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Search for long-lived, multi-charged particles in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV using the ATLAS detector

**ATLAS Collaboration**

**A R T I C L E   I N F O**

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**A B S T R A C T**

A search for highly ionising, penetrating particles with electric charges from \(|q| = 2e\) to \(6e\) is performed using the ATLAS detector at the CERN Large Hadron Collider. Proton–proton collision data taken at \( \sqrt{s} = 7 \) TeV during the 2011 running period, corresponding to an integrated luminosity of 4.4 \( \text{fb}^{-1} \), are analysed. No signal candidates are observed, and 95% confidence level cross-section upper limits are interpreted as mass-exclusion lower limits for a simplified Drell–Yan production model. In this model, masses are excluded from 50 GeV up to 430, 480, 490, 470 and 420 GeV for charges \(2e\) and \(3e\), \(4e\), \(5e\) and \(6e\), respectively.

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**1. Introduction**

Numerous theories of physics beyond the Standard Model (SM) predict long-lived\(^1\) exotic objects producing anomalous ionisation. These include magnetic monopoles [1], dyons [2], long-lived micro black holes in models of low-scale gravity [3] and Q-balls [4], which are non-topological solitons predicted by minimal supersymmetric generalisations of the SM. No such particles have so far been observed in cosmic-ray and collider searches [1,5–7], including several recent searches at the Large Hadron Collider (LHC) [8–13]. The high centre-of-mass energy of the LHC makes a new energy regime accessible, and searching for multi-charged particles with electric charges \(2e \leq |q| \leq 6e\) complements the searches for slow singly charged particles [10] and for particles with charges beyond \(6e\) [8].

The existence of long-lived particles with an electric charge \(|q| > e\) could have implications for the formation of composite dark matter [14]. Two extensions of the SM in which heavy stable multi-charged particles are predicted are the AC model [15] and the walking technicolour model [16–18]. The AC model is based on the approach of almost-commutative geometry [19] which extends the fermion content of the SM by two heavy particles with opposite electric charges, \(\pm q\). The minimal walking technicolour model predicts the existence of three particle pairs, with electric charges given in general by \(q + e\), \(q\), and \(q - e\), which would behave like leptons in the detector. In both of these models, \(|q|\) may be larger than \(e\).

This Letter describes a search for multi-charged particles in \(\sqrt{s} = 7 \) TeV \( pp \) collisions using data collected in 2011 by the ATLAS detector at the CERN LHC. The data sample corresponds to an integrated luminosity of 4.4 \( \text{fb}^{-1} \). Multi-charged particles will be highly ionising, and thus leave an abnormally large specific ionisation signal, \(dE/dx\). In this Letter, a search for such particles traversing the ATLAS detector leaving a track in the inner tracking detector, and producing a signal in the muon spectrometer, is reported. A SM-like coupling proportional to the electric charge is assumed as the production model of the multi-charged particles. Therefore, the main production mode is Drell–Yan (DY) with no weak coupling. Multi-charged particles can also be pair-produced from radiated photons resulting in a larger production cross section, and in some cases non-perturbative effects [20] can also enhance the production rate. In the derivation of limits, neither enhancement is included in the calculation resulting in conservative limits in these scenarios.

**2. ATLAS detector**

The ATLAS detector [21] covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector (ID) comprising a silicon pixel detector (pixel), a silicon microstrip...
ground estimation is data-driven, muons from per bunch crossing was typically between 5 and 20. These samples served distribution of the number of proton–proton collisions per additional collision events (“pile-up”) in order to reproduce the ob-

dication between the observed dE/dx of the track and that expected for muons, measured in units of the uncertainty of the measurement:

\[ S(dE/dx) = \frac{dE/dx_{track} - (dE/dx_{\mu\mu})}{\sigma(dE/dx_{\mu\mu})}. \]

Here \( dE/dx_{\mu\mu} \) represents the estimated \( dE/dx \) of the track, and \( (dE/dx_{\mu\mu}) \) and \( \sigma(dE/dx_{\mu\mu}) \), respectively, are the mean and the width of the \( dE/dx \) distribution for muons in data.

To obtain expected \( dE/dx \) values and their resolution for the different detector components (MDT, TRT, Pixel), the \( dE/dx \) variables are calibrated with muons from \( Z \to \mu\mu \) events in data and simulation. Muons for this calibration are selected by requiring a track reconstructed in the MS matched to a good quality track in the ID with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.4 \). Each muon is further required to belong to an oppositely charged pair with dimuon mass between 81 GeV and 101 GeV. Fig. 1 shows the comparison between these muons in data and simulation for the MDT and TRT \( dE/dx \) significance. While the TRT distribution shows good agreement except in the tails, a discrepancy between simulation and data is observed for the MDT significance. This discrepancy has a small effect on the limit setting, and the effect is included in the systematic uncertainties. Fig. 2 shows the distributions of the MDT and TRT \( dE/dx \) significance for simulated muons from \( Z \to \mu\mu \) production compared to those of multi-charged particles for different charges (2e, 4e and 6e) and for a mass of 200 GeV. For the multi-charge particle search, the \( S(\text{MDT} \, dE/dx) \) and \( S(\text{TRT} \, dE/dx) \)
variables are required to exceed threshold values. These thresholds are established from the separation of the \(dE/dx\) significance distributions between muons and |\(q| = 2e\) signal particles. The \(dE/dx\) significance distributions for higher charge values, |\(q| > 2e\), are further separated from muons, as seen for simulated events in Fig. 2. The detailed response for these higher charge particles may not be perfectly modelled by the simulation due to saturation effects. However, their \(dE/dx\) response will certainly be higher than that of |\(q| = 2e\) particles, and thus their detailed response has no significance for the analysis. The separation power of the pixel \(dE/dx\) significance is shown in Fig. 3 for a 2e charge at \(m = 200, 400\) and 600 GeV. The behaviour of the \(dE/dx\) significance distributions is found to be as expected with respect to \(p_T\), \(\eta\), and \(\phi\). For simulated multi-charged particles the \(dE/dx\) significances strongly depend on the particle's charge and weakly on the particle's mass.

5. Event and candidate selection

Multi-charged candidates are sought for among those particles traversing the entire ATLAS detector, thus being initially selected as muons. Candidates are selected by analysing the specific ionisation losses in the different detectors. The search is based on a cut-and-count method, described in Section 6, where the signal region is defined by high \(dE/dx\) significances of the track measured by the TRT and MDT detectors.

Track reconstruction assumes particles with charge \(\pm 1e\), whereas particles with higher charges bend more in the magnetic field. Therefore, the effective cut on the momentum of the multi-charged particle imposed by the trigger and selection is a factor of |\(q|/e\) higher than the cut on the muon candidate. In the following, we will refer to \(p_T\) as the reconstructed transverse momentum assuming charge |\(q| = 1e\).

5.1. Trigger and event selection

Events collected with a single-muon trigger [31] with a transverse momentum threshold of \(p_T = 18\) GeV are considered. In simulated events the trigger efficiency from the RPC is corrected as a function of a particle's \(\eta\) and \(\beta\), where \(\beta\) is the ratio of the particle's velocity to the speed of light. Events are further required to contain either at least one muon with \(p_T > 75\) GeV or at least two muons with \(p_T > 15\) GeV.

5.2. Candidate selection

Candidate particles are tracks reconstructed in the MS which are required to be matched to the object passing the muon trigger, and to originate within tolerances from the primary interaction point. They must also be within the acceptance region |\(\eta| < 2.0\). Candidate particles with \(p_T > 20\) GeV and leave a high-quality track in the ID. However, because of potential pixel readout saturation, there is no requirement that a candidate particle has pixel information. The \(p_T\) measured by the muon system is smaller than the \(p_T\) of |\(q|\) higher than the cut on the muon candidate. In the following, we will refer to \(p_T\) as the reconstructed transverse momentum assuming charge |\(q| = 1e\).

4 Information on the MDT \(dE/dx\) is not available in the standard ATLAS data stream. Hence, this analysis is based on a special stream which includes this information. The \(p_T\) requirements on muons given here are imposed for the preparation of this stream and are not optimised for the current analysis.
measured in the ID due to energy loss in the calorimeters, and the \( p_T \) in the ID is used for candidate selection. In the track candidate selection, the measurement of the ionisation energy loss in the calorimeter system was not used. However, the calorimeter energy loss was validated for use as an independent cross-check in case of an observation of candidates above the expected background.

An initial preselection of highly ionising candidates is based on the pixel \( dE/dx \) significance and the TRT high-threshold fraction \( f^{HT} \). As seen in Fig. 3, the pixel \( dE/dx \) significance is a powerful discriminator for particles with \(|q| = 2e\). The signal region is defined by candidates with a significance greater than 10. For higher values of \(|q|\), the pixel readout saturates and the \( dE/dx \) signal is no longer reliable. Therefore, to search for particles with \(|q| > 2e\), the TRT \( f^{HT} \) (see Fig. 4) is used as a discriminating variable instead. The signal region is defined by requiring the \( f^{HT} \) to be above 0.4. This preselection using the pixel \( dE/dx \) or the \( f^{HT} \) reduces the background contribution by almost three orders of magnitude for both \(|q| = 2e\) and \(|q| > 2e\).

In the final step of the search, the MDT \( dE/dx \) significance, \( S(MDT \; dE/dx) \), and the TRT \( dE/dx \) significance, \( S(\text{TRT} \; dE/dx) \), are used as discriminating variables to separate the signal and background. These variables are shown for real data and simulated signal events in Fig. 5 (Fig. 6) for candidates preselected as \(|q| = 2e\) (\(|q| > 2e\)). Only the signal sample for a mass of 200 GeV is shown.

### 6. Background estimation

The background contribution to the signal region is estimated using an ABCD method. In this method, the regions A, B, C and D are defined by dividing the plane of the uncorrelated TRT and MDT \( dE/dx \) significances using the final selection cuts, as seen in Figs. 5 and 6.

The region D is defined as the signal region, with regions A, B and C as control regions for the background. The expected number of candidates from background in the region D, \( N^D_{\text{data}} \), is estimated from the numbers of observed data candidates in regions A, B and C (\( N^{A,B,C}_{\text{data}} \)).
The observed candidate yields in data for an integrated luminosity of 4.4 fb\(^{-1}\). The last column shows the expected background in the signal region D with statistical uncertainty.

| \(|q| = 2\) | A | B | C | D | \(D_{\text{exp}}\) |
|---|---|---|---|---|---|
| 8541 | 92 | 38 | 0 | 0.41 ± 0.08 |
| 4940 | 754 | 9 | 0 | 1.37 ± 0.46 |

Table 2

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
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<td>(</td>
<td>q</td>
<td>= 2)</td>
<td>43</td>
<td>8.6</td>
<td>12.6</td>
<td>12.6</td>
<td>10.9</td>
</tr>
<tr>
<td>(</td>
<td>q</td>
<td>= 3)</td>
<td>2.0</td>
<td>5.5</td>
<td>9.2</td>
<td>9.9</td>
<td>9.0</td>
</tr>
<tr>
<td>(</td>
<td>q</td>
<td>= 4)</td>
<td>0.3</td>
<td>2.3</td>
<td>4.6</td>
<td>5.8</td>
<td>5.6</td>
</tr>
<tr>
<td>(</td>
<td>q</td>
<td>= 5)</td>
<td>0.01</td>
<td>0.4</td>
<td>1.8</td>
<td>2.5</td>
<td>2.9</td>
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<td>0.003</td>
<td>0.07</td>
<td>0.5</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 3

7. Signal selection efficiency

The signal cross section is given by

\[
\sigma = \frac{N_{\text{rec}}^\text{data}}{2 \times \mathcal{L} \times \epsilon}.
\]

where \(\mathcal{L}\) is the integrated luminosity of the analysed data, \(N_{\text{rec}}^\text{data}\) the number of candidate particles in data above the expected background and the factor of 2 is the number of particles per event in the DY model. The efficiency \(\epsilon\) includes trigger, reconstruction and selection efficiencies. The efficiency is the number of all multi-charged particles that satisfy the selection criteria divided by the number of all simulated multi-charged particles.

The efficiency to find a multi-charged particle is given in Table 3 for each signal sample. Several factors contribute to the overall low efficiency and its dependencies on mass and charge. The \(|\eta| < 2.0\) selection and the requirement to reach the MS with a \(\beta\) which fits the timing window for the trigger are the primary causes of the reduction in efficiency. For the simulated signal samples, this timing requirement generally implies a momentum requirement stricter than the explicit \(p_T\) selection. The implied selection can be as high as approximately \(p_T/q > 120\) GeV. The charge dependence of the efficiency results from higher ionisation and the higher effective single-muon \(p_T\) selection, which are augmented by the factors \(q^2\) and \(q\), respectively. The mass dependence has two competing factors: at low mass there are more candidates above \(|\eta| = 2.0\), while at high mass the \(\beta\) spectrum is softer.

8. Systematic uncertainties

The systematic uncertainties on the background estimate and on the signal efficiency are determined by varying the selection cuts within the uncertainty on each selection variable.

8.1. Background estimation uncertainty

The background estimate in the signal region, D, relies on the fact that the \(S(\text{TRT } dE/dx)\) and the \(S(\text{MDT } dE/dx)\) are uncorrelated. To estimate potential influences of signal contamination close to the region boundaries and remaining correlations in the tails of the distributions, the ABCD regions are varied. For this estimate, the signal region D is maintained, but regions A, B and C are redefined by excluding the region close to the default cut from the background estimation. This ensures a higher background purity. This test is performed for many different definitions of the control regions and leads to an uncertainty of 5% on the estimated background contribution in the signal region.

8.2. Trigger efficiency uncertainty

The uncertainty on the trigger efficiency has two sources: the standard uncertainty on the trigger efficiency of 1% as determined by ATLAS muon performance studies [31] and a \(\beta\)-dependent trigger uncertainty. The size of the \(\beta\)-dependent part is dominated by the uncertainty on the timing correction of the RPC trigger efficiency (trigger for \(|q| < 1.05\)). This correction is varied by ±50% to account for the large dependence of the efficiency on the trigger timing. The relative difference of the trigger efficiencies between the nominal and the varied correction depends on the mass and charge of the benchmark samples, and ranges from less than 1% for \(|q| = 6\), \(m = 50\) GeV to 24% for \(|q| = 5\), \(m = 600\) GeV. The timing in the TGC (trigger for \(|\eta| > 1.05\)) for data and simulation is in good agreement, and the systematic uncertainty for the TGC timing correction is negligible. The systematic uncertainty on whether a candidate particle would reach the MS in the timing window for the trigger selection also depends on the simulation of energy losses in the calorimeters and the material description of the detector. In a study using muons from \(Z \rightarrow \mu\mu\) events in data and simulation, the energy losses were shown to be in excellent agreement. The energy-loss difference between data and simulation is less than 5%. A cross-check that varies the amount of material by ±10% has a negligible effect on the total systematic uncertainty.

8.3. Uncertainties due to selection

The uncertainties on the selection efficiency arise from the uncertainties on each selection variable used. The following variations of the nominal cuts are studied: \(p_T\) by ±3%, \(S(\text{pixel } dE/dx)\) by ±5%, TRT HT fraction by ±20%, \(S(\text{TRT } dE/dx)\) by ±5% and \(S(\text{MDT } dE/dx)\) by −5% and +50%. For the \(p_T\) cut this corresponds to the resolution of the track \(p_T\) measurements. The variation of 20% of the TRT HT fraction arises from the pile-up dependence of this variable. For the pixel and the TRT \(dE/dx\) significances, 5% corresponds to the observed agreement of the mean and width of these distributions in the \(Z \rightarrow \mu\mu\) events in data and simulation. This is also applied to the lower variation of \(S(\text{MDT } dE/dx)\). Here, a relative shift between simulation and data is observed. The magnitude and direction of this shift suggest a variation of \(S(\text{MDT } dE/dx)\) by 50% in the positive direction. While this would have been important for a potential signal interpretation, it has only a small effect on the limit setting. For other variables the variations have no observable effect in any of the signal samples. The total systematic uncertainties on the efficiency arising from these cut variations range up to 2.1%.

8.4. Summary of systematic uncertainties

In Table 4 the quadratic sums of all the systematic uncertainties considered above are summarised for the different signal
Fig. 7. Upper limits on the production cross section of multi-charged highly ionising particles from pair-production as a function of particle mass. The dotted line shows the expected limit with the $\pm \sigma$ and $\pm 2\sigma$ uncertainty bands. The observed limit is compared with the predicted rapidly falling cross section from the DY model. The plots are shown separately for charges $|q| = 2e$ to $|q| = 6e$. In the $|q| = 2e$ case, the observed limit lies on top of the expected limit.

Table 4
Summary of relative systematic uncertainties on the expected number of candidates derived from the uncertainties on the background estimation, trigger efficiency, Monte Carlo statistics and due to selection cuts.

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>Quadratic sum of systematic uncertainties [%]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td>50</td>
<td>8</td>
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<tr>
<td>100</td>
<td>10</td>
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<td>500</td>
<td>18</td>
</tr>
<tr>
<td>600</td>
<td>22</td>
</tr>
</tbody>
</table>

samples. The two main uncertainties are the uncertainty on the trigger efficiency and the uncertainty due to the small number of Monte Carlo events. The latter makes a significant contribution for some of the high-charge and low-mass samples. The 50 GeV samples were produced with a selection at the generator level requiring $p_T/q > 15$ GeV in order to decrease the statistical uncertainty. The systematic uncertainties vary between 6% and 28% in total.

The uncertainty on the integrated luminosity is estimated to be 3.9% from Van der Meer scans [32,33] and is not included in Table 4.

9. Results

No signal candidates are found for either the $|q| = 2e$ or the $|q| > 2e$ selected sample. The results are consistent with the expectation of $0.41 \pm 0.08 \pm 0.02$ and $1.37 \pm 0.46 \pm 0.07$ background candidates, respectively. From these numbers the expected and observed limits are computed using pseudo-experiments. For the total cross-section limit, the systematic uncertainties on efficiency and the luminosity are taken into account in the pseudo-experiments. For every benchmark point, 100,000 pseudo-experiments are used. The measurement excludes DY model pair-production over wide ranges of tested masses. Fig. 7 shows the observed 95% confidence level cross-section limits as a function of mass for the five different charges. Due to the low number of expected events, the dominant uncertainty arises from Poisson statistics as reflected in the asymmetric uncertainty bands. The limits range from around $10^{-2}$ pb for the lower charges to $10^{-1}$ pb for $|q| = 6e$. In addition to the expected and observed limits the predicted cross section is shown for the simplified Drell-Yan model. For the given model the cross-section limits can be transformed into mass-exclusion lower limits from 50 GeV to 430, 480, 490, 470 and 420 GeV for charges $|q| = 2e$, $3e$, $4e$, $5e$ and $6e$, respectively. Fig. 8 summarises the observed limits.

10. Summary

A search for long-lived, multi-charged particles has been performed using an integrated luminosity of 4.4 fb$^{-1}$ of $pp$ collisions recorded by the ATLAS detector at the LHC. No candidates are found in the 2011 data set, consistent with the background expectation. The results presented here are the first mass limits from
ATLAS for charges of 2e to 6e, filling the missing range of charges between the searches for slow singly charged long-lived particles [10] and searches for particles with charges from 6e to 17e [8].

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