Search for direct top squark pair production in events with a Higgs or Z boson, and missing transverse momentum in \( \sqrt{s} = 13 \) TeV \( pp \) collisions with the ATLAS detector

The ATLAS Collaboration

DOI
10.1007/JHEP08(2017)006

Publication date
2017

Document Version
Final published version

Published in
JHEP

License
CC BY

Citation for published version (APA):

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

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Search for direct top squark pair production in events with a Higgs or $Z$ boson, and missing transverse momentum in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for direct top squark pair production resulting in events with either a same-flavour opposite-sign dilepton pair with invariant mass compatible with a $Z$ boson or a pair of jets compatible with a Standard Model (SM) Higgs boson ($h$) is presented. Requirements on the missing transverse momentum, together with additional selections on leptons, jets, jets identified as originating from $b$-quarks are imposed to target the other decay products of the top squark pair. The analysis is performed using proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the LHC in 2015–2016, corresponding to an integrated luminosity of 36.1 fb$^{-1}$. No excess is observed in the data with respect to the SM predictions. The results are interpreted in two sets of models. In the first set, direct production of pairs of lighter top squarks ($\tilde{t}_1$) with long decay chains involving $Z$ or Higgs bosons is considered. The second set includes direct pair production of the heavier top squark pairs ($\tilde{t}_2$) decaying via $\tilde{t}_2 \rightarrow Z\tilde{t}_1$ or $\tilde{t}_2 \rightarrow h\tilde{t}_1$. The results exclude at 95% confidence level $\tilde{t}_2$ and $\tilde{t}_1$ masses up to about 800 GeV, extending the exclusion region of supersymmetric parameter space covered by previous LHC searches.

KEYWORDS: Beyond Standard Model, Hadron-Hadron scattering (experiments), Higgs physics

ArXiv ePrint: 1706.03986
1 Introduction

Supersymmetry (SUSY) \([1–6]\) is one of the most studied extensions of the Standard Model (SM). It predicts new bosonic partners for the existing fermions and fermionic partners for the known bosons. If \(R\)-parity is conserved \([7]\), SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable, providing a possible dark-matter candidate. The SUSY partners of the charged (neutral) Higgs bosons and electroweak gauge bosons mix to form the mass eigenstates known as charginos \((\tilde{\chi}_k^\pm, k = 1, 2)\) and neutralinos \((\tilde{\chi}_m^0, m = 1, \ldots, 4)\), where the increasing index denotes increasing mass. The scalar partners of right-handed and left-handed quarks, \(\tilde{q}_R\) and \(\tilde{q}_L\), mix to form two mass eigenstates, \(\tilde{q}_1\) and \(\tilde{q}_2\), with \(\tilde{q}_1\) defined to be the lighter of the two. To address the SM hierarchy problem \([8–11]\), TeV-scale masses are required \([12, 13]\) for the supersymmetric partners of the gluons (gluinos, \(\tilde{g}\)) and the top squarks \([14, 15]\). Furthermore, the higgsino is required not to be heavier than a few hundred GeV.

Top squark production with Higgs \((h)\) or \(Z\) bosons in the decay chain can appear either in production of the lighter top squark mass eigenstate \((\tilde{t}_1)\) decaying via \(\tilde{t}_1 \to t\tilde{\chi}_2^0\) with \(\tilde{\chi}_2^0 \to h/Z\tilde{\chi}_1^0\), or in production of the heavier top squark mass eigenstate \((\tilde{t}_2)\)
decaying via $\tilde{t}_2 \rightarrow h/Z \tilde{t}_1$, as illustrated in figure 1. Such signals can be discriminated from the SM top quark pair production ($tt$) background by requiring a pair of $b$-tagged jets originating from the $h \rightarrow b\bar{b}$ decay or a same-flavour opposite-sign lepton pair originating from the $Z \rightarrow \ell^+\ell^-$ decay. Although the pair production of $\tilde{t}_1$ has a cross-section larger than that of the $\tilde{t}_2$, and their decay properties can be similar, searches for the latter can provide additional sensitivity in regions where the $\tilde{t}_1$ falls in a phase space difficult to experimentally discriminate from the background due to the similarities in kinematics with $tt$ pair production, such as scenarios where the lighter top squark is only slightly heavier than the sum of the masses of the top quark and the lightest neutralino ($\tilde{\chi}^0_1$).

Simplified models [16–18] are used for the analysis optimisation and interpretation of the results. In these models, direct top squark pair production is considered and all SUSY particles are decoupled except for the top squarks and the neutralinos involved in their decay. In all cases the $\tilde{\chi}^0_1$ is assumed to be the LSP. Simplified models featuring direct $\tilde{t}_1$ production with $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_2$ and either $\tilde{\chi}^0_2 \rightarrow Z\tilde{\chi}^0_1$ or $\tilde{\chi}^0_2 \rightarrow h\tilde{\chi}^0_1$ are considered. Additional simplified models featuring direct $\tilde{t}_2$ production with $\tilde{t}_2 \rightarrow Z\tilde{t}_1$ or $\tilde{t}_2 \rightarrow h\tilde{t}_1$ decays and $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1$ are also considered, where the mass difference between the lighter top squark and the neutralino is set to 180 GeV, a region of the mass parameter space not excluded by previous searches for $\tilde{t}_1$ with mass greater than 191 GeV [19].

This paper presents the results of a search for top squarks in final states with $h$ or $Z$ bosons at $\sqrt{s} = 13$ TeV using the data collected by the ATLAS experiment [20] in proton-proton ($pp$) collisions during 2015 and 2016, corresponding to 36.1 fb$^{-1}$. Searches for direct $\tilde{t}_1$ pair production have been performed by the ATLAS Collaboration at $\sqrt{s} = 7,8$ TeV using LHC Run-1 data [19, 21] and $\sqrt{s} = 13$ TeV with 2015 data [22] and by the CMS Collaboration at $\sqrt{s} = 8$ TeV [23–28], searches for direct $\tilde{t}_2$ production were performed at $\sqrt{s} = 8$ TeV by both collaborations [19, 29, 30].
2 ATLAS detector

The ATLAS experiment [20] is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.\(^1\) The interaction point is surrounded by an inner detector (ID) for tracking, a calorimeter system, and a muon spectrometer.

The ID provides precision tracking of charged particles for pseudorapidities \(|\eta| < 2.5\) and is surrounded by a superconducting solenoid providing a 2 T axial magnetic field. It consists of silicon pixel and microstrip detectors inside a transition radiation tracker. One significant upgrade for the running period at \(\sqrt{s} = 13\) TeV is the presence of the insertable B-layer [31], an additional pixel layer close to the interaction point, which provides high-resolution hits at small radius to improve the tracking performance.

In the pseudorapidity region \(|\eta| < 3.2\), high-granularity lead/liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. A steel/scintillator tile calorimeter measures hadron energies for \(|\eta| < 1.7\). The endcap and forward regions, spanning \(1.5 < |\eta| < 4.9\), are instrumented with LAr calorimeters for both the EM and hadronic energy measurements.

The muon spectrometer consists of three large superconducting toroids with eight coils each, and a system of trigger and precision-tracking chambers, which provide triggering and tracking capabilities in the ranges \(|\eta| < 2.4\) and \(|\eta| < 2.7\), respectively.

A two-level trigger system is used to select events [32]. The first-level trigger is implemented in hardware and uses a subset of the detector information. This is followed by the software-based high-level trigger stage, which runs offline reconstruction and calibration software, reducing the event rate to about 1 kHz.

3 Data set and simulated event samples

The data were collected by the ATLAS detector during 2015 with a peak instantaneous luminosity of \(L = 5.2 \times 10^{33}\) cm\(^{-2}\) s\(^{-1}\), and during 2016 with a peak instantaneous luminosity of \(L = 1.4 \times 10^{34}\) cm\(^{-2}\) s\(^{-1}\), resulting in a mean number of additional pp interactions per bunch crossing (pile-up) of \(\langle \mu \rangle = 14\) in 2015 and \(\langle \mu \rangle = 24\) in 2016. Data quality requirements are applied to ensure that all subdetectors were operating at nominal conditions, and that LHC beams were in stable-collision mode. The integrated luminosity of the resulting data set is 36.1 fb\(^{-1}\) with an uncertainty of ±3.2%. The luminosity and its uncertainty are derived following a methodology similar to that detailed in ref. [33] from a preliminary calibration of the luminosity scale using a pair of \(x-y\) beam-separation scans performed in August 2015 and May 2016.

\(^1\)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 upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln \tan(\theta/2)\). Rapidity is defined as \(y = 0.5 \ln [(E + p_z)/(E - p_z)]\) where \(E\) denotes the energy and \(p_z\) is the component of the momentum along the beam direction.
Monte Carlo (MC) simulated event samples are used to aid in the estimation of the background from SM processes and to model the SUSY signal. The choices of MC event generator, parton shower and hadronisation, the cross-section normalisation, the parton distribution function (PDF) set and the set of tuned parameters (tune) for the underlying event of these samples are summarised in table 1, and more details of the event generator configurations can be found in refs. \[34-37\]. Cross-sections calculated at next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD) including resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms are used for top quark production processes. For production of top quark pairs in association with vector and Higgs bosons, cross-sections calculated at next-to-leading order (NLO) are used, and the event generator cross-sections from Sherpa (at NLO for most of the processes) are used when normalising the multi-boson backgrounds. In all MC samples, except those produced by Sherpa, the EvtGen v1.2.0 program \[38\] is used to model the properties of the bottom and charm hadron decays.

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Generator</th>
<th>Parton shower</th>
<th>Cross-section normalisation</th>
<th>PDF set</th>
<th>Tune</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUSY Signals</td>
<td>MadGraph5_aMC@NLO 2.2.2</td>
<td>SHERPA 2.2.1</td>
<td>NLO + NLL</td>
<td>NNPDF23LO</td>
<td>A14 (45)</td>
</tr>
<tr>
<td>$W(\rightarrow \ell\nu) + \text{jets}$</td>
<td>Sherpa 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>NLO CT10</td>
<td>Sherpa default</td>
<td></td>
</tr>
<tr>
<td>$Z/Z^{*}(\rightarrow \ell\ell) + \text{jets}$</td>
<td>Sherpa 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>NLO CT10</td>
<td>Sherpa default</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>Powheg-box v2</td>
<td>Pythia 6.428</td>
<td>NNLO + NNLL</td>
<td>NLO CT10</td>
<td>PERUGIA2012</td>
</tr>
<tr>
<td>$t$-channel</td>
<td>Powheg-box v1</td>
<td>Pythia 6.428</td>
<td>NNLO + NNLL</td>
<td>NLO CT10</td>
<td>PERUGIA2012</td>
</tr>
<tr>
<td>Single-top</td>
<td>Powheg-box v2</td>
<td>Pythia 6.428</td>
<td>NNLO + NNLL</td>
<td>NLO CT10</td>
<td>PERUGIA2012</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>MadGraph5_aMC@NLO 2.2.2</td>
<td>SHERPA 2.2.1</td>
<td>NLO CT10</td>
<td>NNPDF23LO</td>
<td>A14 (45)</td>
</tr>
<tr>
<td>Diboson</td>
<td>SHERPA 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>Generator NLO</td>
<td>CT10</td>
<td>Sherpa default</td>
</tr>
<tr>
<td>$tW/Z/Z^{*}$</td>
<td>MadGraph5_aMC@NLO 2.2.2</td>
<td>HERWIG 2.7.1</td>
<td>NLO CT10</td>
<td>CTEQ6L1</td>
<td>A14</td>
</tr>
<tr>
<td>$tW/Z/Z^{*}$</td>
<td>MadGraph5_aMC@NLO 2.2.2</td>
<td>Pythia 8.186</td>
<td>NLO CT10</td>
<td>NNPDF23LO</td>
<td>A14</td>
</tr>
<tr>
<td>$tW/Z/Z^{*}$</td>
<td>MadGraph5_aMC@NLO 2.2.2</td>
<td>Pythia 8.186</td>
<td>NLO CT10</td>
<td>NNPDF23LO</td>
<td>A14</td>
</tr>
<tr>
<td>$tW/Z/Z^{*}$</td>
<td>MadGraph5_aMC@NLO 2.2.2</td>
<td>Pythia 8.186</td>
<td>NLO CT10</td>
<td>NNPDF23LO</td>
<td>A14</td>
</tr>
<tr>
<td>Triboson</td>
<td>SHERPA 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>Generator LO, NLO</td>
<td>CT10</td>
<td>Sherpa default</td>
</tr>
</tbody>
</table>

Table 1. Simulated signal and background event samples: the corresponding event generator, the parton shower, the cross-section normalisation, the PDF set and the underlying-event tune are shown.
To simulate the effects of additional $pp$ collisions in the same and nearby bunch crossings, additional interactions are generated using the soft QCD processes as provided by Pythia 8.186 with the A2 tune [68] and the MSTW2008LO PDF set [69], and overlaid onto each simulated hard-scatter event. The MC samples are reweighted so that the pile-up distribution matches the one observed in the data. The MC samples are processed through an ATLAS detector simulation [70] based on Geant4 [71] or, in the case of $tt$ and the SUSY signal samples, a fast simulation using a parameterisation of the calorimeter response and Geant4 for the other parts of the detector [72]. All MC samples are reconstructed in the same manner as the data.

4 Event selection

Candidate events are required to have a reconstructed vertex [73] with at least two associated tracks with transverse momentum ($p_T$) larger than 400 MeV which are consistent with originating from the beam collision region in the $x$-$y$ plane. The vertex with the highest scalar sum of the squared transverse momentum of the associated tracks is considered to be the primary vertex of the event.

Two categories of leptons (electrons and muons) are defined: “candidate” and “signal” (the latter being a subset of the “candidate” leptons satisfying tighter selection criteria). Electron candidates are reconstructed from isolated electromagnetic calorimeter energy deposits matched to ID tracks and are required to have $|\eta| < 2.47$, a transverse momentum $p_T > 10\text{ GeV}$, and to pass a “loose” likelihood-based identification requirement [74, 75]. The likelihood input variables include measurements of shower shapes in the calorimeter and track properties in the ID.

Muon candidates are reconstructed in the region $|\eta| < 2.5$ from muon spectrometer tracks matching ID tracks. Candidate muons must have $p_T > 10\text{ GeV}$ and pass the medium identification requirements defined in ref. [76], based on the number of hits in the different ID and muon spectrometer subsystems, and on the significance of the charge to momentum ratio $q/p$.

Jets are reconstructed from three-dimensional energy clusters in the calorimeter [77] using the anti-$k_t$ jet clustering algorithm [78] with a radius parameter $R = 0.4$. Only jet candidates with $p_T > 30\text{ GeV}$ and $|\eta| < 2.5$ are considered as selected jets in the analysis. Jets are calibrated as described in refs. [79, 80], and the expected average energy contribution from pile-up clusters is subtracted according to the jet area [79]. In order to reduce the effects of pile-up, for jets with $p_T < 60\text{ GeV}$ and $|\eta| < 2.4$ a significant fraction of the tracks associated with each jet must have an origin compatible with the primary vertex, as defined by the jet vertex tagger [81].

Events are discarded if they contain any jet with $p_T > 20\text{ GeV}$ not satisfying basic quality selection criteria designed to reject detector noise and non-collision backgrounds [82].

Identification of jets containing $b$-hadrons is performed with a multivariate discriminant that makes use of track impact parameters and reconstructed secondary vertices ($b$-tagging) [83, 84]. A requirement is chosen corresponding to a 77% average efficiency obtained for $b$-quark jets in simulated $tt$ events. The rejection factors for light-quark and
gluon jets, $c$-quark jets and $\tau \to$ hadrons $+$ $\nu$ decays in simulated $t\bar{t}$ events are approximately 380, 12 and 54, respectively. To compensate for differences between data and MC simulation in the $b$-tagging efficiencies and mis-tag rates, correction factors are applied to the simulated samples [84].

Jet candidates within $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.2$ of a lepton candidate are discarded, unless the jet has a value of the $b$-tagging discriminant larger than the value corresponding to approximately 85% $b$-tagging efficiency, in which case the lepton is discarded since it probably originated from a semileptonic $b$-hadron decay. Any remaining electron candidate within $\Delta R = 0.4$ of a non-pile-up jet, and any muon candidate within $\Delta R = \min \{0.4, 0.04 + p_T(\mu)/10 \text{ GeV} \}$ of a non-pile-up jet is discarded. In the latter case, if the jet has fewer than three associated tracks or the muon $p_T$ is larger than half of the jet $p_T$, the muon is retained and the jet is discarded instead to avoid inefficiencies for high-energy muons undergoing significant energy loss in the calorimeter. Any muon candidate reconstructed with ID and calorimeter information only which shares an ID track with an electron candidate is removed. Finally, any electron candidate sharing an ID track with a remaining muon candidate is also removed.

Tighter requirements on the lepton candidates are imposed, which are then referred to as “signal” electrons or muons. Signal electrons must satisfy the “medium” likelihood-based identification requirement as defined in refs. [74, 75]. Signal leptons must have $p_T > 20$ GeV. The associated tracks must have a significance of the transverse impact parameter with respect to the reconstructed primary vertex, $d_0$, of $|d_0|/\sigma(d_0) < 5$ for electrons and $|d_0|/\sigma(d_0) < 3$ for muons, and a longitudinal impact parameter with respect to the reconstructed primary vertex, $z_0$, satisfying $|z_0\sin\theta| < 0.5$ mm. Isolation requirements are applied to both the signal electrons and muons. The scalar sum of the $p_T$ of tracks within a variable-size cone around the lepton, excluding its own track, must be less than 6% of the lepton $p_T$. The size of the track isolation cone for electrons (muons) is given by the smaller of $\Delta R = 10 \text{ GeV}/p_T$ and $\Delta R = 0.2 \ (0.3)$, that is, a cone of size 0.2 (0.3) at low $p_T$ but narrower for high-$p_T$ leptons. In addition, in the case of electrons the energy of calorimeter energy clusters in a cone of $\Delta R_\eta = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the electron (excluding the deposition from the electron itself) must be less than 6% of the electron $p_T$.

Simulated events are corrected to account for minor differences in the signal lepton trigger, reconstruction, identification and isolation efficiencies between data and MC simulation.

The missing transverse momentum vector, whose magnitude is denoted by $E_T^{\text{miss}}$, is defined as the negative vector sum of the transverse momenta of all identified electrons, photons, muons and jets, and an additional soft term. The soft term is constructed from all tracks originating from the primary vertex which are not associated with any identified particle or jet. In this way, the $E_T^{\text{miss}}$ is adjusted for the best calibration of particles and jets listed above, while maintaining pile-up independence in the soft term [85, 86].

The events are required to have a $E_T^{\text{miss}}$ value above 100 GeV and are classified in a further step into two exclusive categories: at least three leptons plus a $b$-tagged jet ($3\ell 1b$ selection, aimed at top squark decays involving $Z$ bosons), or at least four $b$-tagged jets and one or two leptons ($1\ell 4b$ selection, aimed at top squark decays involving Higgs bosons).
Table 2. Definition of the signal regions used in the 3ℓ1b selection (see text for details).

In the 3ℓ1b selection, events are accepted if they pass a trigger requiring either two electrons, two muons or an electron and a muon. In the 1ℓ4b selection, events are accepted if they pass a trigger requiring an isolated electron or muon. The trigger-level requirements on the \( p_T \), identification and isolation of the leptons involved in the trigger decision are looser than those applied offline to ensure that trigger efficiencies are constant in the relevant phase space [32].

Additional requirements are applied depending on the final state, as described in the following. These requirements are optimised for the best discovery significance using the simplified models featuring \( \tilde{t}_2 \) production with \( \tilde{t}_2 \rightarrow Z\tilde{t}_1 \) or \( \tilde{t}_2 \rightarrow h\tilde{t}_1 \) decays.

4.1 3ℓ1b selection

Events of interest are selected if they contain at least three signal leptons (electrons or muons), with at least one same-flavour opposite-sign lepton pair whose invariant mass is compatible with the \( Z \) boson mass (\( |m_{\ell\ell} - m_Z| < 15 \) GeV, with \( m_Z = 91.2 \) GeV). To maximise the sensitivity in different regions of the mass parameter space, three overlapping signal regions (SRs) are defined as shown in table 2. Signal region SR\(_A^{3\ell1b}\) is optimised for large \( \tilde{t}_2 - \chi^0\) mass splitting, where the \( Z \) boson in the \( \tilde{t}_2 \rightarrow Z\tilde{t}_1 \) decay is boosted, and large \( p_T^{\ell\ell} \) and leading-jet \( p_T \) are required. Signal region SR\(_B^{3\ell1b}\) covers the intermediate case, featuring slightly softer kinematic requirements than in SR\(_A^{3\ell1b}\). Signal region SR\(_C^{3\ell1b}\) is designed to improve the sensitivity for compressed spectra (\( m_{\tilde{t}_2} \gtrsim m_{\tilde{t}_1} + m_\tau + m_Z \)) with softer jet-\( p_T \) requirements and an upper bound on \( p_T^{\ell\ell} \).

4.2 1ℓ4b selection

Similarly to the 3ℓ1b case, three overlapping SRs are defined in the 1ℓ4b selection to have a good sensitivity in different regions of the mass parameter space. Only events with one or two signal leptons are selected to ensure orthogonality with the SRs in the 3ℓ1b selection, with at least one lepton having \( p_T > 30 \) GeV, and the electron candidates are also required.
to satisfy the tight likelihood-based identification requirement as defined in refs. [74, 75].

These SRs are defined as shown in table 3.

Signal region $\text{SR}_{A}^{1\ell 4b}$ is optimised for large $\tilde{t}_2 - \chi^0_1$ mass splitting, where the Higgs boson in the $\tilde{t}_2 \rightarrow h \tilde{t}_1$ decay is boosted. In this signal region, the pair of $b$-tagged jets with the smallest $\Delta R^{bb}$ is required to have an invariant mass consistent with the Higgs boson mass ($|m_{bb} - m_h| < 15$ GeV, with $m_h = 125$ GeV), and the transverse momentum of the system formed by these two $b$-tagged jets ($p_T^{bb}$) is required to be above 300 GeV. Signal region $\text{SR}_{B}^{1\ell 4b}$ covers the intermediate case, featuring slightly harder kinematic requirements than $\text{SR}_{A}^{1\ell 4b}$. Finally, signal region $\text{SR}_{C}^{1\ell 4b}$ is designed to be sensitive to compressed spectra ($m_{\tilde{t}_2} \gtrsim m_{\chi^0_1} + m_t + m_h$). This region has softer jet $p_T$ requirements and an upper bound on the $p_T$ of the leading $b$-tagged jet. Signal region $\text{SR}_{A}^{1\ell 4b}$ includes requirements on $H_T$ (computed as the scalar sum of the $p_T$ of all the jets in the event), while both signal regions $\text{SR}_{B}^{1\ell 4b}$ and $\text{SR}_{C}^{1\ell 4b}$ include requirements on the transverse mass $m_T$ computed using the missing-momentum and lepton-momentum vectors: $m_T = \sqrt{2p_T^\ell E_T^{miss}(1 - \cos[\Delta\phi(\ell, E_T^{miss})])}$.

### Table 3. Definition of the signal regions used in the $1\ell 4b$ selection (see text for details).

<table>
<thead>
<tr>
<th>Requirement / Region</th>
<th>$\text{SR}_{A}^{1\ell 4b}$</th>
<th>$\text{SR}_{B}^{1\ell 4b}$</th>
<th>$\text{SR}_{C}^{1\ell 4b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>1–2</td>
<td>1–2</td>
<td>1–2</td>
</tr>
<tr>
<td>$n_b$–tagged jets</td>
<td>$\geq 4$</td>
<td>$\geq 4$</td>
<td>$\geq 4$</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>—</td>
<td>$&gt; 150$</td>
<td>$&gt; 125$</td>
</tr>
<tr>
<td>$H_T$ [GeV]</td>
<td>$&gt; 1000$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td>$&gt; 120$</td>
<td>$&gt; 150$</td>
<td>$&gt; 150$</td>
</tr>
<tr>
<td>Leading $b$-tagged jet $p_T$ [GeV]</td>
<td>—</td>
<td>—</td>
<td>$&lt; 140$</td>
</tr>
<tr>
<td>$m_{bb}$ [GeV]</td>
<td>95–155</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$p_T^{bb}$ [GeV]</td>
<td>$&gt; 300$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$n_{jets} (p_T &gt; 60$ GeV$)$</td>
<td>$\geq 6$</td>
<td>$\geq 5$</td>
<td>—</td>
</tr>
<tr>
<td>$n_{jets} (p_T &gt; 30$ GeV$)$</td>
<td>—</td>
<td>—</td>
<td>$\geq 7$</td>
</tr>
</tbody>
</table>

### 5 Background estimation

The main SM background processes satisfying the SR requirements are estimated by simulation, which is normalised and verified (whenever possible) with data events in separate statistically independent regions of the phase space. Dedicated control regions (CRs) enhanced in a particular background component, such as the production of top quark pairs in association with a $Z$ boson ($ttZ$) and multi-boson production in the $3\ell 1b$ selection, and $t\bar{t}$ in the $1\ell 4b$ selection, are used for the normalisation. For each signal region, a simultaneous “background fit” is performed to the numbers of events found in the CRs, using a minimisation based on likelihoods with the HistFitter package [87]. In each fit, the normalisations of the background contributions having dedicated CRs are allowed to float freely, while the other backgrounds are determined directly using simulation or from additional independent...
studies in data. This way the total post-fit prediction is forced to be equal to the number of data events in the CR and its total uncertainty is given by the data statistical uncertainty. When setting 95\% confidence level (CL) upper limits on the cross-section of specific SUSY models, the simultaneous fits also include the observed yields in the SR.

Systematic uncertainties in the MC simulation affect the ratio of the expected yields in the different regions and are taken into account to determine the uncertainty in the background prediction. Each uncertainty source is described by a single nuisance parameter, and correlations between background processes and selections are taken into account. The fit affects neither the uncertainty nor the central value of these nuisance parameters. The systematic uncertainties considered in the fit are described in section 6.

Whenever possible, the level of agreement of the background prediction with data is compared in dedicated validation regions (VRs), which are not used to constrain the background normalisation or nuisance parameters in the fit.

5.1 Background estimation in the 3\ell 1b selection

The dominant SM background contribution to the SRs in the 3\ell 1b selection is expected to be from \ttZ, with minor contribution from multi-boson production (mainly WZ) and backgrounds containing jets misidentified as leptons (hereafter referred to as “fake” leptons) or non-prompt leptons from decays of hadrons (mainly in \tt events). The normalisation of the main backgrounds (\ttZ, multi-boson) is obtained by fitting the yield to the observed data in two control regions, then extrapolating this yield to the SRs as described above. Backgrounds from other sources (\ttW, \ttH and rare SM processes), which provide a subdominant contribution to the SRs, are determined from MC simulation only.

The background from fake or non-prompt leptons is estimated from data with a method similar to that described in refs. [88, 89]. Two types of lepton identification criteria are defined for this evaluation: “tight” and “loose”, corresponding to the signal and candidate electrons and muons described in section 4. The leading lepton is considered to be prompt, which is a valid assumption in more than 95\% of the cases according to simulations. The method makes use of the number of observed events with the second and third leading leptons being loose-loose, loose-tight, tight-loose and tight-tight in each region. The probability for prompt leptons satisfying the loose selection criteria to also satisfy the tight selection is measured using a data sample enriched in $\Z \to \ell^+\ell^-$ ($\ell = e, \mu$) decays. The equivalent probability for fake or non-prompt leptons is measured using events with one electron and one muon with the same charge. The number of events with one or two fake or non-prompt leptons is calculated from these probabilities and the number of observed events with loose and tight leptons. The modelling of the background from fake or non-prompt leptons is validated in events passing a selection similar to the SRs, but removing the $E_T^{\text{miss}}$ requirements and inverting the $m_{\ell\ell}$ requirements.

The two dedicated control regions used for the \ttZ (CR$_{ttZ}^{3\ell 1b}$) and multi-boson (CR$_{VV}^{3\ell 1b}$) background estimation in this selection are defined as shown in table 4. To ensure orthogonality with the SRs, an upper bound on $E_T^{\text{miss}} < 100$ GeV is required in CR$_{ttZ}^{3\ell 1b}$, while a $b$-jet veto is applied in CR$_{VV}^{3\ell 1b}$. 
Table 4. Definition of the control regions used in the 3ℓ1b selection.

<table>
<thead>
<tr>
<th>Requirement / Region</th>
<th>( \text{CR}_{3\ell 1b}^{t\bar{t}Z} )</th>
<th>( \text{CR}_{3\ell 1b}^{VV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>( \geq 3 )</td>
<td>( \geq 3 )</td>
</tr>
<tr>
<td>(</td>
<td>m_{\ell\ell} - m_Z</td>
<td>) [GeV]</td>
</tr>
<tr>
<td>Leading lepton ( p_T ) [GeV]</td>
<td>( &gt; 40 )</td>
<td>( &gt; 40 )</td>
</tr>
<tr>
<td>Leading jet ( p_T ) [GeV]</td>
<td>( &gt; 60 )</td>
<td>( &gt; 30 )</td>
</tr>
<tr>
<td>( n_b )-tagged jets</td>
<td>( \geq 1 )</td>
<td>0</td>
</tr>
<tr>
<td>( n_{\text{jets}}(p_T &gt; 30\text{ GeV}) )</td>
<td>( \geq 4 )</td>
<td>( \geq 4 )</td>
</tr>
<tr>
<td>( E^{\text{miss}}_T ) [GeV]</td>
<td>( &lt; 100 )</td>
<td>—</td>
</tr>
<tr>
<td>( p_T^{\ell} ) [GeV]</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 2. Jet multiplicity distributions in control regions (a) \( \text{CR}_{3\ell 1b}^{t\bar{t}Z} \) and (b) \( \text{CR}_{3\ell 1b}^{VV} \), after normalising the \( t\bar{t}Z \) and multi-boson background processes via the simultaneous fit described in section 5. The contributions from all SM backgrounds are shown as a histogram stack; the bands represent the total uncertainty in the background prediction. The “Others” category contains the contributions from \( t\bar{t}, tW, t\bar{t}W, t\bar{t}W, tW, \) and \( Zh \) production. The last bin in each figure contains the overflow. The lower panels show the ratio of the observed data to the total SM background prediction, with bands representing the total uncertainty in the background prediction.

Table 5 shows the observed and expected yields in the two CRs for each background source, and figure 2 shows the \( n_{\text{jet}} \) distribution in these regions after the background fit. The normalisation factors for the \( t\bar{t}Z \) and multi-boson backgrounds do not differ from unity by more than 30% and the post-fit MC-simulated jet multiplicity distributions agree well with the data.

5.2 Background estimation in the 1ℓ4b selection

The dominant SM background contribution to the SRs in the 1ℓ4b selection is expected to be top quark pair (\( tt \)) production, amounting to more than 80% of the total background.
Table 5. Background fit results for the control regions in the 3ℓ1b selection. The nominal predictions from MC simulation are given for comparison for those backgrounds (ttZ, multi-boson) that are normalised to data. The “Others” category contains the contributions from ℓh, ℓWW, ℓℓℓ, ℓℓℓℓ, Wh, and Zh production. Combined statistical and systematic uncertainties are given. The individual uncertainties can be correlated and do not necessarily add in quadrature to the total systematic uncertainty. The number of events with fake or non-prompt leptons is estimated with the data-driven technique described in section 5.

<table>
<thead>
<tr>
<th></th>
<th>CR$^{3ℓ1b}_{ttZ}$</th>
<th>CR$^{3ℓ1b}_{VV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>109</td>
<td>131</td>
</tr>
<tr>
<td>Total (post-fit) SM events</td>
<td>109 ± 10</td>
<td>131 ± 11</td>
</tr>
<tr>
<td>Fit output, multi-boson</td>
<td>14.5 ± 2.7</td>
<td>105 ± 13</td>
</tr>
<tr>
<td>Fit output, ttZ</td>
<td>66 ± 14</td>
<td>10.2 ± 2.7</td>
</tr>
<tr>
<td>Fake or non-prompt leptons</td>
<td>14 ± 6</td>
<td>12 ± 7</td>
</tr>
<tr>
<td>ℓZ, ℓWZ</td>
<td>11 ± 6</td>
<td>2.7 ± 1.4</td>
</tr>
<tr>
<td>Others</td>
<td>3.2 ± 0.5</td>
<td>1.0 ± 0.3</td>
</tr>
</tbody>
</table>

The normalisation of the tt̄ background for each of the three SRs is obtained by fitting the yield to the observed data in a dedicated CR, then extrapolating this yield to the SRs as described above. Other background sources (single top, ℓℓh and rare SM processes), which provide a subdominant contribution to the SRs, are determined from MC simulation only. The contribution from events with fake or non-prompt leptons is found to be negligible in this selection. The three tt̄ CRs (named CR$^{1ℓ4b}_{tt,A}$, CR$^{1ℓ4b}_{tt,B}$ and CR$^{1ℓ4b}_{tt,C}$) are described in table 6. They are designed to have kinematic properties resembling as closely as possible those of each of the three SRs (SR$^{1ℓ4b}_A$, SR$^{1ℓ4b}_B$ and SR$^{1ℓ4b}_C$, respectively), while having a high purity in tt̄ background and only a small contamination from signal. The CRs are built by inverting the SR requirements on $E_T^{miss}$ and relaxing or inverting those on $m_{bb}$ or $m_T$. Figure 3 shows the jet multiplicity distributions in these CRs after the background fit. In a similar manner, three validation regions (named VR$^{1ℓ4b}_A$, VR$^{1ℓ4b}_B$ and VR$^{1ℓ4b}_C$) are defined, each of them corresponding to a different CR, with the same requirements on $E_T^{miss}$ as the SR and relaxing or inverting the requirements on $m_{bb}$, $m_T$ or jet multiplicity, as shown in table 6. These VRs are used to provide a statistically independent cross-check of the extrapolation in a selection close to that of the SR but with small signal contamination. Table 7 shows the observed and expected yields in the CRs and VRs for each background source. The large correction to tt̄ normalisation after the background fit has also been observed in other analyses [90] and is due to a mismodelling of the tt̄+bb, cc component in the MC simulation. The background prediction is in agreement with the observed data in all VRs.
<table>
<thead>
<tr>
<th>Requirement / Region</th>
<th>CR_{4b}^{ll,A}</th>
<th>VR_{4b}^{ll,A}</th>
<th>CR_{4b}^{ll,B}</th>
<th>VR_{4b}^{ll,B}</th>
<th>CR_{4b}^{ll,C}</th>
<th>VR_{4b}^{ll,C}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>1–2</td>
<td>1–2</td>
<td>1–2</td>
<td>1–2</td>
<td>1–2</td>
<td>1–2</td>
</tr>
<tr>
<td>n_b-tagged jets</td>
<td>≥ 4</td>
<td>≥ 4</td>
<td>≥ 4</td>
<td>≥ 4</td>
<td>≥ 4</td>
<td>≥ 4</td>
</tr>
<tr>
<td>m_T [GeV]</td>
<td>—</td>
<td>—</td>
<td>&gt; 100</td>
<td>&gt; 150</td>
<td>&lt; 125</td>
<td>&lt; 125</td>
</tr>
<tr>
<td>E_T^{miss} [GeV]</td>
<td>&lt; 120</td>
<td>&gt; 120</td>
<td>&lt; 150</td>
<td>&gt; 150</td>
<td>&lt; 150</td>
<td>&gt; 150</td>
</tr>
<tr>
<td>Leading b-tagged jet p_T [GeV]</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>&lt; 140</td>
<td>&lt; 140</td>
<td>—</td>
</tr>
<tr>
<td>m_{bb} [GeV]</td>
<td>95–155</td>
<td>95–155</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>n_jets (p_T &gt; 60 GeV)</td>
<td>≥ 5</td>
<td>≥ 5</td>
<td>≥ 5</td>
<td>≤ 4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>n_jets (p_T &gt; 30 GeV)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>≥ 7</td>
<td>≥ 7</td>
</tr>
</tbody>
</table>

Table 6. Summary of selection criteria for the control and validation regions in the 1\ell 4b selection.

<table>
<thead>
<tr>
<th>CR_{4b}^{ll,A}</th>
<th>VR_{4b}^{ll,A}</th>
<th>CR_{4b}^{ll,B}</th>
<th>VR_{4b}^{ll,B}</th>
<th>CR_{4b}^{ll,C}</th>
<th>VR_{4b}^{ll,C}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>863</td>
<td>258</td>
<td>340</td>
<td>86</td>
<td>963</td>
</tr>
<tr>
<td>Total (post-fit) SM events</td>
<td>863 ± 29</td>
<td>266 ± 34</td>
<td>340 ± 18</td>
<td>96 ± 13</td>
<td>963 ± 31</td>
</tr>
<tr>
<td>Fit output, t\bar{t}</td>
<td>783 ± 33</td>
<td>235 ± 33</td>
<td>307 ± 19</td>
<td>88 ± 12</td>
<td>891 ± 33</td>
</tr>
<tr>
<td>Single top</td>
<td>16 ± 5</td>
<td>9.0 ± 2.1</td>
<td>5.5 ± 1.8</td>
<td>1.7 ± 0.9</td>
<td>12.2 ± 2.4</td>
</tr>
<tr>
<td>V+jets, multi-boson</td>
<td>11.8 ± 2.9</td>
<td>3.1 ± 1.1</td>
<td>4.7 ± 1.4</td>
<td>1.05 ±0.20</td>
<td>9.8 ± 2.1</td>
</tr>
<tr>
<td>t\bar{t}h, Vh</td>
<td>27 ± 4</td>
<td>7.9 ± 1.3</td>
<td>12.7 ± 2.0</td>
<td>3.9 ± 0.7</td>
<td>31 ± 5</td>
</tr>
<tr>
<td>t\bar{t}W, t\bar{t}Z</td>
<td>19 ± 4</td>
<td>7.2 ± 1.6</td>
<td>7.1 ± 1.7</td>
<td>2.2 ± 0.5</td>
<td>15.6 ± 3.1</td>
</tr>
<tr>
<td>Others</td>
<td>5.0 ± 2.6</td>
<td>3.6 ± 1.9</td>
<td>3.2 ± 1.7</td>
<td>0.57 ± 0.31</td>
<td>2.7 ± 1.4</td>
</tr>
</tbody>
</table>

Table 7. Background fit results for the control and validation regions in the 1\ell 4b selection. The nominal predictions from MC simulation are given for comparison for the t\bar{t} background, which is normalised to data. The “Others” category contains the contributions from t\bar{t}WW, t\ell t, t\ell t, t\ell Z, and t\ell WZ production. Combined statistical and systematic uncertainties are given. The individual uncertainties can be correlated and do not necessarily add in quadrature to the total systematic uncertainty.
Figure 3. Jet multiplicity distributions in control regions (a) CR$^{14b}_{tA}$, (b) CR$^{14b}_{tB}$, and (c) CR$^{14b}_{tC}$ after normalising the $tt$ background process via the simultaneous fit described in section 5. The $tt$ background normalisation is constrained to the data observation for jet multiplicity values above the requirements shown in Table 6. The contributions from all SM backgrounds are shown as a histogram stack; the bands represent the total uncertainty. The “Others” category contains the contributions from $tth$, $tWtW$, $ttt$, $ttW$, $Wht$, and $Zht$ production. The last bin in each figure contains the overflow. The lower panels show the ratio of the observed data to the total SM background prediction, with the bands representing the total uncertainty in the background prediction.
6 Systematic uncertainties

The primary sources of systematic uncertainty are related to the jet energy scale, the jet energy resolution, the theoretical and the MC modelling uncertainties in the background determined using CRs ($t\bar{t}Z$ and multi-bosons in the $3\ell 1b$ selection, as well as $t\bar{t}$ in the $1\ell 4b$ selection). The statistical uncertainty of the simulated event samples is taken into account as well. The effects of the systematic uncertainties are evaluated for all signal samples and background processes. Since the normalisation of the dominant background processes is extracted in dedicated CRs, the systematic uncertainties only affect the extrapolation to the SRs in these cases.

The jet energy scale and resolution uncertainties are derived as a function of the $p_T$ and $\eta$ of the jet, as well as of the pile-up conditions and the jet flavour composition (more quark-like or gluon-like) of the selected jet sample. They are determined using a combination of simulated and data samples, through measurements of the jet response asymmetry in dijet, $Z$+jet and $\gamma$+jet events [91]. Uncertainties associated with the modelling of the $b$-tagging efficiencies for $b$-jets, $c$-jets and light-flavour jets [92, 93] are also considered.

The systematic uncertainties related to the modelling of $E_T^{\text{miss}}$ in the simulation are estimated by propagating the uncertainties in the energy and momentum scale of all identified electrons, photons, muons and jets, as well as the uncertainties in the soft-term scale and resolution [85].

Other detector-related systematic uncertainties, such as those in the lepton reconstruction efficiency, energy scale and energy resolution, and in the modelling of the trigger [76], are found to have a small impact on the results.

The uncertainties in the modelling of the $t\bar{t}$ and single-top backgrounds in simulation in the $1\ell 4b$ selection are estimated by varying the renormalisation and factorisation scales, as well as the amount of initial- and final-state radiation used to generate the samples [34]. Additional uncertainties in the parton-shower modelling are assessed as the difference between the predictions from POWHEG showered with PYTHIA and HERWIG, and due to the event generator choice by comparing POWHEG and MADGRAPH5_AMC@NLO [34], in both cases showered with PYTHIA.

The diboson background MC modelling uncertainties are estimated by varying the renormalisation, factorisation and resummation scales used to generate the samples [94]. For $t\bar{t}Z$, the predictions from the MADGRAPH5_AMC@NLO and SHERPA event generators are compared, and the uncertainties related to the choice of renormalisation and factorisation scales are assessed by varying the corresponding event generator parameters up and down by a factor of two around their nominal values [95].

The cross-sections used to normalise the MC samples are varied according to the uncertainty in the cross-section calculation, i.e., 6% for diboson, 13% for $t\bar{t}W$ and 12% $t\bar{t}Z$ production [39]. For $t\bar{t}WW$, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}h$, $t\bar{t}t$, $t\bar{t}\bar{t}$, and triboson production processes, which constitute a small background, a 50% uncertainty in the event yields is assumed.

Systematic uncertainties are assigned to the estimated background from fake or non-prompt leptons in the $3\ell 1b$ selection to account for potentially different compositions (heavy flavour, light flavour or conversions) between the signal and control regions, as well as the
Table 8. Summary of the main systematic uncertainties and their impact (in %) on the total SM background prediction in each of the signal regions studied. The total systematic uncertainty can be different from the sum in quadrature of individual sources due to the correlations between them resulting from the fit to the data. The quoted theoretical uncertainties include modelling and cross-section uncertainties.

contamination from prompt leptons in the regions used to measure the probabilities for loose fake or non-prompt leptons to pass the tight signal criteria.

Table 8 summarises the contributions of the different sources of systematic uncertainty in the total SM background predictions in the signal regions. The dominant systematic uncertainties in the $3\ell 1b$ SRs are due to the limited number of events in CR$_{3\ell 1b}$ and theoretical uncertainties in $t\bar{t}Z$ production, while in the $1\ell 4b$ SRs the dominant uncertainties are due to $t\bar{t}$ modelling.


7 Results

The observed number of events and expected yields are shown in table 9 for each of the six SRs. The SM backgrounds are estimated as described in section 5. Data agree with the SM background prediction within uncertainties and thus exclusion limits for several beyond-the-SM (BSM) scenarios are extracted. Figure 4 shows the $E_T^{miss}$ distributions after applying all the SR selection requirements except those on $E_T^{miss}$.

The HistFitter framework, which utilises a profile-likelihood-ratio-test statistic [96], is used to estimate 95% confidence intervals using the CL$_s$ prescription [97]. The likelihood is built as the product of a probability density function describing the observed number of events in the SR and the associated CR(s) and, to constrain the nuisance parameters
Figure 4. Distribution of $E_{\text{miss}}$ for events passing all the signal candidate selection requirements, except that on $E_{\text{miss}}$, for (a) SR$^{14b}$, (c) SR$^{14b}$, (e) SR$^{14b}$ and (b) SR$^{14b}$, (d) SR$^{14b}$, (f) SR$^{14b}$ after the background fit described in section 5. The contributions from all SM backgrounds are shown; the bands represent the total uncertainty. The expected distributions for signal models with $m(t_2) = 700$ GeV and $m(\chi_1^0) = 0$ GeV, and $m(t_2) = 650$ GeV and $m(\chi_1^0) = 250$ GeV are also shown as dashed lines. The last bin in each figure contains the overflow. The lower panels show the ratio of the observed data to the total SM background prediction, with the bands representing the total uncertainty in the background prediction.
associated with the systematic uncertainties, Gaussian distributions whose widths correspond to the sizes of these uncertainties; Poisson distributions are used instead to model statistical uncertainties affecting the observed and predicted yields in the CRs. Table 9 also shows upper limits (at the 95% CL) on the visible BSM cross-section \( \sigma_{\text{vis}} = \frac{S_{\text{obs}}}{L \Delta t} \), defined as the product of the production cross-section, acceptance and efficiency.

Model-dependent limits are also set in specific classes of SUSY models. For each signal hypothesis, the background fit is redone taking into account the signal contamination in the CRs, which is found to be below 15\% for signal models close to the Run-1 exclusion limits. All uncertainties in the SM prediction are considered, including those that are correlated between signal and background (for instance, jet energy scale uncertainties), as well as all uncertainties in the predicted signal, excluding PDF- and scale-induced uncertainties in the theoretical cross-section. Since the three SRs are not orthogonal, only the SR with best expected sensitivity is used for each signal point. “Observed limits” are calculated from the observed event yields in the SRs. “Expected limits” are calculated by setting the nominal event yield in each SR to the corresponding mean expected background.

Figure 5 shows the limits on simplified models in which pair-produced \( \tilde{t}_1 \) decay with 100\% branching ratio into the \( \tilde{\chi}^0_2 \) and a top quark, assuming \( B(\tilde{\chi}^0_2 \rightarrow Z \tilde{\chi}^0_1) = 0.5 \) and \( B(\tilde{\chi}^0_2 \rightarrow h \tilde{\chi}^0_1) = 0.5 \). A massless LSP and a minimum mass difference between the \( \tilde{\chi}^0_2 \) and \( \tilde{\chi}^0_1 \) of 130 GeV, needed to have on-shell decays for both the Higgs and Z bosons, are assumed in this model. Limits are presented in the \( \tilde{t}_1-\tilde{\chi}^0_2 \) mass plane. The two SRs with best expected sensitivity from the 3\( \ell \)b and 1\( \ell \)b selections are statistically combined to derive the limits on this model. For a \( \tilde{\chi}^0_2 \) mass above 200 GeV, \( \tilde{t}_1 \) masses up to about 800 GeV are excluded at 95\% CL.

Limits for simplified models, in which pair-produced \( \tilde{t}_2 \) decay with 100\% branching ratio into the \( \tilde{t}_1 \) and either a Z or a h boson, with \( \tilde{t}_1 \rightarrow t \tilde{\chi}^0_1 \), in the \( \tilde{t}_2-\tilde{\chi}^0_1 \) mass plane are shown in figure 6. When considering the \( \tilde{t}_2 \) decays via a Z boson, probed by the 3\( \ell \)b selection, \( \tilde{t}_2 \) masses up to 800 GeV are excluded at 95\% CL for a \( \tilde{\chi}^0_1 \) of about 50 GeV and \( \tilde{\chi}^0_1 \) masses up to 350 GeV are excluded for \( \tilde{t}_2 \) masses below 650 GeV. Assuming 100\% branching ratio into \( \tilde{t}_1 \) and a h boson, probed by the 1\( \ell \)b selection, \( \tilde{t}_2 \) masses up to 880 GeV are excluded at 95\% CL for a \( \tilde{\chi}^0_1 \) of about 50 GeV, and \( \tilde{\chi}^0_1 \) masses up to 260 GeV are excluded for \( \tilde{t}_2 \) masses between 650 and 710 GeV. These results extend the previous limits on the \( \tilde{t}_2 \) mass from ATLAS \( \sqrt{s} = 8 \) TeV analyses [19, 29] by up to 250 GeV depending on the \( \tilde{\chi}^0_1 \) mass.

Exclusion limits as a function of the \( \tilde{t}_2 \) branching ratios are shown in figure 7 for representative values of the masses of \( \tilde{t}_2 \) and \( \tilde{\chi}^0_1 \). For \( \tilde{t}_2 \) mass of 600 GeV, SUSY models with \( B(\tilde{t}_2 \rightarrow Z \tilde{t}_1) \) above 58\% are excluded. For higher top squark mass (\( m_{\tilde{t}_2} = 650 \) GeV), models with \( B(\tilde{t}_2 \rightarrow Z \tilde{t}_1) \) above 50\% or \( B(\tilde{t}_2 \rightarrow h \tilde{t}_1) \) above 80\% are excluded. The region with large \( B(\tilde{t}_2 \rightarrow t \tilde{\chi}^0_1) \) can be probed by searches targeting direct \( \tilde{t}_1 \) pair production [19].
<table>
<thead>
<tr>
<th></th>
<th>$SR_{A}^{3\ell 4b}$</th>
<th>$SR_{B}^{3\ell 4b}$</th>
<th>$SR_{C}^{3\ell 4b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Total (post-fit) SM events</td>
<td>1.9 ± 0.4</td>
<td>2.7 ± 0.6</td>
<td>2.0 ± 0.3</td>
</tr>
<tr>
<td>Fit output, multi-boson</td>
<td>0.26 ± 0.08</td>
<td>0.28 ± 0.10</td>
<td>0.23 ± 0.05</td>
</tr>
<tr>
<td>Fit output, $t\bar{t}Z$</td>
<td>1.1 ± 0.3</td>
<td>1.4 ± 0.5</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td>$tZ$, $tWZ$</td>
<td>0.43 ± 0.23</td>
<td>0.36 ± 0.19</td>
<td>0.19 ± 0.10</td>
</tr>
<tr>
<td>Fake or non-prompt leptons</td>
<td>0.00^{+0.30}_{-0.00}</td>
<td>0.45 ± 0.19</td>
<td>0.00^{+0.30}_{-0.00}</td>
</tr>
<tr>
<td>Others</td>
<td>0.09 ± 0.02</td>
<td>0.23 ± 0.06</td>
<td>0.36 ± 0.06</td>
</tr>
<tr>
<td>Fit input, multi-boson</td>
<td>0.35</td>
<td>0.37</td>
<td>0.30</td>
</tr>
<tr>
<td>Fit input, $t\bar{t}Z$</td>
<td>1.2</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>$S_{\text{obs}}^{95}$</td>
<td>4.5</td>
<td>3.8</td>
<td>5.8</td>
</tr>
<tr>
<td>$S_{\text{exp}}^{95}$</td>
<td>4.2^{+1.9}_{-0.4}</td>
<td>4.9^{+1.5}_{-1.1}</td>
<td>4.4^{+1.8}_{-0.5}</td>
</tr>
<tr>
<td>$\sigma_{\text{vis}}$ [fb]</td>
<td>0.13</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>$p(s = 0)$</td>
<td>0.42</td>
<td>0.93</td>
<td>0.23</td>
</tr>
<tr>
<td>Total (post-fit) SM events</td>
<td>13.6 ± 3.0</td>
<td>29 ± 5</td>
<td>10.5 ± 3.2</td>
</tr>
<tr>
<td>Fit output, $t\bar{t}$</td>
<td>11.3 ± 2.9</td>
<td>24 ± 5</td>
<td>9.3 ± 3.1</td>
</tr>
<tr>
<td>Single top</td>
<td>0.50 ± 0.18</td>
<td>1.7 ± 0.4</td>
<td>0.24 ± 0.07</td>
</tr>
<tr>
<td>$V+$jets, multi-boson</td>
<td>0.20 ± 0.15</td>
<td>0.23 ± 0.10</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>$t\bar{t}h$, $Vh$</td>
<td>0.89 ± 0.16</td>
<td>1.19 ± 0.35</td>
<td>0.56 ± 0.13</td>
</tr>
<tr>
<td>$t\bar{t}W$, $t\bar{t}Z$</td>
<td>0.36 ± 0.21</td>
<td>1.09 ± 0.31</td>
<td>0.10 ± 0.10</td>
</tr>
<tr>
<td>Others</td>
<td>0.37 ± 0.20</td>
<td>1.33 ± 0.69</td>
<td>0.34 ± 0.18</td>
</tr>
<tr>
<td>Fit input, $t\bar{t}$</td>
<td>7.1</td>
<td>14</td>
<td>6.0</td>
</tr>
<tr>
<td>$S_{\text{obs}}^{95}$</td>
<td>7.8</td>
<td>14.6</td>
<td>15.6</td>
</tr>
<tr>
<td>$S_{\text{exp}}^{95}$</td>
<td>9.6^{+4.1}_{-2.3}</td>
<td>15.5^{+5.6}_{-4.4}</td>
<td>10.4^{+4.2}_{-2.6}</td>
</tr>
<tr>
<td>$\sigma_{\text{vis}}$ [fb]</td>
<td>0.21</td>
<td>0.40</td>
<td>0.43</td>
</tr>
<tr>
<td>$p(s = 0)$</td>
<td>0.63</td>
<td>0.82</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 9. Observed and expected numbers of events in the six signal regions. The nominal predictions from MC simulation are given for comparison for those backgrounds ($t\bar{t}Z$, multi-boson for the $3\ell 4b$ selection and $t\bar{t}$ for the $1\ell 4b$ selection) that are normalised to data in dedicated control regions. For $SR_{A}^{3\ell 4b}$, $SR_{B}^{3\ell 4b}$ and $SR_{C}^{3\ell 4b}$, the “Others” category contains the contributions from $t\bar{t}h$, $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, $Wh$, and $Zh$ production. For $SR_{A}^{1\ell 4b}$, $SR_{B}^{1\ell 4b}$ and $SR_{C}^{1\ell 4b}$, the “Others” category contains the contributions from $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, $tZ$, and $tWZ$ production. Combined statistical and systematic uncertainties are given. Signal model-independent 95% CL upper limits on the visible BSM cross-section ($\sigma_{\text{vis}}$), the visible number of signal events ($S_{\text{obs}}^{95}$), the number of signal events ($S_{\text{exp}}^{95}$) given the expected number of background events (and ±1σ variations of the expected background), and the discovery $p$-value ($p(s = 0)$), all calculated with pseudo-experiments, are also shown for each signal region.
Figure 5. Exclusion limits at 95% CL from the analysis of 36.1 fb$^{-1}$ of 13 TeV $pp$ collision data on the masses of the $\tilde{t}_1$ and $\tilde{\chi}_2^0$, for a fixed $m(\tilde{\chi}_1^0) = 0$ GeV, assuming $B(\tilde{\chi}_{2}^{0} \to Z \tilde{\chi}_{1}^{0}) = 0.5$ and $B(\tilde{\chi}_{2}^{0} \to h \tilde{\chi}_{1}^{0}) = 0.5$. The dashed line and the shaded band are the expected limit and its $\pm 1\sigma$ uncertainty, respectively. The thick solid line is the observed limit for the central value of the signal cross-section. The expected and observed limits do not include the effect of the theoretical uncertainties in the signal cross-section. The dotted lines show the effect on the observed limit when varying the signal cross-section by $\pm 1\sigma$ of the theoretical uncertainty.
Figure 6. Exclusion limits at 95% CL from the analysis of 36.1 fb$^{-1}$ of 13 TeV $pp$ collision data on the masses of the $\tilde{t}_2$ and $\tilde{\chi}_1^0$, for a fixed $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 180$ GeV and assuming (a) $B(\tilde{t}_2 \to Z\tilde{t}_1) = 1$ or (b) $B(\tilde{t}_2 \to h\tilde{t}_1) = 1$. The dashed line and the shaded band are the expected limit and its $\pm 1\sigma$ uncertainty, respectively. The thick solid line is the observed limit for the central value of the signal cross-section. The expected and observed limits do not include the effect of the theoretical uncertainties in the signal cross-section. The dotted lines show the effect on the observed limit when varying the signal cross-section by $\pm 1\sigma$ of the theoretical uncertainty. The shaded area in the lower-left corner shows the observed exclusion from the ATLAS $\sqrt{s} = 8$ TeV analysis [19, 29].
Figure 7. Exclusion limits at 95% CL from the analysis of 36.1 fb$^{-1}$ of 13 TeV $pp$ collision data as a function of the $\tilde{t}_2$ branching ratio for $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$, $\tilde{t}_2 \rightarrow \tilde{t}_1 h$ and $\tilde{t}_2 \rightarrow t \tilde{\chi}^0_1$. The blue and red exclusion regions correspond to the 3$l_1b$ and 1$l_4b$ selections respectively. The limits are given for two different values of the $\tilde{t}_2$ and $\tilde{\chi}^0_1$ masses. The dashed lines are the expected limit and the solid lines are the observed limit for the central value of the signal cross-section.

8 Conclusion

This paper reports a search for direct top squark pair production resulting in events with either a leptonically decaying $Z$ boson or a pair of $b$-tagged jets from a Higgs boson decay, based on 36.1 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment at the LHC in 2015 and 2016. Good agreement is found between the yield of observed events and the SM predictions. Model-independent limits are presented, which allow the results to be reinterpreted in generic models that also predict similar final states in association with invisible particles. The limits exclude, at 95% confidence level, beyond-the-SM processes with visible cross-sections above 0.11 (0.21) fb for the 3$l_1b$ (1$l_4b$) selections.

Results are also interpreted in the context of simplified models characterised by the decay chain $\tilde{t}_1 \rightarrow t \tilde{\chi}^0_2$ with $\tilde{\chi}^0_2 \rightarrow Z/h \tilde{\chi}^0_1$, or $\tilde{t}_2 \rightarrow Z/h \tilde{t}_1$ with $\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$. The results exclude at 95% confidence level $\tilde{t}_2$ and $\tilde{t}_1$ masses up to about 800 GeV, extending the region of supersymmetric parameter space covered by previous LHC searches.

Acknowledgments

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

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

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [98].

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

**References**


CMS collaboration, *Search for direct pair production of scalar top quarks in the single- and dilepton channels in proton-proton collisions at \( \sqrt{s} = 8 \text{ TeV} \), JHEP 07 (2016) 027 [Erratum ibid. 09 (2016) 056] [arXiv:1602.03169] [inSPIRE].


ATLAS collaboration, *Simulation of top quark production for the ATLAS experiment at \( \sqrt{s} = 13 \text{ TeV} \), ATL-PHYS-PUB-2016-004, CERN, Geneva Switzerland, (2016).*


ATLAS collaboration, *Modelling of the ttH and ttV (V = W, Z) processes for \( \sqrt{s} = 13 \text{ TeV} \) ATLAS analyses, ATL-PHYS-PUB-2016-005, CERN, Geneva Switzerland, (2016).*


[82] ATLAS collaboration, Data-quality requirements and event cleaning for jets and missing transverse energy reconstruction with the ATLAS detector in proton-proton collisions at a center-of-mass energy of \( \sqrt{s} = 7 \) TeV, ATLAS-CONF-2010-038, CERN, Geneva Switzerland, (2010).


The ATLAS collaboration

INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPHI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kabayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homel L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
ING Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada; (g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy

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

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

(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Énergie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Department Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby BC, Canada

SLAC National Accelerator Laboratory, Stanford CA, United States of America

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

(a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

(a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Tomsk State University, Tomsk, Russia

Department of Physics, University of Toronto, Toronto ON, Canada

(a) INFN-TIFPA; (b) University of Trento, Trento, Italy

(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
America

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

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Department of Physics, University of Illinois, Urbana IL, United States of America

Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain

Department of Physics, University of British Columbia, Vancouver BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

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

Department of Physics, University of Wisconsin, Madison WI, United States of America

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

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

Department of Physics, Yale University, New Haven CT, United States of America

Yerevan Physics Institute, Yerevan, Armenia

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

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

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

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

Also at Novosibirsk State University, Novosibirsk, Russia

Also at TRIUMF, Vancouver BC, Canada

Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America

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

Also at Department of Physics, California State University, Fresno CA, United States of America

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

Also at Institute of Computational Science, Gran Sasso Science Institute (L’Aquila, Italy)

Also at LLNL Computational Sciences Group, Lawrence Livermore National Laboratory, Livermore, California, United States of America

Also at TRIUMF, Vancouver BC, Canada

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

Also at Borough of Manhattan Community College, City University of New York, New York City, United States of America

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

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

Also at Louisiana Tech University, Ruston LA, United States of America

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

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

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

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University