Search for bottom-squark pair production in pp collision events at root $s=13$ TeV with hadronically decaying tau-leptons, b-jets, and missing transverse momentum using the ATLAS detector

Aad, G.; Abbott, B.; Abbott, DC; Abud, AA; Abeling, K.; Abhayasinghe, D.K.; Abidi, S.H.; AbouZeid, Ossama Sherif Alexander; Abraham, NL; Abramowicz, H.; Camplani, Alessandra; Dam, Mogens; Hansen, Peter Henrik; Hansen, Jørn Dines; Hansen, Jørgen Beck; Ignazzi, Rosanna; Petersen, Troels Christian; Wiglesworth, Graig; Xella, Stefania; ATLAS Collaboration

Published in: Physical Review D

DOI: 10.1103/PhysRevD.104.032014

Publication date: 2021

Document version
Publisher's PDF, also known as Version of record

Document license:
CC BY

Citation for published version (APA):
Search for bottom-squark pair production in pp collision events at \( \sqrt{s} = 13 \) TeV with hadronically decaying \( \tau \)-leptons, \( b \)-jets, and missing transverse momentum using the ATLAS detector

G. Aad et al.*
(ATLAS Collaboration)

(Received 16 March 2021; accepted 9 July 2021; published 31 August 2021)

A search for pair production of bottom squarks in events with hadronically decaying \( \tau \)-leptons, \( b \)-tagged jets, and large missing transverse momentum is presented. The analyzed dataset is based on proton-proton collisions at \( \sqrt{s} = 13 \) TeV delivered by the Large Hadron Collider and recorded by the ATLAS detector from 2015 to 2018, and corresponds to an integrated luminosity of 139 fb\(^{-1}\). The observed data are compatible with the expected Standard Model background. Results are interpreted in a simplified model where each bottom squark is assumed to decay into the second-lightest neutralino \( \tilde{\chi}^0_2 \) and a bottom quark, with \( \tilde{\chi}^0_2 \) decaying into a Higgs boson and the lightest neutralino \( \tilde{\chi}^0_1 \). The search focuses on final states where at least one Higgs boson decays into a pair of hadronically decaying \( \tau \)-leptons. This allows the acceptance and thus the sensitivity to be significantly improved relative to the previous results at low masses of the \( \tilde{\chi}^0_2 \), where bottom-squark masses up to 850 GeV are excluded at the 95% confidence level, assuming a mass difference of 130 GeV between \( \tilde{\chi}^0_2 \) and \( \tilde{\chi}^0_1 \). Model-independent upper limits are also set on the cross section of processes beyond the Standard Model.

DOI: 10.1103/PhysRevD.104.032014

I. INTRODUCTION

Although the Standard Model (SM) of particle physics is a very successful theory, it does not provide a natural explanation for the large hierarchy between the energy scale of electroweak interactions and the Planck scale related to the gravitational interaction, nor does it have a viable candidate particle for dark matter, and it does not include a quantum description of gravity. Supersymmetry (SUSY) [1–6] is a theoretical framework that extends the SM by introducing partner states for the known particles, where the partners have the same quantum numbers as the respective SM particles but differ in spin by half a unit. This leads to new loop corrections to the Higgs boson mass that cancel out those involving SM particles, thereby solving the hierarchy problem [7–10]. When conservation of R-parity [11] is assumed, the lightest supersymmetric particle is stable and would be a viable candidate for dark matter if it is weakly interacting [12,13]. However, SUSY must be broken symmetry in order to allow the supersymmetric particles to be heavier than their SM partners and evade detection so far. Naturalness arguments [14,15] support the assumption that the partner states of the third-generation quarks, the top squarks, and the bottom squarks \( \tilde{b} \) should be light and thus have relatively large production cross sections. They might even be the only strongly produced supersymmetric states within the current mass reach of the LHC.

This paper presents a search for pair production of bottom squarks \( \tilde{b} \) that decay via the second-lightest neutralino \( \tilde{\chi}^0_2 \) to the lightest neutralino \( \tilde{\chi}^0_1 \). The neutralinos \( \tilde{\chi}^0_{1,2,3,4} \) together with the charginos \( \tilde{\chi}^\pm_{1,2} \) are mixtures of the partner states of the electroweak gauge bosons (bino and winos) and Higgs bosons (Higgsinos). The simplified model [16–18] of production and decay of supersymmetric particles considered in this search is shown in Fig. 1. It is inspired by the minimal supersymmetric Standard Model [19,20] in scenarios where the branching ratio \( B(\tilde{\chi}^0_2 \to h\tilde{\chi}^0_1) \) is enhanced, e.g., when the \( \tilde{\chi}^0_1 \) is binolike and the \( \tilde{\chi}^0_2 \) a wino-Higgsino mixture. The branching ratio \( B(\tilde{b} \to b\tilde{\chi}^0_2) \) is large compared to that of the direct decay \( B(\tilde{b} \to b\tilde{\chi}^0_1) \), which is studied elsewhere [21], when the mixture of the bottom squark is such that it is mostly the superpartner of the left-chiral bottom quark, the \( \tilde{\chi}^0_1 \) is mostly bino, and the \( \tilde{\chi}^0_2 \) mostly wino. A wino- or Higgsino-like \( \tilde{\chi}^0_2 \) will be accompanied by a \( \tilde{\chi}^\pm_1 \), which allows the decay \( \tilde{b} \to b\tilde{\chi}^\pm_1 \). This decay mode is relevant if the mass difference between the bottom squark and the

*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by SCOAP3.
The signal model illustrated in Fig. 1 yields a final state with two bottom quarks, two Higgs bosons, and missing transverse momentum from the two \( \tilde{\chi}_1^0 \) particles that escape the detector without interacting. This analysis selects a final state with a pair of \( \tau \)-leptons arising from the decay of one of the Higgs bosons, such that it complements a previous ATLAS search [22], which focuses on final states with multiple \( b \)-jets. This particular decay mode of the Higgs boson has never been exploited by a bottom-squark search until now. The neutrinos from the \( \tau \)-lepton decays provide a source of missing transverse momentum in addition to the pair of \( \tilde{\chi}_1^0 \). This increases the acceptance of the search in the region of parameter space where the \( \tilde{\chi}_2^0 \) is relatively light and the \( \tilde{\chi}_1^0 \) moderately boosted, where the previous ATLAS analysis has limited sensitivity. The same simplified model has been employed by the CMS Collaboration in a search targeting sensitivity. The same simplified model has been employed in the ATLAS analysis has limited acceptance of the search in the region of parameter space. 

The paper is structured as follows. After this introduction, Sec. II briefly describes the ATLAS detector, and Sec. III presents the dataset and simulated event samples. The reconstruction of physics objects is described in Sec. IV, and the signal selection and analysis discriminants are detailed in Sec. V. The procedures to derive the background estimate are explained in Sec. VI, followed by a summary of the systematic uncertainties in Sec. VII. Section VIII presents the results from the analysis and their interpretation, and conclusions are given in Sec. IX.

II. ATLAS DETECTOR

The ATLAS experiment [24–26] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4\( \pi \) coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range |\( \eta \)| < 2.5. It consists of silicon pixel, silicon microstrip, and transition radiation detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range (|\( \eta \)| < 1.7). The end cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to |\( \eta \)| = 4.9. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. A two-level trigger system is used to select events. The level-1 trigger is implemented in hardware and uses information from the calorimeters and the muon spectrometer to accept events at a maximum rate of 100 kHz. This is followed by a software-based high-level trigger (HLT) that reduces the event rate to 1 kHz on average depending on the data-taking conditions.

III. DATA AND SIMULATED EVENT SAMPLES

The dataset used in this analysis consists of proton-proton collision data collected with the ATLAS detector during the second run of the LHC from 2015 to 2018 at a center-of-mass energy of \( \sqrt{s} = 13 \) TeV and with a minimum separation of 25 ns between consecutive crossings of proton bunches from the two beams. After applying data-quality requirements that ensure that all detector subsystems were operational, the total integrated luminosity of this data sample is 139 fb\(^{-1}\) with an uncertainty of 1.7%.

\(^1\)ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the \( z \)-axis along the beam pipe. The \( x \)-axis points from the IP to the center of the LHC ring, and the \( y \)-axis points upward. Cylindrical coordinates \( (r, \phi) \) are used in the transverse plane, \( \phi \) being the azimuthal angle around the \( z \)-axis. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = - \ln \tan(\theta/2) \). Angular distance is measured in units of \( \Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \).
The SUSY signal and SM background processes are modeled with Monte Carlo (MC) simulations, except for the multijet background, which is estimated from data. The modeling of the two dominant SM background processes, namely top-quark production and production of $Z$ bosons with decays into $\tau$-leptons ($Z(\tau\tau)$), was improved by normalizing their contributions to data as described in Sec. VI. Simulated samples were produced using the ATLAS simulation infrastructure [29] with either a full simulation of the ATLAS detector in GEANT4 [30], or a faster variant that relies on a parametrized response of the calorimeters [31]. The latter was only used for the simulation of bottom-squark signals and to evaluate systematic uncertainties associated with generator modeling. The effect of multiple interactions in the same and neighboring bunch crossings (pileup) was modeled by overlaying the hard-scattering event with simulated inelastic $pp$ collisions generated with PYTHIA8.186 [32] using the NNPDF2.3LO set of parton distribution functions (PDFs) [33] and the A3 set of tuned parameters (tune) [34]. Simulated event samples were weighted to reproduce the distribution of the number of pileup interactions observed in the data. For all simulated samples except those generated with SHERPA [35], the Evt Gen [36] program was used to simulate the decays of bottom and charm hadrons.

The production of $t\bar{t}$ events was modeled using the POWHEG BOXv2 generator [37–40] at next-to-leading order (NLO) in QCD with the NNPDF3.0NLO PDF set [41] and the $h_{\text{damp}}$ parameter$^2$ set to 1.5$m_{\text{top}}$ [42]. Parton showering, hadronization, and the underlying event were modeled with PYTHIA8.230 [43], using the A14 tune [44] and the NNPDF2.3LO PDF set. The $t\bar{t}$ sample was normalized to the cross-section prediction at next-to-next-to-leading order (NNLO) in QCD, including the resummation of next-to-next-to-leading-logarithmic (NNLL) soft-gluon terms calculated using TOP++2.0 [45–51].

The production of a top quark in association with a $W$ boson was modeled using the POWHEG BOXv2 generator [38–40,52] at NLO in QCD using the five-flavor scheme. Single-top-quark production in the $t$-channel was modeled using the POWHEG BOXv2 generator [38–40,53] at NLO in QCD using the four-flavor scheme. The $s$-channel production was modeled using the POWHEG BOXv2 generator [38–40,54] at NLO in QCD in the five-flavor scheme. For all three channels, the NNPDF3.0NLO PDF set was used for the matrix elements calculation. The events were interfaced with PYTHIA8.230 using the A14 tune and the NNPDF2.3LO PDF set.

Production of top-quark pairs in association with a $W$, $Z$, or Higgs boson (collectively denoted by $t\bar{t}X$) was modeled using the MadGraph5_aMC@NLOv2.3 generator [55] at NLO in QCD with NNPDF3.0NLO PDFs. The events were interfaced to PYTHIA8.210 using the A14 tune and the NNPDF2.3LO PDF set.

The production of $V + j$ets ($V = W, Z$) was simulated with the SHERPA2.2.1 generator [35] using NLO matrix elements for up to two jets, and leading-order (LO) matrix elements for up to four jets calculated with the COMIX [56] and OpenLoops libraries [57,58]. They were matched with the SHERPA parton showers [59] using the MEPS@NLO prescription [60–63] and the tune developed by the SHERPA authors. The NNPDF3.0NNLO PDF set [41] was used and the samples were normalized to a NNLO prediction [64].

The SUSY signal samples were generated with MadGraph5_aMC@NLOv2.2.3 [55] using NNPDF2.3LO PDFs, and the modeling of the parton showering, hadronization, and underlying event was performed with PYTHIA8.210 with the A14 tune. The LO matrix elements include the emission of up to two additional partons. The matching between parton showers and matrix elements was done with the CKKW-L prescription [65,66], with a matching scale set to one quarter of the mass of the bottom squark. Signal samples were generated with bottom-squark masses $m(\tilde{b})$ ranging from 250 to 1000 GeV, and masses of the second-lightest neutralino $m(\tilde{\chi}_2^0)$ between 131 and 380 GeV. Signal cross sections were calculated to approximate NNLO in QCD, adding the resummation of soft-gluon emission at NNLL accuracy [67–74]. The nominal cross sections and their uncertainties were derived using the PDF4LHC15_mc PDF set, following the recommendations of Ref. [75], and decrease from $24.8 \pm 1.6$ pb at $m(\tilde{b}) = 250$ GeV to $14.5 \pm 1.5$ fb at $m(\tilde{b}) = 900$ GeV.

**IV. EVENT RECONSTRUCTION**

In this section, the reconstruction of the analysis objects from the detector data is described. The search presented in this paper is based on events which have $b$-jets, hadronically decaying $\tau$-leptons, and large missing transverse momentum in the final state. In addition to these, selections are used where $\tau$-leptons are substituted with muons to improve the background model.

Inner-detector tracks with $p_T > 500$ MeV are used to reconstruct primary vertices [76]. If several vertex candidates are found, the one with the largest sum of the squared transverse momenta of associated tracks $\sum p_T^2$ is treated as the hard-scattering vertex.

An anti-$k_t$ clustering algorithm [77,78] with a radius parameter of $R = 0.4$ is used to reconstruct jet candidates in...
the calorimeter. Jets are built from massless positive-energy topological clusters [79] of calorimeter cells containing energy above a noise threshold, measured at the electromagnetic energy scale. The jet candidates are calibrated using jet energy scale (JES) corrections derived from data and simulation [80]. A global sequential calibration procedure is applied to improve the jet energy resolution (JER). Jets with $p_T > 20$ GeV and $|\eta| < 2.8$ are selected, and a set of quality criteria are applied to reject jets not originating from $p p$ collisions [81]. To suppress jets frompileup interactions, a jet-vertex-tagging algorithm [82] is employed for jets with $p_T < 120$ GeV and $|\eta| < 2.5$. Jets containing $b$-hadrons are tagged as $b$-jets using a boosted decision tree (BDT) algorithm that exploits the impact parameters of tracks within the jet as well as secondary vertex information [83,84]. The optimal working point for this analysis has an efficiency of 77%, with an additional soft term including all tracks from the primary vertex that are not associated with a reconstructed object [92]. The magnitude of $p_T^{\text{miss}}$ is denoted by $E_T^{\text{miss}}$.

An overlap-removal procedure is performed after event reconstruction to resolve ambiguities when a single physical object is reconstructed as multiple final-state objects. If two electrons share the same track, the electron with lower transverse momentum is discarded. Any $\tau$-leptons overlapping with an electron or a muon within $\Delta R_{\tau-e} \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$ are removed. If an electron and a muon share the same inner-detector track, the muon is removed if it is tagged as a minimum-ionizing particle in the calorimeter, otherwise the electron is discarded. If a jet overlaps with an electron or a muon candidate within $\Delta R_{\tau} < 0.2$, the jet is removed. An exception is when a jet that has more than two associated tracks overlaps with a muon within $\Delta R_{\tau} < 0.2$, in which case the jet is kept and the muon is discarded. Finally, electron and muon candidates lying $0.2 < \Delta R_{\tau} < 0.4$ from a jet and jets within $\Delta R_{\tau} = 0.2$ of a $\tau$-lepton candidate are discarded.

The same reconstruction and identification algorithms are used for both data and simulation. Dedicated correction factors are applied to jet, $\tau$-lepton, electron, and muon candidates to account for differences in efficiencies and energy calibrations between data and simulation.

### V. EVENT SELECTION

All selections used in this analysis require events to pass an $E_T^{\text{miss}}$ trigger [93] or a combined $E_T^{\text{miss}} + b$-jet trigger [94], except for specific selections used for the background.

---

3The transverse impact parameter is defined as the distance of closest approach in the transverse plane between a track and the beam line. The longitudinal impact parameter corresponds to the $z$-coordinate distance between the point along the track at which the transverse impact parameter is defined and the primary vertex.
estimate which rely on single-muon or single-jet triggers as described in Sec. VI. The \( b \)-jet and muon objects reconstructed by the trigger algorithms are required to geometrically match the corresponding reconstructed analysis objects defined in Sec. IV, otherwise the event is discarded.

The HLT threshold of the \( E_T^{\text{miss}} \) trigger increased from 70 to 110 GeV over the data-taking period. The \( E_T^{\text{miss}} + b \)-jet trigger had HLT thresholds of 60 GeV on \( E_T^{\text{miss}} \) and 80 GeV on the transverse momentum of the \( b \)-jet, and the efficiency of the online \( b \)-jet identification algorithm determined for simulated \( t \bar{t} \) events was 60% in 2016 and 50% in 2017 and 2018. This trigger increases the acceptance for low-\( E_T^{\text{miss}} \) signals expected from low-mass bottom squarks. The dataset associated with the \( E_T^{\text{miss}} + b \)-jet trigger has a reduced integrated luminosity of 127 fb\(^{-1}\) because this trigger was not active in 2015, and stricter data-quality requirements are applied to \( b \)-jet triggers in 2016 and 2017 to ensure a valid beam-spot determination.

Events are rejected if no primary vertex with at least two tracks is found or if they contain a jet failing to meet the loose quality criteria described in Ref. [81]. Furthermore, events are rejected if they contain muons with a large track-curvature uncertainty or muons which are likely to originate from cosmic rays as indicated by a large displacement from the primary vertex.

Events are required to have at least three jets, among which at least two must be \( b \)-tagged unless stated otherwise. The leading and subleading jets are required to have \( p_T > 140 \text{ GeV} \) and \( p_T > 100 \text{ GeV} \), respectively, and the leading \( b \)-jet is required to have \( p_T > 100 \text{ GeV} \). The \( E_T^{\text{miss}} \) requirement depends on the trigger considered: the \( E_T^{\text{miss}} + b \)-jet trigger reaches maximum efficiency for \( E_T^{\text{miss}} > 160 \text{ GeV} \), while the \( E_T^{\text{miss}} \) trigger requires \( E_T^{\text{miss}} > 200 \text{ GeV} \) to be fully efficient.

To suppress the multijet background, events are vetoed if the angular separation in the transverse plane \( \Delta \phi (\text{jet}_1, \text{jet}_2, \vec{p}_T^{\text{miss}}) \) between one of the two leading jets and \( \vec{p}_T^{\text{miss}} \) is less than 0.5. All analysis selections require the presence of at least one \( \tau \)-lepton or one muon in the event. This common preselection is summarized in Table I. In the

| \( N_{\tau} + N_{\mu} \) | \( \geq 1 \) |
| \( N_{\text{jets}} \) | \( \geq 3 \) |
| \( p_T (\text{jet}_1) \) | \( > 140 \text{ GeV} \) |
| \( p_T (\text{jet}_2) \) | \( > 100 \text{ GeV} \) |
| \( \Delta \phi (\text{jet}_1, \text{jet}_2, \vec{p}_T^{\text{miss}}) \) | \( > 0.5 \) |
| \( N_{b\text{-jet}} \) | \( \geq 2 \) |
| \( p_T (b\text{-jet}) \) | \( > 100 \text{ GeV} \) |
| \( \text{Trigger} \) | \( E_T^{\text{miss}} + b\text{-jet} \) OR \( E_T^{\text{miss}} > 160 \text{ GeV} \) OR \( E_T^{\text{miss}} > 200 \text{ GeV} \) |

The \( \Theta_{\text{min}} \) requirement

| \( \Theta_{\text{min}} \) | \( > 0.6 \) |

The \( m_{T2} \) variable is computed as

\[
m_{T2} = \min \left( \max \left[ m_T(\vec{p}_T^{\tau_1}, \vec{p}_T^{\tau_2}), m_T(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) \right] \right),
\]

Following, the number of objects in an event is generically written as \( N_{\text{object}} \), and indices “1” and “2” refer to the leading and subleading objects, respectively, which are ordered by decreasing transverse momentum.

On top of the preselection from Table I, a set of signal regions (SRs) are defined in order to target the bottom-squark signal processes illustrated in Fig. 1. All SRs require at least two hadronically decaying \( \tau \)-leptons with opposite electric charge (referred to as the OS criterion) and no muon to be present.

Additional kinematic selections are applied to suppress the SM background. These selections are described in the following and summarized in Table II. They are optimized by maximizing the signal significance [95] in the previously nonexcluded parameter space of the targeted signal model.

To ensure compatibility with a Higgs boson decay, the visible invariant mass of the two leading \( \tau \)-leptons must satisfy \( 55 \text{ GeV} < m(\tau_1, \tau_2) < 120 \text{ GeV} \). The lower bound suppresses the \( Z(\tau \tau) \) background, while the upper bound reduces “nonresonant” background contributions where the \( \tau \)-leptons do not originate from the same resonance. Events are required to have \( H_T > 1100 \text{ GeV} \), where \( H_T = \sum p_T^\tau + \sum p_T^\mu + \sum p_T^{\text{jet}} \) is the scalar sum of the transverse momenta of all \( \tau \)-leptons, muons, and jets in the event. This variable exploits the fact that signals with large bottom-squark masses are expected to produce highly boosted particles in the final state.

The transverse mass variable [96,97] denoted \( m_{T2} \) is used to discriminate between the signal process and the top-quark production background. It is designed to have an end point for background processes such as top-quark production where the two \( \tau \)-leptons originate from separate decay branches. For the signal process, the two \( \tau \)-leptons originate from a resonant Higgs boson decay, and the \( m_{T2} \) spectrum has a pronounced tail toward larger values. The \( m_{T2} \) variable is computed as

\[
m_{T2} = \min \left( \max \left[ m_T(\vec{p}_T^{\tau_1}, \vec{p}_T^{\tau_2}), m_T(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) \right] \right),
\]

The following, the number of objects in an event is generically written as \( N_{\text{object}} \), and indices “1” and “2” refer to the leading and subleading objects, respectively, which are ordered by decreasing transverse momentum.

On top of the preselection from Table I, a set of signal regions (SRs) are defined in order to target the bottom-squark signal processes illustrated in Fig. 1. All SRs require at least two hadronically decaying \( \tau \)-leptons with opposite electric charge (referred to as the OS criterion) and no muon to be present.

Additional kinematic selections are applied to suppress the SM background. These selections are described in the following and summarized in Table II. They are optimized by maximizing the signal significance [95] in the previously nonexcluded parameter space of the targeted signal model.

To ensure compatibility with a Higgs boson decay, the visible invariant mass of the two leading \( \tau \)-leptons must satisfy \( 55 \text{ GeV} < m(\tau_1, \tau_2) < 120 \text{ GeV} \). The lower bound suppresses the \( Z(\tau \tau) \) background, while the upper bound reduces “nonresonant” background contributions where the \( \tau \)-leptons do not originate from the same resonance. Events are required to have \( H_T > 1100 \text{ GeV} \), where \( H_T = \sum p_T^\tau + \sum p_T^\mu + \sum p_T^{\text{jet}} \) is the scalar sum of the transverse momenta of all \( \tau \)-leptons, muons, and jets in the event. This variable exploits the fact that signals with large bottom-squark masses are expected to produce highly boosted particles in the final state.

The transverse mass variable [96,97] denoted \( m_{T2} \) is used to discriminate between the signal process and the top-quark production background. It is designed to have an end point for background processes such as top-quark production where the two \( \tau \)-leptons originate from separate decay branches. For the signal process, the two \( \tau \)-leptons originate from a resonant Higgs boson decay, and the \( m_{T2} \) spectrum has a pronounced tail toward larger values. The \( m_{T2} \) variable is computed as

\[
m_{T2} = \min \left( \max \left[ m_T(\vec{p}_T^{\tau_1}, \vec{p}_T^{\tau_2}), m_T(\vec{p}_T^{\mu_1}, \vec{p}_T^{\mu_2}) \right] \right),
\]
where $\vec{p}_T^{\tau}\tau$ correspond to the transverse momenta of the two leading $\tau$-leptons, and $(a, b)$ refers to two invisible particles assumed to be produced with transverse momentum $p_T^{\text{inv}}$. The masses of the invisible particles are free parameters and set to $m_a = m_b = m_{\text{inv}}$. The transverse mass $m_T$ is defined as $m_T^2(\vec{p}_T^\tau/\vec{p}_T^\tau) = m_T^2(\vec{p}_T^\tau - \vec{p}_T^{\tau}) + 2(p_T^{\tau})^2(p_T^{\tau} - \vec{p}_T^{\tau})$, where the $\tau$-lepton mass is set to 0 GeV. The $m_{T2}$ distribution peaks at 0 GeV for both the bottom-squark signal and the dominant $t\bar{t}$ background when setting $m_{\text{inv}}$ to 0 GeV, providing poor discrimination. The discrimination improves as $m_{\text{inv}}$ is increased, and a value of 120 GeV is found to result in an $m_{T2}$ distribution that best separates the signal from the background. All SRs require $m_{T2} > 140$ GeV.

Some of the control regions (CRs) also make use of the transverse mass of a $\tau$-lepton, which is computed as $(m_T^\tau)^2 = 2(p_T^{\tau} - \vec{p}_T^{\tau})^2$.

The last discriminant is $\Theta_{\min}$ defined as the smallest three-dimensional angle of the four combinations between either of the two leading $\tau$-leptons and either of the two leading $b$-jets. For the $t\bar{t}$ background, the smallest angle is expected from configurations where the $t$-jet and the $\tau$-lepton originate from the same top-quark decay, resulting in relatively low values of $\Theta_{\min}$. For $Z(\tau\tau) + b\bar{b}$ events with a highly boosted $Z$ boson, the pair of $\tau$-leptons recoils against the $b$-jets, and large values of $\Theta_{\min}$ are expected. For signal events where $b \rightarrow b\chi^0_2 \rightarrow bh(\tau\tau)\chi^0_1$, the angle between the $b$-jet and the $\tau$-lepton pair increases with the $b$ mass, and so does $\Theta_{\min}$. A multibin SR with three $\Theta_{\min}$ bins $(<0.5, [0.5, 1.0], >1.0)$ is defined in order to take advantage of these features. A single-bin SR requiring $\Theta_{\min} > 0.6$ is used to provide cross-section limits on generic processes beyond the Standard Model (BSM). The probability for a signal event to enter the single-bin SR ranges between $6.4 \times 10^{-6}$ at $m(\tilde{b}) = 250$ GeV and $m(\tilde{\chi}^0_2) = 150$ GeV and $1.4 \times 10^{-3}$ at $m(\tilde{b}) = 900$ GeV and $m(\tilde{\chi}^0_2) = 150$ GeV, taking into account the Higgs boson and $\tau$-lepton branching ratios, the SR acceptance, and particle reconstruction and identification efficiencies.

The requirement responsible for the largest decrease in signal acceptance is the presence of two hadronically decaying $\tau$-leptons in the final state.

Examples of signal and background kinematic distributions are shown in Fig. 2. The three plots show the $H_T$, $m(t_1, t_2)$, and $m_{T2}$ variables after the preselection. The estimated SM background is scaled by the normalization factors from the background fit described in Sec. VI, and the distributions for several signal models are overlaid.

VI. BACKGROUND ESTIMATION

The largest backgrounds in the SRs are from $t\bar{t}$ and single-top-quark processes referred to as top-quark background, and $Z(\tau\tau)$ produced in association with $b$-jets. Subdominant contributions arise from $t\bar{t}X$ processes, while other backgrounds such as multijet or diboson and triboson production are found to be negligible. The normalization of the two dominant backgrounds is fitted to the data in dedicated CRs kinematically close to the SRs but where little signal is expected. The normalization factors are derived with a likelihood fit based on the HistFitter framework [98]. The fit uses as input the observed data yields, the expected yields predicted from simulation, as well as the statistical and systematic uncertainties described in Sec. VII. Two main fit setups are employed in the analysis. The background-only fit refers to the configuration that only includes the CRs, and where no signal is considered. The signal-plus-background fit includes both the CRs and the SRs, and it takes into account a possible signal

FIG. 2. Kinematic distributions of data and SM background for events that pass the preselection and have at least two hadronically decaying $\tau$-leptons. Predictions from three signal models are also shown, where the masses $m(\tilde{b})$ and $m(\tilde{\chi}^0_2)$ are given in GeV in the legend. Distributions are displayed for the (a) $H_T$, (b) $m(t_1, t_2)$, and (c) $m_{T2}$ variables. The hatched band indicates the total statistical and systematic uncertainty of the SM background. The “Other” contribution includes all the backgrounds not explicitly listed in the legend [$V + \text{jets}$ except $Z(\tau\tau) + \text{jets}$, diboson/triboson, multijet]. The top-quark and $Z(\tau\tau)$ background contributions are scaled with the normalization factors obtained from the background-only fit described in Sec. VI. The rightmost bin includes the overflow. The bottom panel shows the ratio of the observed data and the expected Standard Model background.
contribution in the fitted regions. It is used to establish exclusion limits as discussed in Sec. VIII. In both cases, the fit is performed simultaneously over all the relevant regions. Subdominant background contributions are normalized according to their cross sections and the integrated luminosity of the data. The multijet background is determined from data. Validation regions (VRs) are defined in phase-space regions as close as possible to that of the SRs. The VRs are not included in the fit. They are used to validate the background-model extrapolation from the CRs to the SRs by comparing the observed data with the fitted background predictions. As such, they are designed to have little signal contribution. The methods used to estimate the various backgrounds are described in the following, together with the associated CRs and VRs.

Multijet production is an important background at hadron colliders, but it is efficiently suppressed in this analysis by the requirement of two hadronically decaying τ-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.

The design of the control regions for the top-quark and $\tau\tau$ backgrounds is driven by two main considerations. First, the hadronically decaying τ-leptons selected in the analysis are either prompt τ-leptons from electromagnetically decaying $\tau$-leptons, two b-jets, large $E_T^{\text{miss}}$, and $\Delta\phi(\text{jet}_1, \text{jet}_2, \text{miss}^\tau) > 0.5$. A data-driven jet-smearing method [99] is employed to estimate this background. Events recorded by single-jet triggers are processed through an energy-smearing procedure that emulates $E_T^{\text{miss}}$ originating from resolution effects. The normalization of the smeared pseudodata template is derived in events where one of the two leading jets is aligned with $\text{miss}^\tau$ in the transverse plane. Except for that multijet-enriched selection, the multijet background is found to be negligible in all analysis selections. Therefore, its normalization is kept constant in the fits, for simplicity.
muon), the top-quark production yields are further multiplied by additional freely floating normalization factors $\omega_{1\mu}$ and $\omega_{1\mu}$, which are constrained mainly through the regions $\text{CR}_{\text{Top}}-\tau_{\text{true}}$ and $\text{CR}_{\text{Top}}-\mu$. A transfer factor $\text{TF}_{\text{Top}} \equiv \omega_{1\mu}/\omega_{1\mu}$ is used to correct for the difference between requiring a muon and a true $\tau$-lepton. This means that a simulated top-quark event with one true and one fake $\tau$-lepton in one of the signal regions receives a normalization factor $\omega_{\text{fake}} \times \text{TF}_{\text{Top}}$, and a simulated top-quark event with two true $\tau$-leptons a normalization factor $\omega_{\text{true}} \times \text{TF}_{\text{Top}}$.

Figure 4 shows several examples of distributions from the four control regions associated with the top-quark background. In these plots, the predicted background contributions from simulation are scaled with the normalization factors obtained from the background-only fit. All of the CRs show good agreement between the SM prediction and the data. They also have high purity in the respective top-quark background processes except for $\text{CR}_{\text{Top}}-\mu_{\text{fake}}$, where the purity is only 43% because it is difficult to isolate the contribution of the top-quark background with fake $\tau$-leptons.

The three control regions that target the $Z(\tau\tau)$ background are summarized in Table IV. The $\text{CR}_{Z}\tau\mu2b$ selection is defined using events with two muons of opposite electric charge, taken as proxies for two true $\tau$-leptons, and two $b$-jets. Since $Z(\mu\mu)$ + jets processes do not have large $E_{T}^{\text{miss}}$ in the final state, the events are selected using a single-muon trigger, which has its efficiency plateau at $p_{T}(\mu) > 30$ GeV. The invariant mass of the dimuon system is required to be within 10 GeV of the Z-boson mass, and $E_{T}^{\text{miss}}$ to be lower than 100 GeV to increase the purity of the selection. To move the CR closer to the relevant phase space, $H_{T}$ must be in the range [600, 1000] GeV, and the transverse momentum of the muon pair $p_{T}(\mu_{1}, \mu_{2})$ must be larger than 200 GeV, which is a typical value found in simulation for the $p_{T}$ of the Z boson in $Z(\tau\tau)$ events after the preselection. The $Z(\mu\mu)$ background is multiplied by the freely floating normalization factor $\omega_{Z\mu\mu2b}$, which is constrained through $\text{CR}_{Z}\mu\mu2b$.

The two additional control regions $\text{CR}_{Z}\mu\mu0b$ and $\text{CR}_{Z}\tau0b$ are used to correct for the difference in acceptance and efficiency when replacing the $\tau$-leptons with muons to estimate the $Z +$ jets background. The interplay of these CRs is illustrated in Fig. 3(b). The $\text{CR}_{Z}\mu\mu0b$ selection is the same as for $\text{CR}_{Z}\mu\mu2b$ but with a $b$-jet veto, whereas $\text{CR}_{Z}\tau0b$ requires the presence of two $\tau$-leptons with opposite electric charge and no $b$-jet. The $\text{CR}_{Z}\tau0b$ events are selected with an $E_{T}^{\text{miss}}$ trigger and $E_{T}^{\text{miss}} > 200$ GeV as is done for the SRs, and muons are vetoed in this region. Additionally, the sum of $\tau$-lepton transverse masses $m_{\tau1} + m_{\tau2}$ has to be lower than 100 GeV to increase the purity in $Z(\tau\tau)$ events. In all of these three CRs, $H_{T}$ is again required to be within [600, 1000] GeV.

From these two auxiliary control regions, the freely floating normalization factor $\omega_{Z\mu\mu0b}$ and transfer factor $\text{TF}_{Z} \equiv \omega_{Z\tau0b}/\omega_{Z\mu\mu0b}$ are derived in the background fit. The background normalization in $\text{CR}_{Z}\mu\mu0b$ is absorbed into $\omega_{Z\mu\mu0b}$. The transfer factor $\text{TF}_{Z}$ transfers the

**TABLE III.** Definition of the control regions used for the top-quark background. The requirements are applied in addition to the preselection. Three center dots mean that no requirement on this variable is applied.

<table>
<thead>
<tr>
<th>$N_{\mu}$</th>
<th>$N_{\tau}$</th>
<th>$\text{OS}(\mu, \tau)$</th>
<th>$H_{T}$</th>
<th>$m_{T}^{\tau}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>&lt;600 GeV</td>
<td>&lt;80 GeV</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>&lt;1000 GeV</td>
<td>&gt;100 GeV</td>
</tr>
</tbody>
</table>

**FIG. 3.** Schematic representation of the control region setup that is used to constrain the normalization of the (a) top-quark and (b) $Z(\tau\tau)$ + jets backgrounds in the signal regions. The arrows represent the transfer factors associated with the replacement of muons with true $\tau$-leptons, which correct for acceptance. For the top-quark background, the sketch illustrates the normalization strategy for the $\tau_{\text{true}}\tau_{\text{true}}$ contribution. A similar strategy is employed for the $\tau_{\text{true}}\tau_{\text{fake}}$ contribution, where the $\tau_{\text{fake}}$ can originate from a jet from a hadronically decaying W boson, a $b$-jet, or a jet from initial-state radiation.
normalization from \( CR_{\text{Z}\mu\tau} \) to \( CR_{\text{Z}\tau\tau} \), and from \( CR_{\text{Z}\mu\tau} \) to the SRs; \( Z(\tau\tau) + b\bar{b} \) events in the SRs are scaled by \( \omega_{\text{Z}\mu\tau} \cdot T_{FZ} \).

All normalization and transfer factors are obtained from a simultaneous fit of the seven CRs for the top-quark and \( Z(\tau\tau) \) backgrounds. Table V lists the values of the normalization factors and transfer factors and their uncertainties, the names of the control regions that determine the normalization factors, and the respective purities of the control regions in top-quark or \( Z + \text{jets} \) events. The transfer factors \( T_{F\text{Top}} \) and \( T_{FZ} \) are computed from ratios of two normalization factors as explained above. For these, one row in the table \( (\omega_{\text{Top}} \text{ and } \omega_{\text{Z}\mu\tau}) \) gives the values forming the respective denominators of the ratios, showing how well the data and simulated events agree in these regions. The row below gives the transfer factor \( (T_{F\text{Top}} \text{ and } T_{FZ}, \text{respectively}) \). In these rows, the table lists the second control region (the numerator of the ratio) and its purity.
TABLE IV. Definition of the control regions used for the $Z + $ jets background. The requirements are applied in addition to the set of preselection criteria reported in the upper part of Table I. Three center dots mean that no requirement on this variable is applied.

<table>
<thead>
<tr>
<th>CR $Z_{\mu\mu}$2b</th>
<th>CR $Z_{\mu\mu}$0b</th>
<th>CR $Z_{\tau\tau}$0b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>Single muon</td>
<td>$E_{\text{miss}}^T$</td>
</tr>
<tr>
<td>$N_{\mu}$</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>$N_{\tau}$</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>$N_{b\text{-jets}}$</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>$p_T(\mu_1)$</td>
<td>$&gt;30$ GeV</td>
<td>$&lt;200$ GeV</td>
</tr>
<tr>
<td>$E_{\text{miss}}^T$</td>
<td>$&lt;100$ GeV</td>
<td>$&gt;200$ GeV</td>
</tr>
<tr>
<td>$m(\mu_1,\mu_2)$</td>
<td>[81, 101] GeV</td>
<td>$&lt;100$ GeV</td>
</tr>
<tr>
<td>$m_{\tau_1}^2 + m_{\tau_2}^2$</td>
<td>$&lt;100$ GeV</td>
<td></td>
</tr>
<tr>
<td>$H_T$</td>
<td>[600, 1000] GeV</td>
<td></td>
</tr>
</tbody>
</table>

Three validation regions are defined to check the extrapolation from CR_{Top,\mu\tau_{true}}, CR_{Top,\mu\tau_{fake}}, and CR $Z_{\mu\mu}$2b in the $H_T$ variable. This is done by changing the requirement on $H_T$ that is applied in the CRs from 600 GeV $< H_T < 1000$ GeV to 1000 GeV $< H_T < 1500$ GeV in the VRs, while keeping all other requirements the same as for the respective CRs. Shifting the $H_T$ range moves the validation regions closer to the signal regions, which require $H_T > 1100$ GeV. The VRs and the SRs are mutually exclusive due to the muon veto that is part of the signal-region selections. The names of the three VRs match those of the corresponding CRs. A fourth validation region VR_{Top,\tau\tau} is defined to validate the extrapolation from muons to $\tau$-leptons in events with two $b$-jets and two hadronically decaying $\tau$-leptons which pass the $E_{\text{miss}}^T$ trigger or the $E_{\text{miss}}^T + b$-jet trigger and the corresponding trigger-plauate requirements. To avoid overlap of this VR with the SRs, $H_T$ is required to be within [600,1000] GeV. In addition, the visible di-$\tau$ mass $m(\tau_1,\tau_2)$ is required to be either lower than 40 GeV or larger than 90 GeV to reduce the contribution from a possible bottom-squark signal.

Figure 5 shows that the expected background yields after the fit and the observed yields agree within 1 standard deviation for all four validation regions, demonstrating good modeling of the SM background. Figure 6 shows various kinematic distributions in the validation regions. Good agreement between the background model and the data is observed in VR $Z_{\mu\mu}$2b, VR_{Top,\mu\tau_{true}}, and VR_{Top,\tau\tau}. In VR_{Top,\mu\tau_{true}}, the modeling of kinematic distributions is reasonable. The contribution of a potential signal from the model in Fig. 1 to the control regions does not exceed 7% at the low end of the range of bottom-squark masses covered by the signal models and quickly falls to below a percent at the high end. For the validation regions it is around 15% for low $m(\tilde{b})$ and again falls to a percent or less for larger $m(\tilde{b})$.

VII. SYSTEMATIC UNCERTAINTIES

The experimental uncertainties considered in this analysis comprise systematic uncertainties in the reconstruction, identification, calibration, and corrections applied to the physical objects used in the analysis. They are assumed to be correlated across analysis regions and between the background processes and the signal. Theoretical uncertainties include contributions from generator modeling as well as cross-section uncertainties. They are assumed to be correlated across analysis regions but uncorrelated between different background processes. When assuming no correlation between analysis regions, the total background uncertainty increases by about 5 percentage points for the single-bin SR, and the exclusion contour does not change significantly.

The experimental uncertainties related to jets include uncertainties in the energy scale [80] and resolution [100], jet-vertex-tagging uncertainties [82], and flavor-tagging uncertainties [83,101,102]. Flavor-related uncertainties come from the uncertainties in data-to-simulation correction factors for efficiencies and fake rates and from the extrapolation over jet $p_T$. The $\tau$-lepton uncertainties arise

TABLE V. Values of normalization and transfer factors with their statistical and systematic uncertainties as obtained from the background-only fit, in the top part of the table for top-quark background processes, and in the bottom part for $Z + $ jets. The control regions that primarily affect the normalization factors are listed, together with the purity of the CR in the relevant background process. As TF_{Top} and TF_{Z} are ratios of two normalization factors, one of which (the denominator) is listed in the row directly above, the table lists the respective second control region (the numerator of the ratio) and its purity in top-quark or $Z(\tau\tau) + bb$ events.

<table>
<thead>
<tr>
<th>Normalization/transfer factor</th>
<th>Fitted value</th>
<th>Control region</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{\tau_{true}}$</td>
<td>0.88 ± 0.16</td>
<td>CR_{Top,\mu\tau_{true}}</td>
<td>86%</td>
</tr>
<tr>
<td>$\omega_{\tau_{fake}}$</td>
<td>0.79 ± 0.30</td>
<td>CR_{Top,\mu\tau_{fake}}</td>
<td>53%</td>
</tr>
<tr>
<td>$\omega_{\mu}$</td>
<td>0.91 ± 0.10</td>
<td>CR_{Top,\mu}</td>
<td>43%</td>
</tr>
<tr>
<td>$\omega_{Z_{\mu\mu}}$</td>
<td>0.98 ± 0.04</td>
<td>CR_{Top,\mu\tau_{true}}</td>
<td>94%</td>
</tr>
<tr>
<td>$\omega_{Z_{\tau\tau}}$</td>
<td>1.28 ± 0.12</td>
<td>CR $Z_{\mu\mu}$2b</td>
<td>88%</td>
</tr>
<tr>
<td>$\omega_{Z_{\tau\tau}0b}$</td>
<td>1.00 ± 0.05</td>
<td>CR $Z_{\mu\mu}$0b</td>
<td>89%</td>
</tr>
<tr>
<td>$\omega_{Z_{\tau\tau}0b}$</td>
<td>0.99 ± 0.17</td>
<td>CR $Z_{\tau\tau}$0b</td>
<td>96%</td>
</tr>
</tbody>
</table>

032014-10
The variations are normalized to the nominal sum of weights so that the effect on the normalization included in the cross-section uncertainty is not double-counted. For all simulated processes that are not normalized to the data, uncertainties in the cross section and in the integrated luminosity of the data are applied.

For $t\bar{t}$ and single-top-quark production, generator uncertainties related to hard scattering and matching are evaluated by comparing POWHEG BOX+PYTHIA with MadGraph5_aMC@NLO+PYTHIA. Parton-showering uncertainties are estimated by comparison with POWHEG BOX +HERWIG7. Uncertainties in the initial-state and final-state radiation are evaluated by simultaneously testing the impact of scale variations and eigenvariations of the A14 tune [44]. For $t\bar{t}$ production, an additional comparison with the $h_{\text{damp}}$ parameter set to $3m_{\text{top}}$ is included. For single-top-quark production, an uncertainty in the treatment of the $Wt/\bar{t}\bar{t}$ interference is considered by comparing samples produced with the nominal diagram-removal scheme [104] with alternative samples generated with a diagram-subtraction scheme [42,104].

For the $V+$jets processes, additional uncertainties related to the resummation and CKKW matching scales [62,63] are considered. For the $Z(\mu\mu)+$jets and $Z(\tau\tau)+$jets backgrounds, the nominal SHERPA samples are compared with alternative samples produced with MadGraph5_aMC@NLO+PYTHIA. For diboson and $t\bar{t}X$ samples, the PDF, scale, and cross-section uncertainties are used.

For the bottom-squark signal samples, uncertainties in the acceptance related to the factorization and renormalization scales, merging scales, parton shower tuning, and radiation uncertainties are considered. An additional uncertainty accounts for differences between samples produced with the full detector simulation and the parametrized calorimeter response.

A summary of the dominant systematic uncertainties in the background prediction for the signal regions is given in Table VI. The largest source of uncertainty is the generator modeling, and here in particular the modeling of the top-quark background, mainly the modeling of the hard-scatter process and initial state radiation uncertainties. Second leading in size is the total uncertainty in the normalization and transfer factors, which is obtained from the fit. As the transfer factors are ratios of normalization factors, and a large part of the uncertainties cancel out in the ratio, the uncertainties in the transfer factors are comparatively small.

**VIII. RESULTS**

The event yields for all signal regions are reported in Table VII. The SM background prediction is based on the background-only fit described in Sec. VI. To illustrate the order of magnitude of the contribution of signal events, the expected yields for three benchmark signal models are included in the table. The single-bin SR and the first two
bins of the multibin SR are dominated by top-quark production, whereas for $\Theta_{\text{min}} > 1.0$ the $Z(\tau\tau)$ background is the largest contribution. Other SM processes contribute very little to the signal regions. Figure 7 shows a comparison of data and background yields in the SRs together with the corresponding significances quantifying the deviation of the observed yields from the SM expectation in the bottom panel. No significant excess of data

| Uncertainty                         | Single-bin SR | $\Theta_{\text{min}} < 0.5$ | $0.5 < \Theta_{\text{min}} < 1.0$ | $\Theta_{\text{min}} > 1.0$
|------------------------------------|---------------|-----------------------------|------------------------------------|-----------------------------
| Generator modeling                 | 37%           | 42%                         | 44%                                | 27%                         |
| Normalization / transfer factors   | 15%           | 11%                         | 12%                                | 18%                         |
| JER and JES                        | 12%           | 5.1%                        | 9.8%                               | 22%                         |
| $\tau$-leptons                     | 8.3%          | 3.5%                        | 2.3%                               | 15%                         |
| MC statistical uncertainty         | 6.9%          | 6.8%                        | 7.2%                               | 11%                         |
| Flavor tagging                     | 3.8%          | 1.0%                        | 1.8%                               | 5.4%                         |
| Other                              | 2.9%          | 1.3%                        | 1.8%                               | 6.6%                         |
| Total                              | 40%           | 43%                         | 46%                                | 41%                         |
TABLE VII. The observed event yields in data, the total expected yields from SM processes obtained from the background-only fit and breakdown of individual contributions, and the expected signal contributions for three benchmark models are shown for the single-bin
signal region and the three bins of the multibin signal region. Total uncertainties combining the statistical and systematic uncertainties
are quoted for the background processes. For the signal, the quoted uncertainties are only statistical. “Other” combines all SM
background contributions that are not listed explicitly, covering $V + $jets except for $Z(\tau \tau) + $jets, multijet, diboson,
and triboson contributions. The three center dots mean that no events pass the selection.

<table>
<thead>
<tr>
<th></th>
<th>Single-bin SR</th>
<th></th>
<th>Multibin SR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Theta_{\text{min}} &lt; 0.5$</td>
<td>$0.5 &lt; \Theta_{\text{min}} &lt; 1.0$</td>
<td>$\Theta_{\text{min}} &gt; 1.0$</td>
<td></td>
</tr>
<tr>
<td>Observed events</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Total SM background</td>
<td>3.8 $\pm$ 1.5</td>
<td>2.7 $\pm$ 1.1</td>
<td>3.5 $\pm$ 1.6</td>
<td>1.5 $\pm$ 0.6</td>
</tr>
<tr>
<td>Top quark $\tau_{\text{true}}$</td>
<td>1.4 $\pm$ 0.9</td>
<td>1.6 $\pm$ 0.7</td>
<td>1.9 $\pm$ 1.0</td>
<td>0.30 $^{+0.41}_{-0.30}$</td>
</tr>
<tr>
<td>Top quark $\tau_{\text{fake}}$</td>
<td>0.92 $\pm$ 0.62</td>
<td>0.76 $\pm$ 0.43</td>
<td>0.96 $\pm$ 0.69</td>
<td>0.22 $\pm$ 0.17</td>
</tr>
<tr>
<td>Top quark $\tau_{\text{fake}}$</td>
<td>0.11 $^{+0.26}_{-0.11}$</td>
<td>0.06 $\pm$ 0.06</td>
<td>0.12 $^{+0.23}_{-0.12}$</td>
<td>0.04 $^{+0.05}_{-0.04}$</td>
</tr>
<tr>
<td>$t\bar{t}X$</td>
<td>0.52 $\pm$ 0.42</td>
<td>0.18 $\pm$ 0.10</td>
<td>0.26 $^{+0.31}_{-0.26}$</td>
<td>0.31 $\pm$ 0.22</td>
</tr>
<tr>
<td>$Z(\tau \tau) + $jets</td>
<td>0.73 $\pm$ 0.25</td>
<td>0.05 $\pm$ 0.05</td>
<td>0.17 $\pm$ 0.16</td>
<td>0.59 $\pm$ 0.22</td>
</tr>
<tr>
<td>Other</td>
<td>0.07 $\pm$ 0.04</td>
<td>...</td>
<td>0.04 $\pm$ 0.01</td>
<td>0.06 $\pm$ 0.03</td>
</tr>
<tr>
<td>$m(\tilde{b}, \tilde{\chi}^0_2) = (800, 131) $GeV</td>
<td>5.6 $\pm$ 1.4</td>
<td>0.14 $\pm$ 0.06</td>
<td>1.5 $\pm$ 0.4</td>
<td>4.3 $\pm$ 1.1</td>
</tr>
<tr>
<td>$m(\tilde{b}, \tilde{\chi}^0_2) = (800, 180) $GeV</td>
<td>9.3 $\pm$ 2.2</td>
<td>0.08 $^{+0.14}_{-0.08}$</td>
<td>2.4 $\pm$ 0.6</td>
<td>7.1 $\pm$ 1.7</td>
</tr>
<tr>
<td>$m(\tilde{b}, \tilde{\chi}^0_2) = (350, 280) $GeV</td>
<td>6.4 $\pm$ 2.1</td>
<td>2.7 $\pm$ 0.9</td>
<td>4.1 $\pm$ 1.3</td>
<td>4.8 $\pm$ 1.8</td>
</tr>
</tbody>
</table>

above the expected yields from the SM background
processes is observed in any of the signal regions. The
$p$-value for the event yield in the single-bin signal region to fluctuate to at least the observed value under the background-only hypothesis is $p(s = 0) = 0.44$.

Exclusion contours at the 95% confidence level (C.L.)
are derived from the yields in the multibin signal region for
the two-dimensional parameter space of $m(\tilde{b})$ and $m(\tilde{\chi}^0_2)$ in
the simplified model from Fig. 1. A fixed mass difference
of 130 GeV between the second-lightest neutralino $\tilde{\chi}^0_2$ and
lightest neutralino $\tilde{\chi}^0_1$ is assumed for all signal models. The
probabilities that the data are compatible with the background-only and signal-plus-background hypotheses are evaluated using a one-sided profile-likelihood-ratio test statistic and the CL$_s$ prescription [105]. The computations
rely on asymptotic properties of the profile-likelihood ratio

FIG. 7. Comparison of the expected and observed event yields in
the signal regions defined in Table II. The top-quark and $Z(\tau \tau)$
background contributions are scaled with the normalization
factors obtained from the background-only fit. The “Other”
contribution includes all the backgrounds not explicitly listed
in the legend [$V + $jets except $Z(\tau \tau) + $jets, diboson/multijet]. The hatched band indicates the total statistic
and systematic uncertainty of the SM background. The contributions
from three signal models to the signal regions are also displayed,
where the masses $m(\tilde{b})$ and $m(\tilde{\chi}^0_2)$ are given in GeV in the legend.
The lower panel shows the significance of the deviation of the
observed yield from the expected background yield.

FIG. 8. Exclusion contours at the 95% C.L. as a function of
$m(\tilde{b})$ and $m(\tilde{\chi}^0_2)$, assuming $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) = 130$ GeV. Observed
and expected limits are shown for the present search that requires
hadronically decaying $\tau$-leptons, $b$-jets, and $E_{\text{T}}^{\text{miss}}$ in the final state. The observed exclusion limit from a previous ATLAS
search [22] that requires $b$-jets and $E_{\text{T}}^{\text{miss}}$ in the final state is also
displayed. The region $m(\tilde{b}) < 400$ GeV is excluded by a
previous search from CMS [23].
but it stays within the uncertainty band of the expected inward from the expected contour with increasing yield is larger than the expected total background in the around the observed limit contour. Since the observed data

\[ \sigma \]

for the visible cross section

\[ \text{profile-likelihood-ratio test statistic} \]

is evaluated using SR, assuming no signal contribution in the CRs. The performed simultaneously over the CRs and the single-bin approach can be used to search for a \( \tilde{b} \) signal, and a single-bin signal region is employed for a model-independent statistical interpretation. The data observed in the signal regions are compatible with the expected Standard Model background. Exclusion limits are placed on the bottom-squark mass at the 95% confidence level. For \( m(\tilde{b}) \) ranging from 130 to 180 GeV, bottom-squark masses below 775 to 850 GeV are excluded. This extends significantly beyond the reach of a previous ATLAS search\[22\], which was performed in final states with \( \tilde{b} \)-jets and large \( E_T^{\text{miss}} \), in this challenging region of parameter space.

**TABLE VIII.** Upper limits at 95% C.L. on the visible cross section \( \sigma_{\text{vis}} \), on the number of signal events \( S_{\text{obs}}^{95} \), and on the number of signal events given the expected number (and \( \pm 1\sigma \) excursions of the expectation) of background events \( S_{\text{exp}}^{95} \). The last two columns indicate the \( \text{CL}_b \) value, i.e., the confidence level observed for the background-only hypothesis, the discovery \( p\)-value \([p(s = 0)]\), and its associated significance \( Z \).

<table>
<thead>
<tr>
<th>Signal region</th>
<th>( \sigma_{\text{vis}} ) (fb)</th>
<th>( S_{\text{obs}}^{95} )</th>
<th>( S_{\text{exp}}^{95} )</th>
<th>( \text{CL}_b )</th>
<th>( p(s = 0) ) (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-bin SR</td>
<td>0.05</td>
<td>6.6</td>
<td>( 6.0^{+2.3}_{-1.6} )</td>
<td>0.62</td>
<td>0.34 (0.41)</td>
</tr>
</tbody>
</table>

[95]. Systematic uncertainties are treated as nuisance parameters with Gaussian probability densities in the likelihood function. The resulting observed and expected exclusion contours are shown in Fig. 8. The uncertainties in the cross section of the supersymmetric signal are not included in the fit but shown as an uncertainty band around the observed limit contour. Since the observed data yield is larger than the expected total background in the highest \( \Theta_{\text{min}} \) bin, which is most sensitive to models with large \( m(\tilde{b}) \), the observed exclusion contour deviates inward from the expected contour with increasing \( m(\tilde{b}) \), but it stays within the uncertainty band of the expected limit. The search is optimized for the low-\( m(\tilde{\chi}^0_2) \) region and has sensitivity to models with \( m(\tilde{\chi}^0_2) \) up to 300 GeV. Bottom squarks with masses up to 850 GeV are excluded in this region. For \( m(\tilde{\chi}^0_2) \) below about 200 GeV, the softer \( E_T^{\text{miss}} \) spectrum of the signal results in a lower acceptance, leading to a slightly reduced exclusion reach in bottom-squark mass. The parameter-space region where \( \Delta m(\tilde{b}, \tilde{\chi}^0_2) < 20 \text{ GeV} \) cannot be excluded as the bottom-squark decay products are not boosted enough, and the stringent kinematic requirements in the SRs result in low signal acceptance. These results are overlaid on the observed exclusion contour from a previous ATLAS search\[22\] to demonstrate the complementarity of the two approaches. The new results have unique sensitivity to a previously uncovered region of parameter space at low \( \tilde{\chi}^0_2 \) masses, where the previous search quickly loses sensitivity.

The results from the single-bin signal region can be interpreted in terms of model-independent upper limits on the event yields from potential BSM processes. The fit is performed simultaneously over the CRs and the single-bin SR, assuming no signal contribution in the CRs. The profile-likelihood-ratio test statistic is evaluated using pseudexperiments. An upper limit of 0.05 fb is derived for the visible cross section \( \sigma_{\text{vis}} \) defined as the product of the cross section, acceptance, and selection efficiency of such processes. In addition, Table VIII summarizes the expected and observed 95% C.L. upper limits on the number of BSM events, as well as the confidence level of the background-only hypothesis \( \text{CL}_b \). The \( p\)-value and the corresponding significance for the background-only hypothesis to fluctuate to at least the observed values are also included.

**IX. CONCLUSION**

A search for bottom-squark pairs in events with \( b\)-jets, hadronically decaying \( \tau\)-leptons, and large missing transverse momentum is presented. A simplified SUSY model assuming \( \tilde{b} \rightarrow b\tilde{\chi}^0_1 \rightarrow bh\nu_\tau \) is considered, where at least one Higgs boson decays into a pair of \( \tau\)-leptons. This analysis has unique sensitivity at low \( \tilde{\chi}^0_2 \) masses due to the presence of hadronically decaying \( \tau\)-leptons, which mitigates the Standard Model background, and to the associated \( \nu_\tau\)-neutrinos that add to the \( E_T^{\text{miss}} \) originating from the \( \tilde{\chi}^0_1 \). A multibin signal region exploiting angular correlations between the \( b\)-jets and the hadronically decaying \( \tau\)-leptons is used to search for a \( \tilde{b} \) signal, and a single-bin signal region is employed for a model-independent statistical interpretation. The data observed in the signal regions are compatible with the expected Standard Model background. Exclusion limits are placed on the bottom-squark mass at the 95% confidence level. For \( m(\tilde{\chi}^0_2) \) ranging from 130 to 180 GeV, bottom-squark masses below 775 to 850 GeV are excluded. This extends significantly beyond the reach of a previous ATLAS search\[22\], which was performed in final states with \( b\)-jets and large \( E_T^{\text{miss}} \), in this challenging region of parameter space.

**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; ANID, Chile; CAS, MOST, and NSFC, China; Minciencias, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IFRF, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC and Hong Kong SAR, China; ISF 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; JINR; MES of Russia and NRC KI, Russian Federation; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; SNSC and MICST, Thailand; TUBITAK and TÜBİTAK, Turkey; STFC, the United Kingdom; DOE and NSF, United States; and all the other funding agencies and funding sources not mentioned individually above.
Investissements d'Avenir Labex, Investissements d’Avenir Exppériment, Innovation and Public Health, INRS, and the Groupe de Recherche en Physique des Hautes Energies (GRPhyHE, Canada; BCKDF, CANARIE, Compute Canada, CRC, and IVADO, Canada; Beijing Municipal Science & Technology Commission, China; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex, and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales, and Aristoteia programs co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya, and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; 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. [106].


G. Aad$^{102}$ B. Abbott$^{128}$ D. C. Abbott$^{103}$ A. Abid Abd$^{36}$ K. Abeless$^{53}$ D. K. Abhayasinghe$^{94}$ S. H. Abidi$^{167}$ O. S. AbouZeid$^{40}$ N. L. Abraham$^{156}$ H. Abramowicz$^{161}$ H. Abreu$^{160}$ Y. Abulaiti$^{6}$ B. S. Acharya$^{57}$ S. Batlamous$^{35}$ J. R. Batley$^{32}$ B. Batool$^{151}$ M. Battaglia$^{145}$ M. Bauce$^{73}$ F. Bauer$^{144}$ T. Barklow$^{153}$ R. Barnea$^{160}$ B. M. Barnett$^{143}$ R. M. Barnett$^{18}$ Z. Barnovska-Blenessy$^{60}$ A. Baroncelli$^{60}$ G. Barone$^{29}$ L. Beresford$^{134}$ M. Beretta$^{134}$ M. Bellgardt$^{9}$ A. S. Bell$^{95}$ G. Bella$^{161}$ L. Bellagamba$^{23}$ A. Bellerive$^{34}$ P. Bellos$^{9}$ K. Beloborodov$^{122}$ K. Belotskiy$^{112}$ N. L. Belyaev$^{112}$ D. Benckhroun$^{35}$ N. Benekos$^{10}$ Y. Benhammou$^{161}$ D. P. Benjamin$^{26}$ M. Benoit$^{39}$ J. R. Bensinger$^{26}$ S. Bentvelsen$^{120}$ L. Beresford$^{134}$ M. Beretta$^{51}$ D. Barge$^{19}$ E. Bergeaas Kuutmann$^{172}$ N. Berger$^{5}$ B. Bergmann$^{141}$
(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton AB, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5LAPP, Univ. 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
13Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
14Faculty of Physics, Bogazici University, Istanbul, Turkey
15Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
16Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
17Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
18Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
19Physics Department, Tsinghua University, Beijing, China
20Institute of Physics, University of Belgrade, Belgrade, Serbia
21School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
SEARCH FOR BOTTOM-SQUARK PAIR PRODUCTION IN PP ...

PHYS. REV. D 104, 032014 (2021)

22a Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia  
22b Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia, Colombia  
22c INFN Bologna and Università di Bologna, Dipartimento di Fisica, Italy  
22d INFN Sezione di Bologna, Italy  
24 Physikalisches Institut, Universität Bonn, Bonn, Germany  
25 Department of Physics, Boston University, Boston, Massachusetts, USA  
26 Department of Physics, Brandeis University, Waltham, Massachusetts, USA  
27a Transilvania University of Brasov, Brasov, Romania  
27b Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania  
27c Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania  
27d National Institute for Research and Development of Isotopic and Molecular Technologies,  
   Physics Department, Cluj-Napoca, Romania  
27e University Politehnica Bucharest, Bucharest, Romania  
27f West University in Timisoara, Timisoara, Romania  
28a Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic  
28b Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences,  
   Kosice, Slovak Republic  
29 Physics Department, Brookhaven National Laboratory, Upton, New York, USA  
30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina  
31 California State University, California, USA  
32 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom  
33a Department of Physics, University of Cape Town, Cape Town, South Africa  
33b iThemba Labs, Western Cape, South Africa  
33c Department of Mechanical Engineering Science, University of Johannesburg,  
   Johannesburg, South Africa  
33d National Institute of Physics, University of the Philippines Diliman, Philippines  
33e University of South Africa, Department of Physics, Pretoria, South Africa  
33f School of Physics, University of the Witwatersrand, Johannesburg, South Africa  
34 Department of Physics, Carleton University, Ottawa ON, Canada  
35a Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université  
   Hassan II, Casablanca, Morocco  
35b Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco  
35c Moroccan Foundation for Advanced Science Innovation and Research (MAscIR), Rabat, Morocco  
35d LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco  
35e Faculté des sciences, Université Mohammed V, Rabat, Morocco  
35f CERN, Geneva, Switzerland  
37 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA  
38 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France  
39 Nevis Laboratory, Columbia University, Irvington, New York, USA  
40 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark  
41 Dipartimento di Fisica, Università della Calabria, Rende, Italy  
41b INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy  
42 Physics Department, Southern Methodist University, Dallas, Texas, USA  
43 Physics Department, University of Texas at Dallas, Richardson, Texas, USA  
44 National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece  
45a Department of Physics, Stockholm University, Sweden  
45b Oskar Klein Centre, Stockholm, Sweden  
46 Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany  
47 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany  
48 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany  
49 Department of Physics, Duke University, Durham, North Carolina, USA  
50 SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom  
51 INFN e Laboratori Nazionali di Frascati, Frascati, Italy  
52 Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany  
53 Il. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany  
54 Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland  
55a Dipartimento di Fisica, Università di Genova, Genova, Italy  
55b INFN Sezione di Genova, Italy  
56 II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
<table>
<thead>
<tr>
<th>Code</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>Physics Department, Lancaster University, Lancaster, United Kingdom</td>
</tr>
<tr>
<td>91</td>
<td>Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom</td>
</tr>
<tr>
<td>92</td>
<td>Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia</td>
</tr>
<tr>
<td>93</td>
<td>School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom</td>
</tr>
<tr>
<td>94</td>
<td>Department of Physics, Royal Holloway University of London, Egham, United Kingdom</td>
</tr>
<tr>
<td>95</td>
<td>Department of Physics and Astronomy, University College London, London, United Kingdom</td>
</tr>
<tr>
<td>96</td>
<td>Louisiana Tech University, Ruston, Louisiana, USA</td>
</tr>
<tr>
<td>97</td>
<td>Fysiska institutionen, Lunds universitet, Lund, Sweden</td>
</tr>
<tr>
<td>98</td>
<td>Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France</td>
</tr>
<tr>
<td>99</td>
<td>Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain</td>
</tr>
<tr>
<td>100</td>
<td>Institut für Physik, Universität Mainz, Mainz, Germany</td>
</tr>
<tr>
<td>101</td>
<td>School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom</td>
</tr>
<tr>
<td>102</td>
<td>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France</td>
</tr>
<tr>
<td>103</td>
<td>Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA</td>
</tr>
<tr>
<td>104</td>
<td>Department of Physics, McGill University, Montreal QC, Canada</td>
</tr>
<tr>
<td>105</td>
<td>School of Physics, University of Melbourne, Victoria, Australia</td>
</tr>
<tr>
<td>106</td>
<td>Department of Physics, University of Michigan, Ann Arbor, Michigan, USA</td>
</tr>
<tr>
<td>107</td>
<td>Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA</td>
</tr>
<tr>
<td>108</td>
<td>B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus</td>
</tr>
<tr>
<td>109</td>
<td>Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus</td>
</tr>
<tr>
<td>110</td>
<td>Group of Particle Physics, University of Montreal, Montreal QC, Canada</td>
</tr>
<tr>
<td>111</td>
<td>P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia</td>
</tr>
<tr>
<td>112</td>
<td>National Research Nuclear University MEPhI, Moscow, Russia</td>
</tr>
<tr>
<td>113</td>
<td>D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia</td>
</tr>
<tr>
<td>114</td>
<td>Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany</td>
</tr>
<tr>
<td>115</td>
<td>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany</td>
</tr>
<tr>
<td>116</td>
<td>Nagasaki Institute of Applied Science, Nagasaki, Japan</td>
</tr>
<tr>
<td>117</td>
<td>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan</td>
</tr>
<tr>
<td>118</td>
<td>Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA</td>
</tr>
<tr>
<td>119</td>
<td>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands</td>
</tr>
<tr>
<td>120</td>
<td>Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands</td>
</tr>
<tr>
<td>121</td>
<td>Department of Physics, Northern Illinois University, DeKalb, Illinois, USA</td>
</tr>
<tr>
<td>122</td>
<td>Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia</td>
</tr>
<tr>
<td>122b</td>
<td>Novosibirsk State University Novosibirsk, Russia</td>
</tr>
<tr>
<td>123</td>
<td>Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia</td>
</tr>
<tr>
<td>124</td>
<td>Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre “Kurchatov Institute”, Moscow, Russia</td>
</tr>
<tr>
<td>125</td>
<td>Department of Physics, New York University, New York, New York, USA</td>
</tr>
<tr>
<td>125a</td>
<td>Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan</td>
</tr>
<tr>
<td>126</td>
<td>The Ohio State University, Columbus, Ohio, USA</td>
</tr>
<tr>
<td>127</td>
<td>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA</td>
</tr>
<tr>
<td>128</td>
<td>Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA</td>
</tr>
<tr>
<td>129</td>
<td>Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic</td>
</tr>
<tr>
<td>130</td>
<td>Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA</td>
</tr>
<tr>
<td>131</td>
<td>Graduate School of Science, Osaka University, Osaka, Japan</td>
</tr>
<tr>
<td>132</td>
<td>Department of Physics, University of Oslo, Oslo, Norway</td>
</tr>
<tr>
<td>133</td>
<td>Department of Physics, Oxford University, Oxford, United Kingdom</td>
</tr>
<tr>
<td>134</td>
<td>LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France</td>
</tr>
<tr>
<td>135</td>
<td>Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA</td>
</tr>
<tr>
<td>136</td>
<td>Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia</td>
</tr>
<tr>
<td>137</td>
<td>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA</td>
</tr>
<tr>
<td>138</td>
<td>Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal</td>
</tr>
<tr>
<td>139</td>
<td>Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal</td>
</tr>
<tr>
<td>140</td>
<td>Departamento de Física, Universidade de Coimbra, Coimbra, Portugal</td>
</tr>
</tbody>
</table>
Deceased.

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

Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.

Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain.

Also at TRIUMF, Vancouver BC, Canada.

Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

Also at Physics Department, An-Najah National University, Nablus, Palestinian Authority.

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

Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.

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

Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), 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, New York, USA.

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

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

Also at Centro Studi e Ricerche Enrico Fermi, Italy.

Also at Department of Physics, California State University, East Bay, USA.

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

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

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

Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.

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

Also at CERN, Geneva, Switzerland.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Hellenic Open University, Patras, Greece.

Also at Center for High Energy Physics, Peking University, China.

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

Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy.

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

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

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

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

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

Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

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 and Astronomy, Michigan State University, East Lansing, Michigan, USA.