The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/202306

Please be advised that this information was generated on 2019-10-15 and may be subject to change.
I. INTRODUCTION

This article describes a search for heavy long-lived multicharged particles (MCPs) in $\sqrt{s} = 13$ TeV proton-proton collision data collected in 2015 and 2016 by the ATLAS detector at the CERN Large Hadron Collider (LHC) [1]. The search, conducted on a sample of data corresponding to an integrated luminosity of 36.1 fb$^{-1}$, is performed in the MCP mass range from 50 to 1400 GeV, for electric charges $|q| = ze$, with charge numbers $2 \leq z \leq 7$. An observation of such particles, possessing an electric charge above the elementary charge $e$, would be a signature for physics beyond the Standard Model (SM). Several theoretical models predict such particles. AC-leptons, as predicted by the almost-commutative model [2], are pairs of SU(2) electroweak singlets with opposite electromagnetic charges and no other gauge charges of the SM, which makes them behave as heavy stable charged leptons. Technibaryons, predicted by the walking-technicolor model [3], are Goldstone bosons made of two techniquarks or two anti-techniquarks with an arbitrary value of the electric charge. The lightest technibaryon is expected to be stable in the absence of processes violating the technibaryon number conservation law. Doubly charged Higgs bosons are predicted by the left-right symmetric model [4] in Higgs triplets in a model postulating a right-handed version of the weak interaction. Its gauge symmetry is spontaneously broken at a high mass scale, leading to parity-violation in the weak-interaction sector of the SM. Only leptonic decay modes would be characteristic of such particles, as shown in the model described in Ref. [5]. The $H^{\pm\pm} \to W^\pm W^\pm$ decays are assumed to be suppressed. The supersymmetric left-right model [5], which imposes lepton number conservation, predicts a light $H^{\pm\pm}$ boson with null lepton number, forbidding its decays to two same-sign leptons and making the $H^{\pm\pm}$ boson long-lived. Any observation of the particles predicted by the first two models could have implications for the formation of composite dark matter: the doubly charged particles (or, in general, particles with an even charge $|q| = 2ne$) could explain some excesses (e.g., positron excess) observed in direct and indirect searches for dark matter [6,7]. Particles with half-integer charge are considered in this search in order to allow continuous mass limits to be set between the $2e$ and $7e$ cases. So far, no such particles have been observed in cosmic-ray [8] or collider searches, including several recent searches at the Tevatron [9] and the LHC [10–12].

A purely electromagnetic coupling, proportional to the electric charge of the MCPs, is assumed for the production model. In this search the MCPs are assumed to live long enough to traverse the entire ATLAS detector without decaying, and thus the analysis exploits their muonlike signature, making the muon trigger a natural choice. They are highly ionizing, and thus generate an abnormally large ionization signal, $dE/dx$, which leads to their significant slowdown. Especially for MCPs with the highest charge and lowest mass values, this causes an event to not be triggered and/or MCPs to fail reconstruction as muons (this and the LHC– Tevatron searches, including several recent searches at the Tevatron [9] and the LHC [10–12].

A purely electromagnetic coupling, proportional to the electric charge of the MCPs, is assumed for the production model. In this search the MCPs are assumed to live long enough to traverse the entire ATLAS detector without decaying, and thus the analysis exploits their muonlike signature, making the muon trigger a natural choice. They are highly ionizing, and thus generate an abnormally large ionization signal, $dE/dx$, which leads to their significant slowdown. Especially for MCPs with the highest charge and lowest mass values, this causes an event to not be triggered and/or MCPs to fail reconstruction as muons (this and the LHC– Tevatron searches, including several recent searches at the Tevatron [9] and the LHC [10–12].

A purely electromagnetic coupling, proportional to the electric charge of the MCPs, is assumed for the production model. In this search the MCPs are assumed to live long enough to traverse the entire ATLAS detector without decaying, and thus the analysis exploits their muonlike signature, making the muon trigger a natural choice. They are highly ionizing, and thus generate an abnormally large ionization signal, $dE/dx$, which leads to their significant slowdown. Especially for MCPs with the highest charge and lowest mass values, this causes an event to not be triggered and/or MCPs to fail reconstruction as muons (this and the LHC– Tevatron searches, including several recent searches at the Tevatron [9] and the LHC [10–12].
calorimeter will lead to a nonzero $E_T$ vector sum and will make this trigger fire. Also, this trigger accepts events with high-mass MCPs that are too slow to fall within the muon-trigger timing window. The offline analysis searches for muonlike tracks with high $dE/dx$ values in several subdetector systems. The background expected from the SM processes (largely high-$p_T$ muons) is estimated using a data-driven technique.

II. ATLAS DETECTOR

The ATLAS detector [13] covers nearly the entire solid angle around the collision point. The inner tracking detector (ID) consists of a silicon pixel detector (pixel), a silicon microstrip detector (SCT) and a transition radiation tracker (TRT). The pixel detector was upgraded in 2014 with the insertion of an additional layer, the insertable B-layer (IBL) [14], mounted on a new beam pipe of smaller diameter. The pixel detector provides at least four precise space-point measurements per track. At normal incidence, the average charge released by a minimum-ionizing particle (MIP) in a pixel sensor is $\approx 20000 e^{-}$ ($\approx 16000 e^{-}$ for the IBL) and the charge threshold is set to $3500 e^{-}$ ($2500 e^{-}$ for the IBL) [15]. Signals are accepted if they are larger than this threshold. The time interval with the signal above the threshold is approximately proportional to the ionization charge and its dynamic range corresponds to 8.5 times (1.5 times for the IBL) the average charge released by a MIP if its track is normal to the silicon detectors and it deposits all its ionization charge in a single pixel. If this value is exceeded in the IBL, the electronics signals an excess with an overflow bit; if it is exceeded in the other three layers of the pixel detector, the hit information is not recorded due to electronics limitations (nor is the fact of the overflow). However, since the charge released by a particle crossing the pixel detector is rarely contained within just one pixel, the neighboring pixels preserve the spatial information of this hit. The SCT consists of four double-layer silicon sensors with binary readout architecture, each with a small stereo angle, typically providing eight measurements per track. The TRT, covering the pseudorapidity range $|\eta| < 2.0$, is a straw-tube tracking detector capable of particle identification via transition-radiation and ionization-energy-loss measurements [16]. A particle typically crosses 32 straws. Discriminators are used to compare the signal from a straw with a low threshold and a high threshold (HT). The HT is designed to discriminate between energy depositions from transition-radiation photons and the energy loss of MIPs. Roughly three times the energy deposition of a MIP is needed to generate an HT hit. MCPs would produce a large number of HT hits along their trajectories due to their high ionizing power.

The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, and by a high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeter. An iron/scintillator tile calorimeter provides hadronic-energy measurements in the central pseudorapidity region. The end cap and forward regions are instrumented with LAr electromagnetic and hadronic calorimeters. The calorimeter system is surrounded by a muon spectrometer (MS) incorporating three superconducting toroidal magnet assemblies. The MS is instrumented with tracking detectors designed to measure the momenta of muons. Resistive-plate chambers (RPC) in the barrel region ($|\eta| < 1.05$) and thin-gap chambers (TGC) in the end cap regions ($1.05 < |\eta| < 2.4$) provide signals for the trigger. Monitored-drift-tube (MDT) chambers typically provide 20–25 hits per crossing track in the pseudorapidity range $|\eta| < 2.7$, from which a high-precision momentum measurement is derived. In each amplifier-shaper-discriminator channel, an analog-to-digital converter is used to measure the signal charge in the 18.5 ns integration gate following the initial threshold crossing [17]. Cathode-strip chambers complement the tracking capabilities of the MDTs in the high-rate forward regions.

A two-level trigger system is used to select interesting events [18]. The first trigger level is implemented in hardware and uses a subset of the detector information to reduce the event rate to a design value of at most 100 kHz. This is followed by the software-based high-level trigger, which reduces the event rate to about 1 kHz.

The amount of material in the ID varies from one-half to two radiation lengths. The overall amount of material traversed by an MCP up to the last measurement surface, which includes the calorimeters and the MS, may be as high as 75 radiation lengths. Muons typically lose 3 GeV penetrating the calorimeter system. The energy loss for MCPs with charge $z$ would be $z^2$ times this value, i.e., up to 150 GeV for $z = 7$.

The muon transverse momentum measured by the MS after the energy loss in the calorimeters is denoted by $p_T^\mu$, while transverse momentum of charged particles measured by the ID or the combination of the ID and MS is denoted by $p_T$. Charged-particle trajectories are reconstructed using standard algorithms. Since these algorithms assume particles with unit electric charge, the momenta of MCPs are underestimated by a factor $z$, as the track curvature is proportional to $p_T/z$.

III. SAMPLES OF SIMULATED EVENTS

Benchmark samples of simulated events with MCPs were generated for a mass of 50 GeV and for a range of
masses between 200 and 1400 GeV in steps of 200 GeV, for charges \( z \) with \( z = 2, 2.5, \ldots, 7 \). Leptonlike pairs of MCPs were generated via the lowest-order Drell-Yan (DY) process implemented in \textsc{MadGraph5}_\textsc{aMC} 2.3.3 [19] with only photon exchange included. This implementation of the DY production process models the kinematic distributions and determines the cross sections. Cross-section values for MCP pair production range from hundreds of picobarns (mass of 50 GeV, \( z = 7 \)) down to a hundredth of a femtobarn (mass of 1400 GeV, \( z = 2 \)). Events were generated using the NNPDF23LO [20] parton distribution functions with the A14 set of tuned parameters [21], and \textsc{Pythia} 8.205 [22,23] was used for hadronization and underlying-event generation.

Simulated samples with muons from \( Z \to \mu \mu \) decays were generated using \textsc{Powheg-Box} v2 [24,25] interfaced to the \textsc{Pythia} 8.186 parton shower model. The AZNLO tuned parameters [26] were employed, with the CTEQ6L1 PDF set [27] for the modeling of nonperturbative effects. The \textsc{EvtGen} 1.2.0 program [28] was utilized for the properties of \( b \)- and \( c \)-hadron decays.

A full \textsc{Geant} 4 simulation [29,30] was used to model the response of the ATLAS detector. Each simulated hard-scattering event was overlaid with simulated minimum-bias events ("pileup") generated with \textsc{Pythia} in order to reproduce the observed distribution of the number of proton-proton collisions per bunch crossing. The simulated events are reconstructed and analyzed in the same way as the experimental data.

IV. EVENT AND CANDIDATE SELECTIONS

The search relies on the ionization energy released by high-charge particles and measured in the pixel, TRT, and MDT subdetector systems. Acceptance is restricted to the pseudorapidity range \( |\eta| < 2.0 \) because of the TRT geometrical limitation.

The selection is logically divided into four steps: trigger and event selection, preselection, tight selection, and final selection. While the first two steps rely on muon and missing-transverse-momentum (\( E_{T}^{\text{miss}} \)) signals as well as event topology, the tight and final selection steps rely on the ionization estimators not available at the trigger level. These estimators are introduced later in this section. An event is considered to be a candidate event if it has at least one candidate MCP (a reconstructed particle, which satisfies all selection criteria).

A. Trigger and event selections

Events collected in 2015 and 2016 with a single-muon trigger with no isolation requirement and a transverse-momentum threshold of \( p_{T}/z = 50 \) GeV are considered. This trigger is only sensitive to particles with velocity \( \beta = v/c > 0.6 \) due to a timing window, within which particles must reach the MS, which limits the trigger efficiency.

To compensate for inefficiencies in the single-muon trigger, an additional calorimeter-based trigger that imposes a threshold on the magnitude of the \( E_{T}^{\text{miss}} \) was employed. The \( E_{T}^{\text{miss}} \) threshold was 70 GeV in 2015 and was raised twice in 2016, first to 90 GeV and later to 110 GeV. Particles reconstructed in the MS are not accounted for in the trigger \( E_{T}^{\text{miss}} \) calculation, which only takes into account energy deposited in the calorimeters. Large missing transverse momentum can be due to a major difference between the energy deposited by the two MCPs in the calorimeter leading to a nonzero \( E_{T} \) vector sum (because of significant random fluctuations of the deposited energy) and also due to an MCP-MCP system recoiling against a jet, given that the energy deposited by the MCPs in the calorimeter would not balance the jet energy.

If an event is selected by both of these triggers, it is assigned to the single-muon trigger for the following analysis. On average, the exclusive contribution of the \( E_{T}^{\text{miss}} \) trigger is about 20% of the overall number of triggered signal events.

B. Candidate track preselection

Each candidate track is required to be a "combined" muon, i.e., reconstructed by combining track segments in the ID with those in the MS. These candidate muons must satisfy the "medium" criteria defined in Ref. [31], have \( p_{T}/z > 50 \) GeV, and fall within the acceptance region of the TRT (\( |\eta| < 2.0 \)).

In order to reduce the background of high-ionization signals from two or more tracks firing the same TRT straws or MDT tubes, each candidate is required not to have any adjacent tracks with \( p_{T}/z > 0.5 \) GeV within \( \Delta R < 0.01 \).

C. Ionization estimators and tight/final selections

The definitions of the tight and final selections require the introduction of ionization estimators.

The average specific energy loss, \( dE/dx \), is described by the Bethe-Bloch formula [32]. Since a particle’s energy loss increases quadratically with its charge, an MCP would leave a very characteristic signature of high ionization in the detector. Estimates of \( dE/dx \) are evaluated for the pixel, TRT and MDT subdetector systems. The pixel \( dE/dx \) is calculated from the truncated mean of the \( dE/dx \) values of the clusters associated with the track, excluding the largest (one or two) \( dE/dx \) measurements. The TRT \( dE/dx \) is the truncated mean of the hit-level \( dE/dx \) estimates, derived from the time interval when the signal remains above the low threshold. Each drift tube of the MDT system provides a signal proportional to the charge from ionization; a truncated mean of these measurements is treated as the MDT \( dE/dx \) estimator. Apart from the mentioned tail truncations, calibrations and corrections of these \( dE/dx \) estimators include removal of their dependencies on geometrical quantities (pseudorapidity, distance between a particle track and an
anode wire for the TRT and MDT) and of those related to detector effects: dependence on the number of hits, radiation damage leading to run-by-run response difference for the pixel detector, detector occupancy for the pixel detector and TRT, difference between the response in the different detector sections for the MDT, etc.

The significance of the \( dE/dx \) variable in each sub-detector is defined by comparing the observed signal, \( dE/dx \), with the average value for a highly relativistic muon:

\[
S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}.
\]

Here \( \langle dE/dx \rangle_\mu \) and \( \sigma(dE/dx)_\mu \) represent, respectively, the mean and the root-mean-square width of the \( dE/dx \) distribution for such muons in data. To calculate these two parameters, a control sample of muons was obtained from \( Z \rightarrow \mu\mu \) events. The muon selection is the same as in the analysis selection discussed in Sec. IV B. Also, muons are required to belong to an oppositely charged pair with dimuon mass between 81 and 101 GeV. These requirements effectively suppress muons from other processes.

In addition to the \( dE/dx \) estimates, the number of IBL clusters with at least one hit in overflow (called in the rest of the paper, for simplicity, the number of overflowing IBL clusters) and the fraction of HT TRT hits \( f^{HT} \) are estimators of the energy loss and are used in the tight selection.

As seen in Fig. 1, \( S(\text{pixel } dE/dx) \) is a powerful discriminator for particles with \( z = 2 \). The signal region of the tight selection is defined by requiring \( S(\text{pixel } dE/dx) \) greater than 10. For higher values of \( z \), the pixel readout saturates and the corresponding hits are not recorded. Therefore, to search for particles with \( z > 2 \), the number of overflowing IBL clusters and \( f^{HT} \) (see Fig. 2) are used as discriminating variables instead, with the signal regions of the tight selection defined by requiring at least one overflowing IBL cluster and \( f^{HT} \) to be above 0.5.

For both the \( z = 2 \) and \( z > 2 \) search cases, the tight selection criteria reduce the background contribution (mainly from the high-\( p_T \) muons) by at least 3 orders of magnitude, while keeping the signal efficiency above 90% relative to the efficiency obtained in the previous selection step.

In the final selection, \( S(\text{MDT } dE/dx) \) and \( S(\text{TRT } dE/dx) \) are used as additional discriminating variables to separate signal from background. Figure 3 shows the distributions of these variables for muons from \( Z \rightarrow \mu\mu \) events compared with those expected from signal particles with different charges (\( z = 2.0, 4.5, \) and 7.0) and a mass of 800 GeV. It demonstrates that there is good separation between signal and background, which increases with increasing charge. The \( S(\text{MDT } dE/dx) \) distribution shape broadens noticeably

\[ \text{FIG. 1. Normalized distributions of the } dE/dx\text{ significance in the pixel system, } S(\text{pixel } dE/dx) \text{ for muons from } Z \rightarrow \mu\mu \text{ events (data and simulation) and for simulated MCPs passing the preselection requirements. Signal distributions are shown for } z = 2 \text{ and masses of 200, 800, and 1400 GeV. The red dotted line indicates the threshold of the selection criterion for the } z = 2 \text{ search case.} \]

\[ \text{FIG. 2. Normalized distributions of the number of overflowing IBL clusters (left) and } f^{HT}\text{ (right) for muons from } Z \rightarrow \mu\mu \text{ events (data and simulation) and for simulated MCPs passing the preselection requirements. Signal distributions are shown for } z = 2.5, 5.0, 7.0 \text{ and a mass of 800 GeV. The blue dotted lines indicate the thresholds of the selection criteria for the } z > 2 \text{ search case.} \]
with charge because, relative to typical muons, MCPs produce a larger number of $\delta$-rays, which give early-time hits in adjacent drift tubes. This results in the $\delta$-rays’ ionization loss being measured instead of the MCP’s loss, reducing the total ionization measured along the track. The detailed detector response to these high-charge particles may not be well simulated due to imperfect modeling of the saturation effects. However, since these two detectors (TRT and MDT) do not lose signal at saturation, their most probable $dE/dx$ values are higher than those of $z=2$ particles.

During the 2012 data-taking period, gas leaks started to develop in TRT pipes, located mostly in inaccessible areas, making their repair impossible [33]. Due to the high cost of the xenon-based gas mixture, leaking modules were supplied with an argon-based mixture instead. The simulation does not fully model this change, resulting in a slightly narrower TRT $dE/dx$ distribution in simulation than in data. This is a small effect because the ratio of signal amplitude to the low threshold for the argon-filled straws was tuned to be the same as for xenon-filled ones. It is accounted for in the systematic uncertainties calculation in Sec. VII B.

The energy loss in the calorimeters is not used in the search because they have coarser granularity than the tracking detectors and, thus, worse energy-loss resolution. Ionization-estimators discrepancies between data and simulation are accounted for as systematic uncertainties as described in Sec. VII B.

Two-dimensional distributions of $S(MDT \, dE/dx)$ versus $S(TRT \, dE/dx)$ are shown for data and simulated signal events in Fig. 4 for candidates passing the tight selection for $z=2$ (left) and $z>2$ (right). As seen, the subdetector signatures are different for the two samples, and thus the final signal regions are chosen differently. They are defined by $S(TRT \, dE/dx) > 2.5$ and $S(MDT \, dE/dx) > 4$ for candidates selected as $z=2$ and by $S(TRT \, dE/dx) > 3.5$ and $S(MDT \, dE/dx) > 4$ for candidates selected as $z>2$. The selection was optimized using only simulated samples and $Z \rightarrow \mu\mu$ data control samples without examining the signal region in the data.

![Figure 3](image1.png)

**FIG. 3.** Normalized distributions of the $dE/dx$ significance in the TRT, $S(TRT \, dE/dx)$, (left) and in the MDT, $S(MDT \, dE/dx)$, (right) for muons from $Z \rightarrow \mu\mu$ events (data and simulation) and for simulated MCPs passing preselection requirements. Signal distributions are shown for $z=2.0$, 4.5, and 7.0, for a mass of 800 GeV.

![Figure 4](image2.png)

**FIG. 4.** $S(MDT \, dE/dx)$ versus $S(TRT \, dE/dx)$ after the $z=2$ (left) and $z>2$ (right) tight selections. The distributions of the data and the simulated signal samples (for charges $z=2.0$, 2.5, 5.0, and 7.0, and masses of 200, 800, and 1400 GeV) are shown. The meaning of the A, B, C and D regions is discussed in the text.
A summary of the preselection, tight selection and final selection requirements for candidate tracks is presented in Table I.

### Table I. Summary of preselection, tight selection and final selection requirements.

<table>
<thead>
<tr>
<th>Candidate track preselection</th>
<th>Tight selection</th>
<th>Final selection</th>
</tr>
</thead>
</table>
| Requirements $z = 2$ | Combined muon with “medium” identification criteria, $p_T^\mu / z > 50$ GeV, $|\eta| < 2.0$, no other tracks with $p_T^\mu / z > 0.5$ GeV within $\Delta R < 0.01$ | Preselected candidate with $S(\text{pixel } dE/dx) > 10$ | Tightly selected candidate with $S(\text{TRT } dE/dx) > 2.5$, $S(\text{MDT } dE/dx) > 4$
| $z > 2$ | $S(\text{MDT } dE/dx)$ | Preselected candidate with $\geq 1$ overflowing IBL cluster, $f^\text{HT} > 0.5$ | Tightly selected candidate with $S(\text{TRT } dE/dx) > 3.5$, $S(\text{MDT } dE/dx) > 4$

The probability $f$ is derived from the cumulative $S(\text{MDT } dE/dx)$ distribution for preselected muons in data with an anti-tight selection applied as shown in Fig. 5. The anti-tight selection is defined by inverting one of the tight selection criteria: a muon must have $f^\text{HT} < 0.5$ or must not have any overflowing IBL clusters. If two or more muons are present in the same event, only the highest-$p_T^\mu$ muon is chosen to contribute to the distribution.

This method relies on the fact that $S(\text{MDT } dE/dx)$ is not correlated with the tight selection quantities in background events. A check was performed to demonstrate the absence of such correlations: the distributions of $S(\text{pixel } dE/dx)$, number of IBL clusters in overflow, $f^\text{HT}$ and $S(\text{TRT } dE/dx)$ for muons in data with low $S(\text{MDT } dE/dx)$ values (between −10 and 0) were compared with those for muons with high $S(\text{MDT } dE/dx)$ values (between 0 and 10). An agreement at a level of 98.5% between the two cases is found, which shows that there are no correlations between ionization estimators in different subdetectors for background. Also, an additional check was performed to make sure that the shapes of cumulative $S(\text{MDT } dE/dx)$ distributions for the cases of

\[
N^D_{\text{data}} = N^B_{\text{observed}} \times f.
\]

![Figure 5](image-url)
anti-tight (see Fig. 5) and regular tight selections lay within their statistical uncertainties. Any residual differences are attributed to a systematic uncertainty as explained in Sec. VII A.

The expected background contributions to the D regions and quantities used for their calculation are shown in Tables II and III for the $z = 2$ and $z > 2$ search cases, respectively. Systematic uncertainties in these values are estimated according to the method discussed in Sec. VII A.

In principle, the absence of candidates in the C region may be translated into a Poisson upper limit at 95% confidence level of 2.996 events, and the expected background may be translated into a Poisson upper limit at 95% confidence level of 2.996 events, and the expected background contribution (in events) to the D region in data for the $z = 2$ selection, as well as quantities used for its calculation. The observed contribution is shown in the rightmost column.

### Table II.

<table>
<thead>
<tr>
<th>$N_A$</th>
<th>$N_B$</th>
<th>$N_C$</th>
<th>$N_D$</th>
<th>$N_D^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>22117</td>
<td>379</td>
<td>9</td>
<td>0.15</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The fraction of signal events satisfying the cumulative selection requirements is given in Table IV for several examples.

Several factors contribute to the efficiency dependencies on mass and charge of the MCPs. For low masses, the $|\eta| < 2.0$ selection requirement and especially the $p_T^\mu/z$ requirement are the main sources of efficiency loss. This $p_T^\mu/z$ implied selection can be as high as approximately $p_T^\mu > 50 \times 7 = 350$ GeV, where 7 is the highest charge value used in the analysis. For high masses, the requirement to reach the MS with a velocity $\beta$ which satisfies the trigger timing window is the primary reason for the reduction in efficiency. Also, high ionization loss makes particles slow down: they may not fall within the trigger timing window or may lose all their kinetic energy before reaching the MS. The charge dependence of the efficiency results from higher ionization and the higher effective $p_T^\mu/z$ selection, which are augmented by the factors $z^2$ and $z$, respectively. Also, the increased production of $\delta$-rays at higher charges leads to a smaller number of reconstructed combined muons. For events with only one MCP reaching the MS, the $E_T^{miss}$ will be larger for heavier and/or higher-charged MCPs and therefore the $E_T^{miss}$ trigger will be more likely to fire in such events.

### Table III.

<table>
<thead>
<tr>
<th>$N_B$</th>
<th>$f$</th>
<th>$N_D^*$</th>
<th>$N_D^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>4.3 x 10^-4</td>
<td>(2.9 ± 0.4 (stat.) ± 2.2 (syst.)) x 10^-2</td>
<td>0</td>
</tr>
</tbody>
</table>

**VI. SIGNAL EFFICIENCY**

The cross-section limit is inversely proportional to the integrated luminosity of the analyzed data times the overall signal efficiency, which includes trigger and selection efficiencies. This efficiency, as estimated from simulation, is shown in Fig. 6 for the signal samples used in this analysis.

![ATLAS Simulation](image)

**FIG. 6.** The signal efficiencies for different MCP charges and masses for the DY production model versus, respectively, mass (left) and charge (right) values. Despite the analysis being performed separately for $z = 2$ and $z > 2$ MCPs, it is still sensitive to MCPs with $2 < z < 2.5$. In the right figure, the efficiencies at $z = 2.0$ indicated by the continuous lines correspond to the efficiency values as if the $z > 2$ selection was applied to the $z = 2$ samples, thus denoting the conservative efficiency estimates for the $2.0 < z < 2.5$ particles.
TABLE IV. Fractions of signal events with at least one MCP candidate, which satisfy the given requirements (including all previous selection requirements). The uncertainties quoted are statistical only.

<table>
<thead>
<tr>
<th>Signal benchmark point</th>
<th>Trigger selection [%]</th>
<th>Candidate event selection [%]</th>
<th>Tight selection [%]</th>
<th>Final selection [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>Mass [GeV]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>200</td>
<td>51.6 ± 0.3</td>
<td>41.6 ± 0.3</td>
<td>39.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>54.5 ± 0.3</td>
<td>44.6 ± 0.3</td>
<td>41.3 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>39.9 ± 0.3</td>
<td>32.0 ± 0.3</td>
<td>28.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>19.2 ± 0.2</td>
<td>13.8 ± 0.2</td>
<td>13.4 ± 0.2</td>
</tr>
<tr>
<td>4.5</td>
<td>800</td>
<td>44.3 ± 0.3</td>
<td>31.3 ± 0.3</td>
<td>30.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>33.6 ± 0.3</td>
<td>22.6 ± 0.2</td>
<td>22.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>5.5 ± 0.1</td>
<td>1.42 ± 0.07</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td>7.0</td>
<td>800</td>
<td>21.0 ± 0.2</td>
<td>8.3 ± 0.2</td>
<td>7.9 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>18.3 ± 0.2</td>
<td>6.7 ± 0.1</td>
<td>6.5 ± 0.1</td>
</tr>
</tbody>
</table>

VII. UNCERTAINTIES IN THE BACKGROUND ESTIMATION AND SIGNAL YIELD

Uncertainties in the background estimate, the signal selection efficiency, and the integrated luminosity affect the sensitivity of the search for MCPs. The contributions of these uncertainties are described below.

A. Background estimation uncertainty

To assess a systematic uncertainty in the expected number of background events, so-called “dead regions” are introduced in the ABCD plane (see Fig. 7, left), and then the background estimate is recalculated for several dead-region choices using the two methods described in Sec. V. The dead regions used are: $S_{\text{MDT}}^\text{lower} < S(\text{MDT} \, dE/dx) < 4.0$ with $S_{\text{MDT}}^\text{lower} = 2.0, 2.5, 3.0,$ and $3.5$ for both the $z = 2$ and $z > 2$ cases; and $S_{\text{TRT}}^\text{lower} < S(\text{TRT} \, dE/dx) < S_{\text{TRT}}^\text{upper}$ with $S_{\text{TRT}}^\text{lower} = 0.5, 1.0, 1.5,$ and $2.0$ for the $z = 2$ case and $S_{\text{TRT}}^\text{upper} = 1.5, 2.0, 2.5,$ and $3.0$ for the $z > 2$ case. The entries inside the dead regions do not contribute to the background estimate used to assess the systematic uncertainty. This method provides an insight into any possible correlations between the two variables used to construct the ABCD plane.

The maximum differences (calculated over several dead regions) between a new background expectation in the $D$ region and the nominal one are 67% (0.1 events) and 3.4% (10^{-3} events) for the $z = 2$ and $z > 2$ cases, respectively, and are treated as systematic uncertainties in the estimation of the expected background.

An additional uncertainty is assigned for the $z > 2$ case due to a mismatch between the spectra of the fraction of events with a muon passing the $S(\text{MDT} \, dE/dx) < 4.0$ cut for the tight and anti-tight selections (see Fig. 7, right) at $S(\text{MDT} \, dE/dx)$ values close to 4. Both distributions were fit with a $p_0 \times e^{p_1 \cdot x + p_2}$ function (a first-degree polynomial in the exponent was chosen for simplicity) within the range of $3 < S(\text{MDT} \, dE/dx) < 4$, where $x$ represents the $S(\text{MDT} \, dE/dx)$ cut value and $p_0, p_1,$ and $p_2$ are free fit

![Figure 7](https://example.com/fig7.png)

FIG. 7. Left: ABCD plane (for the $z = 2$ case) used to assess the systematic uncertainty in the expected number of background events. Entries inside the “dead region” (here within $1.0 < S(\text{TRT} \, dE/dx) < 2.5$, shown by black shading) do not contribute to the background estimate used to assess the systematic uncertainty. Right: overall $S(\text{MDT} \, dE/dx)$ distribution with the anti-tight selection applied (black points) and with the regular tight selection applied (green points). Both distributions are shown zoomed in around the final selection cut (shown by a solid blue vertical line) and are fit with $p_0 \times e^{p_1 \cdot x + p_2}$ functions to quantify their difference at $S(\text{MDT} \, dE/dx) = 4$. 
parameters. The difference between the two fits at $S(\text{MDT} \, dE/dx) = 4$ is used to assign an additional 75% systematic uncertainty (0.022 events).

Summarizing the above, the final systematic uncertainties in the estimation of the expected background are 67% for $z = 2$ and 75% for $z > 2$.

**B. Signal yield uncertainty**

Several sources of systematic uncertainty in the signal efficiency are considered. The most significant uncertainties are those due to imperfect agreement between data and simulation, the trigger efficiency, and the parametrization of the parton distribution function used in the signal generation.

The uncertainty due to the disagreement between data and simulation is evaluated by varying the signal acceptance requirements used in the analysis. Several considerations motivate these variations. The uncertainty in the amount of material in front of the MS, which is about 1% [35], propagates into an uncertainty in the selection efficiency, as well as the resulting values of the relative uncertainties (rightmost column).

### TABLE V. Overview of the most significant individual contributions (in %) to the overall systematic uncertainties in the signal selection efficiency, as well as the resulting values of the relative uncertainties (rightmost column).

<table>
<thead>
<tr>
<th>Signal benchmark point</th>
<th>Data-simulation comparison [%]</th>
<th>Trigger efficiency [%]</th>
<th>PDF parametrization [%]</th>
<th>Selection efficiency overall uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>Mass [GeV]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>200</td>
<td>12</td>
<td>0.9</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>7.2</td>
<td>3.6</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>6.1</td>
<td>5.0</td>
<td>17</td>
</tr>
<tr>
<td>4.5</td>
<td>200</td>
<td>8.9</td>
<td>1.4</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>5.7</td>
<td>2.4</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>5.9</td>
<td>10.2</td>
<td>17</td>
</tr>
<tr>
<td>7.0</td>
<td>200</td>
<td>9.3</td>
<td>3.1</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>6.6</td>
<td>8.2</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>6.7</td>
<td>5.6</td>
<td>18</td>
</tr>
</tbody>
</table>
distribution for muons measured in the full $Z \rightarrow \mu \mu$ data sample. The uncertainty, assessed as the maximum relative difference between the nominal efficiency values and those obtained after the variations, ranges up to 1% for signal particles with the highest charges and masses. For the TGC trigger, no mismatch between the timing distributions in data and simulation was observed; therefore the trigger efficiency as obtained from simulation can be trusted.

For MCPs with $\beta$ significantly less than 1 the drift time in the TRT and MDT could be mismeasured (due to the arrival time of the particle to the detector), worsening the momentum resolution, but TRT and MDT simulations model this effect. In the TRT, the effect is hardly noticeable due to the relatively small distance between the interaction point and the TRT. An MCP traveling one meter gets delayed by 0.6 ns for $\beta = 0.8$, while the TRT time bin is 3.1 ns. Also, the track reconstruction accepts hits within a timing uncertainty of $\pm (3-4)$ ns. The time difference is larger for the MS (up to 7 ns); however, the total drift time in MDT, with drift tubes of radius 15 mm, is about 700 ns, and thus any likely difference between data and simulation would not contribute significantly to the track reconstruction efficiency.

The NNPDF23LO parton distribution function (PDF) was varied within its error sets, each with a slightly different parametrization. These variations were translated into an uncertainty in the signal efficiency, ranging from 6% for low-mass MCPs to 18% for MCPs with the highest mass.

A 2.1% uncertainty was assigned to the integrated luminosity used for this analysis. This uncertainty is derived, following a methodology similar to that detailed in Ref. [36], from a calibration of the luminosity scale using $x$-$y$ beam-separation scans.

A subset of contributions from the separate sources of the most significant systematic uncertainties in the signal selection efficiency, as well as the resulting values of overall systematic uncertainties, are shown in Table V for several benchmark points.

### VIII. RESULTS

No candidate events with MCPs were found for either the $z = 2$ search or the $z > 2$ search. The results are consistent with the expectation of $0.15 \pm 0.05 \text{ (stat.)} \pm 0.10 \text{ (syst.)}$ and $(2.9 \pm 0.4 \text{ (stat.)} \pm 2.2 \text{ (syst.)}) \times 10^{-2}$ background events, respectively. Since the number of events expected from background is very small and no signal events were found, the observed and expected limits are practically identical.

The limits are computed with the RooStats framework [37], which uses the CLs method [38] to discriminate between the background-only hypothesis and the signal-plus-background hypothesis, and determines exclusion limits for various MCP scenarios. The signal selection efficiency, luminosity, expected and observed numbers of events and their uncertainties (as well as signal leakages (fractions of the signal distributions outside the D region of the ABCD plane), handled as nuisance parameters, are

---

**TABLE VI.** Observed 95% C.L. lower mass limits of leptonlike MCPs for the Drell-Yan production model.

<table>
<thead>
<tr>
<th>$z$</th>
<th>Lower limit on MCP mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.98 1.06 1.13 1.17 1.20 1.22 1.22 1.21 1.19 1.16 1.12</td>
</tr>
<tr>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>3.5</td>
<td>5.0</td>
</tr>
<tr>
<td>4.0</td>
<td>6.0</td>
</tr>
<tr>
<td>4.5</td>
<td>6.5</td>
</tr>
<tr>
<td>5.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

---

**FIG. 9.** Observed 95% C.L. lower mass limits of leptonlike MCPs for charges $z \in [2, 7]$ with a Drell-Yan pair-production model. The mismatch between the left end of the continuous line and the marker at $z = 2.0$ (a shift by 150 GeV) is due to the difference in efficiencies between the cases where the $z = 2$ and $z > 2$ selections are applied to the $z = 2.0$ samples, making this line segment constitute a conservative mass limit for $2.0 < z < 2.5$ particles.
taken as input for pseudoexperiments, resulting in an observed limit at 95% confidence level (C.L.).

The measurement excludes the DY model of leptonlike MCP pair production over wide ranges of tested masses. Figure 8 summarizes the observed 95% C.L. cross-section limits as a function of mass for several MCP charges and compares them with those predicted by the DY model. For this model, the cross-section limits can be transformed into mass exclusion regions from 50 GeV up to 980 GeV. Upper limits are derived on the cross sections using a Drell-Yan production model and no events are observed. Upper limits are obtained from the intersection of the observed limits and the theoretical cross-section values.

IX. CONCLUSION

This article reports on a search for long-lived multicharged particles produced in proton-proton collisions with the ATLAS detector at the LHC. The search uses a data sample with a center-of-mass energy of \( \sqrt{s} = 13 \) TeV and an integrated luminosity of 36.1 fb\(^{-1}\). Leptonlike particles are searched for with electric charges from \(|q| = 2e\) to \(|q| = 7e\) penetrating the full ATLAS detector and producing anomalously high ionization signals in multiple detector elements. Less than one background event is expected and no events are observed. Upper limits are derived on the cross sections using a Drell-Yan production model and exclude leptonlike multicharged particles with masses between 50 and 980–1220 GeV.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; 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 DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/Irfu, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW 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 DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/Irfu, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, 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), SRNSFG (Georgia), BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, 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. [39].

Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des sciences, Université Mohammed V, Rabat, Morocco
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
Dipartimento di Fisica, Università della Calabria, Rende, Italy
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
Department of Physics, Stockholm University, Sweden
Oskar Klein Centre, Stockholm, 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, North Carolina, USA
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
INFN Sezione 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
LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
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, KLPPAC-MoE, SKLPPC, Shanghai, China
Tsung-Dao Lee Institute, Shanghai, China
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
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, Indiana, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
INFN Sezione di Lecce, Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
INFN Sezione di Milano, Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
INFN Sezione di Napoli, Napoli, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
INFN Sezione di Pavia, Pavia, Italy
INFN Sezione di Pisa, Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
INFN Sezione di Roma, Roma, Italy
Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
INFN Sezione di Roma Tor Vergata, Roma, Italy
SEARCH FOR HEAVY LONG-LIVED MULTICHARGED … PHYS. REV. D 99, 052003 (2019)

71b Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
71c INFN Sezione di Roma Tre, Roma, Italy
72b Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
72a INFN-TIFPA, Trento, Italy
73b Università degli Studi di Trento, Trento, Italy
74 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
75 University of Iowa, Iowa City, Iowa, USA
76 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
77 Joint Institute for Nuclear Research, Dubna, Russia
78a Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
78b Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
78c Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil
78d Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
78e KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
80 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
81a Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
81b Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
82 Faculty of Science, Kyoto University, Kyoto, Japan
83 Kyoto University of Education, Kyoto, Japan
84 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
86 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
87 Physics Department, Lancaster University, Lancaster, United Kingdom
88 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
89 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
90 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
91 Department of Physics, Royal Holloway University of London, Egham, United Kingdom
92 Department of Physics and Astronomy, University College London, London, United Kingdom
93 Louisiana Tech University, Ruston, Louisiana, USA
94 Fysiska institutionen, Lunds universitet, Lund, Sweden
95 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
96 Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
97 Institut für Physik, Universität Mainz, Mainz, Germany
98 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
99 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
100 Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
101 Department of Physics, McGill University, Montreal, Québec, Canada
102 School of Physics, University of Melbourne, Victoria, Australia
103 Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
104 Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
105 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
106 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
107 Group of Particle Physics, University of Montreal, Montréal, Québec, Canada
108 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
109 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
110 National Research Nuclear University MEPhI, Moscow, Russia
111 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
112 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
113 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
114 Nagasaki Institute of Applied Science, Nagasaki, Japan
115 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
116 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

052003-23
117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
118 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
120 Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia
Novosibirsk State University Novosibirsk, Russia
121 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
122 Department of Physics, New York University, New York, New York, USA
123 The Ohio State University, Columbus, Ohio, USA
124 Faculty of Science, Okayama University, Okayama, Japan
125 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
126 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
127 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
128 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
129 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
130 Graduate School of Science, Osaka University, Osaka, Japan
131 Department of Physics, University of Oslo, Oslo, Norway
132 Department of Physics, Oxford University, Oxford, United Kingdom
133 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
134 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
135 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
136 Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
137 Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
138 Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
139 Departamento de Física, Universidade do Minho, Braga, Portugal
137 Departoamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
137 Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
138 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
139 Czech Technical University in Prague, Prague, Czech Republic
140 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
141 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
142 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
143 Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
144 Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
145 Department of Physics, University of Washington, Seattle, Washington, USA
146 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
147 Department of Physics, Shinshu University, Nagano, Japan
148 Department Physik, Universität Siegen, Siegen, Germany
149 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
150 SLAC National Accelerator Laboratory, Stanford, California, USA
151 Physics Department, Royal Institute of Technology, Stockholm, Sweden
152 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
153 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
154 School of Physics, University of Sydney, Sydney, Australia
155 Institute of Physics, Academia Sinica, Taipei, Taiwan
156 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
157 High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
158 Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
159 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
160 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
161 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
162 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
SEARCH FOR HEAVY LONG-LIVED MULTICHARGED …

PHYS. REV. D 99, 052003 (2019)

162 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
163 Tomsk State University, Tomsk, Russia
164 Department of Physics, University of Toronto, Toronto, Ontario, Canada
165a TRIUMF, Vancouver, British Columbia, Canada
165b Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
166 Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
167 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
168 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
169 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
170 Department of Physics, University of Illinois, Urbana, Illinois, USA
171 Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain
172 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
173 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
175 Department of Physics, University of Warwick, Coventry, United Kingdom
176 Waseda University, Tokyo, Japan
177 Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
178 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
179 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
180 Department of Physics, Yale University, New Haven, Connecticut, USA
181 Yerevan Physics Institute, Yerevan, Armenia

a Deceased.
b Also at Department of Physics, King’s College London, London, United Kingdom.
c Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
d Also at Instituto de Física Teórica de la Universidad Autónoma de Madrid, Spain.
e Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
f Also at TRIUMF, Vancouver, British Columbia, Canada.
g Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
h Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
i Also at Departamento de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
j Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
k Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
l Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.
m Also at Universita di Napoli Parthenope, Napoli, Italy.
n Also at Institute of Particle Physics (IPP), Canada.
o Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
p Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
q Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
r Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
s Also at Borough of Manhattan Community College, City University of New York, New York, USA.
t Also at Department of Physics, California State University, Fresno, California, USA.
u Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
v Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
w Also at Louisiana Tech University, Ruston, Louisiana, USA.
x Also at California State University, East Bay, California, USA.
y Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
z Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
a Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
b Also at Graduate School of Science, Osaka University, Osaka, Japan.
c Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
d Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
e Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
f Also at CERN, Geneva, Switzerland.
g Also at Department of Physics, Stanford University, Stanford, California, USA.
h Also at Joint Institute for Nuclear Research, Dubna, Russia.

052003-25
Also at Hellenic Open University, Patras, Greece.

Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.

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

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

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

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

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

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

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

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

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

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

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

Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

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