Search for supersymmetry in final states with two same-sign or three leptons and jets using 36 fb⁻¹ of √s = 13 TeV pp collision data with the ATLAS detector

The ATLAS Collaboration

DOI
10.1007/JHEP09(2017)084

Publication date
2017

Document Version
Final published version

Published in
JHEP

License
CC BY

Citation for published version (APA):
The ATLAS Collaboration (2017). Search for supersymmetry in final states with two same-sign or three leptons and jets using 36 fb⁻¹ of √s = 13 TeV pp collision data with the ATLAS detector. JHEP, 2017(9), [084]. https://doi.org/10.1007/JHEP09(2017)084

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)

Download date:11 Dec 2022
Search for supersymmetry in final states with two same-sign or three leptons and jets using 36 fb$^{-1}$ of $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for strongly produced supersymmetric particles using signatures involving multiple energetic jets and either two isolated same-sign leptons (e or $\mu$), or at least three isolated leptons, is presented. The analysis relies on the identification of $b$-jets and high missing transverse momentum to achieve good sensitivity. A data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider in 2015 and 2016, corresponding to a total integrated luminosity of 36.1 fb$^{-1}$, is used for the search. No significant excess over the Standard Model prediction is observed. The results are interpreted in several simplified supersymmetric models featuring $R$-parity conservation or $R$-parity violation, extending the exclusion limits from previous searches. In models considering gluino pair production, gluino masses are excluded up to 1.87 TeV at 95% confidence level. When bottom squarks are pair-produced and decay to a chargino and a top quark, models with bottom squark masses below 700 GeV and light neutralinos are excluded at 95% confidence level. In addition, model-independent limits are set on a possible contribution of new phenomena to the signal region yields.

KEYWORDS: Hadron-Hadron scattering (experiments), Supersymmetry

ArXiv ePrint: 1706.03731

https://doi.org/10.1007/JHEP09(2017)084
1 Introduction

Supersymmetry (SUSY) [1–6] is one of the best-motivated extensions of the Standard Model (SM). A general review can be found in ref. [7]. In its minimal realization (the MSSM) [8, 9] it predicts a new bosonic (fermionic) partner for each fundamental SM fermion (boson), as well as an additional Higgs doublet. If \( R \)-parity [10] is conserved (RPC) the lightest supersymmetric particle (LSP) is stable and can be the lightest neutralino\(^1\) \( \tilde{\chi}^0_1 \). In many models, the LSP can be a dark-matter candidate [11, 12] and produce signatures with large missing transverse momentum. If instead \( R \)-parity is violated (RPV), the LSP decay can generate events with high jet and lepton multiplicity. Both RPC and RPV scenarios can produce the final-state signatures considered in this article.

In order to address the SM hierarchy problem with SUSY models [13–16], TeV-scale masses are required [17, 18] for the partners of the gluons (gluinos \( \tilde{g} \)) and of the top quarks (top squarks \( \tilde{t}_L \) and \( \tilde{t}_R \)), due to the large top Yukawa coupling.\(^2\) The latter also favours significant \( \tilde{t}_L \sim \tilde{t}_R \) mixing, so that the mass eigenstate \( \tilde{t}_1 \) is lighter than all the

\(^1\)The SUSY partners of the Higgs and electroweak gauge bosons, the electroweakinos, mix to form the mass eigenstates known as charginos (\( \tilde{\chi}^{\pm}_l \), \( l = 1, 2 \) ordered by increasing mass) and neutralinos (\( \tilde{\chi}^0_m \), \( m = 1, \ldots, 4 \) ordered by increasing mass).

\(^2\)The partners of the left-handed (right-handed) quarks are labelled \( \tilde{q}_L(R) \). In the case where there is significant L/R mixing (as is the case for third-generation squarks) the mass eigenstates of these squarks are labelled \( \tilde{q}_{1,2} \) ordered by increasing mass.
other squarks in many scenarios \cite{19, 20}. Bottom squarks ($\tilde{b}_1$) may also be light, being bound to top squarks by $SU(2)_L$ invariance. This leads to potentially large production cross-sections for gluino pairs ($\tilde{g}\tilde{g}$), top-antitop squark pairs ($\tilde{t}_1\tilde{t}^*_1$) and bottom-antibottom squark pairs ($\tilde{b}_1\tilde{b}^*_1$) at the Large Hadron Collider (LHC) \cite{21}. Production of isolated leptons may arise in the cascade decays of those superpartners to SM quarks and neutralinos $\tilde{\chi}^0_1$, via intermediate neutralinos $\tilde{\chi}^0_{2,3,4}$ or charginos $\tilde{\chi}^\pm_{1,2}$ that in turn lead to $W$, $Z$ or Higgs bosons, or to lepton superpartners (sleptons, $\tilde{\ell}$). Light third-generation squarks would also enhance gluino decays to top or bottom quarks relative to the generic decays involving light-flavour squarks, favouring the production of heavy-flavour quarks and, in the case of top quarks, additional isolated leptons.

This article presents a search for SUSY in final states with two leptons (electrons or muons) of the same electric charge, referred to as same-sign (SS) leptons, or three leptons (3L), jets and in some cases also missing transverse momentum, whose magnitude is referred to as $E_T^{\text{miss}}$. Only prompt decays of SUSY particles are considered. It is an extension of an earlier search performed by the ATLAS experiment \cite{22} with $\sqrt{s} = 13$ TeV data \cite{23}, and uses the data collected in proton-proton ($pp$) collisions during 2015 and 2016. Similar searches for SUSY in this topology were also performed by the CMS experiment at $\sqrt{s} = 13$ TeV \cite{24-26}. While the same-sign or three-lepton signatures are present in many scenarios of physics beyond the SM (BSM), SM processes leading to such final states have very small cross-sections. Compared to other BSM searches, analyses based on these signatures therefore allow the use of looser kinematic requirements (for example, on $E_T^{\text{miss}}$ or on the momentum of jets and leptons), preserving sensitivity to scenarios with small mass differences between the produced gluinos/squarks and the LSP, or in which $R$-parity is not conserved. This sensitivity to a wide range of BSM physics processes is illustrated by the interpretation of the results in the context of twelve different SUSY simplified models \cite{27-29} that may lead to same-sign or three-lepton signatures.

For RPC models, the first four scenarios studied focus on gluino pair production with decays into on-shell (figure 1a) or off-shell (figure 1b) top quarks, as well as on-shell light quarks. The latter are accompanied by a cascade decay involving a $\tilde{\chi}^0_1$ and a $\tilde{\chi}^0_2$ (figure 1c) or a $\tilde{\chi}^0_2$ and light sleptons (figure 1d). The other two RPC scenarios target the direct production of third-generation squark pairs with subsequent electroweakino-mediated decays (figures 1e and 1f). The former is characterized by final states with bottom squark pairs decaying to $t\bar{t}WW\tilde{\chi}^0_1\tilde{\chi}^0_1$. The latter, addressed here by looking at a final state with three same-sign leptons, is a model that could explain the slight excess seen in same-sign lepton signatures during Run 1 \cite{30}. Finally, a full SUSY model with low fine-tuning, the non-universal Higgs model with two extra parameters (NUHM2) \cite{31, 32}, is also considered. When the soft-SUSY-breaking electroweakino mass, $m_{1/2}$, is in the range 300-800 GeV, the model mainly involves gluino pair production with gluinos decaying predominantly to $t\bar{t}\tilde{\chi}^0_1$ and $tb\tilde{\chi}^+_1$, giving rise to final states with two same-sign leptons and $E_T^{\text{miss}}$.

In the case of non-zero RPV couplings in the baryonic sector ($\lambda''_{ijk}$), as proposed in scenarios with minimal flavour violation \cite{33-35}, gluinos and squarks may decay directly to top quarks, leading to final states with same-sign leptons \cite{36, 37} and $b$-quarks (figures 1g and 1h). Although these figures illustrate decay modes mediated by non-zero $\lambda''_{131}$ (resp.
Figure 1. RPC SUSY processes featuring gluino ((a), (b), (c), (d)) or third-generation squark ((e), (f)) pair production studied in this analysis. RPV SUSY models considered are gluino pair production ((g), (h), (i), (j)) and t-channel production of down squark-rights ((k), (l)) which decay via baryon- or lepton-number violating couplings $\lambda''$ and $\lambda'$ respectively. In the diagrams, $q \equiv u, d, c, s$ and $\ell \equiv e, \mu, \tau$. In figure 1d, $\ell \equiv e, \mu, \tau$ and $\bar{\nu} \equiv \bar{\nu} e, \bar{\nu} \mu, \bar{\nu} \tau$. In figure 1f, the $W^+$ labels indicate largely off-shell $W$ bosons — the mass difference between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ is around 1 GeV.

$\lambda''_{321}$ couplings, the exclusion limits set for these scenarios also hold for non-zero $\lambda''_{311}$ (resp. $\lambda''_{312}$ or $\lambda''_{322}$), as these couplings lead to experimentally indistinguishable final states. Alternatively a gluino decaying to a neutralino LSP that further decays to SM particles via a non-zero RPV coupling in the leptonic sector, $\lambda'$, or in the baryonic sector $\lambda''$, is also possible (figures 1i and 1j). Lower $E_T^{\text{miss}}$ is expected in these scenarios, as there is no stable LSP, and the $E_T^{\text{miss}}$ originates from neutrinos produced in the $\tilde{\chi}_1^0$ and top quark decays. Pair production of same-sign down squark-rights$^3$ (figures 1k and 1l) is also considered. In all of these scenarios, antitop squarks decay into the charge-conjugate final states of those indicated for the corresponding squarks, and gluinos decay with equal probabilities into the given final state or its charge conjugate.

2 ATLAS detector

The ATLAS experiment [22] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4$\pi$ coverage in solid angle.$^4$ The interaction

---

$^3$These RPV baryon-number-violating couplings only apply to SU(2) singlets.

$^4$ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre
point is surrounded by an inner detector (ID) for tracking, a calorimeter system, and a muon spectrometer (MS). The ID provides precision tracking of charged particles with pseudorapidities $|\eta| < 2.5$ and is surrounded by a superconducting solenoid providing a 2 T axial magnetic field. It consists of silicon pixel and silicon micro-strip detectors inside a transition radiation tracker. One significant upgrade for the $\sqrt{s} = 13$ TeV running period is the presence of the insertable B-Layer [38], an additional pixel layer close to the interaction point, which provides high-resolution hits at small radius to improve the tracking and vertexing performance. In the pseudorapidity region $|\eta| < 2.5$, high-granularity lead/liquid-argon electromagnetic sampling calorimeters are used. A steel/scintillator tile calorimeter measures hadron energies for $|\eta| < 1.7$. The endcap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with liquid-argon calorimeters for both the electromagnetic and hadronic measurements. The MS consists of three large superconducting toroids with eight coils each and a system of trigger and precision-tracking chambers, which provide triggering and tracking capabilities in the ranges $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively. A two-level trigger system is used to select events [39]. The first-level trigger is implemented in hardware. This is followed by the software-based high-level trigger, which can run algorithms similar to those used in the offline reconstruction software, reducing the event rate to about 1 kHz.

3 Data set and simulated event samples

The data used in this analysis were collected during 2015 and 2016 with a peak instantaneous luminosity of $L = 1.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$. The mean number of $pp$ interactions per bunch crossing (pile-up) in the data set is 24. After the application of beam, detector and data-quality requirements, the integrated luminosity considered corresponds to 36.1 fb$^{-1}$. The uncertainty in the combined 2015+2016 integrated luminosity is 3.2%. It is derived, following a methodology similar to that detailed in ref. [40], from a preliminary calibration of the luminosity scale using beam-separation scans performed in August 2015 and May 2016.

Monte Carlo (MC) simulated event samples are used to model the SUSY signals and to estimate the irreducible SM background with two same-sign and/or three “prompt” leptons. Prompt leptons are produced directly in the hard-scattering process, or in the subsequent decays of $W$, $Z$ and $H$ bosons or prompt $\tau$ leptons. The reducible background, mainly arising from $t\bar{t}$ production, is estimated from the data as described in section 5.1. The MC samples were processed through a detailed ATLAS detector simulation [41] based on Geant4 [42] or a fast simulation using a parameterization of the calorimeter response and Geant4 for the ID and MS [43]. To simulate the effects of additional $pp$ collisions in the same and nearby bunch crossings, inelastic interactions were generated using the soft of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Rapidity is defined as $y = 0.5 \ln \left( (E+p_z)/(E-p_z) \right)$ where $E$ denotes the energy and $p_z$ is the component of the momentum along the beam direction. The transverse momentum $p_T$, the transverse energy $E_T$ and the missing transverse momentum $E_T^{\text{miss}}$ are defined in the $x$-$y$ plane.
Table 1. Simulated signal and background event samples: the corresponding event generator, parton shower, cross-section normalization, PDF set and set of tuned parameters are shown for each sample. Because of their very small contribution to the signal-region background estimate, $t\bar{t}WW$, $t\bar{t}WZ$, $t\bar{t}Z$, $t\bar{t}$, $W\bar{H}$, $ZH$ and triboson are summed and labelled “rare” in the following. NLO-Prospino2 refers to RPV down squark models of figures 1k and 1l, as well as the NUHM2 model.

Table 1. Simulated signal and background event samples: the corresponding event generator, parton shower, cross-section normalization, PDF set and set of tuned parameters are shown for each sample. Because of their very small contribution to the signal-region background estimate, $t\bar{t}WW$, $t\bar{t}WZ$, $t\bar{t}Z$, $t\bar{t}$, $W\bar{H}$, $ZH$ and triboson are summed and labelled “rare” in the following. NLO-Prospino2 refers to RPV down squark models of figures 1k and 1l, as well as the NUHM2 model.

The SUSY signals from figure 1 are defined by an effective Lagrangian describing the interactions of a small number of new particles [27–29]. All SUSY particles not included in the decay of the pair-produced squarks and gluinos are effectively decoupled. These simplified models assume one production process and one decay channel with a 100% branching fraction. Apart from figure 1j, where events were generated with *Herwig++* [51], all simplified models were generated from leading-order (LO) matrix elements with up to two extra partons in the matrix element (only up to one for the $\tilde{g} \rightarrow q\bar{q}(\ell\ell/\nu\nu)\chi^0_1$ model) using MG5\_aMC@NLO 2.2.3 [48] interfaced to *Pythia* 8 with the A14 tune [50] for the modelling of the parton shower, hadronization and underlying event. Jet-parton matching was realized following the CKKW-L prescription [65], with a matching scale set to one quarter of the pair-produced superpartner mass. All signal models were generated with prompt decays of the SUSY particles. Signal cross-sections were calculated at next-to-leading order (NLO) in the strong coupling constant, adding the resummation of soft-gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [52–56], except for the RPV models of figures 1k and 1l and the NUHM2 model where NLO cross-sections were used [52, 66]. The nominal cross-sections and the uncertainties were taken from envelopes of cross-section pre-
dictions using different PDF sets and factorization and renormalization scales, as described in refs. [21, 57]. Typical pair-production cross-sections are: $4.7 \pm 1.2 \text{ fb}$ for gluinos with a mass of 1.7 TeV, $28 \pm 4 \text{ fb}$ for bottom squarks with a mass of 800 GeV, and $15.0 \pm 2.0 \text{ fb}$ for down squark-rights with a mass of 800 GeV and a gluino mass of 2.0 TeV.

The two dominant irreducible background processes are $t\bar{t}V$ (with $V$ being a $W$ or $Z/\gamma^*$ boson) and diboson production with final states of four charged leptons $\ell$, three charged leptons and one neutrino, or two same-sign charged leptons and two neutrinos. The MC simulation samples for these are described in refs. [67] and [62], respectively. For diboson production, the matrix elements contain the doubly resonant diboson processes and all other diagrams with four or six electroweak vertices, such as $W^+W^-jj$, or two $(WZ, ZZ)$ extra partons. NLO cross-sections for $t\bar{t}W$, $t\bar{t}Z/\gamma^*(\to \ell\ell)$, and leptonic diboson processes are respectively $0.60 \text{ pb}$ [60], $0.12 \text{ pb}$ and $6.0 \text{ pb}$ [62]. The processes $t\bar{t}H$ and $4t$, with NLO cross-sections of $507.1 \text{ fb}$ [60] and $9.2 \text{ fb}$ [48] respectively, are also considered.

Other background processes, with small cross-sections and no significant contribution to any of the signal regions, are grouped into a category labelled “rare”. This category contains $t\bar{t}WW$ and $t\bar{t}WZ$ events generated with no extra parton in the matrix element, and $tZ$, $tWZ$, $tt\bar{t}$, $WH$ and $ZH$ as well as triboson ($WWW$, $WWZ$, $WZZ$ and $ZZZ$) production with fully leptonic decays, leading to up to six charged leptons. The processes $WWW$, $WZZ$ and $ZZZ$ were generated at NLO with additional LO matrix elements for up to two extra partons, while $WWZ$ was generated at LO with up to two extra partons.

4 Event reconstruction and selection

Candidate events are required to have a reconstructed vertex [69] with at least two associated tracks with $p_T > 400 \text{ MeV}$. The vertex with the largest $\Sigma p_T^2$ of the associated tracks is chosen as the primary vertex of the event.

For the data-driven background estimations, two categories of electrons and muons are used: “candidate” and “signal” with the latter being a subset of the “candidate” leptons satisfying tighter selection criteria. Electron candidates are reconstructed from energy depositions in the electromagnetic calorimeter which were matched to an ID track and are required to have $|\eta| < 2.47$, $p_T > 10 \text{ GeV}$, and pass the “Loose” likelihood-based identification requirement [70]. Candidates within the transition region between the barrel and endcap electromagnetic calorimeters, $1.37 < |\eta| < 1.52$, are not considered. The track matched with the electron must have a significance of the transverse impact parameter $d_0$ with respect to the reconstructed primary vertex of $|d_0|/\sigma(d_0) < 5$. Muon candidates are reconstructed in the region $|\eta| < 2.5$ from muon spectrometer tracks matching ID tracks. All muon candidates must have $p_T > 10 \text{ GeV}$ and must pass the “Medium” identification requirements [71].

Jets are reconstructed with the anti-$k_t$ algorithm [72] with radius parameter $R = 0.4$, using three-dimensional topological energy clusters in the calorimeter [73] as input. All jets

\footnote{All lepton flavours are included here and $\tau$ leptons subsequently decay leptonically or hadronically.}

\footnote{This cross-section is computed using the configuration described in refs. [48, 68].}
must have $p_T > 20$ GeV and $|\eta| < 2.8$. For all jets the expected average energy contribution from pile-up is subtracted according to the jet area\cite{74, 75}. Jets are then calibrated as described in ref.\cite{75}. In order to reduce the effects of pile-up, a significant fraction of the tracks in jets with $p_T < 60$ GeV and $|\eta| < 2.4$ must originate from the primary vertex, as defined by the jet vertex tagger (JVT)\cite{76}.

Identification of jets containing $b$-hadrons ($b$-tagging) is performed with the MV2c10 algorithm, a multivariate discriminant making use of track impact parameters and reconstructed secondary vertices\cite{77, 78}. A requirement is chosen corresponding to a 70\% average efficiency for tagging $b$-jets in simulated $t\bar{t}$ events. The rejection factors for light-quark/gluon jets, $c$-quark jets and $\tau \rightarrow \nu +$ hadron decays in simulated $t\bar{t}$ events are approximately 380, 12 and 54, respectively\cite{78, 79}. Jets with $|\eta| < 2.5$ which satisfy the $b$-tagging and JVT requirements are identified as $b$-jets. Correction factors and uncertainties determined from data for the $b$-tagging efficiencies and mis-tag rates are applied to the simulated samples\cite{78}.

After the object identification, overlaps between the different objects are resolved. Any jet within a distance $\Delta R_y = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.2$ of a lepton candidate is discarded, unless the jet is $b$-tagged,\footnote{In this case the $b$-tagging operating point corresponding to an efficiency of 85\% is used.} in which case the lepton is discarded since it probably originated from a semileptonic $b$-hadron decay. Any remaining lepton within $\Delta R_y = \min\{0.4, 0.1 + 9.6 \text{ GeV}/p_T(\ell)\}$ of a jet is discarded. In the case of muons, the muon is retained and the jet is discarded if the jet has fewer than three associated tracks. This reduces inefficiencies for high-energy muons undergoing significant energy loss in the calorimeter.

Signal electrons must satisfy the “Medium” likelihood-based identification requirement\cite{70}. In regions with large amounts of material in the tracker, an electron (positron) is more likely to emit a hard bremsstrahlung photon; if the photon subsequently converts to an asymmetric electron-positron pair, and the positron (electron) has high momentum and is reconstructed, the lepton charge can be misidentified (later referred to as “charge-flip”). To reduce the impact of charge misidentification, signal electrons must satisfy $|\eta| < 2.0$. Furthermore, signal electrons that are likely to be reconstructed with an incorrect charge assignment are rejected using the electron cluster and track properties including the impact parameter, the curvature significance, the cluster width, and the quality of the matching between the cluster and its associated track, in terms of both energy and position. These variables, as well as the electron $p_T$ and $\eta$, are combined into a single classifier using a boosted decision tree (BDT) algorithm. A selection requirement on the BDT output is chosen to achieve a rejection factor of 7-8 for electrons with a wrong charge assignment while selecting correctly measured electrons with an efficiency of 97\%. Correction factors to account for differences in the selection efficiency between data and MC simulation are applied to the selected electrons in MC simulation. These correction factors are determined using $Z \rightarrow ee$ events\cite{80}.

Signal muons must fulfill the requirement $|d_0|/\sigma(d_0) < 3$. Tracks associated with the signal electrons or muons must have a longitudinal impact parameter $z_0$ with respect to the reconstructed primary vertex satisfying $|z_0 \sin \theta| < 0.5$ mm. Isolation requirements are
applied to both the signal electrons and muons. The scalar sum of the $p_T$ of tracks within a variable-size cone around the lepton, excluding its own track, must be less than 6% of the lepton $p_T$.

The track isolation cone size for electrons (muons) $\Delta R_{\eta} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ is given by the smaller of $\Delta R_{\eta} = 10 \text{ GeV}/p_T$ and $\Delta R_{\eta} = 0.2$ (0.3). In addition, in the case of electrons the calorimeter energy clusters in a cone of $\Delta R_{\eta} = 0.2$ around the electron (excluding the deposit from the electron itself) must be less than 6% of the electron $p_T$. Simulated events are corrected to account for differences in the lepton trigger, reconstruction, identification and isolation efficiencies between data and MC simulation.

The missing transverse momentum is defined as the negative vector sum of the transverse momenta of all identified candidate objects (electrons, photons \cite{81}, muons and jets) and an additional soft term. The soft term is constructed from all tracks associated with the primary vertex but not with any physics object. In this way, the $E_T^{\text{miss}}$ is adjusted for the best calibration of the jets and the other identified physics objects listed above, while maintaining approximate pile-up independence in the soft term \cite{82, 83}.

Events are selected using a combination of dilepton and $E_T^{\text{miss}}$ triggers, the latter being used only for events with $E_T^{\text{miss}} > 250 \text{ GeV}$. The trigger-level requirements on $E_T^{\text{miss}}$ and the leading and subleading lepton $p_T$ are looser than those applied offline to ensure that trigger efficiencies are constant in the relevant phase space. The event selection requires at least two signal leptons with $p_T > 20 \text{ GeV}$ (apart from two signal regions where the lower bound on the subleading lepton $p_T$ is 10 GeV).\footnote{To ensure that the trigger efficiency is constant for selected events where the subleading lepton $p_T$ lies between 10 and 20 GeV only the $E_T^{\text{miss}}$ trigger is used in this case.} If the event contains exactly two signal leptons, they must have the same electric charge. In order to reject detector noise and non-collision backgrounds (including those from cosmic rays, beam-gas and beam-halo interactions), events are discarded if they contain any jet not satisfying basic quality criteria \cite{84, 85}.

To maximize the sensitivity to the signal models of figure 1, 19 non-exclusive\footnote{Each signal region partially overlaps with at least one other signal region.} signal regions (SRs) are defined in table 2. The SRs are named in the form $SNLMbX$, where $S$ indicates if the signal region is targeting an RPC or RPV model, $N$ indicates the number of leptons required, $M$ the number of $b$-jets required, and $X$ indicates the severity of the $E_T^{\text{miss}}$ or $m_{\text{eff}}$ requirements (Soft, Medium or Hard). All signal regions, except Rpvlb0, allow any number of additional leptons in addition to a $e^\pm e^\pm$, $e^\pm \mu^\pm$ or $\mu^\pm \mu^\pm$ pair. Signal regions with a three lepton selection can either require any lepton charge combination (RpclbH, RpclbS) or that all three leptons have the same charge (Rpclsslb). The other requirements used to define the SRs are the number of signal leptons ($N_{\text{leptons}}$), number of $b$-jets with $p_T > 20 \text{ GeV}$ ($N_{b,jets}$), number of jets with $p_T$ above 25, 40 or 50 GeV, regardless of their flavour ($N_{\text{jets}}$), $E_T^{\text{miss}}$, the effective mass ($m_{\text{eff}}$) and the charge of the signal leptons. The $m_{\text{eff}}$ variable is defined as the scalar sum of the $p_T$ of the signal leptons, jets and the $E_T^{\text{miss}}$. For SRs where the $Z$+jets background is important (Rpclsslb, Rpvlb0 and RpvlbH), events in which the invariant mass of two same-sign electrons is close to the $Z$ boson mass are vetoed. For SRs targeting the production of down squark pairs (Rpvlb0, RpvlbS, RpvlbM), only events with at least two
Table 2. Summary of the signal region definitions. Unless explicitly stated in the table, at least two signal leptons with $p_T > 20$ GeV and same charge (SS) are required in each signal region. Requirements are placed on the number of signal leptons ($N_{signal\ leptons}$), the number of $b$-jets with $p_T > 20$ GeV ($N_{b\ jets}$), the number of jets ($N_{jets}$) above a certain $p_T$ threshold ($p_T^{jet}$), $E_{miss}$, $m_{eff}$ and/or $E_{miss}/m_{eff}$. The last column indicates the targeted signal model. The Rpc3L1b and Rpc3L1bH SRs are not motivated by a particular signal model and can be seen as a natural extension of the Rpc3L0b SRs with the same kinematic selections but requiring at least one $b$-jet.

negatively charged leptons are considered, as the down squarks decay exclusively to top antiquarks. Finally, SRs targeting signal scenarios with lepton $p_T$ spectra softer than typical background processes impose an upper bound on the leptons’ $p_T$. The last column of table 2 indicates the targeted signal model. The Rpc3L1b and Rpc3L1bH SRs are not motivated by a particular signal model and can be seen as a natural extension of the Rpc3L0b SRs with the same kinematic selections but requiring at least one $b$-jet.

The values of acceptance times efficiency of the SR selections for the RPC SUSY signal models, with masses near the exclusion limit, typically range between 0.5% and 7% for models with a light $\tilde{\chi}^0_1$ and between 0.5 and 2% for models with a heavy $\tilde{\chi}^0_1$. For RPV SUSY signal models, these values are in the range 0.2-4%. To increase the signal efficiency for the SUSY models with low-energy leptons (figure 1b), the $p_T$ threshold of leptons is relaxed from 20 GeV to 10 GeV in the SR definition.

5 Background estimation

Two main sources of SM background can be distinguished in this analysis. The first category is the reducible background, which includes events containing electrons with mis-measured charge, mainly from the production of top quark pairs, and events containing

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|c|c|c|c|}
\hline
Signal region & $N_{signal\ leptons}$ & $N_{b\ jets}$ & $N_{jets}$ & $p_T^{jet}$ & $E_{miss}$ & $m_{eff}$ & $E_{miss}/m_{eff}$ & Other & Targeted Signal \\
\hline
Rpc2L2bS & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 100$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1a \\
Rpc2L2bH & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 100$ & $> 1800$ & $> 0.15$ & -- & -- & Figure 1a, NUHM2 \\
Rpc2Lsoft1b & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 100$ & $> 900$ & $> 0.5$ & $20.10 < p_T^{jet} < 100$ GeV & -- & Figure 1b \\
Rpc2Lsoft2b & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 1000$ & $> 0.25$ & $20.10 < p_T^{jet} < 100$ GeV & -- & Figure 1b \\
Rpc2L0S & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1c \\
Rpc2L0H & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 1000$ & $> 0.25$ & -- & -- & Figure 1c \\
Rpc3L0S & $\geq 3$ & $\geq 3$ & $\geq 3$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1d \\
Rpc3L0H & $\geq 3$ & $\geq 3$ & $\geq 3$ & $> 200$ & $> 1600$ & $> 0.25$ & -- & -- & Figure 1d \\
 Rpc3L1S & $\geq 3$ & $\geq 3$ & $\geq 3$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Other \\
Rpc3L1H & $\geq 3$ & $\geq 3$ & $\geq 3$ & $> 200$ & $> 1600$ & $> 0.25$ & -- & -- & Other \\
Rpc2L1S & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 250$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1e \\
Rpc2L1H & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 250$ & $> 1000$ & $> 0.25$ & -- & -- & Figure 1e \\
Rpc3LSS1b & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1f \\
Rpc2L1bH & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1f \\
Rpc2L0b & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1f \\
Rpc2L2M & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1f \\
Rpc2L2S & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1f \\
Rpc2L1S & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1f \\
Rpc2L1M & $\geq 2$ & $\geq 2$ & $\geq 2$ & $> 200$ & $> 600$ & $> 0.25$ & -- & -- & Figure 1f \\
\hline
\end{tabular}
\end{table}
at least one fake or non-prompt (FNP) lepton. The FNP lepton mainly originates from heavy-flavour hadron decays in events containing top quarks, or $W$ or $Z$ bosons. Hadrons misidentified as leptons, electrons from photon conversions and leptons from pion or kaon decays in flight are other possible sources. Data-driven methods used for the estimation of this reducible background in the signal and validation regions are described in section 5.1.

The second background category is the irreducible background from events with two same-sign prompt leptons or at least three prompt leptons and is estimated using the MC simulation samples. Since diboson and $t\bar{t}V$ events are the main irreducible backgrounds in the signal regions, dedicated validation regions (VR) with an enhanced contribution from these processes, and small signal contamination, are defined to verify the background predictions from the simulation (section 5.2). Section 5.3 discusses the systematic uncertainties considered when performing the background estimation in the signal and validation regions.

5.1 Reducible background estimation methods

Charge misidentification is only relevant for electrons. The contribution of charge-flip events to the SR/VR is estimated using the data. The electron charge-flip probability is extracted in a $Z/\gamma^* \rightarrow ee$ data sample using a likelihood fit which takes as input the numbers of same-sign and opposite-sign electron pairs observed in a window of 10 GeV around the $Z$ boson mass. The charge-flip probability is a free parameter of the fit and is extracted as a function of the electron $p_T$ and $\eta$. These probabilities are around 0.5% (1%) and 0.1% (0.2%) for the candidate and signal electrons for $|\eta| < 1.37$ ($|\eta| > 1.52$), respectively. The former is used only in the FNP lepton background estimation. The event yield of the charge-flip electron background in the signal or validation regions is obtained by multiplying the measured charge-flip probability with the number of events in data regions with the same kinematic requirements as the signal or validation regions but with opposite-sign lepton pairs.

Two data-driven methods are used to estimate the FNP lepton background, referred to as the “matrix method” and the “MC template method”. The estimates from these methods are combined to give the final estimate. These two methods are described below.

The first estimation of the FNP lepton background is performed with a matrix method similar to that described in ref. [86]. Two types of lepton identification criteria are defined: “tight”, corresponding to the signal lepton criteria described in section 4, and “loose”, corresponding to candidate leptons after object overlap removal and the charge-flip BDT selection described also in section 4. The matrix method relates the number of events containing prompt or FNP leptons to the number of observed events with tight or loose-not-tight leptons using the probability for loose prompt or FNP leptons to satisfy the tight criteria. The probability for loose prompt leptons to satisfy the tight selection criteria ($\varepsilon$) is obtained using a $Z/\gamma^* \rightarrow \ell\ell$ data sample and is modelled as a function of the lepton $p_T$ and $\eta$. The efficiencies for electrons (muons) rise from 60% (80%) at low $p_T$ to almost 100% at $p_T$ above 50 GeV — apart from endcap electrons, for which they reach only 95%. The probability for loose FNP leptons to satisfy the tight selection criteria (FNP lepton rate, $f$) is determined from data in SS control regions enriched in non-prompt leptons mostly originating from heavy-flavour hadron decays in single-lepton $t\bar{t}$ events. These regions
contain events with at least one $b$-jet, one well-isolated muon (referred to as the “tag”), and an additional loose electron or muon which is used for the measurement. The rates $f$ are measured as a function of $p_T$ after subtracting the small contribution from prompt-lepton processes predicted by simulation and the data-driven estimation of events with electron charge-flip.\footnote{For muons with $p_T < 20\text{ GeV}$, $f$ is parameterized as a function of $p_T$ and $\eta$.} For electrons, and muons with $|\eta| < 2.3$, $f$ is constant at around 10\% for $p_T < 30\text{ GeV}$ (20\% for muons with $|\eta| > 2.3$) and increases at higher $p_T$. With these values of $\varepsilon$ and $f$, the method has been demonstrated to correctly estimate the FNP lepton background.

The second method for FNP lepton estimation is the MC template method described in details in refs. \cite{86,87}. It relies on the correct modelling of the kinematic distributions of the FNP leptons and charge-flipped electron processes in $t\bar{t}$ and $V+$jets samples. These samples were simulated with the Powheg-Box generator \cite{88,89,90} and the parton shower and hadronization performed by either PYTHIA 6.428 \cite{92} ($t\bar{t}$) or PYTHIA 8.186 ($V+$jets). The FNP leptons are classified in five categories, namely electrons and muons originating from $b$- and light-quark jets as well as electrons from photon conversions. Normalization factors for each of the five sources are adjusted to match the observed data in dedicated control regions. Events are selected with at least two same-sign signal leptons, $E_T^{\text{miss}} > 40\text{ GeV}$, two or more jets, and are required not to belong to the SRs. They are further split into regions with or without $b$-jets and with different lepton flavours of the same-sign lepton pair, giving a total of six control regions. The global normalization factors applied to the MC samples for estimating the reducible background in each SR vary from $1:2$ to $2:9$, where the errors account for statistical uncertainties and uncertainties related to the choice of event generator (see section 5.3).

Since the FNP lepton predictions from the MC template and matrix methods in the signal and validation regions are consistent with each other, a weighted average of the two results is used. With this approach, the combined estimate is always dominated by systematic uncertainties, which is not always the case when only the matrix method is used due to small number of events in the control regions. To check the validity and robustness of the FNP lepton estimate, the distributions of several discriminating variables in data are compared with the predicted background after various requirements on the number of jets and $b$-jets. Examples of such distributions are shown in figure 2, and illustrate that the data are described by the prediction within uncertainties. The apparent disagreement for $m_{\text{eff}}$ above 1 TeV in figure 2d is covered by the large theory uncertainty for the diboson background, which is not shown but amounts to about 30\% for $m_{\text{eff}}$ above 1 TeV.

### 5.2 Validation of irreducible background estimates

Dedicated validation regions are defined to verify the estimate of the $t\bar{t}V$, $WZ$ and $W^\pm W^\pm$ background in the signal regions. The corresponding selections are summarized in table 3. The overlap with the signal regions is resolved by removing events that are selected in the signal regions. The purity of the targeted background processes in these regions ranges from 35\% to 65\%. The expected signal contamination is generally below 5\% for models near
the limit of exclusion in $t\bar{t}Z$, $WZ$ and $W^\pm W^\mp$ VRs and about 20% in the $t\bar{t}W$ VR. The observed yields, compared with the background predictions and uncertainties, are shown in table 4. There is good agreement between data and the estimated background in all the validation regions.

5.3 Systematic uncertainties

Statistical uncertainties due to the number of data events in the loose and tight lepton control regions are considered in the FNP lepton background estimate. In the matrix method, the systematic uncertainties mainly come from potentially different compositions of $b$-jets, light-quark jets and photon conversions between the signal regions and the regions where the FNP lepton rates are measured. The uncertainty coming from the prompt-lepton contamination in the FNP lepton control regions is also considered. Overall, the uncertainty in the FNP lepton rate $f$ amounts to 30% at low $p_T$, and can reach 85% for muons with
Table 3. Summary of the event selection in the validation regions (VRs). Requirements are placed on the number of signal leptons ($N_{\text{signal}}$), the number of $b$-jets with $p_T > 20$ GeV ($N_{b\text{-jets}}$) or the number of jets ($N_{\text{jets}}$) above a certain $p_T$ threshold ($p_T^{\text{jet}}$). The two leading-$p_T$ leptons are referred to as $\ell_1, \ell_2$ with decreasing $p_T$. Additional requirements are set on $E_T^{\text{miss}}$, $m_{\text{eff}}$, the invariant mass of the two leading leptons $m_{\ell+\ell}$, the presence of SS leptons or a pair of same-flavour opposite-sign leptons (SFOS) and its invariant mass $m_{\text{SFOS}}$. A minimum angular separation between the leptons and the jets ($\Delta R_0(\ell_1, \ell_2, j)$) and between the two leptons ($\Delta R_0(\ell_1, \ell_2)$) is imposed in the $W^\pm W^\pm jj$ VR. For the two $WZ$ VRs the selection also relies on the ratio of the $E_T^{\text{miss}}$ in the event to the sum of $p_T$ of all signal leptons $p_T$ ($E_T^{\text{miss}} / \sum p_T^{\ell}$). The ratio of the scalar sum of the $p_T$ of all $b$-jets to that of all jets in the event ($\sum p_T^{b\text{-jet}} / \sum p_T^{\text{jet}}$) is used in the $ttW$ VR selection.

<table>
<thead>
<tr>
<th>Validation Region</th>
<th>$t\ell W$</th>
<th>$tt\ell$</th>
<th>$WZ4j$</th>
<th>$WZ5j$</th>
<th>$W^\pm W^\pm jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\ell Z/\gamma^*$</td>
<td>6.2 ± 0.9</td>
<td>123 ± 17</td>
<td>17.8 ± 3.5</td>
<td>10.1 ± 2.3</td>
<td>1.06 ± 0.22</td>
</tr>
<tr>
<td>$t\ell W$</td>
<td>19.0 ± 2.9</td>
<td>1.71 ± 0.27</td>
<td>1.30 ± 0.32</td>
<td>0.45 ± 0.14</td>
<td>4.1 ± 0.8</td>
</tr>
<tr>
<td>$ttH$</td>
<td>5.8 ± 1.2</td>
<td>3.6 ± 1.8</td>
<td>1.8 ± 0.6</td>
<td>0.96 ± 0.34</td>
<td>0.69 ± 0.14</td>
</tr>
<tr>
<td>$4\ell$</td>
<td>1.02 ± 0.22</td>
<td>0.27 ± 0.14</td>
<td>0.04 ± 0.02</td>
<td>0.03 ± 0.02</td>
<td>0.03 ± 0.02</td>
</tr>
<tr>
<td>$W^\pm W^\pm$</td>
<td>0.5 ± 0.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>26 ± 14</td>
</tr>
<tr>
<td>$WZ$</td>
<td>1.4 ± 0.8</td>
<td>29 ± 17</td>
<td>200 ± 110</td>
<td>70 ± 40</td>
<td>27 ± 14</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.04 ± 0.03</td>
<td>5.5 ± 3.1</td>
<td>22 ± 12</td>
<td>9 ± 5</td>
<td>0.53 ± 0.30</td>
</tr>
<tr>
<td>Rare</td>
<td>2.2 ± 0.5</td>
<td>26 ± 13</td>
<td>7.3 ± 2.1</td>
<td>3.0 ± 1.0</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>Fake/non-prompt leptons</td>
<td>18 ± 16</td>
<td>22 ± 14</td>
<td>49 ± 31</td>
<td>17 ± 12</td>
<td>13 ± 10</td>
</tr>
<tr>
<td>Charge-flip electrons</td>
<td>3.4 ± 0.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.74 ± 0.22</td>
</tr>
<tr>
<td>Total SM background</td>
<td>57 ± 16</td>
<td>212 ± 35</td>
<td>300 ± 130</td>
<td>110 ± 50</td>
<td>77 ± 31</td>
</tr>
<tr>
<td>Observed</td>
<td>71</td>
<td>209</td>
<td>257</td>
<td>106</td>
<td>99</td>
</tr>
</tbody>
</table>

Table 4. The numbers of observed data and expected background events in the validation regions. The rare category is defined in the text. Background categories with yields shown as “—” do not contribute to a given region (e.g. charge flips in three-lepton regions) or their estimates are below 0.01 events. The displayed yields include all statistical and systematic uncertainties described in section 5.3.
$p_T > 40 \text{ GeV}$, and 50\% for electrons with $p_T > 20 \text{ GeV}$; these values are driven respectively by the dependency of the isolation of non-prompt muons on the kinematic properties of the jets which emit them, and the uncertainty in the proportion of non-prompt electrons from heavy-flavoured hadron decays with respect to other sources of FNP electrons (mainly converted photons). The uncertainties in the prompt-lepton efficiency $\varepsilon$ are much smaller. The uncertainties in the FNP lepton background estimated with the matrix method in each VR and SR are then evaluated by propagating the $f$ and $\varepsilon$ uncertainties. In the MC template method, the systematic uncertainty is obtained by changing the generator from POWHEG-Box to SHERPA and propagating uncertainties from the control region fit to the global normalization scale factors applied to the MC samples. The uncertainties in these scale factors are in the range 75–80\%, depending on the SRs. When combining the results of the MC template method and the matrix method to obtain the final estimate, systematic uncertainties are propagated assuming conservatively a full correlation between the two methods.

The uncertainty in the electron charge-flip probability mainly originates from the number of events in the regions used in the charge-flip probability measurement and the uncertainty related to the background subtraction from the $Z$ boson’s mass peak. The relative error in the charge-flip rate is below 20\% (30\%) for signal (candidate) electrons with $p_T$ above 20 GeV.

The systematic uncertainties related to the estimated background from same-sign prompt leptons arise from the experimental uncertainties (jet energy scale calibration, jet energy resolution and $b$-tagging efficiency) as well as theoretical modelling and theoretical cross-section uncertainties. The statistical uncertainty of the simulated event samples is also taken into account.

The cross-sections used to normalize the MC samples are varied according to the uncertainty in the cross-section calculation, which is 13\% for $t\bar{t}W$, 12\% for $t\bar{t}Z$ production [60], 6\% for diboson production [62], 8\% for $t\bar{t}H$ [60] and 30\% for $4t$ [48]. Additional uncertainties are assigned to some of these backgrounds to account for the theoretical modelling of the kinematic distributions in the MC simulation. For $t\bar{t}W$ and $t\bar{t}Z$, the predictions from the MG5\_aMC@NLO and SHERPA generators are compared, and the renormalization and factorization scales used to generate these samples are varied independently within a factor of two, leading to a 15–35\% uncertainty in the expected SR yields for these processes. For diboson production, uncertainties are estimated by varying the QCD and matching scales, as well as the parton shower recoil scheme, leading to a 30–40\% uncertainty for these processes after the SR selections. For $t\bar{t}H$, $4t$ and rare production processes, a 50\% uncertainty in their total contribution is assigned.

6 Results and interpretation

Figure 3a shows the event yields for data and the expected background contributions in all signal regions. Detailed information about the yields can be found in table 5. In all 19 SRs the number of observed data events is consistent with the expected background within the uncertainties. The contributions listed in the rare category are dominated by triboson,
Figure 3. Comparison of (a) the observed and expected event yields in each signal region and (b) the relative uncertainties in the total background yield estimate. For the latter, “statistical uncertainty” corresponds to reducible and irreducible background statistical uncertainties. The background predictions correspond to those presented in table 5 and the rare category is explained in the text.

$tWZ$ and $t\bar{t}WW$ production\textsuperscript{11} the triboson processes generally dominate in the SRs with no $b$-jets, while $tWZ$ and $t\bar{t}WW$ dominate in the SRs with one and two $b$-jets, respectively.

Figure 3b summarizes the contributions from the different sources of systematic uncertainty to the total SM background predictions in the signal regions. The uncertainties amount to 25–50% of the total background depending on the signal region, dominated by systematic uncertainties coming from the reducible background or the theory.

In the absence of any significant deviation from the SM predictions, upper limits on possible BSM contributions to the signal regions are derived, as well as exclusion limits

\textsuperscript{11}Contributions from $WH$, $ZH$, $tZ$ and $t\bar{t}t$ production never represent more than 20% of the rare background.
Table 5. Numbers of events observed in the signal regions compared with the expected backgrounds. The rare category is defined in the text. Background categories with yields shown as a "−" do not contribute to a given region (e.g. charge flips in three-lepton regions) or their estimates are below 0.01. The 95% confidence level (CL) upper limits are shown on the observed and expected numbers of BSM events, $S_{\text{obs}}^{95\%}$ and $S_{\text{exp}}^{95\%}$ (as well as the $1\sigma$ excursions from the expected limit), respectively. The 95% CL upper limits on the visible cross-section ($\sigma_{\text{vis}}$) are also given. Finally, the p-values ($p_0$) give the probabilities to observe a deviation from the predicted background at least as large as that in the data. The number of equivalent Gaussian standard deviations ($Z$) is also shown when $p_0 < 0.5$. 

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>$t\bar{t}W, t\bar{t}Z\gamma^{*}$</th>
<th>$t\bar{t}H$</th>
<th>4t</th>
<th>Diboson</th>
<th>Rare</th>
<th>Fake/non-prompt leptons</th>
<th>Charge-flip electrons</th>
<th>Total Background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{CL0}}$</td>
<td>5.5</td>
<td>3.6</td>
<td>6.3</td>
<td>7.7</td>
<td>8.3</td>
<td>6.1</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>$S_{\text{exp}}$</td>
<td>5.6 $^{+2.2}_{-1.5}$</td>
<td>3.9 $^{+1.4}_{-0.4}$</td>
<td>7.1 $^{+1.2}_{-1.5}$</td>
<td>6.2 $^{+0.9}_{-1.5}$</td>
<td>7.5 $^{+1.8}_{-1.8}$</td>
<td>5.3 $^{+1.3}_{-1.3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{vis}}$ [fb]</td>
<td>0.15</td>
<td>0.10</td>
<td>0.17</td>
<td>0.21</td>
<td>0.23</td>
<td>0.17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_0$ (Z)</td>
<td>0.71 (−)</td>
<td>0.91 (−)</td>
<td>0.69 (−)</td>
<td>0.30 (0.5σ)</td>
<td>0.36 (0.4σ)</td>
<td>0.35 (0.4σ)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>$t\bar{t}W, t\bar{t}Z\gamma^{*}$</th>
<th>$t\bar{t}H$</th>
<th>4t</th>
<th>Diboson</th>
<th>Rare</th>
<th>Fake/non-prompt leptons</th>
<th>Charge-flip electrons</th>
<th>Total Background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{CL0}}$</td>
<td>8.3</td>
<td>5.4</td>
<td>14.7</td>
<td>6.1</td>
<td>13.7</td>
<td>12.4</td>
<td>3.9</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>$S_{\text{exp}}$</td>
<td>9.3 $^{+3.1}_{-1.4}$</td>
<td>5.8 $^{+2.2}_{-1.5}$</td>
<td>12.6 $^{+4.1}_{-3.4}$</td>
<td>5.9 $^{+1.2}_{-1.5}$</td>
<td>10.0 $^{+1.7}_{-1.8}$</td>
<td>9.7 $^{+1.6}_{-1.8}$</td>
<td>4.0 $^{+1.8}_{-1.8}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{vis}}$ [fb]</td>
<td>0.23</td>
<td>0.15</td>
<td>0.41</td>
<td>0.17</td>
<td>0.38</td>
<td>0.34</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_0$ (Z)</td>
<td>0.72 (−)</td>
<td>0.85 (−)</td>
<td>0.32 (0.5σ)</td>
<td>0.46 (1σ)</td>
<td>0.17 (1σ)</td>
<td>0.21 (0.8σ)</td>
<td>0.56 (−)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>$t\bar{t}W, t\bar{t}Z\gamma^{*}$</th>
<th>$t\bar{t}H$</th>
<th>4t</th>
<th>Diboson</th>
<th>Rare</th>
<th>Fake/non-prompt leptons</th>
<th>Charge-flip electrons</th>
<th>Total Background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{CL0}}$</td>
<td>5.6 $^{+0.4}_{-0.3}$</td>
<td>5.2</td>
<td>3.9</td>
<td>17.5</td>
<td>18.1</td>
<td>11.4</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>$S_{\text{exp}}$</td>
<td>4.8 $^{+1.9}_{-1.4}$</td>
<td>4.0 $^{+1.7}_{-0.3}$</td>
<td>4.1 $^{+1.4}_{-0.3}$</td>
<td>16.8 $^{+1.2}_{-1.2}$</td>
<td>17.2 $^{+1.2}_{-1.2}$</td>
<td>7.4 $^{+2.5}_{-1.8}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{vis}}$ [fb]</td>
<td>0.13</td>
<td>0.14</td>
<td>0.11</td>
<td>0.48</td>
<td>0.50</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_0$ (Z)</td>
<td>0.33 (0.4σ)</td>
<td>0.19 (0.9σ)</td>
<td>0.55 (−)</td>
<td>0.48 (1σ)</td>
<td>0.44 (0.2σ)</td>
<td>0.07 (1.5σ)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
on the masses of SUSY particles in the benchmark scenarios of figure 1. The HistFitter framework [93], which utilizes a profile-likelihood-ratio test [94], is used to establish 95% confidence intervals using the CLs prescription [95]. The likelihood is built as the product of a Poisson probability density function describing the observed number of events in the signal region and, to constrain the nuisance parameters associated with the systematic uncertainties, Gaussian distributions whose widths correspond to the sizes of these uncertainties; Poisson distributions are used instead for MC simulation statistical uncertainties. Correlations of a given nuisance parameter between the backgrounds and the signal are taken into account when relevant. The hypothesis tests are performed for each of the signal regions independently.

Table 5 presents 95% confidence level (CL) observed (expected) model-independent upper limits on the number of BSM events, $S_{\text{obs}}^{95}$ ($S_{\text{exp}}^{95}$), that may contribute to the signal regions. Normalizing these by the integrated luminosity $L$ of the data sample, they can be interpreted as upper limits on the visible BSM cross-section ($\sigma_{\text{vis}}$), defined as $\sigma_{\text{vis}} = \sigma_{\text{prod}} \times A \times \epsilon = S_{\text{obs}}^{95}/L$, where $\sigma_{\text{prod}}$ is the production cross-section, $A$ the acceptance and $\epsilon$ the reconstruction efficiency. The largest deviation of the data from the background prediction corresponds to an excess of 1.5 standard deviations in the Rpv2L1bM SR.

Exclusion limits at 95% CL are also set on the masses of the superpartners involved in the SUSY benchmark scenarios considered. Apart from the NUHM2 model, simplified models are used, corresponding to a single production mode and with 100% branching ratio to a specific decay chain, with the masses of the SUSY particles not involved in the process set to very high values. Figures 4, 5 and 6 show the exclusion limits in all the models considered in figure 1 and the NUHM2 model. The assumptions about the decay chain considered for the different SUSY particles are stated above each figure. For each region of the signal parameter space, the SR with the best expected sensitivity is chosen.

For the RPC models, the limits set are compared with the existing limits set by other ATLAS SUSY searches [23, 96]. For the models shown in figure 4, the mass limits on gluinos and bottom squarks are up to 400 GeV higher than the previous limits, reflecting the improvements in the signal region definitions as well as the increase in integrated luminosity. Gluinos with masses up to 1.75 TeV are excluded in scenarios with a light $\tilde{\chi}_1^0$ in figure 4a. This limit is extended to 1.87 TeV when $\tilde{\chi}_2^0$ and slepton masses are in-between the gluino and the $\tilde{\chi}_1^0$ masses (figure 4c). More generally, gluino masses below 1.57 TeV and bottom squarks with masses below 700 GeV are excluded in models with a massless LSP. The “compressed” regions, where SUSY particle masses are close to each other, are also better covered and LSP masses up to 1200 and 250 GeV are excluded in the gluino and bottom squark pair-production models, respectively. Of particular interest is the observed exclusion of models producing gluino pairs with an off-shell top quark in the decay (figure 1b), see figure 4a. In this case, models are excluded for mass differences between the gluino and neutralino of 205 GeV (only 35 GeV larger than the minimum mass difference for decays into two on-shell $W$ bosons and two $b$-quarks) for a gluino mass below 0.9 TeV. The Rpc3LSS1b SR allows the exclusion of top squarks with masses below 700 GeV when the top squark decays to a top quark and a cascade of electroweakinos $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^+ W^- \rightarrow W^* W^\pm \tilde{\chi}_1^0$ (see figure 4e for the conditions on the sparticle masses).
Figure 4. Observed and expected exclusion limits on the $\tilde{g}$, $\tilde{b}_1$, $\tilde{t}_1$ and $\tilde{\chi}_1^0$ masses in the context of RPC SUSY scenarios with simplified mass spectra. The signal regions used to obtain the limits are specified in the subtitle of each scenario. All limits are computed at 95% CL. The dotted lines around the observed limit illustrate the change in the observed limit as the nominal signal cross-section is scaled up and down by the theoretical uncertainty. The contours of the band around the expected limit are the $\pm 1\sigma$ results ($\pm 2\sigma$ is also considered in figure (e), including all uncertainties except the theoretical uncertainties in the signal cross-section. In figures (a)–(d), the diagonal line indicates the kinematic limit for the decays in each specified scenario and results are compared with the observed limits obtained by previous ATLAS searches [23, 96].
Figure 5. Observed and expected exclusion limits on the $\tilde{g}$, $\tilde{t}_1$, $\tilde{d}_i$, and $\tilde{\chi}_1^0$ masses in the context of RPV SUSY scenarios with simplified mass spectra featuring $\tilde{g}\tilde{g}$ or $\tilde{d}_i\tilde{d}_j$ pair production with exclusive decay modes. The signal regions used to obtain the limits are specified in the subtitle of each scenario. All limits are computed at 95% CL. The dotted lines around the observed limit illustrate the change in the observed limit as the nominal signal cross-section is scaled up and down by the theoretical uncertainty. The contours of the band around the expected limit are the $\pm 1\sigma$ results, including all uncertainties except theoretical uncertainties in the signal cross-section ($\pm 2\sigma$ is also considered in figures 5e and 5f). In figures 5a–5d, the diagonal line indicates the kinematic limit for the decays in each specified scenario. For figures 5e and 5f, theoretical production cross-sections are shown for two different gluino masses in red (1.4 TeV) and blue (2.0 TeV).
Figure 6. Observed and expected exclusion limits as a function of $m_{1/2}$ in the NUHM2 model [31, 32]. The signal region Rpc2L2bH is used to obtain the limits. The contours of the green (yellow) band around the expected limit are the ±1σ (±2σ) results, including all uncertainties. The limits are computed at 95% CL.

For the RPV models with gluino pair production (figures 5a–5d), a generic exclusion of gluinos with masses below 1.3 TeV is obtained. Weaker exclusion limits, typically around 500 GeV, are obtained in models with pair production of $\tilde{d}_R$ (figures 5e, 5f).

Finally, in the NUHM2 model with low fine-tuning, values of the parameter $m_{1/2}$ below 615 GeV are excluded, corresponding to gluino masses below 1500 GeV (figure 6).

7 Conclusion

A search for supersymmetry in events with two same-sign leptons or at least three leptons, multiple jets, $b$-jets and large $E_T^{\text{miss}}$ and/or large $m_{\text{eff}}$ is presented. The analysis is performed with proton-proton collision data at $\sqrt{s} = 13$ TeV collected in 2015 and 2016 with the ATLAS detector at the Large Hadron Collider corresponding to an integrated luminosity of 36.1 fb$^{-1}$. With no significant excess over the Standard Model prediction observed, results are interpreted in the framework of simplified models featuring gluino and squark production in $R$-parity-conserving and $R$-parity-violating scenarios. Lower limits on particle masses are derived at 95% confidence level. In the $\tilde{g}\tilde{g}$ simplified RPC models considered, gluinos with masses up to 1.87 TeV are excluded in scenarios with a light $\tilde{\chi}_1^0$. RPC models with bottom squark masses below 700 GeV are also excluded in a $\tilde{b}_1\tilde{b}_1^*$ simplified model with $\tilde{b}_1 \to tW^{-}\tilde{\chi}_1^0$ and a light $\tilde{\chi}_1^0$. In RPV scenarios, masses of down squark-rights are probed up to $m_{\tilde{d}_R} \approx 500$ GeV. All models with gluino masses below 1.3 TeV are excluded, greatly extending the previous exclusion limits obtained within this search. Model-independent limits on the cross-section of a possible signal contribution to the signal regions are set.
Acknowledgments

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSc and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; SRNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-funded by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [97].

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References


[67] ATLAS collaboration, Modelling of the $t\bar{t}H$ and $t\bar{t}V(V=W,Z)$ processes for $\sqrt{s}=13$ TeV ATLAS analyses, ATL-PHYS-PUB-2016-005 (2016).


[87] ATLAS collaboration, Search for supersymmetry using events with three leptons, multiple jets, and missing transverse momentum in 13 fb$^{-1}$ of pp collisions with the ATLAS detector at √s = 8 TeV, ATLAS-CONF-2012-151 (2012).


D. Costanzo, G. Cottin, G. Cowan, B.E. Cox, K. Cranmer, S.J. Crawley,
R.A. Creager, G. Creel, S. Crépé-Renaudin, F. Crescioli, W.A. Cribbs,
M. Cristinziani, V. Croft, G. Ciofetti, A. Cueto, T. Cuhadar Donszelmann,
A.R. Cukierman, J. Cummings, M. Curatolo, J. Cúth, S. Czekierda,
P. Czodrowski, G. D’ame, O. D’amerio, M. D’Onofrio,
M.J. Da Cunha Sargedas De Sousa, C. Da Via, W. Dahrougi, T. Dado,
T. Dai, O. Dale, F. Dallaire, C. Dallapiccola, M. Dam, J.R. Danon,
N.P. Dang, A.C. Daniels, N.S. Dann, M. Damninger, M. Dano Hoffmann,
V. Dao, G. Darbo, S. Darmona, J. Dassoulas, A. Dattagupta, T. Daubney,
C. David, T. Davidek, D.R. Davis, P. Davison, E. Davey,
K. De, R. de Asmundis, A. De Benedetti, S. De Castro, N. De Groot,
P. de Jong, H. De la Torre, F. De Lorenzi, A. De Maria, D. De Pedis,
A. De Salvo, U. De Sanctis, A. De Santo, K. De Vasconcelos Corga,
J.B. De Vivie de Regie, R. Debbi, C. Debenedetti, D.V. Dedovich,
N. Delghanian, I. Deigaard, M. Del Gaudio, J. Del Peso, D. Delgove,
F. Deflot, C.M. Delitzsch, A. Dell’Acqua, L. Dell’Asti, M. Dell’Orso,
M. Dell’Asta, D. della Pietra, D. della Volpe, M. Delmastro,
C. Delportele, P.A. Delsart, D.A. DeMarco, S. Demers,
A. Demilly, S.P. Deniso, D. Denysin, D. Derendarz, J.E. Derkouei,
F. Derni, P. Dervan, K. Desch, C. Deterre, K. Dette, M.R. Devesa,
F. Deviveiros, A. Dewhurst, S. Dhital, F.A. Di Bello, A. Di Ciaccio,
W.K. Di Clemente, C. Di Donato, A. Di Girolamo, B. Di Girolamo,
D. Di Valentino, C. Diaconu, M. Diamond, F.A. Dias, M.A. Diaz,
E.B. Diehl, J. Dietrich, S. Diaz Cornell, A. Dimitrievska,
J. Dingfelder, P. Ditta, S. Ditta, F. Dittus, F. Djama, T. Djobava,
J.I. Djuvsland, M.A.B. do Vale, D. Dobos, M. Dobre, P. Doglioni,
J. Dolejsi, Z. Doleza, M. Donadelli, S. Donati, A. Dondero,
J. Donini, J. Dopke, A. Doria, M.T. Dova, A. Doyle,
E. Drechsler, M. Dris, Y. Du, J. Duarte-Campderros, A. Dubreuil,
E. Duchovni, G. Duckeck, A. Ducouthil, O.A. Duc, D. Duda,
A. Dudarev, A. Ch. Duddr, E.M. Duffyield, L. Dullot,
M. Dührsenn, C. Dulsen, M. Dunaucic, A.E. Dumitriu,
A.K. Duncan, M. Dunford, H. Duran, Yildiz, M. Düren,
A. Durglishvili, D. Duschinger, B. Dutta, D. Duvnjak, M. Dyndal,
B.S. Dziedzic, C. Eckardt, K.M. Ecker, R.C. Edgar, T. Eifert,
G. Eigen, K. Einsweiler, T. Eckelof, M. El Kacimi, R. El Karossi,
V. Ellakovska, M. Ellert, S. Elles, F. Ellingham, A.A. Elliot,
N. Ellis, J. Elmshennar, M. Elsing, D. Emelyanov, Y. Enari,
O.C. Endner, J.S. Emnits, J. Erdmann, A. Ereditato,
M. Ernst, S. Errede, M. Escalier, C. Escobar, B. Esposito,
O. Estrada Pastor, A.I. Etienvre, E. Etzion, H. Evans,
A. Ezhilov, M. Ezzi, F. Fabbrini, L. Fabbrini, V. Fabiani,
G. Facini, R.M. Fakhruddin, J. Falciano, R.J. Falla, J. Faltova,
Y. Fang, M. Fant, A. Farbin, A. Farilla, C. Farina, E.M. Farinella,
T. Farooque, S. Farrell, S.M. Farrington, P. Farton, S. Fassi,
D. Fassouliotis, M. Fauci, G. Giannelli, A. Favaresco, J.W. Fawcett,
L. Fayard, O.L. Fedi, W. Fedorko, S. Feigl, H. Feng,
M.J. Fenton, A.B. Fenzyuk, F. Fernandes Martinez, S. Fernandez Perez,
J. Ferrando, A. Ferrari, P. Ferrari, R. Ferrari, D.E. Ferreira de Lima,
A. Ferrer, D. Ferrere, C. Ferretti, F. Fiedler, A. Filipic,
M. Filippuzzi, F. Filthaut, M. Fincke-Keeler, K.D. Finelli,
M.C.N. Fioli, G. Flacher, L. Fiorini, A. Fischer, C. Fischer,
J. Fischer, W.C. Fisher, N. Flaschel, I. Fleck, P. Fleischmann,
R.R.M. Fletcher, T. Flick,
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, U.S.A.
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; Department of Physics, The University of Hong Kong, Hong Kong; Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Taiwan, Taiwan
Department of Physics, Indiana University, Bloomington IN, U.S.A.
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, U.S.A.
Department of Physics and Astronomy, Iowa State University, Ames IA, U.S.A.
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce; Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston LA, U.S.A.
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, U.S.A.
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.
Department of Physics and Astronomy, Michigan State University, East Lansing MI, U.S.A.
INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

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

Department of Physics, University of Wisconsin, Madison WI, U.S.A.

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

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

Department of Physics, Yale University, New Haven CT, U.S.A.

Yerevan Physics Institute, Yerevan, Armenia

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taïpei, Taiwan

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

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

Also at Novosibirsk State University, Novosibirsk, Russia

Also at TRIUMF, Vancouver BC, Canada

Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, U.S.A.

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

Also at Department of Physics, California State University, Fresno CA, U.S.A.

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

Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

Also at Departamento de Física e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal

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

Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China

Also at Università di Napoli Parthenope, Napoli, Italy

Also at Institute of Particle Physics (IPP), Canada

Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania

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

Also at Borough of Manhattan Community College, City University of New York, New York City, U.S.A.

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

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa

Also at Louisiana Tech University, Ruston LA, U.S.A.

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

Also at Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.

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

Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

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

Also at Department of Physics, The University of Texas at Austin, Austin TX, U.S.A.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia

Also at CERN, Geneva, Switzerland

Also at Georgian Technical University (GTU), Tbilisi, Georgia

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan

Also at Manhattan College, New York NY, U.S.A.
Also at Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Also at The City College of New York, New York NY, U.S.A.
Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal
Also at Department of Physics, California State University, Sacramento CA, U.S.A.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
Also at Departement de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
Also at School of Physics, Sun Yat-sen University, Guangzhou, China
Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
Also at National Research Nuclear University MEPhI, Moscow, Russia
Also at Department of Physics, Stanford University, Stanford CA, U.S.A.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
Also at Giresun University, Faculty of Engineering, Turkey
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Also at Department of Physics, Nanjing University, Jiangsu, China
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
* Deceased