institut de Recherches sur les Lois Fondamentales de l’Univers, DSM/IRFU, CEA Saclay, Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz California, USA
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
Department of Physics, University of Washington, Seattle Washington, USA
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Department Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby British Columbia, Canada
SLAC National Accelerator Laboratory, Stanford California, USA
Departments of Physics and Astronomy, Stony Brook University, Stony Brook New York, USA
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Tomsk State University, Tomsk, Russia
Department of Physics, University of Toronto, Toronto Ontario, Canada
TRIUMF, Vancouver British Columbia, 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
Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
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, Spain
Department of Physics, University of British Columbia, Vancouver British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The 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
Yerevan Physics Institute, Yerevan, Armenia

† Deceased.

a Also at Borough of Manhattan Community College, City University of New York, New York City, USA.
b Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
c Also at CERN, Geneva, Switzerland.
d Also at CPPM, Aix-Marseille Université and CNRS-IN2P3, Marseille, France.
e Also at Departament de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain.
f Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.
g Also at Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland.
h Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
i Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
SEARCH FOR SUPERSYMMETRY IN EVENTS WITH FOUR …

PHYS. REV. D 98, 032009 (2018)

1Also at Department of Physics, California State University, Fresno California, USA.
2Also at Department of Physics, California State University, Sacramento California, USA.
3Also at Department of Physics, King’s College London, London, United Kingdom.
4Also at Department of Physics, Nanjing University, Jiangsu, China.
5Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
6Also at Department of Physics, Stanford University, Stanford California, USA.
7Also at Department of Physics, The University of Michigan, Ann Arbor Michigan, USA.
8Also at Department of Physics, The University of Texas at Austin, Austin, Texas, USA.
9Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
10Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
11Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
12Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.
13Also at Georgian Technical University (GTU), Tbilisi, Georgia.
14Also at Graduate School of Science, Osaka University, Osaka, Japan.
15Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania.
16Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.
17Also at Institut Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
18Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.
19Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
20Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
21Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
22Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
23Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
24Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
25Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
26Also at Louisiana Tech University, Ruston Louisiana, USA.
27Also at Manhattan College, New York New York, USA.
28Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
29Also at National Research Nuclear University MEPhI, Moscow, Russia.
30Also at Novosibirsk State University, Novosibirsk, Russia.
31Also at Ochanomizu University, Tokyo, Japan.
32Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
33Also at The City College of New York, New York New York, USA.
34Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
35Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
36Also at TRIUMF, Vancouver British Columbia, Canada.
37Also at Universita di Napoli Parthenope, Napoli, Italy.
38Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.