Search for $B-L$ $R$-parity-violating top squarks in $\sqrt{s}=13$ TeV $pp$ collisions with the ATLAS experiment

M. Aaboud et al.*
(ATLAS Collaboration)

(Received 16 October 2017; published 6 February 2018)

A search is presented for the direct pair production of the stop, the supersymmetric partner of the top quark, that decays through an $R$-parity-violating coupling to a final state with two leptons and two jets, at least one of which is identified as a $b$-jet. The data set corresponds to an integrated luminosity of 36.1 fb$^{-1}$ of proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV, collected in 2015 and 2016 by the ATLAS detector at the LHC. No significant excess is observed over the Standard Model background, and exclusion limits are set on stop pair production at a 95% confidence level. Lower limits on the stop mass are set between 600 GeV and 1.5 TeV for branching ratios above 10% for decays to an electron or muon and a $b$-quark.

DOI: 10.1103/PhysRevD.97.032003

I. INTRODUCTION

The extension of the Standard Model (SM) of particle physics with supersymmetry (SUSY) [1–6] leads to processes that violate both baryon number ($B$) and lepton number ($L$), such as rapid proton decay. A common theoretical approach to reconcile the strong constraints from the nonobservation of these processes is to introduce a multiplicative quantum number called $R$-parity [7], defined as $R = (-1)^{3B-2L+n}$ where $n$ is the spin of the particle. If $R$-parity is conserved, then SUSY particles are produced in pairs, and the lightest supersymmetric particle (LSP) is stable. The LSP cannot carry electric charge or color charge without coming into conflict with astrophysical data [8,9].

A number of theoretical models beyond the Standard Model (BSM) predict $R$-parity violation (RPV) [10–13]. The benchmark model for this search considers an additional local symmetry $U(1)_{B-L}$ to the $SU(3)_C \times SU(2)_L \times U(1)_Y$ Standard Model with right-handed neutrino supermultiplets. The minimal supersymmetric extension then only needs a vacuum expectation value for a right-handed scalar neutrino in order to spontaneously break the $B-L$ symmetry [14–18]. This minimal $B-L$ model violates lepton number but not baryon number. The couplings for RPV are highly suppressed as they are related to the neutrino masses, and the model is consistent with the experimental bounds on proton decay and lepton number violation. At the LHC, the most noticeable effect is that the LSP is no longer stable and can now decay via RPV processes, and it also may now carry color and electric charge. This leads to unique signatures that are forbidden in conventional models with $R$-parity conservation. A novel possibility is a top squark or stop ($\tilde{t}$) as the LSP with a rapid RPV decay. The supersymmetric partners of the left- and right-handed top quarks, $\tilde{t}_L$ and $\tilde{t}_R$, mix to form two mass eigenstates consisting of the lighter $\tilde{t}_1$ and heavier $\tilde{t}_2$. Given the large top quark mass, the lighter $\tilde{t}_1$ is expected to be significantly lighter than the other squarks due to renormalization group effects [19,20]. The lighter $\tilde{t}_1$, denoted $\tilde{t}$ for simplicity, is the target of this analysis.

This paper presents a search performed by ATLAS for direct stop pair production, with the RPV decay of each $\tilde{t}$ to a $b$-quark and a charged lepton ($\tilde{t} \rightarrow b\ell^\pm$), as shown in Fig. 1. In contrast to $R$-parity-conserving searches for $\tilde{t}$, there is no significant missing transverse momentum in 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.

FIG. 1. Feynman diagram for stop pair production, with $\tilde{t}$ and anti-$\tilde{t}(\tilde{t}^\ast)$ decay to a charged lepton of any flavor and a $b$-quark through an $R$-parity-violating coupling $\lambda'$. 
decay. The $t$ decay branching ratios to each lepton flavor are related to the neutrino mass hierarchy \cite{21,22}, and a large phase space in the branching ratio plane is currently available. With an inverted mass hierarchy, the branching ratio to the $be$ final state may be as large as 100%, and with a normal mass hierarchy the branching ratio to the $b\mu$ final state may be as high as 90%. The experimental signature is therefore two oppositely charged leptons of any flavor and two $b$-jets. In this analysis, only events with electron or muon signatures are selected, and final states are split by flavor into $ee$, $e\mu$, and $\mu\mu$ selections. At least one of the two jets is required to be identified as initiated by a $b$-quark, improving the selection efficiency of signal events over a requirement of two $b$-jets. Events are chosen in which the two reconstructed $b\ell$ pairs have roughly equal mass.

Previous searches with similar final states have targeted the pair production of first-, second-, and third-generation leptoquarks at ATLAS \cite{23,24} and at CMS \cite{25,26}. However, they consider final states within the same generation ($eejj$, $\mu\mu jj$, $ttbb$, where $j$ indicates a light-flavor jet) and do not focus on final states with both electrons or muons ($e\mu\mu$, $\mu\mu\mu$), nor consider final states with both electrons and muons ($\mu\mu\mu$). The results of the Run 1 leptoquark searches were reinterpreted for the mass and its decay branching ratios in the $B\to L$ model \cite{21,22}, setting lower mass limits between 424 and 900 GeV at a 95% confidence level.

The ATLAS detector and the data set collected during Run 2 of the LHC are described in Sec. II, with the corresponding Monte Carlo simulation samples presented in Sec. III. The identification and reconstruction of jets and leptons is presented in Sec. IV, and the discriminating variables used to construct the signal regions are described in Sec. V. The method of background estimation is described in Sec. VI, and the systematic uncertainties are detailed in Sec. VII. The results are presented in Sec. VIII, and the conclusions are given in Sec. IX.

II. ATLAS DETECTOR AND DATA SET

The ATLAS detector \cite{27} consists of an inner detector tracking system, electromagnetic and hadronic sampling calorimeters, and a muon spectrometer. Charged-particle tracks are reconstructed in the inner detector (ID), which spans the pseudorapidity range $|\eta| < 2.5$, and consists of three subdetectors: a silicon pixel tracker, a silicon microstrip tracker, and a straw-tube transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing an axial magnetic field of 2 T, allowing the measurement of charged-particle momenta. In preparation for Run 2, a new innermost layer of the silicon pixel tracker, the insertable B-layer (IBL) \cite{28}, was introduced at a radial distance of 3.3 cm from the beam line to improve track reconstruction and the identification of jets initiated by $b$-quarks.

The ATLAS calorimeter system consists of high-granularity electromagnetic and hadronic sampling calorimeters covering the region $|\eta| < 4.9$. The electromagnetic calorimeter uses liquid argon (LAr) as the active material with lead absorbers in the region $|\eta| < 3.2$. The central hadronic calorimeter incorporates plastic scintillator tiles and steel absorbers in the region $|\eta| < 1.7$. The hadronic endcap calorimeter ($1.5 < |\eta| < 3.2$) and the forward calorimeters ($3.1 < |\eta| < 4.9$) use LAr with copper or tungsten absorbers.

The muon spectrometer (MS) surrounds the calorimeters and measures muon tracks within $|\eta| < 2.7$ using three layers of precision tracking chambers and dedicated trigger chambers. A system of three superconducting air-core toroidal magnets provides a magnetic field for measuring muon momenta.

The ATLAS trigger system begins with a hardware-based level-1 (L1) trigger followed by a software-based high-level trigger (HLT) \cite{29}. The L1 trigger is designed to accept events at an average rate of 100 kHz, and the HLT is designed to accept events to write out to disk at an average rate of 1 kHz. Electrons are triggered in the pseudorapidity range $|\eta| < 2.5$, where the electromagnetic calorimeter is finely segmented and track reconstruction is available. Compact electromagnetic energy deposits triggered at L1 are used as the seeds for HLT algorithms that are designed to identify electrons based on calorimeter and fast track reconstruction. The muon trigger at L1 is based on a coincidence of trigger chamber layers. The parameters of muon candidate tracks are then derived in the HLT by fast reconstruction algorithms in both the ID and MS.

The data sample used for this search was collected from proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV in 2015 and 2016. An integrated luminosity of 36.1 fb$^{-1}$ was collected while all tracking detectors, calorimeters, muon chambers, and magnets were fully operational. The uncertainty in the combined 2015 and 2016 integrated luminosity is 3.2%. It is derived from a preliminary calibration of the luminosity scale using $x$-$y$ beam-separation scans performed in August 2015 and May 2016, following a methodology similar to that detailed in Ref. \cite{30}. The LHC collided protons with bunch-crossing intervals of 25 ns, and the average number of interactions per bunch crossing was estimated to be $\langle \mu \rangle = 23.7$.

For this analysis, events are selected using single-electron and single-muon triggers requiring leptons above.
a transverse momentum \((p_T)\) threshold and satisfying various lepton identification and isolation criteria. The trigger-level criteria for the \(p_T\), identification, and isolation of the leptons are less stringent than those applied in the event selection to ensure that trigger efficiencies are constant in the analysis phase space.

III. MONTE CARLO SIMULATION

Monte Carlo (MC) simulation is used to predict the backgrounds from SM processes, estimate the detector response and efficiency to reconstruct the signal process, and estimate systematic uncertainties. The largest sources of SM background with different-flavor leptons are top quark pair production \((t\bar{t})\) and single-top-quark production \((t\bar{t})\), while the largest source with same-flavor leptons is \(Z + \text{jets}\) production. The yields of these three backgrounds are estimated through data-driven methods described in Sec. VI. The smaller backgrounds are estimated through Monte Carlo simulation tuned parameters (UE tune)\[42\], approximation through with additional radiation simulated to the leading-logarithm accuracy in perturbative QCD. The contribution from events with jets misreconstructed as leptons or with nonprompt leptons is evaluated with the MC simulation and is negligible. Details of the MC simulations are given below and are summarized in Table I.

The \(t\bar{t}\) and single-top processes were simulated\[37\] at next-to-leading-order (NLO) accuracy in perturbative QCD using the POWHEG-BOX v1 event generator\[38\] for \(t\bar{t}\), \(Wt\), and \(s\)-channel single-top production, and using the POWHEG-BOX v1 generator for the electroweak \(t\)-channel single-top production. For these processes the spin correlations in top quark production and decay were preserved, and the top quark mass was set to 172.5 GeV. The matrix element was interfaced with the CT10 parton distribution function (PDF) set\[39\], and the parton shower (PS), fragmentation, and underlying event were simulated with PYTHIA 6.428\[40\] using the CTEQ6L1 PDF set\[41\] and the T-ordered parton showers\[43\].

The \(Z + \text{jets}\) and \(W + \text{jets}\) samples were generated at NLO\[44\] with the SHERPA 2.2.1 event generator\[45\]. Matrix elements were calculated for up to two partons at NLO and four partons at LO using Comix\[46\] and OpenLoops\[47\], and merged with the SHERPA PS\[48\] using the ME + PS@NLO prescription\[49\]. The NNPDF3.0 PDF set\[50\] was used in conjunction with a dedicated SHERPA PS tuning developed by the SHERPA authors. Diboson samples with two, three, or four leptons were similarly generated with SHERPA 2.2.1. The diboson matrix elements contain all diagrams with four electroweak vertices, and were calculated for up to one (ZZ) or zero (WW, WZ) partons at NLO and up to three partons at LO. Electroweak- and loop-induced diboson events were simulated with SHERPA 2.1.1, using the same prescriptions as above but with the CT10 PDF set used in conjunction with the dedicated SHERPA PS tuning. The production of \(t\bar{t}\) with a \(W\) or \(Z\) boson (\(t\bar{t} + V\)) was simulated at NLO using MG5_AMC@NLO (MG5_AMC@NLO) 2.2.3\[51\] and interfaced to PYTHIA 8.212\[52\] with the CKKW-L prescription\[53\]. These samples are generated with the A14 UE tune\[54\] and NNPDF2.3 PDF set\[55\].

The RPV stop signal events were generated at leading order using the MG5_AMC@NLO 2.2.3 event generator with the NNPDF2.3 PDF set and interfaced to PYTHIA 8.186\[52\] using the A14 UE tune. The matrix element was matched to the PS using the CKKW-L prescription, with the matching scale set to one quarter of the generated stop mass. All other supersymmetric particles are assumed to be decoupled. The signal cross sections are calculated to NLO accuracy in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithm accuracy (NLO + NLL)\[56-59\]. The nominal cross section and the uncertainty for each mass value are taken from a combination of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in Ref.\[36\]. Stop samples were generated at masses between 600 and 1000 GeV in steps of 100 GeV and between 1000 and 1600 GeV in steps of 50 GeV. The cross section ranges from 175 ± 23 fb for a \(\tilde{t}\) mass of 600 GeV to 0.141 ± 0.038 fb for a mass of 1600 GeV. The generated stops decay promptly through \(\tilde{t} \rightarrow b\tilde{\chi}^0\) with a 1/3 branching ratio (\(\tilde{B}\)) for each lepton flavor. When optimizing the signal event selection, the generated events are reweighted to have

**TABLE I.** MC simulation details by physics process.

<table>
<thead>
<tr>
<th>Process</th>
<th>Event generator</th>
<th>PS and hadronization</th>
<th>UE tune</th>
<th>PDF</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t\bar{t}) single-top</td>
<td>POWHEG-Box v2</td>
<td>PYTHIA 6.428</td>
<td>P2012</td>
<td>CT10</td>
<td>NNLO + NNLL</td>
</tr>
<tr>
<td>((Wt) and (s)-channel)</td>
<td>POWHEG-Box v2</td>
<td>PYTHIA 6.428</td>
<td>P2012</td>
<td>CT10</td>
<td>NNLO + NNLL</td>
</tr>
<tr>
<td>((t)-channel)</td>
<td>POWHEG-Box v1</td>
<td>PYTHIA 6.428</td>
<td>P2012</td>
<td>CT10</td>
<td>NNLO + NNLL</td>
</tr>
<tr>
<td>(Z/W + \text{jets})</td>
<td>SHERPA 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>Default</td>
<td>NNPDF3.0</td>
<td>NNLO</td>
</tr>
<tr>
<td>Diboson</td>
<td>SHERPA 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>Default</td>
<td>NNPDF3.0</td>
<td>NLO</td>
</tr>
<tr>
<td>Diboson (EW/loop)</td>
<td>SHERPA 2.1.1</td>
<td>SHERPA 2.1.1</td>
<td>Default</td>
<td>CT10</td>
<td>NLO</td>
</tr>
<tr>
<td>(t\bar{t} + W/Z)</td>
<td>MG5_AMC@NLO 2.2.3</td>
<td>PYTHIA 8.212</td>
<td>A14</td>
<td>NNPDF2.3</td>
<td>NLO</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>MG5_AMC@NLO 2.2.3</td>
<td>PYTHIA 8.1868.186</td>
<td>A14</td>
<td>NNPDF2.3</td>
<td>NLO + NNLL</td>
</tr>
</tbody>
</table>
$B(\bar{t} \rightarrow b e) = B(\bar{t} \rightarrow b \mu) = 0.5$ and $B(\bar{t} \rightarrow b \tau) = 0$, and various weightings are used to derive limits for different branching ratio assumptions.

All background samples are normalized using the available NLO or next-to-next-to-leading order (NNLO) cross sections, as indicated in Table I. The modeling of c-hadron and b-hadron decays in samples generated with POWHEG-BOX or MG5_AMC@NLO was performed with EVTGEN 1.2.0 [60]. Generated events were propagated through a full simulation of the ATLAS detector [61] based on Geant4 [62], which describes the interactions of the particles with the detector. A parametrized simulation of the ATLAS calorimeter called Atlfast-II [61] was used for faster detector simulation of signal samples, and was found to agree well with the full simulation. Multiple overlapping $pp$ interactions (pileup) were included by overlaying simulated minimum-bias events onto the simulated hard-scatter event. Minimum-bias events were generated using PYTHIA 8.186 with the A2 UE tune [63] and MSTW2008LO PDF set [64]. The simulated events are weighted such that the distribution of the average number of $pp$ interactions per bunch crossing agrees with data.

IV. EVENT RECONSTRUCTION

Events and individual leptons and jets are required to satisfy several quality criteria to be considered by the analysis. Events recorded during stable beam and detector conditions are required to satisfy data-quality criteria [65]. Each event is required to have a primary reconstructed vertex with two or more associated tracks with $p_T > 400$ MeV, where the primary vertex is chosen as the vertex with the highest $\Sigma p_T^2$ of associated tracks. Two stages of quality and kinematic requirements are applied to leptons and jets. The looser baseline requirements are first applied, and baseline leptons and jets are used to resolve any misidentification or overlap between electrons, muons, and jets. The subsequent tighter signal requirements are then applied to identify high-quality leptons and jets in the kinematic phase space of interest.

Electron candidates are reconstructed from energy deposits in the electromagnetic calorimeter matched to a charged-particle track in the ID. Baseline electron candidates must have $p_T > 10$ GeV, $|\eta| < 2.47$, and satisfy a loose electron likelihood identification [66]. Signal electrons must pass the baseline electron selection, have $p_T > 40$ GeV, and satisfy a tight electron likelihood identification. In addition, they must be isolated from nearby activity, satisfying a loose $p_T$-dependent track-based criterion [67]. Finally, their trajectory must be consistent with the primary vertex, such that their impact parameter in the transverse plane ($d_0^{TV}$) satisfies $|d_0^{TV}|/\sigma_{d_0^{TV}} < 5$, where $\sigma_{d_0^{TV}}$ is the uncertainty in $d_0^{TV}$. Each signal electron must have a longitudinal impact parameter with respect to the primary vertex ($z_0^{PV}$) that satisfies $|z_0^{PV} \sin \theta| < 0.5$ mm.

Muon candidates are reconstructed by combining tracks in the ID with tracks in the MS. Baseline muon candidates must have $p_T > 10$ GeV, $|\eta| < 2.7$, and satisfy the medium muon identification criteria [68]. Signal muons must pass the baseline muon selection, have $p_T > 40$ GeV, $|\eta| < 2.5$, $|z_0^{PV} \sin \theta| < 0.5$ mm, and $|d_0^{PV}|/\sigma_{d_0^{PV}} < 3$. As with electrons, muons must satisfy the $p_T$-dependent loose track-based isolation criteria. Events containing a poorly measured signal muon, as determined by having incompatible momentum measurements in the ID and the MS, are rejected. Absolute requirements of $|z_0^{PV}| < 1$ mm and $|d_0^{PV}| < 0.2$ mm on the impact parameters of signal muons are applied to reject cosmic muons.

Jets are reconstructed using the anti-$k_t$ algorithm [69,70] with a radius parameter $R = 0.4$ from clusters of energy deposits in the calorimeters [71]. Jets are corrected for pileup contamination on an event-by-event basis using the jet area subtraction method [72,73]. Jets are further calibrated to account for the predicted detector response in MC simulation, and a residual calibration of jets in data is derived through in situ measurements [74]. Baseline jet candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.8$. Jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are required to satisfy pileup-rejection criteria based on charged-particle tracks and implemented through the jet vertex tagger algorithm [72]. Signal jets must pass the baseline jet selection and have $p_T > 60$ GeV. Events are rejected if they contain a jet that fails the loose quality criteria [75], reducing contamination from calorimeter noise bursts and noncollision backgrounds. Jets within $|\eta| < 2.5$ that are initiated by $b$-quarks are identified using the multivariate MV2c10 $b$-tagging algorithm [76,77], which exploits the impact parameters of charged-particle tracks, the parameters of reconstructed secondary vertices, and the topology of $b$- and c-hadron decays inside a jet. The working point is chosen to provide a $b$-tagging efficiency of $77\%$ per $b$-jet in simulated $t\bar{t}$ events with a rejection factor of approximately 130 for jets initiated by gluons or light-flavor quarks and 6 for jets initiated by c-quarks [77]. Correction factors are applied to events to compensate for differences between data and MC simulation in the $b$-tagging efficiency for $b$-jets, c-jets, and light-flavor jets.

To avoid reconstructing a single detector signature as multiple leptons or jets, an overlap removal procedure is performed on baseline leptons and jets. The requirements are applied sequentially, and failing particles are removed from consideration in the subsequent steps. If an electron and muon share a track in the ID, the electron is removed. Any jet that is not $b$-tagged and is within a distance $^{2}$ $\Delta R(\ell, \text{jet}) \leq 0.2$ of a lepton is removed. If the jet is

$\Delta R = \sqrt{\Delta \eta^2 + (\Delta \phi)^2}$, where $\Delta \eta$ is their distance in rapidity and $\Delta \phi$ is their azimuthal distance. The distance with respect to a jet is calculated from its central axis.

$^{2}$The distance between two four-momenta is defined as $\Delta R = \sqrt{\Delta \eta^2 + (\Delta \phi)^2}$, where $\Delta \eta$ is their distance in rapidity and $\Delta \phi$ is their azimuthal distance. The distance with respect to a jet is calculated from its central axis.
The trigger, reconstruction, identification, and isolation efficiencies of electrons [67] and muons [68] in MC simulation are corrected using events in data with leptonic \( Z \) and \( J/\psi \) decays. Similarly, corrections to the \( b \)-tagging efficiency and mis-tag rate in MC simulation are derived from various control regions in data [77].

V. EVENT SELECTION

To identify the pair production of stops, events are required to have at least two leptons and two jets. If more than two leptons or two jets are found, the two highest-\( p_T \)
leptons and jets are selected. At least one of the two leading jets must be $b$-tagged. The selected leptons are required to have opposite charge, and one of them must be consistent with the associated single-lepton trigger. This trigger requirement is highly efficient for signal events, with an efficiency of 93% for the $\mu\mu$ channel, 95% for the $e\mu$ channel, and 98% for the $ee$ channel.

The lepton-jet pair from each $\tilde{t}$ decay generally reconstructs the invariant mass $m_{\text{hf}}$ of the original $\tilde{t}$. In an event with two leptons and two jets, two pairings are possible; one that reconstructs the correct $\tilde{t}$ masses, and one which inverts the pairing and incorrectly reconstructs the masses. As the two masses should be roughly equal, the pairing that minimizes the mass asymmetry between $m_{\text{hf}}^0$ and $m_{\text{hf}}^1$ is chosen, defined as

$$m_{\text{asym}} = \frac{m_{\text{hf}}^0 - m_{\text{hf}}^1}{m_{\text{hf}}^0 + m_{\text{hf}}^1}.$$

Here $m_{\text{hf}}^0$ is chosen to be the larger of the two masses. Events are further selected to have small mass asymmetry $m_{\text{asym}}^0 < 0.2$. This reduces the contamination from background processes, whose random pairings lead to a more uniform $m_{\text{asym}}^0$ distribution.

Two nested signal regions (SRs) are constructed to optimize the identification of signal over background events. The signal regions are optimized using MC signal and background predictions, assuming $\tilde{t}$ decays of $B(\tilde{t} \to b\ell) = B(\tilde{t} \to b\mu) = 50\%$. A primary kinematic selection of the signal regions is on $m_{\text{hf}}^0$, with SR800 requiring $m_{\text{hf}}^0 > 800$ GeV and SR1100 requiring $m_{\text{hf}}^0 > 1100$ GeV. By defining two signal regions the sensitivity to high-mass signals above 1100 GeV is improved, while maintaining sensitivity to lower-mass signals. Several other kinematic selections, common to both SRs, are defined to reduce the contribution from the largest backgrounds. As the $\tilde{t}$ decay products are generally very energetic, a selection on their $p_T$ sum,

$$H_T = \sum_{i=1}^{2} p_{T\ell}^i + \sum_{j=1}^{2} p_{T\text{jet}}^j,$$

is applied, such that $H_T > 1000$ GeV. To reduce contamination from $Z +$ jets events, a requirement is placed on the invariant mass of two same-flavor leptons, with $m_{\ell\ell} > 300$ GeV. A large fraction of the background from processes involving a top quark is suppressed through the requirement on $m_{\text{hf}}^0$ and $m_{\text{asym}}^0$, with correctly reconstructed top quark masses falling well below the signal region requirements. However, top quark decays in which the lepton and $b$-jet decay products are mispaired can enter the SRs if the incorrectly reconstructed masses happen to be large. In such cases it is the rejected pairing that properly reconstructs the top quark decay, with one of the two $b\ell$ pair masses below the kinematic limit for a top quark decay. To suppress such backgrounds, events are rejected if the subleading $b\ell$ mass of the rejected pairing, $m_{\text{hf}}^0(\text{rej})$, is compatible with that of a reconstructed top quark, with $m_{\text{hf}}^0(\text{rej}) < 150$ GeV.

The distribution of predicted signal and background events is shown for the SR800 region in Fig. 2 for $m_{\text{hf}}^0$, $H_T$, $m_{\text{asym}}^0$, $m_{\ell\ell}$, and $m_{\text{hf}}^1(\text{rej})$, demonstrating the potential for background rejection. For the model with a $\tilde{t}$ mass of 1000 GeV (1500 GeV), the SR800 selections are 21% (24%) efficient for events with two $\tilde{t} \to b\ell$ decays, 16% (16%) for events with two $\tilde{t} \to b\mu$ decays, and 0.1% (0.3%) for events with two $\tilde{t} \to b\tau$ decays.

**VI. BACKGROUND ESTIMATION**

For each of the relevant backgrounds in the signal regions, one of two methods is used to estimate the contribution. The minor backgrounds from diboson, $\tilde{t}\tilde{t} + V$, and $W +$ jets processes are estimated directly from MC simulation and the normalization is corrected to the highest-order theoretical cross section available. For the dominant $\tilde{t}\tilde{t}$, single-top, and $Z +$ jets backgrounds, the expected yield in the SRs is estimated by scaling each MC prediction by a normalization factor (NF) derived from three dedicated control regions (CRs), one for each background process. Each control region is defined to be kinematically close to the SRs while inverting or relaxing specific selections to enhance the contribution from the targeted background process while reducing the contamination from other backgrounds and the benchmark signals.

To derive a background-only estimate, the normalizations of the $\tilde{t}\tilde{t}$, single-top, and $Z +$ jets backgrounds are determined through a likelihood fit [78] performed simultaneously to the observed number of events in each CR. The expected yield in each region is given by the inclusive sum over all background processes in the $ee$, $e\mu$, and $\mu\mu$ channels. The NF for each of the $\tilde{t}\tilde{t}$, single-top, and $Z +$ jets backgrounds are free parameters of the fit. The systematic uncertainties are treated as nuisance parameters in the fit and are not significantly constrained.

Several validation regions (VRs) are defined to test the extrapolation from the CRs to SRs over the relevant kinematic variables. The VRs are disjoint from both the CRs and SRs, and are constructed to fall between one or more CRs and the SRs in one of the extrapolated variables. The VRs are not included in the fit, but provide a statistically independent cross-check of the background prediction in regions with a negligible signal contamination. Three VRs are constructed to test the extrapolation in the $m_{\text{hf}}^0$, $m_{\text{hf}}^1(\text{rej})$, and $H_T$ observables. A fourth VR is constructed to validate the extrapolation of the $Z +$ jets CR in $m_{\ell\ell}$. Details of the selection criteria in each CR and VR are presented below, and a summary of the selections is provided in Table II.
TABLE II. Summary of the selections of the signal, control, and validation regions. All regions require at least two oppositely charged leptons and at least two jets. Each region requires at least one of the two leading jets to be b-tagged with the exception of CRst, which requires both leading jets to be b-tagged, and VRZ, which requires zero b-tagged jets in the event. A mass asymmetry selection of \( m_{Z\ell\ell}^{\text{min}} < 0.2 \) is applied to all regions. The contranverse mass selection \( m_{\ell\ell}^{\text{CT}} \) [Eq. (1)] is only applied to events in CRtt with exactly two b-tagged jets, as indicated by the *, ensuring the region is orthogonal to CRst.

<table>
<thead>
<tr>
<th>Region</th>
<th>( N_b )</th>
<th>( m_{b\ell}^0 ) [GeV]</th>
<th>( H_T ) [GeV]</th>
<th>( m_{b\ell}^\text{ rej} ) [GeV]</th>
<th>( m_{r\ell} ) [GeV]</th>
<th>( m_{CT} ) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR800</td>
<td>( \geq 1 )</td>
<td>( &gt; 800 )</td>
<td>( &gt; 1000 )</td>
<td>( &gt; 150 )</td>
<td>( &gt; 300 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>SR1100</td>
<td>( \geq 1 )</td>
<td>( &gt; 1100 )</td>
<td>( &gt; 1000 )</td>
<td>( &gt; 150 )</td>
<td>( &gt; 300 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>CRst</td>
<td>( = 2 )</td>
<td>[200,500]</td>
<td>( &lt; 800 )</td>
<td>( &lt; 150 )</td>
<td>( &lt; 120 )</td>
<td>( &gt; 200 )</td>
</tr>
<tr>
<td>CRtt</td>
<td>( \geq 1 )</td>
<td>[200,500]</td>
<td>[600,800]</td>
<td>( &lt; 150 )</td>
<td>( &gt; 300 )</td>
<td>( &lt; 200^* )</td>
</tr>
<tr>
<td>CRZ</td>
<td>( \geq 1 )</td>
<td>( &gt; 700 )</td>
<td>( &gt; 1000 )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>VRm_{b\ell}^0</td>
<td>( \geq 1 )</td>
<td>( &gt; 500 )</td>
<td>[600,800]</td>
<td>( &lt; 150 )</td>
<td>( &gt; 300 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>VRm_{b\ell}^\text{ rej}</td>
<td>( \geq 1 )</td>
<td>[200,500]</td>
<td>[600,800]</td>
<td>( &gt; 150 )</td>
<td>( &gt; 300 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>VRH_{T}</td>
<td>( \geq 1 )</td>
<td>[200,500]</td>
<td>( &gt; 800 )</td>
<td>( &lt; 150 )</td>
<td>( &gt; 300 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>VRZ</td>
<td>( = 0 )</td>
<td>[500,800]</td>
<td>( &gt; 1000 )</td>
<td>( &gt; 150 )</td>
<td>( &gt; 300 )</td>
<td>( \ldots )</td>
</tr>
</tbody>
</table>

A. Single-top control region

The single-top background enters the SR through the \( Wt \) process, when the b-jet and lepton produced in the semi-leptonic top quark decay are incorrectly paired with the lepton from the \( W \) decay and an additional jet, respectively. The CRst control region is designed to target the \( Wt \) production in a less-energetic kinematic region or where the rejected \( b\ell \) pairing correctly combines the decay products of the top quark. To separate CRst from the SRs, the \( H_T \) and \( m_{b\ell}^0 \) requirements are reversed such that \( H_T < 800 \) GeV and \( 200 < m_{b\ell}^0 < 500 \) GeV. To target events in which the top quark is reconstructed in the rejected \( b\ell \) pairing, the selection on \( m_{b\ell}^\text{ rej} \) is reversed, requiring \( m_{b\ell}^\text{ rej} < 150 \) GeV. As there is no dilepton resonance in this background process the \( m_{\ell\ell} \) selection is lowered to increase the CRst yield and improve the statistical precision of the constraint.

After these selections the control region is dominated by \( t\bar{t} \) production, which has a significantly higher cross section than the \( Wt \) process. The contranverse mass \( m_{\ell\ell}^{\text{CT}} \) [79] is introduced to discriminate between \( Wt \) and \( t\bar{t} \) events and increase the \( Wt \) purity in the CRst. The \( m_{\ell\ell}^{\text{CT}} \) observable attempts to reconstruct the invariant mass of pair-produced particles which decay into visible and invisible decay products. For two identical decays of top quarks into two visible b-quarks \( b_1 \) and \( b_2 \), and two W bosons, each of whose decay products may include an invisible particle, \( m_{\ell\ell}^{\text{CT}} \) is defined as

\[
m_{\ell\ell}^{\text{CT}}(b_1, b_2) = [E_{T}(b_1) + E_{T}(b_2)]^2 - |p_{T}(b_1) - p_{T}(b_2)|^2.
\]

(1)

where \( E_T = \sqrt{\not{p}_T + m^2} \) is calculated from the kinematics of the reconstructed b-jet. For an event with two top quarks, the \( m_{\ell\ell}^{\text{CT}} \) observable therefore has a kinematic endpoint at

\[ m_{\ell\ell}^{\text{max}} = \frac{m_t^2 - m_W^2}{m_t}, \]

where \( m_t \) and \( m_W \) are the masses of the top quark and W boson, respectively. Requiring this variable to exceed a minimum value is effective in suppressing the \( t\bar{t} \) contribution, for which \( m_{\ell\ell}^{\text{CT}} \) has a kinematic endpoint of about 135 GeV, and a strict requirement of \( m_{\ell\ell}^{\text{CT}} > 200 \) GeV is applied in CRst. The \( m_{\ell\ell}^{\text{CT}} \) variable is only effective in rejecting \( t\bar{t} \) events in which the \( b \)-quark decay products of both top quarks are properly identified, and both leading jets (and only the leading jets) are required to be b-tagged in CRst, such that \( N_b = 2 \). The \( m_{\ell\ell}^{\text{CT}} \) distribution of the backgrounds in CRst is shown in Fig. 3(a) when no \( m_{\ell\ell}^{\text{CT}} \) requirement is applied, and a significant single-top contribution above 55% is seen for \( m_{\ell\ell}^{\text{CT}} > 200 \) GeV.

B. \( t\bar{t} \) control region

The CRtt control region is constructed to target \( t\bar{t} \) events with kinematics similar to the SRs. As with CRst, the \( H_T \) and \( m_{b\ell}^0 \) requirements are inverted such that \( 600 < H_T < 800 \) GeV and \( 200 < m_{b\ell}^0 < 500 \) GeV. The selection on \( m_{b\ell}^\text{ rej} \) is also inverted, requiring \( m_{b\ell}^\text{ rej} < 150 \) GeV, such that one of the two top quarks is reconstructed in the rejected \( b\ell \) pairings. The distribution of \( m_{b\ell}^\text{ rej} \) in CRtt is shown in Fig. 3(b), showing the mispairing of \( t\bar{t} \) events is well modeled in MC simulation. Due to the larger cross section of the \( t\bar{t} \) process, contamination from \( Wt \) events is minimal. However, to maintain orthogonality with CRst, a requirement of \( m_{\ell\ell}^{\text{CT}} < 200 \) GeV is applied to events in which both leading jets (and only the leading jets) are b-tagged, with \( N_b = 2 \).

C. \( Z + \text{jets} \) control region

The CRZ control region targets \( Z + \) jets events by applying a selection on the invariant mass of the dilepton pair. The contransverse mass \( m_{\ell\ell}^{\text{CT}} \) [76] is only applied to events in CRtt with exactly two b-tagged jets, as indicated by the *, ensuring the region is orthogonal to CRst.
Both leptons are required to be of the same flavor. The \( m_{ll} \) selection is effective in removing signal contamination, and the SR \( H_T \) selection is left unchanged, while the \( m_0bl \) selection is slightly relaxed to \( m_0bl > 700 \) GeV to enhance the event yield.

**D. Validation regions**

Four disjoint validation regions are used to test the extrapolation of the background fit from the CRs to the SRs. A full list of the region selections is given in Table II. The VR\( m_0bl \), VR\( m_1bl(rej) \), and VR\( H_T \) test the extrapolation from CRst and CRtt to the SRs in the \( m_0bl \), \( m_1bl(rej) \), and \( H_T \) observables by requiring \( m_0bl > 500 \) GeV, \( m_1bl(rej) > 150 \) GeV, and \( H_T > 800 \) GeV, respectively. In this way VR\( m_0bl \), VR\( m_1bl(rej) \), and VR\( H_T \) all lie between the SRs and both CRtt and CRst, with signal contamination below 1% for all signal mass values. No requirement is placed on \( m_{CT} \) in any VR, allowing both the \( t\bar{t} \) and \( Wt \) contributions to be validated.

A fourth validation region, VR\( Z \), is used to test the extrapolation from CR\( Z \) to the SRs in the \( m_{ll} \) observable, requiring \( m_{ll} > 300 \) GeV. As the \( m_{ll} \) variable provides the only separation between CR\( Z \) and the SRs, the requirement on \( m_0bl \) is relaxed to \( 500 < m_0bl < 800 \) GeV, and any event with a \( b \)-tagged jet is rejected, such that \( N_b = 0 \). The \( Z + \) jets MC prediction is found to model the data well in both \( m_{bl} \) and \( N_b \), with a signal contamination in VR\( Z \) below 5% for mass values above 1000 GeV.

The observed data yield and the postfit background prediction for each CR and VR are shown in Fig. 4. Good agreement is seen in all validation regions, with differences between the data and SM prediction below 1\( \sigma \). The modeling of the extrapolated variable for each VR is shown in Fig. 5, demonstrating good agreement in the shape of the variables of interest.

**VII. SYSTEMATIC UNCERTAINTIES**

Systematic uncertainties in the signal and background predictions arise from theoretical uncertainties in the expected yield and MC modeling, and from experimental sources. The dominant uncertainties are summarized in Table III.

Experimental uncertainties reflect the precision of the energy and momentum calibration of jets and leptons, as well as the assumptions about the identification and reconstruction efficiencies in MC simulation. The dominant experimental uncertainties are related to jets, including those in the jet energy scale and resolution [80,81] and the calibration of the \( b \)-tagging efficiency for \( b \)-jets, \( c \)-jets, and...
The largest experimental uncertainties in the fitted background prediction in SR800 (SR1100) are from the $b$-tagging efficiency of light-flavor jets and the jet energy resolution. The experimental uncertainties associated with leptons each have a small impact on the final measurement, and include uncertainties in the energy scale and resolution of electrons [67] and muons [68], and the calibration of the lepton trigger, identification, reconstruction, and isolation efficiencies. The 3.2% uncertainty in the measured integrated luminosity also has a marginal effect on the final result.

Theoretical and MC modeling uncertainties of the $t\bar{t}$ and $Wt$ backgrounds account for the choice of event generator, underlying-event tune, and their parameters. The uncertainties are derived separately for each background process and are treated as uncorrelated nuisance parameters. As the $t\bar{t}$ ($Wt$) background normalization is constrained in the likelihood fits, the uncertainties are derived on the transfer of the NF from the CRtt (CRst) to both SR800 and SR1100 by comparing CR-to-SR yield ratios in alternative models. The uncertainty in the background estimate due to the choice of MC event generator is estimated for $t\bar{t}$ and $Wt$ by light-flavor jets [77].

TABLE III. Summary of the dominant experimental and theoretical uncertainties in SR800 and SR1100 before the likelihood fits, quoted relative to the total prefit MC background predictions. The individual uncertainties can be correlated, and do not necessarily add in quadrature to the total postfit background uncertainty.

<table>
<thead>
<tr>
<th>Source \ Region</th>
<th>SR800</th>
<th>SR1100</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental uncertainty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2%</td>
<td>10%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>Electrons</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>Muons</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Theoretical modeling uncertainty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>8%</td>
<td>17%</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>8%</td>
<td>45%</td>
</tr>
<tr>
<td>Single-top</td>
<td>21%</td>
<td>22%</td>
</tr>
<tr>
<td>$Z$ + jets</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>Diboson</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>$t\bar{t}$ + $W/Z$</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>$W$ + jets</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>
comparing the CR-to-SR yield ratios derived using MG5_AMC@NLO 2.2.3 with the one derived using POWHEG-BOX v2, both showered with Herwig+ + v2.7.1 [82] using the UEE5 UE tune [83]. The generator uncertainties are found to be conservative due to the limited statistical precision of the MG5_AMC@NLO samples. The hadronization and fragmentation modeling uncertainty is similarly estimated in both $t\bar{t}$ and $Wt$ by comparing the nominal POWHEG + PYTHIA sample with the same POWHEG + HERWIG sample. The uncertainty due to the choice of parameters in the POWHEG + PYTHIA generator and P2012 underlying-event tune are derived by varying the parameters related to the amount of initial- and final-state radiation, the factorization and renormalization scales, and (for $t\bar{t}$ only) the $p_T$ of the first additional emission beyond the Born level [37]. An uncertainty in the single-top yield due to the destructive interference between the $t\bar{t}$ and $Wt$ processes is estimated by using inclusively generated $WWbb$ events in a comparison with the combined yield of $t\bar{t}$ and $Wt$ samples, all generated at LO with MG5_AMC@NLO 2.5.5.

The theoretical uncertainties of the $Z + \text{jets}$, diboson, and $t\bar{t} + V$ samples are estimated by varying event generator parameters related to the factorization, renormalization, resummation, and CKKW matching scales. The envelope of these variations is taken as the theoretical uncertainty in the predicted yield in each SR. As the diboson and $t\bar{t} + V$ samples are not normalized in the CRs, the uncertainty in the theoretical cross section is also included. The uncertainty in the NLO cross section is taken to be 6% for the diboson process [84] and 13% for the $t\bar{t} + V$ process [51]. A 50% uncertainty is applied to the small $W + \text{jets}$ yield in both SRs.

The stop signal model uncertainties are dominated by the cross-section uncertainty, derived from the envelope of cross-section predictions from several distinct PDF sets and varying the factorization and renormalization scales, as described in Ref. [36]. The uncertainty in the cross section varies from 13% for the 600 GeV mass value to 27% for the 1600 GeV mass value. The electron efficiency uncertainties are between 3% and 4% for the various stop masses when assuming $B(\tilde{t} \rightarrow b e) = B(\tilde{t} \rightarrow b\mu) = 50\%$, and are between 5% and 8% when assuming $B(\tilde{t} \rightarrow b e) = 100\%$. Similarly, the muon efficiency uncertainties are between 2% and 4% when assuming $B(\tilde{t} \rightarrow b e) = B(\tilde{t} \rightarrow b\mu) = 50\%$, and rise to 6% when assuming $B(\tilde{t} \rightarrow b\mu) = 100\%$. The electron, muon, and jet energy scale and resolution uncertainties are generally below 1% for the stop signal models, reaching 1% for masses near the $m_{\tilde{t}_R}$ threshold of 800 GeV for SR800 and 1100 GeV for SR1100. The $b$-tagging efficiency uncertainties are between 1% and 3%, reaching the largest value for the 600 GeV signal model.

### VIII. RESULTS

The observed yields and fitted background predictions in SR800 and SR1100 are shown in Table IV. One event is

<table>
<thead>
<tr>
<th></th>
<th>SR800</th>
<th></th>
<th>SR1100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inclusive</td>
<td>ee</td>
<td>$\mu\mu$</td>
</tr>
<tr>
<td>Observed yield</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total postfit bkg yield</td>
<td>5.2 ± 1.4</td>
<td>1.8 ± 0.5</td>
<td>2.1 ± 0.8</td>
</tr>
<tr>
<td>Postfit Z + jets yield</td>
<td>2.0 ± 1.3</td>
<td>0.6 ± 0.4</td>
<td>1.1 ± 0.7</td>
</tr>
<tr>
<td>Postfit $t\bar{t}$ yield</td>
<td>1.40 ± 0.33</td>
<td>0.30 ± 0.24</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>Postfit diboson yield</td>
<td>1.0 ± 0.5</td>
<td>0.27 ± 0.14</td>
<td>0.54 ± 0.25</td>
</tr>
<tr>
<td>Postfit $t\bar{t} + V$ yield</td>
<td>0.64 ± 0.23</td>
<td>0.14 ± 0.05</td>
<td>0.31 ± 0.12</td>
</tr>
<tr>
<td>Postfit $W + \text{jets}$ yield</td>
<td>0.12 ± 0.03</td>
<td>0.01 ± 0.01</td>
<td>0.07 ± 0.02</td>
</tr>
<tr>
<td>Total MC bkg yield</td>
<td>0.03 ± 0.03</td>
<td>0.04 ± 0.04</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td>MC single-top yield</td>
<td>4.9 ± 1.2</td>
<td>1.7 ± 0.4</td>
<td>2.0 ± 0.7</td>
</tr>
<tr>
<td>MC $Z + \text{jets}$ yield</td>
<td>1.9 ± 1.0</td>
<td>0.57 ± 0.34</td>
<td>1.0 ± 0.6</td>
</tr>
<tr>
<td>MC $t\bar{t}$ yield</td>
<td>1.15 ± 0.21</td>
<td>0.65 ± 0.17</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>MC diboson yield</td>
<td>1.1 ± 0.5</td>
<td>0.57 ± 0.26</td>
<td>0.22 ± 0.10</td>
</tr>
<tr>
<td>MC $t\bar{t} + V$ yield</td>
<td>0.64 ± 0.23</td>
<td>0.14 ± 0.05</td>
<td>0.31 ± 0.12</td>
</tr>
<tr>
<td>MC $W + \text{jets}$ yield</td>
<td>0.12 ± 0.03</td>
<td>0.01 ± 0.01</td>
<td>0.07 ± 0.02</td>
</tr>
<tr>
<td>MC $W + \text{jets}$ yield</td>
<td>0.03 ± 0.03</td>
<td>0.04 ± 0.04</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td>$\sigma^{95%_{\text{exp}}}$ ee</td>
<td>$6.4^{+3.0}_{-1.9}$</td>
<td>$4.1^{+1.8}_{-1.1}$</td>
<td>$4.0^{+2.2}_{-0.9}$</td>
</tr>
<tr>
<td>$\sigma^{95%_{\text{obs}}}$ ee</td>
<td>4.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$\sigma_{\text{vis}}$ [fb]</td>
<td>0.11</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>
observed in SR1100 and two are observed in SR800, in agreement with the SM prediction. The SR1100 event is included in SR800 by definition, and both events are found in the $\mu\mu$ channel. The SR1100 event has a high $H_T$ due to a high-$p_T$ muon with a large $p_T$ uncertainty. The observed and predicted $m_{bc}^0$, $H_T$, $m_{bc}^\text{asym}$, $m_{\ell\ell}$, and $m_{bc}^1(\text{rej})$ distributions in SR800 are shown in Fig. 2.

For each SR, model-independent upper limits are derived on the visible cross section of potential BSM processes at a 95% confidence level (C.L.). A likelihood fit is performed to the number of observed events in all three CRs and the target SR, and a generic BSM process is assumed to contribute to the SR only. No theoretical or systematic uncertainties are considered for the signal model except the luminosity uncertainty. The observed ($\sigma_{\text{vis}}^{\text{obs}}$) and expected ($\sigma_{\text{vis}}^{\text{exp}}$) limits on the number of BSM events are derived at 95% C.L. in each flavor channel and inclusively, and are shown in the lower rows of Table IV. Also shown are the observed limits on the visible cross section $\sigma_{\text{vis}}$, defined as $\sigma_{\text{vis}}^{\text{obs}}$ normalized to the integrated luminosity, and representing the product of the production cross section, acceptance, and selection efficiency of a generic BSM signal. Limits on $\sigma_{\text{vis}}$ are set between 0.08 and 0.13 fb, with the weaker limit set in the $\mu\mu$ channel due to the two observed events.

Exclusion limits are derived at 95% C.L. for the $\tilde{t}$ signal samples. Limits are obtained through a profile log-likelihood ratio test using the CLs prescription [85], following the simultaneous fit to the CRs and a target SR [78]. The signal contributions in both the SR and CRs are accounted for in the fit, although they are negligible in the latter. Exclusion fits are performed separately for various branching ratio assumptions, sampling values of $B(\tilde{t} \rightarrow b\ell)$, $B(\tilde{t} \rightarrow b\mu)$, and $B(\tilde{t} \rightarrow b\tau)$ whose sum is unity in steps of 5%, and reweighting events in the signal samples according to the generated decays. For both SR800 and SR1100, limits are derived in the $ee$, $e\mu$, $\mu\mu$, and inclusive channels. Observed limits are reported for the SR and channel combination with the lowest expected

![Image of graph showing exclusion limits at 95% C.L. for various $\tilde{t}$ mass values and branching ratios.](image-url)
be with higher trigger efficiency for electrons than for muons. Stops slightly stronger for increasing $B$ where the expected number of events with electrons or branching ratios are shown in Fig. 6 for each simulated branching ratios.

because a substantial fraction of signal events has two $ee$ channel is always more sensitive than the $e \mu$ channel as a function of $B$ when $B(\bar{t} \rightarrow t \tau)$ increases, the expected number of events with electrons or muons in the final state decreases, reducing the mass reach of the exclusion.

$B_{\text{ex}}$ value, and therefore best expected sensitivity, at a given mass value and branching ratio. The inclusive channel typically has the stronger expected sensitivity when $B(\bar{t} \rightarrow be)$ and $B(\bar{t} \rightarrow b\mu)$ are both above 15%, while the $ee$ ($e\mu$) channel is more sensitive when $B(\bar{t} \rightarrow b\mu)$ ($B(\bar{t} \rightarrow be)$) is below 15%. The inclusive channel is always more sensitive than the $e\mu$ channel because a substantial fraction of signal events has two leptons of the same flavor, regardless of individual branching ratios.

The expected and observed exclusion contours for the branching ratios are shown in Fig. 6 for each simulated $\bar{t}$ mass. The limits are strongest at low values of $B(\bar{t} \rightarrow b\tau)$, where the expected number of events with electrons or muons in the final state is largest. Expected limits are slightly stronger for increasing $B(\bar{t} \rightarrow be)$, reflecting a higher trigger efficiency for electrons than for muons. Stops with $B(\bar{t} \rightarrow b\tau)$ up to 80% or more are excluded for masses between 600 and 1000 GeV, while those with larger $B(\bar{t} \rightarrow be)$ or $B(\bar{t} \rightarrow b\mu)$ may be excluded up to 1500 GeV. Observed limits are stronger than expected for $\bar{t}$ masses of 1100 GeV or below, reflecting the lower-than-expected event yield in SR800 in the $ee$ channel and inclusively. Exclusion contours reflecting the highest $\bar{t}$ mass excluded at a 95% C.L. for a given point in the branching ratio plane are shown in Fig. 7.

**IX. CONCLUSIONS**

This paper presents the first ATLAS results on the search for the pair production of stops, each decaying via an $R$-parity-violating coupling to a $b$-quark and a lepton. The final state requires two jets, at least one of which is $b$-tagged, and two light, oppositely charged leptons (electron or muon). The search uses 36.1 fb$^{-1}$ of $\sqrt{s} = 13$ TeV proton-proton collision data collected with the ATLAS detector at the LHC in 2015 and 2016. No significant excess of events over the Standard Model prediction is observed, and limits are set on the $\bar{t}$ mass at a 95% confidence level. These results significantly extend the lower-mass exclusion limits on the $B \rightarrow L$ stop model from reinterpretations of Run 1 leptoquark searches. Model-independent upper limits are set on the cross section of potential BSM processes in the $ee$, $e\mu$, and $\mu\mu$ channels and inclusively. A scan of various $\bar{t}$ branching ratios is performed to set branching-ratio-dependent limits on decays to $be$, $b\mu$, and $b\tau$ for various $\bar{t}$ mass models. Limits are set on $\bar{t}$ masses between 600 GeV for large $b\tau$ decay branching ratios and 1500 GeV for a $be$ branching ratio of 100%.

**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; STSC, Belarus; CNPq and FAPESP, Brazil; NSERC, SRC and CFI, Canada; CERN, COFINTY, 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; SRNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, USA. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme.
Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [86].


[80] ATLAS Collaboration, Jet energy resolution in proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2010
SEARCH FOR $B - L$ R-PARITY-VIOLATING TOP …  

PHYS. REV. D 97, 032003 (2018)
SEARCH FOR $B - L$ R-PARITY-VIOLATING TOP …

PHYS. REV. D 97, 032003 (2018)

S. H. Robertson, 90a A. Robichaud-Veronneau, 90 D. Robinson, 30 J. E. M. Robinson, 45 A. Rosbon, 56 E. Rocco, 86
C. Roda, 126a,126b Y. Rodina, 88,4d S. Rodionei, 98 D. Ross, 222a,222b S. M. Romano Saez, 37 E. Romero Adam,
N. Rompotis, 77 M. Ronzoni, 51 L. Ros, 83 S. Rosati, 134a K. Rosbach, 51 P. Rose, 139 N.-A. Rosien, 57 E. Rossii,
L. P. Rossi, 53a J. H. N. Rosten, 30 R. Rosten, 140 M. Rotaru, 28b J. Rothberg, 140 D. Rousseau, 119 A. Rozanov, 88 Y. Rozen,
X. Ruan, 147c F. Rubbo, 145 F. Rühr, 51 A. Ruiz-Martinez, 31 Z. Rurikova, 51 N. A. Rusakovich, 68 H. L. Russell,
J. P. Rutherford, 76 N. Rummel, 22 Y. F. Ryabov, 125 M. Rybar, 169 G. Rybkin, 139 S. Ryu, 6 A. Ryzhov, 32 G. F. Rzehorz,
A. F. Saavedra, 152 G. Sabato, 109 S. Sacerdoti, 122 H. F.-W. Sadrozinski, 139 R. Sadykov, 68 F. Safai Tehrani, 134a P. Saho,
M. Sahinsoy, 60a M. Saimpert, 45 M. Saito, 157 T. Saito, 157 H. Sakamoto, 157 Y. Sakuragi, 174 G. Salamanna,
J. E. Salazar Loyola, 34b D. Salek, 109 P. H. Sales De Brun, 168 D. Salihagic, 103 A. Salnikov, 145 J. Salt, 170 D. Salvatore,
F. Salvatore, 151 A. Salvucci, 62a 62c A. Salzburger, 32 D. Sammel, 51 D. Sampsonidou, 156 D. Sampsonidou, 156 J. Sánchez,
V. Sanchez Martinez, 170 A. Sanchez Pineda, 167a,167b H. Sandaker, 122 R. L. Sandbach, 79 C. O. Sander, 45 M. Sandhoff,
C. Sandoval, 21 D. P. C. Sankey, 133 M. Sanno, 53a,53b Y. Sano, 105 A. Sansoni, 50 C. Santoni, 37 H. Santos,
I. Santoyo Castillo, 151 A. Saponov, 68,42 128a,128d B. Sarrazin, 22 O. Sasaki, 69 K. Sato, 164 E. Sauvan, 4 G. Savage,
P. Savard, 161d N. Savic, 103 C. Sawyer, 133 L. Sawyer, 92a J. Saxion, 53 C. Sbarza, 22a A. Sbrizzi, 22a,22b T. Scalon,
D. A. Scannicchio, 166 J. Schier, 140 P. Schacht, 103 B. M. Schachtner, 102 D. Schaefer, 23 L. Schaefer, 86 H. Schulz,
J. Schumacher, 198 B. A. Schumm, 159 Ph. Schune, 138 A. Schwartman, 145 T. A. Schwarz, 95 H. Schwerdt,
Ph. Schwenming, 138 R. Schwenhorst, 93 J. Schwindling, 138 A. Seidner, 23 G. Seicola, 22a,40b M. Seonajengeh,
F. Scru, 126a,126b F. Scutti, 91 J.海域, 92 C. Peema, 23 S. C. Seidel, 107 A. Seiden, 139 J. M. Seixas, 26a G. Sekhniadez, 106a
K. Sekhon, 92 S. J. Sekula, 43 N. Semprini-Cesari, 134a,134b S. Sen, 22b S. Senkin, 37 C. Serfon, 121 L. Serin, 119 L. Serkin,
M. Sessa, 136a,136b R. Seuster, 172 H. Severini, 115 T. Sfiligoj, 78 F. Sforza, 165 A. Sfliry, 52 E. Shabalina, 57 N. W. Shakh,
L. Y. Shan, 35a R. Sch. 169 J. T. Shank, 24 M. Shapiro, 16 P. B. Shatalov, 99 K. Shaw, 167a,167b S. M. Shaw, 87
C. O. Shimmin, 179 M. Shimjojima, 104 I. P. Shipsey, 122 Z. Shirabe, 73 M. Shiya, 96a,am J. Shlomi, 175 A. Shmeleva,
D. Shoaleh Saadi, 97 M. J. Schot, 99 S. Shojai, 94a,94b D. R. Shope, 115 S. Shresta, 117 A. Shulga, 106a M. Shupi, 7 P. Sichow,
A. M. Sickles, 169 P. E. Sidebo, 149 E. Sideras Haddad, 147c O. Sidirovoulou, 177 A. Sidioti, 22a,22b F. Siegert, 47 D. Sijacki,
J. Silva, 128a,128d S. B. Silverstein, 148a V. Simak, 138 L. Simic, 68 S. Simion, 119 E. Simioni, 86 B. Simmons, 81 M. Simon,
A. V. Schegeelys, 128c D. Scheirich, 131 M. Schermu, 166 C. Schiavi, 133a,133b S. Schier, 139 L. K. Schildgen, 22c C. Schillo,
M. Schioppa, 140a,40b S. Schlenker, 32 K. R. Schmidt-Sommerfeld, 103 K. Schmieden, 32 C. Schmitt, 86 S. Schmitt, 45 S. Schmitz,
U. Schnoor, 115 T. Schoeffel, 138 A. Schoenig, 60 B. D. Schoenrock, 93 E. Schopf, 23 M. Schott, 167a,167b J. F. P. Schouwenberg,
J. Schovancova, 32 S. Schram, 52 N. Schuh, 86 A. Schulte, 86 M. J. Schultens, 23 H.-C. Schultz-Coulon, 60a H. Schulz,
J. Schumacher, 198 B. A. Schumm, 159 Ph. Schune, 138 A. Schwartzman, 145 T. A. Schwarz, 95 H. Schwerdt,
Ph. Schwenming, 138 R. Schwenhorst, 93 J. Schwindling, 138 A. Seidner, 23 G. Seicola, 22a,40b M. Seonajengeh,
F. Scru, 126a,126b F. Scutti, 91 J.海域, 92 C. Peema, 23 S. C. Seidel, 107 A. Seiden, 139 J. M. Seixas, 26a G. Sekhniadez, 106a
K. Sekhon, 92 S. J. Sekula, 43 N. Semprini-Cesari, 134a,134b S. Sen, 22b S. Senkin, 37 C. Serfon, 121 L. Serin, 119 L. Serkin,
M. Sessa, 136a,136b R. Seuster, 172 H. Severini, 115 T. Sfiligoj, 78 F. Sforza, 165 A. Sfliry, 52 E. Shabalina, 57 N. W. Shakh,
L. Y. Shan, 35a R. Sch. 169 J. T. Shank, 24 M. Shapiro, 16 P. B. Shatalov, 99 K. Shaw, 167a,167b S. M. Shaw, 87
C. O. Shimmin, 179 M. Shimjojima, 104 I. P. Shipsey, 122 Z. Shirabe, 73 M. Shiya, 96a,am J. Shlomi, 175 A. Shmeleva,
D. Shoaleh Saadi, 97 M. J. Schot, 99 S. Shojai, 94a,94b D. R. Shope, 115 S. Shresta, 117 A. Shulga, 106a M. Shupi, 7 P. Sichow,
A. M. Sickles, 169 P. E. Sidebo, 149 E. Sideras Haddad, 147c O. Sidirovoulou, 177 A. Sidioti, 22a,22b F. Siegert, 47 D. Sijacki,

(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 Alberta, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Istanbul, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
7Department of Physics, University of Arizona, Tucson Arizona, USA
8Department of Physics, The 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, The University of Texas at Austin, Austin Texas, USA
12Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
13Institut de Física d’Altes Energies (IAFE), The Barcelona Institute of Science and Technology, Barcelona, Spain
14Institute of Physics, University of Belgrade, Belgrade, Serbia
15Department for Physics and Technology, University of Bergen, Bergen, Norway
16Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
17Department of Physics, Humboldt University, Berlin, Germany
18Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20aDepartment of Physics, Bogazici University, Istanbul, Turkey
20bDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20cIstanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
20dBahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
21Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
212INFN Sezione di Bologna, Italy
22bDipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
23Physikalisches Institut, University of Bonn, Bonn, Germany
24Department of Physics, Boston University, Boston Massachusetts, USA
25Department of Physics, Brandeis University, Waltham Massachusetts, USA
26aUniversidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
26bElectrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
26cFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
26dInstituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27Physics Department, Brookhaven National Laboratory, Upton New York, USA
28aTransilvania University of Brasov, Brasov, Romania
28bHoria Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
28cDepartment of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
28dNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
28eUniversity Politehnica Bucharest, Bucharest, Romania
28fWest University in Timisoara, Timisoara, Romania
29Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina

032003-23
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa Ontario, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Department of Physics, Nanjing University, Jiangsu, China

Physics Department, Tsinghua University, Beijing 100084, China

Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China

School of Physics, Shandong University, Shandong, China

Department of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai(also at PKU-CHEP), China

Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington New York, USA

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy

Dipartimento di Fisica, Università della Calabria, Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas Texas, USA

Physics Department, University of Texas at Dallas, Richardson Texas, USA

DESY, Hamburg and Zeuthen, Germany

Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham North Carolin, USA

SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN e Laboratori Nazionali di Frascati, Frascati, Italy

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

Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Italy

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia

High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

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

Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge Massachusetts, USA

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China

Department of Physics, The University of Hong Kong, Hong Kong, China

Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Department of Physics, National Tsing Hua University, Taiwan, Taiwan

Department of Physics, Indiana University, Bloomington Indiana, USA

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City Iowa, USA

Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan
SEARCH FOR B – L R-PARITY-VIOLATING TOP …

PHYS. REV. D 97, 032003 (2018)
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Tomsk State University, Tomsk, Russia
Department of Physics, University of Toronto, Toronto Ontario, Canada
INFN-TIFPA, Italy
University of Trento, Trento, Italy
TRIUMF, Vancouver British Columbia, Canada
Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine California, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana Illinois, USA
Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Spain
Department of Physics, University of British Columbia, Vancouver British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison Wisconsin, USA
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

†Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at TRIUMF, Vancouver BC, Canada.
Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
Also at Physics Department, An-Najah National University, Nablus, Palestine.
Also at Department of Physics, California State University, Fresno CA, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.
Also at Departament de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain.
Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
Also at Universita di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Borough of Manhattan Community College, City University of New York, New York City, 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 LA, USA.
Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.

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

Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.

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

Also at CERN, Geneva, Switzerland.

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

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

Also at Manhattan College, New York NY, USA.

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

Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal.

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

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

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

Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

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

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

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

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

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

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

Also at Giresun University, Faculty of Engineering, Turkey.

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

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

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

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

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