Search for pair production of gluinos decaying via stop and sbottom in events with $b$-jets and large missing transverse momentum in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
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 ($\tilde{t}_1$), 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: $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ ($\tilde{b} \rightarrow b\tilde{\chi}_1^0$). 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 $\tilde{g} \rightarrow b\tilde{g}_L\tilde{\chi}_1^0$ or $\tilde{g} \rightarrow t\tilde{g}_R\tilde{\chi}_1^0$, and that the only parameters of the simplified models are the gluino and $\tilde{\chi}_1^0$ masses.$^1$

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

$^1$Models with on-shell sbottom and stop were studied in Run 1 [17], and the limits on the gluino and the $\tilde{g}_L$ masses were found to be mostly independent of the stop and sbottom masses, except when the stop is very light.
**FIG. 1.** The decay topologies in the (a) Gbb and (b) Gtt simplified models.

experimental signature also contains four $b$ jets and $E_T^{miss}$, 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 ($W \rightarrow q\bar{q}$). 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 $E_T^{miss}$, 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 $\tilde{\chi}^0_1$ masses. For the Gtt models with a large mass difference (mass splitting) between the gluino and $\tilde{\chi}^0_1$, 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 $E_T^{miss}$ [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. 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.
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 fb$^{-1}$ with an associated uncertainty of ±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 $G\bar{b}b$ and $Gtt$ processes are generated with up to two additional partons using MADGRAPH$_5$$_{\text{aMC}}$@NLO [38] v2.2.2 at leading order (LO) with CTEQ6L1 [39] parton density function (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 $t\bar{t}t\bar{t}$, $W/Z+jets$ and $WW/WZ/ZZ$ (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 MADGRAPH$_5$$_{\text{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 $G\bar{b}b$ signals, are passed through the full ATLAS detector simulation using GEANT4 [55,56]. The $G\bar{b}b$ signal samples are passed through a fast simulation that uses a parameterized 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 UEEE5 [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>MADGRAPH$<em>5$$</em>{\text{aMC}}$@NLO-2.2.1 + HERWIG++-2.7.1</td>
<td>UEEE5</td>
<td>CT10</td>
<td>NLO [66]</td>
</tr>
<tr>
<td>Dibosons</td>
<td>SHERPA-2.1.1</td>
<td>Default</td>
<td>CT10</td>
<td>NNLO [67]</td>
</tr>
<tr>
<td>WW, WZ, ZZ</td>
<td>SHERPA-2.1.1</td>
<td>Default</td>
<td>CT10</td>
<td>NNLO [67]</td>
</tr>
</tbody>
</table>

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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 $t\bar{t}t\bar{t}$, $W/Z+jets$ and $WW/WZ/ZZ$ (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 MADGRAPH$_5$$_{\text{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].

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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 $p_T > 0.4 \text{ GeV}$ 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 ($\sum |p_{T,\text{track}}|^2$) [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 noncollision sources or detector noise [79]. Further selections are applied to reject jets that originate from pileup interactions [80]. Candidate jets are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.8$. Signal jets, selected after resolving overlaps with electrons and muons, are required to satisfy the stricter requirement of $p_T > 30 \text{ GeV}$.

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 $p_T > 300 \text{ GeV}$ and to have $|\eta| < 2.0$. A large-$R$ jet is tagged as a top candidate if it has a mass above 100 GeV.

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 $p_T > 20 \text{ GeV}$ 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 $\max(0.2, 10/p_T^{lep})$, where $p_T^{lep}$ 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 transverse momentum ($p_T^{\text{miss}}$) 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 Gbb signal regions employ the inclusive effective mass $m^{\text{incl}}_{\text{eff}}$,

$$m^{\text{incl}}_{\text{eff}} = \sum_i p_{T,jet,i} + \sum_j p_{T,\ell} + E_T^{\text{miss}},$$

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 $m^{4j}_{\text{eff}}$,

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

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 $W + \text{jets}$ events,

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

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 $m^{b\text{-jets}}_{T,\text{min}}$, the minimum transverse mass formed by $E_T^{\text{miss}}$ and any of the three leading $b$-tagged jets in the event,

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

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, $\Delta \phi^{4j}_{\text{min}}$, is required to be greater than 0.4,

$$\Delta \phi^{4j}_{\text{min}} = \min(|\phi_{jet1} - \phi_{p_T^{\text{miss}}}|, \ldots, |\phi_{jet4} - \phi_{p_T^{\text{miss}}}|) > 0.4.$$

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 $E_T^{\text{miss}}$, $m^{\text{incl}}_{\text{eff}}$, $m^{b\text{-jets}}_{T,\text{min}}$, 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 $\Delta \phi^{4j}_{\text{min}} > 0.4$. Figure 3 shows the multiplicity of signal jets, $b$-tagged signal jets, top-tagged large-$R$ jets, and signal leptons in the preselection. 

\footnote{$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ defines the distance between objects in $(\eta, \phi)$ space.}
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 $\ell\bar{\ell}$ 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 extrapolation over $m_T$ for the Gtt 1-lepton region A is denoted by “VR-$m_T$-Gtt-IL-A.”

The experimental signature for the Gbb model is characterized by four high-$p_T$ $b$ jets, large $E_T^{\text{miss}}$, and no leptons [Fig. 1(a)]. The following requirements are applied to all Gbb signal regions. Events containing a candidate lepton are vetoed and at least four signal small-$R$ jets are required, of which at least three must be $b$ tagged. The remaining multijet background is rejected by requiring $\Delta R_{\text{min}} > 0.4$. The Gbb signal regions are described in the leftmost column of Table II. The three signal regions A, B, and C are designed to cover Gbb models with large ($\gtrsim 1$ TeV), moderate (between $\approx 200$ GeV and $\approx 1$ TeV), and small ($\lesssim 200$ GeV) mass splittings between the gluino.
FIG. 3. Distributions of the number of (a) signal jets, (b) $b$-tagged jets, (c) top-tagged large-$R$ jets, and (d) signal leptons in the preselection region described in the text. 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 $t\bar{t}h$, $t\bar{t}t\bar{t}$, and diboson events. Example signal models with cross sections enhanced by a factor of 100 are overlaid for comparison.

and the LSP, respectively. All regions feature stringent cuts on $E_T^{miss}$, $m_{4j}^T$, and the jet transverse momentum $p_T^{jet}$.

The experimental signature for the Gt model is characterized by several high-$p_T$ jets of which four are $b$ jets, large $E_T^{miss}$, and potentially leptons [Fig. 1(b)]. The Gt signal regions are classified into regions with a signal lepton veto (0-lepton channel) and regions with at least one signal lepton (1-lepton channel). The Gt 0-lepton signal regions are defined in the leftmost column of Table III. In all Gt 0-lepton signal regions at least eight signal jets, $\Delta \phi_{4j} > 0.4$ and $m_{4j}^{T, \text{min}} > 80$ GeV are required. Three Gt 0-lepton signal regions are defined to cover Gt 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 ($N_{\text{top}}^{\text{all}} \geq 1$). The requirements on $E_T^{miss}$ and $m_{4j}^{T, \text{eff}}$ decrease with the mass splitting between the gluino and the LSP. However, the required number of $b$-tagged jets $N_{b\text{-jet}}^{\text{eff}}$ 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 Gt 1-lepton signal regions are defined in the leftmost column of Table IV. Two signal regions A and B are defined to cover Gt 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 $m_T > 150$ GeV are required. Region A has tighter requirements on $m_{4j}^{T, \text{eff}}$ ($m_{\text{eff}}^{\text{incl}} > 1100$ GeV) and the number of top-tagged large-$R$ jets ($N_{\text{top}}^{\text{all}} \geq 1$). Region B has a softer requirement on $m_{4j}^{T, \text{eff}}$ than region A, but it features a tighter cut on $E_T^{miss}$ 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 $\Delta \phi_{\text{min}}^{ij}$, which is in radians. The jet $p_T$ requirement is also applied to $b$-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>$\cdots$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$N_{\text{Signal Lepton}}$</td>
<td>$1$</td>
<td>$\cdots$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{min}}^{ij}$</td>
<td>$&gt;0.4$</td>
<td>$\cdots$</td>
<td>$&gt;0.4$</td>
<td>$&gt;0.4$</td>
</tr>
<tr>
<td>$m_T^{b-jets}$</td>
<td>$&lt;160$</td>
<td>$\cdots$</td>
<td>$&lt;160$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>Region A (Large mass splitting)</td>
<td>$p_T^{\text{jet}}$</td>
<td>$&gt;90$</td>
<td>$&gt;90$</td>
<td>$&gt;90$</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt;350$</td>
<td>$&gt;250$</td>
<td>$&gt;250$</td>
</tr>
<tr>
<td></td>
<td>$m_{\text{eff}}^{ij}$</td>
<td>$&gt;1600$</td>
<td>$&gt;1200$</td>
<td>$&lt;1400$</td>
</tr>
<tr>
<td>Region B (Moderate mass splitting)</td>
<td>$p_T^{\text{jet}}$</td>
<td>$&gt;90$</td>
<td>$&gt;90$</td>
<td>$&gt;90$</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt;450$</td>
<td>$&gt;300$</td>
<td>$&gt;300$</td>
</tr>
<tr>
<td></td>
<td>$m_{\text{eff}}^{ij}$</td>
<td>$&gt;1400$</td>
<td>$&gt;1000$</td>
<td>$&lt;1400$</td>
</tr>
<tr>
<td>Region C (Small mass splitting)</td>
<td>$p_T^{\text{jet}}$</td>
<td>$&gt;30$</td>
<td>$&gt;30$</td>
<td>$&gt;30$</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt;500$</td>
<td>$&gt;400$</td>
<td>$&gt;400$</td>
</tr>
<tr>
<td></td>
<td>$m_{\text{eff}}^{ij}$</td>
<td>$&gt;1400$</td>
<td>$&gt;1200$</td>
<td>$&lt;1400$</td>
</tr>
</tbody>
</table>

B. Background estimation and $\tilde{t}\tilde{t}$ control regions

The largest background in all signal regions is $\tilde{t}\tilde{t}$ produced with additional high-$p_T$ jets. The other relevant backgrounds are $\tilde{t}\bar{t}W$, $\tilde{t}\bar{t}Z$, $\tilde{t}\tilde{t}f$, $\tilde{t}\bar{t}h$, single-top, $W +$ jets, $Z +$ 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 $\tilde{t}\tilde{t}$ background is normalized in a dedicated control region. The $\tilde{t}\tilde{t}$ normalization factor

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

<table>
<thead>
<tr>
<th>Criteria common to all Gtt 0-lepton regions: $p_T^{\text{jet}} &gt; 30$ GeV</th>
<th>Variable</th>
<th>Signal region</th>
<th>Control region</th>
<th>VR1L</th>
<th>VR0L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria common to all regions of the same type</td>
<td>$N_{\text{Signal Lepton}}$</td>
<td>$0$</td>
<td>$1$</td>
<td>$1$</td>
<td>$0$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi_{\text{min}}^{ij}$</td>
<td>$&gt;0.4$</td>
<td>$\cdots$</td>
<td>$&gt;0.4$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{jet}}$</td>
<td>$\geq 8$</td>
<td>$\geq 7$</td>
<td>$\geq 7$</td>
<td>$\geq 8$</td>
</tr>
<tr>
<td></td>
<td>$m_T^{b-jets}$</td>
<td>$&gt;80$</td>
<td>$\cdots$</td>
<td>$&gt;80$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td></td>
<td>$m_T^{\text{min}}$</td>
<td>$&lt;150$</td>
<td>$&lt;150$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>Region A (Large mass splitting)</td>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt;400$</td>
<td>$&gt;250$</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
</tr>
<tr>
<td></td>
<td>$m_{\text{eff}}^{\text{incl}}$</td>
<td>$&gt;1700$</td>
<td>$&gt;1350$</td>
<td>$&gt;1350$</td>
<td>$&gt;1400$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{b-tag}}^{\text{top}}$</td>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>Region B (Moderate mass splitting)</td>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt;350$</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
</tr>
<tr>
<td></td>
<td>$m_{\text{eff}}^{\text{incl}}$</td>
<td>$&gt;1250$</td>
<td>$&gt;1000$</td>
<td>$&gt;1000$</td>
<td>$&gt;1100$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{b-tag}}^{\text{top}}$</td>
<td>$\geq 4$</td>
<td>$\geq 4$</td>
<td>$\geq 4$</td>
<td>$\geq 3$</td>
</tr>
<tr>
<td>Region C (Small mass splitting)</td>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt;350$</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
<td>$&gt;200$</td>
</tr>
<tr>
<td></td>
<td>$m_{\text{eff}}^{\text{incl}}$</td>
<td>$&gt;1250$</td>
<td>$&gt;1000$</td>
<td>$&gt;1000$</td>
<td>$&gt;1250$</td>
</tr>
<tr>
<td></td>
<td>$N_{\text{b-tag}}^{\text{top}}$</td>
<td>$\geq 4$</td>
<td>$\geq 4$</td>
<td>$\geq 4$</td>
<td>$\geq 3$</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 $E_{T}^{miss}$ and $m_{T}$ are, however, relaxed in the control regions to achieve a sufficiently large $t\bar{t}$ yield and small signal contamination ($<15\%$). The Gtt 1-lepton control regions are defined by inverting the $m_{T}$ cut and removing the $m_{T,min}^{b-jets}$ 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 $m_{T,min}^{b-jets}$ and $m_{T}^{b-jets}$ to reduce signal contamination and ensure orthogonality with the signal regions. In addition, the requirement on $E_{T}^{miss}$ 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 (VRIL) and one with a signal lepton veto (VROL). The regions VRIL have exactly the same criteria as their corresponding control regions except that they require $m_{T,min}^{b-jets} > 80$ GeV, similar to the signal regions, in order to test the extrapolation over $m_{T,min}^{b-jets}$ between the control and the signal regions. Simulation studies show that the heavy-flavor fraction of the additional jets in the $t\bar{t} + \text{jets}$ 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 VRIL regions. This is achieved by requiring the same number of $b$-tagged jets for all three types of regions.

### 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>Criteria common to all Gtt 1-lepton regions: $\geq 1$ signal lepton, $p_{T}^{signal} &gt; 30$ GeV</th>
<th>Variable</th>
<th>Signal region</th>
<th>Control region</th>
<th>VR-$m_{T}$</th>
<th>VR-$m_{T,min}^{b-jets}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria common to all regions of the same type</td>
<td>$m_{T}$</td>
<td>$&gt; 150$</td>
<td>$&lt; 150$</td>
<td>$&gt; 150$</td>
<td>$&lt; 150$</td>
</tr>
<tr>
<td></td>
<td>$N^{b-tag}$</td>
<td>$\geq 6$</td>
<td>$= 6$</td>
<td>$\geq 5$</td>
<td>$\geq 6$</td>
</tr>
<tr>
<td></td>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
<td>$= 3$</td>
<td>$= 3$</td>
<td></td>
</tr>
<tr>
<td>Region A (Large mass splitting)</td>
<td>$E_{T}^{miss}$</td>
<td>$&gt; 200$</td>
<td>$&gt; 200$</td>
<td>$&gt; 200$</td>
<td>$&gt; 200$</td>
</tr>
<tr>
<td></td>
<td>$m_{T}^{incl}$</td>
<td>$&gt; 1100$</td>
<td>$&gt; 1100$</td>
<td>$&gt; 600$</td>
<td>$&gt; 600$</td>
</tr>
<tr>
<td></td>
<td>$m_{T}^{eff}$</td>
<td>$&gt; 160$</td>
<td>$\cdots$</td>
<td>$\leq 160$</td>
<td>$\leq 140$</td>
</tr>
<tr>
<td></td>
<td>$N^{top}$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>Region B (Moderate to small mass splitting)</td>
<td>$E_{T}^{miss}$</td>
<td>$&gt; 300$</td>
<td>$&gt; 300$</td>
<td>$&gt; 200$</td>
<td>$&gt; 200$</td>
</tr>
<tr>
<td></td>
<td>$m_{T}^{incl}$</td>
<td>$&gt; 900$</td>
<td>$&gt; 900$</td>
<td>$&gt; 600$</td>
<td>$&gt; 600$</td>
</tr>
<tr>
<td></td>
<td>$m_{T}^{b-jets}$</td>
<td>$&gt; 160$</td>
<td>$\cdots$</td>
<td>$&lt; 160$</td>
<td>$&lt; 160$</td>
</tr>
</tbody>
</table>
While the theoretical uncertainties in the heavy-flavor fraction of the additional jets in the $\ell \ell + \text{jets}$ events (i.e., $\ell \ell + b \bar{b}$ and $\ell \ell + c \bar{c}$) 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 $\ell \ell$ 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 $m_{T,\text{min}}^{b\text{-jets}} < 80$ GeV is applied to all VR0L regions to ensure orthogonality with the signal regions. The regions VR0L test the extrapolation of the $\ell \ell$ normalization from a 1-lepton to a 0-lepton region. Simulation studies show that the VR0L regions have a composition of semileptonic $\ell \ell$ 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 $\ell \ell$ 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 $m_{T,\text{min}}^{b\text{-jets}}$ (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-$m_{T,\text{min}}^{b\text{-jets}}$, which respectively test, one at a time, the extrapolations over $m_T$ and $m_{T,\text{min}}^{b\text{-jets}}$. 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 $m_{T,\text{min}}^{b\text{-jets}}$ is inverted. Other requirements are relaxed to achieve sufficiently large background yields and small signal contamination. For the VR-$m_{T,\text{min}}^{b\text{-jets}}$ 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 $\ell \ell$ dilepton events dominate in the signal regions, in particular due to the requirement on $m_T$, while semileptonic $\ell \ell$ events dominate in the control regions. This extrapolation is cross-checked by the VR-$m_T$ regions, which have a $\ell \ell$ 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 $\ell \ell$ 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 v6.4.28 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 $\ell \ell$ 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 $\ell \ell$ 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 $\ell \ell$ 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 $W/Z + \text{jets}$ 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 variations in the expected background yields due to $t\bar{t}$ modeling uncertainties range between 10% and 30% for the $Gbb$ signal regions, and between 47% and 57% in most $Gtt$ signal regions. 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
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 $t\bar{t}$ events in all Gbb and Gtt signal regions. The subdominant contributions in the Gbb and Gtt 0-lepton signal regions are $Z(\rightarrow \nu \bar{\nu}) + \text{jets}$ 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, $t\bar{t}W$ and $t\bar{t}Z$.

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. Results of the likelihood fit extrapolated to the Gbb 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 background category “Others” includes $t\bar{t}h$, $t\bar{t}t$, and diboson events. Expected yields for two example Gbb models are also shown. |
|------------------|------------------|------------------|
|                  | SR-Gbb-A         | SR-Gbb-B         | SR-Gbb-C         |
| Fitted background events | $1.3 \pm 0.4$   | $1.5 \pm 0.6$   | $7.6 \pm 1.7$   |
| $t\bar{t}$       | $0.63 \pm 0.30$ | $0.9 \pm 0.5$   | $4.3 \pm 1.5$   |
| $Z + \text{jets}$| $0.23 \pm 0.08$ | $0.23 \pm 0.09$ | $1.2 \pm 0.5$   |
| $W + \text{jets}$| $0.17 \pm 0.06$ | $0.13 \pm 0.05$ | $0.82 \pm 0.28$ |
| Single-top       | $0.25 \pm 0.14$ | $0.15 \pm 0.14$ | $0.65 \pm 0.33$ |
| $t\bar{t}W/Z$    | $<0.1$           | $<0.1$           | $0.22 \pm 0.12$ |
| Others           | $<0.1$           | $<0.1$           | $0.39 \pm 0.22$ |
| MC-only background prediction | $1.7$ | $1.5$ | $6.7$ |
| $\mu_{t\bar{t}}$| $0.64 \pm 0.33$ | $1.0 \pm 0.4$   | $1.2 \pm 0.4$   |
| Gbb ($m_g = 1700$ GeV, $m_{\chi^0} = 200$ GeV) | $3.8$ | $3.5$ | $4.2$ |
| Gbb ($m_g = 1400$ GeV, $m_{\chi^0} = 800$ GeV) | $5.3$ | $7.2$ | $10.5$ |

| TABLE VI. Results of the likelihood fit extrapolated to the Gtt 0-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. |
|------------------|------------------|------------------|
|                  | SR-Gtt-0L-A      | SR-Gtt-0L-B      | SR-Gtt-0L-C      |
| Fitted background events | $2.1 \pm 0.5$   | $2.9 \pm 1.8$   | $3.4 \pm 1.8$   |
| $t\bar{t}$       | $1.4 \pm 0.4$   | $2.4 \pm 1.7$   | $2.6 \pm 1.8$   |
| $Z + \text{jets}$| $0.22 \pm 0.09$ | $0.11 \pm 0.06$ | $0.14 \pm 0.07$ |
| $W + \text{jets}$| $0.19 \pm 0.08$ | $0.14 \pm 0.06$ | $0.18 \pm 0.08$ |
| Single-top       | $0.17 \pm 0.17$ | $0.14 \pm 0.13$ | $0.17 \pm 0.15$ |
| $t\bar{t}W/Z$    | $<0.1$           | $<0.1$           | $0.10 \pm 0.07$ |
| Others           | $<0.1$           | $<0.1$           | $0.20 \pm 0.17$ |
| MC-only background prediction | $1.8$ | $1.9$ | $2.5$ |
| $\mu_{t\bar{t}}$| $1.3 \pm 0.4$   | $1.8 \pm 0.8$   | $1.5 \pm 0.7$   |
| Gtt ($m_g = 1600$ GeV, $m_{\chi^0} = 200$ GeV) | $3.8$ | $2.8$ | $2.9$ |
| Gtt ($m_g = 1400$ GeV, $m_{\chi^0} = 800$ GeV) | $2.0$ | $3.7$ | $4.1$ |
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 CLs 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 ($S_{\text{obs}}^{95}$) and expected ($S_{\text{exp}}^{95}$) 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 CLs prescription in the asymptotic approximation [97]. The signal contamination in the control regions and the experimental

| 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>Signal region</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 ± 0.6</td>
<td>1.2 ± 0.8</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.8 ± 0.6</td>
<td>0.8 ± 0.7</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>$\ldots$</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 ± 0.14</td>
<td>0.14 ± 0.12</td>
</tr>
<tr>
<td>$t\bar{t}W/Z$</td>
<td>0.14 ± 0.08</td>
<td>0.15 ± 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 ± 0.28</td>
<td>1.0 ± 0.4</td>
</tr>
<tr>
<td>Gtt ($m_{\tilde{g}} = 1600$ GeV, $m_{\tilde{\chi}_1} = 200$ GeV)</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Gtt ($m_{\tilde{g}} = 1400$ GeV, $m_{\tilde{\chi}_1} = 800$ GeV)</td>
<td>3.8</td>
<td>4.6</td>
</tr>
</tbody>
</table>

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.
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 theory lines around the observed limits are obtained by changing the SUSY cross section by 1 standard deviation, as described in Sec. III. The yellow band around the expected limit shows the ±1σ 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>$S_{\text{obs}}^{95}$</th>
<th>$S_{\text{exp}}^{95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-Gbb-A</td>
<td>0.94</td>
<td>3.0</td>
<td>3.9±1.3</td>
</tr>
<tr>
<td>SR-Gbb-B</td>
<td>0.94</td>
<td>3.0</td>
<td>3.8±1.4</td>
</tr>
<tr>
<td>SR-Gbb-C</td>
<td>1.74</td>
<td>5.6</td>
<td>7.2±2.6</td>
</tr>
<tr>
<td>SR-Gtt-1L-A</td>
<td>1.49</td>
<td>4.8</td>
<td>3.9±1.4</td>
</tr>
<tr>
<td>SR-Gtt-1L-B</td>
<td>0.91</td>
<td>3.0</td>
<td>3.0±1.4</td>
</tr>
<tr>
<td>SR-Gtt-0L-A</td>
<td>1.13</td>
<td>3.6</td>
<td>4.4±1.7</td>
</tr>
<tr>
<td>SR-Gtt-0L-B</td>
<td>1.16</td>
<td>3.7</td>
<td>4.4±1.9</td>
</tr>
<tr>
<td>SR-Gtt-0L-C</td>
<td>1.10</td>
<td>3.5</td>
<td>4.5±2.0</td>
</tr>
</tbody>
</table>

FIG. 6. Distributions of $E_T^{\text{miss}}$ for (a) SR-Gbb-B, (b) SR-Gtt-0L-C, and (c) SR-Gtt-1L-A. The $E_T^{\text{miss}}$ threshold is set to 200 GeV for these plots, with the red lines indicating the threshold values in the actual signal regions for SR-Gbb-B and SR-Gtt-0L-C (the $E_T^{\text{miss}}$ threshold in SR-Gtt-1L-A is 200 GeV). The statistical and experimental systematic uncertainties are included in the uncertainty band. Two example signal models are overlaid.

TABLE VIII. The 95% C.L. upper limits on the visible cross section ($\sigma_{\text{vis}}$), defined as the product of acceptance, reconstruction efficiency, and production cross section, and the observed and expected 95% C.L. upper limits on the number of BSM events ($S_{\text{obs}}^{95}$ and $S_{\text{exp}}^{95}$).
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-1L-B and SR-Gtt-0L-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-1L-B and SR-Gtt-0L-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.

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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(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, 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
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

032003-27
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Modern Physics, University of Science and Technology of China, Anhui, China
Department of Physics, Nanjing University, Jiangsu, China
School of Physics, Shandong University, Shandong, China
Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (also affiliated with PKU-CHEP), China
Physics Department, Tsinghua University, Beijing 100084, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Physics Department, Tsinghua University, Beijing 100084, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Department of Physics, University of Copenhagen, Kobenhavn, Denmark
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
Institut 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 Carolina, USA
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Italy
Dipartimento di Fisica, Università di Genova, 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
Department of Physics, Hampton University, Hampton, Virginia, USA
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
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, 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, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
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
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
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96 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
77 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
78 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
79 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
80 Department of Physics and Astronomy, University College London, London, United Kingdom

81 Louisiana Tech University, Ruston, Louisiana, USA
82 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
83 Fysiska institutionen, Lunds universitet, Lund, Sweden
84 Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
85 Institut für Physik, Universität Mainz, Mainz, Germany
86 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
87 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
88 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
89 Department of Physics, McGill University, Montreal, Québec, Canada
90 School of Physics, University of Melbourne, Victoria, Australia
91 Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
92 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

93 INFN Sezione di Milano, Italy
94 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
95 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
96 Group of Particle Physics, University of Montreal, Montreal, Québec, Canada
97 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
98 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
99 National Research Nuclear University MEPhI, Moscow, Russia
100 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
101 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
102 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
103 Nagasaki Institute of Applied Science, Nagasaki, Japan
104 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
105 INFN Sezione di Napoli, Italy
106 Dipartimento di Fisica, Università di Napoli, Napoli, Italy
107 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
108 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
109 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
110 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
111 Department of Physics, New York University, New York, New York, USA
112 Ohio State University, Columbus, Ohio, USA
113 Faculty of Science, Okayama University, Okayama, Japan
114 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
115 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
116 Palacký University, RCPTM, Olomouc, Czech Republic
117 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
118 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
119 Graduate School of Science, Osaka University, Osaka, Japan
120 Department of Physics, University of Oslo, Oslo, Norway
121 Department of Physics, Oxford University, Oxford, United Kingdom
122 INFN Sezione di Pavia, Italy
123 Dipartimento di Fisica, Università di Pavia, Pavia, Italy
124 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
125 National Research Centre “Kurchatov Institute” B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
126 INFN Sezione di Pisa, Italy
127 Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
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161 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
163 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
164 INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
165 ICTP, Trieste, Italy
166 Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
168 Department of Physics, University of Illinois, Urbana, Illinois, USA
169 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
170 Department of Physics, University of Warwick, Coventry, United Kingdom
171 Waseda University, Tokyo, Japan
172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
173 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
175 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
176 Department of Physics, Yale University, New Haven, Connecticut, USA
177 Yerevan Physics Institute, Yerevan, Armenia
178 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

aDeceased.
bAlso at Department of Physics, King’s College London, London, United Kingdom.
cAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
dAlso at Novosibirsk State University, Novosibirsk, Russia.
eAlso at TRIUMF, Vancouver BC, Canada.
fAlso at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
gAlso at Department of Physics, California State University, Fresno CA, USA.
hAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.
iAlso at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
jAlso at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
kAlso at Tomsk State University, Tomsk, Russia.
lAlso at Universita di Napoli Parthenope, Napoli, Italy.
mAlso at Institute of Particle Physics (IPP), Canada.
nAlso at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
oAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
pAlso at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
qAlso at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
rAlso at Louisiana Tech University, Ruston LA, USA.
sAlso at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
tAlso at Graduate School of Science, Osaka University, Osaka, Japan.
uAlso at Department of Physics, National Tsing Hua University, Taiwan.
wAlso at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
xAlso at Department of Physics, The University of Texas at Austin, Austin TX, USA.
yAlso at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
zAlso at CERN, Geneva, Switzerland.
a Also at Georgian Technical University (GTU), Tbilisi, Georgia.
b Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
c Also at Manhattan College, New York NY, USA.
d Also at Hellenic Open University, Patras, Greece.
e Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
f Also at School of Physics, Shandong University, Shandong, China.
g Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
h Also at Section de Physique, Université de Genève, Geneva, Switzerland.

032003-31
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 Flensburg University of Applied Sciences, Flensburg, Germany.

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

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