

# Search for charginos and neutralinos with $B-L$ $R$ -parity violating decays in $\sqrt{s} = 13$ TeV and 13.6 TeV $pp$ collisions with the ATLAS detector

G. Aad *et al.*<sup>\*</sup>  
(ATLAS Collaboration)



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A search is performed for the electroweak pair production of charginos and associated production of a chargino and neutralino, each of which decays through an  $R$ -parity-violating coupling into a lepton and a  $W$ ,  $Z$ , or Higgs boson. This search targets the Higgs boson decay channel of the charginos and neutralinos, using events with three or more  $b$ -tagged jets and one or two electrons or muons. The analyzed data corresponds to an integrated luminosity of  $140 \text{ fb}^{-1}$  and  $56 \text{ fb}^{-1}$  of proton-proton collision data produced by the Large Hadron Collider at center-of-mass energies of  $\sqrt{s} = 13$  TeV and  $\sqrt{s} = 13.6$  TeV, respectively, collected by the ATLAS experiment between 2015 and 2023. The data are found to be consistent with predictions from the Standard Model. The results are interpreted as limits at 95% confidence level on model-independent cross sections for processes beyond the Standard Model. Limits are also set on the production of charginos and neutralinos for a minimal supersymmetric Standard Model with an additional  $B-L$  gauge symmetry that is spontaneously broken. Charginos and neutralinos with masses between 150 GeV and 1100 GeV are excluded at 95% confidence level for a scenario in which they decay via Higgs bosons, assuming equal decay branching fractions to each lepton flavor. Additional limits on chargino and neutralino production are derived for flavor-specific decay scenarios where the charginos decay into a single lepton flavor.

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## I. INTRODUCTION

Supersymmetry (SUSY) is an extension of the Standard Model (SM) [1–6] that offers solutions to many open problems in particle physics, including the hierarchy problem [7–10]. However, the full SUSY model space allows for baryon number ( $B$ ) and lepton number ( $L$ ) violation. While this can lead to rapid proton decay or large flavor-changing neutral currents in processes like  $\mu \rightarrow e\gamma$ , these processes can be prevented by requiring conservation of  $R$ -parity [11], a multiplicative quantum number defined as  $R = (-1)^{3(B-L)+2s}$ , where  $s$  is the particle's spin. Enforcing the conservation of  $R$ -parity (or equivalently, the quantity  $B-L$ ) has additional phenomenological consequences for SUSY models. SM particles have  $R = +1$ , whereas their SUSY partner particles (“superpartners”) have  $R = -1$ . Therefore, in  $R$ -parity conserving SUSY models, superpartners must be pair produced at the Large Hadron Collider (LHC) [12], and the lightest supersymmetric particle (LSP) must be stable.

$R$ -parity conservation, however, is an *ad hoc* solution and may be too restrictive; there are phenomenologically viable  $R$ -parity violating (RPV) SUSY theories. One such theory, known as the  $B-L$  minimal supersymmetric Standard Model, introduces a  $U(1)_{B-L}$  gauge symmetry in addition to the SM  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge group, along with right-handed sterile neutrinos [13–16]. When the superpartners to the right-handed neutrino fields obtain a vacuum expectation value, the  $U(1)_{B-L}$  symmetry is spontaneously broken in a way that violates only lepton number, while providing a mechanism to give the left-handed Standard Model neutrinos their small masses. RPV couplings allow direct decay of superpartners to SM particles, including the decay of the LSP, producing signatures that are forbidden in  $R$ -parity conserving theories. These couplings remain weak, so the production mechanisms of superpartners are not significantly affected.

A wino LSP and next-to-lightest supersymmetric particle (NLSP), superpartners to the electroweak bosons whose primary component comes from the  $W$  boson superpartners, provide a unique search scenario for this model due to the possibility of a charged LSP. The charged component, the chargino  $\tilde{\chi}_1^\pm$ , and the neutral component, the neutralino  $\tilde{\chi}_1^0$ , are expected to be nearly mass degenerate, with less than 200 MeV mass difference [17,18]. This small mass splitting suppresses  $R$ -parity conserving decays of the NLSP to the

<sup>\*</sup>Full author list given at the end of the article.

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LSP. The chargino undergoes prompt RPV decays into a Higgs boson and a charged lepton ( $\tilde{\chi}_1^\pm \rightarrow h\ell^\pm$ ), to a  $Z$  boson and a charged lepton ( $\tilde{\chi}_1^\pm \rightarrow Z\ell^\pm$ ), or to a  $W$  boson and a neutrino ( $\tilde{\chi}_1^\pm \rightarrow W^\pm\nu$ ). Similarly, the neutralino undergoes prompt decays into a Higgs boson and a neutrino ( $\tilde{\chi}_1^0 \rightarrow h\nu$ ), to a  $Z$  boson and a neutrino ( $\tilde{\chi}_1^0 \rightarrow Z\nu$ ), or to a  $W$  boson and a charged lepton ( $\tilde{\chi}_1^0 \rightarrow W^\pm\ell^\mp$ ). While the proportion of these decays depends on parameters of the SUSY theory, the branching fractions for decays for  $\tilde{\chi}_1^\pm \rightarrow h\ell^\pm$  and  $\tilde{\chi}_1^0 \rightarrow h\nu$  are expected to be above 80% for most scenarios [18] and are therefore targeted in this search. The relative branching fractions of these decays for different lepton flavors depends on the neutrino mass hierarchy [18].

This paper presents a search for chargino-chargino pair production ( $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ ) and chargino-neutralino production ( $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ ) with RPV  $\tilde{\chi}_1^\pm \rightarrow h\ell^\pm$  and  $\tilde{\chi}_1^0 \rightarrow h\nu$  decays. The data was collected with the ATLAS detector in proton-proton ( $pp$ ) collisions at the LHC and comprises  $140\text{ fb}^{-1}$  at  $\sqrt{s} = 13\text{ TeV}$  taken from 2015–2018 (Run 2) and  $56\text{ fb}^{-1}$  at  $\sqrt{s} = 13.6\text{ TeV}$  taken from 2022–2023 (partial Run 3). This analysis only considers the dominant decay of the Higgs boson into  $b$ -quarks [ $\mathcal{B}(h \rightarrow b\bar{b}) = 58\%$ ]. Higgs bosons are reconstructed from pairs of jets, and the selection requires at least three jets to be identified as originating from  $b$ -hadrons ( $b$ -tagged jets). Diagrams for the signal model are shown in Fig. 1. In the case of  $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$  production, final states should contain two leptons with opposite-sign electric charge, while for  $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$  production, final states should contain one lepton and missing transverse momentum ( $\vec{p}_T^{\text{miss}}$ , with magnitude  $E_T^{\text{miss}}$ ), due to the undetected neutrino. While  $\tau$  leptons are not explicitly targeted by this search, they are included in the signal sample generation and contribute to the sensitivity through their leptonic decays. The search strategy aims at reconstructing the mass of the chargino  $m_C$  from Higgs-lepton resonances and the transverse mass of the neutralino  $m_{N,T}$  from a Higgs boson and the  $\vec{p}_T^{\text{miss}}$ .

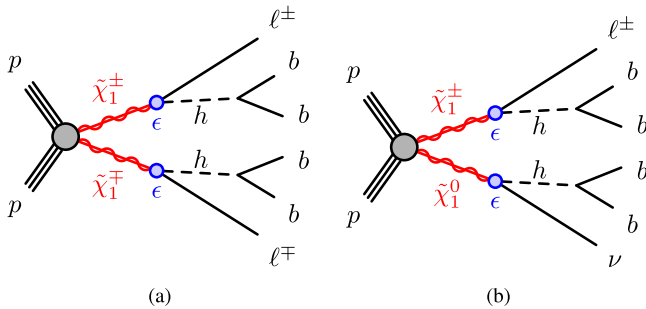


FIG. 1. Representative diagrams of the signal model processes considered in this analysis with (a) the chargino-chargino process ( $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ ) and (b) the chargino-neutralino process ( $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ ). The RPV effective vertices are marked with the bilinear RPV coupling  $\epsilon$ .

A previous ATLAS search for electroweakino pair production with RPV decays targeted chargino decays into  $Z\ell$  with subsequent  $Z \rightarrow \ell\ell$  by searching for a tripleton resonance using the full Run 2 dataset [19]. The search described in this paper provides complementary sensitivity by targeting chargino and neutralino decays into Higgs bosons and leptons, making use of different regions of phase space.

A dedicated series of Run 2 searches for RPV  $B-L$  scenarios has also been carried out considering the superpartner of the top quark to be the LSP [20,21]. These were optimized for the pair production of top squarks with RPV decays into a bottom quark and charged lepton. The final state signature is a pair of resonances formed from a  $b$ -jet and a lepton, requiring  $\geq 1$   $b$ -jets in the signal region.

This analysis benefits from developments in the capability of identifying jets originating from  $b$ -hadrons, namely the GN2 algorithm [22], which allows significantly better background reduction as compared with the previous algorithm. The analysis also benefits from strong background rejection due to the requirement of reconstructing two Higgs boson candidates. The sensitivity in the  $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$  channel is driven by low background due to tight selections, while the sensitivity in the  $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$  channel is due to good mass resolution for the chargino resonance from the reconstruction algorithms.

This paper is organized as follows. The ATLAS detector is described in Sec. II. The data and simulated samples used are described in Sec. III. Analysis objects are defined in Sec. IV. The definition of analysis regions and the background estimation strategy are described in Sec. V, and Sec. VI, respectively. Systematic uncertainties are discussed in Sec. VII, and analysis results are shown in Sec. VIII. Concluding remarks are made in Sec. IX.

## II. ATLAS DETECTOR

The ATLAS experiment [23,24] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle.<sup>1</sup> It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The inner tracking detector covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of silicon pixel (including the insertable  $B$  layer),

<sup>1</sup>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. Polar coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$  and is equal to the rapidity  $y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right)$  in the relativistic limit. Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ .

silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region  $|\eta| < 3.2$ . A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). The end cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to  $|\eta| = 4.9$ . The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to  $|\eta| = 2.7$  and fast detectors for triggering up to  $|\eta| = 2.4$ . The luminosity is measured mainly by the LUCID-2 detector that is located close to the beampipe. A two-level trigger system was used to select events [25,26]. The first-level trigger is implemented in hardware and used a subset of the detector information to accept events at a rate close to 100 kHz. This is followed by a software-based trigger that reduced the accepted rate of complete events to 1.25 kHz and 3 kHz on average in Run 2 and Run 3, respectively, depending on the data-taking conditions. A software suite [27] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

### III. DATA AND SIMULATED SAMPLES

This analysis is performed using  $pp$  collision data collected by the ATLAS experiment during Run 2 of the LHC from 2015 to 2018 and Run 3 of the LHC from 2022 to 2023. The LHC collided protons at a center-of-mass energy of  $\sqrt{s} = 13$  TeV during Run 2 and  $\sqrt{s} = 13.6$  TeV during Run 3. The data sample corresponds to a total integrated luminosity of  $196 \text{ fb}^{-1}$ , with  $140 \text{ fb}^{-1}$  from Run 2 and  $56 \text{ fb}^{-1}$  from Run 3. The uncertainty in the

2015–2018 (2022–2023) integrated luminosity is 0.83% [28] (2.0% [29]), obtained using the LUCID-2 detector [30] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters. Data quality requirements are applied to ensure that only data with stable LHC beams and operational subdetectors are used [31]. Data were collected using triggers requiring the presence of an electron or a muon [26,32,33]. The triggers have varying requirements on the identification working point, isolation, and transverse momentum ( $p_T$ ) thresholds of the leptons.

Monte Carlo (MC) simulations are used to model the signals and SM background processes for this analysis. All samples were produced with the ATLAS simulation framework [27,34] based on GEANT4 [35]. The signal samples simulate  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production at leading order (LO) with up to two additional partons in the matrix element. In the benchmark model considered, the masses of the chargino and neutralino are set to be equal. The production cross sections are computed at next-to-leading-order (NLO) plus next-to-leading-logarithm (NLL) precision in a limit of mass-degenerate wino  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ , with all the other sparticles assumed to be heavy and decoupled [36–38]. These vary from about 2612 fb (5181 fb) for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ ) production at a chargino and neutralino mass of 150 GeV to about 0.62 fb (1.34 fb) for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ ) production at 1000 GeV for Run 2, with slightly higher cross sections for Run 3. The decay branching ratios are set to  $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h\ell^\pm) = 100\%$  and  $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h\nu) = 100\%$ , with equal branching fractions to each lepton generation. Samples were generated with MADGRAPH5\_AMC@NLO 3.5.3 [39] with the NNPDF3.0NLO [40] parton distribution function (PDF). The parton shower, hadronization, and underlying event were modeled using PYTHIA 8.310 [41] with the A14 set of tuned parameters (tune) [42]. The MC setup for the signal, along with the SM background processes, is shown in Table I.

TABLE I. Details of the MC simulation for each physics process, including the calculations used for normalization, the generator used for the parton shower (PS) and hadronization, the PS parameter tunes, and the order in  $\alpha_s$  of the production cross-section calculations. NLO stands for next-to-leading-order, NNLO stands for next-to-next-to-leading-order, NLL stands for next-to-leading-logarithm, and NNLL stands for next-to-next-to-leading-logarithm. The default table values are for Run 2, with Run 3 in parentheses if they differ.

| Process                                                                           | Event generator                           | PS and hadronization     | PS tune  | Cross section accuracy |
|-----------------------------------------------------------------------------------|-------------------------------------------|--------------------------|----------|------------------------|
| $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ | MADGRAPH5_AMC@NLO 3.5.3[39]               | PYTHIA 8.310 [41]        | A14 [42] | NLO+NNL                |
| $t\bar{t}b\bar{b}$                                                                | POWHEG BOX RES [43] and OPENLOOPS [44–46] | PYTHIA 8.309(8.312)      | A14      | NLO                    |
| $t\bar{t}$                                                                        | POWHEG BOX v2 [47–50]                     | PYTHIA 8.230(8.308) [51] | A14      | NNLO+NNLL [52–58]      |
| $t\bar{t}h$                                                                       | POWHEG BOX v2                             | PYTHIA 8.230(8.308)      | A14      | NLO [59]               |
| $t\bar{t}W$                                                                       | SHERPA 2.2.14 [60]                        | SHERPA 2.2.14            | Default  | NLO [59]               |
| $t\bar{t}Z$                                                                       | MADGRAPH5_AMC@NLO 2.8.1(3.5.1)            | PYTHIA 8.210(8.309)      | A14      | NLO [59]               |
| Single-top ( $s/t$ -channel)                                                      | POWHEG BOX v2                             | PYTHIA 8.230(8.308)      | A14      | NNLO [61]              |
| Single-top ( $Wt$ )                                                               | POWHEG BOX v2                             | PYTHIA 8.309(8.308)      | A14      | NLO+NNLL [62,63]       |
| Diboson                                                                           | SHERPA 2.2                                | SHERPA 2.2               | Default  | NLO                    |
| $V + \text{jets}$                                                                 | SHERPA 2.2.11(2.2.14)                     | SHERPA 2.2.11(2.2.14)    | Default  | NNLO [64]              |

The dominant background in this analysis is from top-quark pair production ( $t\bar{t}$ ). The production of  $t\bar{t}$  events was modeled using the POWHEG BOX v2 [47–50] generator at NLO with the NNPDF3.0NLO PDF set and the  $h_{\text{damp}}$  parameter<sup>2</sup> set to  $1.5 m_{\text{top}}$  [65]. The events were interfaced to PYTHIA 8.230(8.308) [51] for Run 2 (Run 3) to model the parton shower, hadronization, and underlying event, with parameters set according to the A14 tune and using the NNPDF2.3LO set of PDFs [66].

These  $t\bar{t}$  events are separated by particle flavor into  $t\bar{t}$  with additional light-flavor jets ( $t\bar{t} + \text{light}$ ),  $c$ -jets ( $t\bar{t} + \geq 1c$ ), or  $b$ -jets ( $t\bar{t} + \geq 1b$ ). This classification uses generator-level jets, which are reconstructed from stable particles using the anti- $k_t$  algorithm [67,68] with a radius parameter of  $R = 0.4$ . The filtering classifies the flavor of generator-level jets by using a  $\Delta R$  matching with heavy-flavor hadrons (excluding hadrons with the top quark or  $W$  boson as parent particles). Generator-level jets with  $p_T > 15$  GeV and  $|\eta| < 2.5$  are labeled  $b$  flavored if they are matched within  $\Delta R = 0.4$  to a  $b$ -hadron with  $p_T > 5$  GeV, and events containing at least one such jet are labeled  $t\bar{t} + \geq 1b$  events. Jets that are not matched to a  $b$ -hadron but are matched to a  $c$ -hadron with  $p_T > 5$  GeV within  $\Delta R = 0.4$  are labeled  $c$  flavored, and events containing at least one such jet and no  $b$  flavored jets are labeled  $t\bar{t} + \geq 1c$  events. All  $t\bar{t}$  events that do not contain a  $b$  flavored or  $c$  flavored jet are classified as  $t\bar{t} + \text{light}$  events. The  $t\bar{t} + \geq 1b$  events are removed from the inclusive  $t\bar{t}$  sample and are instead modeled with dedicated  $t\bar{t}b\bar{b}$  samples. The  $t\bar{t} + \geq 1c$  and  $t\bar{t} + \text{light}$  events are removed from the  $t\bar{t}b\bar{b}$  samples. These  $t\bar{t}b\bar{b}$  events were produced using the POWHEG BOX RES [43] generator at NLO and OPENLOOPS [44–46], and the NNPDF3.1NLO [69] PDF set. The events were interfaced to PYTHIA 8.309(8.312) in Run 2 (Run 3) using the A14 set of tuned parameters and using the NNPDF2.3LO set of PDFs. The four-flavor scheme was used with the  $b$ -quark mass set to 4.95 GeV.

The production of  $t\bar{t}h$  events was modeled using the POWHEG BOX v2 [70] generator at NLO with the NNPDF3.0NLO PDF set. The production of  $t\bar{t}Z$  events was modeled using the MADGRAPH5\_AMC@NLO 2.8.1 (3.5.1) generator at NLO with the NNPDF3.0NLO PDF in Run 2 (Run 3). The production of  $t\bar{t}W$  events was modeled using SHERPA 2.2.14 [60] with up to one additional parton at NLO and two additional partons at LO and the NNPDF3.0NNLO [40] PDF set. Events from the  $t\bar{t}h$ ,  $t\bar{t}Z$ , and  $t\bar{t}W$  processes are collectively labeled  $t\bar{t}X$ .

Single-top  $s$ - and  $t$ -channel production were modeled using the POWHEG BOX v2 [50] generator at NLO in QCD in the five-flavor scheme with the NNPDF3.0NLO PDF set,

<sup>2</sup>The  $h_{\text{damp}}$  parameter is a resummation damping factor and one of the parameters that controls the matching of POWHEG matrix elements to the parton shower. It thus effectively regulates the high- $p_T$  radiation against which the  $t\bar{t}$  system recoils.

while  $Wt$  samples were generated using POWHEG BOX v2 at NLO interfaced with PYTHIA 8.309 (PYTHIA 8.308) for Run 2 (Run 3). The  $Wt$  samples used the diagram removal scheme [71]. Diboson production was modeled using the SHERPA 2.2.14 or 2.2.16 generator depending on the process, including off-shell effects and Higgs boson contributions, where appropriate. Fully leptonic final states and semileptonic final states were generated using matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions. Samples for  $gg \rightarrow VV$  were generated for Run 2 using SHERPA 2.2.2 with LO-accurate matrix elements for up to one additional parton emission for both the cases of fully leptonic and semileptonic final states. The NNPDF3.0NNLO PDF set was used for all diboson samples. The production of  $V + \text{jets}$  was modeled using SHERPA 2.2.14 in Run 3 as well as in Run 2  $Z \rightarrow \tau\tau$ , and SHERPA 2.2.11 for the remainder of Run 2 processes, with up to two additional partons at NLO and up to five additional partons at LO. The virtual QCD corrections were provided by the OPENLOOPS library. The NNPDF3.0NLO PDF set was used.

For all samples using SHERPA, the matrix elements were merged with the parton shower using the MEPS@NLO prescription [72–75]. For all samples using PYTHIA for the parton shower model, the decays of bottom and charm hadrons were simulated using EVTGEN [76]. The effect of multiple interactions in the same and neighboring bunch crossings (pileup) was modeled by overlaying [77] the simulated hard-scattering event with inelastic  $pp$  events generated from a mix of EPOS 2.0.14 [78] and PYTHIA 8.308. The EPOS events were generated with the EPOS LHC tune [79] and the PYTHIA events with the A3 tune [80] and the NNPDF2.3LO set of PDFs. PYTHIA pileup events include either a high- $p_T$  jet, a prompt photon, or a lepton from a  $b$ -hadron decay, while EPOS was filtered to simulate all remaining pileup events in the overlay sample. The individual simulations were first reweighted to ensure a smooth connection across jet  $p_T$ , and then the combination reweighted to match the distribution of the actual number of interactions per bunch crossing ( $\mu$ ) measured in data.

#### IV. OBJECT RECONSTRUCTION

Charged-particle tracks are required to have  $p_T > 0.5$  GeV [81–83]. Primary vertex candidates are reconstructed from at least two charged-particle tracks [84]. To identify the hard-scattering interaction, the event’s primary vertex is chosen as the vertex with the largest sum of the squared track  $p_T$  ( $\sum p_{T,\text{track}}^2$ ).

Electrons, muons, and jets are defined for this analysis at two levels: “baseline” and “signal quality.” Baseline objects are used as inputs to the  $\vec{p}_T^{\text{miss}}$  calculation and overlap removal, while signal-quality objects are used for event selections. A summary of the  $p_T$  and  $\eta$  requirements on signal-quality objects is shown in Table II. Electrons are

TABLE II. Summary of the  $p_T$  and  $\eta$  requirements for signal-quality objects. Signal-quality electrons and jets use the same requirements in Run 2 and Run 3.

| Signal-quality object | $p_T$ [GeV] | $ \eta $ |
|-----------------------|-------------|----------|
| Electrons             | $> 40$      | $< 2.47$ |
| Muons (Run 2)         | $> 40$      | $< 2.7$  |
| Muons (Run 3)         | $> 40$      | $< 2.5$  |
| Jets                  | $> 20$      | $< 2.8$  |

reconstructed as described in Ref. [85] and are calibrated based on the procedure and results described in Refs. [85,86]. For Run 3, there are additional corrections on the *in situ* scale and resolution corrections that account for small differences in the ATLAS reconstruction software, increased uncertainties to reflect the Run 3 pileup conditions, and a change in optimal filtering coefficients for the LAr calorimeter readout. Baseline electrons are required to satisfy the *Loose* likelihood identification criteria with at least one  $B$ -layer hit [87] and have  $p_T > 10$  GeV,  $|\eta| < 2.47$ , and a selection of  $|z_0 \sin(\theta)| < 0.5$  mm on the longitudinal impact parameter  $z_0$ . Baseline electrons that survive the overlap removal procedure described at the end of this section, satisfy the *Loose* (*Tight*) isolation requirements [87] in Run 2 (Run 3), satisfy the *Tight* identification criteria, have  $p_T > 40$  GeV, and have a transverse impact parameter significance  $|d_0|/\sigma(d_0) < 5$  are labeled as signal-quality electrons. The large  $p_T$  threshold is used to suppress jets and photons misidentified as electrons.

Muons are identified using tracks in the ID and MS and are calibrated to match data [88,89]. Baseline muons are required to satisfy the *Medium* identification requirement [90] and have  $p_T > 10$  GeV,  $|\eta| < 2.7$ , and a selection of  $|z_0 \sin(\theta)| < 0.5$  mm. For Run 3, baseline muons are also required to have  $|\eta| < 2.5$ . Other selections and requirements match those used in Run 2. Muons with transverse impact parameter  $|d_0| \geq 0.2$  mm or longitudinal impact parameter  $|z_0| \geq 1$  mm are removed to reject muons originating from cosmic-ray interactions, and events containing baseline muons flagged as bad due to misalignments between the inner detector and muon spectrometer are vetoed. Baseline muons that survive overlap removal, satisfy the *Loose* isolation working point, satisfy the *HighPt* identification criteria [90], have  $p_T > 40$  GeV, and have transverse impact parameter significance  $|d_0|/\sigma(d_0) < 3$  are labeled signal-quality muons. Events with signal-quality muons flagged as bad are again removed, as the criteria are different for the *HighPt* working point. The large  $p_T$  threshold is used to suppress objects misidentified as muons.

Jets are reconstructed using the anti- $k_t$  algorithm [67,68] with a radius parameter of  $R = 0.4$ . This uses particle-flow objects [91] as inputs, which are formed using calorimeter energy clusters [92] and ID tracks. Calibrations are applied

for the jet energy scale and jet energy resolution and include components derived both from simulation and *in situ* measurements [93]. Events containing jets from noncollision backgrounds are vetoed [94]. Baseline jets are required to have  $p_T > 20$  GeV and  $|\eta| < 2.8$ . Baseline jets are used in the overlap removal described below. Baseline jets that survive overlap removal are subjected to jet vertex tagger (JVT) requirements to suppress pileup, with remaining jets labeled signal-quality jets. Jets with  $p_T < 60$  GeV and  $|\eta| < 2.5$  are subjected to the *FixedEffPt* JVT working point [95], while jets with  $p_T < 60$  GeV and  $|\eta| > 2.5$  use the *Loose* forward jet vertex tagger (fJVT) working point [96].

Jets containing  $b$ -hadrons ( $b$ -jets) are identified using the GN2 tagger at a working point corresponding to 77% efficiency as measured in  $t\bar{t}$  events [22]. The tagger uses a transformer-based model utilizing information about secondary vertices and other jet and track properties to identify  $b$ -jets.

Baseline photons are reconstructed as described in Ref. [85]. They are required to satisfy the *Tight* identification working point [85,87] and have  $p_T > 25$  GeV and  $|\eta| < 2.37$ . The *Tight* identification working point removes photons in the crack region of the detector,  $1.37 < |\eta| < 1.52$ . Baseline photons are used in the  $\vec{p}_T^{\text{miss}}$  calculation, but not in the overlap removal procedure described below nor in any analysis selections.

The missing transverse momentum  $\vec{p}_T^{\text{miss}}$ , with magnitude  $E_T^{\text{miss}}$ , is defined as the negative vector sum of the  $p_T$  of all selected and calibrated baseline physics objects in the event, with an extra term added to account for soft energy in the event that is not associated with any of the selected objects [97]. This soft term is calculated from inner detector tracks matched to the primary vertex to make it more resilient to pileup contamination. Jets that fail to meet the JVT requirement are not considered in the  $\vec{p}_T^{\text{miss}}$  calculation, while jets that fail to meet the fJVT requirement are considered.

A procedure is applied to remove overlaps between baseline electrons, muons, and jets. First, any muon that is identified using the calorimeter and shares an ID track with an electron is rejected. Next, any electron sharing an ID track with a remaining muon is removed. If a jet is found to be within  $\Delta R = 0.2$  of a remaining electron, the jet is removed. If an electron is found to be within  $\Delta R = 0.4$  from a remaining jet, the electron is removed. Next, any jet with an associated muon ID track or a muon within  $\Delta R = 0.2$  of its axis is removed if the jet has less than three tracks. Lastly, any muon is removed if it is found to be within  $\Delta R = 0.4$  from any remaining jet.

## V. EVENT SELECTION

The event selection for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow h\ell^\pm h\ell^\mp \rightarrow b\bar{b}\ell^\pm b\bar{b}\ell^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0 \rightarrow h\ell^\pm h\nu \rightarrow b\bar{b}\ell^\pm b\bar{b}\nu$  requires events to have at least four jets, at least two of which must be identified as

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$b$ -jets, and have at least one electron or muon. If there are two or more electrons or muons in an event, the two leading leptons are required to have opposite charge. Reconstructed signal-quality leptons, defined in Sec. IV, have tighter identification working point requirements than applied at online level to ensure high trigger efficiency for selected events. Events are required to have at least one reconstructed signal-quality lepton that activated one of the triggers and has an offline  $p_T$  higher than a trigger-dependent offline threshold. The lowest  $p_T$  thresholds are 27 GeV (27.3 GeV) for electrons (muons) in 2015–2018, while for 2022–2023 they are 27 GeV (25.2 GeV).

### A. Analysis variables

Higgs boson candidates are reconstructed using four jets. If there are four or more  $b$ -jets in an event, the four with the highest  $p_T$  are used. If there are fewer than four  $b$ -jets, all of the  $b$ -jets in the event are used, with the highest  $p_T$  non- $b$ -tagged jets used for the remaining Higgs boson candidate jets. The jets are paired to form two Higgs boson candidates by looking for pairs of jets with a small opening angle  $\Delta R_{jj}(h)$ , where  $\Delta R_{jj}(h)$  is the angular distance between the two jets from the decay of the Higgs boson  $h$  and is calculated for each possible pairing. The jet pairing that minimizes  $\max(\Delta R_{jj}(h_1), \Delta R_{jj}(h_2))$  is chosen. Studies on generator-level signal MC simulations show that this algorithm makes the correct assignment around 40% of the time for low chargino masses, rising to 95% of the time for high chargino masses. The highest  $p_T$  Higgs boson candidate is labeled  $h_1$ , and the other is labeled  $h_2$ . The reconstructed masses of the Higgs boson candidates are referred to as  $m_{h1}$  and  $m_{h2}$ , respectively.

Higgs boson candidates, electrons, muons, and  $\vec{p}_T^{\text{miss}}$  are used to reconstruct chargino and neutralino candidates. First, the four-momentum of each Higgs boson candidate is rescaled by the factor required to yield an invariant mass of 125 GeV to improve the mass resolution of the reconstructed charginos and neutralinos, as studied in signal MC simulation. This correction is only applied for the chargino and neutralino reconstruction. In events with two or more charged leptons, the two Higgs boson candidates and the two leading leptons are used to reconstruct two chargino candidates by pairing each Higgs boson candidate with one lepton. Both possible pairings are tested, and the pairing with the minimum mass asymmetry is selected. The mass asymmetry is defined as

$$\mathcal{A}_C = \frac{|m_{C1} - m_{C2}|}{m_{C1} + m_{C2}}, \quad (1)$$

where the  $m_{C1}$  is the mass of the chargino candidate with the higher reconstructed mass, and  $m_{C2}$  is the mass of the chargino candidate with the lower reconstructed mass. The alternative jet pairing with the maximum mass asymmetry is used to define the variable  $m_{C2}^{\text{rej}}$ , which corresponds to the

lower of the two reconstructed chargino candidate masses in that “rejected” pairing. In events with only one charged lepton, one Higgs boson candidate is paired with the lepton to form a chargino candidate, while the other is paired with the  $\vec{p}_T^{\text{miss}}$  (representing the neutrino in the signal model) to form a neutralino candidate. The one-lepton channel is optimized to search for high-mass charginos and neutralinos, which tend to each decay into a back-to-back Higgs boson and lepton. The pairing that maximizes the  $\Delta R$  between the Higgs boson candidate and the charged lepton is therefore used. As only the transverse component of the neutrino momentum is available (from  $\vec{p}_T^{\text{miss}}$ ), the mass of the neutralino cannot be fully reconstructed. Instead, the neutralino’s transverse mass  $m_{N,T} = m_T(h, \vec{p}_T^{\text{miss}})$  is used. The transverse mass of objects  $i, j$  is calculated as

$$m_T(i, j) = \sqrt{m_i^2 + m_j^2 + 2(E_{T,i}E_{T,j} - p_{T,i}p_{T,j}\cos(\Delta\phi_{ij}))}, \quad (2)$$

where  $\Delta\phi_{ij}$  is the transverse angular separation between the objects, and  $E_{T,i} = \sqrt{m_i^2 + p_{T,i}^2}$ . The  $\vec{p}_T^{\text{miss}}$  is assumed to come from a massless neutrino. For both one-lepton and two-lepton regions,  $H_T$  is defined as the scalar sum of  $p_T$  of the four jets and one to two charged leptons used in the chargino and neutralino reconstruction.

### B. Region definitions

Two signal regions (SRs) are defined for this analysis, SR2 $\ell$  and SR1 $\ell$ . These regions are used to search for new physics in a simultaneous fit, described in more detail in Secs. VI and VIII. Their definitions, as well as those of the control and validation regions described in Sec. VI, are shown in Tables III and IV, respectively. Each region has a Run 2 and a Run 3 counterpart, using the same definitions.

SR2 $\ell$  targets  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production in events with two leptons (2 $\ell$ ). The reconstructed Higgs boson masses,  $m_{h1}$  and  $m_{h2}$ , are required to be close to the Higgs boson mass of 125 GeV. The  $m_{h2}$  requirements are shifted to lower masses as muons and neutrinos from  $b$ -hadron decays can lead to an underestimate of the Higgs boson mass. The  $H_T$  selection is used to reject lower-energy background processes, while the requirement that the dilepton invariant mass  $m_{\ell\ell}$  is at least 15 GeV higher than the  $Z$  boson mass is used to reject processes with leptonic  $Z$  decays including  $t\bar{t}Z$ ,  $Z$  + jets, and diboson production. The  $\mathcal{A}_C$  requirement rejects background processes by ensuring that the two reconstructed chargino masses are consistent. The prefit distribution of  $\mathcal{A}_C$  in Run 2 SR2 $\ell$  without this selection is shown in Fig. 2(a). The  $m_{C2}^{\text{rej}}$  selection reduces  $t\bar{t}$  backgrounds. SR2 $\ell$  is binned in  $m_{C1}$ , using eight bins with lower bin edges of [125, 175, 225, 300, 400, 500, 600, 700] GeV, where the last bin includes all events with  $m_{C1} > 700$  GeV. The bins

TABLE III. Summary of the signal, control, and validation regions used for the two-lepton analysis regions targeting  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  signals. All regions require at least four jets and two oppositely charged leptons. Each region has both a Run 2 and a Run 3 version, which use the same definition.

| Region        | $N_{b\text{-jet}}$ | $m_{h1}$ [GeV]      | $m_{h2}$ [GeV]     | $H_T$ [GeV] | $m_{\ell\ell}$ [GeV] | $A_C$   | $m_{C2}^{\text{rej}}$ [GeV] | $m_{C1}$ [GeV] |
|---------------|--------------------|---------------------|--------------------|-------------|----------------------|---------|-----------------------------|----------------|
| SR2 $\ell$    | $\geq 3$           | $\in [100, 150]$    | $\in [85, 135]$    | $> 400$     | $> 106.2$            | $< 0.2$ | $> 200$                     | $\dots$        |
| CR2 $\ell$ 2b | 2                  | $\in [100, 150]$    | $\in [85, 135]$    | $\dots$     | $> 106.2$            | $< 0.2$ | $< 200$                     | $< 500$        |
| CR2 $\ell$ 3b | $\geq 3$           | $\notin [100, 150]$ | $\notin [85, 135]$ | $> 400$     | $> 106.2$            | $> 0.2$ | $\dots$                     | $< 700$        |
| VR2 $\ell$ 2b | 2                  | $\in [100, 150]$    | $\in [85, 135]$    | $\dots$     | $> 106.2$            | $< 0.2$ | $> 200$                     | $< 500$        |
| VR2 $\ell$ 3b | $\geq 3$           | $\notin [100, 150]$ | $\in [85, 135]$    | $> 400$     | $> 106.2$            | $> 0.2$ | $\dots$                     | $\dots$        |

TABLE IV. Summary of the signal, control, and validation regions used for the one-lepton analysis regions targeting  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  signals. All regions require at least four jets and one lepton. Each region has both a Run 2 and a Run 3 version, which use the same definition.

| Region         | $N_{b\text{-jet}}$ | $m_{h1}$ [GeV]      | $m_{h2}$ [GeV]     | $H_T$ [GeV] | $m_{T,\text{min}}^{b\text{-jets}}$ [GeV] | $E_T^{\text{miss}}$ [GeV] | $m_T^\ell$ [GeV] |
|----------------|--------------------|---------------------|--------------------|-------------|------------------------------------------|---------------------------|------------------|
| SR1 $\ell$     | $\geq 3$           | $\in [100, 150]$    | $\in [85, 135]$    | $> 800$     | $> 80$                                   | $> 150$                   | $> 100$          |
| CR1 $\ell$ 3b  | $\geq 3$           | $\notin [100, 150]$ | $\notin [85, 135]$ | $> 800$     | $> 80$                                   | $> 150$                   | $\leq 100$       |
| VR1 $\ell$ 3b1 | $\geq 3$           | $\notin [100, 150]$ | $\in [85, 135]$    | $> 800$     | $> 80$                                   | $> 150$                   | $\leq 100$       |
| VR1 $\ell$ 3b2 | $\geq 3$           | $\notin [100, 150]$ | $\notin [85, 135]$ | $> 800$     | $> 80$                                   | $> 150$                   | $> 100$          |

start at 125 GeV as the chargino must be heavier than the Higgs boson. The bins are narrower at low masses to capture features of the distribution and wider at high masses to avoid creating bins with very low event counts. The expected prefit distribution of  $m_{C1}$  in Run 2 SR2 $\ell$  using this binning is shown in Fig. 2(b).

SR1 $\ell$  targets  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production in events with one lepton (1 $\ell$ ). This region makes use of the higher cross section relative to  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  to provide increased signal yields for high-mass signals. Similarly to SR2 $\ell$ , the two reconstructed Higgs boson candidates are required to have masses consistent with the Higgs boson mass. The  $H_T$  selection of 800 GeV is tighter than for SR2 $\ell$ , as SR1 $\ell$  is optimized for higher mass signals that yield higher  $H_T$  values. The minimum transverse mass of the  $\vec{p}_T^{\text{miss}}$  and any of the three leading  $b$ -jets is labeled  $m_{T,\text{min}}^{b\text{-jets}}$ , computed with the  $b$ -jet mass set to 0 GeV. For  $t\bar{t}$  events with a single leptonic  $W$  boson decay,  $m_{T,\text{min}}^{b\text{-jets}}$  has an upper bound of  $\sqrt{m_t^2 - m_W^2} \approx 150$  GeV and is used to further reduce the semileptonic  $t\bar{t}$  background. Events with low  $E_T^{\text{miss}}$  are rejected because signals have high  $E_T^{\text{miss}}$  values due to the energetic neutrino from the neutralino decay. The transverse mass of the lepton and  $\vec{p}_T^{\text{miss}}$  [ $m_T^\ell$ , see Eq. (2)] is required to be above the  $W$  boson mass to reject events with leptonic  $W$  boson decays from processes such as  $t\bar{t}$ ,  $t\bar{t}W$ , single-top (including  $Wt$ ), and diboson production. SR1 $\ell$  uses a single bin due to the low predicted event count. The expected prefit distribution of  $m_{N,T}$  in Run 2 SR1 $\ell$  is shown in Fig. 2(c).

Four regions, referred to as “discovery regions,” are used to obtain results on new physics, independent of a specific signal hypothesis. The first two, SR2 $\ell$  and SR1 $\ell$ , are single-bin regions matching the definitions for the SRs in

Tables III and IV. In addition, SR2 $\ell$ 700 is defined as SR2 $\ell$  with an additional requirement of  $m_{C1} > 700$  GeV and is equivalent to the last bin of SR2 $\ell$ . Finally, SR1 $\ell$ 600 is defined as SR1 $\ell$  with an additional requirement on the transverse mass of the neutralino  $m_{N,T} > 600$  GeV. Each of these four regions is defined for both Run 2 and Run 3 as they cannot be combined in a model-independent way due to the different center-of-mass energies.

## VI. BACKGROUND ESTIMATION

The background is estimated by using the MC simulation samples described in Sec. III. The main backgrounds are from  $t\bar{t}$  ( $t\bar{t} + \geq 1b$ ,  $t\bar{t} + \geq 1c$ , and  $t\bar{t} + \text{light}$ ) production and are normalized to data in control regions (CRs). Separate normalizations are used for the one-lepton and two-lepton regions due to the different phase space. The largest contribution in the SRs is given by  $t\bar{t} + \geq 1b$  production. Smaller backgrounds that are present in this search are  $t\bar{t}h$ ,  $t\bar{t}Z$ ,  $t\bar{t}W$ , single-top,  $Z + \text{jets}$ ,  $W + \text{jets}$ , and diboson production. These backgrounds, referred to as minor backgrounds, collectively constitute less than 10% of the prefit expected background in SR2 $\ell$  and less than a third of the prefit expected background in SR1 $\ell$ .

Two CRs, CR2 $\ell$ 2b and CR2 $\ell$ 3b, are used to measure the normalizations of dileptonic  $t\bar{t}$  backgrounds. Separate normalizations are determined for Run 2 and Run 3 due to differences in the experimental setup and simulations. These CRs are defined in Table III. CR2 $\ell$ 3b is constructed by inverting the SR2 $\ell$  selections on  $m_{h1}$ ,  $m_{h2}$ , and  $A_C$  to select a region with low signal contribution while removing the requirements on  $m_{C2}^{\text{rej}}$  to further reduce signal contamination and lower the statistical uncertainty. An additional

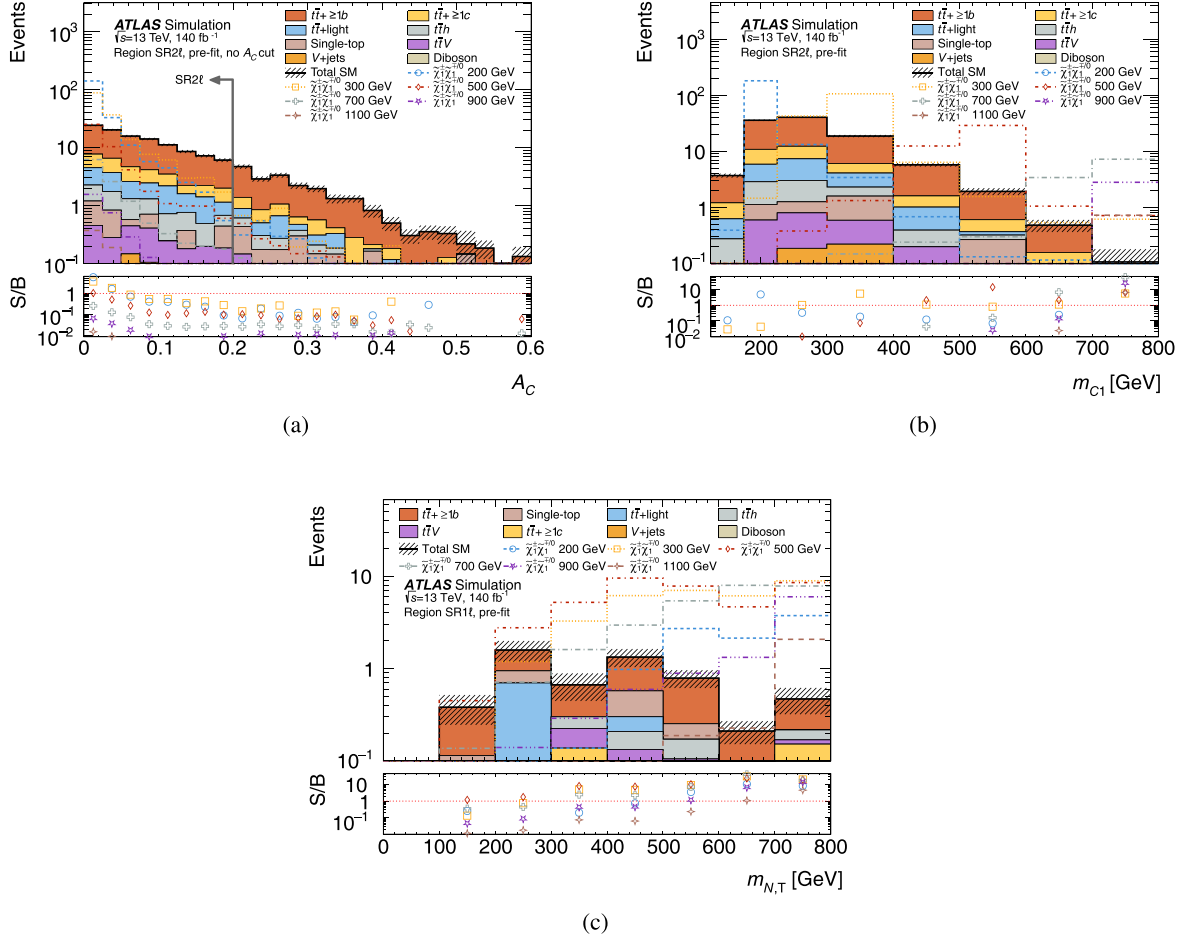


FIG. 2. Expected Run 2 prefit distributions for signal and background samples for (a) the mass asymmetry  $A_C$  in  $\text{SR}2\ell$  before the  $A_C$  selection, (b) the higher mass of the two reconstructed chargino candidates  $m_{C1}$  in  $\text{SR}2\ell$ , and (c) the transverse mass of the neutralino  $m_{N,T}$  in  $\text{SR}1\ell$ . The lower panels show the signal to background ratios. The hatching shows the MC statistical uncertainty in the predicted background yields. The sum of the signal contributions from  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  is shown, assuming  $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h\ell^\pm) = 100\%$  and  $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h\nu) = 100\%$ , with equal decay branching fractions to each lepton flavor. The generator-level signal masses are shown in the legend. Overflow is included in the last bin.

requirement is placed on  $m_{C1}$  to prevent contributions from signals with large chargino masses. This region is used to measure a common normalization factor for  $\tilde{t}\tilde{t} + \geq 1b$  and  $\tilde{t}\tilde{t} + \geq 1c$  production, referred to as  $\tilde{t}\tilde{t} + \text{HF}$  (heavy flavor). MC simulation predicts similar relative contributions from  $\tilde{t}\tilde{t} + \geq 1b$  and  $\tilde{t}\tilde{t} + \geq 1c$  in  $\text{CR}2\ell 3b$  and  $\text{SR}2\ell$ , allowing a joint measurement with smaller statistical uncertainty. The  $\tilde{t}\tilde{t} + \text{HF}$  purity in this region is over 80%. The expected signal contributions are found to be less than 8% of the prefit expected background for any signal mass hypothesis.

$\text{CR}2\ell 2b$  is used to measure the  $\tilde{t}\tilde{t} + \text{light}$  normalization. This uses events with only two  $b$ -jets, as  $\tilde{t}\tilde{t}b\bar{b}$  events have four true  $b$ -jets, and  $\tilde{t}\tilde{t} + \geq 1c$  events are more likely than  $\tilde{t}\tilde{t} + \text{light}$  events to have a third reconstructed  $b$ -jet due to the higher charm mistagging rate compared to light jets. Contributions from signals are limited by inverting the  $\text{SR}2\ell$  selection on  $m_{C2}^{\text{rej}}$  and removing the requirement on  $H_T$ . An upper bound is placed on  $m_{C1}$  to prevent

contributions from signals with large chargino masses.  $\text{CR}2\ell 2b$  has a  $\tilde{t}\tilde{t} + \text{light}$  purity of approximately 80%. The expected signal contributions are found to be less than 2% of the prefit expected background for any signal mass hypothesis.

$\text{CR}1\ell 3b$  is used to measure the normalization of semileptonic  $\tilde{t}\tilde{t}$  backgrounds. Separate normalizations are determined for Run 2 and Run 3. This measures a common normalization factor for all semileptonic  $\tilde{t}\tilde{t}$  backgrounds ( $\tilde{t}\tilde{t} + \geq 1b$ ,  $\tilde{t}\tilde{t} + \geq 1c$ , and  $\tilde{t}\tilde{t} + \text{light}$ ), jointly referred to as  $\tilde{t}\tilde{t} 1\ell$ . These are measured jointly to lower the statistical uncertainty, as the  $\tilde{t}\tilde{t} + \geq 1c$  and  $\tilde{t}\tilde{t} + \text{light}$  backgrounds are expected to contribute a total of less than one event in  $\text{SR}1\ell$  and therefore do not require separate measurements. The dominant background component in  $\text{SR}1\ell$  and  $\text{CR}1\ell 3b$  is  $\tilde{t}\tilde{t} + \geq 1b$ .  $\text{CR}1\ell 3b$  is defined in Table IV and is constructed by inverting the  $\text{SR}1\ell$  requirements on  $m_{h1}$ ,  $m_{h2}$ , and  $m_T^\ell$  to reduce signal contributions. The  $\tilde{t}\tilde{t} 1\ell$  purity in this region

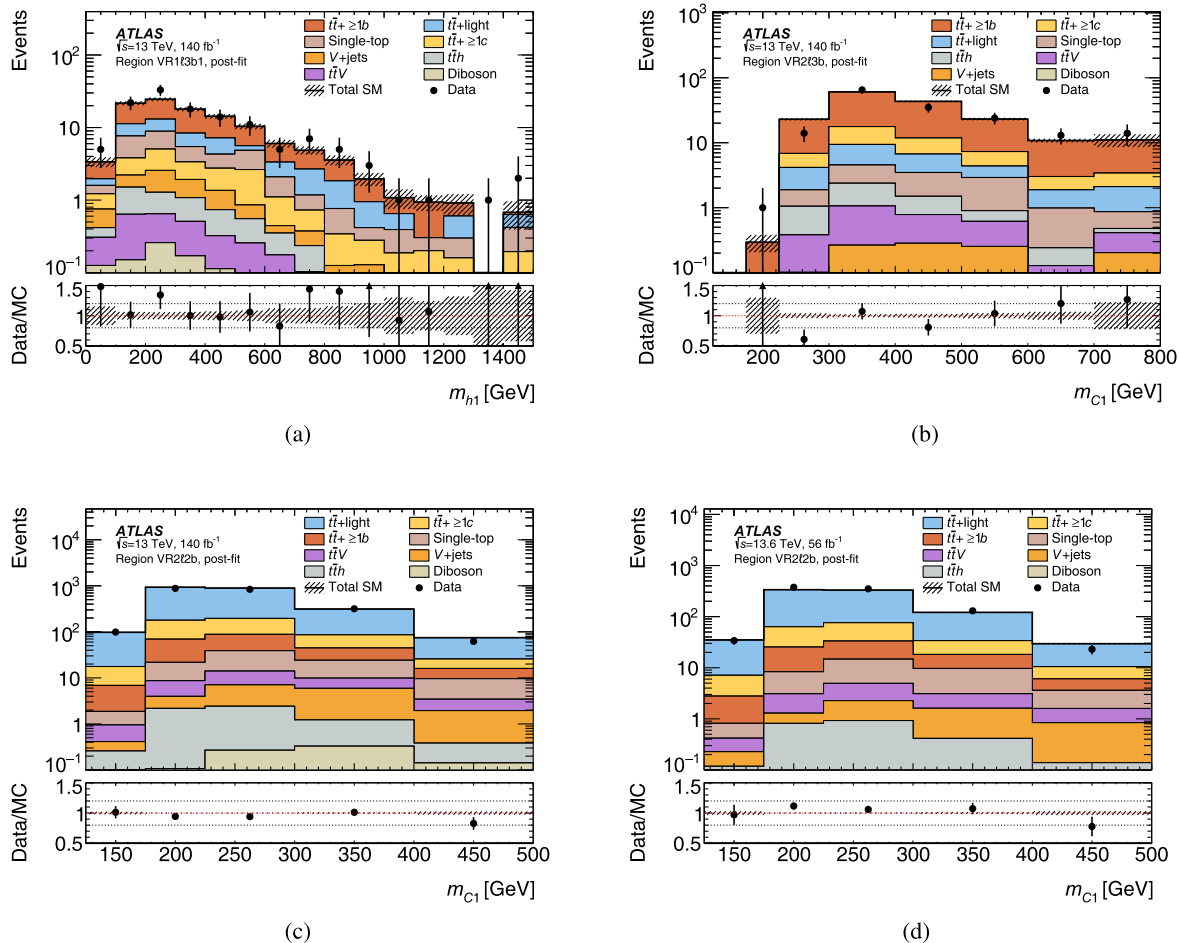


FIG. 3. Data and background distributions in the validation regions for (a) the  $m_{h1}$  distribution in Run 2 VR1 $\ell$ 3b1, (b) the  $m_{C1}$  distribution in Run 2 VR2 $\ell$ 3b, (c) the  $m_{C1}$  distribution in Run 2 VR2 $\ell$ 2b, and (d) the  $m_{C1}$  distribution in Run 3 VR2 $\ell$ 2b. The backgrounds are calculated using prefit values but with the normalization factors measured from the CR background-only fit applied. The hatching shows the MC statistical uncertainty in the predicted background yields. The lower panels show the ratio of data to predicted background. Overflow is included in the last bin.

is over 80%, while the expected signal contributions are found to be less than 1% of the prefit expected background for any signal mass hypothesis.

Validation regions (VRs) are constructed to test the extrapolation of the background model from the CRs to the SRs. These regions are defined to fall in the phase space between their corresponding CR and SR, as shown in Tables III and IV. VR2 $\ell$ 2b and VR2 $\ell$ 3b test the extrapolations over  $m_{C2}^{\text{rej}}$  and  $m_{h2}$ , respectively, while VR1 $\ell$ 3b1 and VR1 $\ell$ 3b2 test the extrapolations over  $m_{h2}$  and  $m_T^\ell$  respectively. The expected signal contributions are found to be less than 12% of the prefit expected background in each VR for any signal mass hypothesis.

The agreement between data and predicted backgrounds for different variables are checked in each CR and VR except VR1 $\ell$ 3b2. This region is only checked in a single bin as it has high signal contamination in some kinematic

regimes. Reconstructed chargino and Higgs boson masses are shown for the VRs in Fig. 3, where good modeling of the SM background is seen.

### A. Background-only fit results

Profile-likelihood fits are performed to measure the agreement between data and predicted background. There are six free-floating background normalization factors in total. Each Run has two normalization factors for  $t\bar{t} + \text{HF}$  and  $t\bar{t} + \text{light flavor}$  production in two-lepton regions and one normalization factor for  $t\bar{t}$  production in one-lepton regions. The MC statistical uncertainties and the systematic uncertainties described in Sec. VII are treated as nuisance parameters. Unless otherwise noted, all fits use these six normalization factors and both one-lepton and two-lepton regions in both Run 2 and Run 3. All fits are performed using the PYHF framework [98,99].

TABLE V. Fit results for normalization factors from the background-only fit in the CRs. The first listed uncertainties are from the fit using all systematic and statistical uncertainties, while the values in parentheses are determined from the fit using only statistical uncertainties. Due to correlations between the normalization factors and systematic uncertainties, the relative uncertainties in the predicted background yields may be smaller than those on the normalization factors.

| Process (Channel)                 | Run 2 norm. factor                      | Run 3 norm. factor                      |
|-----------------------------------|-----------------------------------------|-----------------------------------------|
| $t\bar{t} + \text{HF} (2\ell)$    | $1.16 \pm 0.46 (\pm 0.06 \text{ stat})$ | $1.08 \pm 0.42 (\pm 0.10 \text{ stat})$ |
| $t\bar{t} + \text{light} (2\ell)$ | $0.93 \pm 0.20 (\pm 0.03 \text{ stat})$ | $0.85 \pm 0.20 (\pm 0.05 \text{ stat})$ |
| $t\bar{t} (1\ell)$                | $0.88 \pm 0.33 (\pm 0.06 \text{ stat})$ | $1.01 \pm 0.45 (\pm 0.08 \text{ stat})$ |

A background-only fit is performed in the CRs using a single bin for each region. The measured normalization factors are shown in Table V.

Results from the background-only fit are extrapolated to the VRs, with the agreement between data and the postfit background prediction shown in Fig. 4. No significant mismodeling is observed. The largest deviation in yield between data and predicted background is  $1.2\sigma$ , which is seen in Run 3 VR2 $\ell$ 2b.

## VII. SYSTEMATIC UNCERTAINTIES

Predicted signal and background MC simulation yields are subject to uncertainties. Three types of uncertainties are applied: experimental uncertainties, theoretical uncertainties, and MC statistical uncertainties.

Experimental uncertainties account for systematic effects in ATLAS calibration procedures and efficiency

measurements and are applied to all signal and background MC simulations. Experimental jet uncertainties are applied on the jet energy scale and resolution [91–93], JVT [95] and fJVT [96], and flavor tagging efficiencies [22]. Experimental muon uncertainties include uncertainties on the muon isolation, reconstruction, and trigger efficiency correction factors [26,33,88–90]. Additional systematic uncertainties affect the muon momenta due to variations in the momentum scale, track resolution, and charge-dependent corrections. For electrons, experimental uncertainties are applied on the identification, isolation, reconstruction, and trigger efficiency correction factors, as well as on the energy scale and resolution [26,32,87,101]. Scale and resolution uncertainties are applied on the  $E_T^{\text{miss}}$  soft term [97,102]. Further experimental uncertainties considered are on the pileup conditions [103] and luminosity [28,29]. Luminosity uncertainties are not applied to  $t\bar{t}$  and  $t\bar{t}b\bar{b}$  backgrounds as they rely on data-driven normalization measurements. Uncertainties related to electrons,  $E_T^{\text{miss}}$ , and most of the jet energy scale and resolution components are correlated between Run 2 and Run 3, while the remaining uncertainties are not correlated between Runs. The largest experimental uncertainties are related to the jet energy resolution. As measured using the background-only fit extrapolated to the signal regions, these are collectively 1.3% (3.5%) of the postfit yields in Run 2 (Run 3) SR2 $\ell$  and 23% (35%) of the postfit yields in the Run 2 (Run 3) SR1 $\ell$ .

Theoretical uncertainties are applied to the background and signal MC samples. These uncertainties are evaluated by comparing simulations using nominal values of theory parameters with alternative or reweighted samples using variations on these parameters. Uncertainties in the matrix element, parton shower model, factorization and renormalization scales, modeling of initial and final-state radiation, parton distribution functions, and strong coupling constant are applied to the  $t\bar{t} + \geq 1b$ ,  $t\bar{t} + \geq 1c$ , and  $t\bar{t} + \text{light}$  backgrounds. The matrix element and parton shower uncertainties are calculated by comparing the nominal samples to samples generated with the PYTHIA 8  $p_{T,\text{hard}}$  parameter set to 1.0 and with the HERWIG7 parton shower model [104–107], respectively. In addition, uncertainties on the  $h_{\text{damp}}$  parameter are applied to the  $t\bar{t} + \geq 1c$  and

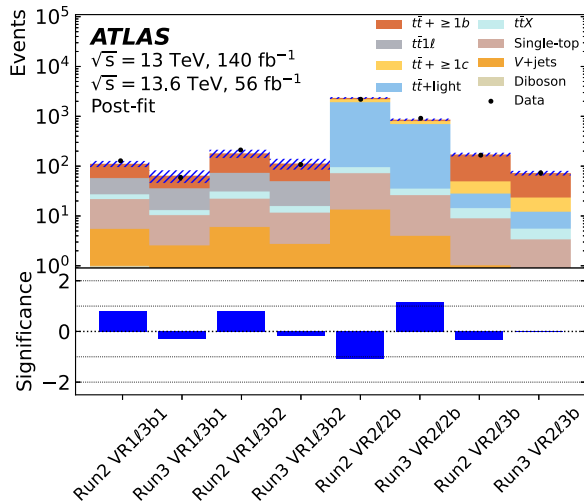


FIG. 4. Data and postfit background yields as determined from the background-only fit extrapolated to the validation regions. The hatching shows the uncertainty in the predicted yields from MC statistical and systematic effects. The lower panel shows the significance of the deviations between data and predicted background. The  $t\bar{t} 1\ell$  category includes all  $t\bar{t} + \geq 1c$  and  $t\bar{t} + \text{light}$  production with one reconstructed lepton.  $t\bar{t}X$  includes  $t\bar{t}h$ ,  $t\bar{t}Z$ , and  $t\bar{t}W$  production. Significances are calculated following the method in Ref. [100].

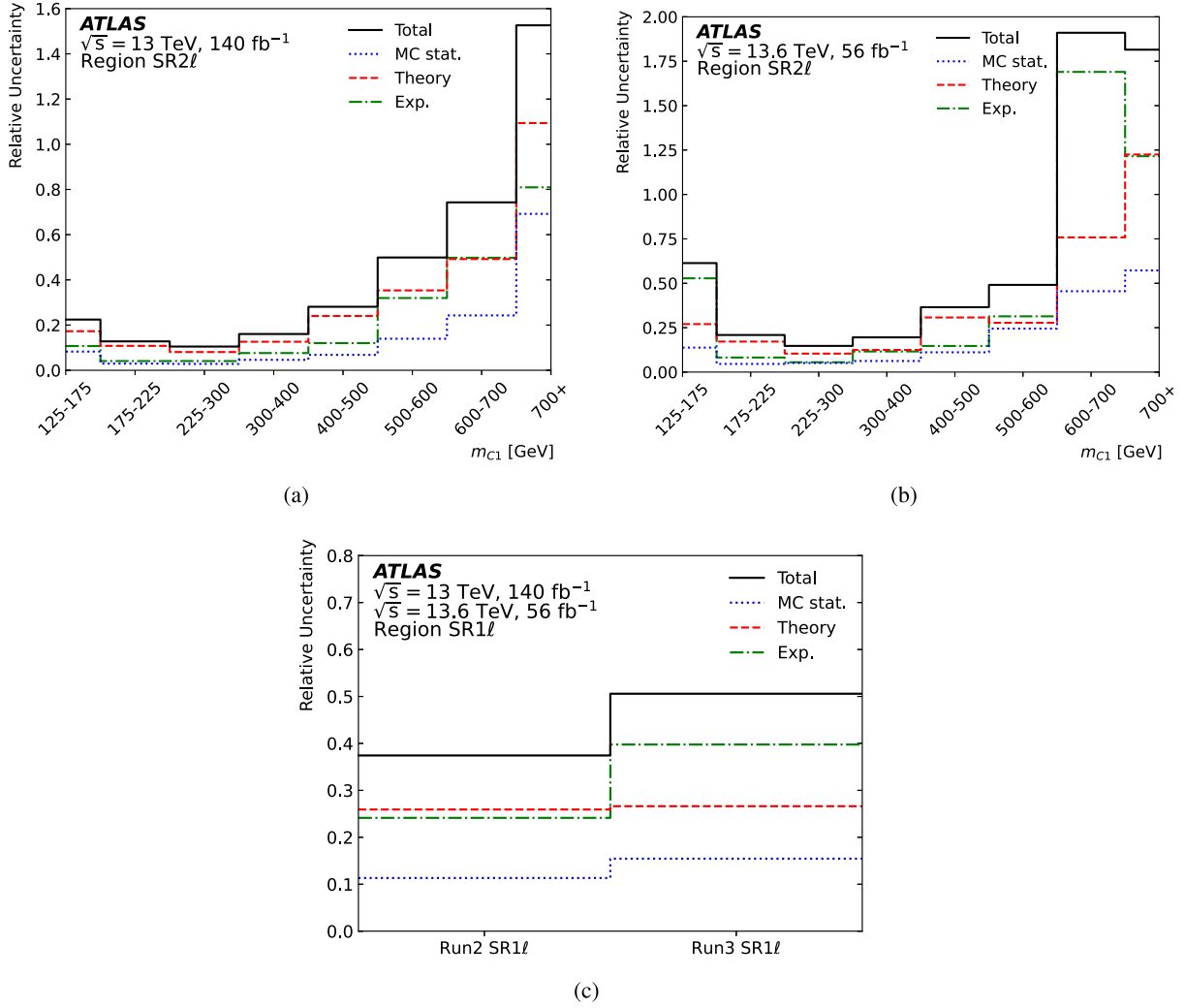


FIG. 5. Background uncertainties as a fraction of total postfit yields as determined from the background-only fit extrapolated to the signal regions for (a) Run 2 SR2 $\ell$ , (b) Run 3 SR2 $\ell$ , and (c) Run 2 and Run 3 SR1 $\ell$ . Exp. stands for the experimental uncertainty, while MC stat. stands for MC statistical uncertainty. The total uncertainty includes systematic and MC statistical uncertainties. The total uncertainty is not necessarily equal to the quadrature sum of the individual uncertainties due to correlations.

$t\bar{t}$  + light backgrounds by comparing the nominal samples to samples produced with the  $h_{\text{damp}}$  parameter set to 3.0  $m_{\text{top}}$ . A 50% normalization uncertainty is applied to each of the remaining background samples ( $t\bar{t}h$ ,  $t\bar{t}V$ , single- $t$ ,  $V$  + jets, and diboson). As the background is dominated by  $t\bar{t}$  and  $t\bar{t}b\bar{b}$  and the analysis is statistically limited, the uncertainties on these minor backgrounds have no significant impact on the results. Background theoretical uncertainties are correlated between Run 2 and Run 3 but are not correlated between one-lepton and two-lepton regions due to the different phase space. The largest theoretical uncertainties in SR2 $\ell$  are from the parton shower model. As measured using the background-only fit extrapolated to the signal regions, these are collectively 4.2%–6.0% of the postfit yields in the two-lepton SRs, depending on the Run. The largest theoretical uncertainties in SR1 $\ell$  are from the modeling of final-state radiation and the parton shower

modeling. As measured using the background-only fit extrapolated to the signal regions, these are each 3%–20% of the postfit yields in the one-lepton SRs, depending on the uncertainty and Run. For signal samples, uncertainties on the factorization and renormalization scales, merging scale, parton shower tuning, parton distribution function, and  $\alpha_s$  are considered. The factorization and renormalization scale uncertainties are the largest of these, ranging from 6.1%–11% for  $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$  signals in SR2 $\ell$  and 8.4%–12.6% for  $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$  signals in SR1 $\ell$ , depending on the mass point.

The effects of different sources of uncertainties on the SR2 $\ell$  and SR1 $\ell$  postfit background yields are shown in Fig. 5. Background theory uncertainties are larger than experimental uncertainties in Run 2, while for Run 3 experimental uncertainties are larger than theoretical uncertainties in SR1 $\ell$  and some bins of SR2 $\ell$ . MC statistical

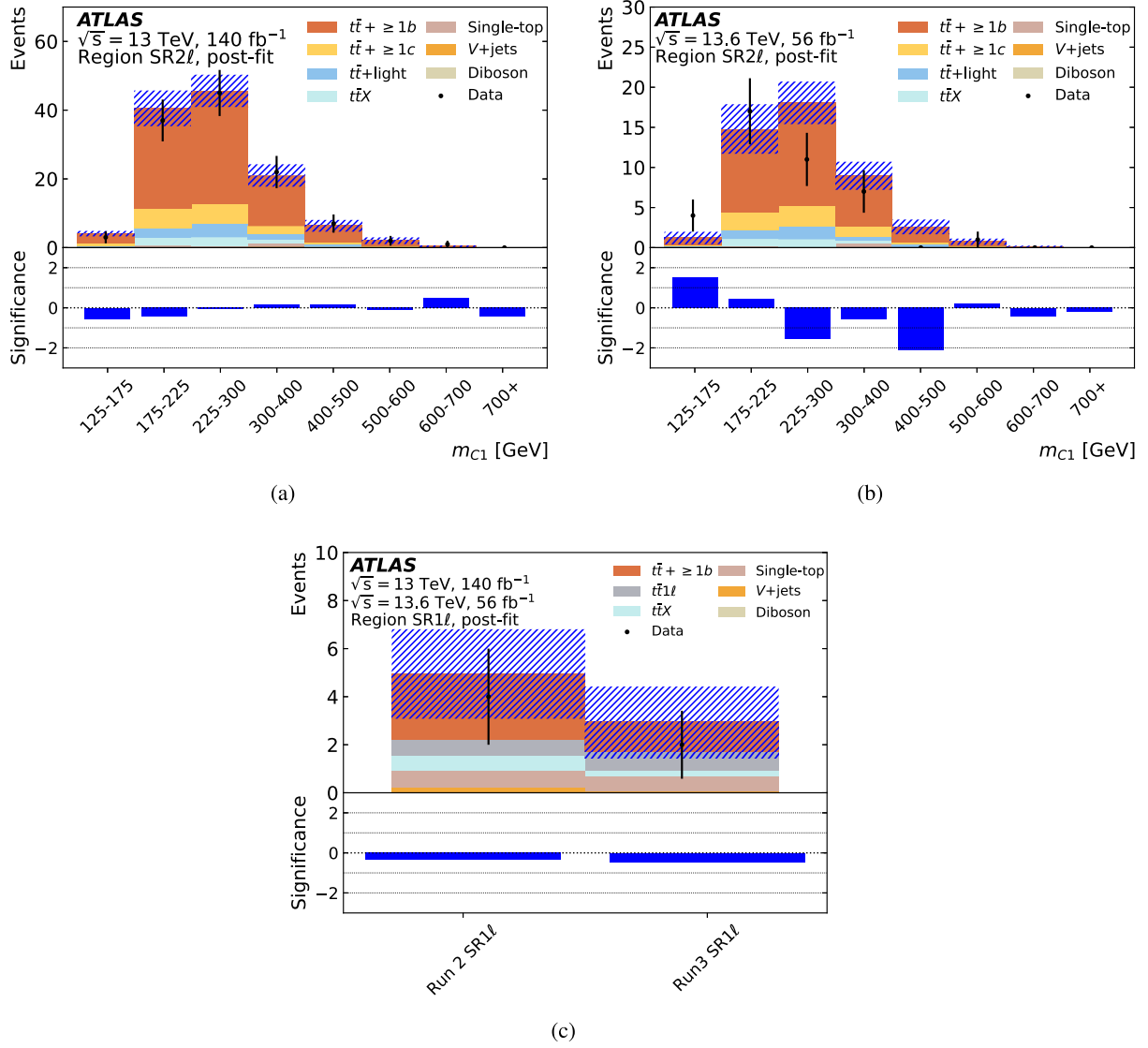


FIG. 6. Data and postfit background yields as determined from the background-only fit extrapolated to the signal regions for (a) Run 2 SR2 $\ell$ , (b) Run 3 SR2 $\ell$ , and (c) Run 2 and Run 3 SR1 $\ell$ . The hatching shows the uncertainty in the predicted yields from MC statistical and systematic effects. The lower panel shows the significance of the deviations between data and predicted background. The  $t\bar{t}\ell\ell$  category includes all  $t\bar{t} + \geq 1c$  and  $t\bar{t} + \text{light}$  production with one reconstructed lepton.  $t\bar{t}X$  includes  $t\bar{t}h$ ,  $t\bar{t}Z$ , and  $t\bar{t}W$  production. Significances are calculated following the method in Ref. [100].

uncertainties are smaller than both background theory and experimental uncertainties. SR1 $\ell$  and the high- $m_{C1}$  bins in SR2 $\ell$  have low MC event statistics, making the systematic uncertainty estimates prone to statistical fluctuations.

## VIII. RESULTS

Results are obtained using three types of fits. First, the results of the background-only fit described in Sec. VI are extrapolated to the SRs to show the level of agreement between data and predicted background. Second, fits are performed in each discovery region to search for evidence for and set constraints on new physics in a model-independent manner. Third, an exclusion fit is performed

in the SRs to set limits on the simplified model described in Sec. I.

### A. Background-only fit results

Results from the background-only fit performed in the CRs (described in Sec. VI) are extrapolated to the SRs. The agreement between data and the postfit background prediction is shown for SR1 $\ell$  and each bin of SR2 $\ell$  in Fig. 6. Note that the discovery region SR2 $\ell$ 700 is defined as the last bin of SR2 $\ell$ . No significant excess is observed. The largest excess observed is in the 125 GeV–175 GeV bin of Run 3 SR2 $\ell$ , with four observed events and  $1.24 \pm 0.76$  predicted background events. This corresponds to a local

TABLE VI. Results for the model-independent discovery regions. The second column shows the number of observed events ( $N_{\text{obs}}$ ), while the third column shows the postfit number of predicted events obtained using a background-only fit ( $N_{\text{pred}}$ ). The fourth column shows the 95% CL observed upper limit on the efficiency times cross section of beyond-the-SM processes ( $\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$  [fb]). The fifth and sixth columns show the 95% CL observed ( $S_{\text{obs}}^{95}$ ) and expected ( $S_{\text{exp}}^{95}$ ) upper limits on the number of events from processes beyond the SM, with the  $\pm 1\sigma$  uncertainty included with the expected limit. Uncertainties in  $S_{\text{exp}}^{95}$  less than 0.05 are reported as 0.0 due to rounding. The seventh column shows  $\text{CL}_b$ , the confidence level observed for the background-only hypothesis. The final column shows the discovery  $p$  value [ $p(s=0)$ ] and its significance. The  $p$  value is not calculated but instead set to 0.5 for regions with a deficit relative to the postfit background prediction. SR2 $\ell$  and SR1 $\ell$  are the same regions used for exclusions.

| Region               | $N_{\text{obs}}$ | $N_{\text{pred}}$ | $\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb] | $S_{\text{obs}}^{95}$ | $S_{\text{exp}}^{95}$ | $\text{CL}_b$ | $p(s=0)$    |
|----------------------|------------------|-------------------|-------------------------------------------------------|-----------------------|-----------------------|---------------|-------------|
| Run 2 SR2 $\ell$     | 117              | $120 \pm 10$      | 0.24                                                  | 33                    | $31^{+12}_{-8}$       | 0.58          | 0.50 (0.00) |
| Run 2 SR2 $\ell$ 700 | 0                | $0.11 \pm 0.17$   | 0.022                                                 | 3.1                   | $3.0^{+0.1}_{-0.0}$   | 0.08          | 0.50 (0.00) |
| Run 2 SR1 $\ell$     | 4                | $5.0 \pm 1.9$     | 0.048                                                 | 6.7                   | $6.7^{+2.6}_{-1.6}$   | 0.50          | 0.50 (0.00) |
| Run 2 SR1 $\ell$ 600 | 1                | $0.62 \pm 0.51$   | 0.031                                                 | 4.3                   | $3.3^{+1.3}_{-0.1}$   | 0.78          | 0.13 (1.14) |
| Run 3 SR2 $\ell$     | 40               | $46.4 \pm 6.1$    | 0.27                                                  | 15                    | $18.4^{+7.6}_{-5.2}$  | 0.30          | 0.50 (0.00) |
| Run 3 SR2 $\ell$ 700 | 0                | $0.023 \pm 0.041$ | 0.053                                                 | 3.0                   | $3.0^{+0.0}_{-0.0}$   | 0.95          | 0.50 (0.00) |
| Run 3 SR1 $\ell$     | 2                | $2.9 \pm 1.5$     | 0.078                                                 | 4.4                   | $5.0^{+2.0}_{-1.2}$   | 0.36          | 0.50 (0.00) |
| Run 3 SR1 $\ell$ 600 | 0                | $0.35 \pm 0.36$   | 0.054                                                 | 3.0                   | $3.0^{+0.6}_{-0.0}$   | 0.19          | 0.50 (0.00) |

significance of  $1.5\sigma$ . The largest deficit occurs in the 400 GeV–500 GeV bin of Run 3 SR2 $\ell$ , with zero observed events and  $2.58 \pm 0.94$  predicted background events. This corresponds to a local significance of  $-2.1\sigma$ .

### B. Model-independent results

Model-independent results are obtained for each discovery region of the analysis. A separate fit is performed for each discovery region. For a given fit, CRs and normalization factors corresponding to a different Run or number of leptons than the discovery region are not used. Significances and upper limits are determined, respectively, using the  $q_0$  and  $\tilde{q}_\mu$  test statistics [108] based on the profile likelihood ratio. The upper limits are set at 95% confidence level (CL) using the  $\text{CL}_s$  prescription [109]. Regions with nonzero observed events use 50,000 pseudoexperiments to calculate  $p$  values, limits, and the confidence level observed for the background-only hypothesis,  $\text{CL}_b$ . Regions with zero observed events use 100,000 pseudoexperiments. It is assumed that no signal events enter the CRs. Results are shown in Table VI. No significant excess is observed, and limits are set on the yield and cross section of beyond-the-SM physics processes.

### C. Model-dependent exclusion limits

As no significant excess is observed in the discovery regions, upper limits are set at 95% CL for the simplified signal model for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production with RPV decays  $\tilde{\chi}_1^\pm \rightarrow h\ell^\pm$  and  $\tilde{\chi}_1^0 \rightarrow h\nu$  described in Sec. I. Other decay modes of the charginos and neutralinos are assumed to be negligible after selections and are not considered. The limits are determined for each mass point through signal-plus-background fits using all CRs, Run 2 and Run 3 SR1 $\ell$ , and Run 2 and Run 3 SR2 $\ell$ , with each SR2 $\ell$  binned in  $m_{C1}$ .

The Run 2 and Run 3 counterparts of each region are treated as separate regions. The  $\tilde{q}_\mu$  test statistic [108] with the  $\text{CL}_s$  prescription [109] and the asymptotic approximation are used [108].

Results for the hypothesis where each flavor of charged lepton is equally likely are shown in Fig. 7. SR2 $\ell$  provides most of the sensitivity to low chargino and neutralino masses ( $\lesssim 500$  GeV), while SR1 $\ell$  and SR2 $\ell$  have similar sensitivity to high chargino and neutralino masses. For the branching fractions  $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h\ell^\pm) = 100\%$  and

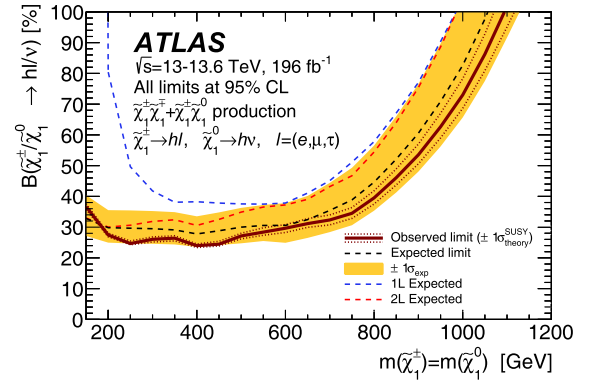


FIG. 7. 95% CL upper limits on  $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h\ell^\pm)$ , with  $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h\nu)$  assumed to be equal, for the hypothesis where the charginos are equally likely to decay into each flavor of charged lepton. The expected and observed limits are shown by the dashed and solid lines, respectively. The shaded bands around the expected limit show the  $\pm 1\sigma$  variations due to statistical and systematic uncertainties, while the dotted bands around the observed limit show the  $\pm 1\sigma$  variations from the theoretical uncertainty on the signal cross section. The expected limits using only one-lepton (two-lepton) regions are shown by the dashed blue and dashed red lines, respectively.

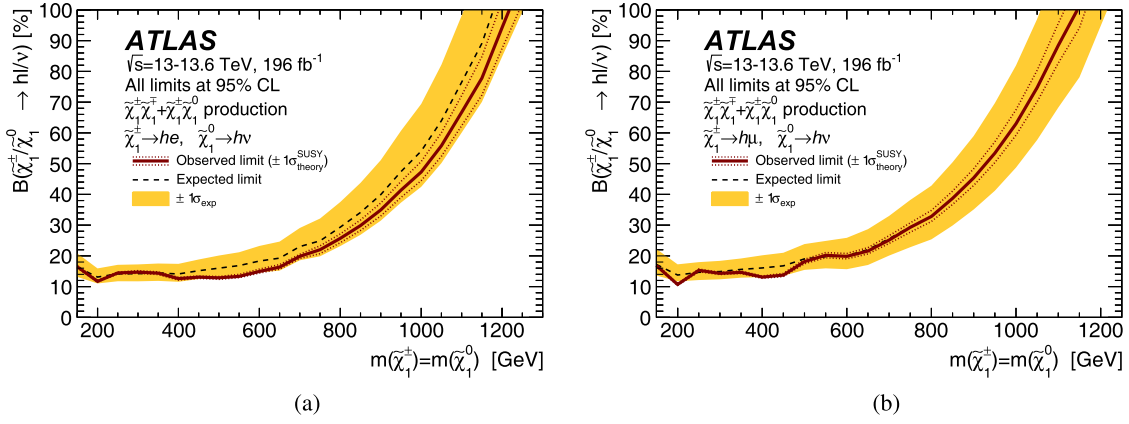


FIG. 8. 95% CL upper limits on  $B(\tilde{\chi}_1^\pm \rightarrow h\ell^\pm \nu)$ , with  $B(\tilde{\chi}_1^0 \rightarrow h\nu)$  assumed to be equal, for (a) the hypothesis where the charged lepton from the decay is always an electron and (b) the hypothesis where the charged lepton from the decay is always a muon. The expected and observed limits are shown by the dashed and solid lines, respectively. The shaded bands around the expected limit show the  $\pm 1\sigma$  variations due to statistical and systematic uncertainties, while the dotted bands around the observed limit show the  $\pm 1\sigma$  variations from the theoretical uncertainty on the signal cross section.

$B(\tilde{\chi}_1^0 \rightarrow h\nu) = 100\%$ , charginos and neutralinos with masses between 150 GeV and 1100 GeV are excluded. This has complementary sensitivity to the previous search for a trilepton resonance [19], which excludes charginos and neutralinos with masses between 100 GeV and 975 GeV for the alternate  $B(\tilde{\chi}_1^\pm \rightarrow Z\ell^\pm) = 100\%$  and  $B(\tilde{\chi}_1^0 \rightarrow Z\nu) = 100\%$  assumptions.

Results are also obtained for alternative flavor hypotheses. In addition to the usual SR requirements, the pure-electron (pure-muon) interpretation requires the reconstructed lepton in SR1 $\ell$  and two leading reconstructed leptons in SR2 $\ell$  to be electrons (muons). Figure 8(a) shows the upper limits for the hypothesis where the charged lepton

from the decay is always an electron, while Fig. 8(b) shows the upper limits for the hypothesis where the charged lepton from the decay is always a muon. Charginos and neutralinos with masses between 150 GeV and 1225 GeV (150 GeV and 1150 GeV) are excluded for the pure-electron (pure-muon) interpretation. Figure 9 shows the upper limits for scenarios with  $B(\tilde{\chi}_1^\pm \rightarrow h\tau^\pm) = 100\%$ , excluding charginos and neutralinos with masses between 450 GeV and 750 GeV. The pure-electron and pure-muon interpretations have greater sensitivity than the pure- $\tau$  scenario because the analysis does not reconstruct hadronically decaying  $\tau$  leptons. In addition, only part of the energy from leptonically decaying  $\tau$  leptons is retained by the daughter electron or muon, which can cause the lepton  $p_T$  to be below the 40 GeV threshold as well as lead to misreconstruction of the chargino pairs. This also causes the pure-electron and pure-muon scenarios to have higher sensitivity than the equal electron, muon, and  $\tau$ -lepton scenario. The pure-electron scenario has slightly higher sensitivity than the pure-muon scenario due to a higher electron reconstruction efficiency.

## IX. CONCLUSION

A search for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production where each chargino and neutralino decays into a Higgs boson and a lepton was performed in a final state with one or two charged leptons and at least four jets, with at least three identified  $b$ -jets. This search complements a previous search for RPV chargino decays into a  $Z$  boson and a lepton in a channel with three or more leptons and provides the first constraints on the simplified signal model for charginos with high decay branching fractions to Higgs bosons and leptons. The data correspond to an integrated luminosity of 196 fb $^{-1}$  of proton-proton collision data produced at center-of-mass energies of  $\sqrt{s} = 13$  TeV and  $\sqrt{s} = 13.6$  TeV,

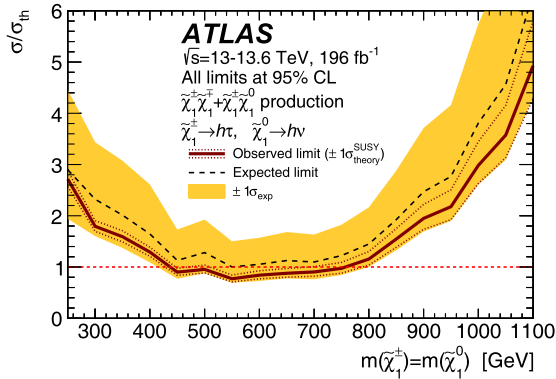


FIG. 9. 95% CL upper limits on the cross section for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  production normalized to the theoretical prediction, assuming  $B(\tilde{\chi}_1^\pm \rightarrow h\tau^\pm) = 100\%$  and  $B(\tilde{\chi}_1^0 \rightarrow h\nu) = 100\%$ . The expected and observed limits are shown by the dashed and solid lines, respectively. The shaded bands around the expected limit show the  $\pm 1\sigma$  variations due to statistical and systematic uncertainties, while the dotted bands around the observed limit show the  $\pm 1\sigma$  variations from the theoretical uncertainty on the signal cross section.

collected by the ATLAS experiment at the LHC between 2015 and 2023.

No significant excess above the SM prediction was observed. Model-independent limits are set at 95% CL on the visible cross section for new physics processes. Charginos and neutralinos with masses between 150 GeV and 1100 GeV are excluded at 95% CL for the  $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h\ell^\pm) = 100\%$  and  $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow h\nu) = 100\%$  hypothesis, where each flavor of charged lepton (electron, muon, and  $\tau$  lepton) is equally likely to be produced. Lower limits of 1225 GeV and 1150 GeV are also set on the chargino and neutralino masses for the  $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h e^\pm) = 100\%$  and  $\mathcal{B}(\tilde{\chi}_1^\pm \rightarrow h \mu^\pm) = 100\%$  hypotheses, respectively.

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## DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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 T. Wang<sup>61</sup> W. T. Wang<sup>127</sup> W. Wang<sup>113c</sup> X. Wang<sup>164</sup> X. Wang<sup>141a</sup> X. Wang<sup>47</sup> Y. Wang<sup>148</sup> Y. Wang<sup>114</sup>  
 Z. Wang<sup>14</sup> Z. Wang<sup>63b</sup> C. Wanotayaroj<sup>82</sup> A. Warburton<sup>104</sup> A. L. Warnerbring<sup>144</sup> S. Waterhouse<sup>96</sup>  
 A. T. Watson<sup>21</sup> H. Watson<sup>51</sup> M. F. Watson<sup>21</sup> E. Watton<sup>37</sup> G. Watts<sup>140</sup> B. M. Waugh<sup>96</sup> J. M. Webb<sup>53</sup>  
 C. Weber<sup>30</sup> M. S. Weber<sup>20</sup> C. Wei<sup>61</sup> Y. Wei<sup>53</sup> A. R. Weidberg<sup>127</sup> E. J. Weik<sup>118</sup> J. Weingarten<sup>48</sup> C. Weiser<sup>53</sup>  
 C. J. Wells<sup>47</sup> P. S. Wells<sup>37</sup> T. Wenaus<sup>30</sup> T. Wengler<sup>37</sup> N. S. Wenke<sup>110</sup> N. Wermes<sup>25</sup> D. Werner<sup>47</sup>  
 M. Wessels<sup>62a</sup> A. M. Wharton<sup>91</sup> A. S. White<sup>37</sup> A. White<sup>8</sup> M. J. White<sup>1</sup> D. Whiteson<sup>162</sup>  
 L. Wickremasinghe<sup>125</sup> W. Wiedenmann<sup>172</sup> M. Wielers<sup>135</sup> R. Wierda<sup>147</sup> C. Wiglesworth<sup>42</sup> H. G. Wilkens<sup>37</sup>  
 J. J. H. Wilkinson<sup>33</sup> S. Williams<sup>33</sup> S. Willocq<sup>103</sup> D. J. Wilson<sup>101</sup> P. J. Windischhofer<sup>39</sup> F. I. Winkel<sup>31</sup>  
 F. Winklmeier<sup>124</sup> B. T. Winter<sup>53</sup> M. Wittgen<sup>146</sup> M. Wobisch<sup>97</sup> T. Wojtkowski<sup>59</sup> Z. Wolffs<sup>116</sup> J. Wollrath<sup>37</sup>  
 M. W. Wolter<sup>86</sup> H. Wolters<sup>131a,131c</sup> M. C. Wong<sup>137</sup> E. L. Woodward<sup>41</sup> S. D. Worm<sup>47</sup> B. K. Wosiek<sup>86</sup>  
 K. A. Wozniak<sup>55</sup> K. W. Woźniak<sup>86</sup> S. Wozniowski<sup>54</sup> K. Wraight<sup>58</sup> C. Wu<sup>158</sup> J. Wu<sup>156</sup> M. Wu<sup>112b</sup>  
 M. Wu<sup>115</sup> S. L. Wu<sup>172</sup> S. Wu<sup>14,ss</sup> X. Wu<sup>61</sup> Y. Q. Wu<sup>158</sup> Y. Wu<sup>61</sup> Z. Wu<sup>102</sup> Z. Wu<sup>112a</sup> J. Wuerzinger<sup>110</sup>  
 T. R. Wyatt<sup>101</sup> B. M. Wynne<sup>51</sup> S. Xella<sup>42</sup> L. Xia<sup>112a</sup> M. Xie<sup>61</sup> A. Xiong<sup>124</sup> I. Xioidis<sup>37</sup> D. Xu<sup>14</sup> H. Xu<sup>61</sup>  
 L. Xu<sup>61</sup> R. Xu<sup>129</sup> T. Xu<sup>106</sup> W. Xu<sup>112a</sup> Y. Xu<sup>140</sup> Z. Xu<sup>51</sup> R. Xue<sup>130</sup> B. Yabsley<sup>150</sup> S. Yacoob<sup>11</sup>  
 Y. Yamaguchi<sup>82</sup> E. Yamashita<sup>156</sup> H. Yamauchi<sup>160</sup> T. Yamazaki<sup>18a</sup> Y. Yamazaki<sup>84</sup> S. Yan<sup>58</sup> Z. Yan<sup>103</sup>  
 C. Yang<sup>18a</sup> H. J. Yang<sup>141a</sup> H. T. Yang<sup>61</sup> S. Yang<sup>61</sup> X. Yang<sup>37</sup> X. Yang<sup>14</sup> Y. Yang<sup>156</sup> Y. Yang<sup>61</sup>  
 W-M. Yao<sup>18a</sup> C. L. Yardley<sup>149</sup> J. Ye<sup>14</sup> S. Ye<sup>30</sup> X. Ye<sup>61</sup> I. Yeletsikh<sup>38</sup> B. Yeo<sup>18b</sup> M. R. Yexley<sup>96</sup>  
 T. P. Yildirim<sup>127</sup> K. Yorita<sup>170</sup> C. J. S. Young<sup>37</sup> C. Young<sup>146</sup> I. N. L. Young<sup>58</sup> N. D. Young<sup>124</sup> D. Yu<sup>141b,5</sup>  
 Y. Yu<sup>61</sup> J. Yuan<sup>14,112c,ss</sup> M. Yuan<sup>106</sup> R. Yuan<sup>141b</sup> L. Yue<sup>96</sup> M. Zaazoua<sup>61</sup> B. Zabinski<sup>86</sup> I. Zahir<sup>36a</sup>  
 Q. U. A. Zahoore<sup>51</sup> A. Zaio<sup>56b,56a</sup> Z. K. Zak<sup>86</sup> T. Zakareishvili<sup>165</sup> S. Zambito<sup>55</sup> J. Zang<sup>156</sup> R. Zanzottera<sup>70a,70b</sup>  
 O. Zaplatilek<sup>133</sup> I. Zatocilova<sup>53</sup> E. Zaya<sup>147</sup> C. Zeitnitz<sup>173</sup> H. Zeng<sup>14</sup> D. T. Zenger Jr.<sup>27</sup> T. Ženiš<sup>29a</sup> S. Zenz<sup>94</sup>  
 W. Zhan<sup>61</sup> B. Zhang<sup>169</sup> D. F. Zhang<sup>142</sup> G. Zhang<sup>14,ss</sup> J. Zhang<sup>113b</sup> J. Zhang<sup>6</sup> L. Zhang<sup>61</sup> L. Zhang<sup>112a</sup>  
 P. Zhang<sup>14,112c</sup> R. Zhang<sup>112a</sup> S. Zhang<sup>14</sup> Y. Zhang<sup>140</sup> Y. Zhang<sup>96</sup> Y. Zhang<sup>61</sup> Y. Zhang<sup>112a</sup> Z. Zhang<sup>149</sup>  
 Z. Zhang<sup>101</sup> Z. Zhang<sup>18a</sup> Z. Zhang<sup>113b</sup> Z. Zhang<sup>65</sup> H. Zhao<sup>140</sup> T. Zhao<sup>113b</sup> Y. Zhao<sup>35</sup> Z. Zhao<sup>61</sup>  
 Z. Zhao<sup>61</sup> A. Zhemchugov<sup>38</sup> J. Zheng<sup>112a</sup> K. Zheng<sup>164</sup> L. Zheng<sup>113b</sup> X. Zheng<sup>61</sup> Z. Zheng<sup>146</sup> D. Zhong<sup>164</sup>  
 B. Zhou<sup>106</sup> B. Zhou<sup>141b,141a</sup> N. Zhou<sup>141a</sup> Y. Zhou<sup>15</sup> Y. Zhou<sup>112a</sup> Y. Zhou<sup>7</sup> Z. Zhou<sup>61</sup> J. Zhu<sup>106</sup> X. Zhu<sup>141b</sup>  
 Y. Zhu<sup>141a</sup> X. Zhuang<sup>14</sup> K. Zhukov<sup>67</sup> P. Ziakas<sup>4</sup> N. I. Zimine<sup>38</sup> J. Zinsser<sup>62b</sup> M. Ziolkowski<sup>144</sup>  
 L. Živković<sup>16</sup> A. Zoccoli<sup>24b,24a</sup> K. Zoch<sup>37</sup> A. Zografos<sup>37</sup> T. G. Zorbas<sup>142</sup> and L. Zwalinski<sup>37</sup>

## (ATLAS Collaboration)

- <sup>1</sup>Department of Physics, University of Adelaide, Adelaide, Australia  
<sup>2</sup>Department of Physics, University of Alberta, Edmonton AB, Canada  
<sup>3a</sup>Department of Physics, Ankara University, Ankara, Türkiye  
<sup>3b</sup>Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye  
<sup>4</sup>LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France  
<sup>5</sup>APC, Université Paris Cité, CNRS/IN2P3, Paris, France  
<sup>6</sup>High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America  
<sup>7</sup>Department of Physics, University of Arizona, Tucson AZ, United States of America  
<sup>8</sup>Department of Physics, University of Texas at Arlington, Arlington TX, United States of America  
<sup>9</sup>Physics Department, National and Kapodistrian University of Athens, Athens, Greece  
<sup>10</sup>Physics Department, National Technical University of Athens, Zografou, Greece  
<sup>11</sup>Department of Physics, University of Texas at Austin, Austin TX, United States of America  
<sup>12</sup>Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan  
<sup>13</sup>Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain  
<sup>14</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China  
<sup>15</sup>Physics Department, Tsinghua University, Beijing, China  
<sup>16</sup>Institute of Physics, University of Belgrade, Belgrade, Serbia  
<sup>17</sup>Department for Physics and Technology, University of Bergen, Bergen, Norway  
<sup>18a</sup>Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA, United States of America  
<sup>18b</sup>University of California, Berkeley CA, United States of America  
<sup>19</sup>Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany  
<sup>20</sup>Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland  
<sup>21</sup>School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom  
<sup>22a</sup>Department of Physics, Bogazici University, Istanbul, Türkiye  
<sup>22b</sup>Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye  
<sup>22c</sup>Department of Physics, Istanbul University, Istanbul, Türkiye  
<sup>23a</sup>Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia  
<sup>23b</sup>Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia  
<sup>24a</sup>Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy  
<sup>24b</sup>INFN Sezione di Bologna, Italy  
<sup>25</sup>Physikalisches Institut, Universität Bonn, Bonn, Germany  
<sup>26</sup>Department of Physics, Boston University, Boston MA, United States of America  
<sup>27</sup>Department of Physics, Brandeis University, Waltham MA, United States of America  
<sup>28a</sup>Transilvania University of Brasov, Brasov, Romania  
<sup>28b</sup>Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania  
<sup>28c</sup>Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania  
<sup>28d</sup>National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania  
<sup>28e</sup>National University of Science and Technology Politehnica, Bucharest, Romania  
<sup>28f</sup>West University in Timisoara, Timisoara, Romania  
<sup>28g</sup>Faculty of Physics, University of Bucharest, Bucharest, Romania  
<sup>29a</sup>Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic  
<sup>29b</sup>Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic  
<sup>30</sup>Physics Department, Brookhaven National Laboratory, Upton NY, United States of America  
<sup>31</sup>Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina  
<sup>32</sup>California State University, CA, United States of America  
<sup>33</sup>Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom  
<sup>34a</sup>Department of Physics, University of Cape Town, Cape Town, South Africa  
<sup>34b</sup>iThemba Labs, Western Cape, South Africa  
<sup>34c</sup>Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa  
<sup>34d</sup>National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines  
<sup>34e</sup>Department of Physics, Stellenbosch University, Matieland, South Africa  
<sup>34f</sup>University of KwaZulu-Natal, School of Agriculture and Science, Mathematics, Westville, South Africa  
<sup>34g</sup>University of South Africa, Department of Physics, Pretoria, South Africa  
<sup>34h</sup>University of Pretoria, Department of Mechanical and Aeronautical Engineering, Pretoria, South Africa

- <sup>34i</sup>University of Zululand, KwaDlangezwa, South Africa
- <sup>34j</sup>School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>35</sup>Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>36a</sup>Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Morocco
- <sup>36b</sup>Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
- <sup>36c</sup>Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
- <sup>36d</sup>LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco
- <sup>36e</sup>Faculté des sciences, Université Mohammed V, Rabat, Morocco
- <sup>36f</sup>Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco
- <sup>37</sup>CERN, Geneva, Switzerland
- <sup>38</sup>Affiliated with an international laboratory covered by a cooperation agreement with CERN
- <sup>39</sup>Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>40</sup>LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- <sup>41</sup>Nevis Laboratory, Columbia University, Irvington NY, United States of America
- <sup>42</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>43a</sup>Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>43b</sup>INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- <sup>44</sup>Physics Department, Southern Methodist University, Dallas TX, United States of America
- <sup>45</sup>National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece
- <sup>46a</sup>Department of Physics, Stockholm University, Sweden
- <sup>46b</sup>Oskar Klein Centre, Stockholm, Sweden
- <sup>47</sup>Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- <sup>48</sup>Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
- <sup>49</sup>Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>50</sup>Department of Physics, Duke University, Durham NC, United States of America
- <sup>51</sup>SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>52</sup>INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>53</sup>Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- <sup>54</sup>II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- <sup>55</sup>Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- <sup>56a</sup>Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>56b</sup>INFN Sezione di Genova, Italy
- <sup>57</sup>II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>58</sup>SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>59</sup>LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- <sup>60</sup>Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- <sup>61</sup>Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
- <sup>62a</sup>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>62b</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>63a</sup>Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
- <sup>63b</sup>Department of Physics, University of Hong Kong, Hong Kong, China
- <sup>63c</sup>Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>64</sup>Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- <sup>65</sup>IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
- <sup>66</sup>Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain
- <sup>67</sup>Department of Physics, Indiana University, Bloomington IN, United States of America
- <sup>68a</sup>INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
- <sup>68b</sup>ICTP, Trieste, Italy
- <sup>68c</sup>Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
- <sup>69a</sup>INFN Sezione di Lecce, Italy
- <sup>69b</sup>Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>70a</sup>INFN Sezione di Milano, Italy
- <sup>70b</sup>Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>71a</sup>INFN Sezione di Napoli, Italy
- <sup>71b</sup>Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>72a</sup>INFN Sezione di Pavia, Italy
- <sup>72b</sup>Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>73a</sup>INFN Sezione di Pisa, Italy

- <sup>73b</sup>Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy  
<sup>74a</sup>INFN Sezione di Roma, Italy  
<sup>74b</sup>Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy  
<sup>75a</sup>INFN Sezione di Roma Tor Vergata, Italy  
<sup>75b</sup>Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy  
<sup>76a</sup>INFN Sezione di Roma Tre, Italy  
<sup>76b</sup>Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy  
<sup>77a</sup>INFN-TIFPA, Italy  
<sup>77b</sup>Università degli Studi di Trento, Trento, Italy  
<sup>78</sup>Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria  
<sup>79</sup>Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America  
<sup>80</sup>Istinye University, Sariyer, Istanbul, Türkiye  
<sup>81a</sup>Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil  
<sup>81b</sup>Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil  
<sup>81c</sup>Instituto de Física, Universidade de São Paulo, São Paulo, Brazil  
<sup>81d</sup>Rio de Janeiro State University, Rio de Janeiro, Brazil  
<sup>81e</sup>Federal University of Bahia, Bahia, Brazil  
<sup>82</sup>KEK, High Energy Accelerator Research Organization, Tsukuba, Japan  
<sup>83a</sup>Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates  
<sup>83b</sup>New York University Abu Dhabi, Abu Dhabi, United Arab Emirates  
<sup>83c</sup>United Arab Emirates University, Al Ain, United Arab Emirates  
<sup>83d</sup>University of Sharjah, Sharjah, United Arab Emirates  
<sup>84</sup>Graduate School of Science, Kobe University, Kobe, Japan  
<sup>85a</sup>AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland  
<sup>85b</sup>Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland  
<sup>86</sup>Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland  
<sup>87</sup>Faculty of Science, Kyoto University, Kyoto, Japan  
<sup>88</sup>Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan  
<sup>89</sup>L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France  
<sup>90</sup>Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina  
<sup>91</sup>Physics Department, Lancaster University, Lancaster, United Kingdom  
<sup>92</sup>Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom  
<sup>93</sup>Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia  
<sup>94</sup>Department of Physics and Astronomy, Queen Mary University of London, London, United Kingdom  
<sup>95</sup>Department of Physics, Royal Holloway University of London, Egham, United Kingdom  
<sup>96</sup>Department of Physics and Astronomy, University College London, London, United Kingdom  
<sup>97</sup>Louisiana Tech University, Ruston LA, United States of America  
<sup>98</sup>Fysiska institutionen, Lunds universitet, Lund, Sweden  
<sup>99</sup>Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain  
<sup>100</sup>Institut für Physik, Universität Mainz, Mainz, Germany  
<sup>101</sup>School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom  
<sup>102</sup>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France  
<sup>103</sup>Department of Physics, University of Massachusetts, Amherst MA, United States of America  
<sup>104</sup>Department of Physics, McGill University, Montreal QC, Canada  
<sup>105</sup>School of Physics, University of Melbourne, Victoria, Australia  
<sup>106</sup>Department of Physics, University of Michigan, Ann Arbor MI, United States of America  
<sup>107</sup>Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America  
<sup>108</sup>Group of Particle Physics, University of Montreal, Montreal QC, Canada  
<sup>109</sup>Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany  
<sup>110</sup>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany  
<sup>111</sup>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan  
<sup>112a</sup>Department of Physics, Nanjing University, Nanjing, China  
<sup>112b</sup>School of Science, Shenzhen Campus of Sun Yat-sen University, China  
<sup>112c</sup>University of Chinese Academy of Science (UCAS), Beijing, China  
<sup>113a</sup>School of Physics, Nankai University, Tianjin, China

- <sup>113b</sup>*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- <sup>113c</sup>*School of Physics, Zhengzhou University, China*
- <sup>114</sup>*Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America*
- <sup>115</sup>*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
- <sup>116</sup>*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- <sup>117</sup>*Department of Physics, Northern Illinois University, DeKalb IL, United States of America*
- <sup>118</sup>*Department of Physics, New York University, New York NY, United States of America*
- <sup>119</sup>*Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
- <sup>120</sup>*Ohio State University, Columbus OH, United States of America*
- <sup>121</sup>*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America*
- <sup>122</sup>*Department of Physics, Oklahoma State University, Stillwater OK, United States of America*
- <sup>123</sup>*Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic*
- <sup>124</sup>*Institute for Fundamental Science, University of Oregon, Eugene, OR, United States of America*
- <sup>125</sup>*Graduate School of Science, University of Osaka, Osaka, Japan*
- <sup>126</sup>*Department of Physics, University of Oslo, Oslo, Norway*
- <sup>127</sup>*Department of Physics, Oxford University, Oxford, United Kingdom*
- <sup>128</sup>*LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
- <sup>129</sup>*Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America*
- <sup>130</sup>*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America*
- <sup>131a</sup>*Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal*
- <sup>131b</sup>*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- <sup>131c</sup>*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- <sup>131d</sup>*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- <sup>131e</sup>*Departamento de Física, Escola de Ciências, Universidade do Minho, Braga, Portugal*
- <sup>131f</sup>*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
- <sup>131g</sup>*Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
- <sup>132</sup>*Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- <sup>133</sup>*Czech Technical University in Prague, Prague, Czech Republic*
- <sup>134</sup>*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- <sup>135</sup>*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- <sup>136</sup>*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- <sup>137</sup>*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America*
- <sup>138a</sup>*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- <sup>138b</sup>*Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile*
- <sup>138c</sup>*Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile*
- <sup>138d</sup>*Universidad Andres Bello, Department of Physics, Santiago, Chile*
- <sup>138e</sup>*Universidad San Sebastian, Recoleta, Chile*
- <sup>138f</sup>*Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile*
- <sup>138g</sup>*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- <sup>139</sup>*Department of Physics, Institute of Science, Tokyo, Japan*
- <sup>140</sup>*Department of Physics, University of Washington, Seattle WA, United States of America*
- <sup>141a</sup>*State Key Laboratory of Dark Matter Physics, School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China*
- <sup>141b</sup>*State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China*
- <sup>142</sup>*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- <sup>143</sup>*Department of Physics, Shinshu University, Nagano, Japan*
- <sup>144</sup>*Department Physik, Universität Siegen, Siegen, Germany*
- <sup>145</sup>*Department of Physics, Simon Fraser University, Burnaby BC, Canada*
- <sup>146</sup>*SLAC National Accelerator Laboratory, Stanford CA, United States of America*
- <sup>147</sup>*Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
- <sup>148</sup>*Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America*
- <sup>149</sup>*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*

- <sup>150</sup>*School of Physics, University of Sydney, Sydney, Australia*  
<sup>151</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan*  
<sup>152a</sup>*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*  
<sup>152b</sup>*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*  
<sup>152c</sup>*University of Georgia, Tbilisi, Georgia*  
<sup>153</sup>*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*  
<sup>154</sup>*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*  
<sup>155</sup>*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*  
<sup>156</sup>*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*  
<sup>157</sup>*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*  
<sup>158</sup>*Department of Physics, University of Toronto, Toronto ON, Canada*  
<sup>159a</sup>*TRIUMF, Vancouver BC, Canada*  
<sup>159b</sup>*Department of Physics and Astronomy, York University, Toronto ON, Canada*  
<sup>160</sup>*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*  
<sup>161</sup>*Department of Physics and Astronomy, Tufts University, Medford MA, United States of America*  
<sup>162</sup>*Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America*  
<sup>163</sup>*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*  
<sup>164</sup>*Department of Physics, University of Illinois, Urbana IL, United States of America*  
<sup>165</sup>*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*  
<sup>166</sup>*Department of Physics, University of British Columbia, Vancouver BC, Canada*  
<sup>167</sup>*Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*  
<sup>168</sup>*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*  
<sup>169</sup>*Department of Physics, University of Warwick, Coventry, United Kingdom*  
<sup>170</sup>*Waseda University, Tokyo, Japan*  
<sup>171</sup>*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*  
<sup>172</sup>*Department of Physics, University of Wisconsin, Madison WI, United States of America*  
<sup>173</sup>*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*  
<sup>174</sup>*Department of Physics, Yale University, New Haven CT, United States of America*  
<sup>175</sup>*Yerevan Physics Institute, Yerevan, Armenia*

<sup>a</sup>Deceased.

<sup>b</sup>Also at Department of Physics, King's College London, London, United Kingdom.

<sup>c</sup>Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

<sup>d</sup>Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia.

<sup>e</sup>Also at Department of Physics, University of Thessaly, Greece.

<sup>f</sup>Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

<sup>g</sup>Also at An-Najah National University, Nablus, Palestine.

<sup>h</sup>Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

<sup>i</sup>Also at Department of Physics, Westmont College, Santa Barbara, United States of America.

<sup>j</sup>Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

<sup>k</sup>Also at University of Siena, Italy.

<sup>l</sup>Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN.

<sup>m</sup>Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

<sup>n</sup>Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia, Bulgaria.

<sup>o</sup>Also at Università di Napoli Parthenope, Napoli, Italy.

<sup>p</sup>Also at Institute of Particle Physics (IPP), Canada.

<sup>q</sup>Also at Department of Physics, Bolu Abant İzzet Baysal University, Bolu, Türkiye.

<sup>r</sup>Also at Faculty of Physics, University of Bucharest, Romania.

<sup>s</sup>Also at Borough of Manhattan Community College, City University of New York, New York NY, United States of America.

<sup>t</sup>Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines.

<sup>u</sup>Also at TRIUMF, Vancouver BC, Canada.

<sup>v</sup>Also at Università degli Studi Link, Italy.

<sup>w</sup>Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

<sup>x</sup>Also at University and INFN Torino, Torino, Italy.

<sup>y</sup>Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

<sup>z</sup>Also at Henan University, China.

<sup>aa</sup> Also at Yeditepe University, Physics Department, Istanbul, Türkiye.

<sup>bb</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

<sup>cc</sup> Also at CERN, Geneva, Switzerland.

<sup>dd</sup> Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.

<sup>ee</sup> Also at Hellenic Open University, Patras, Greece.

<sup>ff</sup> Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China.

<sup>gg</sup> Also at Department of Physics, Stellenbosch University, South Africa.

<sup>hh</sup> Also at School of Physics, University of the Witwatersrand, Johannesburg, South Africa.

<sup>ii</sup> Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.

<sup>jj</sup> Also at University of Colorado Boulder, Department of Physics, Colorado, United States of America.

<sup>kk</sup> Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP), Portugal.

<sup>ll</sup> Also at Indian Institute of Technology (IIT), Jodhpur, India.

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

<sup>nn</sup> Also at Washington College, Chestertown, MD, United States of America.

<sup>oo</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

<sup>pp</sup> Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.

<sup>qq</sup> Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.

<sup>rr</sup> Also at Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile.

<sup>ss</sup> Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.