Search for squarks and gluinos in final states with hadronically decaying τ-leptons, jets, and missing transverse momentum using pp collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector

Aaboud, M.; ATLAS Collaboration

DOI
10.1103/PhysRevD.99.012009

Publication date
2019

Document Version
Final published version

Published in
Physical Review D. Particles and Fields

License
CC BY

Citation for published version (APA):
Search for squarks and gluinos in final states with hadronically decaying \( \tau \)-leptons, jets, and missing transverse momentum using \( pp \) collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector

M. Aaboud * et al. 
(ATLAS Collaboration)

(Received 21 August 2018; published 18 January 2019)

A search for supersymmetry in events with large missing transverse momentum, jets, and at least one hadronically decaying \( \tau \)-lepton is presented. Two exclusive final states with either exactly one or at least two \( \tau \)-leptons are considered. The analysis is based on proton-proton collisions at \( \sqrt{s} = 13 \) TeV corresponding to an integrated luminosity of 36.1 fb\(^{-1}\) delivered by the Large Hadron Collider and recorded by the ATLAS detector in 2015 and 2016. No significant excess is observed over the Standard Model expectation. At 95\% confidence level, model-independent upper limits on the cross section are set for two signal scenarios: a simplified model of gluino pair production with \( \tau \)-rich cascade decays, and a model with gauge-mediated supersymmetry breaking (GMSB). In the simplified model, gluino masses up to 2000 GeV are excluded for low values of the mass of the lightest supersymmetric particle (LSP), while LSP masses up to 1000 GeV are excluded for gluino masses around 1400 GeV. In the GMSB model, values of the supersymmetry-breaking scale are excluded below 110 TeV for all values of \( \tan \beta \) in the range \( 2 \leq \tan \beta \leq 60 \), and below 120 TeV for \( \tan \beta > 30 \).

DOI: 10.1103/PhysRevD.99.012009

1. INTRODUCTION

Supersymmetry (SUSY) [1–6] introduces a symmetry between fermions and bosons, resulting in a SUSY partner (sparticle) for each Standard Model (SM) particle with identical quantum numbers except for a difference of half a unit of spin. Squarks \((\tilde{q})\), gluinos \((\tilde{g})\), charged sleptons \((\tilde{\ell})\), and sneutrinos \((\tilde{\nu})\) are the superpartners of the quarks, gluons, charged leptons, and neutrinos, respectively. The SUSY partners of the gauge and Higgs bosons are called gauginos and higgsinos, respectively. The charged electro-weak gaugino and higgsino states mix to form charginos \((\tilde{\chi}^{\pm}_i, i = 1, 2)\), and the neutral states mix to form neutralinos \((\tilde{\chi}^0_j, j = 1, 2, 3, 4)\). Finally, the gravitino \((\tilde{G})\) is the SUSY partner of the graviton. As no supersymmetric particle has been observed, SUSY must be a broken symmetry. To avoid large violations of baryon- or lepton-number conservation, \(R\)-parity [7] conservation is often assumed. In this case, sparticles are produced in pairs and decay through cascades involving SM particles and other sparticles until the lightest sparticle (LSP), which is stable, is produced.

Final states with \( \tau \)-leptons are of particular interest in SUSY searches, although they are experimentally challenging. Light sleptons could play a role in the coannihilation of neutralinos in the early Universe, and models with light \( \tau \)-sleptons are consistent with constraints on dark matter consisting of weakly interacting massive particles [8–10]. Furthermore, should SUSY or any other physics beyond the Standard Model (BSM) be discovered in leptonic final states, independent studies of all three lepton flavors are necessary to investigate the coupling structure of the new physics, especially with regard to lepton universality.

In this article, an inclusive search for squarks and gluinos produced via the strong interaction in events with jets (collimated sprays of particles from the hadronization of quarks and gluons), at least one hadronically decaying \( \tau \)-lepton, and large missing transverse momentum is presented. Two SUSY models are considered: a simplified model [11–13] of gluino pair production and a model of gauge-mediated SUSY breaking (GMSB) [14–16]. If squarks and gluinos are within the reach of the Large Hadron Collider (LHC), their production may be among the dominant SUSY processes. Final states with exactly one \( \tau \)-lepton (1\( \tau \)) or at least two \( \tau \)-leptons (2\( \tau \)) provide complementary acceptance to SUSY signals. These two channels are optimized separately and the results are statistically combined. Models with a small mass splitting between gluinos or squarks and the LSP, producing soft \( \tau \)-leptons in the final state, are best covered by the 1\( \tau \) channel. Models
with a heavy LSP, producing signatures with low missing transverse momentum, are more easily probed by the $2\tau$ channel due to the lower SM background. For models with a large mass splitting, both channels provide sensitivity.

The analysis is performed using proton-proton ($pp$) collision data at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$ corresponding to an integrated luminosity of 36.1 fb$^{-1}$, recorded with the ATLAS detector at the LHC in 2015 and 2016. For both SUSY models, the exclusion limits obtained significantly improve upon the previous ATLAS results. Besides the increase in the integrated luminosity, the results benefit from an improved analysis and statistical treatment. Previous searches in the same final state have been reported by the ATLAS\cite{17} and CMS\cite{19} collaborations.

In GMSB models, SUSY breaking is communicated from a hidden sector to the visible sector by a set of messenger fields that share the gauge interactions of the SM. SUSY is spontaneously broken in the messenger sector, leading to massive, nondegenerate messenger fields. The free parameters of GMSB models are the SUSY-breaking mass scale in the messenger sector ($\Lambda$), the messenger mass scale ($M_{\text{mes}}$), the number of messenger multiplets ($N_{\bar{5}}$) of the $\bar{5} + \bar{5}$ representation of SU(5), the ratio of the two Higgs-doublet vacuum expectation values at the electroweak scale ($\tan \beta$), the sign of the Higgsino mass term in the superpotential ($\tilde{\mu}$), and a gravitino-mass scale factor ($C_{\text{grav}}$). Details of the GMSB scenarios studied herein can be found in Ref.\cite{19}.

As in previous ATLAS searches, the GMSB model is probed as a function of $\Lambda$ and $\tan \beta$, while the other parameters are set to $M_{\text{mes}} = 250\,\text{TeV}$, $N_{\bar{5}} = 3$, $\tilde{\mu} = 1$, and $C_{\text{grav}} = 1$. The choice of $\tan \beta$ influences the nature of the NLSP. For large values of $\tan \beta$, the NLSP is the $\tilde{\tau}_1$ while for lower $\tan \beta$ values, the $\tilde{\tau}_1$ and the superpartners of the right-handed electron and muon ($\tilde{e}_R, \tilde{\mu}_R$) are almost degenerate in mass. The production of squark pairs dominates at high values of $\Lambda$, with a subdominant contribution from squark-gluino production. A typical GMSB signal process is displayed in Fig. 1(a). The value of $C_{\text{grav}}$ corresponds to prompt decays of the NLSP.

Although minimal GMSB cannot easily accommodate a Higgs boson with mass of approximately 125 GeV, various extensions exist (see, e.g., Refs.\cite{21,22}) that remedy these shortcomings while preserving very similar signatures, in particular the natures of the LSP and the NLSP.

The simplified model of gluino pair production is inspired by generic models such as the $R$-parity-conserving phenomenological MSSM\cite{23,24} with dominant gluino pair production, light $\tilde{\tau}_1$, and a $\tilde{\chi}_1^0$ LSP. Gluinos are assumed to undergo a two-step cascade decay leading to $\tau$-rich final states, as shown in Fig. 1(b). The two free parameters of the model are the masses of the gluino ($m_{\tilde{g}}$) and the LSP ($m_{\tilde{\chi}_1^0}$). Assumptions are made about the masses of other sparticles, namely the $\tilde{\tau}_1$ and $\tilde{\nu}_\tau$ are mass degenerate, and the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are also mass degenerate, with

$$m_{\tilde{\tau}_1} = m_{\tilde{\chi}_2^0} = \frac{1}{2}(m_{\tilde{g}} + m_{\tilde{\chi}_1^0}), \quad m_{\tilde{\tau}_1} = m_{\tilde{\nu}_\tau} = \frac{1}{2}(m_{\tilde{\tau}_1^+} + m_{\tilde{\tau}_1^-}).$$

Gluinos are assumed to decay into $\tilde{\tau}_1^\pm q\bar{q}'$ and $\tilde{\chi}_2^0 q\bar{q}$ with equal branching ratios, where $q, q'$ denote generic first- and second-generation quarks. The neutralino $\tilde{\chi}_1^0$ is assumed to decay into $\tilde{\nu}_\tau \tau$ or $\tilde{\nu}_\tau \nu_\tau$ with equal probability. In the last step of the decay chain, $\tilde{\tau}_1$ and $\tilde{\nu}_\tau$ are assumed to decay into $\tau \tilde{\chi}_1^0$ and $\nu \tilde{\tau}_1^0$, respectively. All other SUSY particles are kinematically decoupled. The topology of signal events depends on the mass-splitting between the gluino and the LSP. The particle decay widths are assumed to be small compared to sparticle masses, such that they play no role in the kinematics.
II. ATLAS DETECTOR

The ATLAS experiment is described in detail in Ref. [25]. It is a multipurpose detector with a forward-backward symmetric cylindrical geometry and a solid angle\(^2\) coverage of nearly 4\(\pi\).

The inner tracking detector (ID), covering the region \(|\eta| < 2.5\), consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The innermost layer of the pixel detector, the insertable B-layer [26], was installed between Run 1 and Run 2 of the LHC. The inner detector is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by a finely segmented lead/liquid-argon (LAr) electromagnetic calorimeter covering the region \(|\eta| < 3.2\). A steel/scintillator-tile hadronic calorimeter provides coverage in the central region \(|\eta| < 1.7\). The end cap and forward regions, covering the pseudorapidity range 1.5 < \(|\eta| < 4.9\), are instrumented with electromagnetic and hadronic LAr calorimeters, with steel, copper, or tungsten as the absorber material. A muon spectrometer system incorporating large superconducting toroidal air-core magnets surrounds the calorimeters. Three layers of precision wire chambers provide muon tracking coverage in the range \(|\eta| < 2.7\), while dedicated fast chambers are used for triggering in the region \(|\eta| < 2.4\).

The trigger system is composed of two stages [27]. The level-1 trigger, implemented with custom hardware, uses information from calorimeters and muon chambers to reduce the event rate from 40 MHz to a maximum of 100 kHz. The high-level trigger reduces the data acquisition rate to about 1 kHz. It is software based and runs reconstruction algorithms similar to those used in the offline reconstruction.

III. DATA AND SIMULATED EVENT SAMPLES

The data used in this analysis consist of \(pp\) collisions at a center-of-mass energy of \(\sqrt{s} = 13\) TeV delivered by the LHC with a 25 ns bunch spacing and recorded by the ATLAS detector in 2015 and 2016. The average number of \(pp\) interactions per bunch crossing, \((\mu)\), was 13.4 in 2015 and 25.1 in 2016. Data quality requirements are applied to ensure that all subdetectors were operating normally, and that LHC beams were in stable collision mode. The integrated luminosity of the resulting data set is 36.1 fb\(^{-1}\).

\(^2\)ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the \(z\) axis along the beam pipe. The \(x\) axis points from the interaction point to the center 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 \(p_z\) represents the momentum component along the \(z\) axis.
LO. The cross section provided by the generator is used for these samples.

The simplified-model signal samples were generated using MG5_aMC@NLO v2.2.3 interfaced to PYTHIA 8.186 with the A14 tune. The ME calculation was performed at tree level and includes the emission of up to two additional partons. The PDF set used for the generation was NNPDF23LO. The ME-PS matching was performed using the CTEQ6L1 prescription, with a matching scale set to one quarter of the gluino mass. The GMSB signal samples were generated with the HERWIG++ 2.7.1 [51] generator, with CTEQ6L1 PDFs and the UE-EE-5-CTEQ6L1 tune [52], using input files generated in the SLHA format with the SPHENO v3.1.12 [53] program. The PS evolution was performed using an algorithm described in Refs. [51,54–56]. Signal cross sections were calculated to next-to-leading order in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithm accuracy (NLO + NLL) [57–61]. The nominal cross section and its uncertainty were taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [62].

IV. EVENT RECONSTRUCTION

This search is based on final states with jets, hadronically decaying \( \tau \)-leptons, and missing transverse momentum. In addition, muons and \( b \)-tagged jets are used for background modeling studies, while electrons are only used for the missing transverse momentum calculation.

Interaction vertices are reconstructed using inner-detector tracks with transverse momentum \( p_T > 400 \text{ MeV} \) [63]. Primary vertex candidates are required to have at least two associated tracks, and the candidate with the largest \( \sum p_T^2 \) is defined as the primary vertex. Events without a reconstructed primary vertex are rejected.

Jets are reconstructed using the anti-\( k_t \) clustering algorithm [64,65] with a distance parameter \( R = 0.4 \). Clusters of calorimeter cells [66], calibrated at the electromagnetic energy scale, are used as input. The jet energy is calibrated using a set of global sequential calibrations [67,68]. Jets are required to have \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.8 \). A jet-vertex-tagging algorithm [69] is used to discriminate hard-interaction jets from pileup jets for jets with \( |\eta| < 2.4 \) and \( p_T < 60 \text{ GeV} \). Events with jets originating from cosmic rays, beam background, or detector noise are rejected [70]. Jets containing \( b \)-hadrons (\( b \)-jets) are identified using a multivariate algorithm exploiting the long lifetime, high decay multiplicity, hard fragmentation, and large mass of \( b \)-hadrons [71]. The \( b \)-tagging algorithm identifies \( b \)-jets with an efficiency of approximately 70% in simulated \( t \bar{t} \) events. The rejection factors for \( c \)-jets, hadronically decaying \( \tau \)-leptons, and light-quark or gluon jets are approximately 8, 26 and 440, respectively [72].

Muon candidates are reconstructed in the region \( |\eta| < 2.5 \) from muon spectrometer tracks matching ID tracks. Muons are required to have \( p_T > 10 \text{ GeV} \) and pass medium identification requirements [73], based on the number of hits in the ID and muon spectrometer, and the compatibility of the charge-to-momentum ratios measured in the two detector systems. Events containing poorly reconstructed muons or cosmic-ray muon candidates are rejected. Details of the electron reconstruction are given in Refs. [74,75].

Hadronically decaying \( \tau \)-leptons are reconstructed [76] from anti-\( k_t \) jets within \( |\eta| < 2.5 \) calibrated with a local cluster weighting technique [77]. The \( \tau \)-lepton candidates are built from clusters of calorimeter cells within a cone of size \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2 \) centered on the jet axis. A boosted regression tree is used to calibrate the energy of reconstructed \( \tau \)-leptons. It exploits shower-shape information from the calorimeter, the track multiplicity, the amount of pileup, and information from particle-flow reconstruction [78] that aims to identify charged and neutral hadrons from the \( \tau \)-lepton decay. The \( \tau \)-leptons are required to have either one or three associated tracks, with a charge sum of \( \pm 1 \). A boosted-decision-tree discriminant is used to separate jets from \( \tau \)-leptons. It relies on track variables from the inner detector as well as shower-shape variables from the calorimeters. The analysis makes use of loose and medium \( \tau \)-leptons, corresponding to identification efficiencies of 60% and 55%, respectively, for one-track \( \tau \)-leptons and 50% and 40%, respectively, for three-track \( \tau \)-leptons. Electrons reconstructed as one-track \( \tau \)-leptons are rejected by imposing a \( p_T \) and \( |\eta| \)-dependent requirement on the likelihood identification variable of the electron, which provides a constant efficiency of 95% for real \( \tau \)-leptons, with a rejection factor for electrons ranging from 30 to 150 depending on the \( |\eta| \) region. Like for jets, events with \( \tau \)-lepton candidates close to inactive calorimeter regions are rejected.

The missing transverse momentum vector \( p_T^{\text{miss}} \), whose magnitude is denoted by \( E_T^{\text{miss}} \), is defined as the negative vector sum of the transverse momenta of all identified and calibrated physics objects (electrons, muons, jets, and \( \tau \)-leptons) and an additional soft term. The soft term is constructed from all the tracks with \( p_T > 400 \text{ MeV} \) which originate from the primary vertex but are not associated with any physics object. This track-based definition makes the soft term largely insensitive to pileup [79].

After the reconstruction, an overlap-removal procedure is applied to remove ambiguities in case the same object is reconstructed by different algorithms. The successive steps of this procedure are summarized in Table I, where the overlap of reconstructed objects is defined in terms of the distance between objects \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \).
TABLE I. Overview of the successive steps in the overlap-removal procedure.

<table>
<thead>
<tr>
<th>Object discarded</th>
<th>Object kept</th>
<th>Matching condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Loose τ</td>
<td>Electron</td>
<td>ΔR&lt;sub&gt;τ&lt;/sub&gt; &lt; 0.2</td>
</tr>
<tr>
<td>2. Loose τ</td>
<td>Muon</td>
<td>ΔR&lt;sub&gt;τ&lt;/sub&gt; &lt; 0.2</td>
</tr>
<tr>
<td>3. Electron</td>
<td>Muon</td>
<td>Shared inner-detector track</td>
</tr>
<tr>
<td>4. Jet</td>
<td>Electron</td>
<td>ΔR&lt;sub&gt;τ&lt;/sub&gt; &lt; 0.2 and jet not b-tagged</td>
</tr>
<tr>
<td>5. Electron</td>
<td>Jet</td>
<td>ΔR&lt;sub&gt;τ&lt;/sub&gt; &lt; 0.4</td>
</tr>
<tr>
<td>6. Jet</td>
<td>Muon</td>
<td>ΔR&lt;sub&gt;τ&lt;/sub&gt; &lt; 0.2, jet with ≤ 2 tracks and not b-tagged</td>
</tr>
<tr>
<td>7. Muon</td>
<td>Jet</td>
<td>ΔR&lt;sub&gt;τ&lt;/sub&gt; &lt; 0.4</td>
</tr>
<tr>
<td>8. Jet</td>
<td>Loose τ</td>
<td>ΔR&lt;sub&gt;τ&lt;/sub&gt; &lt; 0.2</td>
</tr>
</tbody>
</table>

First, loose τ candidates are discarded if they overlap with an electron or muon (steps 1 and 2). If an electron and a muon are reconstructed using the same inner-detector track, the electron is discarded (step 3). For overlapping light leptons (electrons and muons) and jets, the jet is kept in cases where the lepton is likely to result from a heavy-flavor hadron decay within the jet, otherwise the lepton is kept (steps 4–7). Finally, if a jet is also reconstructed as a loose τ-lepton, the jet is discarded (step 8).

V. EVENT SELECTION

A preselection common to the 1τ and 2τ channels is applied. Events are required to pass the missing transverse momentum trigger with the lowest threshold and no bandwidth limitation. To select a phase space where the trigger is fully efficient, the offline selection requires \( E_{T}^{\text{miss}} > 180 \text{GeV} \) and a leading jet with \( p_{T} > 120 \text{GeV} \). Furthermore, an additional jet with \( p_{T} > 25 \text{ GeV} \) is required. The two leading jets are required to be separated from \( p_{T}^{\text{miss}} \) by at least 0.4 in \( \phi \), to reject multijet background where large \( E_{T}^{\text{miss}} \) can arise from jet energy mismeasurements. The 1τ channel requires exactly one medium τ-lepton while the 2τ channel requires at least two medium τ-leptons. The preselection is summarized in Table II.

To isolate signatures of potential SUSY processes from known SM background, additional kinematic variables are utilized:

(i) The transverse mass of the system formed by \( p_{T}^{\text{miss}} \) and the momentum \( p \) of a reconstructed object,

\[
 m_{T} = m_{T}(p, p_{T}^{\text{miss}}) = \sqrt{2 p_{T} E_{T}^{\text{miss}} (1 - \cos \Delta \phi(p, p_{T}^{\text{miss}}))},
\]

where \( \Delta \phi(p, p_{T}^{\text{miss}}) \) denotes the azimuthal angle between the momentum of the reconstructed object and the missing transverse momentum. For events where a lepton \( l' \) and the missing transverse momentum both originate from a \( W(l'\bar{\nu}) \) decay, the \( m_{T}^{l'} \) distribution exhibits a Jacobian peak at the \( W \) boson mass. The transverse mass of various objects is used in this analysis, most notably the transverse mass of the reconstructed τ-lepton.

(ii) The \( m_{T2}^{τ} \) variable [80,81], also called transverse mass, computed as

\[
 m_{T2}^{τ} = \min_{p_{T}^{a},p_{T}^{b}} \left( \max \left[ m_{T}(p^{τ1}, p_{T}^{a}), m_{T}(p^{τ2}, p_{T}^{b}) \right] \right),
\]

where \((a,b)\) refers to two invisible particles that are assumed to be produced with transverse momentum vectors \( p_{T}^{a,b} \). In this calculation, \((a,b)\) are assumed to be massless. The \( m_{T2}^{τ} \) distribution has a kinematic endpoint for processes where massive particles are pair-produced, each particle decaying into a τ-lepton and an undetected particle. When more than two τ-leptons are produced in a decay chain, there is no way to \textit{a priori} select the pair leading to the desired characteristic. Therefore, \( m_{T2}^{τ} \) is calculated using all possible τ-lepton pairs and the largest value is chosen.

(iii) The scalar sum of the transverse momenta of all τ-leptons and jets, \( H_{T} = \sum_{i} p_{T}^{i} + \sum_{j} p_{T}^{j} \).

Figure 2 shows examples of kinematic distributions after the preselection and after applying background normalization factors as described in Sec. VI. The dominant backgrounds in the 1τ channel are \( ℓ\bar{ν} \) production and \( W(ℓν) + \) jets events, with subdominant contributions from \( Z(νν) + \) jets and \( Z(ττ) + \) jets. In the 2τ channel, the spectrum is dominated by \( ℓ\bar{ν}, W(ℓν) + \) jets and \( Z(ττ) + \) jets events. The multijet background does not contribute significantly while contributions from the diboson background are only relevant at high values of \( m_{T}^{τ} + m_{T}^{τ} \).

Multiple phase space regions are then defined. A set of signal regions (SRs) with stringent kinematic requirements and low background contribution is designed to target the different signatures and kinematic configurations of the two SUSY models. A set of control regions (CRs) with negligible signal yield is used to constrain the normalization of the dominant backgrounds in phase space regions close to the SRs. The determination of background normalization factors and the search for a possible signal are performed simultaneously by fitting a signal-plus-background model to

TABLE II. Summary of the preselection criteria applied in the 1τ and 2τ channels. \( N_{jet} \) and \( N_{τ} \) are the number of jets and τ-leptons respectively; other variables are defined in the text.

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>1τ channel</th>
<th>2τ channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>( E_{T}^{\text{miss}} &gt; 180 \text{ GeV}, p_{T}^{jet} &gt; 120 \text{ GeV} )</td>
<td></td>
</tr>
<tr>
<td>Jets</td>
<td>( N_{jet} \geq 2, p_{T}^{jet} &gt; 25 \text{ GeV} )</td>
<td></td>
</tr>
<tr>
<td>Multijet events</td>
<td>( \Delta \phi(p_{T}^{jet1,2}, p_{T}^{miss}) &gt; 0.4 )</td>
<td></td>
</tr>
<tr>
<td>τ-leptons</td>
<td>( N_{τ} = 1 )</td>
<td>( N_{τ} \geq 2 )</td>
</tr>
</tbody>
</table>
the data in the CRs and SRs. Validation regions (VRs) are defined in phase space regions between CRs and SRs. The VRs are not included in the fit; they are used to compare the fitted background predictions with the observed data in the vicinity of SRs to validate the background extrapolation before unblinding the SRs. The CRs, VRs and SRs are mutually exclusive and therefore statistically independent.

In the $1\tau$ channel, two SRs are defined for the simplified model, as summarized in Table III. The $1\tau$ compressed SR targets small mass differences between the gluino and the LSP, up to $\approx 300$ GeV. It exploits topologies where the pair of gluinos recoils against a high-$p_T$ jet from initial-state radiation (ISR). While $\tau$-leptons and additional jets from gluino decays typically have low $p_T$, such ISR events have substantial $E_{\text{miss}}$ since both LSPs tend to be emitted opposite to the ISR jet in the transverse plane. A requirement on the transverse mass is used to suppress $W(\tau\nu) +$ jets events as well as semileptonic $t\bar{t}$ events with a $\tau$-lepton in the final state.

The $1\tau$ medium-mass SR targets larger mass-splittings, motivating a more stringent $m_\tau^T$ criterion and an $H_T$ requirement. These two SRs also provide sensitivity to GMSB signals at low $\tan\beta$, in cases where only one $\tau$-lepton decays hadronically and is reconstructed within the detector acceptance. At high $\tan\beta$, the $1\tau$ channel is not competitive due to the large multiplicity of $\tau$-leptons in signal events.

In the $2\tau$ channel, two SRs are defined for the simplified model, as summarized in Table III. The $2\tau$ compressed SR targets small mass differences between the gluino and the LSP, up to $\approx 300$ GeV. It exploits topologies where the pair of gluinos recoils against a high-$p_T$ jet from initial-state radiation (ISR). While $\tau$-leptons and additional jets from gluino decays typically have low $p_T$, such ISR events have substantial $E_{\text{miss}}$ since both LSPs tend to be emitted opposite to the ISR jet in the transverse plane. A requirement on the transverse mass is used to suppress $W(\tau\nu) +$ jets events as well as semileptonic $t\bar{t}$ events with a $\tau$-lepton in the final state.

The $2\tau$ medium-mass SR targets larger mass-splittings, motivating a more stringent $m_\tau^T$ criterion and an $H_T$ requirement. These two SRs also provide sensitivity to GMSB signals at low $\tan\beta$, in cases where only one $\tau$-lepton decays hadronically and is reconstructed within the detector acceptance. At high $\tan\beta$, the $2\tau$ channel is not competitive due to the large multiplicity of $\tau$-leptons in signal events.

In the $1\tau$ channel, two SRs are defined for the simplified model, as summarized in Table III. The $1\tau$ compressed SR targets small mass differences between the gluino and the LSP, up to $\approx 300$ GeV. It exploits topologies where the pair of gluinos recoils against a high-$p_T$ jet from initial-state radiation (ISR). While $\tau$-leptons and additional jets from gluino decays typically have low $p_T$, such ISR events have substantial $E_{\text{miss}}$ since both LSPs tend to be emitted opposite to the ISR jet in the transverse plane. A requirement on the transverse mass is used to suppress $W(\tau\nu) +$ jets events as well as semileptonic $t\bar{t}$ events with a $\tau$-lepton in the final state.

The $1\tau$ medium-mass SR targets larger mass-splittings, motivating a more stringent $m_\tau^T$ criterion and an $H_T$ requirement. These two SRs also provide sensitivity to GMSB signals at low $\tan\beta$, in cases where only one $\tau$-lepton decays hadronically and is reconstructed within the detector acceptance. At high $\tan\beta$, the $1\tau$ channel is not competitive due to the large multiplicity of $\tau$-leptons in signal events.

In the $2\tau$ channel, two SRs are defined for the simplified model, as summarized in Table III. The $2\tau$ compressed SR targets small mass differences between the gluino and the LSP, up to $\approx 300$ GeV. It exploits topologies where the pair of gluinos recoils against a high-$p_T$ jet from initial-state radiation (ISR). While $\tau$-leptons and additional jets from gluino decays typically have low $p_T$, such ISR events have substantial $E_{\text{miss}}$ since both LSPs tend to be emitted opposite to the ISR jet in the transverse plane. A requirement on the transverse mass is used to suppress $W(\tau\nu) +$ jets events as well as semileptonic $t\bar{t}$ events with a $\tau$-lepton in the final state.

The $2\tau$ medium-mass SR targets larger mass-splittings, motivating a more stringent $m_\tau^T$ criterion and an $H_T$ requirement. These two SRs also provide sensitivity to GMSB signals at low $\tan\beta$, in cases where only one $\tau$-lepton decays hadronically and is reconstructed within the detector acceptance. At high $\tan\beta$, the $2\tau$ channel is not competitive due to the large multiplicity of $\tau$-leptons in signal events.

In the $1\tau$ channel, two SRs are defined for the simplified model, as summarized in Table III. The $1\tau$ compressed SR targets small mass differences between the gluino and the LSP, up to $\approx 300$ GeV. It exploits topologies where the pair of gluinos recoils against a high-$p_T$ jet from initial-state radiation (ISR). While $\tau$-leptons and additional jets from gluino decays typically have low $p_T$, such ISR events have substantial $E_{\text{miss}}$ since both LSPs tend to be emitted opposite to the ISR jet in the transverse plane. A requirement on the transverse mass is used to suppress $W(\tau\nu) +$ jets events as well as semileptonic $t\bar{t}$ events with a $\tau$-lepton in the final state.

The $1\tau$ medium-mass SR targets larger mass-splittings, motivating a more stringent $m_\tau^T$ criterion and an $H_T$ requirement. These two SRs also provide sensitivity to GMSB signals at low $\tan\beta$, in cases where only one $\tau$-lepton decays hadronically and is reconstructed within the detector acceptance. At high $\tan\beta$, the $1\tau$ channel is not competitive due to the large multiplicity of $\tau$-leptons in signal events.

In the $2\tau$ channel, two SRs are defined for the simplified model, as summarized in Table III. The $2\tau$ compressed SR targets small mass differences between the gluino and the LSP, up to $\approx 300$ GeV. It exploits topologies where the pair of gluinos recoils against a high-$p_T$ jet from initial-state radiation (ISR). While $\tau$-leptons and additional jets from gluino decays typically have low $p_T$, such ISR events have substantial $E_{\text{miss}}$ since both LSPs tend to be emitted opposite to the ISR jet in the transverse plane. A requirement on the transverse mass is used to suppress $W(\tau\nu) +$ jets events as well as semileptonic $t\bar{t}$ events with a $\tau$-lepton in the final state.

The $2\tau$ medium-mass SR targets larger mass-splittings, motivating a more stringent $m_\tau^T$ criterion and an $H_T$ requirement. These two SRs also provide sensitivity to GMSB signals at low $\tan\beta$, in cases where only one $\tau$-lepton decays hadronically and is reconstructed within the detector acceptance. At high $\tan\beta$, the $2\tau$ channel is not competitive due to the large multiplicity of $\tau$-leptons in signal events.
In the 2τ channel, three SRs are defined for the simplified model, as summarized in Table IV. The compressed and high-mass SRs target signals with small and large mass-splittings, respectively. The 2τ multibin SR exploits the shape difference between signal and background distributions, in contrast to the other SRs which only exploit the total yields. The multibin approach is less model dependent than a single-bin SR designed to probe a narrow part of the model parameter space, and it provides increased sensitivity to both small and large mass-splittings.

The 2τ compressed SR has a requirement on \( m_{\tau\tau}^{\text{rel}} \) to exploit the kinematic endpoint of \( Z(\tau\tau) + \text{jets} \) and dilepton \( \ell\ell \) events. A requirement on \( m_{\tau\tau}^{\text{sum}} = m_{\tau\tau}^{\text{rel}} + m_T^{\text{miss}} \) is imposed to take advantage of the large \( E_T^{\text{miss}} \) and the high multiplicities of jets and τ-leptons that are expected from gluino decays and the boosted topologies. The upper bound on \( m_{\tau\tau}^{\text{rel}} \) in the compressed SR does not affect the sensitivity to compressed signals. The 2τ high-mass SR includes a stringent requirement on \( m_{\tau\tau}^{\text{rel}} + m_T^{\text{miss}} \) that reduces the contribution from \( Z(\tau\tau) + \text{jets} \) events. The τ-leptons from high-\( p_T \) Z bosons have a small separation in \( \phi \), whereas in low values of \( m_{\tau\tau}^{\text{rel}} + m_T^{\text{miss}} \) given that the τ-neutrinos producing \( E_T^{\text{miss}} \) are collimated with the visible decay products of τ-leptons. An \( H_T \) requirement is applied to significantly reduce background from \( \ell\ell \) and \( W(\nu\nu) + \text{jets} \) events. The multibin SR uses looser selection criteria than the high-mass SR, and comprises seven bins in \( m_{\tau\tau}^{\text{rel}} + m_T^{\text{miss}} \).

A dedicated SR is defined for the GMSB model, based on the high-mass SR. To accommodate the more complex production and decay processes and the higher mass reach in the GMSB model, the minimum \( m_{\tau\tau}^{\text{rel}} + m_T^{\text{miss}} \) requirement, which depends on specific decay topologies, is lowered while the minimum \( H_T \) requirement is raised. The selection criteria defining the GMSB SR in the 2τ channel are summarized in Table IV.

For the simplified model, the two SRs of the 1τ channel can be statistically combined in a simultaneous fit with either the compressed and high-mass SRs of the 2τ channel or the multibin SR of the 2τ channel, as the multibin SR is not mutually exclusive to the other 2τ SRs. For each benchmark point in the parameter space, the most sensitive expected result of these two fits is used. For the GMSB interpretation, the 1τ SRs are combined with the 2τ GMSB SR and the 2τ compressed SR.

VI. BACKGROUND ESTIMATION

Events from \( W(\nu\nu) + \text{jets} \) and, to a smaller extent, diboson production are significant backgrounds in all SRs. Additionally, \( Z(\mu\nu) + \text{jets} \) plays a role in the 1τ channel, while \( Z(\tau\tau) + \text{jets} \) is an important background in some of the 2τ SRs. Multijet production makes a minor contribution in the 1τ channel. Dedicated control regions are used to constrain the normalization of all these backgrounds, except for diboson processes, which are normalized to their respective theoretical cross-sections.

The τ-leptons selected in the Standard Model background events are either prompt leptons from electroweak boson decays (true τ-leptons), or reconstructed objects such as jets that are misidentified as τ-leptons (fake τ-leptons). Backgrounds that contribute almost exclusively to a single channel, with only fake or only true τ-leptons, are each normalized with a single normalization factor. This is the case for \( Z(\nu\nu) + \text{jets} \), multijet and \( Z(\tau\tau) + \text{jets} \) events. The associated control regions are named \( Z(\nu\nu) \) CR, multijet CR and \( Z(\tau\tau) \) CR. For both the \( W(\nu\nu) + \text{jets} \) and \( \ell\ell \) backgrounds, which contribute to both the 1τ and the 2τ SRs with different multiplicities of true and fake τ-leptons, three normalization factors are used. A normalization factor for true τ-leptons is used to correct for differences in the τ-lepton reconstruction and identification efficiencies between data and simulation. A normalization factor for fake τ-leptons accounts for multiple sources of potential mismodeling in the simulation: the quark/gluon composition of jets misidentified as τ-leptons, the parton shower and hadronization models of the generator, and the modeling of particle shower shapes in the calorimeter, which mainly depends on the \textsc{Geant4} hadronic interaction model and the modeling of the ATLAS detector. An overall normalization factor accounts for the modeling of the background kinematics and acceptance, and absorbs the theoretical uncertainties in the cross-section computation, as well as the experimental uncertainties in the measured integrated luminosity of the data. The corresponding CRs are named \( W/\text{top} \) true-τ CR, \( W/\text{top} \) fake-τ CR, and \( W/\text{top} \) kinematic CR, respectively. The separation between \( W/\text{top} \) and CRs is achieved by requiring the absence or presence of a \( b \)-tagged jet.

The kinematic CRs require a muon and no τ candidate, to be independent of the τ-lepton reconstruction and identification. An upper bound on \( m_T^{\nu\nu} \) is applied to select \( W(\nu\nu) + \text{jets} \) events and top-quark background with a muon in the final state. The true-τ CRs target \( W(\tau\nu) + \text{jets} \) events and semileptonic top-quark processes with a true τ-lepton. They are based on events with a τ-lepton, jets, and \( E_T^{\text{miss}} \). Contributions from fake τ-leptons are suppressed by a requirement on \( m_\tau^\tau \). The fake-τ CRs target \( W(\nu\nu) + \text{jets} \) and top-quark processes with a final-state muon, with a jet misidentified as a τ-lepton. They use the same baseline selection as kinematic CRs, but a τ candidate is required. Events with large \( m_\tau^\tau \) values are discarded to suppress the top-quark background with a muon and a true τ-lepton. In the \( W \) fake-τ CR, the invariant mass of the reconstructed τ-lepton and the muon \( m_{\tau\mu} \) is required to be large to suppress \( Z(\tau\tau) \) events where one of the τ-leptons decays into a muon. The \( Z(\nu\nu) \) CR requires one τ-lepton, has a lower bound on \( m_T^{\nu\nu} \) to suppress background with real τ-leptons, a requirement on \( E_T^{\text{miss}}/m_{\ell\ell} \), where \( m_{\ell\ell} = H_T + E_T^{\text{miss}} \), to reject multijet events, and requirements on the \( \Delta\phi \) separations between the missing transverse momentum and the highest-\( p_T \) jet and τ-lepton, to exploit the background topology. The \( Z(\tau\tau) \) CR is designed by inverting the
\( m_{\tau_1}^2 + m_{\tau_2}^2 \) and \( H_T \) requirements from the 2\( \tau \) SRs. This selection requires two medium \( \tau \)-leptons of opposite electric charge and imposes an upper bound on the invariant mass of the \( \tau \)-lepton pair to suppress dileptonic contributions. Both \( Z \) CRs employ a veto on \( b \)-tagged jets to suppress contributions from top-quark processes. A simultaneous fit over all CRs is performed using HistFitter \cite{82} to extract the normalization factors.

The multijet background contributes when jets are misidentified as \( \tau \)-leptons and large missing transverse momentum is induced by jet energy mismeasurements. This, together with the very large production cross section, makes it difficult to simulate a sufficient number of multijet events with the required accuracy, so this background is estimated from data \cite{83}. A data sample with high purity in multijet events is selected using single-jet triggers. Events with well-measured jets are retained by applying an upper bound on the \( E_T^{\text{miss}} \) significance \cite{19}, except for events where the leading \( b \)-tagged jet is aligned with \( p_T^{\text{miss}} \). The latter exception avoids too large of a suppression of high-\( p_T \) \( b \)-hadrons decaying semileptonically and producing high-\( p_T \) neutrinos. Jet energies are then smeared according to the jet energy resolution obtained from simulation and corrected to better describe the data. The smearing is performed multiple times for each selected event, leading to a large pseudo-data set where \( E_T^{\text{miss}} \) originates from resolution effects and which includes an adequate fraction of jets misidentified as \( \tau \)-leptons. A subtraction is performed to account for the small contamination from \( t\bar{t} \) events satisfying this kinematic configuration. The normalization of the pseudo-data is constrained in the simultaneous fit using a multijet CR where either of the two leading jets is aligned with \( p_T^{\text{miss}} \).

The selection criteria defining the various CRs are summarized in Tables V and VI. Figure 3 illustrates the background modeling in CRs after the fit. The fitted normalization factors do not deviate from unity by more than 15\% and are compatible with unity within one standard deviation when considering all systematic uncertainties, except for the \( Z(\nu\bar{\nu}) + \text{jets} \) background, where the normalization factor reaches 1.44 ± 0.29.

---

**TABLE V.** Summary of the \( W \) and top control regions. These requirements are applied in addition to the trigger, jet, and multijet requirements of the preselection. The variables \( N_\tau \), \( N_{\text{jet}} \), \( N_\mu \), and \( N_{b\text{-jet}} \) are the number of \( \tau \)-leptons, jets, muons, and \( b \)-tagged jet, respectively; other variables are defined in the text.

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>( W/\text{top kinematic CR} )</th>
<th>( W/\text{top true-}( \tau ) CR)</th>
<th>( W/\text{top fake-}( \tau ) CR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau )-leptons</td>
<td>( N_\tau = 0 )</td>
<td>( N_\tau = 1 )</td>
<td>( ... )</td>
</tr>
</tbody>
</table>
| Jets                 | \( N_{\text{jet}} \geq 3 \) | \( N_\mu = 0 \) | \( N_\mu = 1 \)
| Muons                | \( N_\mu = 1 \) | \( N_\mu = 1 \) | \( N_{b\text{-jet}} = 0 \) |
| Event kinematics     | \( H_T < 800 \text{ GeV} \) | \( E_T^{\text{miss}} < 300 \text{ GeV} \) | \( m_\mu^\tau < 100 \text{ GeV} \)
| \( m_\tau^\mu < 100 \text{ GeV} \) | \( m_\mu^\tau < 80 \text{ GeV} \) | \( m_\mu^\tau > 60 \text{ GeV (W CR)} \)

**TABLE VI.** Summary of the \( Z(\nu\bar{\nu}) \), \( Z(\tau\tau) \), and multijet control regions. These requirements are applied in addition to the trigger and jet requirements of the preselection. The variables \( N_\tau \) and \( N_\mu \) are the number of \( \tau \)-leptons, and muons, respectively; \( q_i \) is the charge of \( \tau \)-lepton \( i \); other variables are defined in the text.

<table>
<thead>
<tr>
<th>Subject of selection</th>
<th>( Z(\nu\bar{\nu}) ) CR</th>
<th>( Z(\tau\tau) ) CR</th>
<th>Multijet CR</th>
</tr>
</thead>
</table>
| \( \tau \)-leptons   | \( N_\tau = 1 \) | \( N_\tau \geq 2 \), \( q_{\tau_1} = -q_{\tau_2} \) | \( N_\tau = 1 \)
| Multijet events      | \( \Delta\phi(p_T^{\text{jet}_1}, p_T^{\text{miss}}) > 0.4 \) | \( \Delta\phi(p_T^{\text{jet}_1,2}, p_T^{\text{miss}}) < 0.3 \) | 
| Muons                | \( N_\mu = 0 \) | | 
| Top suppression      | \( N_{b\text{-jet}} = 0 \) | | 
| Event kinematics     | \( E_T^{\text{miss}} < 300 \text{ GeV} \) | \( 100 \leq m_T^2 < 200 \text{ GeV} \) | \( E_T^{\text{miss}} / m_{\text{eff}} > 0.3 \)
| \( m_\tau^1 + m_\tau^2 < 100 \text{ GeV} \) | \( m_T^2 < 70 \text{ GeV} \) | \( 100 < m_T^2 < 200 \text{ GeV} \)
| \( E_T^{\text{miss}} / m_{\text{eff}} < 0.2 \) | | | 
| \( \Delta\phi(p_T^{\text{jet}_1}, p_T^{\text{miss}}) > 2.0 \) | | \( \Delta\phi(p_T^{\text{jet}_1}, p_T^{\text{miss}}) > 1.0 \) |
FIG. 3. (a) Scalar sum of transverse momenta of $\tau$-leptons and jets $H_T$ in the top true-$\tau$ CR, (b) missing transverse momentum $E_{\text{miss}}^T$ in the $W$ fake-$\tau$ CR, (c) $H_T$ in the $W$ kinematic CR, (d) sum of $\tau$-lepton transverse masses $m_{\tau_1}^T + m_{\tau_2}^T$ in the $Z(\tau\tau)$ CR, (e) $H_T$ in the $Z(\nu\nu)$ CR, and (f) $E_{\text{miss}}^T$ in the multijet CR, illustrating the background modeling in the CRs after the fit. The contribution labeled as “Other” includes multijet events (except for the multijet CR) and the $V +$ jets processes not explicitly listed in the legend. The last bin of each distribution includes overflow events. The total uncertainty in the background prediction is shown as a shaded band.
Validation regions are used to verify that the background is well modeled after the fit in kinematic regions close to the SRs. In the 1r channel, three VRs are defined for the medium-mass SR and two for the compressed SR, while three VRs are used for the 2τ channel. Their selection criteria are summarized in Tables VII and VIII. The level of agreement between data and background in the VRs is illustrated in Figs. 4 and 5. Distributions are found to be well modeled in both channels. The comparison between the numbers of observed events and the predicted background yields is displayed in Fig. 6. Agreement well within one standard deviation is observed.

### VII. SYSTEMATIC UNCERTAINTIES

Theoretical and experimental systematic uncertainties are evaluated for all simulated processes. The uncertainties from theory include PDF, $\alpha_s$ and scale uncertainties, and generator modeling uncertainties. Experimental uncertainties are related to the reconstruction, identification, and calibration of final-state objects. Specific uncertainties are evaluated for the multijet background, which is estimated from data.

For $V +$ jets and diboson samples, systematic uncertainties related to PDFs, $\alpha_s$, and scales are evaluated using alternative weights from the generator. The PDF uncertainty is obtained as the standard deviation of the 100 PDF variations from the NNPDF3.0nlo set. The effect of the uncertainty in $\alpha_s$ is computed as half the difference resulting from the $\alpha_s = 0.119$ and $\alpha_s = 0.117$ parametrizations. The renormalization scale $\mu_R$ and factorization scale $\mu_F$ are varied up and down by a factor of 2 and all combinations are evaluated, except for the $(2\mu_R, \frac{1}{2}\mu_F)$ and $(\frac{1}{2}\mu_R, 2\mu_F)$ variations, which would lead to large $\log(\mu_R/\mu_F)$ contributions to the cross section. The scale uncertainty is computed as half the difference between the two combinations yielding the largest and smallest deviations from the nominal prediction. Uncertainties due to the resummation and CKKW matching scales for $V +$ jets samples are found to be negligible. Additional generator modeling uncertainties are considered for the dominant $W(\tau\nu) +$ jets background. An uncertainty is derived to cover a mismodeling of the $H_T$ distribution observed in the $W$ kinematic CR (cf. Figure 3(c)). In addition, predictions from SHERPA and MG5_AMC@NLO+PYTHIA8 are compared, and the difference is taken as a systematic uncertainty. For the diboson background, which is not normalized to data in the fit, the uncertainty in the cross section is also taken into account.

For top quark pair production, uncertainties due to PDF and scale variations are derived using POWHEG+PYTHIA8 and applied to the nominal predictions from POWHEG+PYTHIA6. Generator modeling uncertainties are assessed from comparisons with alternative generator samples. An uncertainty in the hard-scattering model is evaluated by comparing predictions from MG5_AMC@NLO+HERWIG++ and POWHEG-BOX+HERWIG++. An uncertainty due to the parton shower and hadronization models is evaluated by comparing predictions from POWHEG-BOX+PYTHIA6 and POWHEG-BOX+HERWIG++. An uncertainty due to the ISR modeling is assessed by varying the POWHEG-BOX parameter which controls the transverse momentum of the first additional parton emission beyond the Born configuration. For the small contributions from single-top-quark production and $t\bar{t} + V$ events, uncertainties in the cross sections are taken into account.

Systematic uncertainties affecting jets arise from the jet energy scale [84], jet energy resolution [85], and efficiency corrections for jet-vertex-tagging [69] as well as $b$-tagging...
FIG. 4. Distributions of (a) \( \tau \)-lepton transverse mass \( m_\tau^T \) in the compressed \( m_\tau^T \) VR, (b) missing transverse momentum \( E_{\text{miss}}^T \) in the compressed \( E_{\text{miss}}^T \) VR, (c) \( m_\tau^T \) in the medium-mass \( m_\tau^T \) VR, (d) \( E_{\text{miss}}^T \) in the medium-mass \( E_{\text{miss}}^T \) VR, and (e) scalar sum of \( \tau \)-lepton and jet transverse momenta \( H_T \) in the medium-mass \( H_T \) VR, illustrating the background modeling in the VRs of the \( 1 \tau \) channel after the fit. The normalization factors obtained in the CRs are applied. The contribution labeled as “Other” includes multijet events and the \( V + \text{jets} \) processes not explicitly listed in the legend. The last bin of each distribution includes overflow events. The total uncertainty in the background prediction is shown as a shaded band.
Jet energy scale uncertainties are mainly determined from measurements of the $p_T$ balance in the calorimeter in $Z/\gamma + \text{jet}$ and multijet events. Remaining uncertainties arise from the relative calibration of forward and central jets, jet flavor composition, pileup, and punch-through for high-$p_T$ jets not fully contained in the calorimeters. A set of five uncertainties that comprises contributions from both absolute and in situ energy calibrations and which preserves the dominant correlations in the $(p_T, \eta)$ phase space is used. An uncertainty in the jet energy resolution is applied to jets in the simulation as a Gaussian energy smearing.

Systematic uncertainties affecting true $\tau$-leptons are related to the reconstruction and identification efficiencies, the electron rejection efficiency, and the energy scale calibration [87]. The uncertainties in the reconstruction efficiency are estimated by varying parameters in the simulation such as the detector material, underlying event, and hadronic shower model. Uncertainties in the identification efficiency and in situ energy calibration, which are derived in $Z(\tau\tau)$ events with a hadronically decaying $\tau$-lepton and a muon, arise from the modeling of true- and fake-$\tau$-lepton templates. The uncertainty in the energy scale also includes nonclosure of the calibration found in simulation and a single-pion response uncertainty. In the case of fake $\tau$-leptons, the misidentification rate in the simulation is largely constrained by the fit to data in the CRs. The process-dependence of the misidentification rate is accounted for by the use of different normalization factors obtained in the CRs are applied. The contribution labeled as “Other” includes multijet events and the $V + \text{jets}$ processes not explicitly listed in the legend. The last bin of each distribution includes overflow events. The total uncertainty in the background prediction is shown as a shaded band.

FIG. 5. (a) Sum of $\tau$-lepton transverse masses $m_T^\tau_1 + m_T^\tau_2$ in the top VR, (b) scalar sum of $\tau$-lepton and jet transverse momenta $H_T$ in the $W$ VR, and (c) $m_T^\tau_1 + m_T^\tau_2$ in the $Z$ VR, illustrating the background modeling in the VRs of the $2\tau$ channel after the fit. The normalization factors obtained in the CRs are applied. The contribution labeled as “Other” includes multijet events and the $V + \text{jets}$ processes not explicitly listed in the legend. The last bin of each distribution includes overflow events. The total uncertainty in the background prediction is shown as a shaded band.
factors for the various backgrounds. Uncertainties in the extrapolation from the CRs to the VRs and SRs are covered by generator modeling uncertainties.

In the case of signal samples, which undergo fast calorimeter simulation, dedicated uncertainties take into account the difference in performance between full and fast simulation. These uncertainties include nonclosure of the energy calibration for both the jets and $\tau$-leptons, as well as differences in reconstruction and identification efficiencies for $\tau$-leptons.

Systematic uncertainties in the missing transverse momentum originate from uncertainties in the energy or momentum calibration of jets, $\tau$-leptons, electrons, and muons, which are propagated to the $E_{T}^{\text{miss}}$ calculation. Additional uncertainties are related to the calculation of the track-based soft term. These uncertainties are derived by studying the $p_{T}$ balance between the soft term and the hard term composed of all reconstructed objects, in $Z(\mu\mu)$ events. Soft-term uncertainties include scale uncertainties along the hard-term axis, and resolution uncertainties along and perpendicular to the hard-term axis [88].

A systematic uncertainty accounts for the modeling of pileup in the simulation, which affects the correlation between the average number of interactions per bunch crossing and the number of reconstructed primary vertices. The modeling mostly depends on the minimum-bias tune and the longitudinal size of the $pp$ interaction region used in the simulation.

Systematic uncertainties in the small multijet background contribution are due to the limited numbers of events in the input data set satisfying the $E_{T}^{\text{miss}}$ significance requirement, the jet resolution parametrization used for jet energy smearing, and the $t\bar{t}$ background subtraction.

The uncertainty in the combined 2015 + 2016 integrated luminosity is 2.1%. It is derived, following a methodology similar to that detailed in Ref. [89], from a calibration of the luminosity scale using $x$-$y$ beam-separation scans performed in August 2015 and May 2016.

The impact of the main systematic uncertainties on the total background predictions in the SRs of the 1$\tau$ and 2$\tau$ channels is summarized in Table IX. These uncertainties are shown after the background fit, assuming that no signal is present in the CRs. In both channels, generator modeling uncertainties for the $W$+jets and $t\bar{t}$ backgrounds are the largest sources of systematic uncertainty. Other dominant uncertainties are jet energy calibration and $\tau$-lepton identification, which contributes more in the 2$\tau$ channel. Uncertainties in the $b$-tagging efficiency and $E_{T}^{\text{miss}}$ calibration have little impact on background predictions, and those affecting electrons and muons are negligible.

### VIII. RESULTS

Kinematic distributions for the SRs of the 1$\tau$ and 2$\tau$ channels are shown in Figs. 7 and 8, respectively. In these plots, all selection criteria defining the respective SRs are applied, except for the one on the variable which is displayed. Data and fitted background predictions are compared, and signal predictions from several benchmark models are overlaid. Variables providing the most

---

**FIG. 6.** Number of observed events $n_{\text{obs}}$ and predicted background yields in the validation regions $n_{\text{pred}}$ of the 1$\tau$ and 2$\tau$ channels. The background predictions are scaled using normalization factors derived in the control regions. The total uncertainty in the background predictions $\sigma_{\text{tot}}$ is shown as a shaded band. The lower panel displays the significance of the deviation of the observed from the expected yield.
TABLE IX. Dominant systematic uncertainties in the total background predictions, for the signal regions of the 1τ (top) and 2τ (bottom) channels after the normalization fit in the control regions. The total systematic uncertainty accounts for other minor contributions not listed in this table. Due to nontrivial correlations between the various sources in the combined fit, the total uncertainty is not identical to the sum in quadrature of the individual components.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>1τ compressed SR</th>
<th>1τ medium-mass SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top generator modeling</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td>V + jets generator modeling</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>τ-lepton energy scale</td>
<td>&lt;1%</td>
<td>2.9%</td>
</tr>
<tr>
<td>τ-lepton identification</td>
<td>1.5%</td>
<td>3.3%</td>
</tr>
<tr>
<td>PDFs</td>
<td>1.9%</td>
<td>13%</td>
</tr>
<tr>
<td>Limited simulation sample size</td>
<td>1.8%</td>
<td>6%</td>
</tr>
<tr>
<td>Background normalization uncertainty</td>
<td>12%</td>
<td>11%</td>
</tr>
</tbody>
</table>

**Total** | 10% | 19% |

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>2τ compressed SR</th>
<th>2τ high-mass SR</th>
<th>2τ GMSB SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top generator modeling</td>
<td>31%</td>
<td>18%</td>
<td>14%</td>
</tr>
<tr>
<td>V + jets generator modeling</td>
<td>7%</td>
<td>15%</td>
<td>21%</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>15%</td>
<td>9%</td>
<td>5%</td>
</tr>
<tr>
<td>τ-lepton energy scale</td>
<td>4%</td>
<td>6%</td>
<td>1.7%</td>
</tr>
<tr>
<td>τ-lepton identification</td>
<td>5%</td>
<td>10%</td>
<td>9%</td>
</tr>
<tr>
<td>PDFs</td>
<td>2.0%</td>
<td>4%</td>
<td>10%</td>
</tr>
<tr>
<td>Limited simulation sample size</td>
<td>10%</td>
<td>8%</td>
<td>21%</td>
</tr>
<tr>
<td>Background normalization uncertainty</td>
<td>13%</td>
<td>13%</td>
<td>13%</td>
</tr>
</tbody>
</table>

**Total** | 35% | 30% | 38% |

![ATLAS plot](image_url)

FIG. 7. Distributions of kinematic variables in extended SR selections of the 1τ channel after the fit: (a) τ-lepton transverse mass $m_\tau^T$ in the compressed SR without the $m_\tau^T > 80$ GeV requirement and (b) scalar sum of τ-lepton and jet transverse momenta $H_T$ in the medium-mass SR without the $H_T > 1000$ GeV requirement. The contribution labeled as “Other” includes multijet events and the $V +jets$ processes not explicitly listed in the legend. The last bin of each distribution includes overflow events. The total uncertainty in the background prediction is shown as a shaded band. Arrows in the Data/SM ratio indicate bins where the entry is outside the plotted range. The signal region is indicated by the arrow in the upper pane. Signal predictions are overlaid for several benchmark models. For the simplified model, LM, MM and HM refer to low, medium, and high mass-splitting scenarios, with $(m_{\tilde{g}}, m_{\tilde{\chi}_0^1})$ set to (1065,825) GeV, (1625,905) GeV, and (1705,345) GeV, respectively. The GMSB benchmark model corresponds to $\Lambda = 120$ TeV and $\tan\beta = 40$.  
discrimination between signal and background are displayed. The $m_{\tau_1}^T + m_{\tau_2}^T$ distribution which is used for the multibin SR of the 2$\tau$ channel is also shown.

Good agreement between data and background expectation is observed. A small discrepancy is observed for $m_{\tau}^T < 200$ GeV in the 1$\tau$ compressed SR [cf. Fig. 7(a)]. This region has been studied in detail and no particular problem has been identified. Given that the deviation is only observed in a restricted region and it is below two standard deviations in all bins, no significant impact on the result is expected.

The numbers of observed events and expected background events in the SRs of the 1$\tau$ and 2$\tau$ channels are reported in Tables X and XI, respectively. In the high-mass and GMSB SRs of the 2$\tau$ channel that both require high $H_T$, a small excess of data with a significance of below 2 standard deviations is observed. Apart from that, no significant deviation of data from the SM prediction is observed.
observed in any of the five single-bin SRs and the seven bins of the multibin SR. Upper limits are set at the 95% confidence level (C.L.) on the number of signal events, or equivalently, on the signal cross section.

The one-sided profile-likelihood-ratio test statistic is used to assess the probability that the observed data is compatible with the background-only and signal-plus-background hypotheses. Systematic uncertainties are included in the likelihood function as nuisance parameters with Gaussian probability densities. Following the standards used for LHC analyses, $p$ values are computed according to the CL$_b$ prescription [90] using HistFitter [82].

Model-independent upper limits on the event yields are calculated for each SR except the multibin SR, assuming no signal contribution in the CRs. No such interpretation can be made for the multibin SR, as the relative signal contribution in each bin of the $m_1^\tau + m_2^\tau$ distribution is model dependent. The results are derived using profile-likelihood-ratio distributions obtained from pseudoexperiments. Upper limits on signal yields are converted into limits on the visible cross section ($\sigma_{\text{vis}}$) of BSM processes by dividing by the integrated luminosity of the data. The visible cross section is defined as the product of production cross section, acceptance, and selection efficiency. Results are summarized at the bottom of Tables X and XI. The observed upper limits on the visible cross section range from 0.18 fb for the compressed SR of the 2$\tau$ channel to 1.37 fb for the compressed SR of the 1$\tau$ channel.

### Table X. Number of observed events and predicted background yields in the two signal regions of the 1$\tau$ channel. The background prediction is scaled using normalization factors derived in the control regions. The numbers in brackets give the background prediction before application of the fitted normalization factors. All systematic and statistical uncertainties are included in the quoted uncertainties. The bottom part of the table shows the observed and expected model-independent upper limits at 95% C.L. on the number of signal events $S_{\text{obs}}^{95}$ and $S_{\text{exp}}^{95}$ respectively, the corresponding observed upper limit on the visible cross section $\langle \sigma_{\text{vis}}^{95} \rangle = \langle \sigma_{\text{obs}}^{95} / \sigma_{\text{exp}}^{95} \rangle$, the confidence level observed for the background-only hypothesis CL$_b$, the $p_0$ value, and corresponding significance $Z$. If the number of observed events is smaller than the expected background yield, the $p_0$ value is set to 0.5, corresponding to a significance $Z$ of 0.0 standard deviations.

<table>
<thead>
<tr>
<th>1$\tau$ channel</th>
<th>Compressed SR</th>
<th>Medium-mass SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>286</td>
<td>12</td>
</tr>
<tr>
<td>Total background</td>
<td>[290]</td>
<td>[9.2 ± 3.0]</td>
</tr>
<tr>
<td>Top quarks</td>
<td>[66]</td>
<td>[5.2 ± 1.6]</td>
</tr>
<tr>
<td>$W(\tau\nu) +$ jets</td>
<td>[57]</td>
<td>[2.4 ± 1.7]</td>
</tr>
<tr>
<td>$Z(\nu\nu) +$ jets</td>
<td>[77]</td>
<td>[2.2 ± 0.5]</td>
</tr>
<tr>
<td>Other $V +$ jets</td>
<td>[52]</td>
<td>[1.9 ± 0.4]</td>
</tr>
<tr>
<td>Diboson</td>
<td>[28]</td>
<td>[3.0 ± 0.6]</td>
</tr>
<tr>
<td>Multijet</td>
<td>[10.0]</td>
<td>[1.2 ± 0.1]</td>
</tr>
</tbody>
</table>

$S_{\text{obs}}^{95} / S_{\text{exp}}^{95} = 49.5 (64.1^{+24.1}_{-14.5})$, $\langle \sigma_{\text{vis}}^{95} / \sigma_{\text{exp}}^{95} \rangle = 1.37$, CL$_b = 0.50$, $p_0 = 0.18$, $Z = 0.50$.

### Table XI. Number of observed events and predicted background yields in the three signal regions of the 2$\tau$ channel. The background prediction is scaled using normalization factors derived in the control regions. The numbers in brackets give the background prediction before application of the fitted normalization factors. All systematic and statistical uncertainties are included in the quoted uncertainties. The bottom part of the table shows the observed and expected model-independent upper limits at 95% C.L. on the number of signal events $S_{\text{obs}}^{95}$ and $S_{\text{exp}}^{95}$ respectively, the corresponding observed upper limit on the visible cross section $\langle \sigma_{\text{vis}}^{95} \rangle = \langle \sigma_{\text{obs}}^{95} / \sigma_{\text{exp}}^{95} \rangle$, the confidence level observed for the background-only hypothesis CL$_b$, the $p_0$ value, and corresponding significance $Z$. If the number of observed events is smaller than the expected background yield, the $p_0$ value is set to 0.5, corresponding to a significance $Z$ of 0.0 standard deviations.

<table>
<thead>
<tr>
<th>2$\tau$ channel</th>
<th>Compressed SR</th>
<th>High-mass SR</th>
<th>GMSB SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>5</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Total background</td>
<td>[4.7]</td>
<td>[2.3]</td>
<td>[1.5]</td>
</tr>
<tr>
<td>Top quarks</td>
<td>[2.3]</td>
<td>[0.9]</td>
<td>[0.34]</td>
</tr>
<tr>
<td>$W(\tau\tau) +$ jets</td>
<td>[0.5]</td>
<td>[0.4]</td>
<td>[0.4]</td>
</tr>
<tr>
<td>$Z(\tau\tau) +$ jets</td>
<td>[0.035]</td>
<td>[0.037]</td>
<td>[0.33]</td>
</tr>
<tr>
<td>$Z(\nu\nu) +$ jets</td>
<td>[0.47]</td>
<td>[0.065]</td>
<td>[0.008]</td>
</tr>
<tr>
<td>Other $V +$ jets</td>
<td>[0.32]</td>
<td>[0.019]</td>
<td>[0.015]</td>
</tr>
<tr>
<td>Diboson</td>
<td>[1.06]</td>
<td>[0.56]</td>
<td>[0.029]</td>
</tr>
<tr>
<td>Multijet</td>
<td>[0.0261]</td>
<td>[0.0214]</td>
<td>[0.065]</td>
</tr>
</tbody>
</table>

$S_{\text{obs}}^{95} / S_{\text{exp}}^{95} = 6.7 (6.7^{+2.5}_{-1.7})$, $\langle \sigma_{\text{vis}}^{95} / \sigma_{\text{exp}}^{95} \rangle = 0.18$, CL$_b = 0.50$, $p_0 = 0.50$, $Z = 0.50$. 
Limits are also set for the two SUSY models discussed in Sec. I. Exclusion contours at the 95% C.L. are derived in the \( (m_{\tilde{g}}, m_{\tilde{g}'}) \) parameter space for the simplified model and in the \( (\Lambda, \tan \beta) \) parameter space for the GMSB model. In the case of model-dependent interpretations, the signal contribution in the control regions is included in the calculation of upper limits, and asymptotic properties of test-statistic distributions are used [91]. Results are shown in Figs. 9 and 10. The solid line and the dashed line correspond to the observed and median expected limits, respectively. The band shows the one-standard-deviation spread of expected limits around the median. The effect of the signal cross-section uncertainty on the observed limits is shown as dotted lines. The inward fluctuation of the \(-1\sigma\) line originates from the method employed to perform the combination.

The previous ATLAS result [19] obtained with 3.2 fb\(^{-1}\) of 13 TeV data is shown as the filled area in the bottom left.

FIG. 9. Exclusion contours at the 95% confidence level as a function of the LSP mass \( m_{\tilde{\chi}} \) and gluino mass \( m_{\tilde{g}} \) for the simplified model of gluino pair production. The solid line and the dashed line correspond to the observed and median expected limits, respectively, for the combination of the \( 1\tau \) and \( 2\tau \) channels. The band shows the one-standard-deviation spread of expected limits around the median. The effect of the signal cross-section uncertainty on the observed limits is shown as dotted lines. The inward fluctuation of the \(-1\sigma\) line originates from the method employed to perform the combination. The previous ATLAS result [19] obtained with 3.2 fb\(^{-1}\) of 13 TeV data is shown as the filled area in the bottom left.

FIG. 10. Exclusion contours at the 95% confidence level as a function of \( \tan \beta \) and the SUSY-breaking mass scale \( \Lambda \) for the gauge-mediated supersymmetry-breaking model. The solid line and the dashed line correspond to the observed and median expected limits, respectively, for the combination of the \( 1\tau \) and \( 2\tau \) channels. The band shows the one-standard-deviation spread of expected limits around the median. The effect of the signal cross-section uncertainty on the observed limits is shown as dotted lines. The gray and orange dash-dotted lines indicate the masses of gluinos and mass-degenerate squarks, respectively. The previous ATLAS result [19] obtained with 3.2 fb\(^{-1}\) of 13 TeV data is shown as the filled area on the left.

Provides increased sensitivity to gluino pair production over a large region of the parameter space.

Expected limits in the model parameter space are shown for each channel, to illustrate their complementarity and the gain in sensitivity achieved with their combination. The green dash-dotted line corresponds to a fit that includes all CRs and the two SRs of the \( 1\tau \) channel. For the \( 2\tau \) channel, in the case of the simplified model, the magenta dash-dotted line corresponds to the best expected exclusion from fits that include either the \( 2\tau \) multibin SR or the combination of the \( 2\tau \) compressed and high-mass SRs. In the GMSB model, the \( 2\tau \) combination is based on the \( 2\tau \) GMSB and compressed SRs. In the simplified model, the \( 1\tau \) and \( 2\tau \) channels have similar sensitivity at high gluino and low LSP masses. For high LSP masses, the combination is dominated by the \( 2\tau \) channel, while in the region with a low mass difference between the gluino and the LSP, the \( 1\tau \) channel drives the exclusion. In the GMSB interpretation, the more stringent limits at high values of \( \tan \beta \) are explained by the nature of the NLSP, which is the lightest \( \tau \)-slepton in this region. For lower values of \( \tan \beta \), the \( \tilde{\tau}_1 \) is nearly mass-degenerate with \( \tilde{\chi}_1 \) and \( \tilde{\mu}_R \), leading to fewer \( \tau \)-leptons in squark and gluino decays, and reduced sensitivity of the \( 2\tau \) GMSB SR. The weaker exclusion at low \( \tan \beta \) is mitigated by the SRs from the \( 1\tau \) channel and the compressed SR of the \( 2\tau \) channel. For high \( \Lambda \), the sensitivity is limited by the strong-production cross section.
While the analysis is mainly sensitive to squark and gluino production, the total GMSB production cross section for high $\Lambda$ is dominated by electroweak production modes.

**IX. CONCLUSION**

A search for squarks and gluinos in events with jets, hadronically decaying $\tau$-leptons, and missing transverse momentum is performed using $pp$ collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC in 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb$^{-1}$. Two channels with exactly one or at least two $\tau$-leptons are considered, and their results are statistically combined. The observed data are consistent with background expectations from the Standard Model. Upper limits are set at 95% confidence level on the number of events that could be produced by processes beyond the Standard Model. Results are also interpreted in the framework of a simplified model of gluino pairs decaying into $\tau$-leptons via $\tau$-sleptons, and a minimal model of gauge-mediated supersymmetry breaking with the lighter $\tau$-slepton as the NLSP at large $\tan \beta$. At 95% C.L. in the simplified model, gluino masses up to 2000 GeV are excluded for low LSP masses, and LSP masses up to 1000 GeV are excluded for gluino masses around 1400 GeV. In the GMSB model, values of the SUSY-breaking scale $\Lambda$ below 110 TeV are excluded at 95% C.L. for all values of $\tan \beta$ in the range $2 \leq \tan \beta \leq 60$, while a stronger limit of 120 TeV is achieved for $\tan \beta > 30$.

**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; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, 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, FORNT, 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 (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [92].


\[ \sqrt{s} = 7 \text{ TeV} \] proton-proton collision data, Phys. Rev. D 87, 012008 (2013).


SEARCH FOR SQUARKS AND GLUINOS IN FINAL …

PHYS. REV. D 99, 012009 (2019)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4Department of Physics, Ankara University, Ankara, Turkey
5LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Department of Physics, University of Texas at Austin, Austin, Texas, USA
12Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
13Department for Physics and Technology, University of Bergen, Bergen, Norway
14Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
15Institute de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
16Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
17Department of Physics, Tsinghua University, Beijing, China
18Department of Physics, Nanjing University, Nanjing, China
19Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
20Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
21School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
22Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia

M. AABOUD et al. PHYS. REV. D 99, 012009 (2019)

23 Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
24 INFN Sezione di Bologna, Italy
25 Physikalisches Institut, Universität Bonn, Bonn, Germany
26 Department of Physics, Boston University, Boston, Massachusetts, USA
27 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
28 Transilvania University of Brasov, Brasov, Romania
29 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
30 Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
31 National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
32 University Politehnica Bucharest, Bucharest, Romania
33 West University in Timisoara, Timisoara, Romania
34 Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
35 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
36 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
37 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
38 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
39 Department of Physics, University of Cape Town, Cape Town, South Africa
40 Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
41 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
42 Department of Physics, Carleton University, Ottawa, Ontario, Canada
43 Centrale de l’Energie des Sciences Techniques Nucleaires (CENESTEN), Rabat, Morocco
44 Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
45 Faculté des sciences, Université Mohammed V, Rabat, Morocco
46 CERN, Geneva, Switzerland
47 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
48 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
49 Nevis Laboratory, Columbia University, Irvington, New York, USA
50 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
51 Dipartimento di Fisica, Università della Calabria, Rende, Italy
52 INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
53 Physics Department, Southern Methodist University, Dallas, Texas, USA
54 Department of Physics, University of Texas at Dallas, Richardson, Texas, USA
55 Department of Physics, Stockholm University, Sweden
56 Oskar Klein Centre, Stockholm, Sweden
57 Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
58 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
59 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
60 Department of Physics, Duke University, Durham, North Carolina, USA
61 SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
62 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
63 Physics Department, Georg-August-Universität Göttingen, Göttingen, Germany
64 Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
65 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
66 Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
67 Dipartimento di Fisica, Università di Genova, Genova, Italy
68 INFN Sezione di Genova, Italy
69 II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
70 SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
71 LPS, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
72 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
73 Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
74 Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
Louisiana Tech University, Ruston, Louisiana, USA
Fysiska institutionen, Lunds universitet, Lund, Sweden
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal, Quebec, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
Group of Particle Physics, University of Montreal, Montreal, Quebec, 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 Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
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, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Novosibirsk State University Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
The Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Université 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
LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Portugal
Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
Departamento de Física, Universidade do Minho, Braga, Portugal
Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
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, Prague, Czech Republic
Czech Technical University in Prague, Prague, Czech Republic
Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

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

Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.

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

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

Also at Borough of Manhattan Community College, City University of New York, New York, USA.

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, Louisiana, USA.

Also at California State University, East Bay, USA.

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

Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.

Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

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

Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

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

Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey.

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

Also at CERN, Geneva, Switzerland.

Also at Department of Physics, Stanford University, Stanford, California, USA.

Also at Manhattan College, New York, New York, USA.

Also at Hellenic Open University, Patras, Greece.

Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.

Also at The City College of New York, New York, New York, USA.

Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.

Also at Department of Physics, California State University, Sacramento, California, USA.

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

Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

Also at Department of Physics, Nanjing University, Nanjing, China.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Department of Physics, University of Malaya, Kuala Lumpur, Malaysia.