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

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A search for heavy long-lived multicharged particles is performed using the ATLAS detector at the LHC. Data with an integrated luminosity of 36.1 fb^{-1} collected in 2015 and 2016 from proton-proton collisions at $\sqrt{s} = 13$ TeV are examined. Particles producing anomalously high ionization, consistent with long-lived massive particles with electric charges from $|q| = 2e$ to $|q| = 7e$, are searched for. No events are observed, and 95% confidence level cross-section upper limits are interpreted as lower mass limits for a Drell-Yan production model. Multicharged particles with masses between 50 and 980–1220 GeV (depending on their electric charge) are excluded.

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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 charges¹ $|q| = ze$, 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 $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ 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 is the main reason for the search to be limited by the $z = 7$ MCPs from above). The addition of the missing-transverse-momentum trigger mitigates the first issue because a difference in energy deposited by the two MCPs in the

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¹Wherever a charge is quoted for exotic particles, the charge conjugate state is also implied.

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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 sub-detector 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.² 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^μ , 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

²ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

masses between 200 and 1400 GeV in steps of 200 GeV, for charges ze with $z = 2, 2.5, \dots, 7$. Leptonlike pairs of MCPs were generated via the lowest-order Drell-Yan (DY) process implemented in MADGRAPH5_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 PYTHIA 8.205 [22,23] was used for hadronization and underlying-event generation.

Simulated samples with muons from $Z \rightarrow \mu\mu$ decays were generated using POWHEG-BOX v2 [24,25] interfaced to the 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 EVTGEN 1.2.0 program [28] was utilized for the properties of b - and c -hadron decays.

A full 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 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^{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^{miss} was employed. The E_T^{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^{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^{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 $p_T^\mu/z > 50$ 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

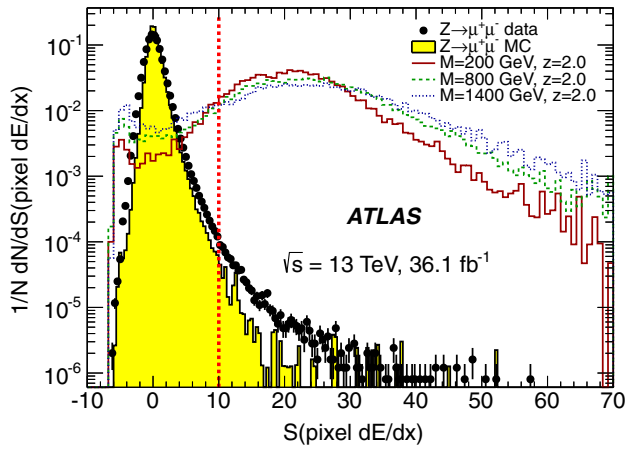
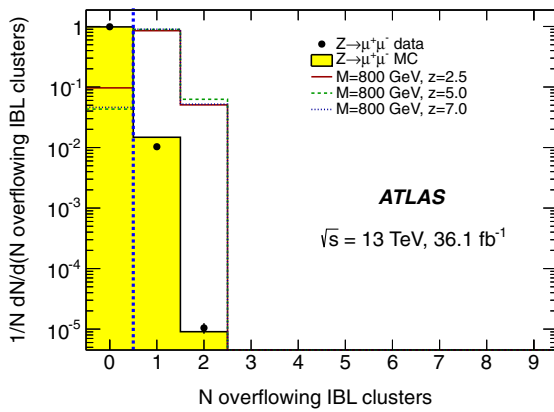


FIG. 1. Normalized distributions of the dE/dx significance in the pixel system, $S(\text{pixel } dE/dx)$ for muons from $Z \rightarrow \mu\mu$ events (data and simulation) and for simulated MCPs passing the preselection requirements. Signal distributions are shown for $z = 2$ and masses of 200, 800,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



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 ($z = 2.0, 4.5, \text{ and } 7.0$) 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

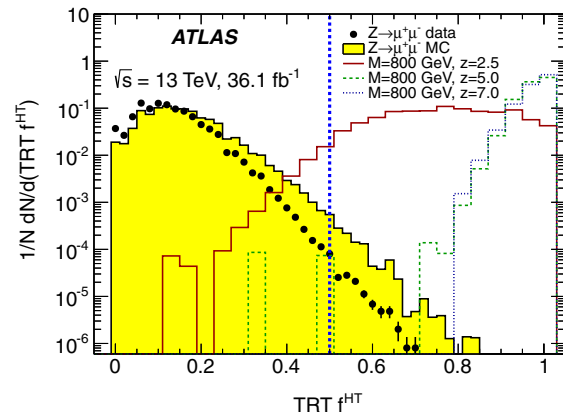


FIG. 2. Normalized distributions of the number of overflowing IBL clusters (left) and f^{HT} (right) for muons from $Z \rightarrow \mu\mu$ events (data and simulation) and for simulated MCPs passing the preselection requirements. Signal distributions are shown for $z = 2.5, 5.0, 7.0$ and a mass of 800 GeV. The blue dotted lines indicate the thresholds of the selection criteria for the $z > 2$ search case.

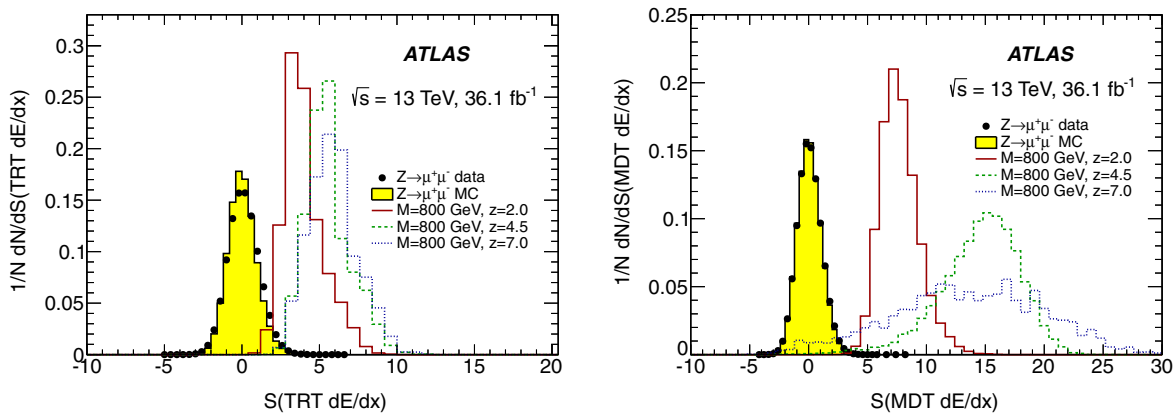


FIG. 3. Normalized distributions of the dE/dx significance in the TRT, $S(\text{TRT } dE/dx)$, (left) and in the MDT, $S(\text{MDT } dE/dx)$, (right) for muons from $Z \rightarrow \mu\mu$ events (data and simulation) and for simulated MCPs passing preselection requirements. Signal distributions are shown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

with charge because, relative to typical muons, MCPs produce a larger number of δ -rays, which give early-time hits in adjacent drift tubes. This results in the δ -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 $S(\text{MDT } dE/dx)$ versus $S(\text{TRT } dE/dx)$ 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 $S(\text{TRT } dE/dx) > 2.5$ and $S(\text{MDT } dE/dx) > 4$ for candidates selected as $z = 2$ and by $S(\text{TRT } dE/dx) > 3.5$ and $S(\text{MDT } dE/dx) > 4$ 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.

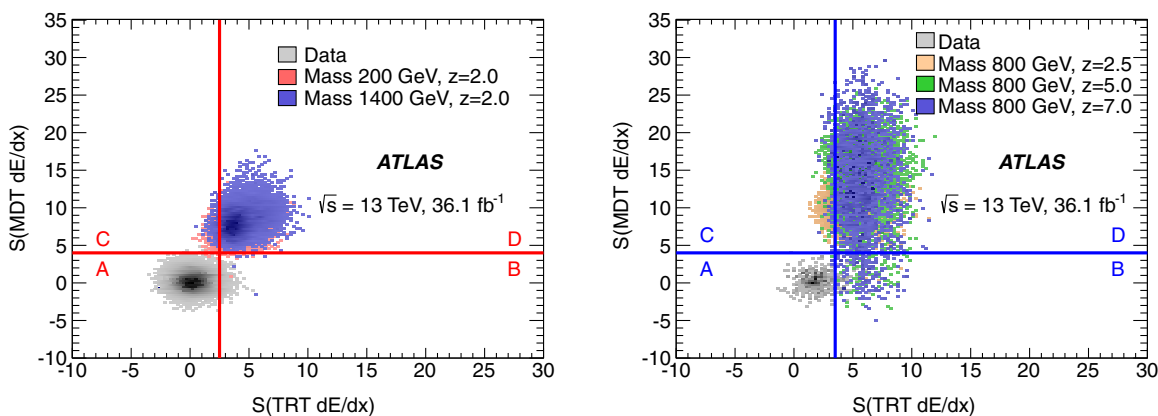


FIG. 4. $S(\text{MDT } dE/dx)$ versus $S(\text{TRT } dE/dx)$ after the $z = 2$ (left) and $z > 2$ (right) tight selections. The distributions of the data and the simulated signal samples (for charges $z = 2.0, 2.5, 5.0,$ and 7.0 , and masses of $200, 800,$ and 1400 GeV) are shown. The meaning of the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

TABLE I. Summary of preselection, tight selection and final selection requirements.

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

A summary of the preselection, tight selection and final selection requirements for candidate tracks is presented in Table I.

V. EXPECTED BACKGROUND ESTIMATION

The source of potential background is of an instrumental origin: it consists mainly of muons with ionization randomly fluctuating toward larger values due to detector occupancy effects (a large number of particles losing their energy in the same detector elements) and δ -ray yields. The expected background rate is estimated with two methods.

For the $z = 2$ search case, it is estimated using an ABCD method [34]. According to this method, the plane of $S(\text{TRT } dE/dx)$ and $S(\text{MDT } dE/dx)$ is divided into regions A, B, C, and D using the final selection cuts as shown in Fig. 4. Region D is defined as the signal region, with regions A, B, and C as control regions.

If two or more particles contribute to the same event on the ABCD plane, only one is retained and shown on the plane according to a “D-C-B-A- p_T^μ ” ranking to avoid double-counting events. It consists in choosing the first particle found when considering region D then C, B, and finally A (ranked from the most populated quadrant to the least populated one in signal simulation). If there are two or more particles in the event and in the same region, the highest- p_T^μ one is chosen.

For the $z = 2$ search, the expected number of background events in the D region, $N_{\text{data}}^{\text{D expected}}$, is estimated from the numbers of observed data events in regions A, B, and C ($N_{\text{data}}^{\text{A,B,C observed}}$):

$$N_{\text{data}}^{\text{D expected}} = \frac{N_{\text{data}}^{\text{B observed}} \times N_{\text{data}}^{\text{C observed}}}{N_{\text{data}}^{\text{A observed}}}.$$

The same method is not used for the $z > 2$ search case, because $N_{\text{data}}^{\text{C observed}} = 0$ [see Fig. 4 (right)], which would lead to a large statistical uncertainty in $N_{\text{data}}^{\text{D expected}}$. Instead, a method which employs sidebands of the two discriminating variables is used [10]. Here, $N_{\text{data}}^{\text{D expected}}$ is estimated from the number of observed events in region B and the probability f to find a particle with $S(\text{MDT } dE/dx) > 4$ in a single event:

$$N_{\text{data}}^{\text{D expected}} = N_{\text{data}}^{\text{B observed}} \times f.$$

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^μ 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^{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

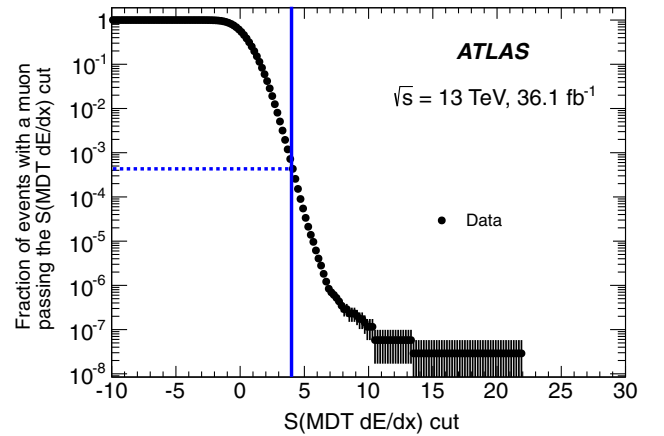


FIG. 5. Cumulative $S(\text{MDT } dE/dx)$ distribution with the anti-tight selection applied, used to calculate the probability f to find a particle with $S(\text{MDT } dE/dx) > 4$. The resulting value of f is indicated by the blue dashed line.

TABLE II. 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.

$N_{\text{data}}^{\text{A observed}}$	$N_{\text{data}}^{\text{B observed}}$	$N_{\text{data}}^{\text{C observed}}$	$N_{\text{data}}^{\text{D expected}}$	$N_{\text{data}}^{\text{D observed}}$
22117	379	9	0.15 ± 0.05 (stat.) ± 0.10 (syst.)	0

TABLE III. 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.

$N_{\text{data}}^{\text{B observed}}$	f	$N_{\text{data}}^{\text{D expected}}$	$N_{\text{data}}^{\text{D observed}}$
66	4.3×10^{-4}	$(2.9 \pm 0.4$ (stat.) ± 2.2 (syst.)) $\times 10^{-2}$	0

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 yield can be further estimated with the $z = 2$ method. However, this results in a less precise estimate with the upper limit of 0.5 background events, which makes the usage of the $z > 2$ method more favorable.

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.

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}^{μ}/z requirement are the main sources of efficiency loss. This p_{T}^{μ}/z implied selection can be as high as approximately $p_{\text{T}}^{\mu} > 50 \times 7 = 350$ GeV, where 7 is the highest charge value used in the analysis. For high masses, the requirement to reach the MS with a velocity β 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}^{μ}/z selection, which are augmented by the factors z^2 and z , respectively. Also, the increased production of δ -rays at higher charges leads to a smaller number of reconstructed combined muons. For events with only one MCP reaching the MS, the $E_{\text{T}}^{\text{miss}}$ will be larger for heavier and/or higher-charged MCPs and therefore the $E_{\text{T}}^{\text{miss}}$ trigger will be more likely to fire in such events.

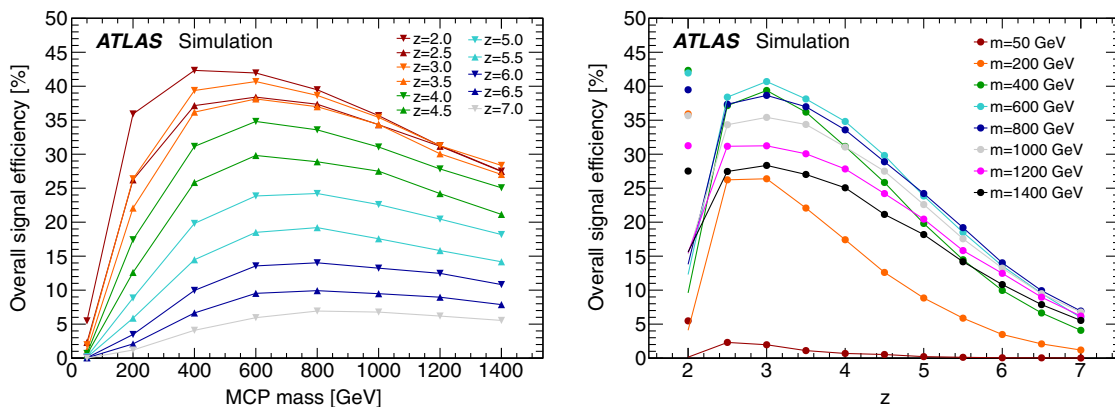


FIG. 6. The signal efficiencies for different MCP charges and masses for the DY production model versus, respectively, mass (left) and charge (right) values. Despite the analysis being performed separately for $z = 2$ and $z > 2$ MCPs, it is still sensitive to MCPs with $2 < z < 2.5$. In the right figure, 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.

Signal benchmark point		Trigger selection [%]	Candidate event selection [%]	Tight selection [%]	Final selection [%]
z	Mass [GeV]				
2.0	200	51.6 ± 0.3	41.6 ± 0.3	39.2 ± 0.3	35.9 ± 0.3
	800	54.5 ± 0.3	44.6 ± 0.3	41.3 ± 0.3	39.5 ± 0.3
	1400	39.9 ± 0.3	32.0 ± 0.3	28.4 ± 0.3	27.5 ± 0.3
4.5	200	19.2 ± 0.2	13.8 ± 0.2	13.4 ± 0.2	12.6 ± 0.2
	800	44.3 ± 0.3	31.3 ± 0.3	30.2 ± 0.3	28.9 ± 0.3
	1400	33.6 ± 0.3	22.6 ± 0.2	22.1 ± 0.2	21.1 ± 0.2
7.0	200	5.5 ± 0.1	1.42 ± 0.07	1.4 ± 0.1	1.19 ± 0.07
	800	21.0 ± 0.2	8.3 ± 0.2	7.9 ± 0.2	6.9 ± 0.2
	1400	18.3 ± 0.2	6.7 ± 0.1	6.5 ± 0.1	5.5 ± 0.1

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 systematic 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: $S_{\text{lower}}^{\text{MDT}} < S(\text{MDT } dE/dx) < 4.0$ with $S_{\text{lower}}^{\text{MDT}} = 2.0, 2.5, 3.0,$ and 3.5 for both the $z = 2$ and $z > 2$ cases; and $S_{\text{lower}}^{\text{TRT}} < S(\text{TRT } dE/dx) < S_{\text{upper}}^{\text{TRT}}$ with $S_{\text{lower}}^{\text{TRT}} = 0.5, 1.0, 1.5,$ and 2.0 for the $z = 2$ case and $S_{\text{upper}}^{\text{TRT}} = 1.5, 2.0, 2.5,$ 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 $S(\text{MDT } dE/dx)$ 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 $p_0 \times e^{p_1 x + p_2}$ function (a first-degree polynomial in the exponent was chosen for simplicity) within the range of $3 < S(\text{MDT } dE/dx) \text{ cut} < 5$, where x represents the $S(\text{MDT } dE/dx)$ cut value and $p_0, p_1,$ and p_2 are free fit

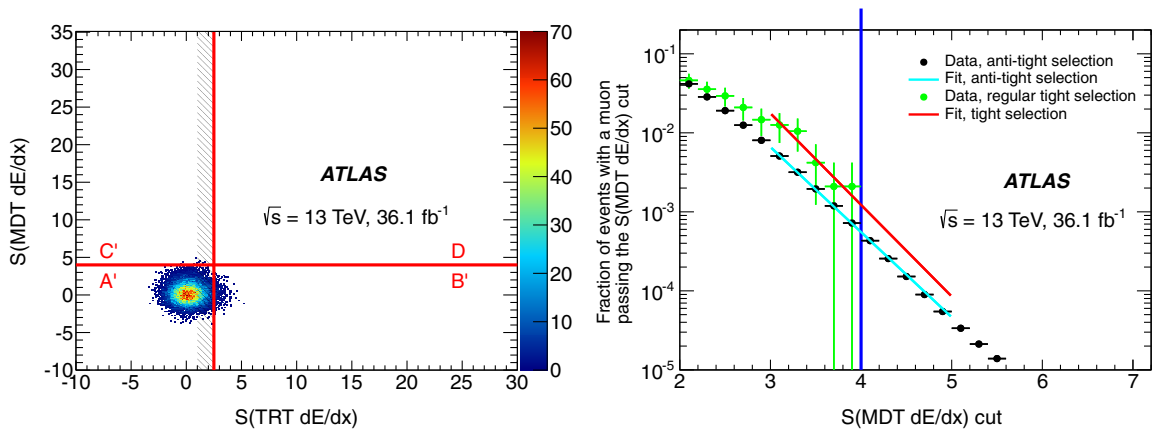


FIG. 7. Left: ABCD plane (for the $z = 2$ case) used to assess the systematic uncertainty in the expected number of background events. Entries inside the “dead region” (here within $1.0 < S(\text{TRT } dE/dx) < 2.5$, shown by black shading) do not contribute to the background estimate used to assess 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 $p_0 \times e^{p_1 x + p_2}$ 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 due to the slowing down of particles, and is covered by varying the p_T^μ requirement. When considering the $Z \rightarrow \mu\mu$ dE/dx distributions together with those of the signal, the lower parts of the dE/dx ranges are the most important for determining the signal efficiency. These correspond to the cores of the $Z \rightarrow \mu\mu$ distributions and are the most relevant because if there is good agreement between data and simulation in that dE/dx range (below the corresponding selection cut), the signal efficiencies will agree between the data and simulation. The variation applied to the nominal p_T^μ requirement is p_T^μ value by $\pm 3\%$.

In addition, the mean and the root-mean-square width of the distributions in $Z \rightarrow \mu\mu$ events disagree between data and simulation, and the ionization estimators may be mismodeled. These are accounted for by the following variations of the signal selection criteria:

- (i) number of overflowing IBL clusters by $\pm 0.5\%$,
- (ii) $S(\text{pixel } dE/dx)$ by $\pm 25\%$,

- (iii) f^{HT} by $\pm 40\%$,
- (iv) $S(\text{TRT } dE/dx)$ by $\pm 15\%$,
- (v) and $S(\text{MDT } dE/dx)$ by $\pm 3\%$.

The values of these variations are obtained by averaging the bin-by-bin ratios of $Z \rightarrow \mu\mu$ yields in data to those in simulation (see Figs. 1–3) in the cores of the corresponding distributions (within $\pm 3\sigma$ with respect to the position of the mean of each distribution). The total systematic uncertainties in the efficiency arising from these variations range between 5% and 80%, where the largest uncertainty corresponds to lower-mass $z = 2.5$ signal samples, which are fairly sensitive to the f^{HT} variation.

The uncertainty in the trigger efficiency also has several sources, including an uncertainty in the muon-trigger efficiency ($< 0.5\%$), accounting for differences between triggering on the same muons in data and simulation, and an uncertainty in the E_T^{miss} trigger efficiency (23% on average). This second uncertainty depends on the accuracy of modeling the E_T^{miss} turn-on curve, and is sensitive to the offline E_T^{miss} reconstruction. The former (9.4%) was assessed by comparing the turn-on curves of the corresponding triggers in data and simulation using $Z \rightarrow \mu\mu$ samples and taking the largest difference between all pairs. The latter (21% on average) was assessed using the offline E_T^{miss} spectra (in events triggered exclusively by the E_T^{miss} trigger), varied to account for any possible uncertainties in the E_T^{miss} term. There is also a β -dependent uncertainty originating from uncertainties in the modeling of the muon-trigger timing for particles with $\beta \ll 1$. In order to improve the description of the trigger simulation, parametrized corrections were applied to the probability for MCPs to fire the RPC trigger. To assess the uncertainty, the parameters of these corrections were varied. The β value of particles was varied between the true generated value and the one reconstructed in the MS from the hypothesized mass and measured momentum. The time interval needed for a signal particle to reach the RPC trigger planes was varied by the root-mean-square width of the timing

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).

Signal benchmark point		Data-simulation comparison [%]	Trigger efficiency [%]	PDF parametrization [%]	Selection efficiency overall uncertainty [%]
z	Mass [GeV]				
2.0	200	12	0.9	6.5	14
	800	7.2	3.6	10	13
	1400	6.1	5.0	17	19
4.5	200	8.9	1.4	6.9	12
	800	5.7	2.4	11	12
	1400	5.9	10.2	17	21
7.0	200	9.3	3.1	7.2	14
	800	6.6	8.2	11	16
	1400	6.7	5.6	18	21

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 β 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

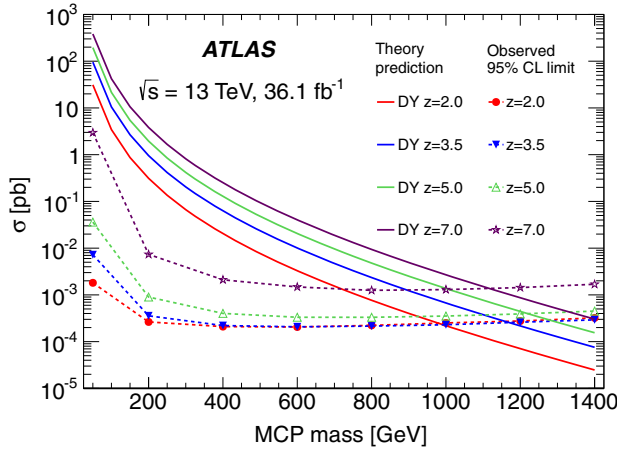


FIG. 8. Observed 95% C.L. cross-section upper limits and theoretical cross sections as functions of the leptonlike MCP's mass for several values of z between 2 and 7.

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

	z										
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Lower mass limit [TeV]	0.98	1.06	1.13	1.17	1.20	1.22	1.22	1.21	1.19	1.16	1.12

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 ± 0.05 (stat.) ± 0.10 (syst.) and $(2.9 \pm 0.4$ (stat.) ± 2.2 (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 CL_s 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

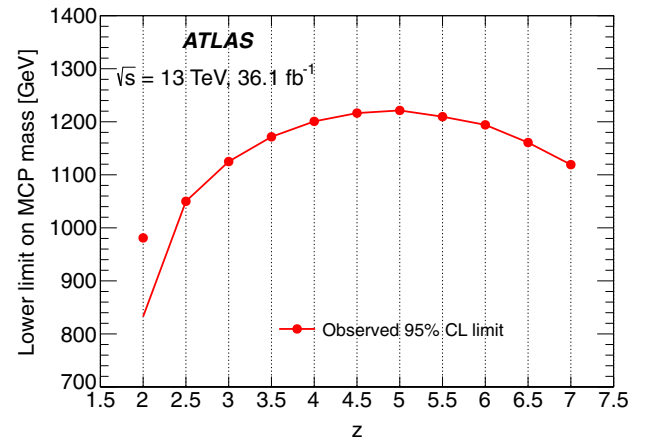


FIG. 9. Observed 95% C.L. lower mass limits of leptonlike MCPs for charges $z \in [2, 7]$ with a Drell-Yan pair-production model. The mismatch between the left end of the continuous line and the marker at $z = 2.0$ (a shift by 150 GeV) is due to the difference in efficiencies between the cases where 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 the values in Table VI. Figure 9 demonstrates the dependence of the lower mass exclusion limits on MCP charge values. The mass 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 multi-charged 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.

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