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A search for supersymmetry involving the pair production of gluinos decaying via third-generation squarks to the lightest neutralino (\(\tilde{\chi}_1^0\)) is reported. It uses an LHC proton-proton data set at a center-of-mass energy \(\sqrt{s} = 13\) TeV with an integrated luminosity of 3.2 fb\(^{-1}\) collected with the ATLAS detector in 2015. The signal is searched for in events containing several energetic jets, of which at least three must be identified as \(b\) jets, large missing transverse momentum, and, potentially, isolated electrons or muons. Large-radius jets with a high mass are also used to identify highly boosted top quarks. No excess is found above the predicted background. For \(\tilde{\chi}_1^0\) masses below approximately 700 GeV, gluino masses of less than 1.78 TeV and 1.76 TeV are excluded at the 95\% C.L. in simplified models of the pair production of gluinos decaying via sbottom and stop, respectively. These results significantly extend the exclusion limits obtained with the \(\sqrt{s} = 8\) TeV data set.

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I. INTRODUCTION

Supersymmetry (SUSY) [1–6] is a generalization of space-time symmetries that predicts new bosonic partners to the fermions and new fermionic partners to the bosons of the Standard Model (SM). If \(R\) parity is conserved [7], SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. The scalar partners of the left- and right-handed quarks, the squarks \(\tilde{q}_L\) and \(\tilde{q}_R\), can mix to form two mass eigenstates \(\tilde{q}_1\) and \(\tilde{q}_2\), ordered by increasing mass. SUSY can solve the hierarchy problem \([8–11]\) by preventing “unnatural” fine-tuning in the Higgs sector provided that the superpartners of the top quark (stop, \(\tilde{t}_1\) and \(\tilde{t}_2\)) have masses not too far above the weak scale. Because of the SM weak isospin symmetry, the mass of the left-handed bottom quark scalar partner (sbottom, \(\tilde{b}_L\)) is tied to the mass of the left-handed top quark scalar partner (\(\tilde{t}_L\)), and as a consequence the mass of the lightest sbottom \(\tilde{b}_1\) is also expected to be close to the weak scale. The fermionic partners of the gluons, the gluinos (\(\tilde{g}\)), are also constrained by naturalness [12,13] to have a mass around the TeV scale to limit their contributions to the radiative corrections to the stop masses. For these reasons, and because the gluinos are expected to be pair produced with a high cross section at the CERN Large Hadron Collider (LHC), the search for gluino production with decays via stop and sbottom quarks is highly motivated at the LHC.

This paper presents the search for gluino pair production where both gluinos decay either to stops via \(\tilde{g} \rightarrow \tilde{t}_1 t\) or to sbottoms via \(\tilde{g} \rightarrow \tilde{b}_1 b\), using a data set of 3.2 fb\(^{-1}\) of proton-proton data collected with the ATLAS detector [14] at a center-of-mass energy of \(\sqrt{s} = 13\) TeV. Each stop (sbottom) is then assumed to decay to a top (bottom) quark and the LSP: \(\tilde{t}_1 \rightarrow \tilde{t}_2^0 (\tilde{b}_1 \rightarrow \tilde{b}_2^0)\). The LSP is assumed to be the lightest neutralino \(\tilde{\chi}_1^0\), the lightest linear superposition of the superpartners of the neutral electroweak and Higgs bosons. The \(\tilde{\chi}_1^0\) interacts only weakly, resulting in final states with substantial missing transverse momentum of magnitude \(E_T^{\text{miss}}\). Diagrams of the simplified models \([15,16]\) considered, which are referred to as “Gbb” and “Gtt” in the following, are shown in Figs. 1(a) and 1(b), respectively. The sbottom and stop are assumed to be produced off shell such that the gluinos undergo the three-body decay \(\tilde{g} \rightarrow b b \tilde{\chi}_1^0\) or \(\tilde{g} \rightarrow t t \tilde{\chi}_1^0\), and that the only parameters of the simplified models are the gluino and \(\tilde{\chi}_1^0\) masses.

The Gbb experimental signature consists of four energetic \(b\) jets (i.e., jets containing \(b\) hadrons) and large \(E_T^{\text{miss}}\). In order to maintain high signal efficiency, at least three of four required jets must be identified as \(b\) jets (\(b\) tagged). This requirement is very effective in rejecting \(t\bar{t}\) events, which constitute the main background for both the Gbb and Gtt signatures, and which contain only two \(b\) jets unless they are produced with additional heavy-flavor jets. The Gtt

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\(^1\)Models with on-shell sbottom and stop were studied in Run 1 [17], and the limits on the gluino and the \(\tilde{\chi}_1^0\) masses were found to be mostly independent of the stop and sbottom masses, except when the stop is very light.
experimental signature also contains four $b$ jets and $E_{T}^{\text{miss}}$, but yields in addition four $W$ bosons originating from the top quark decays $t \rightarrow Wb$. Each $W$ boson can either decay leptonically ($W \rightarrow \ell\nu$) or hadronically ($W \rightarrow q\overline{q}$). A Gtt event would therefore possess a high jet multiplicity, with as many as 12 jets originating from top quark decays and, potentially, isolated charged leptons. In this paper, pair-produced gluinos decaying via stop and sbottom quarks are searched for using events with high jet multiplicity, of which at least three must be identified as $b$ jets, large $E_{T}^{\text{miss}}$, and either zero leptons (referred to as the Gtt 0-lepton channel) or at least one identified charged lepton$^2$ (referred to as the Gtt 1-lepton channel). For both the Gbb and Gtt models, several signal regions are designed to cover different ranges of gluino and $\tilde{\chi}_{1}^{0}$ masses. For the Gtt models with a large mass difference (mass splitting) between the gluino and $\tilde{\chi}_{1}^{0}$, the top quarks tend to be highly boosted and their decay products collimated. In the corresponding signal regions, at least one large-radius, trimmed [18] jet, which is reclustered from small-radius jets [19], is required to have a high mass to identify hadronically decaying boosted top quarks.

Pair production of gluinos, with subsequent decays via sbottom quarks, was searched for in ATLAS Run 1 with a similar analysis requiring at least three $b$-tagged jets [17]. It excluded gluino masses below 1290 GeV for LSP masses below 400 GeV at 95% confidence level (C.L.). That analysis also searched for gluinos decaying via stop quarks in events with at least three $b$-tagged jets and either zero or at least one identified lepton and obtained the best ATLAS limits for the Gtt models with massless and moderately massive LSP [20]. Gluino masses below 1400 GeV were excluded at 95% C.L. for LSP masses below 400 GeV. Pair-produced gluinos with stop-mediated decays have also been searched for by ATLAS in events with high jet multiplicity [21], events with at least one lepton, many jets, and $E_{T}^{\text{miss}}$ [22], and events containing pairs of same-sign leptons or three leptons [23], the latter obtaining the best ATLAS limit for Gtt models with compressed mass spectra between the gluino and the LSP in Run 1 [20] and having since been performed in Run 2 [24].

Similar searches performed with the CMS experiment using $\sqrt{s} = 8$ TeV [25–30] and $\sqrt{s} = 13$ TeV data [31–34] have produced comparable results to ATLAS searches.

II. ATLAS DETECTOR

The ATLAS detector is a multipurpose particle physics detector with a forward-backward symmetric cylindrical geometry and nearly $4\pi$ coverage in solid angle.$^3$ The inner tracking detector (ID) consists of pixel and silicon microstrip detectors covering the pseudorapidity region $|\eta| < 2.5$, surrounded by a transition radiation tracker, which enhances electron identification in the region $|\eta| < 2.0$. Before the start of Run 2, the new innermost pixel layer, the Insertable B-Layer (IBL) [35], was inserted at a mean sensor radius of 3.3 cm. The ID is surrounded by a thin superconducting solenoid providing an axial 2 T magnetic field and by a fine-granularity lead/liquid-argon (LAr) electromagnetic calorimeter covering $|\eta| < 3.2$. A steel/scintillator-tile calorimeter provides coverage for hadronic showers in the central pseudorapidity range $(|\eta| < 1.7)$. The end cap and forward regions ($1.5 < |\eta| < 4.9$) of the hadronic calorimeter are made of LAr active layers with either copper or tungsten as the absorber material. A muon spectrometer with an air-core toroid magnet system surrounds the calorimeters. Three layers of high-precision tracking chambers provide coverage in the range $|\eta| < 2.7$.

$^2$The term “lepton” refers exclusively to an electron or a muon in this paper.

$^3$ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector. The positive $x$ axis is defined by the direction from the interaction point to the center of the LHC ring, with the positive $y$ axis pointing upwards, while the beam direction defines the $z$ axis. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$ axis. The pseudorapidity $\eta$ is defined in terms of the polar angle $\theta$ by $\eta = -\ln \tan(\theta/2)$. 

FIG. 1. The decay topologies in the (a) Gbb and (b) Gtt simplified models.
while dedicated fast chambers allow triggering in the region $|\eta| < 2.4$. The ATLAS trigger system [36] consists of a hardware-based Level-1 trigger followed by a software-based high level trigger.

### III. DATA AND SIMULATED EVENT SAMPLES

The data used in this analysis were collected by the ATLAS detector from $pp$ collisions produced by the LHC at a center-of-mass energy of 13 TeV and 25 ns proton bunch spacing. The full data set corresponds to an integrated luminosity of $3.2 \text{ fb}^{-1}$ with an associated uncertainty of $\pm 5\%$, after requiring that all detector subsystems were operational during data recording. The measurement of the integrated luminosity is derived, following a methodology similar to that detailed in Ref. [37], from a calibration of the luminosity scale using a pair of $x$-$y$ beam-separation scans performed in June 2015. Events are required to pass an $E_T^{\text{miss}}$ trigger that is fully efficient for events passing the preselection defined in Sec. V. Each event includes on average 14 additional inelastic $pp$ collisions (“pileup”) in the same bunch crossing.

Simulated event samples are used to model the signal and background processes in this analysis. The signal samples for the Gbb and Gtt processes are generated with up to two additional partons using MADGRAPH5_aMC@NLO samples for the Gbb and Gtt processes at next-to-leading order (NLO) with CT10 PDF sets and interfaced to PYTHIA v8.186 [40] for the modeling of the parton showering, hadronization, and underlying event.

The dominant background in the signal regions is the production of $t\bar{t}$ pairs with additional high-$p_T$ jets. The sample for the estimation of this background is generated using the POWHEG-BOX [41,42] generator at next-to-leading order (NLO) with CT10 [43] PDFs and interfaced to PYTHIA v6.428 [44] for showering and hadronization. The decays of heavy-flavor hadrons are modeled using the EVTGEN [45] package. The $h_{\text{damp}}$ parameter in POWHEG, which controls the $p_T$ of the first additional emission beyond the Born level and thus regulates the $p_T$ of the recoil emission against the $t\bar{t}$ system, is set to the mass of the top quark ($m_{\text{top}} = 172.5$ GeV). This setting was found to give the best description of the $p_T$ of the $t\bar{t}$ system at $\sqrt{s} = 7$ TeV [46] and $\sqrt{s} = 8$ TeV [47]. All events with at least one semileptonically decaying top quark are included. Fully hadronic $t\bar{t}$ events do not contain sufficient $E_T^{\text{miss}}$ to contribute significantly to the background.

Smaller backgrounds in the signal region come from the production of $t\bar{t}$ pairs in association with $W/Z/h$ and additional jets, single-top production, production of $t\bar{t}t\bar{t}$, $W/Z$ and jets and $WW/ZZ/WW/ZZ$ (diboson) events. The production of $t\bar{t}$ pairs in association with electroweak vector bosons and $t\bar{t}t\bar{t}$ production are modeled by samples generated using MADGRAPH [48] interfaced to PYTHIA v8.186, while samples to model $t\bar{t}h$ production are generated using MADGRAPH5_aMC@NLO [38] v2.2.1 and showered with HERWIG++ [49] v2.7.1. Single-top production in the $s$, $t$, and $Wt$ channels is generated by POWHEG-BOX interfaced to PYTHIA v6.428. $W/Z$ + jets and diboson processes are simulated using the SHERPA v2.1.1 [50] generator with CT10 PDF sets. Matrix elements for these processes are calculated using the Comix [51] and OpenLoops [52] generators and merged with the SHERPA parton shower [53] using the ME + PS@NLO prescription [54].

All simulated event samples, with the exception of the Gbb signals, are passed through the full ATLAS detector simulation using GEANT4 [55,56]. The Gbb signal samples are passed through a fast simulation that uses a parametrized description to simulate the response of the calorimeter systems [57]. The simulated events are reconstructed with the same algorithm as that used for data. All PYTHIA v6.428 samples use the PERUGIA2012 [58] set of tuned parameters (tune) for the underlying event, while PYTHIA v8.186 and HERWIG++ showering are run with the A14 [59] and UEUE5 [60] underlying-event tunes, respectively. In-time and out-of-time pileup interactions from the same or nearby bunch crossings are simulated by overlaying additional $pp$ collisions generated by PYTHIA v8.186 on the hard-scattering events. Details of the sample generation and normalization are summarized in Table I. Additional samples with different generators and settings

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator + fragmentation/hadronization</th>
<th>Tune</th>
<th>PDF set</th>
<th>Cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>POWHEG-BOX v2 + PYTHIA-6.428</td>
<td>PERUGIA2012</td>
<td>CT10</td>
<td>NNLO + NNLL [61]</td>
</tr>
<tr>
<td>Single top</td>
<td>POWHEG-BOX v2 + PYTHIA-6.428</td>
<td>PERUGIA2012</td>
<td>CT10</td>
<td>NNLO + NNLL [62–64]</td>
</tr>
<tr>
<td>$t\bar{t}W/t\bar{t}Z/4$-tops</td>
<td>MADGRAPH-2.2.2 + PYTHIA-8.186</td>
<td>A14</td>
<td>NNPDF2.3 [65]</td>
<td>NLO</td>
</tr>
<tr>
<td>$t\bar{t}h$</td>
<td>MADGRAPH5_aMC@NLO-2.2.1 + HERWIG++2.7.1</td>
<td>UEE5</td>
<td>CT10</td>
<td>NLO [66]</td>
</tr>
<tr>
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<td>SHERPA-2.1.1</td>
<td>Default</td>
<td>CT10</td>
<td>NNLO [67]</td>
</tr>
<tr>
<td>WW, WZ, ZZ</td>
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<td>Default</td>
<td>CT10</td>
<td>NNLO [67]</td>
</tr>
<tr>
<td>W/Z+jets</td>
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<td>Default</td>
<td>CT10</td>
<td>NNLO [67]</td>
</tr>
</tbody>
</table>
are used to estimate systematic uncertainties on the backgrounds, as described in Sec. VI.

The signal samples are normalized using the best cross sections calculated at NLO in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic (NLL) accuracy [68–72]. The nominal cross section and the uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [73]. The cross section of gluino pair production in these simplified models is approximately 325 fb for a gluino mass of 1 TeV, falling to 2.8 fb for 1.8 TeV mass gluinos. All background processes are normalized to the best available theoretical calculation for their respective cross sections. The order of this calculation in perturbative QCD (pQCD) for each process is listed in Table I.

IV. OBJECT RECONSTRUCTION

Interaction vertices from the proton-proton collisions are reconstructed from at least two tracks with \( p_T > 0.4 \) GeV and are required to be consistent with the beam spot envelope. The primary \( pp \) interaction vertex is identified as the one with the largest sum of squares of the transverse momenta from associated tracks \( \left( \sum |p_{T,\text{track}}|^2 \right) \) [74].

Basic selection criteria are applied to define candidates for electrons, muons, and jets in the event. An overlap removal procedure is applied to these candidates to prevent double counting. Further requirements are then made to select the final signal leptons and jets from the remaining objects. The details of the object selections and of the overlap removal procedure are given below.

Candidate jets are reconstructed from three-dimensional topological energy clusters [75] in the calorimeter using the anti-\( k_t \) jet algorithm [76] with a radius parameter of 0.4 (small-\( R \) jets). Each topological cluster is calibrated to the electromagnetic scale response prior to jet reconstruction. The reconstructed jets are then calibrated to the particle level by the application of a jet energy scale (JES) derived from simulation and corrections based on 8 TeV data [77,78]. Quality criteria are imposed to reject events that contain at least one jet arising from noncollisional sources or detector noise [79]. Further selections are applied to reject jets that originate from pileup interactions [80]. Candidate jets are required to have \( p_T > 20 \) GeV and \( |\eta| < 2.8 \). Signal jets, selected after resolving overlaps with electrons and muons, are required to satisfy the stricter requirement of \( p_T > 30 \) GeV.

A multivariate algorithm using information about the impact parameters of inner detector tracks matched to the jet, the presence of displaced secondary vertices, and the reconstructed flight paths of \( b \) and \( c \) hadrons inside the jet [81–83] is used to tag \( b \) jets. The \( b \) tagging working point with an 85% efficiency, as determined from a simulated sample of \( t\bar{t} \) events, was found to be optimal.

The corresponding rejection factors against jets originating from \( c \) quarks, from \( \tau \) leptons, and from light quarks and gluons in the same sample at this working point are 2.6, 3.8, and 27, respectively.

The candidate small-\( R \) jets are used as inputs for further jet reclustering [19] using the anti-\( k_t \) algorithm with a radius parameter of 1.0. These reclustered jets are then trimmed [18,19] by removing subjets whose \( p_T \) falls below \( f_{\text{cut}} = 5\% \) of the \( p_T \) of the original reclustered jet. The resulting large-\( R \) jets are used to tag high-\( p_T \) boosted top quarks in the event. Selected large-\( R \) jets are required to have \( p_T > 300 \) GeV and to have \( |\eta| < 2.0 \). A large-\( R \) jet is tagged as a top candidate if it has a mass above 1 TeV. The mass of the large-\( R \) jets is computed from the four-momentum sum of its constituent small-\( R \) jets, and the mass of the small-\( R \) jets are computed from the four-momentum sum of the topological clusters that make up the jet, which are assumed to be massless. When it is not explicitly stated otherwise, the term “jets” in this paper refers to small-\( R \) jets.

Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter and inner detector tracks and are required to satisfy a set of “loose” quality criteria [84–86]. They are also required to have \( |\eta| < 2.47 \). Muon candidates are reconstructed from matching tracks in the inner detector and in the muon spectrometer. They are required to meet “medium” quality criteria, as described in Refs. [87,88] and to have \( |\eta| < 2.5 \). All electron and muon candidates must have \( p_T > 20 \) GeV and survive the overlap removal procedure. Signal leptons are chosen from the candidates with the following isolation requirement—the scalar sum of \( p_T \) of additional inner detector tracks in a cone around the lepton track is required to be <5% of the lepton \( p_T \). The angular separation between the lepton and the \( b \) jet ensuing from a semileptonic top quark decay narrows as the \( p_T \) of the top quark increases. This increased collimation is accounted for by varying the radius of the isolation cone as \( \max(0.2, 10/p_T^{\text{lep}}) \), where \( p_T^{\text{lep}} \) is the lepton \( p_T \) expressed in GeV. Signal electrons are further required to meet the “tight” quality criteria, while signal muons are required to satisfy the same medium quality criteria as the muon candidates. Electrons (muons) are matched to the primary vertex by requiring the transverse impact parameter \( d_0 \) to satisfy \( |d_0|/\sigma(d_0) < 5 \) (3), where \( \sigma(d_0) \) is the measured uncertainty in \( d_0 \), and the longitudinal impact parameter \( z_0 \) to satisfy \( |z_0 \sin \theta| < 0.5 \text{ mm} \). In addition, events containing one or more muon candidates with \( |d_0| > 0.2 \text{ mm} \) and \( |z_0| > 1 \text{ mm} \) are rejected to suppress cosmic rays.

The overlap removal procedure between muon and jet candidates is designed to remove those muons that are likely to have originated from the decay of hadrons and to retain the overlapping jet. Jets and muons may also appear in close proximity when the jet results from high-\( p_T \) muon bremsstrahlung, and in such cases the jet should be
removed and the muon retained. Such jets are characterized by having very few matching inner detector tracks. Therefore, if the angular distance $\Delta R$ between a muon and a jet is within $\min(0.4, 0.04 + 10 \text{ GeV}/p_T)$ of the axis of a jet, the muon is removed only if the jet has $\geq 3$ matching inner detector tracks. If the jet has fewer than three matching tracks, the jet is removed and the muon is kept [89]. Overlap removal between electron and jet candidates aims to remove jets that are formed primarily from the showering of a prompt electron and to remove electrons that are produced in the decay chains of hadrons. Since electron showers within the cone of a jet contribute to the measured energy of the jet, any overlap between an electron and the jet must be fully resolved. A $p_T$-dependent cone for the purpose of this overlap removal is thus impractical. Consequently, any non-$b$-tagged jet whose axis lies $\Delta R < 0.2$ from an electron is discarded. If the electron is within $\Delta R = 0.4$ of the axis of any jet remaining after this initial overlap removal procedure, the jet is retained and the electron is removed. Finally, electron candidates that lie $\Delta R < 0.01$ from muon candidates are removed to suppress contributions from muon bremsstrahlung.

The missing transverse momentum ($E_T^{\text{miss}}$) in the event is defined as the magnitude of the negative vector sum of transverse momentum ($\vec{p}_T^{\text{miss}}$) of all selected and calibrated objects in the event, with an extra term added to account for soft energy that is not associated with any of the selected objects. This soft term is calculated from inner detector tracks matched to the primary vertex to make it more resilient to contamination from pileup interactions [90,91].

Corrections derived from data control samples are applied to simulated events to account for differences between data and simulation in the reconstruction efficiencies, momentum scale, and resolution of leptons [85–87,92] and in the efficiency and false positive rate for identifying $b$ jets [82,83].

V. EVENT SELECTION

The event selection criteria are defined based on kinematic requirements on the objects defined in Sec. IV and on the following event variables.

Two effective mass variables are used, which would typically have much higher values in pair-produced gluino events than in background events. The Gtt signal regions employ the inclusive effective mass $m_{\text{eff}}^{\text{incl}}$,

$$m_{\text{eff}}^{\text{incl}} = \sum_i p_{T,i}^{\text{jet}i} + \sum_f p_{T,f}^{\ell} + E_T^{\text{miss}},$$

where the first and second sums are over the signal jets and leptons, respectively. The signal regions for the Gbb models, for which four high-$p_T$ $b$ jets are expected, are defined using $m_{\text{eff}}^{4j}$,

$$m_{\text{eff}}^{4j} = \sum_{i \leq 4} p_{T,i}^{\text{jet}i} + E_T^{\text{miss}},$$

where the sum is over the four highest-$p_T$ (leading) signal jets in the event.

In regions with at least one signal lepton, the transverse mass $m_T$ of the leading signal lepton ($\ell$) and $E_T^{\text{miss}}$ is used to discriminate between the signal and backgrounds from semileptonic $t\bar{t}$ and $W +$ jets events,

$$m_T = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} \{1 - \cos[\Delta \phi(p_T^{\text{miss}}, \ell)]\}}.$$  

Neglecting resolution effects, $m_T$ is bounded from above by the $W$ boson mass for these backgrounds and typically has higher values for Gtt events. Another useful transverse mass variable is $m_{\text{T, min}}^{b-jets}$, the minimum transverse mass formed by $E_T^{\text{miss}}$ and any of the three leading $b$-tagged jets in the event,

$$m_{\text{T, min}}^{b-jets} = \min_{i \leq 3} \{\sqrt{2 p_T^{b-jet} E_T^{\text{miss}} \{1 - \cos[\Delta \phi(p_T^{\text{miss}}, b\text{- jet}_i)]\}}\}.$$  

It is bounded below the top quark mass for semileptonic $t\bar{t}$ events while peaking at higher values for Gbb and Gtt events.

The signal regions require either zero or at least one lepton. The requirement of a signal lepton, with the additional requirements on jets, $E_T^{\text{miss}}$, and event variables described in Sec. VA, render the multijet background negligible for the $\geq 1$-lepton signal regions. For the 0-lepton signal regions, the minimum azimuthal angle between $p_T^{\text{miss}}$ and the leading four small-$R$ jets in the event, $\Delta \phi_{\text{min}}^{4j}$, is required to be greater than 0.4,

$$\Delta \phi_{\text{min}}^{4j} = \min(|\phi_{\text{jet}1} - \phi_{p_T^{\text{miss}}}|, \ldots, |\phi_{\text{jet}4} - \phi_{p_T^{\text{miss}}}|) > 0.4.$$  

This requirement ensures that the multijet background, which can produce large $E_T^{\text{miss}}$ if containing poorly measured jets or neutrinos emitted close to the axis of a jet, is also negligible in the 0-lepton signal regions (along with the other requirements on jets, $E_T^{\text{miss}}$, and event variables described in Sec. VA).

Figure 2 shows the kinematic distributions of $E_T^{\text{miss}}$, $m_{\text{eff}}^{\text{incl}}$, $m_{\text{T, min}}^{b-jets}$, and $m_T$ for a preselection that requires $E_T^{\text{miss}} > 200$ GeV, at least four signal jets of which at least three must be $b$ tagged, and $\Delta \phi_{\text{min}}^{4j} > 0.4$. Figure 3 shows the multiplicity of signal jets, $b$-tagged signal jets, top-tagged large-$R$ jets, and signal leptons in the preselection.
Good agreement between data and simulation is observed. Example signal models with enhanced cross sections are overlaid for comparison.

A. Signal regions

The signal regions are designed by optimizing the expected signal discovery reach for the 2015 data set. They are defined in the leftmost column of Tables II, III, and IV for the Gbb, Gtt 0-lepton, and Gtt 1-lepton channels, respectively, and are discussed below. These tables also contain the definition of the control regions used to normalize the $t\bar{t}$ background, discussed in Sec. V B, and the validation regions used to cross-check the background estimate and which are discussed in Section V C. The following region nomenclature is used in the remainder of the paper. Signal, control, and validation region names start with the prefix “SR,” “CR,” and “VR,” respectively, and with the type of validation region specified for the Gtt validation regions. The name of the region is completed by the type of model targeted and a letter corresponding to the level of mass splitting between the gluino and the LSP. For example the validation region that cross-checks the background, discussed in Sec. V B, and $m_T$ (for preselected events with at least one signal lepton). The statistical and experimental systematic uncertainties are included in the uncertainty band, where the systematic uncertainties are defined in Sec. VI. The lower part of each figure shows the ratio of data to the background prediction. All backgrounds (including $t\bar{t}$) are normalized using the best available theoretical calculation described in Sec. III. The background category “Others” includes $t\bar{t}h$, $t\bar{t}t$, and diboson events. Example signal models with cross sections enhanced by a factor of 100 are overlaid for comparison.

FIG. 2. Distributions of kinematic variables in the preselection region described in the text: (a) $E_T^{miss}$, (b) $m_{T,eff}$, (c) $m_{T,min}$, and (d) $m_T$
The experimental signature for the Gtt model is characterized by several high-$p_T$ jets of which four are $b$ jets, large $E_{T}^{\text{miss}}$, and potentially leptons [Fig. 1(b)]. The Gtt signal regions are classified into regions with a signal lepton, at least six signal jets (signal leptons in the leftmost column of Table III. In all Gtt 0-lepton signal regions at least eight signal jets, $\Delta\phi_{\text{jet}} > 0.4$ and $m_{\text{incl, jets}} > 80$ GeV are required. Three Gtt 0-lepton signal regions are defined to cover Gtt models with decreasing mass splitting between the gluino and the sum of the mass of the two top quarks and the LSP: A ($\gtrsim 1$ TeV), B (between $\approx 200$ GeV and $\approx 1$ TeV), and C ($\lesssim 200$ GeV). In the large and moderate mass splitting scenarios, the top quarks tend to have a large $p_T$, and at least one top-tagged large-$R$ jet is required ($N_{\text{top}}^{\text{tag}} \geq 1$). The requirements on $E_{T}^{\text{miss}}$ and $m_{\text{incl}}$ decrease with the mass splitting between the gluino and the LSP. However, the required number of $b$-tagged jets $N_{b\text{-jet}}$ is tightened to four for the lower mass splitting regions B and C in order to maintain a high background rejection despite the softer signal kinematics.

The Gtt 1-lepton signal regions are defined in the leftmost column of Table IV. Two signal regions A and B are defined to cover Gtt models with decreasing mass difference between the gluino and the LSP. In all signal regions at least one signal lepton, at least six signal jets ($p_{T}^{\text{jet}} > 30$ GeV), and $m_{\tau} > 150$ GeV are required. Region A has tighter requirements on $m_{\text{incl}}$ ($m_{\text{eff}} > 1100$ GeV) and the number of top-tagged large-$R$ jets ($N_{\text{top}}^{\text{tag}} \geq 1$). Region B has a softer requirement on $m_{\text{incl}}$ than region A, but it features a tighter cut on $E_{T}^{\text{miss}}$ to achieve a satisfactory background rejection without requiring a top-tagged large-$R$ jet.
TABLE II. Definitions of the Gbb signal, control, and validation regions. The unit of all kinematic variables is GeV except \( \Delta \phi_{\text{min}} \), which is in radians. The jet \( p_T \) requirement is also applied to \( b \)-tagged jets.

Criteria common to all Gbb regions: \( \geq 4 \) signal jets, \( \geq 3b \)-tagged jets

<table>
<thead>
<tr>
<th>Criteria common to all regions of the same type</th>
<th>Variable</th>
<th>Signal region</th>
<th>Control region</th>
<th>Validation region</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{Candidate Lepton}} )</td>
<td>( = 0 )</td>
<td>( \ldots )</td>
<td>( = 0 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>( \Delta \phi_{\text{min}} )</td>
<td>( &gt; 0.4 )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( &gt; 0.4 )</td>
</tr>
<tr>
<td>( m_{b\text{-jets}} )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( &lt; 160 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>( m_T )</td>
<td>( \ldots )</td>
<td>( &lt; 150 )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
</tr>
</tbody>
</table>

Region A (Large mass splitting)

- \( p_T^{\text{jet}} \): \( > 90 \) GeV
- \( E_T^{\text{miss}} \): \( > 350 \) GeV
- \( m_{\phi \text{ff}} \): \( > 1600 \) GeV
- \( m_{\phi \text{ff}} \): \( > 1200 \) GeV
- \( m_{\phi \text{ff}} \): \( < 1400 \) GeV

Region B (Moderate mass splitting)

- \( p_T^{\text{jet}} \): \( > 90 \) GeV
- \( E_T^{\text{miss}} \): \( > 450 \) GeV
- \( m_{\phi \text{ff}} \): \( > 1400 \) GeV
- \( m_{\phi \text{ff}} \): \( > 1000 \) GeV
- \( m_{\phi \text{ff}} \): \( < 1400 \) GeV

Region C (Small mass splitting)

- \( p_T^{\text{jet}} \): \( > 30 \) GeV
- \( E_T^{\text{miss}} \): \( > 500 \) GeV
- \( m_{\phi \text{ff}} \): \( > 1400 \) GeV
- \( m_{\phi \text{ff}} \): \( > 1200 \) GeV
- \( m_{\phi \text{ff}} \): \( < 1400 \) GeV

B. Background estimation and \( \bar{t} \bar{t} \) control regions

The largest background in all signal regions is \( \bar{t} \bar{t} \) produced with additional high-\( p_T \) jets. The other relevant backgrounds are \( \bar{t}W, \bar{t}Z, \bar{t}tt, \bar{t}\bar{h}, \) single-top, \( W + \text{jets}, \) \( Z + \text{jets}, \) and diboson events. All of these smaller backgrounds are estimated with the simulated event samples normalized to the best available theory calculations described in Sec. III. The multijet background is estimated to be negligible in all regions.

For each signal region, the \( \bar{t} \bar{t} \) background is normalized in a dedicated control region. The \( \bar{t} \bar{t} \) normalization factor

TABLE III. Definitions of the Gtt 0-lepton signal, control, and validation regions. The unit of all kinematic variables is GeV except \( \Delta \phi_{\text{min}} \), which is in radians. The jet \( p_T \) requirement is also applied to \( b \)-tagged jets.

Criteria common to all Gtt 0-lepton regions: \( p_T^{\text{jet}} > 30 \) GeV

<table>
<thead>
<tr>
<th>Criteria common to all regions of the same type</th>
<th>Variable</th>
<th>Signal region</th>
<th>Control region VR1L</th>
<th>Control region VR0L</th>
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<tr>
<td>( N_{\text{Candidate Lepton}} )</td>
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<td>( = 1 )</td>
<td>( = 1 )</td>
<td>( = 0 )</td>
</tr>
<tr>
<td>( \Delta \phi_{\text{min}} )</td>
<td>( &gt; 0.4 )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( &gt; 0.4 )</td>
</tr>
<tr>
<td>( N_{\text{jet}} )</td>
<td>( \geq 8 )</td>
<td>( \geq 7 )</td>
<td>( \geq 7 )</td>
<td>( \geq 8 )</td>
</tr>
<tr>
<td>( m_{b\text{-jets}} )</td>
<td>( &gt; 80 )</td>
<td>( \ldots )</td>
<td>( &gt; 80 )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>( m_T )</td>
<td>( \ldots )</td>
<td>( &lt; 150 )</td>
<td>( &lt; 150 )</td>
<td>( \ldots )</td>
</tr>
</tbody>
</table>

Region A (Large mass splitting)

- \( E_T^{\text{miss}} \): \( > 400 \) GeV
- \( m_{\text{incl}} \): \( > 1700 \) GeV
- \( N_{b\text{-tag}} \): \( \geq 3 \) | \( \geq 3 \) | \( \geq 3 \) | \( \geq 2 \) |
- \( N_{\text{top}} \): \( \geq 1 \) | \( \geq 1 \) | \( \geq 1 \) | \( \geq 1 \) |

Region B (Moderate mass splitting)

- \( E_T^{\text{miss}} \): \( > 350 \) GeV
- \( m_{\text{incl}} \): \( > 1250 \) GeV
- \( N_{b\text{-tag}} \): \( \geq 4 \) | \( \geq 4 \) | \( \geq 4 \) | \( \geq 3 \) |
- \( N_{\text{top}} \): \( \geq 1 \) | \( \geq 1 \) | \( \geq 1 \) | \( \geq 1 \) |

Region C (Small mass splitting)

- \( E_T^{\text{miss}} \): \( > 350 \) GeV
- \( m_{\text{incl}} \): \( > 1250 \) GeV
- \( N_{b\text{-tag}} \): \( \geq 4 \) | \( \geq 4 \) | \( \geq 4 \) | \( \geq 3 \) |
SEARCH FOR PAIR PRODUCTION OF GLUINOS …

TABLE IV. Definitions of the Gtt 1-lepton signal, control, and validation regions. The unit of all kinematic variables is GeV. The jet $p_T$ requirement is also applied to $b$-tagged jets.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Signal region</th>
<th>Control region</th>
<th>VR-$m_T$</th>
<th>VR-$m_{T,min}^{b\text{-jets}}$</th>
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<tr>
<td>$m_T$</td>
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<td>&lt; 150</td>
<td>&gt; 150</td>
<td>&lt; 150</td>
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<tr>
<td>$N^{\text{jet}}$</td>
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<td>= 6</td>
<td>≥ 5</td>
<td>≥ 6</td>
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<tr>
<td>$N^{\text{b-tag}}$</td>
<td>≥ 3</td>
<td>≥ 3</td>
<td>= 3</td>
<td>= 3</td>
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</table>

Region A (Large mass splitting)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Signal region</th>
<th>Control region</th>
<th>VR-$m_T$</th>
<th>VR-$m_{T,min}^{b\text{-jets}}$</th>
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</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$</td>
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<td>&gt; 200</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
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<tr>
<td>$m^{\text{incl}}_T$</td>
<td>&gt; 1100</td>
<td>&gt; 1100</td>
<td>&gt; 600</td>
<td>&gt; 600</td>
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<tr>
<td>$m_T^{\text{jet}}$</td>
<td>&gt; 160</td>
<td>⋯</td>
<td>&lt; 160</td>
<td>&gt; 140</td>
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<tr>
<td>$N^{\text{top}}$</td>
<td>≥ 1</td>
<td>≥ 1</td>
<td>≥ 1</td>
<td>≥ 1</td>
</tr>
</tbody>
</table>

Region B (Moderate to small mass splitting)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Signal region</th>
<th>Control region</th>
<th>VR-$m_T$</th>
<th>VR-$m_{T,min}^{b\text{-jets}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>&gt; 300</td>
<td>&gt; 300</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
</tr>
<tr>
<td>$m^{\text{incl}}_T$</td>
<td>&gt; 900</td>
<td>&gt; 900</td>
<td>&gt; 600</td>
<td>&gt; 600</td>
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<tr>
<td>$m_T^{\text{jet}}$</td>
<td>&gt; 160</td>
<td>⋯</td>
<td>&lt; 160</td>
<td>&gt; 160</td>
</tr>
</tbody>
</table>

required for the total predicted yield to match the data in the control region is used to normalize the $t\bar{t}$ background in the signal region. The control regions are designed to be dominated by $t\bar{t}$ events and to have negligible signal contamination, while being kinematically as close as possible to the corresponding signal region. The latter requirement minimizes the systematic uncertainties associated with extrapolating the normalization factors from the control to the signal regions.

The definitions of the control regions are shown next to the signal regions in Tables II, III, and IV for the Gbb, Gtt 0-lepton, and Gtt 1-lepton channels, respectively. In both the Gbb and Gtt 0-lepton channels, exactly one signal lepton is required. This is motivated by background composition studies using simulated events which show that semileptonic $t\bar{t}$ events, for which the lepton is outside the acceptance or is a hadronically decaying $\tau$ lepton, dominate the $t\bar{t}$ yield in the signal regions. An upper cut on $m_T$ is then applied to ensure orthogonality with the Gtt 1-lepton signal regions and to suppress signal contamination. The jet multiplicity requirement is reduced to seven jets in the Gtt 0-lepton control regions (from eight jets in the signal regions), to accept more events and to obtain a number of jets from top quark decay and parton shower similar to that in the signal region. Approximately 40%–60% of the signal region events contain a hadronically decaying $\tau$ lepton that is counted as a jet. Orthogonality between Gtt 0-lepton and Gtt 1-lepton control regions is ensured by requiring exactly six jets in the Gtt 1-lepton control regions (as opposed to the requirement of at least six jets in the signal regions). For all Gbb and Gtt 0-lepton control regions, the number of $b$-tagged jets and top-tagged large-$R$ jets is consistent with the signal region. The requirements on $E_T^{\text{miss}}$ and $m_T^{\text{eff}}$ are, however, relaxed in the control regions to achieve a sufficiently large $t\bar{t}$ yield and small signal contamination ($\lesssim 15\%$). The Gtt 1-lepton control regions are defined by inverting the $m_T$ cut and removing the $m_{T,min}^{b\text{-jets}}$ requirement. All other requirements are exactly the same as for the signal regions.

C. Validation regions

Validation regions are defined to cross-check the background prediction in regions that are kinematically close to the signal regions but yet have a small signal contamination. They are designed primarily to cross-check the assumption that the $t\bar{t}$ normalization extracted from the control regions can be accurately extrapolated to the signal regions. Their requirements are shown in the rightmost column(s) of Tables II, III, and IV for the Gbb, Gtt 0-lepton, and Gtt 1-lepton channels, respectively. Their signal contamination is less than approximately 30% for the majority of Gbb and Gtt model points not excluded in Run 1.

One validation region per signal region is defined for the Gbb model. They feature the same requirements as their corresponding signal region except that upper cuts are applied on $m_{T,min}$ and $m_T^{\text{eff}}$ to reduce signal contamination and ensure orthogonality with the signal regions. In addition, the requirement on $E_T^{\text{miss}}$ is relaxed to obtain a sufficient $t\bar{t}$ yield.

For the Gtt 0-lepton channel, two validation regions per signal region are defined, one requiring exactly one signal lepton (VR1L) and one with a signal lepton veto (VR0L). The regions VR1L have exactly the same criteria as their corresponding control regions except that they require $m_{T,min}^{b\text{-jets}} > 80$ GeV, similar to the signal regions, in order to test the extrapolation over $m_{T,min}^{b\text{-jets}}$ between the control and the signal regions. Simulation studies show that the heavy-flavor fraction of the additional jets in the $t\bar{t}$ + jets events (i.e., $t\bar{t} + b\bar{b}$ and $t\bar{t} + c\bar{c}$), which suffers from large theoretical uncertainties, is similar in the signal, control, and VR1L regions. This is achieved by requiring the same number of $b$-tagged jets for all three types of regions.
While the theoretical uncertainties in the heavy-flavor fraction of the additional jets in the $t\bar{t} +$ jets events (i.e., $t\bar{t} + b\bar{b}$ and $t\bar{t} + c\bar{c}$) are large, they affect signal, control, and the 1-lepton validation regions in a similar way, and are thus largely canceled in the semi-data-driven $t\bar{t}$ normalization based on the observed control region yields.

The VR0L regions have similar requirements on their corresponding signal regions except that the requirements on $E_T^{\text{miss}}$, $m_T^{\text{incl}}$, and the number of $b$-tagged jets are loosened to achieve sufficient event yields. Furthermore, the criterion $m_{T_{\text{miss}}}$ < 80 GeV is applied to all VR0L regions to ensure orthogonality with the signal regions. The regions VR0L test the extrapolation of the $t\bar{t}$ normalization from a 1-lepton to a 0-lepton region. Simulation studies show that the VR0L regions have a composition of semileptonic $t\bar{t}$ events (in particular of hadronically decaying $\tau$ leptons) similar to that in the signal regions, while the control and VR1L regions are by construction dominated by semileptonic $t\bar{t}$ events with a muon or an electron.

Two requirements are different between Gtt 1-lepton control regions and their corresponding signal regions: the requirement on $m_{T_{\text{miss}}}^{b\text{-jets}}$ (absent in the control regions) and the requirement on $m_T$ (inverted in the control regions). Therefore, two validation regions per signal region are defined for the Gtt 1-lepton channel, VR-$m_T$ and VR-$m_{T_{\text{miss}}}^{b\text{-jets}}$, which respectively test, one at a time, the extrapolations over $m_T$ and $m_{T_{\text{miss}}}^{b\text{-jets}}$. Exactly three $b$-tagged jets are required for all 1-lepton validation regions to limit the signal contamination and to be close to the signal regions. For the VR-$m_T$ regions, the same requirement $m_T > 150$ GeV as in the signal region is applied but the criterion on $m_{T_{\text{miss}}}^{b\text{-jets}}$ is inverted. Other requirements are relaxed to achieve sufficiently large background yields and small signal contamination. For the VR-$m_{T_{\text{miss}}}^{b\text{-jets}}$ regions, the signal region requirement on $m_{T_{\text{min}}}^{b\text{-jets}}$ is applied (slightly loosened to 140 GeV instead of 160 GeV in region A) and the criterion on $m_T$ is inverted. Again, other requirements are generally relaxed. Simulation studies show that $t\bar{t}$ dilepton events dominate in the signal regions, in particular due to the requirement on $m_T$, while semileptonic $t\bar{t}$ events dominate in the control regions. This extrapolation is cross-checked by the VR-$m_T$ regions, which have a $t\bar{t}$ dileptonic fraction similar to that in the signal regions.

VI. SYSTEMATIC UNCERTAINTIES

The largest sources of detector-related systematic uncertainties in this analysis relate to the JES, jet energy resolution (JER), and the $b$-tagging efficiencies and mistagging rates. The JES uncertainties are obtained by extrapolating the uncertainties derived from $\sqrt{s} = 8$ TeV data and simulations to $\sqrt{s} = 13$ TeV [77]. The uncertainties in the energy scale of the small-$R$ jets are propagated to the reclustered large-$R$ jets, which use them as inputs. The JES uncertainties are especially important in the Gtt signal regions, since these regions require high jet multiplicities. The impact of these uncertainties on the expected background yields in these regions is between 10% and 25%. Uncertainties in the JER are similarly derived from dijet asymmetry measurements in Run 1 data and extrapolated to $\sqrt{s} = 13$ TeV. The impact of the JER uncertainties on the background yields are in the range of 1%–10%.

Uncertainties in the measured $b$-tagging efficiencies and mistagging rates are the subleading sources of experimental uncertainties in the Gtt 1-lepton signal regions and the leading source in the Gtt 0-lepton and Gbb regions. Uncertainties measured in $\sqrt{s} = 8$ TeV data are extrapolated to $\sqrt{s} = 13$ TeV, with the addition of the new IBL system in Run 2 taken into account. Uncertainties for jet $p_T$ above 300 GeV are estimated using simulated events. The impact of the $b$-tagging uncertainties on the expected background yields in the Gbb and Gtt 0-lepton signal regions is around 22%–30%, and around 15% in the Gtt 1-lepton signal regions.

The uncertainties associated with lepton reconstruction and energy measurements have very small impact on the final results. All lepton and jet measurement uncertainties are propagated to the calculation of $E_T^{\text{miss}}$, and additional uncertainties are included in the scale and resolution of the soft term. The overall impact of the $E_T^{\text{miss}}$ soft term uncertainties on the expected background yields is 5% or less.

Uncertainties in the modeling of the $t\bar{t}$ background are evaluated using additional samples varied by each systematic uncertainty. Hadronization and parton showering uncertainties are estimated using a sample generated with POWHEG and showered by HERWIG++ v2.7.1 [49] with the UEE5 underlying-event tune [60]. Systematic uncertainties in the modeling of initial- and final-state radiation are explored with two alternative settings of POWHEG, both of which are showered by PYTHIA v6.428 as for the nominal sample. The first of these uses the PERUGIA2012 radHi tune and has the renormalization and factorization scales set to twice the nominal value, resulting in more radiation in the final state. It also has $h_{\text{damp}}$ set to $2m_{\text{top}}$. The second sample, using the PERUGIA2012 radLo tune, has $h_{\text{damp}} = m_{\text{top}}$, and the renormalization and factorization scales are set to half of their nominal values, resulting in less radiation in the event. In each case, the uncertainty is taken as the deviation in the expected yield of $t\bar{t}$ background with respect to the nominal sample. The uncertainty due to the choice of generator is estimated by comparing the expected yields obtained using a $t\bar{t}$ sample generated with MADGRAPH5_aMC@NLO, and one that is generated with POWHEG. Both of these samples are showered with HERWIG++ v2.7.1. Finally, a 30% uncertainty is assigned to the cross section of $t\bar{t}$ events with additional heavy-flavor
jets in the final state, in accordance with the results of the ATLAS measurement of this cross section at $\sqrt{s} = 8$ TeV [93]. Uncertainties in single-top and $W/Z +$ jets background processes are similarly estimated by comparisons between the nominal sample and samples with different generators, showering models, and radiation tunes. An additional 5% uncertainty is included in the cross section of single-top processes [94]. A 50% constant uncertainty is assigned to each of the remaining small backgrounds. The impact of the modeling uncertainties for the smaller backgrounds on these yields is consistently below 10% in all signal regions. The uncertainties in the cross sections of signal processes are determined from an envelope of different cross-section predictions, as described in Sec. III.

The cumulative impact of the systematic uncertainties listed above on the background yields ranges between 23% and 63%, depending on the signal region. The typical impact on the signal yields is in the range 10%–30%.

VII. RESULTS

The SM background expectation is determined separately in each signal region with a profile likelihood fit [95], referred to as a background-only fit. The fit uses as a constraint the observed event yield in the associated control region to adjust the $t\bar{t}$ normalization, assuming that a signal does not contribute to this yield, and applies that normalization factor to the number $t\bar{t}$ events predicted by simulation in the signal region. The numbers of observed and predicted events in each control region are described by Poisson probability density functions. The systematic uncertainties in the expected values are included in the fit as nuisance parameters. They are constrained by Gaussian distributions with widths corresponding to the sizes of the uncertainties and are treated as correlated, when appropriate, between the various regions. The product of the various probability density functions forms the likelihood, which the fit maximizes by adjusting the $t\bar{t}$ normalization and the nuisance parameters within their constraints. The inputs to the fit for each signal region are the number of events observed in its associated control region and the number of events predicted by simulation in each region for all background processes.

Figure 4 shows the results of the background-only fit to the control regions, extrapolated to the validation regions. The number of events predicted by the background-only fit is compared to the data in the upper panel. The pull, defined by the difference between the observed number of events ($n_{\text{obs}}$) and the predicted background yield ($n_{\text{pred}}$) divided by the total uncertainty ($\sigma_{\text{tot}}$), is shown for each region in the lower panel. No evidence of significant background mis-modeling is observed in the validation regions. There is a certain tendency for the predicted background to be above the data, in particular for the $Gtt-0L$ validation regions, but the results in the validation regions of a given channel are not independent. The validation and control regions of different mass splittings can overlap, with the overlap fraction ranging from approximately 30% to 70% for $Gtt-0L$. Furthermore, the uncertainties in the predicted

![Figure 4](https://example.com/fig4.png)

**FIG. 4.** Results of the likelihood fit extrapolated to the validation regions. The $t\bar{t}$ normalization is obtained from the fit to the control regions. The upper panel shows the observed number of events and the predicted background yield. The background category “Others” includes $t\bar{t}h$, $t\bar{t}t\bar{t}$, and diboson events. The lower panel shows the pulls in each validation region.
yield are dominated by the same (correlated) systematic uncertainties.

Tables V, VI, and VII show the observed number of events and predicted number of background events from the background-only fit in the Gbb, Gtt 0-lepton, and Gtt 1-lepton signal regions, respectively. In addition, the tables show the numbers of signal events expected for some example values of gluino and LSP masses in the Gtt and Gbb models. The event yields in the signal regions are also shown in Fig. 5, where the pull is shown for each region in the lower panel. No excess is found above the predicted background. The background is dominated by \( \bar{t}t \) events in all Gbb and Gtt signal regions. The subdominant contributions in the Gbb and Gtt 0-lepton signal regions are \( Z(\rightarrow \mu\nu) + \text{jets} \) and \( W(\rightarrow \ell\nu) + \text{jets} \), where for \( W + \text{jets} \) events the lepton is a nonidentified electron or muon or is a hadronically decaying \( \tau \) lepton. In the Gtt 1-lepton signal regions, the subdominant backgrounds are single-top, \( \bar{t}tW \) and \( \bar{t}tZ \).

Figure 6 shows the \( E_T^{\text{miss}} \) distributions in data and simulated samples for SR-Gbb-B, SR-Gtt-0L-C, and SR-Gtt-1L-A, after relaxing the \( E_T^{\text{miss}} \) threshold to 200 GeV.

### Table V

<table>
<thead>
<tr>
<th>Observed events</th>
<th>SR-Gbb-A</th>
<th>SR-Gbb-B</th>
<th>SR-Gbb-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted background events</td>
<td>1.3 ± 0.4</td>
<td>1.5 ± 0.6</td>
<td>7.6 ± 1.7</td>
</tr>
<tr>
<td>( \bar{t}t )</td>
<td>0.63 ± 0.30</td>
<td>0.9 ± 0.5</td>
<td>4.3 ± 1.5</td>
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<tr>
<td>( Z + \text{jets} )</td>
<td>0.23 ± 0.08</td>
<td>0.23 ± 0.09</td>
<td>1.2 ± 0.5</td>
</tr>
<tr>
<td>( W + \text{jets} )</td>
<td>0.17 ± 0.06</td>
<td>0.13 ± 0.05</td>
<td>0.82 ± 0.28</td>
</tr>
<tr>
<td>Single-top</td>
<td>0.25 ± 0.14</td>
<td>0.15 ± 0.14</td>
<td>0.65 ± 0.33</td>
</tr>
<tr>
<td>( \bar{t}tW/Z )</td>
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<td>&lt;0.1</td>
<td>0.22 ± 0.12</td>
</tr>
<tr>
<td>Others</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.39 ± 0.22</td>
</tr>
<tr>
<td>MC-only background prediction</td>
<td>1.7</td>
<td>1.5</td>
<td>6.7</td>
</tr>
<tr>
<td>( \mu_{\bar{g}} )</td>
<td>0.64 ± 0.33</td>
<td>1.0 ± 0.4</td>
<td>1.2 ± 0.4</td>
</tr>
<tr>
<td>Gbb (( m_{\tilde{g}} = 1700 \text{ GeV}, m_{\tilde{\chi}^0_1} = 200 \text{ GeV} ))</td>
<td>3.8</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Gbb (( m_{\tilde{g}} = 1400 \text{ GeV}, m_{\tilde{\chi}^0_1} = 800 \text{ GeV} ))</td>
<td>5.3</td>
<td>7.2</td>
<td>10.5</td>
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### Table VI

<table>
<thead>
<tr>
<th>Observed events</th>
<th>SR-Gtt-0L-A</th>
<th>SR-Gtt-0L-B</th>
<th>SR-Gtt-0L-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted background events</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \bar{t}t )</td>
<td>2.1 ± 0.5</td>
<td>2.9 ± 1.8</td>
<td>3.4 ± 1.8</td>
</tr>
<tr>
<td>( Z + \text{jets} )</td>
<td>1.4 ± 0.4</td>
<td>2.4 ± 1.7</td>
<td>2.6 ± 1.8</td>
</tr>
<tr>
<td>( W + \text{jets} )</td>
<td>0.22 ± 0.09</td>
<td>0.11 ± 0.06</td>
<td>0.14 ± 0.07</td>
</tr>
<tr>
<td>Single-top</td>
<td>0.19 ± 0.08</td>
<td>0.14 ± 0.06</td>
<td>0.18 ± 0.08</td>
</tr>
<tr>
<td>( \bar{t}tW/Z )</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.10 ± 0.07</td>
</tr>
<tr>
<td>Others</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.20 ± 0.17</td>
</tr>
<tr>
<td>MC-only background prediction</td>
<td>1.8</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>( \mu_{\bar{g}} )</td>
<td>1.3 ± 0.4</td>
<td>1.8 ± 0.8</td>
<td>1.5 ± 0.7</td>
</tr>
<tr>
<td>Gtt (( m_{\tilde{g}} = 1600 \text{ GeV}, m_{\tilde{\chi}^0_1} = 200 \text{ GeV} ))</td>
<td>3.8</td>
<td>2.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Gtt (( m_{\tilde{g}} = 1400 \text{ GeV}, m_{\tilde{\chi}^0_1} = 800 \text{ GeV} ))</td>
<td>2.0</td>
<td>3.7</td>
<td>4.1</td>
</tr>
</tbody>
</table>

---

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VIII. INTERPRETATION

Since no significant excess over the expected background from SM processes is observed, the data are used to derive one-sided upper limits at 95% C.L. Model-independent limits on the number of beyond-the-SM (BSM) events for each signal region are derived with pseudoexperiments using the $CL_s$ prescription [96]. They can be translated into upper limits on the visible BSM cross section ($\sigma_{\text{vis}}$), where $\sigma_{\text{vis}}$ is defined as the product of acceptance, reconstruction efficiency, and production cross section. The results are given in Table VIII, where the observed ($\Sigma_{\text{obs}}^{95\%}$) and expected ($\Sigma_{\text{exp}}^{95\%}$) 95% C.L. upper limits on the number of BSM events are also provided.

The measurement is used to place exclusion limits on gluino and LSP masses in the Gbb and Gtt simplified models. The results are obtained using the $CL_s$ prescription in the asymptotic approximation [97]. The signal contamination in the control regions and the experimental

![Graph](image_url)

FIG. 5. Results of the likelihood fit extrapolated to the signal regions. The data in the signal regions are not included in the fit. The upper panel shows the observed number of events and the predicted background yield. The signal regions SR-Gbb-A, SR-Gbb-B, and SR-Gtt-1L-B have no observed events. The background category “Others” includes $t\bar{t}h$, $t\bar{t}t$, and diboson events. The lower panel shows the pulls in each signal region.

TABLE VII. Results of the likelihood fit extrapolated to the Gtt 1-lepton signal regions. The uncertainties shown include all systematic uncertainties. The data in the signal regions are not included in the fit. The row “MC-only background prediction” provides the total background prediction when the $t\bar{t}$ normalization is obtained from a theoretical calculation [61]. The $t\bar{t}$ normalization factor $\mu_{t\bar{t}}$ obtained from the corresponding $t\bar{t}$ control region is also provided. The category “Others” includes $t\bar{t}h$, $t\bar{t}t$, and diboson events. Expected yields for two example Gtt models are also shown.

<table>
<thead>
<tr>
<th>Category</th>
<th>SR-Gtt-1L-A</th>
<th>SR-Gtt-1L-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Fitted background events</td>
<td>$1.2 \pm 0.6$</td>
<td>$1.2 \pm 0.8$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.8 \pm 0.6$</td>
<td>$0.8 \pm 0.7$</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>$\cdots$</td>
<td>$&lt;0.1$</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>$&lt;0.1$</td>
<td>$&lt;0.1$</td>
</tr>
<tr>
<td>Single-top</td>
<td>$0.18 \pm 0.14$</td>
<td>$0.14 \pm 0.12$</td>
</tr>
<tr>
<td>$t\bar{t}W/Z$</td>
<td>$0.14 \pm 0.08$</td>
<td>$0.15 \pm 0.09$</td>
</tr>
<tr>
<td>Others</td>
<td>$&lt;0.1$</td>
<td>$&lt;0.1$</td>
</tr>
<tr>
<td>MC-only background prediction</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>$\mu_{t\bar{t}}$</td>
<td>$0.86 \pm 0.28$</td>
<td>$1.0 \pm 0.4$</td>
</tr>
<tr>
<td>Gtt ($m_{\tilde{g}} = 1600$ GeV, $m_{\tilde{\chi}} = 200$ GeV)</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Gtt ($m_{\tilde{g}} = 1400$ GeV, $m_{\tilde{\chi}} = 800$ GeV)</td>
<td>3.8</td>
<td>4.6</td>
</tr>
</tbody>
</table>
Systematic uncertainties in the signal are taken into account for this calculation. For the Gbb models, the results are obtained from the Gbb signal region with the best expected sensitivity at each point of the parameter space of each model. For the Gtt models, the 0- and 1-lepton channels both contribute to the sensitivity, and they are combined in a simultaneous fit to enhance the sensitivity of the analysis. This is performed by considering all possible permutations between the three Gtt 0-lepton and the two Gtt 1-lepton signal regions for each point of the parameter space, and the best expected combination is used. The 95% C.L. observed and expected exclusion limits for the Gbb and Gtt models are shown in the LSP and gluino mass plane in Figs. 7(a) and 7(b), respectively. The \( \sigma_{\text{SUSY}} \) theory lines around the observed limits are obtained by changing the SUSY cross section by 1 standard deviation (\( \pm 1\sigma \)), as described in Sec. III. The yellow band around the expected limit shows the \( \pm 1\sigma \) uncertainty, including all statistical and systematic uncertainties except the theoretical uncertainties in the SUSY cross section. It has been checked that the observed exclusion limits obtained from pseudoexperiments differ by less than 25 GeV from the asymptotic approximation in gluino or LSP mass in the combined limits in Fig. 7, although the difference can be up to 50 GeV when using

<table>
<thead>
<tr>
<th>Signal channel</th>
<th>( \sigma_{\text{vis}} ) [fb]</th>
<th>( S_{\text{obs}}^{\text{95}} )</th>
<th>( S_{\text{exp}}^{\text{95}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-Gbb-A</td>
<td>0.94</td>
<td>3.0</td>
<td>3.9^{+1.3}_{-0.7}</td>
</tr>
<tr>
<td>SR-Gbb-B</td>
<td>0.94</td>
<td>3.0</td>
<td>3.8^{+1.4}_{-0.8}</td>
</tr>
<tr>
<td>SR-Gbb-C</td>
<td>1.74</td>
<td>5.6</td>
<td>7.2^{+2.0}_{-1.8}</td>
</tr>
<tr>
<td>SR-Gtt-1L-A</td>
<td>1.49</td>
<td>4.8</td>
<td>3.9^{+1.4}_{-0.9}</td>
</tr>
<tr>
<td>SR-Gtt-1L-B</td>
<td>0.91</td>
<td>3.0</td>
<td>3.0^{+1.4}_{-0.8}</td>
</tr>
<tr>
<td>SR-Gtt-0L-A</td>
<td>1.13</td>
<td>3.6</td>
<td>4.4^{+1.7}_{-1.0}</td>
</tr>
<tr>
<td>SR-Gtt-0L-B</td>
<td>1.16</td>
<td>3.7</td>
<td>4.4^{+1.9}_{-1.2}</td>
</tr>
<tr>
<td>SR-Gtt-0L-C</td>
<td>1.10</td>
<td>3.5</td>
<td>4.5^{+2.0}_{-1.2}</td>
</tr>
</tbody>
</table>
FIG. 7. Exclusion limits in the $\chi^0$ and $\tilde{g}$ mass plane for the (a) Gbb and (b) Gtt models. The dashed and solid bold lines show the 95% C.L. expected and observed limits, respectively. The shaded bands around the expected limits show the impact of the experimental and background theoretical uncertainties. The dotted lines show the impact on the observed limit of the variation of the nominal signal cross section by $\pm 1\sigma$ of its theoretical uncertainty. The 95% C.L. observed limits from the $\sqrt{s} = 8$ TeV ATLAS search requiring at least three $b$-tagged jets [17] are also shown.

single analysis regions. The two methods of computation produce equivalent expected limits.

For the Gbb models, gluinos with masses below 1.78 TeV are excluded at 95% C.L. for LSP masses below 800 GeV. At high gluino masses, the exclusion limits are driven by the SR-Gbb-A and SR-Gbb-B signal regions. The best exclusion limit on the LSP mass is approximately 1.0 TeV, which is reached for a gluino mass of approximately 1.6 TeV. The exclusion limit is dominated by SR-Gbb-C for high LSP masses. For the Gtt models, gluino masses up to 1.8 TeV are excluded for massless LSP. For LSP masses below 700 GeV, gluino masses below 1.76 TeV are excluded. For large gluino masses, the exclusion limits are driven by the combination of SR-Gtt-IL-B and SR-Gtt-OL-A. The LSP exclusion extends up to approximately 975 GeV, corresponding to a gluino mass of approximately 1.5 TeV–1.6 TeV. The best exclusion limits are obtained by the combination of SR-Gtt-IL-B and SR-Gtt-OL-C for high LSP masses. The ATLAS exclusion limits obtained with the full $\sqrt{s} = 8$ TeV data set are also shown in Fig. 7. The current results largely improve on the $\sqrt{s} = 8$ TeV limits despite the lower integrated luminosity. The exclusion limit on the gluino mass is extended by approximately 500 GeV and 400 GeV for the Gbb and Gtt models for massless LSP, respectively. This improvement is primarily attributable to the increased center-of-mass energy of the LHC. The addition of the IBL pixel layer in Run 2, which improves the capability to tag $b$ jets [35], also particularly benefits this analysis that employs a data set requiring at least three $b$-tagged jets. The sensitivity of the data analysis is also improved with respect to the $\sqrt{s} = 8$ TeV analysis [17] by using top-tagged large-$R$ jets, lepton isolation adapted to a busy environment, and the $m^{b\text{-jets}}$ variable.

IX. CONCLUSION

A search for pair-produced gluinos decaying via sbottom or stop is presented. LHC proton-proton collision data from the full 2015 data-taking period were analyzed, corresponding to an integrated luminosity of 3.2 fb$^{-1}$ collected at $\sqrt{s} = 13$ TeV by the ATLAS detector. Several signal regions are designed for different scenarios of gluino and LSP masses. They require several high-$p_T$ jets, of which at least three must be $b$ tagged, large $E_T^{\text{miss}}$, and either zero or at least one charged lepton. For the gluino models with stop-mediated decays in which there is a large mass difference between the gluino and the LSP, large-$R$ jets identified as originating from highly boosted top quarks are employed. The background is dominated by $t\bar{t} +$ jets, which is normalized in dedicated control regions. No excess is found above the predicted background of each signal region. Model-independent limits are set on the visible cross section for new physics processes. Exclusion limits are set on gluino and LSP masses in the simplified gluino models with stop-mediated and sbottom-mediated decays. For LSP masses below approximately 700 GeV, gluino masses of less than 1.78 TeV and 1.76 TeV are excluded at the 95% C.L. for the gluino models with sbottom-mediated and stop-mediated decays, respectively. These results significantly extend the exclusion limits obtained with the $\sqrt{s} = 8$ TeV data set.

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[32] CMS Collaboration, Search for new physics with the MT2 variable in all-jets final states produced in $pp$ collisions at $\sqrt{s} = 13$ TeV (to be published).

[33] CMS Collaboration, Search for supersymmetry in $pp$ collisions at $\sqrt{s} = 13$ TeV in the single-lepton final state using the sum of masses of large-radius jets (to be published).

[34] CMS Collaboration, Search for new physics in same-sign dilepton events in proton-proton collisions at $\sqrt{s} = 13$ TeV (to be published).


[94] P. Kant, O. M. Kind, T. Kintscher, T. Lohse, T. Martini, S. Möllbitz, P. Rieck, and P. Uwer, HatHor for single top-quark


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(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 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, 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 (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, 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, Turkey
20dBahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
21Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
22aINFN 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
26Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
26aElectrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
26bFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
26cInstituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27Physics Department, Brookhaven National Laboratory, Upton, New York, USA
28aTransilvania University of Brasov, Brasov, Romania, Romania
28bNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
28cNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
28dUniversity Politehnica Bucharest, Bucharest, Romania
28eWest University in Timisoara, Timisoara, Romania
29Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
30Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31Department of Physics, Carleton University, Ottawa, Ontario, Canada
32CERN, Geneva, Switzerland
33Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
34aDepartamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
34bDepartamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

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76Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
77Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
78School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
79Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
80Department of Physics and Astronomy, University College London, London, United Kingdom
81Louisiana Tech University, Ruston, Louisiana, USA
82Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
83Fysiska institutionen, Lunds universitet, Lund, Sweden
84Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
85Institut für Physik, Universität Mainz, Mainz, Germany
86School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
87CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
88Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
89Department of Physics, McGill University, Montreal, Québec, Canada
90School of Physics, University of Melbourne, Victoria, Australia
91Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
92Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
93aINFN Sezione di Milano, Italy
93bDipartimento di Fisica, Università di Milano, Milano, Italy
94B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
95National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
96Group of Particle Physics, University of Montreal, Montreal, Québec, Canada
97P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
98Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
99National Research Nuclear University MEPhI, Moscow, Russia
100D. V. Skobeltsyn Institute of Nuclear Physics, M. V. Lomonosov Moscow State University, Moscow, Russia
101Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
102Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
103Nagasaki Institute of Applied Science, Nagasaki, Japan
104Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
105INFN Sezione di Napoli, Italy
106Dipartimento di Fisica, Università di Napoli, Napoli, Italy
107Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
108INFN Sezione di Napoli, Italy
109Dipartimento di Fisica, Università di Napoli, Napoli, Italy
110Department of Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
111National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
112Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
113Ohio State University, Columbus, Ohio, USA
114Faculty of Science, Okayama University, Okayama, Japan
115Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
116Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
117Palacký University, RCPTM, Olomouc, Czech Republic
118Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
119LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
120Graduate School of Science, Osaka University, Osaka, Japan
121Department of Physics, University of Oslo, Oslo, Norway
122Department of Physics, Oxford University, Oxford, United Kingdom
123Dipartimento di Fisica, Università di Pavia, Pavia, Italy
124Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
125National Research Centre “Kurchatov Institute” B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
126INFN Sezione di Pavia, Italy
127INFN Sezione di Pisa, Italy
128Dipartimento di Fisica, Università di Pisa, Pisa, Italy

032003-29
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal

Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

Department of Physics, University of Coimbra, Coimbra, Portugal

Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

Departamento de Física, Universidade do Minho, Braga, Portugal

Departamento de Física Teorica y del Cosmos and CAFPE, Universidade de Granada, Granada, Spain

Dep Física and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

Department of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

Czech Technical University in Prague, Praha, Czech Republic

Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic

State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia

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

INFN Sezione di Roma, Italy

Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy

INFN Sezione di Roma Tor Vergata, Italy

Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

INFN Sezione di Roma Tre, Italy

Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies - Université Hassan II, Casablanca, Morocco

Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco

Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco

Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco

Facultés des sciences, Université Mohammed V, Rabat, Morocco

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

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA

Department of Physics, University of Washington, Seattle, Washington, USA

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

Department of Physics, Shinshu University, Nagano, Japan

Fachbereich Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada

SLAC National Accelerator Laboratory, Stanford, California, USA

Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic

Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

Department of Physics, University of Cape Town, Cape Town, South Africa

Department of Physics, University of Johannesburg, Johannesburg, South Africa

School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University, Sweden

The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA

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

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

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

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

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

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

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

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

Department of Physics, University of Toronto, Toronto, Ontario, Canada

TRIUMF, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, York University, Toronto, Ontario, 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) and Departamento de Física Atomica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMTM), University of Valencia and CSIC, Valencia, Spain

Department of Physics, 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

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 Department of Physics, California State University, Fresno CA, USA.

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

Also at Department of Física de la Universitat Autonoma de Barcelona, Barcelona, Spain.

Also at Departamento de Física e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.

Also at Tomsk State University, Tomsk, Russia.

Also at Universita di Napoli Parthenope, Napoli, Italy.

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

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

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

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

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

Also at Louisiana Tech University, Ruston LA, USA.

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

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

Also at Department of Physics, National Tsing Hua University, Taiwan.

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 of 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 Hellenic Open University, Patras, Greece.

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

Also at School of Physics, Shandong University, Shandong, China.

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

Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at Eotvos Lorand University, Budapest, Hungary.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.

Also at School of Physics and Engineering, 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 Institute of Physics, Academia Sinica, Taipei, Taiwan.

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 Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

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

Also at Flensburg University of Applied Sciences, Flensburg, Germany.

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

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

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