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# Search for squarks and gluinos in final states with same-sign leptons and jets using 139 fb$^{-1}$ of data collected with the ATLAS detector

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Abstract: A search for supersymmetric partners of gluons and quarks is presented, involving signatures with jets and either two isolated leptons (electrons or muons) with the same electric charge, or at least three isolated leptons. A data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider between 2015 and 2018, corresponding to a total integrated luminosity of 139 fb$^{-1}$, is used for the search. No significant excess over the Standard Model expectation is observed. The results are interpreted in simplified supersymmetric models featuring both $R$-parity conservation and $R$-parity violation, raising the exclusion limits beyond those of previous ATLAS searches to 1600 GeV for gluino masses and 750 GeV for bottom and top squark masses in these scenarios.

Keywords: Hadron-Hadron scattering (experiments), Supersymmetry

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## Contents





## 1 Introduction

Experimental searches for manifestations of physics beyond the Standard Model (BSM physics) at hadron colliders have long exploited the signature of final states comprising a pair of isolated light leptons (electrons, muons) with the same electric charge ('same-sign leptons'). In the Standard Model (SM), production of prompt same-sign lepton pairs from weak-boson decays is rare. In the context of $\sqrt{s} = 13\,\text{TeV}$ $pp$ collisions, the inclusive cross-section is of the order of 1 pb [1, 2], thus suppressed by more than three orders of magnitude relative to the production of opposite-sign lepton pairs. By constrast, in many scenarios heavy BSM particles, which may be produced in proton-proton ($pp$) collisions, decay into multiple massive SM bosons or top quarks. The subsequent decays of these heavy SM particles into same-sign leptons and jets may then occur with significant branching ratios. Pair production of heavy BSM Majorana fermions can be another abundant source of events with same-sign leptons [3].

At the Large Hadron Collider (LHC) [4], signatures with same-sign prompt leptons have been used by the ATLAS [5] and CMS [6] experiments to explore the landscape of possible SM extensions and their phenomenology. Among these proposed extensions, supersymmetry (SUSY) [7–12] stands out as a particularly compelling framework. It was shown [13–16] to favourably impact the scale evolution of perturbative gauge couplings needed for the unification of strong and electroweak interactions, and can address the SM gauge hierarchy problem. In its minimal realisation, the MSSM [17, 18], each fundamental SM fermion is associated with a pair of new scalar partners — in the case of quarks $q$, the squarks $\tilde{q}_{\mathrm{L}}$ and $\tilde{q}_{\mathrm{R}}$. Similarly, each SM bosonic degree of freedom is partnered with a new fermion. Mixing between the partners of SM electroweak and Higgs bosons[1] results in four massive Majorana fermions and two massive charged fermions (neutralinos $\tilde{\chi}_1^0$ to $\tilde{\chi}_4^0$ and charginos $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^{\pm}$, indexed by increasing mass). The gluinos $\tilde{g}$, partners of the SM gluons, do not mix due to their colour charge.

SUSY can provide a massive dark-matter candidate [19, 20], the lightest supersymmetric particle (LSP), if an additional ad hoc discrete symmetry, called $R$-parity [21], is invoked. When this symmetry is conserved, supersymmetric partners can only be produced in pairs and decay into the LSP and SM particles, possibly in several steps via superpartners of intermediate masses. The LSP, stable and weakly interacting, escapes the detector, leaving a striking experimental signature of large missing transverse momentum. When $R$-parity is not conserved, the final states contain only SM particles; decay channels for squarks include e.g. $\tilde{q}_i \to q_j q_k$ or $\tilde{q}_i \to q_j \ell_k$, if the corresponding coupling strengths [22] $\lambda''_{ijk}$ or $\lambda'_{ijk}$ are non-zero.

Naturalness arguments [23, 24] suggest that the top squark mass may not exceed $\approx 1$ TeV [25, 26]. Significant mixing between the scalar top partners $\tilde{t}_{\mathrm{L}}$ and $\tilde{t}_{\mathrm{R}}$, enhanced relative to other quark flavours, can also lower the mass of the lightest eigenstate $\tilde{t}_1$ below that of other squarks. These constraints indirectly affect gluinos and bottom squark masses as well. Gluinos and third-generation squarks may therefore be among the superpartners with low mass and copiously produced at the LHC. Typical pair-production cross-sections [27] for interesting scenarios in the context of this paper are 9 fb for a 1.6 TeV gluino mass, or 33 fb for the lightest top $\tilde{t}_1$ or bottom $\tilde{b}_1$ squark mass of 800 GeV.

This paper presents a search for gluinos and squarks in final states with two same-sign leptons and jets. The events may include additional leptons. In addition, large missing transverse momentum is required in the case of $R$-parity-conserving models. The event selection also relies on the number of $b$-tagged jets. Signal regions (SRs) are built (section 4) from a set of requirements on the kinematic properties of the selected events, in order to isolate the signature of supersymmetric processes from SM backgrounds. The latter are estimated with Monte Carlo simulation for processes such as $t\bar{t}V$ or $VV$ ($V = W, Z$) leading to prompt same-sign leptons (section 5), while sources of same-sign leptons arising from jets misidentified as leptons or non-prompt leptons from decays of hadrons, as well as other reducible backgrounds, are estimated with data (section 6). Event yields in data are then compared with the estimated contributions from SM processes. The results are presented in section 7 for 139 fb$^{-1}$ of 13 TeV $pp$ collision data recorded by the ATLAS experiment. They are interpreted in terms of exclusion limits (section 8) on the parameters of four benchmark supersymmetric signal scenarios, which are shown in figure 1.

A similar, earlier analysis, realised on a subset of the data for these results, was reported in ref. [28] and found no deviation from SM expectations. Searches based on these event topologies were also performed in the same context with the CMS experiment with the same outcome [29, 30].

[1] The Higgs sector is also enriched by the presence of an additional complex doublet.

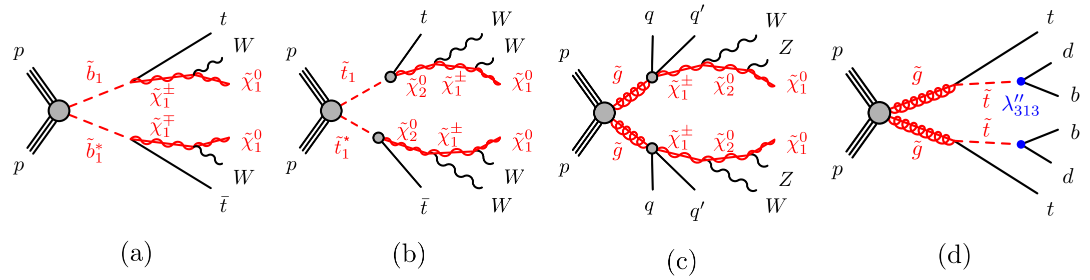



**Figure 1.** Examples of processes allowed in the MSSM, involving the pair production and cascade decays of squarks and gluinos into final states with leptons and jets.

## 2 ATLAS detector

The ATLAS experiment [5] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle.[2] It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadron calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors, completed by the insertable B-layer (IBL) installed before Run 2 [31, 32]. Lead/liquid-argon (LAr) sampling calorimeters provide EM energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range $|\eta| < 1.7$. The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The MS surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T·m across most of the detector. The MS includes a system of precision tracking chambers and fast detectors for triggering. A two-level trigger system [33] is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to at most 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions.

## 3 Event reconstruction

The analysis is performed on a set of $pp$ collision data recorded by the ATLAS detector between 2015 and 2018. In this period, the LHC delivered colliding beams with a peak instantaneous luminosity up to $L = 2.1 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ achieved in 2018, and an average

[2] 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 of the LHC ring, and the $y$-axis points upwards. Cylindrical coordinates $r, \phi$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. The rapidity is defined relative to the beam axis as a function of the velocity $\beta$: $y = 0.5 \times \ln\{(1+\beta\cos\theta)/(1-\beta\cos\theta)\}$. The magnitude of the momentum in the plane transverse to the beam axis is denoted by $p_{\mathrm{T}}$.

JHEP06(2020)046

number of $pp$ interactions per bunch crossing ('pile-up') of 33.7. After requirements on the stability of the beams, the operational status of all ATLAS detector components, and the quality of the recorded data, the total integrated luminosity of the dataset corresponds to 139 fb$^{-1}$ with an uncertainty of 1.7%. It is obtained [34] using the LUCID-2 detector [35] for the primary luminosity measurements.

Proton-proton interaction vertices are reconstructed from charged-particle tracks in the ID with $p_{\mathrm{T}} > 500$ MeV [36, 37]. The presence of at least one such vertex with a minimum of two associated tracks is required, and the primary vertex is chosen as the vertex with the largest sum of $p_{\mathrm{T}}^2$ of associated tracks.

The anti-$k_t$ algorithm [38] with radius parameter $R = 0.4$ implemented in the `FastJet` library [39] is used to reconstruct jets up to $|\eta| = 4.9$, relying on topological energy clusters in the calorimeter [40] at the EM scale. Jets are then calibrated as described in ref. [41]. Only jets with $p_{\mathrm{T}} > 20$ GeV are further considered. Events are vetoed when containing jets induced by calorimeter noise or non-collision background, according to criteria similar to those described in ref. [42]. As decay products of heavy particles tend to be more central, this analysis only considers jets with $|\eta| < 2.8$ in multiplicity-based requirements. An additional discriminant referred to as the `Jet Vertex Tagger` (JVT) is used to exclude jets produced in pile-up processes [43], based on classifying the tracks associated with the jet as pointing or not pointing to the primary vertex.

Jets containing $b$-flavoured hadrons are identified in the region $|\eta| < 2.5$ by the MV2c10 $b$-tagging algorithm [44], which makes use of the impact parameters of tracks associated with the candidate jet, the position of reconstructed secondary vertices and their consistency with the decay chains of such hadrons. For the working point chosen for this analysis, such jets are tagged with an efficiency of 70% in simulated $t\bar{t}$ events, with mis-tag rates of 9% and 0.3% for jets initiated by charm quarks or light quarks/gluons, respectively.

Baseline muon candidates are reconstructed [45] in the region $|\eta| < 2.5$ from MS tracks matching ID tracks. The analysis only considers muons with $p_{\mathrm{T}} > 10$ GeV satisfying the set of requirements on the quality of the tracks which is defined as `Medium` in ref. [45]. The longitudinal impact parameter $z_0$ of the muon track must satisfy $|z_0 \sin\theta| < 0.5$ mm. Signal muons are defined as the baseline candidates sufficiently distant from jets (see below) and other leptons, which satisfy further requirements: the transverse impact parameter $d_0$ of the track must be sufficiently small relative to its uncertainty from the track reconstruction, $|d_0| < 3\sigma(d_0)$, and the candidate must satisfy a track-based isolation criterion. The latter requires the summed scalar $p_{\mathrm{T}}$ of nearby ID tracks not to exceed 6% of the muon $p_{\mathrm{T}}$, for selected tracks in a $p_{\mathrm{T}}$-dependent $\Delta R_\eta = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ cone of maximal size 0.3 around the muon, excluding its own track, similarly to the isolation variables defined in ref. [45]; these tracks must be associated with the primary vertex to limit sensitivity to pile-up.

Baseline electron candidates are reconstructed [46] from energy depositions in the EM calorimeter matched to an ID track and are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.47$, excluding the transition region $1.37 < |\eta| < 1.52$ between the barrel and endcap EM calorimeters. They must satisfy the `LooseAndBLayerLLH` identification discriminant defined in ref. [46], as well as requirements on the track impact parameters $|z_0 \sin\theta| < 0.5$ mm and $|d_0| < 5\sigma(d_0)$. Signal electrons, which must be distant from jets and other leptons, are



JHEP06(2020)046

required to satisfy the tighter MediumLLH identification and FCTight isolation requirements defined in ref. [46]. The latter are similar to the muon isolation requirement, with a maximal cone size of 0.2, but with an additional calorimeter-based isolation requirement using nearby topological clusters instead of tracks. Only signal electrons with $|\eta| < 2.0$ are considered in order to reduce the rate of electrons with wrongly reconstructed charge ('charge-flip'); the latter are further rejected by the application of the ECIDS discriminant described in ref. [46], which exploits further information related to the electron track reconstruction and its compatibility with the primary vertex and the electron cluster.

The missing transverse momentum (whose magnitude is denoted $E_{\mathrm{T}}^{\mathrm{miss}}$) is defined as the negative vector sum of the transverse momenta of all identified objects (baseline electrons, photons [46], baseline 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 [47, 48]. Overlaps between objects in the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation are resolved as described in ref. [47].

To exclude non-prompt leptons produced inside jets, baseline leptons close to jets are discarded according to the angular distance $\Delta R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$ between the two reconstructed objects. A requirement of $\Delta R > \min\{0.4, 0.1 + 9.6\,\mathrm{GeV}/p_{\mathrm{T}}(\ell)\}$ is used.

## 4 Event selection

Events are selected if they contain at least two signal leptons with $p_{\mathrm{T}} > 20$ GeV. In addition, there must be at least one pair of leptons with identical electric charges among the ensemble of signal leptons with $p_{\mathrm{T}} > 10$ GeV.

Data events were recorded via a combination of triggers based on the presence of missing transverse momentum or pairs of leptons [49–52]. For events with $E_{\mathrm{T}}^{\mathrm{miss}} < 250$ GeV, only lepton-based triggers without isolation requirements are used, with lepton $p_{\mathrm{T}}$ thresholds which vary over the data collected in Run 2 up to a maximum of 24 GeV for triggers requiring two electrons, 22 GeV for the leading-$p_{\mathrm{T}}$ muon in triggers requiring two muons, and 17 GeV (14 GeV) for the electron (muon) in mixed dilepton triggers. For events with $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV, triggers based on $E_{\mathrm{T}}^{\mathrm{miss}}$ are also used. For events that are only accepted by lepton triggers with $p_{\mathrm{T}}$ requirements above 20 GeV, the analysis-level lepton $p_{\mathrm{T}}$ requirement is raised to be 1 GeV above the trigger threshold. This results in a relative reduction of the total fiducial acceptance by at most 2% for the benchmark signal scenarios of figure 1. For signal events selected in the SRs presented below, the trigger efficiency is above 95% for $R$-parity-conserving models, and above 93% otherwise. For signal events with $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV, the trigger efficiency is above 99%.

Five SRs are built to isolate signatures of hypothetical supersymmetric signal processes from backgrounds; their definitions are summarised in table 1. They rely on the multiplicities of different reconstructed objects such as the number of leptons $n_\ell$ and their relative electric charges, the number of jets $n_j$ with $p_{\mathrm{T}} > 25$ or 40 GeV, and the number of $b$-tagged jets $n_b$ with $p_{\mathrm{T}} > 20$ GeV. Several kinematic variables are also used: the effective

| SR | $n_\ell$ | $n_b$ | $n_j$ | $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] | $m_{\mathrm{eff}}$ [GeV] | $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ | SUSY |
|---|---|---|---|---|---|---|---|
| `Rpv2L` | $\geq 2$ $(\ell^\pm\ell^\pm)$ | $\geq 0$ | $\geq 6$ ($p_{\mathrm{T}} > 40\,\mathrm{GeV}$) | – | $> 2600$ | – | $\tilde{g} \to t\bar{t}_1^*,\ \tilde{t}_1^* \to qq'$ $(\lambda'' \neq 0)$<br>$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0,\ \tilde{\chi}_1^0 \to 3q$ $(\lambda'' \neq 0)$<br>$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0,\ \tilde{\chi}_1^0 \to qq'\ell$ $(\lambda' \neq 0)$ |
| `Rpc2L0b` | $\geq 2$ $(\ell^\pm\ell^\pm)$ | $= 0$ | $\geq 6$ ($p_{\mathrm{T}} > 40\,\mathrm{GeV}$) | $> 200$ | $> 1000$ | $> 0.2$ | $\tilde{g} \to q\bar{q}'WZ\tilde{\chi}_1^0$ |
| `Rpc2L1b` | $\geq 2$ $(\ell^\pm\ell^\pm)$ | $\geq 1$ | $\geq 6$ ($p_{\mathrm{T}} > 40\,\mathrm{GeV}$) | – | – | $> 0.25$ | $\tilde{b}_1 \to tW\tilde{\chi}_1^0$ |
| `Rpc2L2b` | $\geq 2$ $(\ell^\pm\ell^\pm)$ | $\geq 2$ | $\geq 6$ ($p_{\mathrm{T}} > 25\,\mathrm{GeV}$) | $> 300$ | $> 1400$ | $> 0.14$ | $\tilde{b}_1 \to tW\tilde{\chi}_1^0$<br>$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ |
| `Rpc3LSS1b` | $\geq 3$ $(\ell^\pm\ell^\pm\ell^\pm)$ | $\geq 1$ | no cut but veto $81\,\mathrm{GeV} < m_{e^\pm e^\pm} < 101\,\mathrm{GeV}$ | | | $> 0.14$ | $\tilde{t}_1 \to tW^\pm(W^*)\tilde{\chi}_1^0$ |

**Table 1.** Definition of the signal regions used by the analysis, based on the variables defined in section 4. The last column provides examples of SUSY processes which may contribute to these signal regions.

mass $m_{\mathrm{eff}}$ consisting of the scalar $p_{\mathrm{T}}$ sum of all jets and leptons added to $E_{\mathrm{T}}^{\mathrm{miss}}$, the $E_{\mathrm{T}}^{\mathrm{miss}}$ itself and its ratio to $m_{\mathrm{eff}}$, and the invariant mass of same-sign electron pairs, $m_{e^\pm e^\pm}$. The latter helps to reduce the backgrounds featuring a $Z \to e^+e^-$ decay where the charge of one electron is mismeasured. The SR requirements were chosen loosely so as to provide sensitivity to non-excluded regions of the parameter space for the processes illustrated in figure 1, while preserving sensitivity to other SUSY processes with possibly different final states, as in table 1.

The SR `Rpv2L` targets gluino pair production in $R$-parity-violating scenarios, hence without any $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement. It is inclusive in terms of $b$-tagged jets to be sensitive to various decay modes of gluinos leading to final states with leptons and jets, such as the scenario illustrated in figure 1(d) or the few other examples mentioned in table 1. In this SR, a tight requirement on the effective mass $m_{\mathrm{eff}} > 2.6\,\mathrm{TeV}$ is used to reduce SM backgrounds.

The SR `Rpc2L0b` provides sensitivity to $R$-parity-conserving scenarios not involving third-generation squarks, as in figure 1(c), which are less likely to contain bottom quarks in the final state. A veto on $b$-tagged jets is imposed in order to reduce SM backgrounds with top quarks. Requiring a large number of jets strongly reduces the level of $WZ$ and other multiboson backgrounds.

The SRs `Rpc2L1b` and `Rpc2L2b` provide sensitivity to scenarios involving third-generation squarks, such as $\tilde{b}_1 \to t\tilde{\chi}_1^-$ with a subsequent $\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ decay as in figure 1(a). `Rpc2L2b` uses tighter requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and $m_{\mathrm{eff}}$ than `Rpc2L1b` in order to complement it at low $\tilde{\chi}_1^0$ mass, as well as to provide good sensitivity to scenarios with heavier superpartners such as pair-produced gluinos decaying via $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$.

Finally, the SR `Rpc3LSS1b` probes scenarios with long decay chains but compressed mass spectra leading to final states with softer decay products, such as the $\tilde{t}_1 \to t\tilde{\chi}_2^0 \to tW(W^*)\tilde{\chi}_1^0$ cascade decay shown in figure 1(b) and proposed in ref. [53]. This SR selects events with at least three leptons of identical charge, leading to a huge reduction of the expected SM background yields. Loose requirements on the $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ ratio and the presence of at least one $b$-tagged jet, as well as the rejection of events containing any pair of



JHEP06(2020)046

| Physics process | Event generator | Computation order | Parton shower | Cross-section normalisation | PDF set | Set of tuned parameters |
|---|---|---|---|---|---|---|
| $t\bar{t}W$ [55] | MG5_aMC@NLO 2.3.3 [1] | NLO | Pythia 8.210 [56] | NLO [57] | NNPDF2.3LO [58] | A14 [59] |
| $t\bar{t}Z/\gamma^*$ [55] | MG5_aMC@NLO 2.3.3 [1] | NLO | Pythia 8.210-212 [56] | NLO [57] | NNPDF2.3LO [58] | A14 [59] |
| $t\bar{t}WW$ | MG5_aMC@NLO 2.2.2 [1] | LO | Pythia 8.186 [60] | NLO [1] | NNPDF2.3LO [58] | A14 [59] |
| $t\bar{t}WZ$ | MG5_aMC@NLO 2.2.2 [1] | LO | Pythia 8.212 [56] | NLO [1] | NNPDF2.3LO [58] | A14 [59] |
| $tWZ$, $tZ$ | MG5_aMC@NLO 2.3.3 [1] | LO | Pythia 8.212 [56] | NLO [1] | NNPDF2.3LO [58] | A14 [59] |
| $t\bar{t}H$ [55] | Powheg 2 [61, 62] | NLO | Pythia 8.230 [56] | NLO [57] | NNPDF2.3LO [58] | A14 [59] |
| $3t$, $4t$ | MG5_aMC@NLO 2.2.2 [1] | LO | Pythia 8.186 [60] | NLO [1] | NNPDF2.3LO [58] | A14 [59] |
| $pp \to 4\ell$, $3\ell\nu$ [63] | Sherpa 2.2.2 [64] | NLO (0–1$j$) + LO (2–3$j$) | Sherpa | NLO | NNPDF3.0NNLO [65] | Sherpa |
| $gg \to 4\ell$ [63] | Sherpa 2.2.2 [64] | LO (0–1$j$) | Sherpa | NLO | NNPDF3.0 NNLO [65] | Sherpa |
| $pp \to (2\ell 2\nu/3\ell\nu/4\ell)jj$ [54, 63] | Sherpa 2.2.2 [64] | LO | Sherpa | LO | NNPDF3.0NNLO [65] | Sherpa |
| $WH$, $ZH$ | Pythia 8.186 [60] | LO | Pythia | LO | NNPDF2.3LO [58] | A14 [59] |
| $VVV^{(*)}$ | Sherpa 2.2.1 [64] | LO (0–1$j$) | Sherpa | LO | NNPDF3.0NNLO [65] | Sherpa |
| $VVVjj$ [63] | Sherpa 2.2.2 [64] | LO (0–1$j$) | Sherpa | LO | NNPDF3.0NNLO [65] | Sherpa |

**Table 2.** List of Monte Carlo event generators and their settings used to predict the contributions from SM processes to the various regions of interest in the analysis. When no reference is provided for the cross-section normalisation, the one computed by the generator is used. The LO and NLO acronyms are defined in section 5.

same-sign electrons with $m_{e^\pm e^\pm}$ close to the $Z$ boson mass, help to diminish the residual reducible background to low levels.

A simple cut-and-count analysis is performed in each SR. The number of events in data is reported in section 7 together with the expected contributions from SM processes and the reducible background, the estimations of which are described in the following sections.

## 5 Standard Model backgrounds

Major contributions from SM processes to the SRs arise from $WZ$+jets (with minor contributions from $ZZ$ and $W^\pm W^\pm jj$[3]), $t\bar{t}W$ and $t\bar{t}Z$. The summed contributions of other processes involving associated production of top quarks and massive bosons, with smaller production cross-sections, can also amount to significant fractions of the expected SR event yields. SRs with at least one $b$-tagged jet are populated mainly by processes involving top quarks, while multiboson processes dominate in regions vetoing $b$-jets. In the case of the `Rpc3LSS1b` SR, only processes such as $WZZ$, $ZZZ$, $t\bar{t}WZ$ and $VH/t\bar{t}H$ where the Higgs boson $H$ decays via $H \to 4\ell$ are genuine sources of events with three same-sign prompt leptons.

The contributions of these processes to the SRs are evaluated with Monte Carlo simulations to determine the fiducial acceptance of the various regions as well as the efficiencies of the detector and reconstruction software. Table 2 provides a complete list of the relevant processes considered in this analysis, the event generators used for the predictions and their settings. For the processes with the largest production cross-sections, the scattering amplitudes evaluated for the event generation rely on terms up to the next-to-leading order (NLO) in the perturbative expansion, while for other processes only leading-order

[3]This process corresponds to the production of two same-sign $W$ bosons [54] which at the lowest order of the perturbative expansion are accompanied by two forward jets.

(LO) terms are accounted for. For most processes, the generated events are normalised to the inclusive cross-section computed with NLO accuracy, either taken from the references indicated in table 2, or directly from the generator. The generated events for the $t\bar{t}Z$, $tZ$, $tWZ$, $VZ$ and $VVZ$ processes include matrix elements for non-resonant $Z/\gamma^* \to \ell\ell$ contributions; the same is true for non-resonant $W^* \to \ell\nu$ in events from $VV$ and $VVV$ processes. For the `Rpc3LSS1b` SR, only contributions from processes with three same-sign prompt leptons are evaluated with Monte Carlo simulations, while the others ($VV$, $t\bar{t}V\dots$) are included in the estimation of the reducible background, which is described in section 6.

The generated events were processed through a detailed simulation of the ATLAS detector [66] based on GEANT4 [67]. To simulate the effects of additional $pp$ collisions in the same and nearby bunch crossings, inelastic interactions were generated using the soft strong-interaction processes of PYTHIA 8.1.86 [56] with a set of tuned parameters referred to as the A3 tune [68] and the NNPDF23LO parton distribution function (PDF) set [58]. These inelastic interactions were overlaid onto the simulated hard-scatter events, which were then reweighted to match the pile-up conditions observed in the data. In all Monte Carlo samples, except those produced by the SHERPA event generator, the EVTGEN 1.2.0 program [69] was used to model the properties of bottom and charm hadron decays.

Simulated events are weighted by scale factors to correct for the mismodelling of inefficiencies associated with the reconstruction of leptons, the application of lepton identification and isolation requirements, the lepton-based trigger chains, and the application of pile-up rejection (`JVT`) and $b$-tagging requirements to jets that do or do not contain genuine $b$-flavoured hadrons.

Various sources of systematic uncertainties in the predicted event yields are accounted for. Experimental sources, evaluated for all processes, include uncertainties in the calibration of the momentum scale and resolution for jets, leptons and the soft term of the missing transverse momentum, as well as uncertainties in the various scale factors mentioned above, in the measured integrated luminosity, and in the distribution of the number of additional $pp$ interactions per event.

Uncertainties in the theoretical modelling of each process are also considered. Uncertainties in the inclusive production cross-sections of $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}H$ are taken as 12%, 13% and 8% [57], respectively, while a 6% uncertainty is assigned for $VV$ processes [63]. The impact of the choice of factorisation and renormalisation scales on the estimated fiducial acceptance and reconstruction efficiencies of the SRs is assessed by considering the alternative event weights provided by the generators for up/down variations of these scales (see e.g. appendix B.3 in ref. [1]). The impact of PDF uncertainties is also taken into account by following the prescription in ref. [70] using the sets of eigenvectors provided for each PDF [58, 65].

For $t\bar{t}V$ and $t\bar{t}H$ processes, the modelling of initial- and final-state radiation by the parton shower algorithm is assessed by comparing five related variations of the PYTHIA 8 A14 event tune [59]. For $t\bar{t}W$ the modelling of extra jets is further compared with the prediction of the SHERPA 2.2.2 generator including LO matrix elements with two extra final-state partons; the difference is found to be smaller than the tune-based parton shower uncertainties.



JHEP06(2020)046

| | $n_\ell$ | $n_b$ | $n_j$ | $m_{\rm eff}$ [GeV] | Other requirements |
|---|---|---|---|---|---|
| `VRWZ4j` | $= 3$, | $= 0$ | $\geq 4$ ($p_{\rm T} > 25\,{\rm GeV}$) | $> 600$ | $81\,{\rm GeV} < m_{\rm SFOS} < 101\,{\rm GeV}$, $E_{\rm T}^{\rm miss} > 50\,{\rm GeV}$, |
| `VRWZ5j` | $= 1$ SFOS pair | $= 0$ | $\geq 5$ ($p_{\rm T} > 25\,{\rm GeV}$) | $> 400$ | no fourth baseline lepton |
| `VRttV` | $\geq 2$ ($\ell^\pm\ell^\pm$) | $\geq 1$ | $\geq 3$ ($p_{\rm T} > 40\,{\rm GeV}$) | $> 600$ | $p_{\rm T} > 30\,{\rm GeV}$ for the same-sign leptons, $\sum p_{\rm T}^b > 0.4 \sum p_{\rm T}^j$, $E_{\rm T}^{\rm miss} > 0.1 m_{\rm eff}$, $\Delta R_\eta(\ell_1, j) > 1.1$ |
| All VRs | $m_{\rm eff} < 1.5\,{\rm TeV}$, $E_{\rm T}^{\rm miss} < 250\,{\rm GeV}$; veto `Rpc2L1b`, `Rpc2L2b`, `Rpc2L0b` and `Rpv2L` signal regions. | | | | |

**Table 3.** Event selection defining the three validation regions enriched in $WZ$+jets and $t\bar{t}V$ SM processes, based on the variables defined in section 5.

For $VV$ processes, the impact of the choice of resummation scale (QSF) and CKKW matching scale [71] is also evaluated by comparing the nominal prediction with alternatives obtained with variations of these scales. In addition, the modelling of high jet multiplicities is probed by switching between different parton shower recoil schemes implemented in the Sherpa generator [72, 73].

Overall, modelling uncertainties in the SRs where these processes have sizeable contributions are 35–45% for $t\bar{t}W$, 25–45% for $t\bar{t}Z$, 15–40% for $t\bar{t}H$, and 40–45% for $WZ$. For all other processes, uncertainties of 50% are assigned. The latter numbers are believed to be conservative as these processes produce a larger number of jets at the first order of the perturbative expansion, rendering them less sensitive to parton shower modelling uncertainties. For the largest contribution to the SRs among these rarer processes, namely from $4t$ production, the combined impact of factorisation and renormalisation scales as well as PDF uncertainties was checked and found to be indeed smaller than 50%. Modelling uncertainties are further assumed to be uncorrelated between processes shown in different categories in the tables and figures.

Three validation regions (VRs) enriched respectively in $WZ$+jets (`VRWZ4j`, `VRWZ5j`) and $t\bar{t}V$ (`VRttV`) are used to check the accuracy of the modelling of these processes by comparing event yields predicted in a signal-free environment with data. The definitions of these regions are provided in table 3, and are designed to minimise the level of reducible background. Requirements are set on some of the variables defined in section 4. The presence of a pair of same-flavour opposite-sign (SFOS) leptons is required in `VRWZ4j` and `VRWZ5j`, and its invariant mass $m_{\rm SFOS}$ must be close to $m_Z$. A minimum angular separation between the leading-$p_{\rm T}$ lepton and the jets ($\Delta R(\ell_1, j)$) is required in `VRttV`, together with a requirement on the ratio of the scalar $p_{\rm T}$ sum over all $b$-tagged jets to the sum over all jets. For all VRs, events belonging to any SR (except `Rpc3LSS1b`) are vetoed. Upper bounds on $E_{\rm T}^{\rm miss}$ and $m_{\rm eff}$ are also imposed to minimise contributions from the benchmark SUSY scenarios of figure 1. Modelling uncertainties are evaluated with the same procedure as described above for the SRs, and lead to uncertainties of around 20% for $t\bar{t}V$ and 35% for $WZ$ processes.

The number of events observed in each of the three VRs and the corresponding predictions for SM processes are shown in table 4, including the reducible background described in the next section, accounting for the systematic and statistical uncertainties. The predicted

JHEP06(2020)046

| | VRttV | VRWZ4j | VRWZ5j |
|---|---|---|---|
| Observed | 127 | 355 | 190 |
| Total SM background | $106^{+16}_{-19}$ | $390^{+120}_{-100}$ | $209^{+68}_{-54}$ |
| $t\bar{t}W$ | $25.8^{+5.5}_{-5.6}$ | $0.40^{+0.17}_{-0.15}$ | $0.32^{+0.14}_{-0.15}$ |
| $t\bar{t}Z$ | $34.4^{+8.1}_{-8.2}$ | $37.2^{+8.6}_{-8.8}$ | $27.3^{+7.2}_{-7.4}$ |
| $WZ$ | $5.8^{+2.5}_{-2.2}$ | $310^{+120}_{-90}$ | $153^{+64}_{-50}$ |
| $ZZ$, $W^{\pm}W^{\pm}$, $VH$, $VVV$ | $1.03^{+0.40}_{-0.39}$ | $12.0^{+3.4}_{-2.9}$ | $7.5^{+2.8}_{-2.1}$ |
| $t\bar{t}H$ | $7.3^{+1.1}_{-1.2}$ | $0.90^{+0.18}_{-0.18}$ | $0.81^{+0.18}_{-0.17}$ |
| $t(W)Z$, $t\bar{t}VV$, $3t$, $4t$ | $10.4^{+5.2}_{-5.2}$ | $10.3^{+5.3}_{-5.3}$ | $5.8^{+3.1}_{-3.1}$ |
| Fake/non-prompt | $14^{+8}_{-12}$ | $15^{+7}_{-13}$ | $13.7^{+5.4}_{-8.0}$ |
| Charge-flip | $7.1^{+5.7}_{-5.7}$ | – | – |

**Table 4.** Observed yields in data compared with the expected contributions from relevant SM processes (section 5) and the reducible background (section 6), in the three VRs enriched in $WZ$+jets and $t\bar{t}V$ processes. The displayed numbers include all sources of statistical and systematic uncertainties; since some of the latter might be correlated between different processes, the numbers do not necessarily add up in quadrature to the uncertainty in the total expected background. Selections with three leptons are not affected by the charge-flip electron background, so such contributions are denoted by –.

event yields in all VRs are consistent with the data. In the `VRWZ4j` and `VRWZ5j` regions, the large systematic uncertainties include contributions from theoretical modelling and from experimental sources (dominated by the jet energy scale) due to the large required number of jets.

Other potential sources of same-sign leptons in the SRs are not included, as they were estimated to be negligible. These include simultaneous production of massive bosons or top quarks via either double parton scattering (DPS) or pile-up interactions. Simple estimations of the inclusive production cross-sections were performed for several processes. For DPS the approach from ref. [74] was used, relying on the DPS effective cross-section $\sigma_{\text{eff}}$ [75]. Earlier experiments probed the reliability of this approach for different centre-of-mass energies and physics processes [76], including more recently for $W^{\pm}W^{\pm}$ production [77]. All these measurements display a level of consistency allowing to conclude that DPS processes would not contribute noticeably to the SRs. For pile-up interactions, the estimation was based on the longitudinal density of reconstructed vertices [78], as the impact parameter requirements in the selection of the leptons strongly affect the yields of such processes. The only process for which the pile-up induced contribution is estimated to be more than 1% of the corresponding SM process is $W^{\pm}W^{\pm}$ production, which has been highlighted [79] as a sensitive process for DPS measurements. But this process is in itself a minor source of background for this analysis.



JHEP06(2020)046

Another source, notably highlighted in ref. [80], is the production of additional pairs of leptons in radiative top quark decays, $t \to \ell\nu b\ell\ell$ or $t \to qqb\ell\ell$, which are not included in the generator matrix elements for the $t\bar{t}Z$ process. These contributions were studied by running the PHOTOS++ QED shower program [81] on the tree-level decay products of top quarks generated with MADGRAPH 2.6 or PYTHIA 8. The fraction of events in which an additional lepton is produced drops sharply with the $p_T$ requirement for that lepton; for a $p_T = 10$ GeV threshold[4] this fraction was found to be $\sim 0.2\%$, a similar order of magnitude to that quoted in ref. [81]. An additional isolation requirement similar to that used in the analysis reduces this rate by a factor of three. This represents less than 2% (4%) of the inclusive contribution from $t\bar{t}V$ processes for final states with same-sign (three) leptons; furthermore, the smaller reconstruction and identification efficiencies for low-$p_T$ leptons should further reduce the radiative top quark decay contribution relative to $t\bar{t}V$ processes. The expected contribution to the SRs is therefore small enough to be neglected.

## 6 Backgrounds with non-prompt, fake or charge-flip leptons

Other SM processes that do not lead to genuine production of same-sign prompt leptons, such as $t\bar{t}$ processes and to a much lesser extent production of $W/Z$+jets or single top quarks, might contaminate the SRs via secondary interactions, for example bremsstrahlung or non-prompt leptons in ensuing decays, or misidentification of the reconstructed objects (fakes).

The first source consists of 'charge-flip' electrons, where the charge of a prompt electron is mismeasured due to the emission of a bremsstrahlung photon which through interaction with detector material converts into a pair of secondary electron tracks, one of which happens to better match the position of the calorimeter cluster than the original electron track and has a charge opposite to that of the prompt electron. Thanks to the application of the `ECIDS` discriminant for signal electrons, charge-flip electrons are only a minor background in the SRs. Muon charge-flip is negligible in the $p_T$ range relevant to this analysis.

Backgrounds with charge-flip electrons are estimated by selecting data events with two opposite-sign leptons, and weighting them by the probability of one electron charge to be mismeasured. This offers a large improvement in statistical accuracy over relying directly on the simulation for these backgrounds, as well as the elimination of associated experimental and theory uncertainties. The charge-flip probabilities are measured in simulated $t\bar{t}$ events, as a function of $p_T$ and $|\eta|$. They are corrected by scale factors corresponding to the ratio of probabilities measured in data and simulation from the reconstructed charges of electrons produced in $Z \to e^+e^-$ decays and selected with a 'tag and probe' method [46]. The probabilities reach $\mathcal{O}(0.1\%)$ at $p_T = 100$ GeV for central electrons ($|\eta| < 1.4$), and are about fives times larger at higher $|\eta|$ due to the larger amount of material traversed by electrons. Systematic uncertainties are assessed by propagating the measurement uncertainties, leading to a 70–90% uncertainty in the predicted SR yields for the charge-flip background.

[4] Dilepton $t\bar{t}$ events with an extra $p_T > 10$ GeV lepton satisfy the lepton selection requirements of this analysis.

The data weighting method described above neglects the differences in momentum scale and resolution between standard and charge-flip electrons. This approximation was validated by recomputing the expected SR yields after reducing the $p_{\mathrm{T}}$ of the electron with largest $|\eta|$ by 5 GeV — a value bounding from above the invariant mass resolution of same-sign $ee$ pairs near the Z boson mass — in all weighted data events, which was found to have a negligible impact on the results. For the `Rpc3LSS1b` SR, the method is adapted by simply selecting data events with three or more leptons, which are weighted by the probability of one or more electron charges to be mismeasured such that the resulting event contains three same-sign leptons.

Another, more important, source of reducible background includes fake or non-prompt leptons, referred to in the following as 'F/NP' leptons. These may originate from electroweak-mediated decays of hadrons (in particular $b$- and $c$-flavoured hadrons in decays of top quarks and weak bosons), single pions stopped in the EM calorimeter that fake electron signatures, in-flight decays of kaons into muons, or the conversion of photons into pairs of electrons in the beam pipe or detector material. Lepton candidates reconstructed from these different sources share the properties of being generally not well isolated and being mostly rejected by the lepton identification criteria and impact parameter requirements. Therefore, all sources of background with F/NP leptons are estimated together, using a common method that exploits these properties.

Sources of F/NP leptons in the SRs are mostly semileptonic or dileptonic $t\bar{t}$ processes. To estimate their contributions to the SRs, a matrix method as described in ref. [82] is used, with a different parameterisation of efficiencies and uncertainties as detailed in the following. It relies on data events selected with the same criteria as in the region of interest, but with a loosened lepton selection corresponding to the baseline leptons defined in section 3 after the overlap removal procedure with a few extra adjustments: muons are required to satisfy a loosened transverse impact parameter requirement $|d_0| < 7\sigma(d_0)$, and electrons must both be within $|\eta| < 2.0$ and satisfy the `ECIDS` requirement against charge-flip. These adjustments align the selection with the fiducial acceptance of signal leptons, and eliminate irrelevant sources of reconstructed leptons. The matrix method, for the simplest situation where selected events contain a single lepton, relies on the following asymptotic equality for the observed proportion of events $\mathcal{S}$ where the lepton satisfies the signal lepton requirements:

$$\mathcal{S} = \varepsilon\,(1 - \mathcal{F}) + \zeta\mathcal{F} \tag{6.1}$$

where $\mathcal{F}$ is the unknown proportion of events with a F/NP lepton, while $\varepsilon$ and $\zeta$ are respectively the probabilities for a prompt or F/NP lepton to satisfy the signal lepton requirements. If $\varepsilon$ and $\zeta$ are known, eq. (6.1) can be used to determine $\mathcal{F}$ and thus the number of events with a F/NP lepton in the region of interest. The approach can be generalised to events with arbitrary numbers of leptons, as well as the more realistic situation where $\varepsilon$ and $\zeta$ depend on the flavour and kinematic properties of the leptons.

The probabilities $\varepsilon$ are obtained directly from the $t\bar{t}$ simulation, as a function of $p_{\mathrm{T}}$ and $|\eta|$, accounting for the various lepton-related scale factors mentioned in section 5. For $p_{\mathrm{T}} > 30$ GeV the probabilities are larger than 80% and 90% for electrons and muons, respectively. As $\varepsilon$ might be smaller in data events coming from signal scenarios with busy environments, such as boosted top quarks that decay semileptonically, uncertainties are taken into account as a function of $p_{\mathrm{T}}$ and the proximity to the closest jet and can be as large as 30% for $\Delta R < 0.4$.

The probabilities $\zeta$ are measured in regions of the data enriched in F/NP leptons produced by $t\bar{t}$ processes, defined by selecting events with two same-sign leptons or three leptons, at least one $b$-tagged jet, $E_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$ and $\geq$ 2–3 jets; upper bounds on $E_{\mathrm{T}}^{\mathrm{miss}}$ and $m_{\mathrm{eff}}$ avoid contamination from supersymmetric processes. The probabilities are measured as a function of $p_{\mathrm{T}}$, separately for events with exactly one or exactly two $b$-tagged jets, as the proportion of non-prompt leptons from $b$-flavoured hadron decays is much smaller in the latter case than in events with at most one $b$-tagged jet. They are also measured separately for electrons that were or were not used to accept the event via a lepton-based trigger, as the requirements for electrons reconstructed online differ from those for electrons reconstructed offline. The measured probabilities are $\sim$ 10% for both electrons and muons up to $p_{\mathrm{T}} \sim 35\,\mathrm{GeV}$, and increase to 20% and 35% for electrons and muons with $p_{\mathrm{T}} > 60\,\mathrm{GeV}$. They can be up to twice as large in events with two $b$-tagged jets.

Systematic uncertainties in the measured $\zeta$ probabilities account for variations in the relative contributions of different sources of F/NP leptons or in the environment, and they are assessed in simulated $t\bar{t}$ events. For electrons the latter amount to a 30% additional uncertainty. For muons the probabilities become smaller in events with a larger amount of activity, where non-prompt muons tend to be less well isolated. This leads to extra uncertainties of 30% to 80% for $p_{\mathrm{T}} > 50\,\mathrm{GeV}$, as this effect is not accounted for with the simple $p_{\mathrm{T}}$-based parameterisation used for $\zeta$.

Events with charge-flip electrons may bias the matrix method prediction, as the probability for such electrons to satisfy signal lepton requirements differ from both standard and F/NP electrons. For that reason, estimated charge-flip contributions are subtracted from the data event yields when the method is applied.

The data-driven methods employed to estimate the reducible background are validated by comparing the event yields in data with the combined predictions for these backgrounds, added to Monte Carlo predictions for SM processes as described in section 5. Figure 2 shows such a comparison for a loose event preselection requiring same-sign leptons, $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$ and at least three jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$, binned in the different lepton flavour and $b$-tag multiplicity combinations. Simulation studies show that the sources of reducible background for such a preselection are dominated, as in the SRs, by $t\bar{t}$ processes. While the F/NP lepton background represents a major contribution to the total yields, the charge-flip background is always small. In all bins, the observed and predicted event yields agree within uncertainties. Figure 3 presents the distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the number of jets in events with at least two jets and an otherwise identical preselection, for which good agreement is observed between data and predictions.

As $t\bar{t}$ processes with F/NP leptons produce a major background in this analysis, the estimated SR yields obtained with the matrix method are cross-checked against an alternative method based on a factorisation approach. In the latter, a control region CR is built for each SR by relaxing some of the $E_{\mathrm{T}}^{\mathrm{miss}}$ or $m_{\mathrm{eff}}$ requirements. Another set of regions SR′

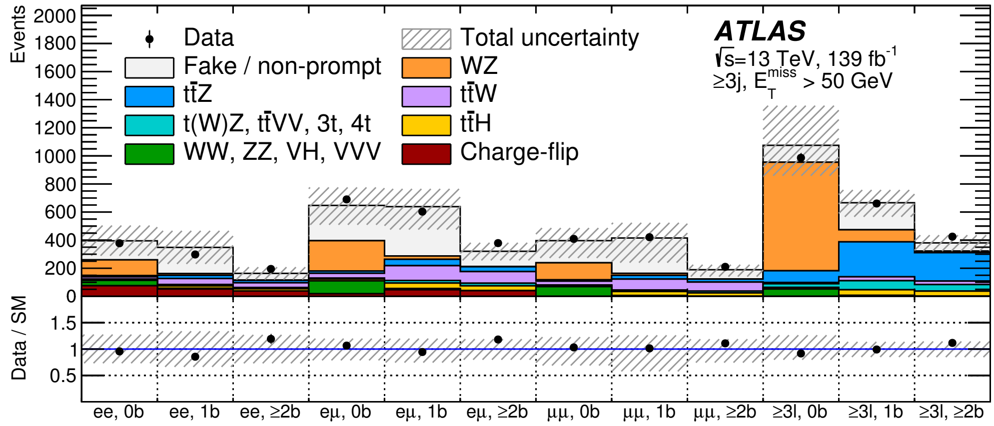



**Figure 2.** Data event yields compared with the expected contributions from relevant SM processes (section 5) and the reducible background (section 6), after a loose preselection requiring events with same-sign leptons, $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$ and at least three jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$. The observed and predicted event yields are classified as a function of the number and flavour of the leptons, as well as the number of $b$-tagged jets. The uncertainties, shown with hashed bands, include the total uncertainties in the reducible background, as well as the modelling and statistical uncertainties for the Monte Carlo simulations.

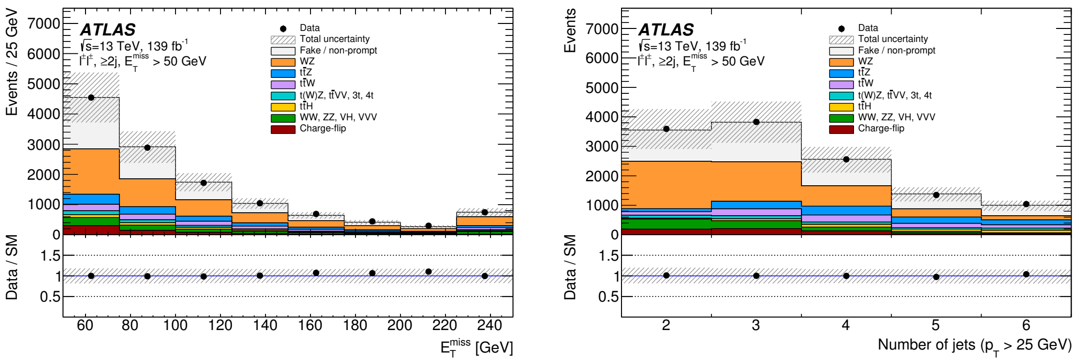



**Figure 3.** Distributions of (left) $E_{\mathrm{T}}^{\mathrm{miss}}$ and (right) the number of jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, after a loose preselection requiring events with same-sign leptons, $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$ and at least two jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$. The uncertainties, shown with hashed bands, include the total uncertainties in the reducible background, as well as the modelling and statistical uncertainty for the Monte Carlo simulations. The last bin is inclusive.

and CR′ is built with identical criteria but using events where a single lepton is selected instead of the same-sign pair, as well as an additional object (jet, $b$-tagged jet, photon) that might be a source of F/NP leptons. Each CR is chosen such that the kinematic properties of the additional object are similar in CR′ and SR′. A 'transfer factor' is built as the ratio of the number of data events in SR′ to the number in CR′. The transfer factor is then multiplied by the number of events with same-sign leptons in the CR to obtain an estimate of the F/NP lepton background yield in the SR. The estimated contributions to

JHEP06(2020)046

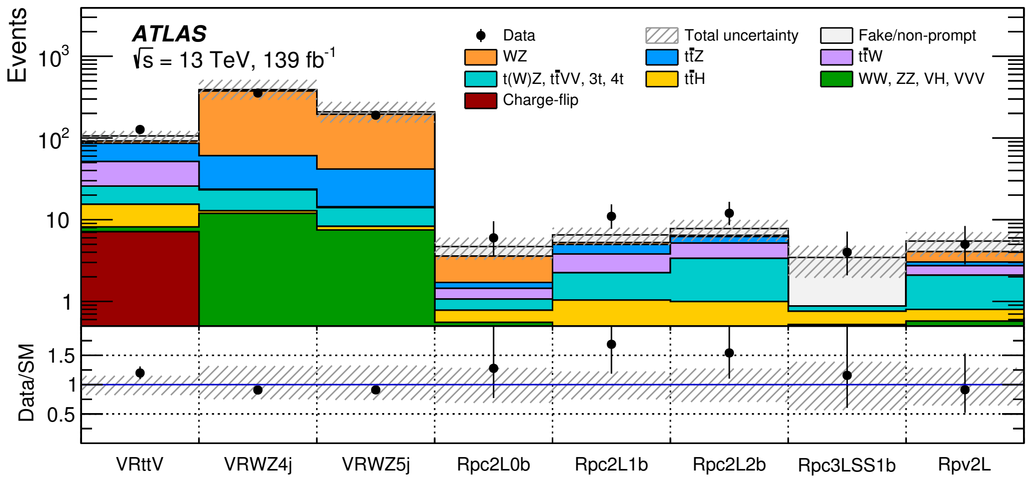



**Figure 4.** Data event yields compared with the expected contributions from relevant SM processes (section 5) and the reducible background (section 6), in the three VRs and the five SRs. The total uncertainties in the expected event yields are shown as the hashed bands.

the CR from SM processes with same-sign prompt leptons are subtracted, as is the charge-flip background. Differences between the transfer factors calculated using different choices for the additional object are treated as a source of systematic uncertainty. The estimated F/NP lepton background yields in the five SRs obtained with this alternative method are consistent with the matrix method prediction within uncertainties.

## 7 Results

The event yields in data in the five SRs, and the corresponding estimates for SM processes and the reducible background, are shown in figure 4 and detailed in table 5. No significant excess over the expected yields is observed in any of the SRs. The SRs `Rpc2L1b` and `Rpc2L2b` overlap by approximately 15% in terms of expected yields from SM processes, and two data events satisfy the requirements for both regions. Among SM processes with smaller cross-sections, the largest contributions originate from $t\bar{t}H$ (in `Rpc2L1b`) and $4t$ (in `Rpc2L2b`, `Rpv2L`). The distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{eff}}$ or the $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ ratio are shown with the SR requirement relaxed for the displayed variable in figure 5 for four of the SRs. When $E_{\mathrm{T}}^{\mathrm{miss}}$ is relaxed (`Rpc2L0b`, `Rpc2L2b`), the $m_{\mathrm{eff}}$ requirement is also loosened by the difference between the actual $E_{\mathrm{T}}^{\mathrm{miss}}$ and the minimum $E_{\mathrm{T}}^{\mathrm{miss}}$ required in the SR, to avoid selecting harder jets or leptons in the low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region. The $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ requirement is loosened similarly. For `Rpc2L0b`, the small number of events in the low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region, compared with the SR, is due to the combined effects of the $m_{\mathrm{eff}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ requirements, preventing high-$m_{\mathrm{eff}}$ events from being selected.

Figure 6 presents a summary of the contributions from different sources of systematic uncertainty to the total uncertainties in the predicted total background yields. These range from 23% to 41%, and are always smaller than the statistical uncertainties in the observed event yields.



JHEP06(2020)046

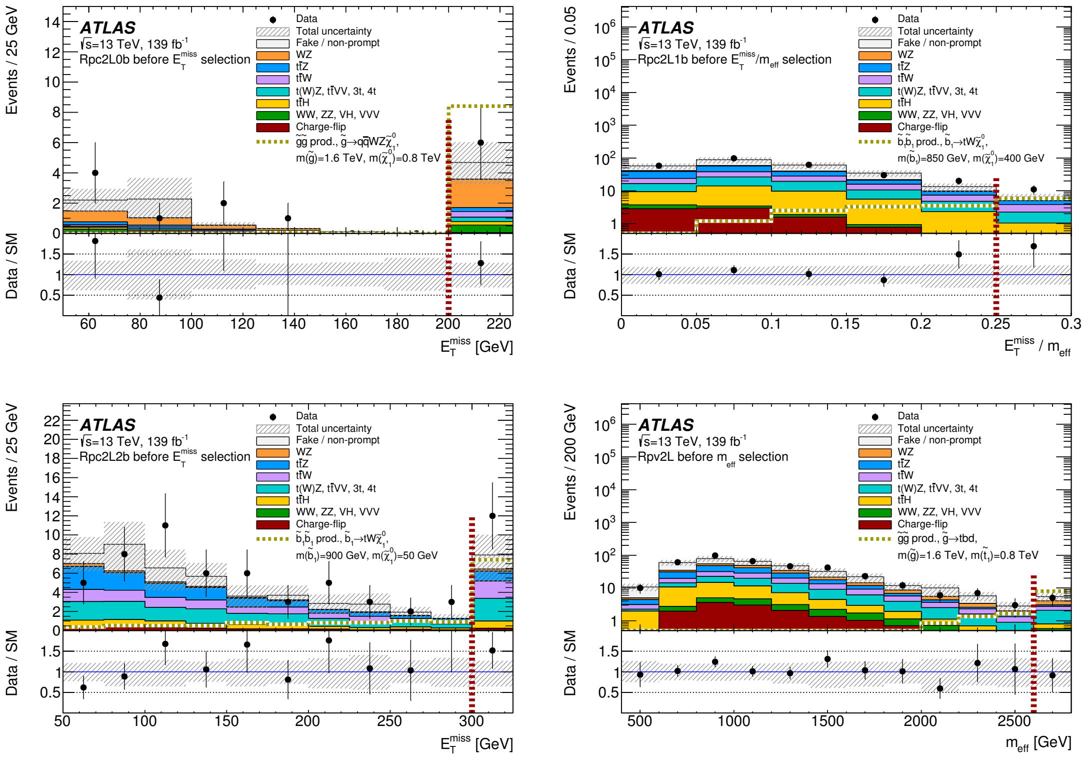



**Figure 5.** Distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{eff}}$ or the $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ ratio near the SRs (top left) `Rpc2L0b`, (top right) `Rpc2L1b`, (bottom left) `Rpc2L2b` and (bottom right) `Rpv2L`. The total uncertainties in the expected event yields are shown as the hashed bands. The last bin, isolated by a vertical red dashed line, is inclusive and corresponds to the SR. Hypothetical contributions from representative SUSY scenarios are displayed by the dashed-line overlaid histograms.

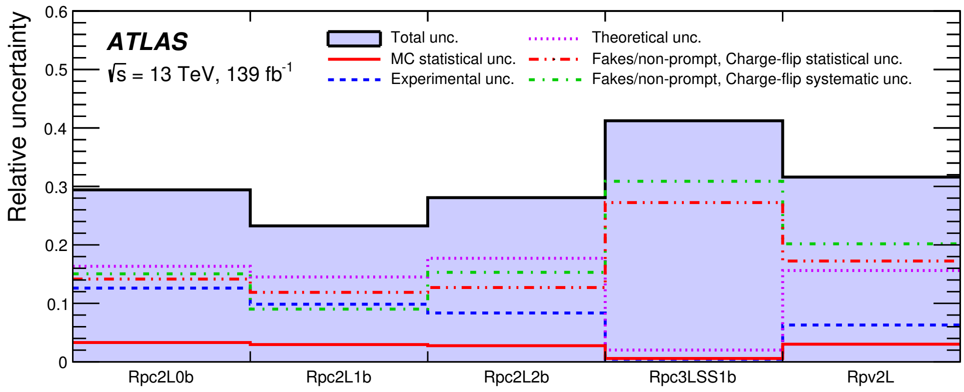



**Figure 6.** Contributions of different categories of uncertainties relative to the expected background yields in the five SRs. The statistical uncertainties originate from the limited number of preselected or opposite-sign data events used in the matrix method and the charge-flip electron background estimate, respectively, as well as the effect of limited numbers of simulated events for SM processes.

| | Rpc2L0b | Rpc2L1b | Rpc2L2b | Rpc3LSS1b | Rpv2L |
|---|---|---|---|---|---|
| Observed | 6 | 11 | 12 | 4 | 5 |
| Total SM background | $4.7^{+1.3}_{-1.5}$ | $6.5^{+1.5}_{-1.6}$ | $7.8^{+2.1}_{-2.3}$ | $3.5^{+1.4}_{-1.5}$ | $5.5^{+1.6}_{-2.0}$ |
| $t\bar{t}W$ | $0.38^{+0.21}_{-0.22}$ | $1.56^{+0.64}_{-0.63}$ | $1.81^{+0.74}_{-0.62}$ | – | $0.64^{+0.30}_{-0.29}$ |
| $t\bar{t}Z$ | $0.26^{+0.13}_{-0.11}$ | $1.17^{+0.43}_{-0.43}$ | $1.04^{+0.34}_{-0.33}$ | – | $0.30^{+0.18}_{-0.17}$ |
| $WZ$ | $1.88^{+0.85}_{-0.76}$ | $0.29^{+0.15}_{-0.15}$ | $0.21^{+0.10}_{-0.11}$ | – | $1.03^{+0.48}_{-0.45}$ |
| $ZZ$, $W^{\pm}W^{\pm}$, $VH$, $VVV$ | $0.50^{+0.18}_{-0.16}$ | $0.04^{+0.02}_{-0.02}$ | $0.03^{+0.01}_{-0.01}$ | $< 0.02$ | $0.43^{+0.13}_{-0.13}$ |
| $t\bar{t}H$ | $0.23^{+0.09}_{-0.08}$ | $0.90^{+0.27}_{-0.26}$ | $0.75^{+0.25}_{-0.20}$ | $0.24^{+0.05}_{-0.05}$ | $0.22^{+0.10}_{-0.09}$ |
| $t(W)Z$, $t\bar{t}VV$, $3t$, $4t$ | $0.29^{+0.17}_{-0.16}$ | $1.21^{+0.63}_{-0.63}$ | $2.4^{+1.2}_{-1.2}$ | $0.12^{+0.06}_{-0.06}$ | $1.29^{+0.67}_{-0.67}$ |
| Fake/non-prompt | $1.1^{+0.8}_{-1.1}$ | $1.3^{+0.9}_{-1.1}$ | $1.4^{+1.4}_{-1.4}$ | $2.6^{+1.3}_{-1.5}$ | $1.4^{+1.2}_{-1.4}$ |
| Charge-flip | $0.05^{+0.04}_{-0.04}$ | $0.11^{+0.11}_{-0.11}$ | $0.22^{+0.22}_{-0.22}$ | $0.52^{+0.39}_{-0.39}$ | $0.14^{+0.14}_{-0.14}$ |

**Table 5.** Observed yields in data and expected contributions from SM processes (section 5) and the reducible background (section 6) to the five SRs. The displayed numbers include all sources of statistical and systematic uncertainty; since some of the latter might be correlated between different processes, the numbers do not necessarily add up in quadrature to the uncertainty in the total expected background. The $WZ$ and $t\bar{t}V$ processes cannot genuinely result in final states with three same-sign leptons, so their contributions to the Rpc3LSS1b signal region are denoted by –. Contributions to Rpc3LSS1b only include those from processes producing final states with three genuine same-sign leptons, such as $t\bar{t}WZ$ or $WZZ$.

| Signal region | $\sigma_{\text{vis}}$ [fb] | $S^{95}_{\text{obs}}$ | $S^{95}_{\text{exp}}$ | $p(s=0)$ |
|---|---|---|---|---|
| Rpc2L0b | 0.05 | 7.6 | $6.4^{+3.2}_{-2.0}$ | 0.33 |
| Rpc2L1b | 0.08 | 11.6 | $7.3^{+3.6}_{-2.3}$ | 0.09 |
| Rpc2L2b | 0.09 | 12.4 | $8.7^{+4.0}_{-2.7}$ | 0.14 |
| Rpc3LSS1b | 0.04 | 6.2 | $5.7^{+2.9}_{-1.8}$ | 0.41 |
| Rpv2L | 0.05 | 6.7 | $6.9^{+3.2}_{-2.0}$ | 0.50 |

**Table 6.** Computed 95% CL upper limits on the numbers of BSM events $S^{95}$, as well as the $\pm 1\sigma$ expected fluctuations around the mean expected limit. These are also translated into upper limits on the visible cross-section $\sigma_{\text{vis}}$. The $p$-values $p(s=0)$ give the probabilities to observe a deviation from the predicted background at least as large as that in the data. They are capped at 0.50.

Upper limits at 95% confidence level (CL) on possible BSM contributions to the SRs are computed with the HistFitter framework [83], relying on a profile-likelihood-ratio test [84] and following the $\text{CL}_\text{s}$ prescription [85]. The hypothesis tests are performed for each of the SRs independently. The likelihood is built as the product of a Poisson probability distribution describing the observed number of events in the SR and the probability distri-

JHEP06(2020)046

butions of the nuisance parameters encoding the systematic uncertainties. The latter are Gaussian distributions for all sources, including statistical uncertainties arising from the limited number of preselected or opposite-sign data events in the estimation of the reducible background, or the limited number of simulated events. Correlations of a given nuisance parameter between the backgrounds and the signal are taken into account when relevant.

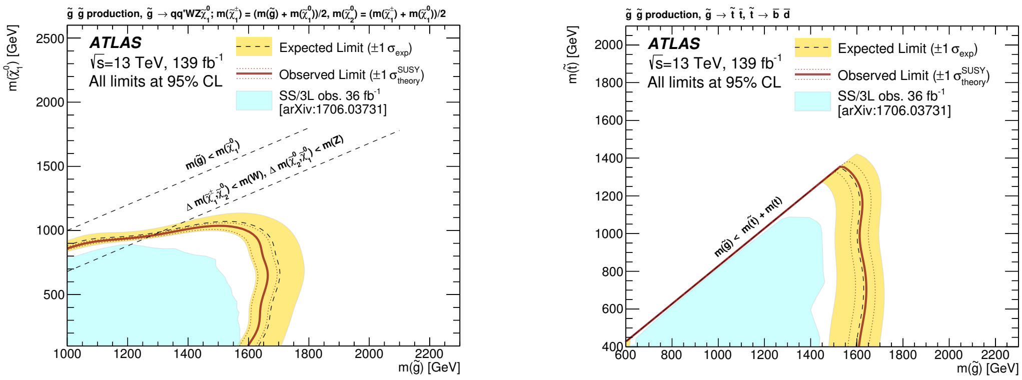
Table 6 presents 95% CL upper limits on the number of BSM events, $S^{95}$, that may contribute to the SRs. Normalising these by the integrated luminosity $L$ of the data sample, they can be interpreted as upper limits on the visible BSM cross-section ($\sigma_{\text{vis}}$), defined as $\sigma_{\text{vis}} = \sigma_{\text{prod}} \times \mathcal{A} \times \epsilon = S^{95}/L$, where $\sigma_{\text{prod}}$ is the production cross-section of an arbitrary BSM signal process, and $\mathcal{A}$ and $\epsilon$ are the corresponding fiducial acceptance and reconstruction efficiencies for the relevant SR. These limits are computed with asymptotic approximations of the probability distributions of the test statistic under the different hypotheses [84]. They were confirmed to be within 10% of an alternative computation based on pseudo-experiments. The probability of the observations being compatible with the SM-only hypothesis is quantified by the $p$-values displayed in table 6; the smallest, for `Rpc2L1b`, corresponds to about 1.3 standard deviations.

## 8 Exclusion limits on SUSY scenarios

Exclusion limits are computed for the masses of superpartners involved in the benchmark SUSY signal scenarios shown in figure 1, using the same statistical tools as those described in section 7. The limits are obtained in the context of simplified models [86–88] assuming a single production process with 100% branching ratio into the chosen decay mode, and where superpartners not involved in the process are treated as decoupled. All superpartners are assumed to decay promptly. The expected signal contributions to the SRs are estimated from simulated Monte Carlo samples produced with the MadGraph5_aMC@NLO 2.2.1 generator using LO matrix elements for the signal process with up to two extra partons. Parton shower, hadronisation and modelling of the underlying event were performed using the Pythia 8.230 generator [56] with the A14 tune [59], using the CKKW-L matching prescription [89] with a matching scale set to one quarter of the mass of the gluinos or squarks produced in the interaction. The samples were processed through a fast simulation of the ATLAS detector using a parameterisation of the calorimeter response but Geant4 for the ID and MS [66, 90]. Such an approach is known to be appropriate for the standard reconstruction techniques described in section 3, and alternative corrections and scale factors to those evoked in sections 3 and 5 are employed. The samples are normalised to the 'NNLO$_{\text{approx}}$+NNLL' reference cross-sections [27], which combine near-threshold approximate next-to-next-to-leading-order corrections [91] to the NLO cross-section with a resummation of soft gluon divergences at next-to-next-to-leading-logarithm accuracy [27]. Corresponding uncertainties are taken from envelopes of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as described in ref. [70]. They range from 12% to 20% for gluino masses from 1 to 2 TeV, and from 7% to 11% for top or bottom squark masses from 400 GeV to 1 TeV.



JHEP06(2020)046

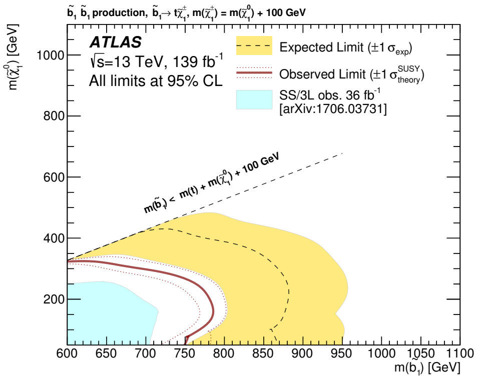



(a) `Rpc2L0b`: $\tilde{g} \to qq'WZ\tilde{\chi}^0_1$ (b) `Rpv2L`: $\tilde{g} \to tbd$

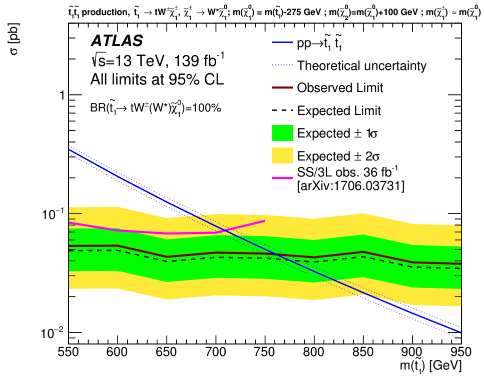
**Figure 7.** 95% CL exclusion limits on the production of pairs of gluinos, assuming production cross-sections as in ref. [27] and 100% branching ratios into the decay modes illustrated in figures 1(c) and 1(d) for the left and right plots, respectively. The limits are determined from the expected contributions of these processes to the `Rpc2L0b` (left) and `Rpv2L` (right) SRs. The coloured bands display the $\pm 1\sigma$ ranges of the expected fluctuations around the mean expected limit, in the absence of contributions from the sought-for signals. They do not account for uncertainties in the signal process cross-sections, the impact of which is illustrated by the dashed lines around the observed limits. The figures show for reference the reach of the previous analysis [28].

Exclusion limits on the masses of gluinos are shown in figure 7. The limits in figure 7(a) are set for pair production of gluinos in an $R$-parity-conserving scenario (figure 1(c)) with decoupled squarks and gluinos decaying in two steps with intermediate $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ into jets, weak bosons and the LSP $\tilde{\chi}^0_1$. The $\tilde{\chi}^\pm_1$ mass is assumed to be $0.5 \times \{m(\tilde{g}) + m(\tilde{\chi}^0_1)\}$, while the $\tilde{\chi}^0_2$ mass is similarly $0.5 \times \{m(\tilde{\chi}^\pm_1) + m(\tilde{\chi}^0_1)\}$. The weak bosons produced in the cascade decays might be off shell, if $\Delta m(\tilde{\chi}^\pm_1, \tilde{\chi}^0_2) < m_W$ or $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) < m_Z$. The limits in figure 7(b) are set for pair production of gluinos in an $R$-parity-violating scenario (figure 1(d)) where gluinos decay via top squarks into $tbd$ or $tbs$ final states (experimentally indistinguishable) when $\lambda''_{313}$ or $\lambda''_{323}$ couplings are non-zero. Sensitivity to these two scenarios is provided by the SRs `Rpc2L0b` and `Rpv2L`, and allows exclusion of gluino masses below 1.6 TeV for $\tilde{\chi}^0_1$ masses up to 1 TeV or $\tilde{t}_1$ masses up to 1.2 TeV. For gluino masses around the exclusion limits, the signal $\mathcal{A} \times \epsilon$ is as large as 0.9% for `Rpc2L0b` and 0.7% for `Rpv2L`.

Exclusion limits on the masses of third-generation squarks are shown in figure 8. The limits in figure 8(a) are set for pair production of bottom squarks in an $R$-parity-conserving scenario (figure 1(a)) with decoupled gluinos and squarks of other flavours, with $\tilde{b}_1$ squarks decaying via an intermediate $\tilde{\chi}^\pm_1$ into a top quark, a $W$ boson and the LSP $\tilde{\chi}^0_1$. The mass of the charginos $\tilde{\chi}^\pm_1$ are assumed equal to $m(\tilde{\chi}^0_1) + 100$ GeV. For each point of the $\{m(\tilde{b}_1), m(\tilde{\chi}^0_1)\}$ parameter space, `Rpc2L1b` and `Rpc2L2b` is chosen according to which provides better expected sensitivity. The former provides sensitivity over most of the plane, while the latter provides some complementarity in the low-$m(\tilde{\chi}^0_1)$ region. The transition between the two regions corresponds to the breaking of the exclusion limits smoothness




(a) Rpc2L1b+Rpc2L2b: $\tilde{b}_1 \to tW^-\tilde{\chi}_1^0$




(b) Rpc3LSS1b: $\tilde{t}_1 \to tW^{\mp}\tilde{\chi}_1^{\pm}$

**Figure 8.** 95% CL exclusion limits on the production of pairs of third-generation squarks, assuming production cross-sections as in ref. [27] (for the left plot) and 100% branching ratios into the decay modes illustrated in figures 1(a) and 1(b) for the left and right plots, respectively. The limits are determined from the expected contributions of these processes to the Rpc2L1b and Rpc2L2b (left) and Rpc3LSS1b (right) SRs. The coloured bands display the $\pm 1\sigma$ ranges (as well as $\pm 2\sigma$ for the right figure) of the expected fluctuations around the mean expected limit, in the absence of contributions from the sought-for signals. They do not account for uncertainties in the signal process cross-sections, the impact of which is illustrated by the dashed lines around the observed limits. The figures show for reference the reach of the previous analysis [28].

at $m(\tilde{\chi}_1^0) \approx 100\,\text{GeV}$. The limits in figure 8(b) are set for pair production of top squarks (figure 1(b)) decaying into a top quark, a chargino and a $W$ boson via a neutralino $\tilde{\chi}_2^0$. The masses are chosen similarly to ref. [53] such that $m(\tilde{t}_1) = m(\tilde{\chi}_2^0) + m_t = m(\tilde{\chi}_1^0) + 275\,\text{GeV}$ to suppress $\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$ and have $\tilde{\chi}_2^0 \to W^{\mp}\tilde{\chi}_1^{\pm}$ as the dominant decay mode, and $m(\tilde{\chi}_1^{\pm}) \approx m(\tilde{\chi}_1^0)$ such that products of the former's decay into the LSP $\tilde{\chi}_1^0$ are invisible. Upper limits on the production cross-section are provided as a function of the $\tilde{t}_1$ mass; top squarks with masses up to 750 GeV are excluded. For squark masses around the exclusion limit, the signal $\mathcal{A} \times \epsilon$ is as large as 0.2% for Rpc2L1b and Rpc2L2b, and close to 0.1% for Rpc3LSS1b.

## 9 Conclusion

A search for supersymmetry in events with same-sign leptons and jets is presented. The analysis is performed with $pp$ collision data collected at a centre-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$ between 2015 and 2018 with the ATLAS detector at the LHC, corresponding to an integrated luminosity of $139\,\text{fb}^{-1}$. Five signal regions are defined to provide sensitivity to a broad range of supersymmetric processes. No significant excess over the yields expected from SM processes is observed, and model-independent limits on the cross-section of possible BSM signal contributions to the signal regions are reported.

The results are interpreted in the framework of four simplified models featuring pair production of gluinos or third-generation squarks. Lower limits on particle masses are derived at 95% confidence level for these models, reaching up to 1.6 TeV for gluinos and



JHEP06(2020)046

750 GeV for bottom and top squarks, raising the exclusion limits beyond those from a previous similar search made by ATLAS on a smaller 13 TeV dataset.

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JHEP06(2020)046

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JHEP06(2020)046

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F. Fiedler[100], A. Filipčič[92], F. Filthaut[119], K.D. Finelli[25], M.C.N. Fiolhais[140a,140c,a], L. Fiorini[174], F. Fischer[114], W.C. Fisher[107], I. Fleck[151], P. Fleischmann[106], R.R.M. Fletcher[137], T. Flick[182], B.M. Flierl[114], L. Flores[137], L.R. Flores Castillo[63a], F.M. Follega[76a,76b], N. Fomin[17], J.H. Foo[167], G.T. Forcolin[76a,76b], A. Formica[145], F.A. Förster[14], A.C. Forti[101], A.G. Foster[21], M.G. Foti[135], D. Fournier[65], H. Fox[90], P. Francavilla[72a,72b], S. Francescato[73a,73b], M. Franchini[23b,23a], S. Franchino[61a], D. Francis[36], L. Franconi[20], M. Franklin[59], A.N. Fray[93], P.M. Freeman[21], B. Freund[110], W.S. Freund[81b], E.M. Freundlich[47], D.C. Frizzell[129], D. Froidevaux[36], J.A. Frost[135], C. Fukunaga[164], E. Fullana Torregrosa[174], E. Fumagalli[55b,55a], T. Fusayasu[116], J. Fuster[174], A. Gabrielli[23b,23a], A. Gabrielli[18], G.P. Gach[84a], S. Gadatsch[54], P. Gadow[115], G. Gagliardi[55b,55a], L.G. Gagnon[110], C. Galea[27b], B. Galhardo[140a], G.E. Gallardo[135], E.J. Gallas[135], B.J. Gallop[144], G. Galster[40], R. Gamboa Goni[93], K.K. Gan[127], S. Ganguly[180], J. Gao[60a], Y. Gao[50], Y.S. Gao[31,m], C. García[174], J.E. García Navarro[174], J.A. García Pascual[15a], C. Garcia-Argos[52], M. Garcia-Sciveres[18], R.W. Gardner[37], N. Garelli[153], S. Gargiulo[52], V. Garonne[134], A. Gaudiello[55b,55a], G. Gaudio[71a], I.L. Gavrilenko[111], A. Gavrilyuk[124], C. Gay[175], G. Gaycken[46], E.N. Gazis[10], A.A. Geanta[27b], C.M. Gee[146], C.N.P. Gee[144], J. Geisen[53], M. Geisen[100], M.P. Geisler[61a], C. Gemme[55b], M.H. Genest[58], C. Geng[106], S. Gentile[73a,73b], S. George[94], T. Geralis[44], L.O. Gerlach[53], P. Gessinger-Befurt[100], G. Gessner[47], S. Ghasemi[151], M. Ghasemi Bostanabad[176], A. Ghosh[65], A. Ghosh[78], B. Giacobbe[23b], S. Giagu[73a,73b], N. Giangiacomi[23b,23a], P. Giannetti[72a], A. Giannini[70a,70b], G. Giannini[14], S.M. Gibson[94], M. Gignac[146], D. Gillberg[34], G. Gilles[182], D.M. Gingrich[3,ax], M.P. Giordani[67a,67c], F.M. Giorgi[23b], P.F. Giraud[145], G. Giugliarelli[67a,67c], D. Giugni[69a], F. Giuli[74a,74b], S. Gkaitatzis[162], I. Gkialas[9,h], E.L. Gkougkousis[14], P. Gkountoumis[10], L.K. Gladilin[113], C. Glasman[99], J. Glatzer[14], P.C.F. Glaysher[46], A. Glazov[46], G.R. Gledhill[132], M. Goblirsch-Kolb[26], D. Godin[110], S. Goldfarb[105], T. Golling[54], D. Golubkov[123], A. Gomes[140a,140b], R. Goncalves Gama[53], R. Gonçalo[140a], G. Gonella[52], L. Gonella[21], A. Gongadze[80], F. Gonnella[21], J.L. Gonski[59], S. González de la Hoz[174], S. Gonzalez-Sevilla[54], G.R. Gonzalvo Rodriguez[174], L. Goossens[36], P.A. Gorbounov[124], H.A. Gordon[29], B. Gorini[36], E. Gorini[68a,68b], A. Gorišek[92], A.T. Goshaw[49], M.I. Gostkin[80], C.A. Gottardo[119], M. Gouighri[35b], D. Goujdami[35c], A.G. Goussiou[148], N. Govender[33c], C. Goy[5], E. Gozani[160], I. Grabowska-Bold[84a], E.C. Graham[91], J. Gramling[171], E. Gramstad[134], S. Grancagnolo[19], M. Grandi[156], V. Gratchev[138], P.M. Gravila[27f], F.G. Gravili[68a,68b], C. Gray[57], H.M. Gray[18], C. Grefe[24], K. Gregersen[97], I.M. Gregor[46], P. Grenier[153], K. Grevtsov[46], C. Grieco[14], N.A. Grieser[129], J. Griffiths[8], A.A. Grillo[146], K. Grimm[31,l], S. Grinstein[14,aa], J.-F. Grivaz[65], S. Groh[100], E. Gross[180], J. Grosse-Knetter[53], Z.J. Grout[95], C. Grud[106], A. Grummer[118], L. Guan[106], W. Guan[181], J. Guenther[36], A. Guerguichon[65], J.G.R. Guerrero Rojas[174], F. Guescini[115], D. Guest[171], R. Gugel[52], T. Guillemin[5], S. Guindon[36], U. Gul[57], J. Guo[60c], W. Guo[106], Y. Guo[60a,t], Z. Guo[102], R. Gupta[46], S. Gurbuz[12c], G. Gustavino[129], M. Guth[52], P. Gutierrez[129], C. Gutschow[95], C. Guyot[145], C. Gwenlan[135], C.B. Gwilliam[91], A. Haas[125], C. Haber[18], H.K. Hadavand[8], N. Haddad[35e], A. Hadef[60a], S. Hageböck[36], M. Haleem[177], J. Haley[130], G. Halladjian[107], G.D. Hallewell[102], K. Hamacher[182], P. Hamal[131], K. Hamano[176], H. Hamdaoui[35e], G.N. Hamity[149], K. Han[60a,z], L. Han[60a], S. Han[15a], Y.F. Han[167], K. Hanagaki[82,x], M. Hance[146], D.M. Handl[114], B. Haney[137], R. Hankache[136], E. Hansen[97], J.B. Hansen[40], J.D. Hansen[40], M.C. Hansen[24], P.H. Hansen[40], E.C. Hanson[101], K. Hara[169], T. Harenberg[182], S. Harkusha[108], P.F. Harrison[178], N.M. Hartmann[114], Y. Hasegawa[150], A. Hasib[50], S. Hassani[145], S. Haug[20], R. Hauser[107], L.B. Havener[39], M. Havranek[142], C.M. Hawkes[21], R.J. Hawkings[36], D. Hayden[107], C. Hayes[155], R.L. Hayes[175], C.P. Hays[135], J.M. Hays[93], H.S. Hayward[91], S.J. Haywood[144], F. He[60a], M.P. Heath[50], V. Hedberg[97], L. Heelan[8], S. Heer[24], K.K. Heidegger[52], W.D. Heidorn[79], J. Heilman[34], S. Heim[46], T. Heim[18], B. Heinemann[46,at], J.J. Heinrich[132], L. Heinrich[36],

C. Heinz[56], J. Hejbal[141], L. Helary[61b], A. Held[175], S. Hellesund[134], C.M. Helling[146], S. Hellman[45a,45b], C. Helsens[36], R.C.W. Henderson[90], Y. Heng[181], S. Henkelmann[175], A.M. Henriques Correia[36], G.H. Herbert[19], H. Herde[26], V. Herget[177], Y. Hernández Jiménez[33e], H. Herr[100], M.G. Herrmann[114], T. Herrmann[48], G. Herten[52], R. Hertenberger[114], L. Hervas[36], T.C. Herwig[137], G.G. Hesketh[95], N.P. Hessey[168a], A. Higashida[163], S. Higashino[82], E. Higón-Rodriguez[174], K. Hildebrand[37], E. Hill[176], J.C. Hill[32], K.K. Hill[29], K.H. Hiller[46], S.J. Hillier[21], M. Hils[48], I. Hinchliffe[18], F. Hinterkeuser[24], M. Hirose[133], S. Hirose[52], D. Hirschbuehl[182], B. Hiti[92], O. Hladik[141], D.R. Hlaluku[33e], X. Hoad[50], J. Hobbs[155], N. Hod[180], M.C. Hodgkinson[149], A. Hoecker[36], F. Hoenig[114], D. Hohn[52], D. Hohov[65], T.R. Holmes[37], M. Holzbock[114], L.B.A.H. Hommels[32], S. Honda[169], T.M. Hong[139], A. Hönle[115], B.H. Hooberman[173], W.H. Hopkins[6], Y. Horii[117], P. Horn[48], L.A. Horyn[37], S. Hou[158], A. Hoummada[35a], J. Howarth[101], J. Hoya[89], M. Hrabovsky[131], J. Hrdinka[77], I. Hristova[19], J. Hrivnac[65], A. Hrynevich[109], T. Hryn'ova[5], P.J. Hsu[64], S.-C. Hsu[148], Q. Hu[29], S. Hu[60c], D.P. Huang[95], Y. Huang[60a], Y. Huang[15a], Z. Hubacek[142], F. Hubaut[102], M. Huebner[24], F. Huegging[24], T.B. Huffman[135], M. Huhtinen[36], R.F.H. Hunter[34], P. Huo[155], A.M. Hupe[34], N. Huseynov[80,ah], J. Huston[107], J. Huth[59], R. Hyneman[106], S. Hyrych[28a], G. Iacobucci[54], G. Iakovidis[29], I. Ibragimov[151], L. Iconomidou-Fayard[65], Z. Idrissi[35e], P. Iengo[36], R. Ignazzi[40], O. Igonkina[120,ac,*], R. Iguchi[163], T. Iizawa[54], Y. Ikegami[82], M. Ikeno[82], D. Iliadis[162], N. Ilic[119,167,af], F. Iltzsche[48], G. Introzzi[71a,71b], M. Iodice[75a], K. Iordanidou[168a], V. Ippolito[73a,73b], M.F. Isacson[172], M. Ishino[163], W. Islam[130], C. Issever[135], S. Istin[160], F. Ito[169], J.M. Iturbe Ponce[63a], R. Iuppa[76a,76b], A. Ivina[180], H. Iwasaki[82], J.M. Izen[43], V. Izzo[70a], P. Jacka[141], P. Jackson[1], R.M. Jacobs[24], B.P. Jaeger[152], V. Jain[2], G. Jäkel[182], K.B. Jakobi[100], K. Jakobs[52], S. Jakobsen[77], T. Jakoubek[141], J. Jamieson[57], K.W. Janas[84a], R. Jansky[54], J. Janssen[24], M. Janus[53], P.A. Janus[84a], G. Jarlskog[97], N. Javadov[80,ah], T. Javůrek[36], M. Javurkova[52], F. Jeanneau[145], L. Jeanty[132], J. Jejelava[159a,ai], A. Jelinskas[178], P. Jenni[52,b], J. Jeong[46], N. Jeong[46], S. Jézéquel[5], H. Ji[181], J. Jia[155], H. Jiang[79], Y. Jiang[60a], Z. Jiang[153,q], S. Jiggins[52], F.A. Jimenez Morales[38], J. Jimenez Pena[115], S. Jin[15c], A. Jinaru[27b], O. Jinnouchi[165], H. Jivan[33e], P. Johansson[149], K.A. Johns[7], C.A. Johnson[66], K. Jon-And[45a,45b], R.W.L. Jones[90], S.D. Jones[156], S. Jones[7], T.J. Jones[91], J. Jongmanns[61a], P.M. Jorge[140a], J. Jovicevic[36], X. Ju[18], J.J. Junggeburth[115], A. Juste Rozas[14,aa], A. Kaczmarska[85], M. Kado[73a,73b], H. Kagan[127], M. Kagan[153], C. Kahra[100], T. Kaji[179], E. Kajomovitz[160], C.W. Kalderon[97], A. Kaluza[100], A. Kamenshchikov[123], M. Kaneda[163], L. Kanjir[92], Y. Kano[163], V.A. Kantserov[112], J. Kanzaki[82], L.S. Kaplan[181], D. Kar[33e], K. Karava[135], M.J. Kareem[168b], S.N. Karpov[80], Z.M. Karpova[80], V. Kartvelishvili[90], A.N. Karyukhin[123], L. Kashif[181], R.D. Kass[127], A. Kastanas[45a,45b], C. Kato[60d,60c], J. Katzy[46], K. Kawade[150], K. Kawagoe[88], T. Kawaguchi[117], T. Kawamoto[163], G. Kawamura[53], E.F. Kay[176], V.F. Kazanin[122b,122a], R. Keeler[176], R. Kehoe[42], J.S. Keller[34], E. Kellermann[97], D. Kelsey[156], J.J. Kempster[21], J. Kendrick[21], O. Kepka[141], S. Kersten[182], B.P. Kerševan[92], S. Ketabchi Haghighat[167], M. Khader[173], F. Khalil-Zada[13], M. Khandoga[145], A. Khanov[130], A.G. Kharlamov[122b,122a], T. Kharlamova[122b,122a], E.E. Khoda[175], A. Khodinov[166], T.J. Khoo[54], E. Khramov[80], J. Khubua[159b], S. Kido[83], M. Kiehn[54], C.R. Kilby[94], Y.K. Kim[37], N. Kimura[95], O.M. Kind[19], B.T. King[91,*], D. Kirchmeier[48], J. Kirk[144], A.E. Kiryunin[115], T. Kishimoto[163], D.P. Kisliuk[167], V. Kitali[46], O. Kivernyk[5], T. Klapdor-Kleingrothaus[52], M. Klassen[61a], M.H. Klein[106], M. Klein[91], U. Klein[91], K. Kleinknecht[100], P. Klimek[121], A. Klimentov[29], T. Klingl[24], T. Klioutchnikova[36], F.F. Klitzner[114], P. Kluit[120], S. Kluth[115], E. Kneringer[77], E.B.F.G. Knoops[102], A. Knue[52], D. Kobayashi[88], T. Kobayashi[163], M. Kobel[48], M. Kocian[153], P. Kodys[143], P.T. Koenig[24], T. Koffas[34], N.M. Köhler[36], T. Koi[153], M. Kolb[61b], I. Koletsou[5], T. Komarek[131], T. Kondo[82], N. Kondrashova[60c], K. Köneke[52], A.C. König[119], T. Kono[126], R. Konoplich[125,ao], V. Konstantinides[95], N. Konstantinidis[95], B. Konya[97],



JHEP06(2020)046

R. Kopeliansky[66], S. Koperny[84a], K. Korcyl[85], K. Kordas[162], G. Koren[161], A. Korn[95], I. Korolkov[14], E.V. Korolkova[149], N. Korotkova[113], O. Kortner[115], S. Kortner[115], T. Kosek[143], V.V. Kostyukhin[166], A. Kotwal[49], A. Koulouris[10], A. Kourkoumeli-Charalampidi[71a,71b], C. Kourkoumelis[9], E. Kourlitis[149], V. Kouskoura[29], A.B. Kowalewska[85], R. Kowalewski[176], C. Kozakai[163], W. Kozanecki[145], A.S. Kozhin[123], V.A. Kramarenko[113], G. Kramberger[92], D. Krasnopevtsev[60a], M.W. Krasny[136], A. Krasznahorkay[36], D. Krauss[115], J.A. Kremer[84a], J. Kretzschmar[91], P. Krieger[167], F. Krieter[114], A. Krishnan[61b], K. Krizka[18], K. Kroeninger[47], H. Kroha[115], J. Kroll[141], J. Kroll[137], J. Krstic[16], U. Kruchonak[80], H. Krüger[24], N. Krumnack[79], M.C. Kruse[49], J.A. Krzysiak[85], T. Kubota[105], O. Kuchinskaia[166], S. Kuday[4b], J.T. Kuechler[46], S. Kuehn[36], A. Kugel[61a], T. Kuhl[46], V. Kukhtin[80], R. Kukla[102], Y. Kulchitsky[108,al], S. Kuleshov[147d], Y.P. Kulinich[173], M. Kuna[58], T. Kunigo[86], A. Kupco[141], T. Kupfer[47], O. Kuprash[52], H. Kurashige[83], L.L. Kurchaninov[168a], Y.A. Kurochkin[108], A. Kurova[112], M.G. Kurth[15a,15d], E.S. Kuwertz[36], M. Kuze[165], A.K. Kvam[148], J. Kvita[131], T. Kwan[104], A. La Rosa[115], L. La Rotonda[41b,41a], F. La Ruffa[41b,41a], C. Lacasta[174], F. Lacava[73a,73b], D.P.J. Lack[101], H. Lacker[19], D. Lacour[136], E. Ladygin[80], R. Lafaye[5], B. Laforge[136], T. Lagouri[33e], S. Lai[53], S. Lammers[66], W. Lampl[7], C. Lampoudis[162], E. Lançon[29], U. Landgraf[52], M.P.J. Landon[93], M.C. Lanfermann[54], V.S. Lang[46], J.C. Lange[53], R.J. Langenberg[36], A.J. Lankford[171], F. Lanni[29], K. Lantzsch[24], A. Lanza[71a], A. Lapertosa[55b,55a], S. Laplace[136], J.F. Laporte[145], T. Lari[69a], F. Lasagni Manghi[23b,23a], M. Lassnig[36], T.S. Lau[63a], A. Laudrain[65], A. Laurier[34], M. Lavorgna[70a,70b], S.D. Lawlor[94], M. Lazzaroni[69a,69b], B. Le[105], E. Le Guirriec[102], M. LeBlanc[7], T. LeCompte[6], F. Ledroit-Guillon[58], A.C.A. Lee[95], C.A. Lee[29], G.R. Lee[17], L. Lee[59], S.C. Lee[158], S.J. Lee[34], B. Lefebvre[168a], M. Lefebvre[176], F. Legger[114], C. Leggett[18], K. Lehmann[152], N. Lehmann[182], G. Lehmann Miotto[36], W.A. Leight[46], A. Leisos[162,y], M.A.L. Leite[81d], C.E. Leitgeb[114], R. Leitner[143], D. Lellouch[180,*], K.J.C. Leney[42], T. Lenz[24], B. Lenzi[36], R. Leone[7], S. Leone[72a], C. Leonidopoulos[50], A. Leopold[136], G. Lerner[156], C. Leroy[110], R. Les[167], C.G. Lester[32], M. Levchenko[138], J. Levêque[5], D. Levin[106], L.J. Levinson[180], D.J. Lewis[21], B. Li[15b], B. Li[106], C-Q. Li[60a], F. Li[60c], H. Li[60a], H. Li[60b], J. Li[60c], K. Li[153], L. Li[60c], M. Li[15a,15d], Q. Li[15a,15d], Q.Y. Li[60a], S. Li[60d,60c], X. Li[46], Y. Li[46], Z. Li[60b], Z. Liang[15a], B. Liberti[74a], A. Liblong[167], K. Lie[63c], C.Y. Lin[32], K. Lin[107], T.H. Lin[100], R.A. Linck[66], J.H. Lindon[21], A.L. Lionti[54], E. Lipeles[137], A. Lipniacka[17], M. Lisovyi[61b], T.M. Liss[173,av], A. Lister[175], A.M. Litke[146], J.D. Little[8], B. Liu[79], B.L. Liu[6], H.B. Liu[29], H. Liu[106], J.B. Liu[60a], J.K.K. Liu[135], K. Liu[136], M. Liu[60a], P. Liu[18], Y. Liu[15a,15d], Y.L. Liu[106], Y.W. Liu[60a], M. Livan[71a,71b], A. Lleres[58], J. Llorente Merino[152], S.L. Lloyd[93], C.Y. Lo[63b], F. Lo Sterzo[42], E.M. Lobodzinska[46], P. Loch[7], S. Loffredo[74a,74b], T. Lohse[19], K. Lohwasser[149], M. Lokajicek[141], J.D. Long[173], R.E. Long[90], L. Longo[36], K.A. Looper[127], J.A. Lopez[147d], I. Lopez Paz[101], A. Lopez Solis[149], J. Lorenz[114], N. Lorenzo Martinez[5], M. Losada[22a], P.J. Lösel[114], A. Lösle[52], X. Lou[46], X. Lou[15a], A. Lounis[65], J. Love[6], P.A. Love[90], J.J. Lozano Bahilo[174], M. Lu[60a], Y.J. Lu[64], H.J. Lubatti[148], C. Luci[73a,73b], A. Lucotte[58], C. Luedtke[52], F. Luehring[66], I. Luise[136], L. Luminari[73a], B. Lund-Jensen[154], M.S. Lutz[103], D. Lynn[29], R. Lysak[141], E. Lytken[97], F. Lyu[15a], V. Lyubushkin[80], T. Lyubushkina[80], H. Ma[29], L.L. Ma[60b], Y. Ma[60b], G. Maccarrone[51], A. Macchiolo[115], C.M. Macdonald[149], J. Machado Miguens[137], D. Madaffari[174], R. Madar[38], W.F. Mader[48], N. Madysa[48], J. Maeda[83], S. Maeland[17], T. Maeno[29], M. Maerker[48], A.S. Maevskiy[113], V. Magerl[52], N. Magini[79], D.J. Mahon[39], C. Maidantchik[81b], T. Maier[114], A. Maio[140a,140b,140d], K. Maj[84a], O. Majersky[28a], S. Majewski[132], Y. Makida[82], N. Makovec[65], B. Malaescu[136], Pa. Malecki[85], V.P. Maleev[138], F. Malek[58], U. Mallik[78], D. Malon[6], C. Malone[32], S. Maltezos[10], S. Malyukov[80], J. Mamuzic[174], G. Mancini[51], I. Mandić[92], L. Manhaes de Andrade Filho[81a], I.M. Maniatis[162], J. Manjarres Ramos[48], K.H. Mankinen[97], A. Mann[114], A. Manousos[77], B. Mansoulie[145], I. Manthos[162], S. Manzoni[120], A. Marantis[162],



JHEP06(2020)046

G. Marceca[30], L. Marchese[135], G. Marchiori[136], M. Marcisovsky[141], C. Marcon[97], C.A. Marin Tobon[36], M. Marjanovic[129], Z. Marshall[18], M.U.F. Martensson[172], S. Marti-Garcia[174], C.B. Martin[127], T.A. Martin[178], V.J. Martin[50], B. Martin dit Latour[17], L. Martinelli[75a,75b], M. Martinez[14,aa], V.I. Martinez Outschoorn[103], S. Martin-Haugh[144], V.S. Martoiu[27b], A.C. Martyniuk[95], A. Marzin[36], S.R. Maschek[115], L. Masetti[100], T. Mashimo[163], R. Mashinistov[111], J. Masik[101], A.L. Maslennikov[122b,122a], L. Massa[74a,74b], P. Massarotti[70a,70b], P. Mastrandrea[72a,72b], A. Mastroberardino[41b,41a], T. Masubuchi[163], D. Matakias[10], A. Matic[114], P. Mättig[24], J. Maurer[27b], B. Maček[92], D.A. Maximov[122b,122a], R. Mazini[158], I. Maznas[162], S.M. Mazza[146], S.P. Mc Kee[106], T.G. McCarthy[115], W.P. McCormack[18], E.F. McDonald[105], J.A. Mcfayden[36], G. Mchedlidze[159b], M.A. McKay[42], K.D. McLean[176], S.J. McMahon[144], P.C. McNamara[105], C.J. McNicol[178], R.A. McPherson[176,af], J.E. Mdhluli[33e], Z.A. Meadows[103], S. Meehan[36], T. Megy[52], S. Mehlhase[114], A. Mehta[91], T. Meideck[58], B. Meirose[43], D. Melini[174], B.R. Mellado Garcia[33e], J.D. Mellenthin[53], M. Melo[28a], F. Meloni[46], A. Melzer[24], S.B. Menary[101], E.D. Mendes Gouveia[140a,140e], L. Meng[36], X.T. Meng[106], S. Menke[115], E. Meoni[41b,41a], S. Mergelmeyer[19], S.A.M. Merkt[139], C. Merlassino[20], P. Mermod[54], L. Merola[70a,70b], C. Meroni[69a], O. Meshkov[113,111], J.K.R. Meshreki[151], A. Messina[73a,73b], J. Metcalfe[6], A.S. Mete[171], C. Meyer[66], J. Meyer[160], J-P. Meyer[145], H. Meyer Zu Theenhausen[61a], F. Miano[156], M. Michetti[19], R.P. Middleton[144], L. Mijović[50], G. Mikenberg[180], M. Mikestikova[141], M. Mikuž[92], H. Mildner[149], M. Milesi[105], A. Milic[167], D.A. Millar[93], D.W. Miller[37], A. Milov[180], D.A. Milstead[45a,45b], R.A. Mina[153,q], A.A. Minaenko[123], M. Miñano Moya[174], I.A. Minashvili[159b], A.I. Mincer[125], B. Mindur[84a], M. Mineev[80], Y. Minegishi[163], L.M. Mir[14], A. Mirto[68a,68b], K.P. Mistry[137], T. Mitani[179], J. Mitrevski[114], V.A. Mitsou[174], M. Mittal[60c], O. Miu[167], A. Miucci[20], P.S. Miyagawa[149], A. Mizukami[82], J.U. Mjörnmark[97], T. Mkrtchyan[184], M. Mlynarikova[143], T. Moa[45a,45b], K. Mochizuki[110], P. Mogg[52], S. Mohapatra[39], R. Moles-Valls[24], M.C. Mondragon[107], K. Mönig[46], J. Monk[40], E. Monnier[102], A. Montalbano[152], J. Montejo Berlingen[36], M. Montella[95], F. Monticelli[89], S. Monzani[69a], N. Morange[65], D. Moreno[22a], M. Moreno Llácer[36], C. Moreno Martinez[14], P. Morettini[55b], M. Morgenstern[120], S. Morgenstern[48], D. Mori[152], M. Morii[59], M. Morinaga[179], V. Morisbak[134], A.K. Morley[36], G. Mornacchi[36], A.P. Morris[95], L. Morvaj[155], P. Moschovakos[36], B. Moser[120], M. Mosidze[159b], T. Moskalets[145], H.J. Moss[149], J. Moss[31,n], E.J.W. Moyse[103], S. Muanza[102], J. Mueller[139], R.S.P. Mueller[114], D. Muenstermann[90], G.A. Mullier[97], J.L. Munoz Martinez[14], F.J. Munoz Sanchez[101], P. Murin[28b], W.J. Murray[178,144], A. Murrone[69a,69b], M. Muškinja[18], C. Mwewa[33a], A.G. Myagkov[123,ap], J. Myers[132], M. Myska[142], B.P. Nachman[18], O. Nackenhorst[47], A.Nag Nag[48], K. Nagai[135], K. Nagano[82], Y. Nagasaka[62], M. Nagel[52], J.L. Nagle[29], E. Nagy[102], A.M. Nairz[36], Y. Nakahama[117], K. Nakamura[82], T. Nakamura[163], I. Nakano[128], H. Nanjo[133], F. Napolitano[61a], R.F. Naranjo Garcia[46], R. Narayan[42], I. Naryshkin[138], T. Naumann[46], G. Navarro[22a], H.A. Neal[106,*], P.Y. Nechaeva[111], F. Nechansky[46], T.J. Neep[21], A. Negri[71a,71b], M. Negrini[23b], C. Nellist[53], M.E. Nelson[135], S. Nemecek[141], P. Nemethy[125], M. Nessi[36,d], M.S. Neubauer[173], M. Neumann[182], P.R. Newman[21], Y.S. Ng[19], Y.W.Y. Ng[171], B. Ngair[35e], H.D.N. Nguyen[102], T. Nguyen Manh[110], E. Nibigira[38], R.B. Nickerson[135], R. Nicolaidou[145], D.S. Nielsen[40], J. Nielsen[146], N. Nikiforou[11], V. Nikolaenko[123,ap], I. Nikolic-Audit[136], K. Nikolopoulos[21], P. Nilsson[29], H.R. Nindhito[54], Y. Ninomiya[82], A. Nisati[73a], N. Nishu[60c], R. Nisius[115], I. Nitsche[47], T. Nitta[179], T. Nobe[163], Y. Noguchi[86], I. Nomidis[136], M.A. Nomura[29], M. Nordberg[36], N. Norjoharuddeen[135], T. Novak[92], O. Novgorodova[48], R. Novotny[142], L. Nozka[131], K. Ntekas[171], E. Nurse[95], F.G. Oakham[34,ax], H. Oberlack[115], J. Ocariz[136], A. Ochi[83], I. Ochoa[39], J.P. Ochoa-Ricoux[147a], K. O'Connor[26], S. Oda[88], S. Odaka[82], S. Oerdek[53], A. Ogrodnik[84a], A. Oh[101], S.H. Oh[49], C.C. Ohm[154], H. Oide[165], M.L. Ojeda[167], H. Okawa[169], Y. Okazaki[86], Y. Okumura[163], T. Okuyama[82], A. Olariu[27b], L.F. Oleiro Seabra[140a], S.A. Olivares Pino[147a], D. Oliveira Damazio[29], J.L. Oliver[1], M.J.R. Olsson[171], A. Olszewski[85], J. Olszowska[85], D.C. O'Neil[152], A.P. O'neill[135], A. Onofre[140a,140e], P.U.E. Onyisi[11], H. Oppen[134], M.J. Oreglia[37], G.E. Orellana[89], D. Orestano[75a,75b], N. Orlando[14], R.S. Orr[167], V. O'Shea[57], R. Ospanov[60a], G. Otero y Garzon[30], H. Otono[88], P.S. Ott[61a], M. Ouchrif[35d], J. Ouellette[29], F. Ould-Saada[134], A. Ouraou[145], Q. Ouyang[15a], M. Owen[57], R.E. Owen[21], V.E. Ozcan[12c], N. Ozturk[8], J. Pacalt[131], H.A. Pacey[32], K. Pachal[49], A. Pacheco Pages[14], C. Padilla Aranda[14], S. Pagan Griso[18], M. Paganini[183], G. Palacino[66], S. Palazzo[50], S. Palestini[36], M. Palka[84b], D. Pallin[38], I. Panagoulias[10], C.E. Pandini[36], J.G. Panduro Vazquez[94], P. Pani[46], G. Panizzo[67a,67c], L. Paolozzi[54], C. Papadatos[110], K. Papageorgiou[9,h], S. Parajuli[43], A. Paramonov[6], D. Paredes Hernandez[63b], S.R. Paredes Saenz[135], B. Parida[166], T.H. Park[167], A.J. Parker[31], M.A. Parker[32], F. Parodi[55b,55a], E.W. Parrish[121], J.A. Parsons[39], U. Parzefall[52], L. Pascual Dominguez[136], V.R. Pascuzzi[167], J.M.P. Pasner[146], E. Pasqualucci[73a], S. Passaggio[55b], F. Pastore[94], P. Pasuwan[45a,45b], S. Pataraia[100], J.R. Pater[101], A. Pathak[181,j], T. Pauly[36], B. Pearson[115], M. Pedersen[134], L. Pedraza Diaz[119], R. Pedro[140a], T. Peiffer[53], S.V. Peleganchuk[122b,122a], O. Penc[141], H. Peng[60a], B.S. Peralva[81a], M.M. Perego[65], A.P. Pereira Peixoto[140a], D.V. Perepelitsa[29], F. Peri[19], L. Perini[69a,69b], H. Pernegger[36], S. Perrella[70a,70b], K. Peters[46], R.F.Y. Peters[101], B.A. Petersen[36], T.C. Petersen[40], E. Petit[102], A. Petridis[1], C. Petridou[162], P. Petroff[65], M. Petrov[135], F. Petrucci[75a,75b], M. Pettee[183], N.E. Pettersson[103], K. Petukhova[143], A. Peyaud[145], R. Pezoa[147d], L. Pezzotti[71a,71b], T. Pham[105], F.H. Phillips[107], P.W. Phillips[144], M.W. Phipps[173], G. Piacquadio[155], E. Pianori[18], A. Picazio[103], R.H. Pickles[101], R. Piegaia[30], D. Pietreanu[27b], J.E. Pilcher[37], A.D. Pilkington[101], M. Pinamonti[74a,74b], J.L. Pinfold[3], M. Pitt[161], L. Pizzimento[74a,74b], M.-A. Pleier[29], V. Pleskot[143], E. Plotnikova[80], P. Podberezko[122b,122a], R. Poettgen[97], R. Poggi[54], L. Poggioli[65], I. Pogrebnyak[107], D. Pohl[24], I. Pokharel[53], G. Polesello[71a], A. Poley[18], A. Policicchio[73a,73b], R. Polifka[143], A. Polini[23b], C.S. Pollard[46], V. Polychronakos[29], D. Ponomarenko[112], L. Pontecorvo[36], S. Popa[27a], G.A. Popeneciu[27d], L. Portales[5], D.M. Portillo Quintero[58], S. Pospisil[142], K. Potamianos[46], I.N. Potrap[80], C.J. Potter[32], H. Potti[11], T. Poulsen[97], J. Poveda[36], T.D. Powell[149], G. Pownall[46], M.E. Pozo Astigarraga[36], P. Pralavorio[102], S. Prell[79], D. Price[101], M. Primavera[68a], S. Prince[104], M.L. Proffitt[148], N. Proklova[112], K. Prokofiev[63c], F. Prokoshin[80], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[84a], D. Pudzha[138], A. Puri[173], P. Puzo[65], J. Qian[106], Y. Qin[101], A. Quadt[53], M. Queitsch-Maitland[46], A. Qureshi[1], M. Racko[28a], P. Rados[105], F. Ragusa[69a,69b], G. Rahal[98], J.A. Raine[54], S. Rajagopalan[29], A. Ramirez Morales[93], K. Ran[15a,15d], T. Rashid[65], S. Raspopov[5], D.M. Rauch[46], F. Rauscher[114], S. Rave[100], B. Ravina[149], I. Ravinovich[180], J.H. Rawling[101], M. Raymond[36], A.L. Read[134], N.P. Readioff[58], M. Reale[68a,68b], D.M. Rebuzzi[71a,71b], A. Redelbach[177], G. Redlinger[29], K. Reeves[43], L. Rehnisch[19], J. Reichert[137], D. Reikher[161], A. Reiss[100], A. Rej[151], C. Rembser[36], M. Renda[27b], M. Rescigno[73a], S. Resconi[69a], E.D. Resseguie[137], S. Rettie[175], E. Reynolds[21], O.L. Rezanova[122b,122a], P. Reznicek[143], E. Ricci[76a,76b], R. Richter[115], S. Richter[46], E. Richter-Was[84b], O. Ricken[24], M. Ridel[136], P. Rieck[115], C.J. Riegel[182], O. Rifki[46], M. Rijssenbeek[155], A. Rimoldi[71a,71b], M. Rimoldi[46], L. Rinaldi[23b], G. Ripellino[154], I. Riu[14], J.C. Rivera Vergara[176], F. Rizatdinova[130], E. Rizvi[93], C. Rizzi[36], R.T. Roberts[101], S.H. Robertson[104,af], M. Robin[46], D. Robinson[32], J.E.M. Robinson[46], C.M. Robles Gajardo[147d], A. Robson[57], A. Rocchi[74a,74b], E. Rocco[100], C. Roda[72a,72b], S. Rodriguez Bosca[174], A. Rodriguez Perez[14], D. Rodriguez Rodriguez[174], A.M. Rodríguez Vera[168b], S. Roe[36], O. Røhne[134], R. Röhrig[115], C.P.A. Roland[66], J. Roloff[59], A. Romaniouk[112], M. Romano[23b,23a], N. Rompotis[91], M. Ronzani[125], L. Roos[136], S. Rosati[73a], K. Rosbach[52], G. Rosin[103], B.J. Rosser[137], E. Rossi[46], E. Rossi[75a,75b], E. Rossi[70a,70b], L.P. Rossi[55b], L. Rossini[69a,69b], R. Rosten[14], M. Rotaru[27b], J. Rothberg[148], D. Rousseau[65], G. Rovelli[71a,71b], A. Roy[11], D. Roy[33e],

A. Rozanov[102], Y. Rozen[160], X. Ruan[33e], F. Rubbo[153], F. Rühr[52], A. Ruiz-Martinez[174], A. Rummler[36], Z. Rurikova[52], N.A. Rusakovich[80], H.L. Russell[104], L. Rustige[38,47], J.P. Rutherfoord[7], E.M. Rüttinger[149], M. Rybar[39], G. Rybkin[65], E.B. Rye[134], A. Ryzhov[123], P. Sabatini[53], G. Sabato[120], S. Sacerdoti[65], H.F-W. Sadrozinski[146], R. Sadykov[80], F. Safai Tehrani[73a], B. Safarzadeh Samani[156], P. Saha[121], S. Saha[104], M. Sahinsoy[61a], A. Sahu[182], M. Saimpert[46], M. Saito[163], T. Saito[163], H. Sakamoto[163], A. Sakharov[125,ao], D. Salamani[54], G. Salamanna[75a,75b], J.E. Salazar Loyola[147d], P.H. Sales De Bruin[172], A. Salnikov[153], J. Salt[174], D. Salvatore[41b,41a], F. Salvatore[156], A. Salvucci[63a,63b,63c], A. Salzburger[36], J. Samarati[36], D. Sammel[52], D. Sampsonidis[162], D. Sampsonidou[162], J. Sánchez[174], A. Sanchez Pineda[67a,67c], H. Sandaker[134], C.O. Sander[46], I.G. Sanderswood[90], M. Sandhoff[182], C. Sandoval[22a], D.P.C. Sankey[144], M. Sannino[55b,55a], Y. Sano[117], A. Sansoni[51], C. Santoni[38], H. Santos[140a,140b], S.N. Santpur[18], A. Santra[174], A. Sapronov[80], J.G. Saraiva[140a,140d], O. Sasaki[82], K. Sato[169], F. Sauerburger[52], E. Sauvan[5], P. Savard[167,ax], N. Savic[115], R. Sawada[163], C. Sawyer[144], L. Sawyer[96,am], C. Sbarra[23b], A. Sbrizzi[23a], T. Scanlon[95], J. Schaarschmidt[148], P. Schacht[115], B.M. Schachtner[114], D. Schaefer[37], L. Schaefer[137], J. Schaeffer[100], S. Schaepe[36], U. Schäfer[100], A.C. Schaffer[65], D. Schaile[114], R.D. Schamberger[155], N. Scharmberg[101], V.A. Schegelsky[138], D. Scheirich[143], F. Schenck[19], M. Schernau[171], C. Schiavi[55b,55a], S. Schier[146], L.K. Schildgen[24], Z.M. Schillaci[26], E.J. Schioppa[36], M. Schioppa[41b,41a], K.E. Schleicher[52], S. Schlenker[36], K.R. Schmidt-Sommerfeld[115], K. Schmieden[36], C. Schmitt[100], S. Schmitt[46], S. Schmitz[100], J.C. Schmoeckel[46], U. Schnoor[52], L. Schoeffel[145], A. Schoening[61b], P.G. Scholer[52], E. Schopf[135], M. Schott[100], J.F.P. Schouwenberg[119], J. Schovancova[36], S. Schramm[54], F. Schroeder[182], A. Schulte[100], H-C. Schultz-Coulon[61a], M. Schumacher[52], B.A. Schumm[146], Ph. Schune[145], A. Schwartzman[153], T.A. Schwarz[106], Ph. Schwemling[145], R. Schwienhorst[107], A. Sciandra[146], G. Sciolla[26], M. Scodeggio[46], M. Scornajenghi[41b,41a], F. Scuri[72a], F. Scutti[105], L.M. Scyboz[115], C.D. Sebastiani[73a,73b], P. Seema[19], S.C. Seidel[118], A. Seiden[146], B.D. Seidlitz[29], T. Seiss[37], J.M. Seixas[81b], G. Sekhniaidze[70a], K. Sekhon[106], S.J. Sekula[42], N. Semprini-Cesari[23b,23a], S. Sen[49], S. Senkin[38], C. Serfon[77], L. Serin[65], L. Serkin[67a,67b], M. Sessa[60a], H. Severini[129], T. Šfiligoj[92], F. Sforza[55b,55a], A. Sfyrla[54], E. Shabalina[53], J.D. Shahinian[146], N.W. Shaikh[45a,45b], D. Shaked Renous[180], L.Y. Shan[15a], R. Shang[173], J.T. Shank[25], M. Shapiro[18], A. Sharma[135], A.S. Sharma[1], P.B. Shatalov[124], K. Shaw[156], S.M. Shaw[101], A. Shcherbakova[138], M. Shehade[180], Y. Shen[129], N. Sherafati[34], A.D. Sherman[25], P. Sherwood[95], L. Shi[158,au], S. Shimizu[82], C.O. Shimmin[183], Y. Shimogama[179], M. Shimojima[116], I.P.J. Shipsey[135], S. Shirabe[88], M. Shiyakova[80,ad], J. Shlomi[180], A. Shmeleva[111], M.J. Shochet[37], J. Shojaii[105], D.R. Shope[129], S. Shrestha[127], E.M. Shrif[33e], E. Shulga[180], P. Sicho[141], A.M. Sickles[173], P.E. Sidebo[154], E. Sideras Haddad[33e], O. Sidiropoulou[36], A. Sidoti[23b,23a], F. Siegert[48], Dj. Sijacki[16], M.Jr. Silva[181], M.V. Silva Oliveira[81a], S.B. Silverstein[45a], S. Simion[65], E. Simioni[100], R. Simoniello[100], S. Simsek[12b], P. Sinervo[167], V. Sinetckii[113,111], N.B. Sinev[132], M. Sioli[23b,23a], I. Siral[106], S.Yu. Sivoklokov[113], J. Sjölin[45a,45b], E. Skorda[97], P. Skubic[129], M. Slawinska[85], K. Sliwa[170], R. Slovak[143], V. Smakhtin[180], B.H. Smart[144], J. Smiesko[28a], N. Smirnov[112], S.Yu. Smirnov[112], Y. Smirnov[112], L.N. Smirnova[113,v], O. Smirnova[97], J.W. Smith[53], M. Smizanska[90], K. Smolek[142], A. Smykiewicz[85], A.A. Snesarev[111], H.L. Snoek[120], I.M. Snyder[132], S. Snyder[29], R. Sobie[176,af], A. Soffer[161], A. Søgaard[50], F. Sohns[53], C.A. Solans Sanchez[36], E.Yu. Soldatov[112], U. Soldevila[174], A.A. Solodkov[123], A. Soloshenko[80], O.V. Solovyanov[123], V. Solovyev[138], P. Sommer[149], H. Son[170], W. Song[144], W.Y. Song[168b], A. Sopczak[142], F. Sopkova[28b], C.L. Sotiropoulou[72a,72b], S. Sottocornola[71a,71b], R. Soualah[67a,67c,g], A.M. Soukharev[122b,122a], D. South[46], S. Spagnolo[68a,68b], M. Spalla[115], M. Spangenberg[178], F. Spanò[94], D. Sperlich[52], T.M. Spieker[61a], R. Spighi[23b], G. Spigo[36], M. Spina[156], D.P. Spiteri[57], M. Spousta[143], A. Stabile[69a,69b], B.L. Stamas[121], R. Stamen[61a], M. Stamenkovic[120],

JHEP06(2020)046

E. Stanecka[85], B. Stanislaus[135], M.M. Stanitzki[46], M. Stankaityte[135], B. Stapf[120], E.A. Starchenko[123], G.H. Stark[146], J. Stark[58], S.H. Stark[40], P. Staroba[141], P. Starovoitov[61a], S. Stärz[104], R. Staszewski[85], G. Stavropoulos[44], M. Stegler[46], P. Steinberg[29], A.L. Steinhebel[132], B. Stelzer[152], H.J. Stelzer[139], O. Stelzer-Chilton[168a], H. Stenzel[56], T.J. Stevenson[156], G.A. Stewart[36], M.C. Stockton[36], G. Stoicea[27b], M. Stolarski[140a], S. Stonjek[115], A. Straessner[48], J. Strandberg[154], S. Strandberg[45a,45b], M. Strauss[129], P. Strizenec[28b], R. Ströhmer[177], D.M. Strom[132], R. Stroynowski[42], A. Strubig[50], S.A. Stucci[29], B. Stugu[17], J. Stupak[129], N.A. Styles[46], D. Su[153], S. Suchek[61a], V.V. Sulin[111], M.J. Sullivan[91], D.M.S. Sultan[54], S. Sultansoy[4c], T. Sumida[86], S. Sun[106], X. Sun[3], K. Suruliz[156], C.J.E. Suster[157], M.R. Sutton[156], S. Suzuki[82], M. Svatos[141], M. Swiatlowski[37], S.P. Swift[2], T. Swirski[177], A. Sydorenko[100], I. Sykora[28a], M. Sykora[143], T. Sykora[143], D. Ta[100], K. Tackmann[46,ab], J. Taenzer[161], A. Taffard[171], R. Tafirout[168a], H. Takai[29], R. Takashima[87], K. Takeda[83], T. Takeshita[150], E.P. Takeva[50], Y. Takubo[82], M. Talby[102], A.A. Talyshev[122b,122a], N.M. Tamir[161], J. Tanaka[163], M. Tanaka[165], R. Tanaka[65], S. Tapia Araya[173], S. Tapprogge[100], A. Tarek Abouelfadl Mohamed[136], S. Tarem[160], K. Tariq[60b], G. Tarna[27b,c], G.F. Tartarelli[69a], P. Tas[143], M. Tasevsky[141], T. Tashiro[86], E. Tassi[41b,41a], A. Tavares Delgado[140a,140b], Y. Tayalati[35e], A.J. Taylor[50], G.N. Taylor[105], W. Taylor[168b], A.S. Tee[90], R. Teixeira De Lima[153], P. Teixeira-Dias[94], H. Ten Kate[36], J.J. Teoh[120], S. Terada[82], K. Terashi[163], J. Terron[99], S. Terzo[14], M. Testa[51], R.J. Teuscher[167,af], S.J. Thais[183], T. Theveneaux-Pelzer[46], F. Thiele[40], D.W. Thomas[94], J.O. Thomas[42], J.P. Thomas[21], A.S. Thompson[57], P.D. Thompson[21], L.A. Thomsen[183], E. Thomson[137], E.J. Thorpe[93], Y. Tian[39], R.E. Ticse Torres[53], V.O. Tikhomirov[111,aq], Yu.A. Tikhonov[122b,122a], S. Timoshenko[112], P. Tipton[183], S. Tisserant[102], K. Todome[23b,23a], S. Todorova-Nova[5], S. Todt[48], J. Tojo[88], S. Tokár[28a], K. Tokushuku[82], E. Tolley[127], K.G. Tomiwa[33e], M. Tomoto[117], L. Tompkins[153,q], B. Tong[59], P. Tornambe[103], E. Torrence[132], H. Torres[48], E. Torró Pastor[148], C. Tosciri[135], J. Toth[102,ae], D.R. Tovey[149], A. Traeet[17], C.J. Treado[125], T. Trefzger[177], F. Tresoldi[156], A. Tricoli[29], I.M. Trigger[168a], S. Trincaz-Duvoid[136], W. Trischuk[167], B. Trocmé[58], A. Trofymov[145], C. Troncon[69a], M. Trovatelli[176], F. Trovato[156], L. Truong[33c], M. Trzebinski[85], A. Trzupek[85], F. Tsai[46], J.C-L. Tseng[135], P.V. Tsiareshka[108,al], A. Tsirigotis[162], N. Tsirintanis[9], V. Tsiskaridze[155], E.G. Tskhadadze[159a], M. Tsopoulou[162], I.I. Tsukerman[124], V. Tsulaia[18], S. Tsuno[82], D. Tsybychev[155], Y. Tu[63b], A. Tudorache[27b], V. Tudorache[27b], T.T. Tulbure[27a], A.N. Tuna[59], S. Turchikhin[80], D. Turgeman[180], I. Turk Cakir[4b,w], R.J. Turner[21], R.T. Turra[69a], P.M. Tuts[39], S. Tzamarias[162], E. Tzovara[100], G. Ucchielli[47], K. Uchida[163], I. Ueda[82], M. Ughetto[45a,45b], F. Ukegawa[169], G. Unal[36], A. Undrus[29], G. Unel[171], F.C. Ungaro[105], Y. Unno[82], K. Uno[163], J. Urban[28b], P. Urquijo[105], G. Usai[8], Z. Uysal[12d], L. Vacavant[102], V. Vacek[142], B. Vachon[104], K.O.H. Vadla[134], A. Vaidya[95], C. Valderanis[114], E. Valdes Santurio[45a,45b], M. Valente[54], S. Valentinetti[23b,23a], A. Valero[174], L. Valéry[46], R.A. Vallance[21], A. Vallier[36], J.A. Valls Ferrer[174], T.R. Van Daalen[14], P. Van Gemmeren[6], I. Van Vulpen[120], M. Vanadia[74a,74b], W. Vandelli[36], A. Vaniachine[166], D. Vannicola[73a,73b], R. Vari[73a], E.W. Varnes[7], C. Varni[55b,55a], T. Varol[158], D. Varouchas[65], K.E. Varvell[157], M.E. Vasile[27b], G.A. Vasquez[176], J.G. Vasquez[183], F. Vazeille[38], D. Vazquez Furelos[14], T. Vazquez Schroeder[36], J. Veatch[53], V. Vecchio[75a,75b], M.J. Veen[120], L.M. Veloce[167], F. Veloso[140a,140c], S. Veneziano[73a], A. Ventura[68a,68b], N. Venturi[36], A. Verbytskyi[115], V. Vercesi[71a], M. Verducci[72a,72b], C.M. Vergel Infante[79], C. Vergis[24], W. Verkerke[120], A.T. Vermeulen[120], J.C. Vermeulen[120], M.C. Vetterli[152,ax], N. Viaux Maira[147d], M. Vicente Barreto Pinto[54], T. Vickey[149], O.E. Vickey Boeriu[149], G.H.A. Viehhauser[135], L. Vigani[61b], M. Villa[23b,23a], M. Villaplana Perez[69a,69b], E. Vilucchi[51], M.G. Vincter[34], G.S. Virdee[21], A. Vishwakarma[46], C. Vittori[23b,23a], I. Vivarelli[156], M. Vogel[182], P. Vokac[142], S.E. von Buddenbrock[33e], E. Von Toerne[24], V. Vorobel[143], K. Vorobev[112], M. Vos[174],

JHEP06(2020)046

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JHEP06(2020)046

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JHEP06(2020)046

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JHEP06(2020)046

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JHEP06(2020)046

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