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

The ATLAS Collaboration

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 TeV, 1.06 TeV, and 2.25 TeV are placed on wino, slepton and gluino masses, respectively.

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1 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, $\tilde{\ell}$, 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 charginos $\tilde{\chi}_i^\pm$ ($i = 1, 2$) and neutralinos $\tilde{\chi}_j^0$ ($j = 1, 2, 3, 4$), 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 dataset 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.

2 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 Section 5.

In all scenarios, the light CP-even Higgs boson, h, of the MSSM Higgs sector is assumed to be practically identical to the SM Higgs boson [28], with the same mass and couplings as measured at the LHC [29–31]. In addition, the decoupling limit is used, which is defined by $m_A \gg m_Z$, 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.

2.1 RPV SUSY scenarios

In generic SUSY models with minimal particle content, the superpotential includes terms that violate conservation of L and B [32, 33]:

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2,$$

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 λ_{ijk}, λ'_{ijk} and λ''_{ijk} parameters are three sets of new Yukawa couplings, while the κ_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:

$$W_{LL\bar{E}} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k.$$

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

$$\tilde{\chi}^0_1 \to \ell^\pm_k\ell^\mp_{i/j}\nu_{j/i}, \tag{1}$$

through a virtual slepton or sneutrino, with the allowed lepton flavors depending on the indices of the associated λ_{ijk} couplings [34]. 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[1] λ_{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 λ_{ijk}. For example, for $\lambda_{121} \neq 0$ the branching ratios for $\tilde{\chi}^0_1 \to e\mu\nu$, $\tilde{\chi}^0_1 \to ee\nu$ and $\tilde{\chi}^0_1 \to \mu\mu\nu$ 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 λ_{ijk} RPV couplings are considered:

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

- $LL\bar{E}i33$ ($i \in 1, 2$) scenarios, where $\lambda_{i33} \neq 0$ and only decays to taus and either electrons or muons are included.

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[1] reduced from 27 by the antisymmetry requirement $\lambda_{ijk} = -\lambda_{jik}$

In both cases, all other RPV couplings are assumed to be zero. The branching ratios for the $\tilde{\chi}_1^0$ decay in the $LL\bar{E}12k$ and $LL\bar{E}i33$ are shown in Table 1. The sensitivity to λ couplings not considered here (e.g. λ_{123}) is expected to be between that achieved in the $LL\bar{E}12k$ and $LL\bar{E}i33$ scenarios.

Scenario	$\tilde{\chi}_1^0$ branching ratios		
$LL\bar{E}12k$	$e^+e^-\nu$ (1/4)	$e^{\pm}\mu^{\mp}\nu$ (1/2)	$\mu^+\mu^-\nu$ (1/4)
$LL\bar{E}i33$	$e^{\pm}\tau^{\mp}\nu$ (1/4)	$\tau^+\tau^-\nu$ (1/2)	$\mu^{\pm}\tau^{\mp}\nu$ (1/4)

Table 1: Decay modes and branching ratios for the $\tilde{\chi}_1^0$ LSP in the RPV models, where ν denotes neutrinos or antineutrinos of any lepton generation.

For the pure-bino $\tilde{\chi}_1^0$ considered here, the $\tilde{\chi}_1^0\tilde{\chi}_1^0$ 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 $LL\bar{E}12k$ and $LL\bar{E}i33$ 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 $LL\bar{E}12k$ and $LL\bar{E}i33$ scenarios:

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

- **$\tilde{\ell}_{\mathrm{L}}/\tilde{\nu}$ NLSP**: mass-degenerate left-handed sleptons and sneutrinos of all three generations are produced in association ($\tilde{\ell}_{\mathrm{L}}\tilde{\ell}_{\mathrm{L}}$, $\tilde{\nu}\tilde{\nu}$, $\tilde{\ell}_{\mathrm{L}}\tilde{\nu}$). The $\tilde{\ell}_{\mathrm{L}}$ ($\tilde{\nu}$) decays to the LSP while emitting a charged lepton (neutrino) as seen in Figure 1(c).

- **$\tilde{g}$ 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 Figure 1(d).

For the RPV models, the LSP mass is restricted to the range $10\,\mathrm{GeV} \leq m(\mathrm{LSP}) \leq m(\mathrm{NLSP}) - 10\,\mathrm{GeV}$ to ensure that both the RPC cascade decay and the RPV LSP decay are prompt. Non-prompt decays of the $\tilde{\chi}_1^0$ in similar models were previously studied in Ref. [35].

2.2 RPC SUSY scenarios

RPC scenarios with light $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ higgsino states are well motivated by naturalness [36, 37]. However, they can be experimentally challenging, as members of the higgsino triplet are close in mass and decays of the $\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}$ to a $\tilde{\chi}_1^0$ LSP result in low-momentum decay products that are difficult to reconstruct efficiently. Searches for higgsino-like $\tilde{\chi}_1^{\pm}$ in approximately mass-degenerate scenarios were performed by the LEP experiments, where chargino masses below 103.5 GeV were excluded [38] (reduced to 92 GeV for chargino–LSP mass differences between 0.1 GeV and 3 GeV). Recently, the ATLAS experiment has excluded higgsino-like $\tilde{\chi}_2^0$ up to masses ~145 GeV and down to $\tilde{\chi}_2^0$–LSP mass differences of 2.5 GeV [39] for scenarios where the $\tilde{\chi}_1^{\pm}$ mass is assumed to be half-way 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, $m \sim 100\,\mathrm{GeV}$ [40, 41]. General Gauge Mediated (GGM) SUSY models [42] predict the $\tilde{G}$ is nearly massless and offer an
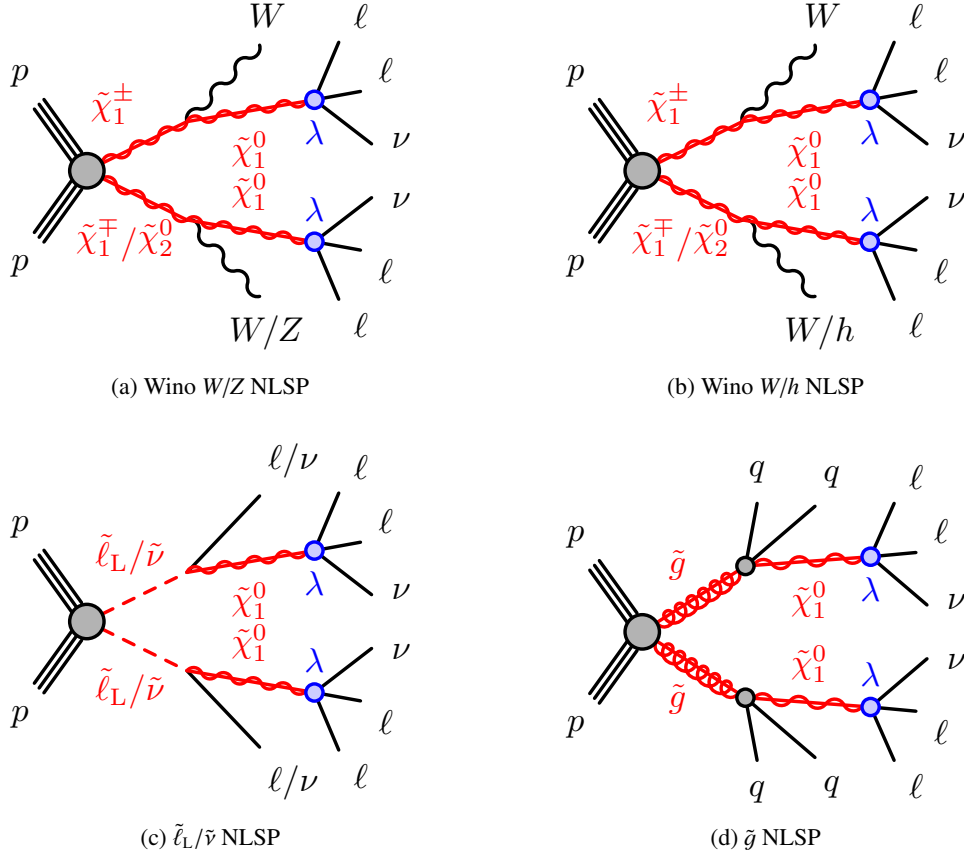
Figure 1: Diagrams of the benchmark SUSY models of RPC NLSP pair-production of (a)-(b) a wino, (c) slepton/sneutrino and (d) gluino, followed by the RPV decay of the $\tilde{\chi}_1^0$ LSP. The LSP is assumed to decay as $\tilde{\chi}_1^0 \to \ell\ell\nu$ with 100% branching ratio.

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 $\tilde{\chi}_1^\pm \tilde{\chi}_1^0 \tilde{\chi}_2^0$ and a massless $\tilde{G}$. To ensure the SUSY decays are prompt, the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses are set to $1\,\text{GeV}$ 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, $\tilde{\chi}_1^0 \to Z/h + \tilde{G}$, where the leptonic decays of the Z/h are targeted in this analysis. Four production processes are included in this higgsino GGM model: $\tilde{\chi}_1^+ \tilde{\chi}_1^-$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_1^0 \tilde{\chi}_2^0$, as shown in Figure 2, and the total SUSY cross section is dominated by $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production. The $\tilde{\chi}_1^0 \to Z\tilde{G}$ branching ratio is a free parameter of the GGM higgsino scenarios, and so offers an opportunity to study 4ℓ signatures with one or more Z candidates.
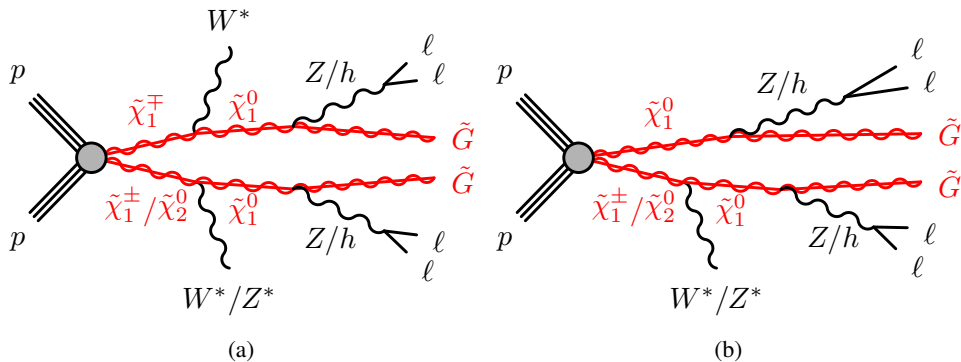
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Figure 2: Diagrams of the processes in the SUSY RPC GGM higgsino models. The W^*/Z^* produced in the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ decays are off-shell ($m \sim 1\,\text{GeV}$) and their decay products are usually not reconstructed.

3 The ATLAS detector

The ATLAS detector [43] is a multipurpose particle physics detector with forward-backward symmetric cylindrical geometry.[2] 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 [44], was added for the $\sqrt{s} = 13\,\text{TeV}$ running period of the LHC. The ID is surrounded by a thin superconducting solenoid providing a $2\,\text{T}$ 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 endcap ($1.5 < |\eta| < 3.2$) 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 [45] selects events to be recorded for offline analysis.

4 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 2. 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+NLL) [46–53]. The nominal signal cross section and its uncertainty were taken from an envelope of cross section predictions

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[2] ATLAS 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 upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Rapidity is defined as $y = 0.5\ln\left[(E + p_z)/(E - p_z)\right]$ where E denotes the energy and p_z is the component of the momentum along the beam direction.

using different parton distribution function (PDF) sets and factorization and renormalization scales, as described in Ref. [54].

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, $t\bar{t}WW$, and $t\bar{t}t\bar{t}$ processes.

For all MC simulation samples, the propagation of particles through the ATLAS detector was modeled with Geant 4 [55] using the full ATLAS detector simulation [56], or a fast simulation using a parameterization of the response of the electromagnetic and hadronic calorimeters [56] and Geant 4 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 Pythia 8 [57] 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.

Process	Generator(s)	Simulation	Cross-section calculation	Tune	PDF set
WZ, WW	Sherpa 2.2.1 [58]	Full	NLO [59]	Sherpa default	NNPDF30NNLO [60]
ZZ	Sherpa 2.2.2 [58]	Full	NLO [59]	Sherpa default	NNPDF30NNLO [60]
VVV	Sherpa 2.2.1	Full	NLO [59]	Sherpa default	NNPDF30NNLO
ggH, VBF, $ggZH$	Powheg v2 [61] + Pythia 8.186 [57]	Full	NNLO+NNLL [62]	AZNLO [63]	CT10 [64]
ZH, WH	Pythia 8.186	Full	NNLO+NNLL	A14 [65]	NNPDF23LO
$t\bar{t}H$	MadGraph5_aMC@NLO 2.3.2 [66] + Pythia 8.186	Full	NLO [67]	A14	NNPDF23LO [68]
$t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}WW$	MadGraph5_aMC@NLO 2.2.2 [69] + Pythia 8.186	Full	NLO [67]	A14	NNPDF23LO
$t\bar{t}Z^{\dagger}$	Sherpa 2.2.1	Fast	NLO [67]	Sherpa default	NNPDF30NNLO
tWZ	aMC@NLO 2.3.2 + Pythia 8.186	Full	NLO [67]	A14	NNPDF23LO
$t\bar{t}(W)$, $t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO 2.2.2 + Pythia 8.186	Full	NLO [69]	A14	NNPDF23LO
$t\bar{t}$	Powheg v2 + Pythia 6.428 [70]	Full	NNLO+NNLL [71]	Perugia2012 [72]	CT10
Z+jets, W+jets	MadGraph5_aMC@NLO 2.2.2 + Pythia 8.186	Full	NNLO [73]	A14	NNPDF23LO
SUSY signal	MadGraph5_aMC@NLO 2.2.2 + Pythia 8.186	Fast	NLO+NLL [46–53]	A14	NNPDF23LO

Table 2: 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 † is used for a cross-check of yields and for studies of systematic uncertainties.

5 Event selection

After the application of beam, detector and data-quality requirements, the total integrated luminosity considered in this analysis corresponds to $36.1 \pm 1.2 \, \text{fb}^{-1}$. 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 $p_{\text{T}} > 400$ MeV associated with it. The primary vertex of an event is identified as the vertex with the highest Σp_{T}^2 of associated tracks.

Preselected electrons are required to have $|\eta| < 2.47$ and $p_{\text{T}} > 7$ GeV, where the p_{T} and η 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 [74], 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 [75], and are required to have $|\eta| < 2.7$ and $p_{\text{T}} > 5$ 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. [75]. 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 [76] 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. [77]. Jets must have $|\eta| < 2.8$ and $p_{\text{T}} > 20$ GeV. To reduce pileup effects, jets with $p_{\text{T}} < 60$ GeV and $|\eta| < 2.4$ must satisfy additional criteria using the jet vertex tagging algorithm described in Ref. [78]. Events containing jets failing to satisfy the quality criteria described in Ref. [79] are rejected to suppress events with large calorimeter noise or non-collision 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 [80] using jets as described above with $|\eta| < 2.47$ and $p_{\text{T}} > 10$ 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 $\tau_{\text{had-vis}}$ predominantly decay to either one or three charged hadrons together with a neutrino and often additional neutral hadrons. The preselected $\tau_{\text{had-vis}}$ are required to have $p_{\text{T}} > 20$ 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 $\tau_{\text{had-vis}}$ energy scale using an η- 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 [81], 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, $E_{\text{T}}^{\text{miss}}$, 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 [82]. Taus are included as jets in the $E_{\text{T}}^{\text{miss}}$. 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.

Finally, to suppress low-mass particle decays, if surviving electrons and muons form an opposite-sign (OS) pair with $m_{OS} < 4\,\text{GeV}$, or form a same-flavor, opposite-sign (SFOS) pair in the $\Upsilon(1S) - \Upsilon(3S)$ mass range $8.4 < m_{SFOS} < 10.4\,\text{GeV}$, both leptons are discarded.

"Signal" light charged leptons, abbreviated as *signal leptons*, are preselected leptons surviving overlap removal and satisfying additional identification criteria. Signal electrons and muons must pass p_T-dependent isolation requirements, to reduce the contributions from semileptonic decays of hadrons and jets misidentified as prompt leptons. The isolation requirements use calorimeter- and track-based information to obtain 95% efficiency for charged leptons with $p_T = 25\,\text{GeV}$ in $Z \rightarrow e^+e^-, \mu^+\mu^-$ events, rising to 99% efficiency at $p_T = 60\,\text{GeV}$. To improve the identification of closely spaced charged leptons (e.g. from boosted decays), contributions to the isolation from nearby electrons and muons passing all other signal lepton requirements are removed. To further suppress electrons and muons originating from secondary vertices, $|z_0 \sin\theta|$ is required to be less than $0.5\,\text{mm}$, and the d_0 normalized to its uncertainty is required to be small, with $|d_0|/\sigma_{d_0} < 5(3)$ for electrons (muons). Signal electrons must also satisfy "medium" likelihood-based identification criteria [74], while signal taus must satisfy the "medium" BDT-based identification criteria against jets [81].

Events are selected using single-lepton or dilepton triggers, where the trigger efficiencies are in the plateau region above the offline p_T thresholds indicated in Table 3. Dilepton triggers are used only when the leptons in the event fail p_T-threshold requirements for the single-lepton triggers. The triggering efficiency for events with four, three and two electrons/muons in signal SUSY scenarios is typically >99%, 96% and 90%, respectively.

6 Signal regions

Events with four or more signal leptons (e, μ, $\tau_{\text{had-vis}}$) 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 $4L0T$, 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 $61.2 < m(LL) < 101.2\,\text{GeV}$. Widening the low-mass side of the $m(LL)$ window used for the selection of a second Z candidate increases signal acceptance. The Z

Trigger	Offline p_T threshold [GeV]	
	2015	2016
Single isolated e	25	27
Single non-isolated e	61	61
Single isolated μ	21	25 or 27
Single non-isolated μ	41	41 or 51
Double e	13, 13	18, 18
Double μ (symmetric)	–	11, 11 or 15, 15
(asymmetric)	19, 9	21, 9 or 23, 9
Combined $e\mu$	8(e), 25(μ)	8(e), 25(μ)

Table 3: The triggers used in the analysis of 2015 and 2016 data. The offline p_T thresholds are required only for reconstructed charged leptons which match to the trigger signatures. Trigger thresholds for data recorded in 2016 are higher than in 2015 due to the increase in beam luminosity, and "or" denotes a move to a higher-threshold trigger during data-taking.

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 $Z \to \ell\ell$ 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^{miss} and the effective mass of the event, m_{eff}, are both used. The m_{eff} is defined as the scalar sum of the E_T^{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_{eff} rather than the E_T^{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^{miss} from neutrinos in the final state. The chosen m_{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 4L0T and a Z veto: a general, model-independent signal region (SR0A) with $m_{eff} > 600$ GeV, and a tighter signal region (SR0B) with $m_{eff} > 1100$ GeV, optimized for the RPV $LL\bar{E}12k$ scenarios. Two further SRs are defined with 4L0T, a first and second Z requirement as described above, and different selections on E_T^{miss}: a loose signal region (SR0C) with $E_T^{miss} > 50$ GeV, and a tighter signal region (SR0D) with $E_T^{miss} > 100$ GeV, optimized for the low-mass and high-mass higgsino GGM scenarios, respectively. Finally, two SRs are optimized for the tau-rich RPV $LL\bar{E}i33$ scenarios: one with 3L1T where the tau has $p_T > 30$ GeV, a Z veto and $m_{eff} > 700$ GeV (SR1), and a second with 2L2T where the taus have $p_T > 30$ GeV, a Z veto and $m_{eff} > 650$ GeV (SR2). The signal region definitions are summarized in Table 4.

7 Background determination

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

Region	$N(e,\mu)$	$N(\tau_{\text{had-vis}})$	$p_{\text{T}}(\tau_{\text{had-vis}})$	Z boson	Selection	Target
SR0A	≥ 4	$= 0$	$> 20\,\text{GeV}$	veto	$m_{\text{eff}} > 600\,\text{GeV}$	General
SR0B	≥ 4	$= 0$	$> 20\,\text{GeV}$	veto	$m_{\text{eff}} > 1100\,\text{GeV}$	RPV $LL\bar{E}12k$
SR0C	≥ 4	$= 0$	$> 20\,\text{GeV}$	require 1st & 2nd	$E_{\text{T}}^{\text{miss}} > 50\,\text{GeV}$	higgsino GGM
SR0D	≥ 4	$= 0$	$> 20\,\text{GeV}$	require 1st & 2nd	$E_{\text{T}}^{\text{miss}} > 100\,\text{GeV}$	higgsino GGM
SR1	$= 3$	≥ 1	$> 30\,\text{GeV}$	veto	$m_{\text{eff}} > 700\,\text{GeV}$	RPV $LL\bar{E}i33$
SR2	$= 2$	≥ 2	$> 30\,\text{GeV}$	veto	$m_{\text{eff}} > 650\,\text{GeV}$	RPV $LL\bar{E}i33$

Table 4: Signal region definitions. The $p_{\text{T}}(\tau_{\text{had-vis}})$ column denotes the p_{T} threshold used for the tau selection or veto. SR0B and SR0D are subsets of SR0A and SR0C, respectively, while SR1 and SR2 are completely disjoint.

to be a prompt and genuinely isolated lepton, while a fake charged lepton is defined to be a non-prompt or non-isolated 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, $t\bar{t}Z$, $t\bar{t}WW$, tWZ, VVZ (ZZZ, WZZ, WWZ), Higgs (ggH, WH, ZH, $t\bar{t}H$), $t\bar{t}t\bar{t}$, $t\bar{t}tW$.

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 Section 7.1).

In the signal regions, the irreducible background is dominated by $t\bar{t}Z$, VVZ ($V = W, Z$), 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 (Section 7.2). 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 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 5. 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.

Reducible Estimation for	Control Region	$N(e,\mu)$ signal	$N(e,\mu)$ loose	$N(\tau_{\text{had-vis}})$ signal	$N(\tau_{\text{had-vis}})$ loose
4L0T	CR1_LLLl	= 3	≥ 1	= 0	≥ 0
	CR2_LLll	= 2	≥ 2	= 0	≥ 0
3L1T	CR1_LLLt	= 3	= 0	= 0	≥ 1
	CR1_LLTl	= 2	= 1	≥ 1	≥ 0
	CR2_LLlt	= 2	= 1	= 0	≥ 1
2L2T	CR1_LLTt	= 2	= 0	= 1	≥ 1
	CR2_LLtt	= 2	= 0	= 0	≥ 2

Table 5: Control region definitions where "L" and "T" denote signal light leptons and taus, while "l" and "t" denote loose light leptons and taus. Loose leptons are preselected leptons surviving overlap removal that do not pass signal lepton criteria. Additional selection for p_T ($\tau_{\text{had-vis}}$), Z veto/requirement, E_T^{miss}, m_{eff} are applied to match a given signal or validation region.

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, η 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:

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

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 GeV 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 1-prong (3-prong) tau p_T increases from 20 GeV to 60 GeV. The contribution to the signal regions from fake light leptons originating from light-flavour jets is very small (less than 1.8% of all e,μ) 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 1.2 to 1.6 as the electron p_T increases from 7 to 25 GeV.

The number $N_{\mathrm{red}}^{\mathrm{SR}}$ 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, $N_{\mathrm{data}}^{\mathrm{CR1}}$ and $N_{\mathrm{data}}^{\mathrm{CR2}}$, according to:

$$N_{\mathrm{red}}^{\mathrm{SR}} = [N_{\mathrm{data}}^{\mathrm{CR1}} - N_{\mathrm{irr}}^{\mathrm{CR1}}] \times F_{w,1} - [N_{\mathrm{data}}^{\mathrm{CR2}} - N_{\mathrm{irr}}^{\mathrm{CR2}}] \times F_{w,1} \times F_{w,2}, \tag{2}$$

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, $N_{\mathrm{irr}}^{\mathrm{CR1,CR2}}$, 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.

7.1 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, μ, τ and jets, and also E_T^{miss}), 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 Figure 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. [83]). The uncertainties associated with pileup and luminosity are included in the total uncertainty in Figure 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
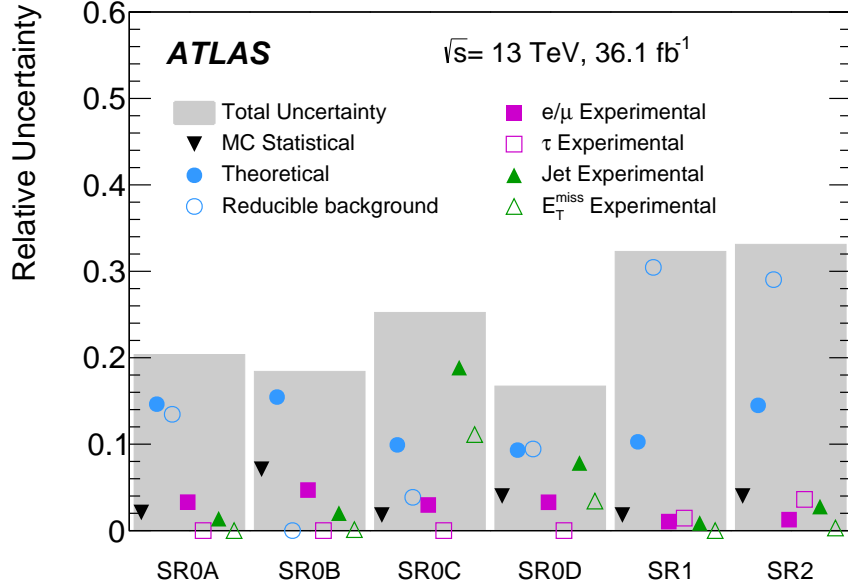
Figure 3: Breakdown of the dominant systematic uncertainties in the background estimates for the signal regions. The individual uncertainties can be correlated, and do not necessarily sum in quadrature to the total background uncertainty. The text provides category details.

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 [59], and 20% for the triboson samples [59], where the order of the cross section calculations is shown in Table 2. For the Higgs boson samples, an uncertainty of 20% is used for WH, ZH and VBF [62], while uncertainties of 100% are assigned to $t\bar{t}H$ and ggH [84]. 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 cancelation 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 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 4L0T validation region (VR) and SR. 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.

7.2 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 6. For signal regions that veto Z boson candidates, three VRs are defined by reversing the m_{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 Section 7.1. The SM background in the VRs is dominated by ZZ, $t\bar{t}$ and Z+jets.

Validation Region	$N(e, \mu)$	$N(\tau_{\text{had-vis}})$	$p_{\text{T}}(\tau_{\text{had-vis}})$	Z boson	Selection	Target
VR0	≥ 4	$= 0$	$> 20\,\text{GeV}$	veto	$m_{\text{eff}} < 600\,\text{GeV}$	$t\bar{t}$, Z+jets, ZZ
VR0Z	≥ 4	$= 0$	$> 20\,\text{GeV}$	require 1st & veto 2nd	–	ZZ
VR1	$= 3$	≥ 1	$> 30\,\text{GeV}$	veto	$m_{\text{eff}} < 700\,\text{GeV}$	$t\bar{t}$, Z+jets
VR2	$= 2$	≥ 2	$> 30\,\text{GeV}$	veto	$m_{\text{eff}} < 650\,\text{GeV}$	$t\bar{t}$, Z+jets

Table 6: Validation region definitions. The $p_{\text{T}}(\tau_{\text{had-vis}})$ column denotes the p_{T} threshold used for the tau selection or veto.

Observed and expected event yields in the VRs are shown in Table 7, where good agreement is seen in general within statistical and systematic uncertainties. No significant excesses above the SM expectations are observed in any VR.

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

Table 7: 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.

The lepton p_{T}, m_{SFOS} and $E_{\text{T}}^{\text{miss}}$ distributions in the VRs are shown in Figure 4 and Figure 5. Figure 4(a) shows that VR0 has a slight downward trend in the ratio of the 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_{eff}, the potential impact of a small mismodeling of one electron in the event was found to be insignificant.

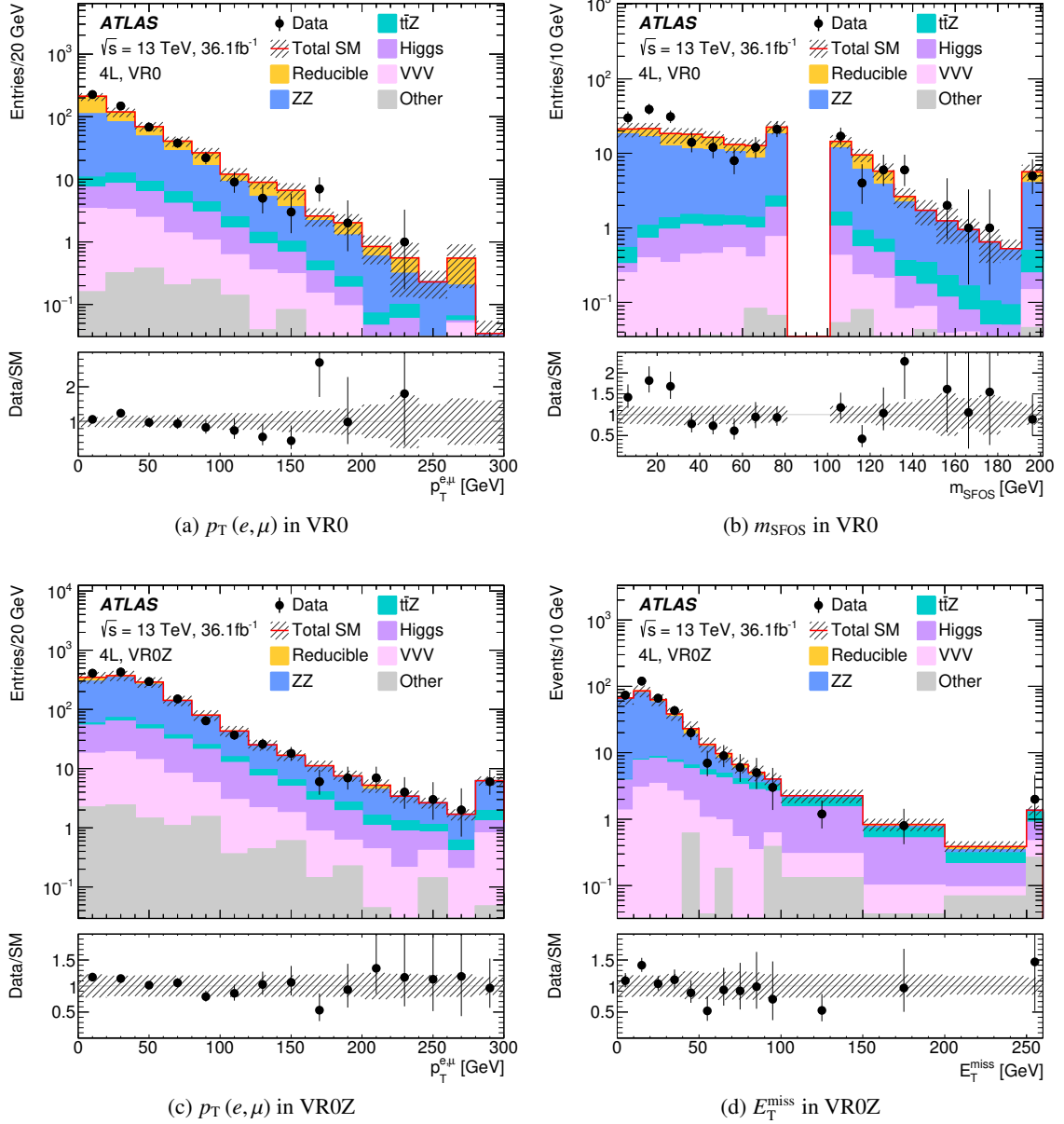The m_{eff} distributions in VR0, VR1 and VR2 can be seen in the lower m_{eff} bins in Figure 6.

(a) $p_T (e, \mu)$ in VR0

(b) m_{SFOS} in VR0

(c) $p_T (e, \mu)$ in VR0Z

(d) E_T^{miss} in VR0Z

Figure 4: The distributions for data and the estimated SM backgrounds in VR0 and VR0Z for (a) & (c) the electron and muon p_T, (b) the SFOS invariant mass, and (d) the E_T^{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.
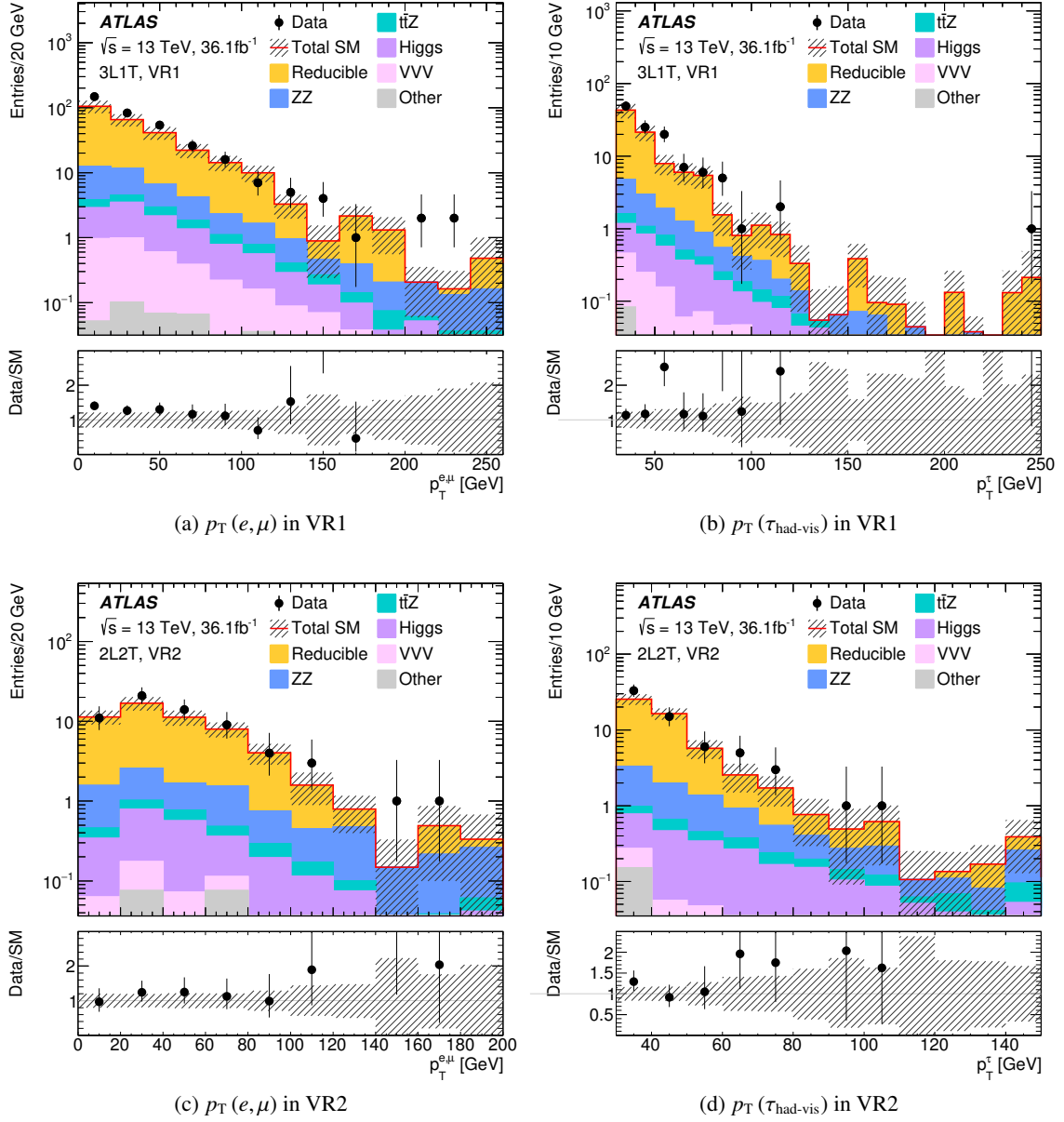
Figure 5: The distributions for data and the estimated SM backgrounds in VR1 and VR2 for (a) & (c) the light lepton p_T, and (b) & (d) the tau p_T. "Other" is the sum of the tWZ, $t\bar{t}WW$, and $t\bar{t}t\bar{t}$ backgrounds. The last bin includes the overflow. Both the statistical and systematic uncertainties in the SM background are included in the shaded band.

8 Results

The expected and observed yields in each signal region are reported in Table 8, 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 2.3σ. The m_{eff} and $E_{\text{T}}^{\text{miss}}$ distributions for all events passing signal region requirements, except the m_{eff} or $E_{\text{T}}^{\text{miss}}$ requirement itself, are shown in Figure 6.

Sample	SR0A	SR0B	SR0C	SR0D	SR1	SR2
Observed	13	2	47	10	8	2
SM Total	10.2 ± 2.1	1.31 ± 0.24	37 ± 9	4.1 ± 0.7	4.9 ± 1.6	2.3 ± 0.8
ZZ	2.7 ± 0.7	0.33 ± 0.10	28 ± 9	0.84 ± 0.34	0.35 ± 0.09	0.33 ± 0.08
$t\bar{t}Z$	2.5 ± 0.6	0.47 ± 0.13	3.2 ± 0.4	1.62 ± 0.23	0.54 ± 0.11	0.31 ± 0.08
Higgs	1.2 ± 1.2	0.13 ± 0.13	0.9 ± 0.8	0.28 ± 0.25	0.5 ± 0.5	0.32 ± 0.32
VVV	0.79 ± 0.17	0.22 ± 0.05	2.7 ± 0.6	0.64 ± 0.14	0.18 ± 0.04	0.20 ± 0.06
Reducible	2.4 ± 1.4	$0.000^{+0.005}_{-0.000}$	$0.9^{+1.4}_{-0.9}$	$0.23^{+0.38}_{-0.23}$	3.1 ± 1.5	1.1 ± 0.7
Other	0.53 ± 0.06	0.165 ± 0.018	0.85 ± 0.19	0.45 ± 0.10	0.181 ± 0.022	0.055 ± 0.012
$\langle\epsilon\sigma\rangle^{95}_{obs}$ fb	0.32	0.14	0.87	0.36	0.28	0.13
S^{95}_{obs}	12	4.9	31	13	10	4.6
S^{95}_{exp}	$9.3^{+3.6}_{-2.3}$	$3.9^{+1.6}_{-0.8}$	23^{+8}_{-5}	$6.1^{+2.1}_{-1.3}$	$6.5^{+3.5}_{-1.3}$	$4.7^{+2.0}_{-1.3}$
CL_b	0.76	0.74	0.83	0.99	0.86	0.47
p_0	0.23	0.25	0.15	0.011	0.13	0.61
Z	0.75	0.69	1.0	2.3	1.2	0

Table 8: 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 $t\bar{t}t\bar{t}$ 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% CL upper limit on the visible cross section times efficiency ($\langle\epsilon\sigma\rangle^{95}_{obs}$), the observed number of signal events(S^{95}_{obs}), and the signal events given the expected number of background events (S^{95}_{exp}, $\pm 1\sigma$ variations of the expected number) calculated by performing pseudo-experiments 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).

The HistFitter [85] 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 pseudo-experiments, where the profile likelihood ratio is used as a test statistic [86] to exclude the signal-plus-background hypothesis. A signal model can be excluded at 95% confidence level (CL) if the CL_s [87] of the signal-plus-background hypothesis is below 0.05. For each signal region, the expected and observed upper limits at 95% CL on the number of beyond-the-SM events (S^{95}_{exp} and S^{95}_{obs}) are calculated using the model-independent signal fit. The 95% CL upper limits on the signal cross section times efficiency ($\langle\epsilon\sigma\rangle^{95}_{obs}$) 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% CL limits are calculated by performing pseudo-experiments 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 $\pm 1\sigma_{\mathrm{exp}}$ uncertainty band indicates the impact on the expected limit of the systematic and statistical uncertainties included in the fit. The $\pm 1\sigma_{\mathrm{theory}}^{\mathrm{SUSY}}$ 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.

Figure 7 shows 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 ($\tilde{\chi}_1^0 \to \ell\ell\nu$ with 100% branching ratio) and the high efficiency of the m_{eff} selections. In the RPV wino NLSP $LL\bar{E}12k$ models shown in Figures 7(a) and 7(b), $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses up to $\sim 1.46\,\mathrm{TeV}$ are excluded for $m(\tilde{\chi}_1^0) > 500\,\mathrm{GeV}$. The sensitivity is reduced for large mass splittings between the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$, where the decay products are strongly boosted, and $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses up to $\sim 1.32\,\mathrm{TeV}$ are excluded for $m(\tilde{\chi}_1^0) > 50\,\mathrm{GeV}$. Figures 7(a) and 7(b) also show exclusion contours for the RPV wino NLSP $LL\bar{E}i33$ models, where $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses up to $\sim 980\,\mathrm{GeV}$ are excluded for $400\,\mathrm{GeV} < m(\tilde{\chi}_1^0) < 700\,\mathrm{GeV}$. The sensitivity is also reduced for large mass differences between the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$, where the tau leptons, in particular, are collimated. These results extend the limits set in a similar model considering only $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production in Ref. [22] by around 400–750 GeV.

Figure 7(c) shows exclusion contours for the RPV $\tilde{\ell}_{\mathrm{L}}/\tilde{\nu}$ NLSP model, where left-handed slepton/sneutrino masses are excluded up to $\sim 1.06\,\mathrm{TeV}$ for $m(\tilde{\chi}_1^0) \simeq 600\,\mathrm{GeV}$ for $LL\bar{E}12k$ models, and up to $780\,\mathrm{GeV}$ for $m(\tilde{\chi}_1^0) \simeq 300\,\mathrm{GeV}$ for $LL\bar{E}i33$ models. These results extend the limits set in a similar model considering only $\tilde{\ell}_{\mathrm{L}}\tilde{\ell}_{\mathrm{L}}$ production in Ref. [22] by around 200–400 GeV.

The exclusion contours for the RPV $\tilde{g}$ NLSP model are shown in Figure 7(d), where gluino masses are excluded up to $\sim 2.25\,\mathrm{TeV}$ for $m(\tilde{\chi}_1^0) > 1\,\mathrm{TeV}$ for $LL\bar{E}12k$ models, and up to $\sim 1.65\,\mathrm{TeV}$ for $m(\tilde{\chi}_1^0) > 500\,\mathrm{GeV}$ for $LL\bar{E}i33$ models. These results significantly improve upon limits set in a similar model in Ref. [22] by around 500–700 GeV.

Figure 7(e) 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, respectively. Higgsino-like $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$ with masses up to 295 GeV are excluded in scenarios with a branching ratio $\mathcal{B}(\tilde{\chi}_1^0 \to Z + \tilde{G}) = 100\%$, while the exclusion is weakened for scenarios with $\mathcal{B}(\tilde{\chi}_1^0 \to Z + \tilde{G}) < 100\%$. This analysis is not sensitive to scenarios with $\mathcal{B}(\tilde{\chi}_1^0 \to h + \tilde{G}) = 100\%$, 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. [88], but the observed limit is not as strong.
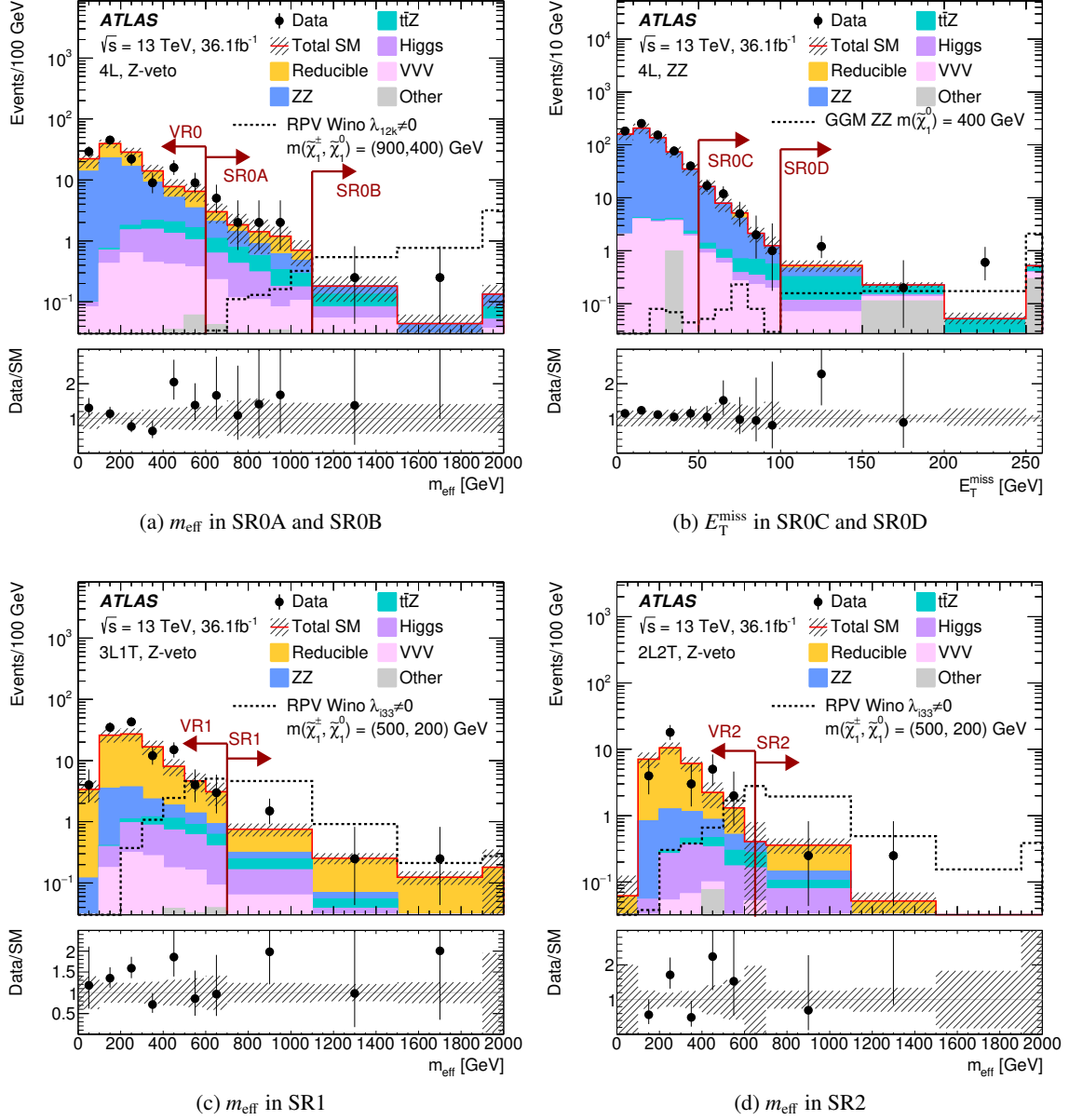
Figure 6: The (a), (c) & (d) m_{eff} distribution for events passing the signal region requirements except the m_{eff} requirement in SR0A, SR0B, SR1 and SR2. The (b) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution is shown for events passing the signal region requirements except the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement in SR0C and SR0D. Distributions for data, the estimated SM backgrounds, and an example SUSY scenario are shown. "Other" is the sum of the tWZ, $t\bar{t}WW$, and $t\bar{t}t\bar{t}$ backgrounds. The last bin captures the overflow events. Both the statistical and systematic uncertainties in the SM background are included in the shaded band. The red arrows indicate the m_{eff} or $E_{\mathrm{T}}^{\mathrm{miss}}$ selections in the signal regions.
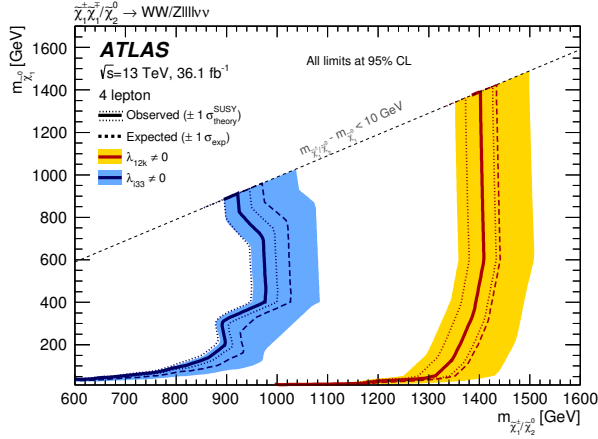
(a) RPV wino W/Z NLSP
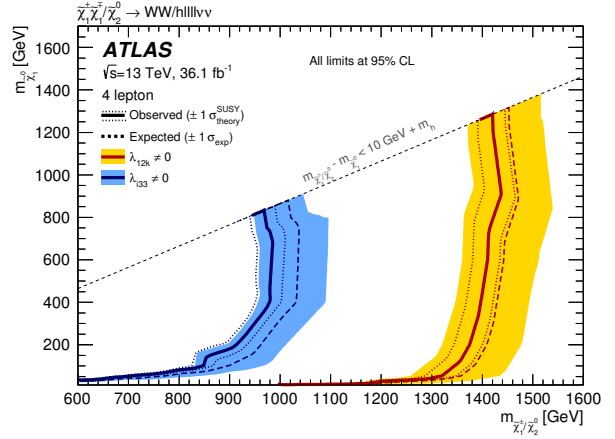
(b) RPV wino W/h NLSP
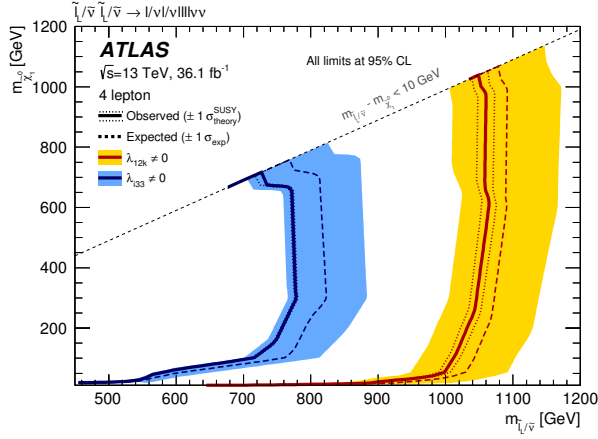
(c) RPV $\tilde{\ell}_L/\tilde{\nu}$ NLSP
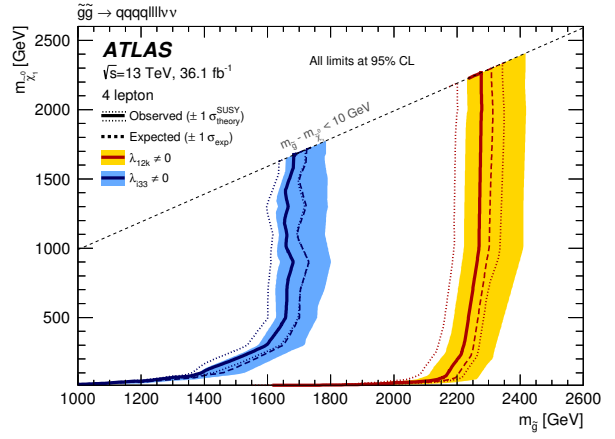
(d) RPV $\tilde{g}$ NLSP
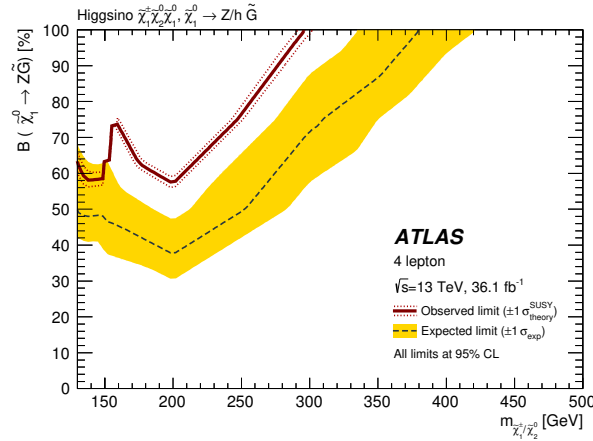
(e) RPC GGM higgsino

Figure 7: Expected (dashed) and observed (solid) 95% CL exclusion limits on (a) wino W/Z NLSP, (b) wino W/h NLSP, (c) $\tilde{\ell}_L/\tilde{\nu}$ NLSP, and (d) gluino NLSP pair production with RPV $\tilde{\chi}_1^0$ decays via λ_{12k}, or λ_{i33} where $i, k \in 1, 2$. Also shown are the exclusion limits on (e) 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 CL_s value is taken from the signal region with the better expected CL_s value.

9 Conclusion

Results are reported from a search for new physics in the final state with four or more leptons (electrons, muons or taus), using $36.1\,\text{fb}^{-1}$ of $\sqrt{s} = 13\,\text{TeV}$ 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 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$, $\tilde{\ell}_L/\tilde{\nu}$, and $\tilde{g}$ 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 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$ 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.

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M. Aaboud[35c], G. Aad[101], B. Abbott[126], O. Abdinov[13,*], B. Abeloos[130], S.H. Abidi[165],
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B.S. Acharya[68a,68b,l], S. Adachi[161], L. Adamczyk[42a], J. Adelman[121], M. Adersberger[114], T. Adye[142],
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F. Ahmadov[81,ah], G. Aielli[75a,75b], S. Akatsuka[84], H. Akerstedt[46a,46b], T.P.A. Åkesson[97], E. Akilli[56],
A.V. Akimov[110], G.L. Alberghi[23b,23a], J. Albert[176], P. Albicocco[53], M.J. Alconada Verzini[87],
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S.A. Tupputi[23b,23a], S. Turchikhin[81], D. Turgeman[180], I. Turk Cakir[5b,w], R. Turra[70a], P.M. Tuts[39], G. Ucchielli[23b,23a], I. Ueda[82a], M. Ughetto[46a,46b], F. Ukegawa[167], G. Unal[36a], A. Undrus[26b], G. Unel[171], F.C. Ungaro[104], Y. Unno[82a], K. Uno[161], C. Unverdorben[114], J. Urban[29b], P. Urquijo[104], P. Urrejola[99], G. Usai[9], J. Usui[82a], L. Vacavant[101], V. Vacek[139], B. Vachon[103], K.O.H. Vadla[132], A. Vaidya[93], C. Valderanis[114], E. Valdes Santurio[46a,46b], M. Valente[56], S. Valentinetti[23b,23a], A. Valero[174], L. Valéry[14], S. Valkar[140], A. Vallier[6], J.A. Valls Ferrer[174], W. Van Den Wollenberg[120], H. van der Graaf[120], P. van Gemmeren[7], J. Van Nieuwkoop[151], I. van Vulpen[120], M.C. van Woerden[120], M. Vanadia[75a,75b], W. Vandelli[36a], A. Vaniachine[164], P. Vankov[120], G. Vardanyan[183], R. Vari[74a], E.W. Varnes[8], C. Varni[57b,57a], T. Varol[44], D. Varouchas[130], A. Vartapetian[9], K.E. Varvell[155], G.A. Vasquez[146b], J.G. Vasquez[182], F. Vazeille[38], D. Vazquez Furelos[14], T. Vazquez Schroeder[103], J. Veatch[55], V. Veeraraghavan[8], L.M. Veloce[165], F. Veloso[137a,137c], S. Veneziano[74a], A. Ventura[69a,69b], M. Venturi[176], N. Venturi[36a], A. Venturini[27], V. Vercesi[72a], M. Verducci[76a,76b], W. Verkerke[120], A.T. Vermeulen[120], J.C. Vermeulen[120], M.C. Vetterli[151,au], N. Viaux Maira[146b], O. Viazlo[97], I. Vichou[173,*], T. Vickey[148], O.E. Vickey Boeriu[148], G.H.A. Viehhauser[133], S. Viel[18], L. Vigani[133], M. Villa[23b,23a], M. Villaplana Perez[70a,70b], E. Vilucchi[53], M.G. Vincter[34], V.B. Vinogradov[81], A. Vishwakarma[47], C. Vittori[23b,23a], I. Vivarelli[154], S. Vlachos[10], M. Vogel[181], P. Vokac[139], G. Volpi[14], H. von der Schmitt[115], E. von Toerne[24], V. Vorobel[140], K. Vorobev[112], M. Vos[174], R. Voss[36a], J.H. Vossebeld[89], N. Vranjes[16], M. Vranjes Milosavljevic[16], V. Vrba[139], M. Vreeswijk[120], T. Šfiligoj[90], R. Vuillermet[36a], I. Vukotic[37], T. Ženiš[29a], L. Živković[16], P. Wagner[24], W. Wagner[181], J. Wagner-Kuhr[114], H. Wahlberg[87], S. Wahrmund[49], J. Walder[88], R. Walker[114], W. Walkowiak[150], V. Wallangen[46a,46b], C. Wang[15b], C. Wang[62b,d], F. Wang[95b], H. Wang[18], H. Wang[4], J. Wang[155], J. Wang[47], Q. Wang[126], R.-J. Wang[96], R. Wang[7], S.M. Wang[156], T. Wang[39], W. Wang[156,m], W. Wang[62a,ag], Z. Wang[62c], C. Wanotayaroj[47], A. Warburton[103], C.P. Ward[32], D.R. Wardrope[93], A. Washbrook[51], P.M. Watkins[21], A.T. Watson[21], M.F. Watson[21], G. Watts[147], S. Watts[100], B.M. Waugh[93], A.F. Webb[11], S. Webb[99], M.S. Weber[20], S.A. Weber[34], S.W. Weber[177], J.S. Webster[7], A.R. Weidberg[133], B. Weinert[67], J. Weingarten[55], M. Weirich[99], C. Weiser[54], H. Weits[120], P.S. Wells[36a], T. Wenaus[26b], T. Wengler[36a], S. Wenig[36a], N. Wermes[24], M.D. Werner[80], P. Werner[36a], M. Wessels[63a], T.D. Weston[20], K. Whalen[129], N.L. Whallon[147], A.M. Wharton[88], A.S. White[105], A. White[9], M.J. White[1], R. White[146b], D. Whiteson[171], B.W. Whitmore[88], F.J. Wickens[142], W. Wiedenmann[95b], M. Wielers[142], C. Wiglesworth[40], L.A.M. Wiik-Fuchs[54], A. Wildauer[115], F. Wilk[100], H.G. Wilkens[36a], H.H. Williams[134], S. Williams[32], C. Willis[106], S. Willocq[102], J.A. Wilson[21], I. Wingerter-Seez[6], E. Winkels[154], F. Winklmeier[129], O.J. Winston[154], B.T. Winter[24], M. Wittgen[31b], M. Wobisch[94,ak], T.M.H. Wolf[120], R. Wolff[101], M.W. Wolter[43], H. Wolters[137a,137c], V.W.S. Wong[175], S.D. Worm[21], B.K. Wosiek[43], J. Wotschack[36a], K.W. Woźniak[43], M. Wu[37], S.L. Wu[95b], X. Wu[56], Y. Wu[105], T.R. Wyatt[100], B.M. Wynne[51], S. Xella[40], Z. Xi[105], L. Xia[15c], D. Xu[15a], L. Xu[26b], T. Xu[144], B. Yabsley[155], S. Yacoob[33a], D. Yamaguchi[163], Y. Yamaguchi[163], A. Yamamoto[82a], S. Yamamoto[161], T. Yamanaka[161], F. Yamane[83], M. Yamatani[161], Y. Yamazaki[83], Z. Yan[25], H. Yang[62c,62d], H. Yang[18], Y. Yang[156], Z. Yang[17], W-M. Yao[18], Y.C. Yap[47], Y. Yasu[82a], E. Yatsenko[6], K.H. Yau Wong[24], J. Ye[44], S. Ye[26b], I. Yeletskikh[81], E. Yigitbasi[25], E. Yildirim[99], K. Yorita[179], K. Yoshihara[134], C.J.S. Young[36a], C. Young[31b], J. Yu[9], J. Yu[80], S.P.Y. Yuen[24], I. Yusuff[32,aw], B. Zabinski[43], G. Zacharis[10], R. Zaidan[14], A.M. Zaitsev[141,am], N. Zakharchuk[47], J. Zalieckas[17], A. Zaman[153], S. Zambito[61], D. Zanzi[104], C. Zeitnitz[181], G. Zemaityte[133], A. Zemla[42a], J.C. Zeng[173], Q. Zeng[31b], O. Zenin[141], D. Zerwas[130], D. Zhang[105], D. Zhang[62b], F. Zhang[95b], G. Zhang[62a,ag], H. Zhang[130], J. Zhang[7], L. Zhang[54], L. Zhang[62a], M. Zhang[173], P. Zhang[15b], R. Zhang[62a,d], R. Zhang[24], X. Zhang[62b], Y. Zhang[170], Z. Zhang[130], X. Zhao[44], Y. Zhao[62b,aj], Z. Zhao[62a], A. Zhemchugov[81], B. Zhou[105], C. Zhou[95b], L. Zhou[44], M. Zhou[170], M. Zhou[153], N. Zhou[15c], C.G. Zhu[62b], H. Zhu[15a], J. Zhu[105], Y. Zhu[62a], X. Zhuang[15a], K. Zhukov[110], A. Zibell[177], D. Zieminska[67], N.I. Zimine[81], C. Zimmermann[99], S. Zimmermann[54], Z. Zinonos[115],

M. Zinser[99], M. Ziolkowski[150], G. Zobernig[95b], A. Zoccoli[23b,23a], R. Zou[37], M. zur Nedden[19], L. Zwalinski[36a].

[1]Department of Physics, University of Adelaide, Adelaide; Australia.

[2](a)Department of Financial and Management Engineering, University of the Aegean, Chios;(b)Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

[3]Physics Department, SUNY Albany, Albany NY; United States of America.

[4]Department of Physics, University of Alberta, Edmonton AB; Canada.

[5](a)Department of Physics, Ankara University, Ankara;(b)Istanbul Aydin University, Istanbul;(c)Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.

[6]LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

[7]High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

[8]Department of Physics, University of Arizona, Tucson AZ; United States of America.

[9]Department of Physics, The University of Texas at Arlington, Arlington TX; United States of America.

[10]Physics Department, National Technical University of Athens, Zografou; Greece.

[11]Department of Physics, The University of Texas at Austin, Austin TX; United States of America.

[12](a)Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;(b)Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;(c)Department of Physics, Bogazici University, Istanbul;(d)Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.

[13]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

[14]Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona; Spain.

[15](a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;(b)Department of Physics, Nanjing University, Jiangsu;(c)Physics Department, Tsinghua University, Beijing; China.

[16]Institute of Physics, University of Belgrade, Belgrade; Serbia.

[17]Department for Physics and Technology, University of Bergen, Bergen; Norway.

[18]Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.

[19]Department of Physics, Humboldt University, Berlin; Germany.

[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.

[21]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.

[22]Centro de Investigaciones, Universidad Antonio Narino, Bogota; Colombia.

[23](a)Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna;(b)INFN Sezione di Bologna; Italy.

[24]Physikalisches Institut, University of Bonn, Bonn; Germany.

[25]Department of Physics, Boston University, Boston MA; United States of America.

[26](a)University of Colorado Boulder, Department of Physics, Colorado;(b)Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.

[27]Department of Physics, Brandeis University, Waltham MA; United States of America.

[28](a)Transilvania University of Brasov, Brasov;(b)Horia Hulubei National Institute of Physics and Nuclear Engineering;(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca;(e)West University in Timisoara, Timisoara; Romania.

[29](a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.

[30]Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.

[31][a]Department of Physics, California State University, Fresno CA;[b]SLAC National Accelerator Laboratory, Stanford CA;[c]Department of Physics, Stanford University, Stanford, California; United States of America.

[32]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.

[33][a]Department of Physics, University of Cape Town, Cape Town;[b]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;[c]School of Physics, University of the Witwatersrand, Johannesburg; South Africa.

[34]Department of Physics, Carleton University, Ottawa ON; Canada.

[35][a]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;[b]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;[c]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;[d]Faculté des sciences, Université Mohammed V, Rabat; Morocco.

[36][a]CERN, Geneva;[b]CERN Tier-0; Switzerland.

[37]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.

[38]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.

[39]Nevis Laboratory, Columbia University, Irvington NY; United States of America.

[40]Niels Bohr Institute, University of Copenhagen, Kobenhavn; Denmark.

[41][a]Dipartimento di Fisica, Università della Calabria, Rende;[b]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.

[42][a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;[b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.

[43]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.

[44]Physics Department, Southern Methodist University, Dallas TX; United States of America.

[45]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.

[46][a]Department of Physics, Stockholm University;[b]The Oskar Klein Centre, Stockholm; Sweden.

[47]DESY, Hamburg and Zeuthen; Germany.

[48]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.

[49]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.

[50]Department of Physics, Duke University, Durham NC; United States of America.

[51]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.

[52]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.

[53]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.

[54]Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg; Germany.

[55]II Physikalisches Institut, Georg-August-Universität, Göttingen; Germany.

[56]Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva; Switzerland.

[57][a]Dipartimento di Fisica, Università di Genova, Genova;[b]INFN Sezione di Genova; Italy.

[58]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.

[59]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.

[60]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.

[61]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.

[62][a]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui;[b]School of Physics, Shandong University, Shandong;[c]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;[(d)]Tsung-Dao Lee Institute, Shanghai; China.

[63][(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;[(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.

[64]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima; Japan.

[65][(a)]Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong;[(b)]Department of Physics, The University of Hong Kong, Hong Kong;[(c)]Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.

[66]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.

[67]Department of Physics, Indiana University, Bloomington IN; United States of America.

[68][(a)]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;[(b)]ICTP, Trieste;[(c)]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine; Italy.

[69][(a)]INFN Sezione di Lecce;[(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.

[70][(a)]INFN Sezione di Milano;[(b)]Dipartimento di Fisica, Università di Milano, Milano; Italy.

[71][(a)]INFN Sezione di Napoli;[(b)]Dipartimento di Fisica, Università di Napoli, Napoli; Italy.

[72][(a)]INFN Sezione di Pavia;[(b)]Dipartimento di Fisica, Università di Pavia, Pavia; Italy.

[73][(a)]INFN Sezione di Pisa;[(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

[74][(a)]INFN Sezione di Roma;[(b)]Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.

[75][(a)]INFN Sezione di Roma Tor Vergata;[(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.

[76][(a)]INFN Sezione di Roma Tre;[(b)]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.

[77][(a)]INFN-TIFPA;[(b)]University of Trento, Trento; Italy.

[78]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.

[79]University of Iowa, Iowa City IA; United States of America.

[80]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.

[81]Joint Institute for Nuclear Research, JINR Dubna, Dubna; Russia.

[82][(a)]KEK, High Energy Accelerator Research Organization, Tsukuba;[(b)]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.

[83]Graduate School of Science, Kobe University, Kobe; Japan.

[84]Faculty of Science, Kyoto University, Kyoto; Japan.

[85]Kyoto University of Education, Kyoto; Japan.

[86]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.

[87]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.

[88]Physics Department, Lancaster University, Lancaster; United Kingdom.

[89]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.

[90]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.

[91]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.

[92]Department of Physics, Royal Holloway University of London, Surrey; United Kingdom.

[93]Department of Physics and Astronomy, University College London, London; United Kingdom.

[94]Louisiana Tech University, Ruston LA; United States of America.

[95][(a)]Department of Physics and Astronomy, University of Louisville, Louisville, KY;[(b)]Department of Physics, University of Wisconsin, Madison WI; United States of America.

[96]Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris; France.

[97]Fysiska institutionen, Lunds universitet, Lund; Sweden.

[98]Departamento de Fisica Teorica C-15 and CIAFF, Universidad Autonoma de Madrid, Madrid; Spain.

[99]Institut für Physik, Universität Mainz, Mainz; Germany.

[100]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.

[101]CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille; France.

[102]Department of Physics, University of Massachusetts, Amherst MA; United States of America.

[103]Department of Physics, McGill University, Montreal QC; Canada.

[104]School of Physics, University of Melbourne, Victoria; Australia.

[105]Department of Physics, The University of Michigan, Ann Arbor MI; United States of America.

[106]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.

[107]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Republic of Belarus.

[108]Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Republic of Belarus.

[109]Group of Particle Physics, University of Montreal, Montreal QC; Canada.

[110]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.

[111]Institute for Theoretical and Experimental Physics (ITEP), 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 NM; United States of America.

[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 IL; United States of America.

[122][(a)]Budker Institute of Nuclear Physics, SB RAS, Novosibirsk;[(b)]Novosibirsk State University Novosibirsk; Russia.

[123]Department of Physics, New York University, New York NY; United States of America.

[124]Ohio State University, Columbus OH; United States of America.

[125]Faculty of Science, Okayama University, Okayama; Japan.

[126]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.

[127]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.

[128]Palacký University, RCPTM, Olomouc; Czech Republic.

[129]Center for High Energy Physics, University of Oregon, Eugene OR; United States of America.

[130]LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.

[131]Graduate School of Science, Osaka University, Osaka; Japan.

[132]Department of Physics, University of Oslo, Oslo; Norway.

[133]Department of Physics, Oxford University, Oxford; United Kingdom.

[134]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.

[135]Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia.

[136]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.

[137][a]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;[b]Faculdade de Ciências, Universidade de Lisboa, Lisboa;[c]Department of Physics, University of Coimbra, Coimbra;[d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa;[e]Departamento de Fisica, Universidade do Minho, Braga;[f]Departamento de Fisica Teorica y del Cosmos, Universidad de Granada, Granada (Spain); Portugal.

[138]Institute of Physics, Academy of Sciences of the Czech Republic, Praha; Czech Republic.

[139]Czech Technical University in Prague, Praha; Czech Republic.

[140]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

[141]State Research Center Institute for High Energy Physics (Protvino), NRC KI; Russia.

[142]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

[143][a]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;[b]Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora;[c]Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei;[d]Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo; Brazil.

[144]Institut de Recherches sur les Lois Fondamentales de l'Univers, DSM/IRFU, CEA Saclay, Gif-sur-Yvette; France.

[145]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

[146][a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;[b]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

[147]Department of Physics, University of Washington, Seattle WA; United States of America.

[148]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

[149]Department of Physics, Shinshu University, Nagano; Japan.

[150]Department Physik, Universität Siegen, Siegen; Germany.

[151]Department of Physics, Simon Fraser University, Burnaby BC; Canada.

[152]Physics Department, Royal Institute of Technology, Stockholm; Sweden.

[153]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

[154]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

[155]School of Physics, University of Sydney, Sydney; Australia.

[156]Institute of Physics, Academia Sinica, Taipei; Taiwan.

[157][a]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;[b]High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.

[158]Department of Physics, Technion: Israel Institute of Technology, Haifa; Israel.

[159]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

[160]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

[161]International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo; Japan.

[162]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.

[163]Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

[164]Tomsk State University, Tomsk; Russia.

[165]Department of Physics, University of Toronto, Toronto ON; Canada.

[166][a]TRIUMF, Vancouver BC;[b]Department of Physics and Astronomy, York University, Toronto ON;

Canada.

[167] Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

[168] Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

[169] Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei; Taiwan.

[170] University of Chinese Academy of Science (UCAS), Beijing; China.

[171] Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

[172] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

[173] Department of Physics, University of Illinois, Urbana IL; United States of America.

[174] Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC; Spain.

[175] Department of Physics, University of British Columbia, Vancouver BC; Canada.

[176] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

[177] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg; Germany.

[178] Department of Physics, University of Warwick, Coventry; United Kingdom.

[179] Waseda University, Tokyo; Japan.

[180] Department of Particle Physics, The Weizmann Institute of Science, Rehovot; Israel.

[181] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.

[182] Department of Physics, Yale University, New Haven CT; United States of America.

[183] Yerevan Physics Institute, Yerevan; Armenia.

[a] Also at Borough of Manhattan Community College, City University of New York, New York City; United States of America.

[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 Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.

[f] Also at Departamento de Fisica 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, KY; United States of America.

[j] Also at Department of Physics, California State University, Fresno CA; United States of America.

[k] Also at Department of Physics, California State University, Sacramento CA; United States of America.

[l] Also at Department of Physics, King's College London, London; United Kingdom.

[m] Also at Department of Physics, Nanjing University, Jiangsu; China.

[n] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.

[o] Also at Department of Physics, Stanford University, Stanford CA; United States of America.

[p] Also at Department of Physics, The University of Michigan, Ann Arbor MI; United States of America.

[q] Also at Department of Physics, The University of Texas at Austin, Austin TX; United States of America.

[r] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.

[s] Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

[t] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow; Russia.

[u] Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg; Germany.

[v] Also at Georgian Technical University (GTU),Tbilisi; Georgia.

[w] Also at Giresun University, Faculty of Engineering; Turkey.

[x] Also at Graduate School of Science, Osaka University, Osaka; Japan.

[y] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering; Romania.

[z] Also at II Physikalisches Institut, Georg-August-Universität, Göttingen; Germany.

[aa] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.

[ab] Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona; Spain.

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

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

[ae] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.

[af] Also at Institute of Particle Physics (IPP); Canada.

[ag] Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.

[ah] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

[ai] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.

[aj] Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.

[ak] Also at Louisiana Tech University, Ruston LA; United States of America.

[al] Also at Manhattan College, New York NY; United States of America.

[am] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.

[an] Also at National Research Nuclear University MEPhI, Moscow; Russia.

[ao] Also at Novosibirsk State University, Novosibirsk; Russia.

[ap] Also at Ochadai Academic Production, Ochanomizu University, Tokyo; Japan.

[aq] Also at School of Physics, Sun Yat-sen University, Guangzhou; China.

[ar] Also at The City College of New York, New York NY; United States of America.

[as] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.

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

[au] Also at TRIUMF, Vancouver BC; Canada.

[av] Also at Universita di Napoli Parthenope, Napoli; Italy.

[aw] Also at University of Malaya, Department of Physics, Kuala Lumpur; Malaysia.

[*] Deceased