Search for heavy charged long-lived particles in proton-proton collisions at $\sqrt{s} = 13$ TeV using an ionisation measurement with the ATLAS detector


Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2018.10.055

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)
Search for heavy charged long-lived particles in proton–proton collisions at $\sqrt{s} = 13$ TeV using an ionisation measurement with the ATLAS detector

The ATLAS Collaboration*

**ABSTRACT**

This Letter presents a search for heavy charged long-lived particles produced in proton–proton collisions at $\sqrt{s} = 13$ TeV at the LHC using a data sample corresponding to an integrated luminosity of 36.1 fb$^{-1}$ collected by the ATLAS experiment in 2015 and 2016. These particles are expected to travel with a velocity significantly below the speed of light, and therefore have a specific ionisation higher than any high-momentum Standard Model particle of unit charge. The pixel subsystem of the ATLAS detector is used in this search to measure the ionisation energy loss of all reconstructed charged particles which traverse the pixel detector. Results are interpreted assuming the pair production of $R$-hadrons as composite colourless states of a long-lived gluino and Standard Model partons. No significant deviation from Standard Model background expectations is observed, and lifetime-dependent upper limits on $R$-hadron production cross-sections and gluino masses are set, assuming the gluino always decays to two quarks and a 100 GeV stable neutralino. $R$-hadrons with lifetimes above 1.0 ns are excluded at the 95% confidence level, with lower limits on the gluino mass ranging between 1290 GeV and 2060 GeV. In the case of stable $R$-hadrons, the lower limit on the gluino mass at the 95% confidence level is 1890 GeV.

© 2018 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license ([http://creativecommons.org/licenses/by/4.0/](http://creativecommons.org/licenses/by/4.0/)). Funded by SCOAP3.

**1. Introduction**

A wide range of physics models that extend the Standard Model (SM) predict the existence of new, massive, long-lived particles (LLPs). These particles appear in proposed solutions to the gauge hierarchy problem [1], including supersymmetric (SUSY) models that either violate [2–4] or conserve [5–12] $R$-parity. $R$-parity is a quantum number defined as $(-1)^{3(B-L)+2S}$ where $S$ is the particle spin and $L$ and $B$ are, respectively, its lepton and baryon number. Within SUSY models, particles, including gluinos, may be long-lived, with lifetimes depending, for instance, on the mass hierarchy parameters, or on the size of any $R$-parity-violating coupling [13].

The study in this Letter is sensitive to many different models of new physics, in particular those that predict the production of massive particles with lifetimes exceeding 1 ns at LHC energies, such as mini-split SUSY [10,14,15] or anomaly-mediated supersymmetry-breaking (AMSB) models [16,17]. Results are presented assuming the production of $R$-hadrons as composite colourless states of a gluino together with SM quarks or gluons [18].

Due to their large mass, LLPs are expected to be slow ($\beta'\gamma \lesssim 0.9^1$ in a large fraction of cases) and therefore, if charged, to have a specific ionisation larger than any SM particle of unit charge at high momentum. The pixel subsystem [19] of the ATLAS detector [20] provides measurements of ionisation energy loss ($dE/dx$) for charged particles with sufficient accuracy to distinguish such highly ionising particles from SM particles. In this Letter, the $dE/dx$ information is used to search for LLPs using a data sample of proton–proton ($pp$) collisions corresponding to an integrated luminosity of 36.1 fb$^{-1}$ collected at $\sqrt{s} = 13$ TeV. This extends the reach beyond that of a previous study [21], thanks to a tenfold increase of the integrated luminosity and to several improvements to the analysis. It also extends the reach beyond that of similar studies by CMS [22] and ATLAS [23] carried out at the same centre-of-mass energy and dedicated to the search for LLPs not decaying inside the detector.

---

* E-mail address: atlas.publications@cern.ch.

1 Here $\beta$ is the speed of the particle relative to the speed of light in vacuum and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$.

https://doi.org/10.1016/j.physletb.2018.10.055

0370-2693/© 2018 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license ([http://creativecommons.org/licenses/by/4.0/](http://creativecommons.org/licenses/by/4.0/)). Funded by SCOAP3.
2. ATLAS detector and ionisation measurement

The ATLAS detector is a general-purpose detector with a forward–backward symmetric cylindrical symmetry described in detail in Ref. [20]. It consists of a tracker for measuring the trajectories of charged particles inside a 2 T solenoidal magnetic field, followed by calorimeters for measuring the energy of particles that interact electromagnetically or hadronically. A muon spectrometer immersed in a toroidal magnetic field surrounds the calorimeters, and provides tracking for muons. A two-level trigger system is used to select events [24]. The first-level trigger is implemented in hardware and uses a subset of the detector information. This is followed by the software-based high-level trigger, which runs offline reconstruction and calibration software, reducing the event rate to about 1 kHz. The detector is hermetic and can therefore measure the magnitude of the missing transverse momentum \( E_{\text{T}}^{\text{miss}} \) associated with each event. The tracker is made of three detector systems organised in concentric layers. The outermost layer is made of densely packed proportional gas-filled detectors [25], the radial region from roughly 30 cm to 55 cm is equipped with silicon microstrip detectors [26] and the innermost layer is covered by a silicon pixel detector [19], which is described below in some detail as it has a crucial role in this analysis.

The pixel detector typically provides four precision measurements for each track in the region \(|\eta| < 2.5\) at radial distances of 33 mm, 50 mm, 88 mm and 122 mm from the LHC beam line. The innermost pixel layer is named the insertable B-layer (IBL) [27] and was designed to maintain efficient operation of the pixel system above \(2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) luminosity, when the next-to-innermost pixel layer begins to lose detection efficiency. The hit efficiency of the pixel detector in the data sample used for this analysis still exceeds 99% in all layers. For each pixel hit the length of time with signal above threshold, known as time over threshold (ToT), is digitised and recorded. The ToT is approximately proportional to the ionisation charge and allows the calculation of the specific ionisation energy, \(dE/dx\), of a track. The ToT measurement is digitised with four bits in the IBL and eight bits in all other pixel layers. If the dynamic range is exceeded for a particular hit in the IBL an overflow bit is set, while for the other layers the hit is not recorded.

The charge released by a moving charged particle is rarely contained within just one pixel; neighbouring pixels registering hits are joined together using a connected component analysis [28,29] to form clusters. The charge of a cluster is calculated by summing the charge of all pixels belonging to the cluster after calibration corrections. To avoid loss of charge, only clusters completely contained in sensor fiducial regions are used (e.g. clusters cannot be in contact with pixels on the sensor edge). The \(dE/dx\) for each reconstructed track is calculated using the average of the individual cluster ionisation measurements (charge collected in the cluster per unit track length in the sensor), for the clusters associated with a track. To reduce the impact of the tails of the Landau distribution, which is expected to describe the energy deposition distribution, the track \(dE/dx\) is evaluated using a truncated-mean method. The average is calculated after removing the highest-\(dE/dx\) cluster, or the two highest-\(dE/dx\) clusters in the relatively rare case of more than four clusters associated with the track. More details of the calculation of \(dE/dx\) may be found in Ref. [21].

3. Analysis overview

The search strategy consists of looking for excesses in the mass distribution of reconstructed tracks with high transverse momentum, \(p_T\), and large \(dE/dx\). The mass value is determined from a parameterisation of the Bethe–Bloch relation and depends on the momentum and \(dE/dx\) of selected tracks.

Two signal regions are considered, and the selection is detailed in Section 6. The first region targets metastable \(R\)-hadrons with lifetimes such that the majority of their decays occur inside the detector. In this region, charged particles that reach the muon spectrometer are removed and the selections are optimised for \(R\)-hadrons with lifetimes from around 1 ns to several tens of ns. A second signal region targets stable \(R\)-hadrons which do not decay within the detector. In this region, no muon veto is applied, since some of the stable \(R\)-hadrons that pass through the muon spectrometer are reconstructed as muons.

Events are selected using the lowest-threshold unprescaled calorimetric \(E_{\text{T}}^{\text{miss}}\) trigger. In metastable \(R\)-hadron events, the measured \(E_{\text{T}}^{\text{miss}}\) largely originates from neutralinos which carry away unmeasured momenta. In stable \(R\)-hadron events, the \(E_{\text{T}}^{\text{miss}}\) leave only modest energy depositions in the calorimeters [30] and only a fraction are reconstructed as muons due to their late arrival time in the muon spectrometer. Therefore, most of the momenta of \(R\)-hadrons are not accounted for in the measurement of \(E_{\text{T}}^{\text{miss}}\), and only QCD initial-state radiation (ISR) provides a visible contribution that results in a measured imbalance. Due to the neutralinos, the \(E_{\text{T}}^{\text{miss}}\) trigger efficiency is higher for metastable than for stable \(R\)-hadrons. The track reconstruction efficiency is, on the contrary, higher for the stable \(R\)-hadrons and penalises particles with lifetimes shorter than 10 ns, which may not have crossed enough detector layers. The searches for stable and metastable \(R\)-hadrons require slightly different optimisations.

The background is estimated with a data-driven approach, as described in Section 7. Data control samples are used to parameterise the momentum and \(dE/dx\) distributions and their interdependence, and then to generate pseudo data which predicts the background distribution. The potential signal contamination is minimised in these background samples by inverting some of the selection criteria.

4. Data and simulation

This search uses data from \(pp\) collisions at \(\sqrt{s} = 13\) TeV provided by the LHC in 2015 and 2016. The integrated luminosity of the data sample is 36.1 fb\(^{-1}\), after requirements on detector status and data quality have been applied. Further detector-level cleaning selections are applied to the data to reject events affected by calorimeter noise and data corruption. An additional data sample, collected in a dedicated low-luminosity run in 2016, is used for the calibration of \(dE/dx\) and mass; it consists of randomly triggered events in bunch crossings where collisions are expected and amounts to about 0.4 nb\(^{-1}\).

Simulation samples are used to determine the efficiency and associated uncertainty for selecting signal events. To model signal events, the pair production of gluinos with masses between 400 GeV and 3000 GeV was simulated in Pythia 6.4.27 [31] at leading order with the AUET2B [32] set of tuned parameters for the underlying event and the CTEQ6L1 [33] parton distribution function (PDF) set. Dedicated routines [34] were used to hadronise the gluinos; after hadronisation, about 2/3 of the events contain at least one charged \(R\)-hadron. All particles except the gluino and
the lightest neutrino are decoupled. The Monte Carlo (MC) signal samples include a modelling of pile-up, adding the expected number of minimum-bias $pp$ interactions from the same and nearby bunch crossings.

In order to more accurately model ISR in the signal events, additional samples of gluinos were generated at leading order with up to two additional partons using MadGraph5_aMC@NLO [35], interfaced to the Pythia 8.186 [36] parton shower model. The NNPDF2.3LO [37] PDF set is used along with the A14 [38] set of tuned parameters. The distribution of the transverse momentum of the gluino–gluino system simulated with Pythia 6.4.27 was reweighted to match that obtained in the samples simulated with MadGraph5_aMC@NLO.

Simulated events undergo full detector simulation [39] based on a Geant4 [40] framework; the hadronic interactions of R-hadrons with the detector were handled by dedicated Geant4 routines based on the model described in Refs. [30,34,41]. Signal samples were generated both for non-decaying gluinos, and for gluinos with a set of lifetimes ranging from 1.0 ns to 50 ns which decay into SM quarks and a 100 GeV stable neutralino via the process $\tilde{g} \rightarrow q\tilde{\chi}^0$. The decay of the $R$-hadrons and the fragmentation and hadronisation of the resulting quarks were performed with a modified version of Pythia 6.4.27.

To normalise the number of expected signal events, gluino pair production cross-sections are calculated at next-to-leading order in the strong coupling constant, including the resummation of soft-gluino emissions at next-to-leading-logarithm accuracy [42–46]. The nominal cross-section values and uncertainties are taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as described in Ref. [47].

5. $dE/dx$ corrections and mass calculation

ATLAS has used the measured $dE/dx$ to search for $R$-hadrons in several previous analyses [21,48,49]. This method has been constantly improved to take into account the evolution of the pixel detector and the experimental conditions. Detailed improvements related to the measurement of $dE/dx$ and mass introduced in this analysis, include:

- Corrections have been made for luminosity- and time-dependent variations of the measured values of $dE/dx$. The variations are due to changes in the operation parameters of the pixel system and to loss of charge collection due to radiation damage caused by the luminosity delivered. The $dE/dx$ measured in data is scaled by a per-run factor derived to keep the most probable value of the energy loss ($MPV_{\Delta E/dx}$) constant versus time. The $MPV_{\Delta E/dx}$ variation with integrated luminosity before corrections is shown in Fig. 1.

- A low-momentum correction for kaons and protons has been added. All particles are treated as pions in the reconstruction program, but, below 500 MeV, the effect of multiple scattering on the trajectories of kaons and protons is different from the effect on a pion and their momenta are underestimated. To correct for this effect, the difference between the generated and the reconstructed momentum of proton and kaon tracks in simulation samples is fitted as a function of momentum. This parameterised correction is then applied to the momentum of protons and kaons in data, where these particles are identified by means of their $dE/dx$ and momentum. This procedure has simplified the $dE/dx$ calibration, which is performed with low-$\beta\gamma$ SM particles.

- There is a small dependence of the $dE/dx$ on the traversed thickness [50]. For that reason the $dE/dx$ calculated in this analysis takes into account its small ($<10\%$) $\eta$-dependence. After this correction, the $dE/dx$ depends only on the particle momentum and mass, which simplifies the background estimation (see Section 7).

- As the simulation does not include the effects of radiation damage to the pixel detector sensors, a scale factor of 0.886 is applied to the measurement of $dE/dx$ in simulation to align the $MPV_{\Delta E/dx}$ of the minimum-ionising particles in MC simulation with data, after the run-dependent corrections to the data $dE/dx$ have been applied.

The $\beta\gamma$ of a particle, and therefore its mass if the momentum is known, can be calculated from the $dE/dx$ of its track using the relationship between $\beta\gamma$ and $dE/dx$. A $\beta\gamma$ value can only be measured in the range $0 < \beta\gamma < 0.9$. On average, particles with $\beta\gamma < 0.3$ have a $dE/dx$ such that the ToT dynamic range is exceeded. Particles with $\beta\gamma > 0.9$ have a $dE/dx$ which is too close to the ionisation plateau of relativistic SM particles for an efficient discrimination. This range overlaps well with the expected average $\beta\gamma$ of $R$-hadrons produced at the LHC, which decreases from around 0.8 for a gluino with mass 600 GeV to around 0.4 for a 2000 GeV gluino.

The mass of a charged particle can be derived from a fit of the specific energy loss and the momentum measurement to an empirical function motivated by the low-$\beta$ behaviour of the Bethe–Bloch distribution. After applying the low-momentum correction for kaons and protons, it is possible to fit the function relating $dE/dx$ to $\beta\gamma$ with only three parameters (instead of five as in the previous analysis [21], as shown in Fig. 2. The parametric function describing the relationship between the most probable value of the energy loss ($MPV_{\Delta E/dx}$) and $\beta\gamma$ is:

$$MPV_{\Delta E/dx} = A/(\beta\gamma)^2 + B$$

The A, B and C calibration constants were measured using low-momentum pions, kaons and protons reconstructed by ATLAS in low-luminosity runs where all reconstructed tracks with $p_T >$
100 MeV are considered. In bins of momentum, the reconstructed $dE/dx$ distribution shows three distinct peaks, to which the nominal pion, kaon, and proton masses are respectively assigned in increasing order of $dE/dx$ to obtain a $\beta\gamma$ for the three measured $dE/dx$ values. The MPV$\beta\gamma/dx$ is extracted from a fit to the distribution of $dE/dx$ values for each particle species across all momentum bins. The mass parameterisation is valid for both data and simulation after the correction to $dE/dx$ in simulation is applied. Given a measured value of $dE/dx$ and momentum, and assuming unit charge, the mass $m$ is calculated from Eq. (1) by numerically solving the equation $\text{MPV}_{\beta\gamma/dx}(p/m) = dE/dx$ for the unknown $m$, where the MPV$\beta\gamma/dx$ is approximated by the truncated-mean measurement of $dE/dx$. Using this method, the reconstructed mass for simulated $R$-hadrons reproduces well the generated mass up to about 1.5 TeV, above which a bias in the measured momentum causes the reconstructed mass to fall below the generated value. The momentum uncertainty dominates the mass resolution above masses of 200 GeV. The measurement of the proton mass in all data-taking runs used in this analysis allows the monitoring of the stability of the $A$, $B$ and $C$ calibration constants. These are found to be stable at the 1% level after all corrections have been applied.

### 6. Event selection

Events are first selected with a trigger based on $E_T^{\text{miss}}$, which is calculated using energy measurements in the calorimeter with corrections for multiple $pp$ interactions in each event [24]. The high-level $E_T^{\text{miss}}$ trigger threshold varies from 70 GeV to 110 GeV during the data-taking period. In the reconstruction, $E_T^{\text{miss}}$ is built from calibrated muons and electrons which pass baseline selections, from calibrated jets reconstructed with the anti-$k_t$ jet clustering algorithm [51] with radius parameter $R = 0.4$ using clusters of energy depositions in the calorimeter as inputs, and from a term that includes soft tracks not associated with any other objects in the event [52] but consistent with the primary vertex (PV). Events are required to have $E_T^{\text{miss}} > 170$ GeV to enhance the signal sensitivity and to ensure that the selected events are near the efficiency plateau of the trigger. To ensure a good calculation of $E_T^{\text{miss}}$, events are rejected if they contain a jet with $E_T > 20$ GeV that is consistent with detector noise or beam-induced backgrounds, as determined from shower shape information. Unlike in standard ATLAS selections for jet-cleaning [53], a requirement on the relationship between track and calorimeter measurements of $p_T$ and a requirement on the fraction of jet energy deposited in the electromagnetic calorimeter are not applied as they are found to be inefficient for signal events in which an $R$-hadron decays before or inside the calorimeters. The trigger is more than 95% efficient for $R$-hadrons with lifetimes of 10 ns or less; the efficiency decreases as more decays happen in or after the calorimeter and falls to around 30–40% for the stable case.

There are two separate signal regions with slightly different optimisations for metastable and stable particles: the isolation selections differ slightly for the two signal regions, and a muon veto is applied only for the metastable region. Additionally, events with a high-$p_T$ muon whose momentum uncertainty is significantly worse after combining tracks from the inner detector and muon system are vetoed in the metastable region, in order to protect the measurement of $E_T^{\text{miss}}$ from rare, pathological reconstructions of muons. After passing the trigger and $E_T^{\text{miss}}$ selections, events are required to have a PV built from at least two reconstructed tracks each with $p_T$ above 400 MeV, and to contain at least one candidate track that passes the track-level selections detailed below. If there are multiple candidate tracks in an event after all selections, the candidate with the highest track $p_T$ is selected.

To enrich the selected sample in potential signal events, candidate tracks are required to have $p_T > 50$ GeV, momentum $p > 150$ GeV, and $|\eta| < 2.0$. To reject non-prompt background tracks and those inconsistent with the PV, the transverse impact parameter of candidate tracks, $d_0$, must be less than 2 mm, and the absolute value of the product of the longitudinal impact parameter, $z_0$, and $\sin\theta$ must be less than 3 mm.3 Reconstructed tracks must have at least seven clusters across the pixel and SCT detectors, and to be considered a candidate the track must have an associated cluster in the innermost pixel layer if it passes through an active detector module.

To reject tracks from leptonic $W$ decays, the transverse mass ($m_T$) of the candidate track and the $E_T^{\text{miss}}$ in the event must be greater than 130 GeV.4 Tracks from electrons are removed by considering any jets within $\Delta R = 0.05$ of the candidate track with $p_T > 20$ GeV, and rejecting the track if any such jet has at least 95% of its energy deposited in the electromagnetic calorimeter. Hadrons are removed by excluding tracks for which any associated jet within $\Delta R = 0.05$ of the track has a calibrated energy larger than the track momentum. In the metastable $R$-hadron signal region, tracks identified as well-reconstructed muons which pass the “medium” quality selection [54] and which have $p_T > 25$ GeV are rejected.

Tracks with high ionisation deposits from multiple SM particles which overlap in the pixel sensors are rejected with two types of isolation selections. The first explicitly requires that no clusters on the track are consistent with two or more tracks [55]. The second requires that the scalar sum of the $p_T$ of other tracks, with $p_T > 1$ GeV and consistent with the PV, in a cone of size $\Delta R = 0.25$ around the candidate track, must be less than 20 GeV for the metastable $R$-hadron selection. To reduce background in

---

3 The transverse impact parameter is defined as the distance of closest approach in the transverse plane between a track and the beam-line. The longitudinal impact parameter corresponds to the z-coordinate distance between the point along the track at which the transverse impact parameter is defined and the primary vertex.

4 $m_T = \sqrt{2p_T E_T^{\text{miss}} \cos \Delta\phi (E_T^{\text{miss}}, \text{track})}$, where $\Delta\phi (E_T^{\text{miss}}, \text{track})$ is the azimuthal separation between the track and the $E_T^{\text{miss}}$ vector.
the stable $R$-hadron region in which muons are not vetoed, the isolation selection is tightened to 5 GeV.

At least two pixel clusters, after discarding the cluster with the highest ionisation, must be included in the truncated mean calculation of $dE/dx$ to ensure it is robust. The relative uncertainty in the momentum measurement must be less than 50%. The specific ionisation of the candidate track measured by the pixel detector must be larger than 1.8 MeV g$^{-1}$ cm$^2$. Relative to inclusive generated $R$-hadron events with a mass of 2000 GeV, the efficiency for events to pass all selections, including the trigger, is 12% for stable $R$-hadrons and 19% for those with a lifetime of 10 ns.

7. Background estimation

The expected background contains tracks from SM processes including vector boson, top-quark, and multi-jet production. Tracks from any SM particle can be measured with high $dE/dx$ due to the unlikely sampling of multiple measurements from the long tail of the Landau distribution, from overlapping particles depositing charge in the same pixels, or from spurious pixel hits from low-momentum particles being incorrectly assigned to the high-momentum track. To correctly estimate both the rate of high-momentum tracks in events with large $E_{T}^{\text{miss}}$ and the probability of measuring a high ionisation energy for those tracks, the background is fully estimated from data.

A template for the momentum distribution of background tracks in signal region (SR) events is obtained from a control region ($p$-CR) in which the ionisation requirement is inverted, $dE/\delta x < 1.8$ MeV g$^{-1}$ cm$^2$, while all other track-level and event-level selections are applied.

The $dE/\delta x$ distribution, in a few bins of momentum, is obtained for the expected background from a low-$E_{T}^{\text{miss}}$ data sample in which $E_{T}^{\text{miss}} < 170$ GeV. Inverting the $E_{T}^{\text{miss}}$ requirement relative to the high-$E_{T}^{\text{miss}}$ SR minimises signal contamination in this control region ($dE/\delta x$-CR), and the lack of correlation between $E_{T}^{\text{miss}}$ and $dE/\delta x$ for high-momentum SM tracks allows the $dE/\delta x$ distribution of the expected background to be derived from low-$E_{T}^{\text{miss}}$ events which pass all other selections. Since the $E_{T}^{\text{miss}}$ trigger thresholds varied as a function of time for the collected data, the events in this control region are reweighted so that the ratio of low-to-high $E_{T}^{\text{miss}}$ events is constant versus time.

The momentum and $dE/\delta x$ distributions obtained in the control regions (CRs) are used as templates to calculate the shape of the expected mass distribution of candidate tracks from background events. A pair of $p$ and $dE/\delta x$ values is obtained by randomly sampling from the $p$-CR distribution, and then randomly sampling from the $dE/\delta x$-CR distribution in the appropriate $p$-bin. The mass for each pair of $p$ and $dE/\delta x$ values is calculated as described in Section 5. The resulting background mass distribution is normalised to data in the region where $m < 160$ GeV, in which signal was previously excluded [48,56], before the high ionisation requirement is imposed.

The procedure for estimating both the normalisation and shape of the expected background is validated in a low-momentum validation region (VR) in which the momentum of tracks is required to be between 50 GeV and 150 GeV. The differences between the selections applied to the SR, CR, and VR are shown in Table 1. The control and validation regions are independently produced for both the metastable and stable $R$-hadron SRs. The expected mass distributions in the two validation regions, along with the observed data, are shown in Fig. 3. Good agreement between the data and the prediction in the VR validates the background estimation procedure.

8. Systematic uncertainties

The background estimation technique described in the previous section relies on the lack of correlation between several key kinematic variables in background events. The largest uncertainties in the central value of the background estimate come from possible residual correlations. In particular, the residual correlation between $\eta$ and $dE/\delta x$ results in an uncertainty in the size of the background estimate ranging from 15% at the lowest mass values to 30% at the highest mass values. This uncertainty is assessed by comparing the nominal background estimate with an estimate performed in $\eta$ bins. Additionally, an uncertainty of 1%–25% in the background yield arises from residual correlations between $p$ and $dE/\delta x$ for tracks entering the background calculation. This is estimated by reweighting the $p$ template from the $p$-CR by the difference in the $p$ distribution between tracks with high and low $dE/\delta x$ in the low-$E_{T}^{\text{miss}}$ region. Similarly, the residual correlation between $E_{T}^{\text{miss}}$ and $dE/\delta x$ is probed by rescaling the template $dE/\delta x$ distribution with a scale factor obtained from the difference between the $dE/\delta x$ distributions in the VR for tracks in events with high $E_{T}^{\text{miss}}$ and low $E_{T}^{\text{miss}}$. This uncertainty ranges from 3% to 12% on the background expectation in different mass windows.

As the background is fully estimated from data, detector or data-taking conditions which affect the measurement of $dE/\delta x$ are accounted for, as long as the luminosity profile of the control regions matches that of the signal region. The reweighting of the $dE/\delta x$-CR control region achieves this. A conservative uncertainty in the time-dependence of the $dE/\delta x$ measurement is assessed by comparing the background estimate with and without the reweighting, which results in an additional uncertainty of 3%–18% on the background yields. The limited numbers of events in the control regions contribute 6% uncertainty. Other uncertainties in the background estimate are below 5%, including an uncertainty in the shape of the $dE/\delta x$ tail from the CR and in the different fractions of muons between the CR and SR.

The uncertainty in the expected number of signal events is dominated by the estimation of the production cross-section of gluino–gluino pairs; the calculation of the cross-section and its uncertainty is described in Section 4. The uncertainty ranges from 14% for gluino masses of 600 GeV to 36% for masses of 2200 GeV. An additional uncertainty in the number of produced signal events

---

Table 1
Summary of the different selection requirements applied to the signal region (SR), the validation region (VR), and the control regions (CR).

<table>
<thead>
<tr>
<th>Selection</th>
<th>SR</th>
<th>VR</th>
<th>p-CR</th>
<th>dE/\delta x-CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track momentum [GeV]</td>
<td>&gt; 150</td>
<td>50–150</td>
<td>&gt; 150</td>
<td>50–150</td>
</tr>
<tr>
<td>$E_{T}^{\text{miss}}$ [GeV]</td>
<td>&gt; 170</td>
<td>&gt; 170</td>
<td>&lt; 170</td>
<td></td>
</tr>
<tr>
<td>Ionisation [MeV g$^{-1}$ cm$^2$]</td>
<td>&gt; 1.8</td>
<td>&lt; 1.8</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

---

$^{5}$ To account for the dependence of $dE/\delta x$ on momentum up to the Fermi plateau. The most probable energy loss reaches a constant value, the Fermi plateau, at large $p_T$. 

---
of 2.1% is due to the uncertainty in the dataset luminosity, which is measured in dedicated $x$-$y$ beam-separation scans performed in May 2016 using a method similar to one described in Ref. [57].

The largest uncertainty on the signal efficiency results from the modelling of ISR production, which affects the $E_{\text{miss}}$ distribution. This uncertainty is estimated as half the difference between the expected number of events calculated with the PyTHIA 6.4.27 gluino–gluino $p_T$ distribution and with the distribution reweighted to match that of the MADGRAPH5_aMC@NLO sample. This uncertainty depends on both the lifetime and mass of the signal sample and ranges from 1% for lifetimes up to 10 ns to 19% for stable samples. Uncertainties ranging from 1% to 6% in the efficiency of the $dE/dx$ selection are included to account for both the shape difference between the ionisation distributions in data and MC simulation and the scale shift in data due to radiation damage. The efficiency of selecting tracks with at least two measurements used to determine the $dE/dx$ depends on the operating conditions of the detector and the instantaneous luminosity. The accuracy of the simulation in modelling this efficiency is tested in $Z \rightarrow \mu\mu$ events in both data and MC simulation; the maximum difference in efficiency as a function of pile-up is found to be 6%, which is taken as an uncertainty. Additional uncertainties, each less than 5%, on the signal selection efficiency are due to uncertainties in how well the simulation models trigger and offline $E_{\text{miss}}$, the pile-up distribution, the scale and uncertainty of the momentum measurement, and the efficiency for reconstructing stable $R$-hadrons as muons.

9. Results

The distributions of the reconstructed mass of candidate tracks in the two signal regions are shown in Fig. 4 for events observed in data, together with the expected background and the predictions from several signal models. The total numbers of expected and observed events in the two SRs as well as in the background CRs and VRs are shown in Table 2. Overall, the number of observed events in the two SRs is consistent with the background expectation.

To quantify the level of agreement between data and background in the shape of the mass distribution, discrete but overlapping asymmetric windows in the reconstructed mass distribution are defined so as to contain at least 70% of the reconstructed mass of a signal sample with a given simulated gluino mass. All windows have an upper boundary of 5000 GeV to remove any unphysical measurements. The lower boundary for a given simulated mass

![Fig. 3. The reconstructed mass distribution in the (a) metastable and (b) stable $R$-hadron validation regions for observed data and the predicted background, including the total uncertainty in the background estimate. The validation regions have the same requirements as the SRs, except the momentum of the candidate tracks is required to be $50 < p < 150$ GeV.](image)

![Fig. 4. The reconstructed candidate track mass distributions for observed data, predicted background, and the expected contribution from two signal models in the (a) metastable and (b) stable $R$-hadron signal regions. The yellow band around the background estimation includes both the statistical and systematic uncertainties.](image)
Table 2
The number of events in each CR, VR, and SR for the predicted background, for the expected contribution from two signal models normalised to 36.1 fb⁻¹, and in the observed data. The predicted background includes the statistical and systematic uncertainties, respectively. The uncertainty in the signal yield includes all systematic uncertainties except that in the theoretical cross-section.

<table>
<thead>
<tr>
<th>Region</th>
<th>Sample</th>
<th>Pred. Bkg (± stat. ± syst.)</th>
<th>Exp. signal</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metastable</td>
<td>p-CR</td>
<td>12.0 ± 0.9</td>
<td>7397</td>
<td></td>
</tr>
<tr>
<td></td>
<td>dE/dx-CR</td>
<td>7.2 ± 0.6</td>
<td>110019</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VR</td>
<td>140 ± 4 ± 28</td>
<td>0.3 ± 0.03</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>71 ± 2 ± 14</td>
<td>52.1 ± 4.2</td>
<td>72</td>
</tr>
<tr>
<td>Stable</td>
<td>p-CR</td>
<td>8.0 ± 1.6</td>
<td>13108</td>
<td></td>
</tr>
<tr>
<td></td>
<td>dE/dx-CR</td>
<td>10.3 ± 2.1</td>
<td>272723</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VR</td>
<td>168 ± 5 ± 32</td>
<td>0.2 ± 0.04</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td>SR</td>
<td>107 ± 3 ± 28</td>
<td>36.0 ± 7.2</td>
<td>107</td>
</tr>
</tbody>
</table>

Fig. 5. The 95% CL upper limit on the cross-section as a function of mass for (a) gluinos with lifetime \( \tau = 10 \text{ ns} \) decaying into \( q\bar{q} \) and a 100 GeV neutralino and for (b) detector-stable gluinos, with the observed limit shown as a solid black line. The predicted production cross-section values are shown in purple along with their uncertainty. The source of this deviation is a mild excess of data events relative to the background prediction around 500–800 GeV.

In the absence of any significant excess, model-independent upper limits at 95% CL on the visible production cross-sections are calculated by dividing the number of signal events consistent at the 95% CL with the expected background and observed data in the most inclusive mass window for each SR by the integrated luminosity. For the metastable R-hadron SR, the \( p \)-value for the background-only hypothesis is 0.15 in the window from 500 to 5000 GeV, and the upper limit on the visible production cross-section is 0.35 fb with an expected limit of 0.25 ± 0.07 fb. In the stable R-hadron SR mass window from 300 to 5000 GeV, the background-only \( p \)-value is 0.09 and the model-independent upper limit on the visible production cross-section is 0.88 fb, with an expected limit of 0.57 ± 0.20 fb. Information in full detail about the expected and observed results in each mass window is provided in Ref. [58].

Expected and observed upper limits on R-hadron production cross-sections are calculated from the predicted background, the expected signal, and the observed event yields in each mass window, using the one-sided profile-likelihood ratio as a test statistic. The upper limits on the cross-sections are evaluated at 95% CL following the CLs prescription [59]. In this procedure, the uncertainties in the signal and background yields are treated as Gaussian-distributed nuisance parameters. The cross-section upper limits for a gluino R-hadron with lifetime of 10 ns decaying into \( q\bar{q} \) and a 100 GeV neutralino and for a detector-stable R-hadron are shown in Fig. 5.

The cross-section limits and the predicted production cross-sections for gluinos are used to set lower limits on expected and observed masses, as a function of lifetime. The excluded regions in the lifetime–mass plane for gluino R-hadrons which decay into a 100 GeV neutralino and quarks are shown in Fig. 6. Masses smaller than 2060 GeV are excluded for the most sensitive lifetime of 10 ns, masses smaller than 1890 GeV are excluded for the stable case, and masses smaller than 1290 GeV are excluded for a lifetime of 1 ns. Sensitivity to signals with lifetimes shorter than 1 ns falls off quickly, and is complemented by searches for disappearing tracks [60] and displaced vertices [61]. The selection and trigger efficiency, and therefore mass sensitivity, is comparable for a wide range of neutralino masses. For neutralino masses that approach the mass of the gluino, the total efficiency drops by up to a factor of three in these highly compressed decays.

10. Conclusion
A search has been performed for stable and metastable non-relativistic long-lived particles produced in pp collisions at \( \sqrt{s} = 13 \text{ TeV} \) at the LHC and identified through their large momenta and anomalous specific ionisation energy loss in the ATLAS pixel...
detector. The data sample analysed corresponds to an integrated luminosity of 36.1 fb^{-1} collected by the ATLAS experiment in 2015 and 2016. Results are interpreted assuming the pair production of R-hadrons as composite colourless states of a long-lived gluino and SM partners. With some model-dependent assumptions, a lifetime-dependent lower limit is set on the mass of metastable and stable gluinos inside R-hadrons. Maximum sensitivity is reached for gluinos with lifetimes of 10 ns, for which masses smaller than 2060 GeV are observed to be excluded at the 95% confidence level. Stable gluinos with masses smaller than 1890 GeV are excluded at 95% confidence level.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BWBFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DANSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; CSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC RfI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIŽS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, Canarie, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristea programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [62].

References


1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (ad) Department of Physics, Ankara University, Ankara; (bd) Istanbul Aydın University, Istanbul; (cd) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografos, Greece
11 Department of Physics, University of Texas at Austin, Austin TX, United States of America
12 (ad) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (bd) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (cd) Department of Physics, Bogazici University, Istanbul, (ad) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14 Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (ad) Physics Department, Tsinghua University, Beijing; (cd) Department of Physics, Nanjing University, Nanjing; (bd) University of Chinese Academy of Science (UCAS), Beijing, China
16 Institute of Physics, University of Belgrade, Belgrade, Serbia
17 Department for Physics and Technology, University of Bergen, Bergen, Norway
18 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
19 Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
20 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
21 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
22 Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
23 (ad) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; (bd) INFN Sezione di Bologna, Italy
24 Physikalisches Institut, Universität Bonn, Bonn, Germany
25 Department of Physics, Boston University, Boston MA, United States of America
26 Department of Physics, Brandeis University, Watertown MA, United States of America
27 (ad) Transilvania University of Brasov, Brasov; (bd) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (cd) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, (ad) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (bd) University Politehnica Bucharest, Bucharest; (cd) West University in Timisoara, Timisoara, Romania
28 (ad) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (bd) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
29 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
Department de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Cape Town, Cape Town, South Africa
Department of Physics, Carleton University, Ottawa ON, Canada
Faculté des Sciences Am Chock, Université de la République du Maroc, Rabat, Morocco
Faculté des Sciences de la Matière, Université d'Orsay, LPHEA-Marrakech, Morocco
Faculté des sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
LPNHE, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington NY, United States of America
Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
Dipartimento di Fisica, Università della Calabria, Rende, INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Physics Department, Southern Methodist University, Dallas TX, United States of America
Physics Department, University of Texas at Dallas, Richardson TX, United States of America
Department of Physics, Stockholm University, Sweden
Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham NC, United States of America
SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN e Laboratori Nazionali di Frascati, Frascati, Italy
Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
Dipartimento di Fisica, Università di Genova, Genova, Italy
II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
LPS, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China
Kavli-IPMU, OECD, SKLPC, Shanghai, China
Tsung-Dao Lee Institute, Shanghai, China
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong
Department of Physics, University of Hong Kong, Hong Kong, China
Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
Department of Physics, Indiana University, Bloomington IN, United States of America
INFN Gruppo Collegato di Udine, Sezione di Trieste, Italy
ICTP, Sezione di Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
INFN Sezione di Lecce; Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano, Italy
INFN Sezione di Napoli; Dipartimento di Fisica, Università di Napoli, Napoli, Italy
INFN Sezione di Pavia; Dipartimento di Fisica, Università di Pavia, Pavia, Italy
INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
INFN Sezione di Roma; Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre; Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
INFN-TIFPA; Università degli Studi di Trento, Trento, Italy
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, United States of America
Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
Joint Institute for Nuclear Research, Dubna, Russia
Instituto de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Achiv University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Faculty of Science, Kyungsung University, Busan, South Korea
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and 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
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Experimental Particle Physics, Jozef Stefan Institute and Department of Physics, University of Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Egham, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston LA, United States of America
Fysikalinstitutum, Lunds universitet, Lund, Sweden
Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, University of Michigan, Ann Arbor MI, United States of America

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

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

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

Department of Particle Physics, University of Montreal, Montreal QC, Canada

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

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

National Research Nuclear University MEPhI, Moscow, Russia

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

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

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

Nagasaki Institute of Applied Science, Nagasaki, Japan

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

Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

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

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

Department of Physics, Northern Illinois University, DeKalb IL, United States of America

(1) Budker Institute of Nuclear Physics, SB RAS, Novosibirsk; (2) Novosibirsk State University Novosibirsk, Russia

Department of Physics, New York University, New York NY, United States of America

Ohio State University, Columbus OH, United States of America

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

Department of Physics, Oklahoma State University, Stillwater OK, United States of America

Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene OR, United States of America

LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

Graduate School of Science, Osaka University, Osaka, Japan

Department of Physics, University of Oslo, Oslo, Norway

Department of Physics, Oxford University, Oxford, United Kingdom

LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France

Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

(16) Laboratório de Instrumentação e Física Experimental de Partículas – LIF (17) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; (18) Departamento de Física, Universidade de Coimbra, Coimbra; (19) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (20) Departamento de Física, Universidade do Minho, Braga; (21) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); (22) Dep Físico y CEFITEC de Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

Czech Technical University in Prague, Prague, Czech Republic

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

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

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

IRFU, CEA, Université Paris-Saclay, Cérs-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

(14) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (15) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Department of Physics, University of Washington, Seattle WA, United States of America

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

Department of Physics, Shinshu University, Nagano, Japan

Department Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby BC, Canada

SLAC National Accelerator Laboratory, Stanford CA, United States of America

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America

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

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

(16) E. Andronikashvili Institute of Physics, lv. Javakhishvili Tbilisi State University, Tbilisi; (17) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

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

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

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

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

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

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

Tomsk State University, Tomsk, Russia

Department of Physics, University of Toronto, Toronto ON, Canada

(16) TRIUMF, Vancouver BC; (17) Department of Physics and Astronomy, York University, Toronto ON, Canada

Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Department of Physics, University of Illinois, Urbana IL, United States of America

Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
Also at Borough of Manhattan Community College, City University of New York, NY; United States of America.

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

Also at CERN, Geneva; Switzerland.

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

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

Also at Departamento de Física da Universitat Autònoma de Barcelona, Barcelona; Spain.

Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain); Spain.

Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.

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

Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

Also at Department of Physics, California State University, Sacramento CA; United States of America.

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

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

Also at Department of Physics, Stanford University; United States of America.

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

Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

Also at Giessen University, Faculty of Engineering, Giessen; Turkey.

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

Also at Hellenic Open University, Patras; Greece.

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

Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.

Also at Institut Catalano de Recerca i Estudis Avançats, ICREA, Barcelona; Spain.

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

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

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

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

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

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

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

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

Also at LAAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.

Also at Louisiana Tech University, Ruston LA; United States of America.

Also at Manhattan College, New York NY; United States of America.

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

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

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

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

Also at The City College of New York, New York NY; United States of America.

Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.

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

Also at TRIUMF, Vancouver BC; Canada.

Also at Universita di Napoli Parthenope, Napoli; Italy.

* Deceased.