Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector

Aaboud, M.; The ATLAS Collaboration

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A search for long-lived, massive particles predicted by many theories beyond the Standard Model is presented. The search targets final states with large missing transverse momentum and at least one high-mass displaced vertex with five or more tracks, and uses 32.8 fb⁻¹ of \(\sqrt{s} = 13\) TeV pp collision data collected by the ATLAS detector at the LHC. The observed yield is consistent with the expected background. The results are used to extract 95% C.L. exclusion limits on the production of long-lived gluinos with masses up to 2.37 TeV and lifetimes of \(O(10^{-2}) - O(10)\) ns in a simplified model inspired by split supersymmetry.

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I. INTRODUCTION

The lack of explanation for the dark matter observed in the universe [1], the gauge hierarchy problem [2,3], and the lack of exact gauge coupling unification at high energies [4] all indicate that the Standard Model (SM) is incomplete and needs to be extended. Many attractive extensions of the SM have been proposed, but decades of searches have set severe constraints on the masses of promptly decaying particles predicted by these models. Searches targeting the more challenging experimental signatures of new long-lived particles (LLPs) have therefore become increasingly important and must be pursued at the Large Hadron Collider (LHC).

A number of beyond-SM (BSM) models predict the existence of massive particles with lifetimes in the picoseCONDS to nanoseconds range. Many of these particles would decay in the inner tracker volume of the experiments at the LHC. The decay products of such particles often contain several electrically charged particles, which can be reconstructed as tracks. If the LLP decays within the tracking volume but at a discernible distance from the interaction point (IP) of the incoming beams, a displaced vertex can be reconstructed by using dedicated tracking and vertexing techniques.

There are various mechanisms by which particles obtain significant lifetimes in BSM theories. The decays of such particles can be suppressed in so-called hidden valley models [5] where large barrier potentials reduce the rate of kinematically allowed decays. Long-lived particles also appear in models with small couplings, such as those often found in \(R\)-parity-violating supersymmetry (SUSY) [6,7]. Finally, decays via a highly virtual intermediate state also result in long lifetimes, as is the case for a simplified model inspired by split SUSY [8,9] used as a benchmark model for the search presented here. In this model, the supersymmetric partner of the gluon, the gluino \(\tilde{g}\), is kinematically accessible at LHC energies while the SUSY partner particles of the quarks, the squarks \(\tilde{q}\), have masses that are several orders of magnitude larger. Figure 1 shows pair production of gluinos decaying to two quarks and the lightest supersymmetric particle (LSP), assumed to be the lightest neutralino \(\tilde{\chi}_1^0\). The \(\tilde{g} \to q \tilde{\chi}_1^0\) decay is suppressed as it proceeds via a highly virtual squark. Depending on the scale of the squark mass, the gluino lifetime can be picoseconds or longer, which is above the hadronization

FIG. 1. Diagram showing pair production of gluinos decaying through \(\tilde{g} \to q \tilde{\chi}_1^0\) via a virtual squark \(\tilde{q}\). In split SUSY scenarios, because of the very large squark mass, the gluinos are long-lived enough to hadronize into \(R\)-hadrons that can give rise to displaced vertices when they decay.
time scale. Therefore, the long-lived gluino, which transforms as a color octet, is expected to hadronize with SM particles and form a bound color-singlet state known as an R-hadron [10].

This search utilizes the ATLAS detector and attempts to reconstruct the decays of massive R-hadrons as displaced vertices (DVs). The analysis searches for LLP decays occurring $O(1$–100) mm from the reconstructed primary vertex (PV) and is sensitive to decays of both electrically charged and neutral states emerging from the PV. The analysis targets final states with at least one DV with a high reconstructed mass and a large track multiplicity in events with large missing transverse momentum $E_{\text{T}}^{\text{miss}}$. This analysis builds on that of Ref. [11] where the ATLAS Collaboration set limits on such processes using 8 TeV $pp$ collisions from the LHC. In Run 2 of the LHC starting in 2015, the increased center-of-mass energy of $\sqrt{s} = 13$ TeV gives significant increases in the production cross sections of heavy particles, providing extended mass sensitivity compared to previous searches. Decays of new, long-lived particles have been searched for in a variety of experimental settings. These include studies by ATLAS [12–21], CMS [22–29], LHCB [30–33], CDF [34], D0 [35,36], BABAR [37], Belle [38], and ALEPH [39]. The searches involve a range of experimental signatures, including final states with leptons, jets, and combinations thereof. Dedicated techniques make use of nonpointing or delayed photons, as well as tracking, energy, and timing measurements of the long-lived particle itself until it decays.

The experimental apparatus is described in Secs. II, and III discusses the data set and simulations used for this analysis. The special reconstruction algorithms and event selection criteria are presented in Sec. IV. Section V discusses the sources of backgrounds relevant to this search and the methods employed to estimate the expected yields. The sensitivity to experimental and theoretical uncertainties of the analysis is described in Sec. VI. Section VII presents the results and their interpretations.

II. ATLAS DETECTOR

The ATLAS experiment [40,41] at the LHC is a multipurpose particle detector with a forward-backward-symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle. The detector consists of several layers of subdetectors. From the IP outwards there is an inner tracking detector (ID), electromagnetic and hadronic calorimeters, and a muon spectrometer (MS).

1ATLAS uses a right-handed coordinate system with its origin at the nominal IP in the center of the detector and the $z$ axis along the beam pipe. The $x$ axis points from the IP to the center of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates $(R, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.

The ID extends from a cylindrical radius of about 33 mm to 1100 mm and to $|z|$ of about 3100 mm, and is immersed in a 2 T axial magnetic field. It provides tracking for charged particles within the pseudorapidity region $|\eta| < 2.5$. At small radii, silicon pixel layers and stereo pairs of silicon microstrip detectors provide high-resolution position measurements. The pixel system consists of four barrel layers and three forward disks on either side of the IP. The barrel pixel layers, which are positioned at radii of 33.3 mm, 50.5 mm, 88.5 mm, and 122.5 mm are of particular relevance to this work. The silicon microstrip tracker (SCT) comprises four double layers in the barrel and nine forward disks on either side. The radial position of the innermost (outermost) SCT barrel layer is 299 mm (514 mm). The final component of the ID, the transition-radiation tracker (TRT), is positioned at larger radii, with coverage up to $|\eta| = 2.0$.

The calorimeter provides coverage over the range $|\eta| < 4.9$. It consists of an electromagnetic calorimeter based on lead and liquid argon with coverage for $|\eta| < 3.2$ and a hadronic calorimeter. Hadronic calorimetry in the region $|\eta| < 1.7$ uses steel absorbers and scintillator tiles as the active medium. Liquid-argon calorimetry with copper absorbers is used in the hadronic end-cap calorimeters, which cover the region $1.5 < |\eta| < 3.2$. A forward calorimeter using copper and tungsten absorbers with liquid argon completes the calorimeter coverage up to $|\eta| = 4.9$.

The MS consists of three large superconducting toroid systems each containing eight coils and a system of trigger and precision tracking chambers, which provide trigger and tracking capabilities in the range $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively.

A two-level trigger system is used to select events [42]. The first-level trigger is implemented in custom electronics and uses information from the MS trigger chambers and the calorimeters. This is followed by a software-based high-level trigger system, which runs reconstruction algorithms similar to those used in off-line reconstruction. Combined, the two levels reduce the 40 MHz bunch-crossing rate to approximately 1 kHz of events saved for further analysis.

III. DATA SET AND SIMULATED EVENTS

The experimental data used in this paper are from proton-proton ($pp$) collisions at $\sqrt{s} = 13$ TeV collected in 2016 at the LHC. After applying requirements on detector status and data quality, the integrated luminosity of the sample corresponds to 32.8 fb$^{-1}$. The uncertainty in the 2016 integrated luminosity is 2.2%. It is derived, following a methodology similar to that detailed in Ref. [43], from a calibration of the luminosity scale using $x$-$y$ beam-separation scans performed in May 2016. The events in this data set have an average of 25 simultaneous $pp$ interactions in the same bunch crossing.

This search makes use of a number of signal Monte Carlo (MC) samples to determine the efficiency
for selecting signal events and the associated uncertainty. In each sample, gluinos were pair produced in $pp$ collisions and then hadronized, forming metastable $R$-hadrons. The gluino contained in each $R$-hadron later decays to SM quarks and a neutralino as shown in Fig. 1. The mass of the gluino ($m_{\tilde{g}}$) in the simulated samples is between 400 and 2000 GeV, its lifetime $\tau$ varies from 0.01 to 50 ns, and the neutralino mass $m_{\tilde{\chi}}$ ranges from 100 GeV to $m_{\tilde{g}} - 30$ GeV. To evaluate signal efficiencies for lifetimes not simulated, events in the produced samples are reweighted to different lifetimes. The samples were simulated with PYTHIA 6.428 [44]. The AUET2B [45] set of tuned parameters for the underlying event and the CTEQ6L1 [46] parton distribution function (PDF) set are used. Dedicated routines [10,47,48] for hadronization of heavy colored particles were used to simulate the production of $R$-hadrons. The hadronization process primarily yields mesonlike states ($\tilde{g}gq\bar{q}$), but baryonlike states ($\tilde{g}qqq$) and glueball-like states ($\tilde{g}\tilde{g}$) are predicted as well. Following the hadronization, approximately half of the $\tilde{g}$-based $R$-hadrons have electric charge $Q \neq 0$, and the charges of the two $R$-hadrons produced in the event are uncorrelated. The electric charge of the $R$-hadron is determined by its SM parton content, and while $Q = -1, 0$, and 1 dominate, a few percent have double charge. It is worth noting that the vertexing algorithms used in this search (see Sec. IV A) are agnostic to the electric charge of the LLP as well as those reconstructed tracks not associated with these objects. The latter contribution accounts for potential diffuse, low-$p_T$ backgrounds. Hadronic jets are reconstructed from calibrated three-dimensional topo clusters [64] using the anti-$k_T$ jet clustering algorithm [65,66] with a radius parameter of 0.4. Jet candidates are initially calibrated assuming their energy depositions originate from electromagnetic showers, and then corrected by scaling their four-momenta to the energies of their constituent particles [67–70]. Electrons, photons, and muons are also reconstructed and calibrated, although no explicit requirements are placed on them in this search. The $E_T^{\text{miss}}$ is calculated using all calibrated objects as well as those reconstructed tracks not associated with these objects. The latter contribution accounts for potential diffuse, low-$p_T$ imbalances [71,72].

A. Reconstruction of displaced tracks and vertices

In the standard ATLAS tracking algorithm [73], triplets of hits in the pixel and/or the SCT detectors are used to seed the track finding. By adding further hits along the seed trajectories, track candidates are fitted and subsequently extrapolated into the TRT. This algorithm places constraints
on the transverse and longitudinal impact parameters of track candidates with respect to the PV\(^2\) (\(|d_0| < 10\) mm and \(|z_0| < 250\) mm, respectively). These constraints result in low efficiency for reconstructing tracks originating from a DV, as such tracks typically have a larger transverse impact parameter than those emerging from the interaction point.

In order to recover tracks from DVs, an additional large-radius tracking (LRT) algorithm pass \([74]\) is performed, using only hits not already associated with tracks reconstructed by the standard tracking algorithm. Requirements on the impact parameters are relaxed, allowing tracks to have \(|d_0| < 300\) mm and \(|z_0| < 1500\) mm. Furthermore, requirements on the number of hits shared by several tracks are slightly relaxed. The tracks from the standard processing and the LRT processing are treated as a single collection in the subsequent reconstruction steps.

Tracks satisfying \(p_T > 1\) GeV are selected for the DV reconstruction. In order to remove fake tracks, a track is discarded if it simultaneously has no TRT hits and fewer than two pixel hits. Tracks with fewer than two pixel hits are therefore required to fall within the TRT acceptance of the PV. If the seed vertex is inside or within several millimeters of a tracker layer, hits of that particular layer are neither forbidden nor required. Kinematic requirements on the direction of the vector sum of the momenta of the tracks associated with the seed vertex are applied to make sure it is consistent with the decay of a particle originating from the PV.

At this stage, a track can be associated with multiple two-track seed vertices. In order to resolve such ambiguities, an iterative process based on the incompatibility graph approach \([75]\) is applied. After this procedure, each track is associated with at most one seed vertex.

Multitrack DVs are then formed iteratively using the collection of seed vertices. For a given seed vertex \(V_1\), the algorithm finds the seed vertex \(V_2\) that has the smallest value of \(d/\sigma_d\), where \(d\) is the three-dimensional distance between \(V_1\) and \(V_2\), and \(\sigma_d\) is the estimated uncertainty in \(d\). If \(d/\sigma_d < 3\), a single DV is formed from all the tracks of both seed vertices and the merged vertex is refitted. The merging is repeated until no other compatible seed vertices are found. Simultaneously, the significance of each track’s association with its vertex is evaluated upon merging, and poorly associated tracks not satisfying additional criteria are removed before the vertex is refitted. This procedure is repeated until no other tracks fail to meet these criteria. Finally, DVs separated by less than 1 mm are combined and refitted. DV candidates are only considered in this search if they fall in the fiducial volume \(R = \sqrt{x^2 + y^2} < 300\) mm and \(|z| < 300\) mm.

Figure 2 shows the DV reconstruction efficiency, defined as the probability for a true LLP decay to be matched with a reconstructed DV fulfilling the vertex preselection criteria. In (a) the efficiencies with and without the special LRT processing are shown for one benchmark signal, while (b) shows two \(R\)-hadron signal samples with different gluino-neutralino mass differences when using LRT processing.

\(^2\)The PV is required to have at least two associated tracks and satisfy \(|z| < 200\) mm. If several exist, the vertex with the largest \(\sum(p_T^{\text{track}})^2\) is selected.
difference, more and higher $p_T$ particles are produced in the gluino decay, which increases the reconstruction efficiency of the DV.

**B. Material-dominated regions and the effect of disabled detector modules**

An important background in any search for displaced vertices comes from hadronic interactions in material-rich regions of the detector [76,77]. In order to suppress this background, a map defining regions with known material is constructed by studying the positions of DVs in $\sqrt{s} = 13$ TeV minimum-bias data. The map is used to reject vertices within the material regions. In these studies, the vertices from the long-lived SM hadrons $K^0_S$ and $\Lambda^0$ are vetoed by discarding vertices that match their expected track multiplicities and reconstructed masses. The application of the map-based veto significantly reduces the contribution from hadronic interactions at the cost of discarding approximately 42% of the fiducial volume. The material map is visualized in Fig. 3, in which the locations of the observed vertices failing this veto are projected onto the $x-y$ and $R-z$ planes.

In addition to the material veto map, a veto is applied to reject vertices in regions sensitive to the effect of disabled pixel modules. This requirement discards 2.3% of the total fiducial volume.

**C. Event and vertex selections**

All events used in this analysis must satisfy the following selection requirements. First, the data were passed through a filter during prompt reconstruction and were made available in a raw data format in order to facilitate the special processing with dedicated track and DV reconstruction required by this analysis. This initial filtering, used as a common preselection for several searches that require special reconstruction, includes requirements on an $E_T^{\text{miss}}$, multijet, or single-lepton trigger. For the $E_T^{\text{miss}}$-triggered events used in the signal region (SR) of this search, an additional requirement is imposed on hadronic $E_T^{\text{miss}}$, a quantity similar to $E_T^{\text{miss}}$ but with all clusters of energy deposited in the calorimeter calibrated as if they come from hadrons. The filtering of the first 75% of the data set also required the presence of one trackless$^3$ jet with $p_T > 70$ GeV or two trackless jets with $p_T > 25$ GeV, and hadronic $E_T^{\text{miss}} > 130$ GeV. For the last 25% of the data set, the trackless jet requirement was removed and hadronic $E_T^{\text{miss}} > 180$ GeV was required instead. This change was made in order to improve sensitivity for low-$\Delta m$ signal scenarios [78–80], which are unlikely to give rise to jets with high $p_T$ from the displaced decays. The MC events used in this analysis were processed separately in two subsamples with sizes proportional to the integrated luminosities of the two subsamples.

Additional detector-level quality requirements are applied, vetoing events that are affected by calorimeter noise, data corruption, or other effects occurring at the time the data were recorded. Events are required to have at least one PV. To mitigate the contamination of high-$E_T^{\text{miss}}$ events from noncollision background (NCB) processes such as beam halo, additional quality requirements are placed on the leading jet in each event. These requirements use the longitudinal calorimeter-sampling profile of these jets to select for high-$p_T$ hadronic activity originating within the detector volume and reduce NCB contributions to at most 10% early in the event selection. Together with the requirement that such events contain a DV candidate, these criteria

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$^3$A jet is considered trackless if $\sum p_T^{\text{track}} < 5$ GeV, where the sum is taken over all tracks reconstructed in the first reconstruction pass matched to both the PV and the jet.
are called the event preselection and, along with additional DV requirements, are used in the construction of the control region (CR).

To further improve signal sensitivity, the full event selection criteria that are used in the construction of the SR require that the event be recorded by an \( E_T^{\text{miss}} \) trigger and satisfy \( E_T^{\text{miss}} > 250 \text{ GeV} \). This last requirement ensures that the events are in the plateau of the efficiency turn-on curve for both the \( E_T^{\text{miss}} \) trigger and the requirement on the hadronic \( E_T^{\text{miss}} \) described above.

The DV candidates are required to satisfy the following conditions, referred to as the vertex preselection:

1. The vertex position must be within the fiducial volume \( R < 300 \text{ mm} \) and \( |z| < 300 \text{ mm} \).
2. The vertex must be separated by at least 4 mm in the transverse plane from all reconstructed PVs.
3. The vertex must not be in a region that is material rich or affected by disabled detector modules, as described in Sec. IV B.
4. The vertex fit must have \( \chi^2/N_{\text{DOF}} < 5 \).

These vertex preselection criteria ensure high-quality measurements of the DV properties and reduce the number of vertices from instrumental effects. Vertices satisfying these criteria are used in the background estimation. For the final vertex selection used in the SR of this search, vertices are required to have at least five associated tracks and a reconstructed invariant mass \( m_{\text{DV}} > 10 \text{ GeV} \). These stricter requirements allow the use of vertices with lower mass and 3–4 tracks for building and validating background estimates, and give a low-background search with good signal sensitivities for a large part of the parameter space for the models of interest.

Figure 4 shows the acceptance times efficiency (\( A \times \varepsilon \)) of the SR, for several benchmark signal models. In Fig. 4(a), the \( A \times \varepsilon \) is shown for models with different gluino and neutralino masses but fixed lifetime of 1 ns. The \( A \times \varepsilon \) depends strongly on the gluino-neutralino mass difference, which is directly proportional to the visible DV mass. For models with \( m_{\tilde{g}} > 1.5 \text{ TeV} \) and \( \Delta m > 1 \text{ TeV} \), the search presented here attains an acceptance times efficiency of as much as 40%. For models with \( \Delta m \lesssim 100 \text{ GeV} \) the \( A \times \varepsilon \) is 5% or lower. In Fig. 4(b), \( \Delta m \) is fixed at 100 GeV while the lifetime \( \tau \) is varied within 0.01 ns < \( \tau \) < 10 ns. The \( A \times \varepsilon \) is highest for lifetimes around 0.1 ns [corresponding to decay lengths of \( O(10) \text{ mm} \)]. Signal models with low \( \Delta m \) are less likely to pass both the event- and vertex-level requirements, due to lower intrinsic \( E_T^{\text{miss}} \) and smaller visible DV mass.

V. BACKGROUND PROCESSES AND THEIR ESTIMATED YIELDS

Given the requirements on the mass (\( m_{\text{DV}} > 10 \text{ GeV} \)) and track multiplicity (\( n_{\text{tracks}} \geq 5 \)) placed on the DV candidates in the SR, there is no irreducible background from SM processes. The entirety of the background expected for this search is instrumental in origin. Three sources of such backgrounds are considered in the analysis. Hadronic interactions can give rise to DVs far from the interaction point, especially where there is material in the detector, support structures, and services. Decays of short-lived SM particles can occur close to each other and be combined into high-mass vertices with large track multiplicities, in particular in the regions closest to the beams. Finally, low-mass vertices from decays of SM particles or hadronic interactions can be promoted to higher mass if accidentally crossed by an unrelated track at a large angle. Each source of background is estimated with a dedicated method, and is separately evaluated in 12 radial detector regions\(^4\) divided approximately by material structures in the ID volume within the fiducial region.

\(^{4}\)The boundaries for these regions are at \( R = 22, 25, 29, 38, 46, 73, 84, 111, 120, 145, 180, \) and 300 mm.
To retain a large number of DVs, the estimates below are performed on events satisfying the event preselection criteria. To obtain a final estimate for the SR, an additional \( \varepsilon_{\text{SR}} \) is applied to account for the potential effect of the assumptions made by this method and the related uncertainties. An additional factor \( \kappa \) is applied to account for the potential effect of obtaining multiple DVs per event but is found to be consistent with 1.0 for the region of DV properties probed in this search.

A. Hadronic interactions

As discussed in Sec. IV, the bulk of the hadronic interactions occur in detector regions with dense material, and these are rejected using the material map. However, residual hadronic interactions may survive the selections, either due to imperfections in the material map or from interactions with gas molecules in regions without solid material. The low-mass region of the \( m_{\text{DV}} \) distribution is dominated by hadronic interactions. Therefore, to estimate this background in the SR, the \( m_{\text{DV}} \) distribution in the region \( m_{\text{DV}} < 10 \text{ GeV} \) is fit to an exponential distribution and extrapolated to the SR with \( m_{\text{DV}} > 10 \text{ GeV} \). The assumptions made by this method and the related uncertainties are discussed in Sec. VI.

B. Merged vertices

The high density of vertices at small radii and the last step of the DV reconstruction, where vertices are combined if they are separated by less than 1 mm, could result in the merging of two DVs with low masses and track multiplicities into a single DV with significantly higher mass and track multiplicity. To quantify this contribution, vertices from distinct events are randomly merged. The distribution of the distance \( d(V_1, V_2) \) between two 2-track or 3-track vertices \( V_1 \) and \( V_2 \) is studied. To obtain a large sample of reference DV pairs, \( d(V_1, V_2) \) is measured in a sample in which \( V_1 \) and \( V_2 \) are taken from different events. This sample is then compared to the sample constructed only from pairs of vertices appearing in the same event. Each of the vertices in these pairs is required to satisfy the DV preselection criteria, and their combined mass is required to be greater than 10 GeV. The resulting distributions are shown in Fig. 5(a) for pairs of 2-track vertices \( (2 + 2) \) and 5(b) for the case of a 2-track vertex paired with a 3-track vertex \( (2 + 3) \). To extract an estimate of the number of SR vertices merged during DV reconstruction, the different-event distribution is normalized to the same-event distribution in the region \( d(V_1, V_2) > 1 \text{ mm} \), and the estimated contribution from merged vertices is given by the scaled template’s integral for \( d(V_1, V_2) < 1 \text{ mm} \).

It is found that the \( z \) positions of \( V_1 \) and \( V_2 \) in the same-event sample are correlated, since they are likely to originate from the same hard-scatter primary vertex. Naturally, this effect is absent in the different-event sample. As a result, the distributions of the longitudinal distance between the vertices in the different-event and same-event samples differ by up to 30% at low values of \( d(V_1, V_2) \). To correct for this difference between the two samples, the DV pairs in the different-event sample are reweighted to match the distribution of distances in \( z \) in the same-event sample before the yield for \( d(V_1, V_2) < 1 \text{ mm} \) is extracted. After applying the weights, the model distribution of the three-dimensional distance \( d(V_1, V_2) \) agrees well with that of the...
same-event sample in the studied range of \(d(V_1, V_2) < 120\) mm. This reweighting procedure is applied in the distributions shown in Figure 5.

The background from merged DV pairs with \(d(V_1, V_2) < 1\) mm and \(n_{\text{tracks}} \geq 5\) tracks is estimated from DV pairs where one DV has two tracks and the other has three tracks. This background is found to be orders of magnitude smaller than the accidental-crossing background discussed below. The background from the merging of two 3-track vertices or a 2-track and a 4-track DV is determined to be negligible compared to other sources for higher track multiplicities.

C. Accidental crossing of vertices and tracks

The final and dominant source of background in the SR for this search is low-mass vertices crossed by an unrelated track in the event. It is common for such crossings to occur at large angles with respect to the distance vector that points from the PV to the DV. This significantly increases the mass of the DV. In order to estimate the contribution from this effect, \((n + 1)\)-track vertices are constructed by adding a pseudotrack to \(n\)-track vertices from the data. The pseudotrack is given track parameters drawn randomly from track templates, extracted separately for each radial detector region. These templates are constructed using all tracks associated with DV candidates satisfying \(n_{\text{tracks}} \geq 3\) and \(m_{\text{DV}} > 3\) GeV found in events passing the event preselection. The templates contain the track \(p_T, \eta,\) and relative azimuthal angle \(\Delta \phi\) with respect to the distance vector. In order to model the effect of high-angle crossings, pseudotracks drawn from the templates are required to be at an angle larger than \(\sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 1\) with respect to the distance vector.

To normalize the prediction from the model constructed by this method, the probability of an accidentally crossing track to become associated with the DV is extracted by comparing the sample of 3-track vertices seen in the data to the \((2 + 1)\)-track vertices from the model in the \(m_{\text{DV}} > 10\) GeV region. This probability is referred to as the crossing factor and is extracted separately for each radial detector region. Figure 6 shows the resulting \((2 + 1)\)-track predictions from the model along with the 3-track vertices for two selected radial regions. The observed differences in shape between the model and the data are used in Sec. VI to assess an uncertainty in the background estimates from the model. These crossing factors are used to project from an \(n\)-track CR to an \((n + 1)\)-track region for events passing the event preselection.

D. Validation of background estimation techniques

To ensure that the methods described above reliably model the backgrounds, two validation regions are constructed and used to test their predictions. The two regions are designed to be free of significant contamination from any signal considered in this analysis. In a low-\(E_T^{\text{miss}}\) validation region, denoted VRLM, the performance of these methods for vertices with exactly four tracks is studied as an intermediate point between the 3-track CR and the \(\geq 5\)-track SR. The VRLM event selection requires \(E_T^{\text{miss}} < 150\) GeV and that the minimum azimuthal angle between the \(E_T^{\text{miss}}\) vector and all reconstructed jets, \(\Delta \phi_{\text{min}}(E_T^{\text{miss}}, \text{jets})\), is less than 0.75. These requirements sufficiently reduce the contribution from the considered signal processes that are not excluded by previous searches [11]. The background estimate extracted from the CR is scaled to account for the efficiency \(\epsilon_{\text{VRLM}}\) of the \(E_T^{\text{miss}}\) and
TABLE I. The number of estimated background vertices with mass $m_{\text{DV}} > 10$ GeV for the DV selections used in the control and validation regions are shown. The $(n + 1)$-track contributions are estimated using the accidental-crossing factor method (Sec. V C), the $(2 + 2)$-track and $(2 + 3)$-track contributions are obtained from merged vertices (Sec. V B), and the pure $n$-track contribution is evaluated using the hadronic interactions (Sec. VA). Also shown are the estimated background event yields in the preselection region with at least five tracks. The predicted background event yield in the signal region appears in the bottom row and includes the transfer factors shown. When two uncertainties are shown, the first is statistical while the second is systematic. When one number is given, it represents the combined uncertainty.

<table>
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<td></td>
<td>Total</td>
<td>150 ± 60</td>
</tr>
<tr>
<td>Event preselection $n_{\text{trk}} \geq 5$, $m_{\text{DV}} &gt; 10$ GeV</td>
<td>5-tracks</td>
<td>(4 + 1)-track</td>
<td>1.30 ± 0.07 ± 0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2 + 3)-track</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pure 5-track</td>
<td>0.92 ± 0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>2.2 ± 2.8</td>
</tr>
<tr>
<td></td>
<td>6-tracks</td>
<td>(5 + 1)-track</td>
<td>0.37 ± 0.03 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pure 6-track</td>
<td>0.3 ± 0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>0.6 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>≥7-tracks</td>
<td>(n + 1)-track</td>
<td>0.37 ± 0.03 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pure ≥ 7-track</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>(after scaling by $\epsilon_{\text{SR}} \times \kappa$)</td>
<td>0.05 ± 0.02</td>
</tr>
</tbody>
</table>

E. Final expected yields

The predicted background yields in the various selections are listed in Table I. The yields are shown separately for each of the estimation methods along with the total for each region. Also shown is the final expected yield in the SR after the application of the scaling factors described above. The total SR prediction from the sum of all background sources is $0.05^{+0.02}_{-0.01}$ events, where the total uncertainty includes both the statistical and systematic uncertainties.

VI. UNCERTAINTIES

The estimation of the hadronic interaction background described in Sec. VA relies on the assumption that the mass spectra of such contributions follow an exponential shape. This assumption is tested using interaction vertices in the GEANT4-based simulations described in Sec. III. Based on studies of the deviations from an exponential shape seen in the simulation, an uncertainty of $-100\%$ and $+300\%$ is applied to the component of the total background from hadronic interactions. The size of this uncertainty is taken...
as the largest deviation observed in all track multiplicities for vertices with $m_{\text{DV}} > 10$ GeV in simulation.

The background in the SR due to merged vertices (Sec. V B) is estimated to be very small with respect to the total background. By comparing the same-event data and different-event model for $(2 + 3)$-track DV pairs, the largest statistically significant discrepancy in any bin in the studied range is observed to be 60%. To be conservative, the systematic uncertainty for this subdominant background is taken to be 100%.

Uncertainties associated with the contribution from low-mass vertices crossed accidentally by an unrelated track (Sec. V C) are dominated by the uncertainty of the extracted crossing factors. By varying the choice of $m_{\text{DV}}$ threshold used for the normalization of the spectra from the background model by $\pm 5$ GeV (with respect to the nominal 10 GeV), an uncertainty is extracted. Since the crossing factors are derived and applied separately for each radial detector region, their uncertainties are as well. The size of the resulting uncertainty for the accidentally crossing track contributions is 10%–20% depending on the radial detector region.

Finally, the event selection transfer factor $\epsilon_{\text{SR}}$ and the correction $\kappa$ from event level to vertex level, described in Sec. V, also have associated uncertainties. Both of these uncertainties are derived by varying the kinematic requirements for the vertices. Varying the vertex-level requirements used in these calculations results in uncertainties of 50% in $\epsilon_{\text{SR}}$ and 16% in $\kappa$. Since these factors are applied to all background contributions to obtain a final SR estimate, these uncertainties propagate directly to the final estimate.

While the background uncertainties and expectations are derived from data, additional modeling uncertainties that only affect the signal efficiencies are considered and derived by varying parameters used in the simulation and reconstruction. The effect of varying the amount of simulated pileup within its modeling uncertainty is a few percent for high-$\Delta m$ samples, and up to 10% for small-$\Delta m$ samples. To estimate the size of the uncertainty due to ISR modeling, the size of the reweighting of PYTHIA 6 to MadGraph5_aMC@NLO as described in Sec. III is taken as another systematic uncertainty. This effect corresponds to an uncertainty of a few percent in the signal efficiency for high-$\Delta m$ models. However, for low-$\Delta m$ samples, where the intrinsic $E_T^{\text{miss}}$ is smaller, the signal acceptance depends heavily on radiation effects. For these models, the uncertainty in the ISR modeling yields an uncertainty of as much as 25% in the acceptance.

The uncertainty in the signal efficiency due to variations in the track and DV reconstruction efficiency is determined to be 5%–10% by randomly removing tracks at a rate given by the expected tracking inefficiency. Additional uncertainties related to the trigger efficiency, the jet energy scale and resolution, as well as the reconstruction of the $E_T^{\text{miss}}$, are evaluated and found to be negligible with respect to the leading uncertainties. No additional uncertainty is considered for the modeling of the production of $R$-hadrons and their interactions with matter. Decays of electrically charged and neutral LLPs are reconstructed as displaced vertices in the ID with similar efficiencies, so this search is less sensitive to the fraction of charged states after hadronization compared to those based on direct-detection signatures. Since the amount of material traversed before a decay in the ID is small, the sensitivity to uncertainties in the per-parton cross section for hadronic interactions is negligible.

VII. RESULTS

The final yields for all regions used in this analysis are shown in Table II. The observed yields are consistent with the expected background in the validation regions, where VRLM contains 9 vertices ($9 \pm 2$ expected) and VRM contains 177 vertices ($150 \pm 60$ expected). The two-dimensional distribution of $m_{\text{DV}}$ and track multiplicity is shown in Fig. 7 for events that satisfy the full event-level selection. The final SR yields are highlighted, with 0 events observed ($0.02^{+0.02}_{-0.01}$ expected).

In the absence of a statistically significant excess in the data, exclusion limits are placed on $R$-hadron models.
These 95% confidence-level (C.L.) upper limits are calculated following the CLs prescription \cite{81} with the profile likelihood used as the test statistic, using the HISTFITTER \cite{82} framework with pseudoexperiments. Upper limits on the cross section for gluino pair production as a function of gluino lifetime are shown in Fig. 8 for example values of $m_{\tilde{g}}$ and $m_{\tilde{\chi}^0_1} = 100$ GeV. Also shown are the signal production cross sections for these gluino masses. Reduced signal selection efficiencies for low-$\Delta m$ samples result in less stringent cross-section limits. For $\Delta m = 100$ GeV, the limits are shown in Fig. 9. Lower limits on the gluino mass are also shown as a function of gluino lifetime in Figs. 8 and 9. DV-level fiducial volume and PV-distance requirements reduce the exclusion power in the high and low extremes of gluino lifetime. Similarly, for a fixed gluino lifetime of $\tau = 1$ ns, 95% C.L. exclusion curves are...

FIG. 7. Two-dimensional distributions of $m_{DVs}$ and track multiplicity are shown for DVs in events that satisfy all signal region event selection criteria. Bin numbers correspond to the observations in data, while the color representation shows example distributions for two $R$-hadron signals used as benchmark models in this search. The dashed line represents the boundary of the signal region requirements, and the expected signal yield in this region is shown.

These 95% confidence-level (C.L.) upper limits are calculated following the CLs prescription \cite{81} with the profile likelihood used as the test statistic, using the HISTFITTER \cite{82} framework with pseudoexperiments. Upper limits on the cross section for gluino pair production as a function of gluino lifetime are shown in Fig. 8 for example values of $m_{\tilde{g}}$ and $m_{\tilde{\chi}^0_1} = 100$ GeV. Also shown are the signal production cross sections for these gluino masses. Reduced signal selection efficiencies for low-$\Delta m$ samples result in less stringent cross-section limits. For $\Delta m = 100$ GeV, the limits are shown in Fig. 9. Lower limits on the gluino mass are also shown as a function of gluino lifetime in Figs. 8 and 9. DV-level fiducial volume and PV-distance requirements reduce the exclusion power in the high and low extremes of gluino lifetime. Similarly, for a fixed gluino lifetime of $\tau = 1$ ns, 95% C.L. exclusion curves are...

FIG. 8. Upper 95% C.L. limits on the signal cross section are shown in (a) for $m_{\tilde{g}} = 1400$ GeV and $m_{\tilde{g}} = 2000$ GeV as a function of lifetime $\tau$, for fixed $m_{\tilde{\chi}^0_1} = 100$ GeV. Horizontal lines denote the $\tilde{g}\tilde{g}$ production cross section for the same values of $m_{\tilde{g}}$, shown with uncertainties on $\sigma_{\text{SUSY}}$, given by variations of the renormalization and factorization scales, and PDF uncertainties. The lower limit on $m_{\tilde{g}}$ for fixed $m_{\tilde{\chi}^0_1} = 100$ GeV as a function of lifetime $\tau$ is shown in (b). The nominal expected and observed limit contours coincide due to the signal region yield’s high level of agreement with expectation.
A search for massive, long-lived particles with decays giving rise to displaced multitrack vertices is performed as a function of \( \tau \) for fixed \( \Delta m = 100 \) GeV. Horizontal lines denote the \( g\bar{g} \) production cross section for the same values of \( m_{\tilde{g}} \), shown with uncertainties on \( \sigma_{\text{theory}}^{\text{SUSY}} \) given by variations of the renormalization and factorization scales, and PDF uncertainties. The 95% C.L. limit as a function of \( m_{\tilde{g}} \) for fixed \( \Delta m = 100 \) GeV as a function of lifetime \( \tau \) is shown in (b). The nominal expected and observed limit contours coincide due to the signal region yield’s high level of agreement with expectation.

![Graph](image)

FIG. 9. Upper 95% C.L. limits on the signal cross section are shown in (a) for \( m_{\tilde{g}} = 1400 \) GeV and \( m_{\tilde{g}} = 2000 \) GeV as a function of lifetime \( \tau \), for fixed \( \Delta m = 100 \) GeV. Horizontal lines denote the \( g\bar{g} \) production cross section for the same values of \( m_{\tilde{g}} \), shown with uncertainties on \( \sigma_{\text{theory}}^{\text{SUSY}} \) given by variations of the renormalization and factorization scales, and PDF uncertainties. The lower limit on \( m_{\tilde{g}} \) for fixed \( \Delta m = 100 \) GeV as a function of lifetime \( \tau \) is shown in (b). The nominal expected and observed limit contours coincide due to the signal region yield’s high level of agreement with expectation.

![Graph](image)

FIG. 10. Upper 95% C.L. limits on the signal cross section are shown in (a) for \( m_{\tilde{g}} = 1400 \) GeV and \( m_{\tilde{g}} = 2000 \) GeV as a function of lifetime \( \tau \), for fixed \( \Delta m = 100 \) GeV. Horizontal lines denote the \( g\bar{g} \) production cross section for the same values of \( m_{\tilde{g}} \), shown with uncertainties on \( \sigma_{\text{theory}}^{\text{SUSY}} \) given by variations of the renormalization and factorization scales, and PDF uncertainties. The 95% C.L. limit as a function of \( m_{\tilde{g}} \) and \( m_{\tilde{g}^0} \) is shown in (b) for fixed \( \tau = 1 \) ns. The nominal expected and observed limit contours coincide due to the signal region yield’s high level of agreement with expectation.

VIII. CONCLUSIONS

A search for massive, long-lived particles with decays giving rise to displaced multitrack vertices is performed with 32.8 fb\(^{-1}\) of \( pp \) collisions at \( \sqrt{s} = 13 \) TeV collected.
by the ATLAS experiment at the LHC. The search presented is sensitive to models predicting events with significant $E_T^{\text{miss}}$ and at least one displaced vertex with five or more tracks and a visible invariant mass greater than 10 GeV. With an expected background of 0.02$^{+0.03}_{-0.01}$ events, no events in the data sample were observed in the signal region. With results consistent with the background-only hypothesis, exclusion limits are derived for models predicting the existence of such particles, reaching roughly $m_{\tilde{g}} = 2000$ GeV to 2370 GeV for $m_{\tilde{g}} = 100$ GeV and gluino lifetimes between 0.02 and 10 ns. For a fixed gluino-neutralino mass difference of $\Delta m = 100$ GeV, exclusion limits reach roughly $m_{\tilde{g}} = 1550$ GeV to 1820 GeV for gluino lifetimes between 0.02 and 4 ns.

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Department of Physics, Ankara University, Ankara, Turkey
Istanbul Aydin University, Istanbul, Turkey
Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
Department of Physics, University of Arizona, Tucson, Arizona, USA
Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
Physics Department, National and Kapodistrian University of Athens, Athens, Greece
Physics Department, National Technical University of Athens, Zografou, Greece
Department of Physics, The University of Texas at Austin, Austin, Texas, USA
Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
Institute of Physics, University of Belgrade, Belgrade, Serbia
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
Department of Physics, Humboldt University, Berlin, Germany
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
Department of Physics, Bogazici University, Istanbul, Turkey
Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
Babes-Bolyai University, Faculty of Engineering and Natural Sciences, Cluj-Napoca, Romania
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Boston University, Boston, Massachusetts, USA
Department of Physics, Brandeis University, Waltham, Massachusetts, USA
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton, New York, USA
Transilvania University of Brasov, Brasov, Romania
Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
Department of Physics, Alexandria Joan Cuza University of Iasi, Iasi, Romania
National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
University Politehnica Bucharest, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa, Ontario, Canada
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa Maria, Valparaiso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Physics, Nanjing University, Jiangsu, China
Physics Department, Tsinghua University, Beijing 100084, China
University of Chinese Academy of Science (UCAS), Beijing, China
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China
School of Physics, Shandong University, Shandong, China
Department of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai(also at PKU-CHEP), China
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

84 Fysiska institutionen, Lunds universitet, Lund, Sweden

85 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

86 Institut für Physik, Universität Mainz, Mainz, Germany

87 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

88 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

89 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA

90 Department of Physics, McGill University, Montreal, Quebec, Canada

91 School of Physics, University of Melbourne, Victoria, Australia

92 Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA

93 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

94a INFN Sezione di Milano, Italy

94b Dipartimento di Fisica, Università di Milano, Milano, Italy

95 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

96 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus

97 Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada

98 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

99 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

100 National Research Nuclear University MEPhI, Moscow, Russia

101 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

102 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

103 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

104 Nagasaki Institute of Applied Science, Nagasaki, Japan

105 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

106a INFN Sezione di Napoli, Italy

106b Dipartimento di Fisica, Università di Napoli, Napoli, Italy

107 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

108a Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

108b 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

123a Dipartimento di Fisica, Università di Pavia, Pavia, Italy

123b Dipartimento di Fisica, University of Pennsylvania, Philadelphia, Pennsylvania, USA

124 National Research Centre “Kurchatov Institute” B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia

124a INFN Sezione di Pisa, Italy

125 Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal

126a Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

127 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

128a Departamento de Físicas, University of Coimbra, Coimbra, Portugal

128b Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

128c Departamento de Física, Universidade do Minho, Braga, Portugal

128d Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada, Spain
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128 Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
129 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
130 Czech Technical University in Prague, Praha, Czech Republic
131 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
132 State Research Institute for High Energy Physics (Protvino), NRC KI, Russia
133 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
134 INFN Sezione di Roma, Italy
135 Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
136 INFN Sezione di Roma Tor Vergata, Italy
137 Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
138 INFN Sezione di Roma Tre, Italy
139 Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
140 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
141 Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
142 Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
143 Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
144 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Énergie Atomique et aux Énergies Alternatives), Gif-sur-Yvette, France
145 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
146 Department of Physics, University of Washington, Seattle, Washington, USA
147 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
148 Department of Physics, Shinshu University, Nagano, Japan
149 Department Physik, Universität Siegen, Siegen, Germany
150 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
151 SLAC National Accelerator Laboratory, Stanford, California, USA
152 Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
153 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
154 Department of Physics, University of Cape Town, Cape Town, South Africa
155 Department of Physics, University of Johannesburg, Johannesburg, South Africa
156 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
157 The Oskar Klein Centre, Stockholm, Sweden
158 Physics Department, Royal Institute of Technology, Stockholm, Sweden
159 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
160 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
161 School of Physics, University of Sydney, Sydney, Australia
162 Institute of Physics, Academia Sinica, Taipei, Taiwan
163 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
164 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
165 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
166 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
167 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
168 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
169 Tomsk State University, Tomsk, Russia
170 Department of Physics, University of Toronto, Toronto, Ontario, Canada
171 INFN-TIFPA, Italy
172 University of Trento, Trento, Italy
173 TRIUMF, Vancouver, British Columbia, Canada
174 Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
175 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
176 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
177 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.

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

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

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

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

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

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

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

Also at Giresun University, Faculty of Engineering, Turkey.

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

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

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

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

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