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

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ABSTRACT

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 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 $2e$, $3e$, $4e$, $5e$ and $6e$, respectively.

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 $2e \leqslant |q| \leqslant 6e$ 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 fb^{-1}. Multi-charged particles will be highly ionising, and thus leave an abnormally large specific ionisation signal, $\mathrm{d}E/\mathrm{d}x$. 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

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[1] The term long-lived in this paper refers to a particle that does not decay within the ATLAS detector.

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detector (SCT) and a Transition Radiation Tracker (TRT). Apart from being a straw-based tracking detector, the TRT (covering $|\eta| < 2.0$)[2] also provides particle identification via transition radiation and ionisation energy-loss measurements [22]. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimeters. An iron-scintillator tile calorimeter provides hadronic energy measurements in the central rapidity region. The endcap and forward regions are instrumented with LAr calorimeters for both electromagnetic and hadronic energy measurements. The calorimeter system is surrounded by a muon spectrometer (MS) incorporating three superconducting toroid magnet assemblies. The MS is a combination of several sub-detectors used to measure muons that traverse the ATLAS calorimeters. The Resistive Plate Chambers (RPC) in the barrel region ($|\eta| < 1.05$) and the Thin Gap Chambers (TGC) in the endcap region ($1.05 < |\eta| < 2.4$) provide signals for the trigger for charged particles reaching the MS. Monitored Drift Tube (MDT) chambers measure the momentum and track positions of muons with very high precision.

3. Simulated samples

Benchmark samples of simulated events with multi-charged particles are produced for masses of 50, 100, 200, 300, 400, 500 and 600 GeV, with charges[3] $2e$, $3e$, $4e$, $5e$ and $6e$. Pairs of long-lived multi-charged particles are simulated using MadGraph5 [23] via the DY process to model the kinematic distributions. The DY production model also determines the cross section used for limit setting. Typical values for the cross sections of simulated multi-charge pair-production range from tens of pb for a mass of 50 GeV down to a few fb at a mass of 600 GeV. Events are generated using the CTEQ6L1 [24] parton distribution functions, and Pythia version 6.425 [25] is used for hadronisation and underlying-event generation. A Geant4 simulation [26,27] is used to model the response of the ATLAS detector, and the samples are reconstructed and analysed in the same way as the data. The production cross sections are estimated using MadGraph5 and are cross-checked with CalcHEP 3.4 [28]. Each simulated event is overlaid with additional collision events (“pile-up”) in order to reproduce the observed distribution of the number of proton–proton collisions per bunch crossing. In 2011 data the average number of interactions per bunch crossing was typically between 5 and 20. These samples are used to determine the detection efficiency, the resolution on the quantities used in the event selection and the associated systematic uncertainties for multi-charged particles. While the background estimation is data-driven, muons from $Z \to \mu\mu$ simulated samples are used to calibrate the selection variables. These samples are generated in Pythia and passed through the Geant4 simulation of the ATLAS detector.

4. Ionisation estimators

The specific energy loss, $\mathrm{d}E/\mathrm{d}x$, is described by the Bethe–Bloch formula [29]. The energy loss depends quadratically on the particle charge, q, so that particles with higher charges have a significantly higher energy loss.

4.1. MDT $\mathrm{d}E/\mathrm{d}x$

Each drift tube of the MDT system provides a signal proportional to the charge from ionisation, which is used to estimate $\mathrm{d}E/\mathrm{d}x$. A truncated mean of $\mathrm{d}E/\mathrm{d}x$, where the maximum value is removed, is used as the overall MDT $\mathrm{d}E/\mathrm{d}x$ estimator. As each track crosses more than 20 drift tubes, the MDT $\mathrm{d}E/\mathrm{d}x$ provides a good estimate of ionisation losses.

4.2. TRT $\mathrm{d}E/\mathrm{d}x$

Energy deposits in a TRT straw greater than 200 eV (low-threshold hits) are used for tracking, while those that exceed 6 keV (high-threshold hits) occur due to the passage of highly ionising particles or due to transition radiation emitted by highly relativistic electrons when they cross radiator material between the straws. The estimated $\mathrm{d}E/\mathrm{d}x$ value for each hit is derived from the time the signal remains above the low threshold. The TRT $\mathrm{d}E/\mathrm{d}x$ is the truncated mean of the $\mathrm{d}E/\mathrm{d}x$ estimates, where the highest estimate is removed. On average, a track in the TRT contains 32 hits. Additionally, the ratio of the number of high-threshold (HT) hits to the total number of TRT hits on a given track f^{HT} provides a second estimator of high ionisation.

4.3. Pixel $\mathrm{d}E/\mathrm{d}x$

The pixel detector measures the charge from ionisation in each pixel. The $\mathrm{d}E/\mathrm{d}x$ from the pixel detector is calculated from the truncated mean of measurements from several clusters of pixels [30]. Particles with charges higher than $2e$ deposit energies which easily exceed the dynamic range of the pixel detector readout. Therefore, the electronic signal is saturated and pixel information will not be read out leading to an unreliable $\mathrm{d}E/\mathrm{d}x$ measurement for such particles.

4.4. $\mathrm{d}E/\mathrm{d}x$ significance

The significance of each $\mathrm{d}E/\mathrm{d}x$ variable is defined as the difference between the observed $\mathrm{d}E/\mathrm{d}x$ of the track and that expected for muons, measured in units of the uncertainty of the measurement:

$$S(\mathrm{d}E/\mathrm{d}x) = \frac{\mathrm{d}E/\mathrm{d}x_{\mathrm{track}} - \langle \mathrm{d}E/\mathrm{d}x_{\mu} \rangle}{\sigma(\mathrm{d}E/\mathrm{d}x_{\mu})}. \tag{1}$$

Here $\mathrm{d}E/\mathrm{d}x_{\mathrm{track}}$ represents the estimated $\mathrm{d}E/\mathrm{d}x$ of the track, and $\langle \mathrm{d}E/\mathrm{d}x_{\mu} \rangle$ and $\sigma(\mathrm{d}E/\mathrm{d}x_{\mu})$, respectively, are the mean and the width of the $\mathrm{d}E/\mathrm{d}x$ distribution for muons in data.

To obtain expected $\mathrm{d}E/\mathrm{d}x$ values and their resolution for the different detector components (MDT, TRT, Pixel), the $\mathrm{d}E/\mathrm{d}x$ 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 $p_{\mathrm{T}} > 20$ 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 $\mathrm{d}E/\mathrm{d}x$ 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 $\mathrm{d}E/\mathrm{d}x$ 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 $S(\mathrm{MDT}\ \mathrm{d}E/\mathrm{d}x)$ and $S(\mathrm{TRT}\ \mathrm{d}E/\mathrm{d}x)$

[2] The ATLAS coordinate system is right-handed with the pseudorapidity, η, defined as $\eta = -\ln[\tan(\theta/2)]$, where the polar angle θ is measured with respect to the LHC beamline. The azimuthal angle, ϕ, is measured with respect to the x-axis, which points towards the centre of the LHC ring. The z-axis is parallel to the anti-clockwise beam viewed from above. Transverse momentum and energy are defined as $p_{\mathrm{T}} = p\sin\theta$ and $E_{\mathrm{T}} = E\sin\theta$, respectively.

[3] Wherever a charge is quoted for the exotic particles, the charge conjugate state is also implied.

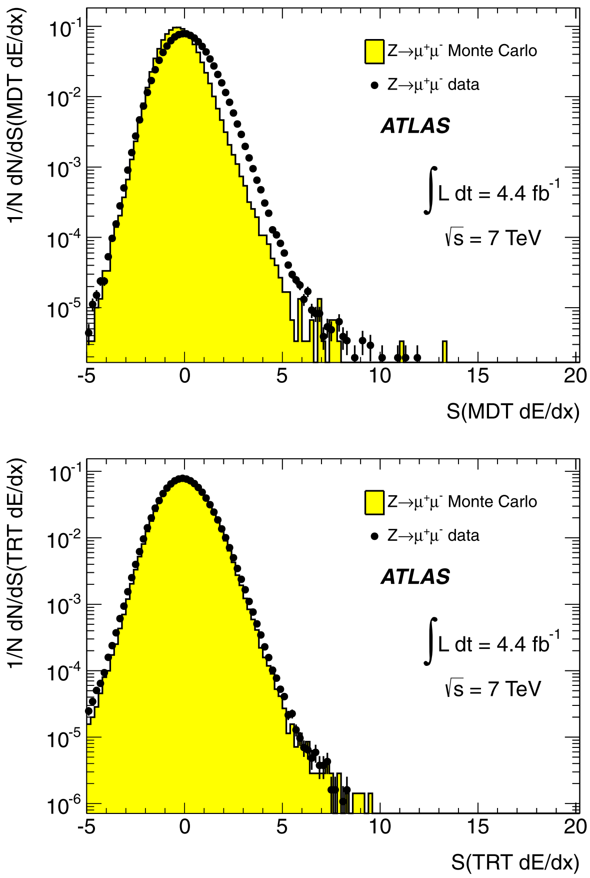

Fig. 1. Comparison of normalised distributions of the $S(\text{MDT d}E/\text{d}x)$ (top) and $S(\text{TRT d}E/\text{d}x)$ (bottom) for muons from $Z \to \mu\mu$ events in data and simulation.

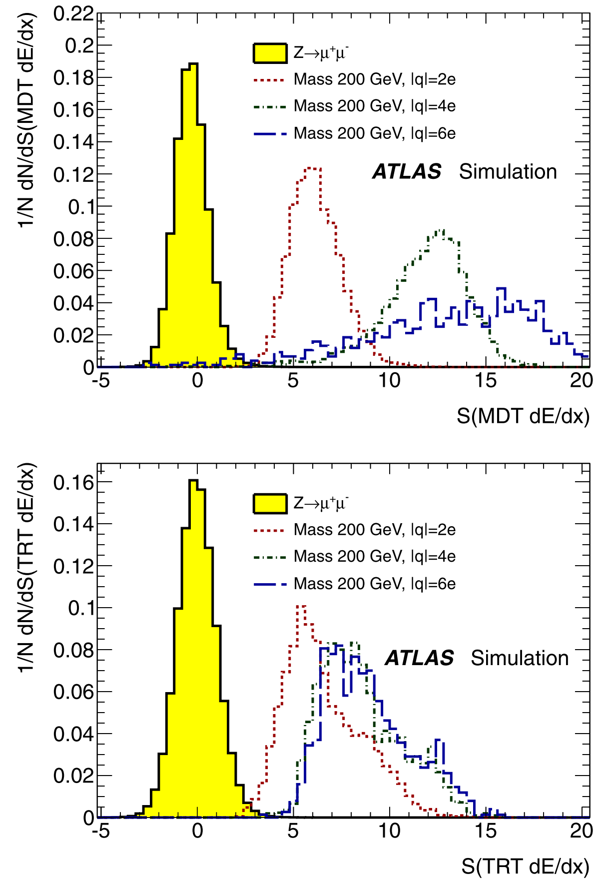

Fig. 2. Normalised distributions of $S(\text{MDT d}E/\text{d}x)$ (top) and $S(\text{TRT d}E/\text{d}x)$ (bottom) for simulated muons and multi-charged particles. Distributions are shown for the signal samples for $|q| = 2e$, $4e$ and $6e$, for a mass of 200 GeV.

variables are required to exceed threshold values. These thresholds are established from the separation of the $\text{d}E/\text{d}x$ significance distributions between muons and $|q| = 2e$ signal particles. The $\text{d}E/\text{d}x$ 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 $\text{d}E/\text{d}x$ 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 $\text{d}E/\text{d}x$ significance is shown in Fig. 3 for a $2e$ charge at $m = 200$, 400 and 600 GeV. The behaviour of the $\text{d}E/\text{d}x$ significance distributions is found to be as expected with respect to p_T, η, and ϕ. For simulated multi-charged particles the $\text{d}E/\text{d}x$ 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 $\text{d}E/\text{d}x$ 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 η and β, where β is the ratio of the particle's velocity to the speed of light. Events are further required[4] 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 $|\eta| < 2.0$, have a $p_T > 20$ 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

[4] Information on the MDT $\text{d}E/\text{d}x$ 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.

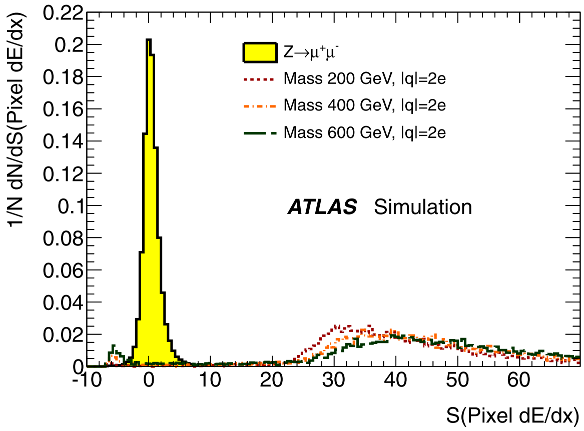

Fig. 3. Normalised distribution of $S(\text{pixel } \mathrm{d}E/\mathrm{d}x)$ for simulated muons and multi-charged particles. Distributions are shown for the signal sample for $|q| = 2e$, for masses of 200, 400 and 600 GeV. The structure at a significance of -5 is from pixel readout saturation.

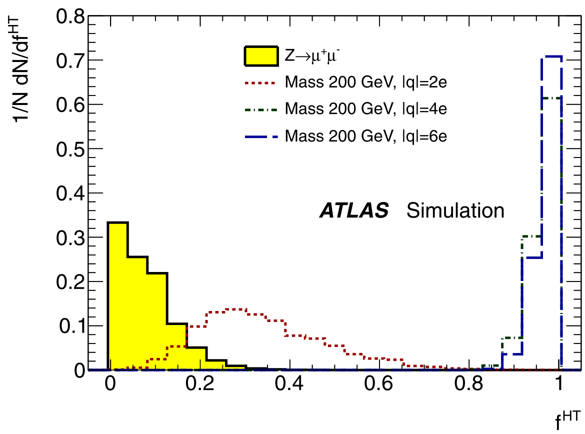

Fig. 4. Normalised distribution of f^{HT} for simulated muons and multi-charged particles. Distributions are shown for the signal samples for $|q| = 2e$, $4e$, and $6e$ for a mass of 200 GeV.

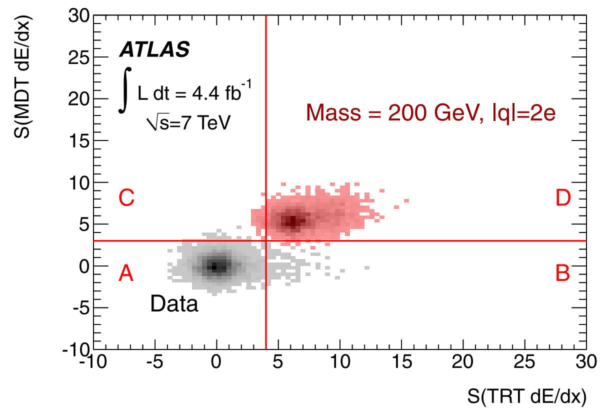

Fig. 5. The plane of TRT and MDT $\mathrm{d}E/\mathrm{d}x$ significances after the $|q| = 2e$ selection. The distributions of the 2011 data and the signal sample (here for a mass of 200 GeV) are shown. The regions labelled A, B and C are control regions used to estimate the background expected in the signal region D.

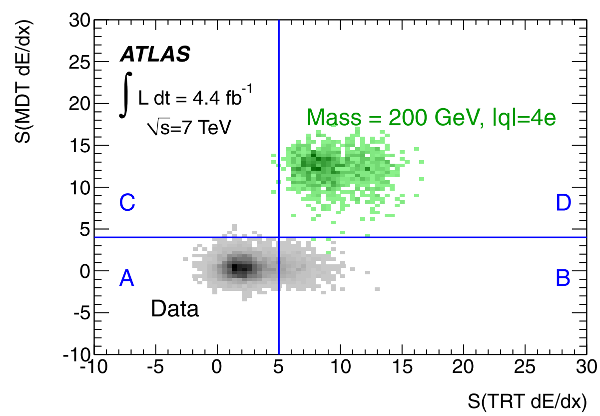

Fig. 6. The plane of TRT and MDT $\mathrm{d}E/\mathrm{d}x$ significances after the $|q| > 2e$ selection. The distributions of the 2011 data and the signal sample (here for a mass of 200 GeV and $|q| = 4e$) are shown. The regions labelled A, B and C are control regions used to estimate the background expected in the signal region D.

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 $\mathrm{d}E/\mathrm{d}x$ significance and the TRT high-threshold fraction f^{HT}. As seen in Fig. 3, the pixel $\mathrm{d}E/\mathrm{d}x$ 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 $\mathrm{d}E/\mathrm{d}x$ 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 $\mathrm{d}E/\mathrm{d}x$ 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 $\mathrm{d}E/\mathrm{d}x$ significance, $S(\text{MDT } \mathrm{d}E/\mathrm{d}x)$, and the TRT $\mathrm{d}E/\mathrm{d}x$ significance, $S(\text{TRT } \mathrm{d}E/\mathrm{d}x)$, 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 as there is very little change in the selection variables for different masses. As seen, the detector signatures are different for the two preselected samples, and thus the final signal regions are chosen differently. They are defined in Table 1. The selection was optimised using only simulated samples and data control samples without examining the signal region in the data.

Table 1
The final signal regions for the two preselections.

	$S(\text{MDT } \mathrm{d}E/\mathrm{d}x)$	$S(\text{TRT } \mathrm{d}E/\mathrm{d}x)$
$\lvert q\rvert = 2e$	> 3	> 4
$\lvert q\rvert > 2e$	> 4	> 5

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 $\mathrm{d}E/\mathrm{d}x$ 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, $N^{\mathrm{D}}_{\mathrm{data}}$, is estimated from the numbers of observed data candidates in regions A, B and C ($N^{\mathrm{A,B,C}}_{\mathrm{data}}$):

Table 2
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.

	A	B	C	D	$D_{exp.}$
$\|q\| = 2e$	8543	92	38	0	0.41 ± 0.08
$\|q\| > 2e$	4940	754	9	0	1.37 ± 0.46

Table 3
The efficiencies to select a signal candidate (in %) for the DY production model.

Mass [GeV]	Efficiencies [%]				
	$\|q\| = 2e$	$\|q\| = 3e$	$\|q\| = 4e$	$\|q\| = 5e$	$\|q\| = 6e$
50	4.3	2.0	0.3	0.03	0.003
100	8.6	5.5	2.3	0.4	0.07
200	12.6	9.2	4.6	1.8	0.5
300	12.6	9.9	5.8	2.5	0.8
400	10.9	9.0	5.6	2.9	1.0
500	9.9	8.5	5.3	2.9	1.3
600	7.8	6.8	4.6	2.3	1.1

$$N_{\text{data}}^{\text{D}} = \frac{N_{\text{data}}^{\text{B}} \times N_{\text{data}}^{\text{C}}}{N_{\text{data}}^{\text{A}}}. \tag{2}$$

Table 2 gives the number of candidates in A, B and C, as well as the observed number of candidates in the signal region D after the final selection. These results are compared to the expected number of background candidates of 0.41 ± 0.08 for the $|q| = 2e$ selection and 1.37 ± 0.46 for the $|q| > 2e$ selection. The uncertainties are statistical. The systematic uncertainty on the background estimation is discussed in Section 8.1.

7. Signal selection efficiency

The signal cross section is given by

$$\sigma = \frac{N_{\text{data}}^{\text{rec}}}{2 \times \mathcal{L} \times \epsilon}, \tag{3}$$

where $\mathcal{L}$ is the integrated luminosity of the analysed data, $N_{\text{data}}^{\text{rec}}$ 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 ϵ 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 β 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 $p_{\text{T}}/q > 120$ 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 β 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 $S(\text{TRT d}E/\text{d}x)$ and the $S(\text{MDT d}E/\text{d}x)$ 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 β-dependent trigger uncertainty. The size of the β-dependent part is dominated by the uncertainty on the timing correction of the RPC trigger efficiency (trigger for $|\eta| < 1.05$). This correction is varied by $\pm 50\%$ 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 $|q| = 6e$, $m = 50$ GeV to 24% for $|q| = 5e$, $m = 600$ GeV. The timing in the TGC (trigger for $|\eta| \geqslant 1.05$) 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 $Z \to \mu\mu$ 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 $\pm 10\%$ 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 $\pm 3\%$, $S(\text{pixel d}E/\text{d}x)$ by $\pm 5\%$, TRT HT fraction by $\pm 20\%$, $S(\text{TRT d}E/\text{d}x)$ by $\pm 5\%$ and $S(\text{MDT d}E/\text{d}x)$ 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 $\text{d}E/\text{d}x$ significances, 5% corresponds to the observed agreement of the mean and width of these distributions in the $Z \to \mu\mu$ events in data and simulation. This is also applied to the lower variation of $S(\text{MDT d}E/\text{d}x)$. Here, a relative shift between simulation and data is observed. The magnitude and direction of this shift suggest a variation of $S(\text{MDT d}E/\text{d}x)$ 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 all 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

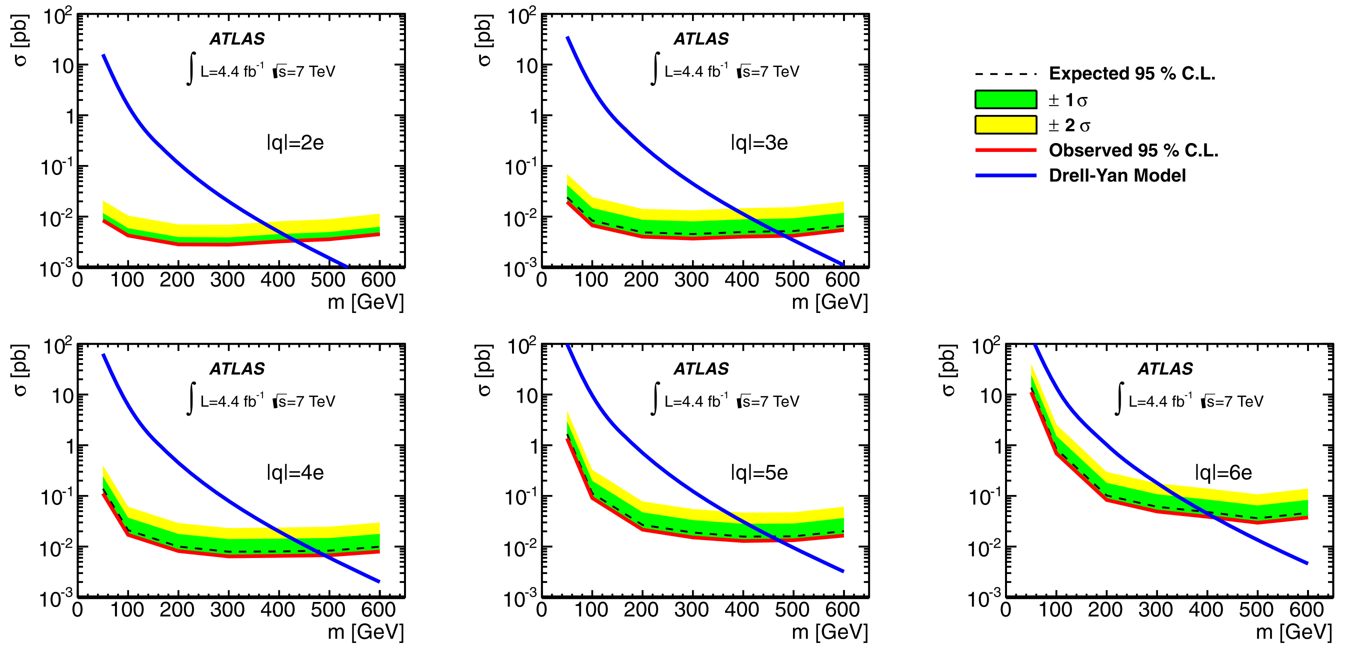

Fig. 7. Upper limits on the production cross section of multi-charged highly ionising particles from pair-production as a function of particle mass. The dotted line shows the expected limit with the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands. The observed limit is compared with the predicted rapidly falling cross section from the DY model. The plots are shown separately for charges from $|q| = 2e$ 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.

Mass [GeV]	Quadratic sum of systematic uncertainties [%]				
	$\lvert q\rvert = 2e$	$\lvert q\rvert = 3e$	$\lvert q\rvert = 4e$	$\lvert q\rvert = 5e$	$\lvert q\rvert = 6e$
50	8	6	6	10	19
100	10	9	7	12	28
200	13	12	10	9	12
300	14	15	15	12	11
400	17	17	18	18	13
500	18	18	19	21	18
600	22	22	23	25	24

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

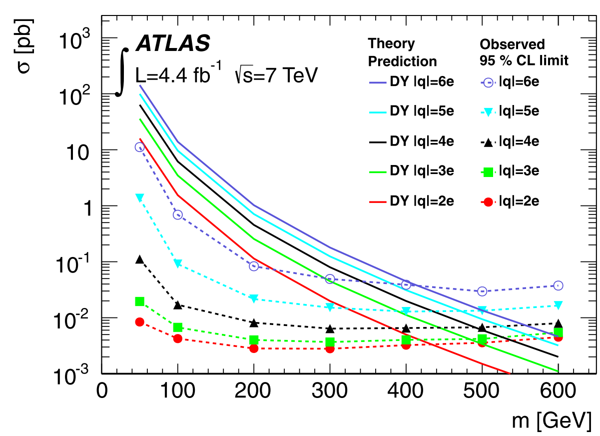

Fig. 8. Observed 95% CL cross-section upper limits and theoretical cross sections as functions of the multi-charged particle mass.

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 2*e* to 6*e*, filling the missing range of charges between the searches for slow singly charged long-lived particles [10] and searches for particles with charges from 6*e* to 17*e* [8].

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A. Engl [98], B. Epp [61], J. Erdmann [176], A. Ereditato [17], D. Eriksson [146a], J. Ernst [2], M. Ernst [25], J. Ernwein [136], D. Errede [165], S. Errede [165], E. Ertel [81], M. Escalier [115], H. Esch [43], C. Escobar [123], X. Espinal Curull [12], B. Esposito [47], F. Etienne [83], A.I. Etienvre [136], E. Etzion [153], D. Evangelakou [54], H. Evans [60], L. Fabbri [20a,20b], C. Fabre [30], R.M. Fakhrutdinov [128], S. Falciano [132a], Y. Fang [33a], M. Fanti [89a,89b], A. Farbin [8], A. Farilla [134a], J. Farley [148], T. Farooque [158], S. Farrell [163], S.M. Farrington [170], P. Farthouat [30], F. Fassi [167], P. Fassnacht [30], D. Fassouliotis [9], B. Fatholahzadeh [158], A. Favareto [89a,89b], L. Fayard [115], P. Federic [144a], O.L. Fedin [121], W. Fedorko [88], M. Fehling-Kaschek [48], L. Feligioni [83], C. Feng [33d], E.J. Feng [6], A.B. Fenyuk [128], J. Ferencei [144b], W. Fernando [6], S. Ferrag [53], J. Ferrando [53], V. Ferrara [42], A. Ferrari [166], P. 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A. Henrichs [176], A.M. Henriques Correia [30], S. Henrot-Versille [115], C. Hensel [54], C.M. Hernandez [8], Y. Hernández Jiménez [167], R. Herrberg [16], G. Herten [48], R. Hertenberger [98], L. Hervas [30], G.G. Hesketh [77], N.P. Hessey [105], E. Higón-Rodriguez [167], J.C. Hill [28], K.H. Hiller [42], S. Hillert [21], S.J. Hillier [18], I. Hinchliffe [15], E. Hines [120], M. Hirose [116], F. Hirsch [43], D. Hirschbuehl [175], J. Hobbs [148], N. Hod [153], M.C. Hodgkinson [139], P. Hodgson [139], A. Hoecker [30], M.R. Hoeferkamp [103], J. Hoffman [40], D. Hoffmann [83], M. Hohlfeld [81], M. Holder [141], S.O. Holmgren [146a], T. Holy [126], J.L. Holzbauer [88], T.M. Hong [120], L. Hooft van Huysduynen [108], S. Horner [48], J-Y. Hostachy [55], S. Hou [151], A. Hoummada [135a], J. Howard [118], J. Howarth [82], I. Hristova [16], J. Hrivnac [115], T. Hryn'ova [5], P.J. Hsu [81], S.-C. Hsu [138], D. Hu [35], Z. Hubacek [30], F. Hubaut [83], F. Huegging [21], A. Huettmann [42], T.B. 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F. Lacava [132a,132b], J. Lacey [29], H. Lacker [16], D. Lacour [78], V.R. Lacuesta [167], E. Ladygin [64], R. Lafaye [5], B. Laforge [78], T. Lagouri [176], S. Lai [48], E. Laisne [55], L. Lambourne [77], C.L. Lampen [7], W. Lampl [7], E. Lançon [136], U. Landgraf [48], M.P.J. Landon [75], V.S. Lang [58a], C. Lange [42], A.J. Lankford [163], F. Lanni [25], K. Lantzsch [30], A. Lanza [119a], S. Laplace [78], C. Lapoire [21], J.F. Laporte [136], T. Lari [89a], A. Larner [118], M. Lassnig [30], P. Laurelli [47], V. Lavorini [37a,37b], W. Lavrijsen [15], P. Laycock [73], O. Le Dortz [78], E. Le Guirriec [83], E. Le Menedeu [12], T. LeCompte [6], F. Ledroit-Guillon [55], H. Lee [105], J.S.H. Lee [116], S.C. Lee [151], L. Lee [176], M. Lefebvre [169], M. Legendre [136], F. Legger [98], C. Leggett [15], M. Lehmacher [21], G. Lehmann Miotto [30], A.G. Leister [176], M.A.L. Leite [24d], R. Leitner [127], D. Lellouch [172], B. Lemmer [54], V. Lendermann [58a], K.J.C. Leney [145b], T. 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Mir [12], G. Mirabelli [132a], J. Mitrevski [137], V.A. Mitsou [167], S. Mitsui [65], P.S. Miyagawa [139], J.U. Mjörnmark [79], T. Moa [146a,146b],

V. Moeller [28], S. Mohapatra [148], W. Mohr [48], R. Moles-Valls [167], A. Molfetas [30], K. Mönig [42], J. Monk [77], E. Monnier [83], J. Montejo Berlingen [12], F. Monticelli [70], S. Monzani [20a,20b], R.W. Moore [3], G.F. Moorhead [86], C. Mora Herrera [49], A. Moraes [53], N. Morange [136], J. Morel [54], G. Morello [37a,37b], D. Moreno [81], M. Moreno Llácer [167], P. Morettini [50a], M. Morgenstern [44], M. Morii [57], A.K. Morley [30], G. Mornacchi [30], J.D. Morris [75], L. Morvaj [101], N. Möser [21], H.G. Moser [99], M. Mosidze [51b], J. Moss [109], R. Mount [143], E. Mountricha [10,aa], S.V. Mouraviev [94,*], E.J.W. Moyse [84], F. Mueller [58a], J. Mueller [123], K. Mueller [21], T. Mueller [81], D. Muenstermann [30], T.A. Müller [98], Y. Munwes [153], W.J. Murray [129], I. Mussche [105], E. Musto [152], A.G. Myagkov [128], M. Myska [125], O. Nackenhorst [54], J. Nadal [12], K. Nagai [160], R. Nagai [157], K. Nagano [65], A. Nagarkar [109], Y. Nagasaka [59], M. 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G. Rahal [178], A.M. Rahimi [109], D. Rahm [25], S. Rajagopalan [25], M. Rammensee [48], M. Rammes [141],
A.S. Randle-Conde [40], K. Randrianarivony [29], K. Rao [163], F. Rauscher [98], T.C. Rave [48], M. Raymond [30],
A.L. Read [117], D.M. Rebuzzi [119a,119b], A. Redelbach [174], G. Redlinger [25], R. Reece [120], K. Reeves [41],
A. Reinsch [114], I. Reisinger [43], C. Rembser [30], Z.L. Ren [151], A. Renaud [115], M. Rescigno [132a], S. Resconi [89a],
B. Resende [136], P. Reznicek [98], R. Rezvani [158], R. Richter [99], E. Richter-Was [5], M. Ridel [78], M. Rijpstra [105],
M. Rijssenbeek [148], A. Rimoldi [119a,119b], L. Rinaldi [20a], R.R. Rios [40], I. Riu [12], G. Rivoltella [89a,89b],
F. Rizatdinova [112], E. Rizvi [75], S.H. Robertson [85,l], A. Robichaud-Veronneau [118], D. Robinson [28],
J.E.M. Robinson [82], A. Robson [53], J.G. Rocha de Lima [106], C. Roda [122a,122b], D. Roda Dos Santos [30], A. Roe [54],
S. Roe [30], O. Røhne [117], S. Rolli [161], A. Romaniouk [96], M. Romano [20a,20b], G. Romeo [27], E. Romero Adam [167],
N. Rompotis [138], L. Roos [78], E. Ros [167], S. Rosati [132a], K. Rosbach [49], A. Rose [149], M. Rose [76],
G.A. Rosenbaum [158], P.L. Rosendahl [14], O. Rosenthal [141], L. Rosselet [49], V. Rossetti [12], E. Rossi [132a,132b],
L.P. Rossi [50a], M. Rotaru [26a], I. Roth [172], J. Rothberg [138], D. Rousseau [115], C.R. Royon [136], A. Rozanov [83],
Y. Rozen [152], X. Ruan [33a,ai], F. Rubbo [12], I. Rubinskiy [42], N. Ruckstuhl [105], V.I. Rud [97], C. Rudolph [44],
G. Rudolph [61], F. Rühr [7], A. Ruiz-Martinez [63], L. Rumyantsev [64], Z. Rurikova [48], N.A. Rusakovich [64],
A. Ruschke [98], J.P. Rutherfoord [7], N. Ruthmann [48], P. Ruzicka [125], Y.F. Ryabov [121], M. Rybar [127],
G. Rybkin [115], N.C. Ryder [118], A.F. Saavedra [150], I. Sadeh [153], H.F-W. Sadrozinski [137], R. Sadykov [64],
F. Safai Tehrani [132a], H. Sakamoto [155], G. Salamanna [75], A. Salamon [133a], M. Saleem [111], D. Salek [30],
D. Salihagic [99], A. Salnikov [143], J. Salt [167], B.M. Salvachua Ferrando [6], D. Salvatore [37a,37b], F. Salvatore [149],
A. Salvucci [104], A. Salzburger [30], D. Sampsonidis [154], B.H. Samset [117], A. Sanchez [102a,102b], J. Sánchez [167],
V. Sanchez Martinez [167], H. Sandaker [14], H.G. Sander [81], M.P. Sanders [98], M. Sandhoff [175], T. Sandoval [28],
C. Sandoval [162], R. Sandstroem [99], D.P.C. Sankey [129], A. Sansoni [47], C. Santamarina Rios [85], C. Santoni [34],
R. Santonico [133a,133b], H. Santos [124a], I. Santoyo Castillo [149], J.G. Saraiva [124a], T. Sarangi [173],
E. Sarkisyan-Grinbaum [8], B. Sarrazin [21], F. Sarri [122a,122b], G. Sartisohn [175], O. Sasaki [65], Y. Sasaki [155],
N. Sasao [67], I. Satsounkevitch [90], G. Sauvage [5,*], E. Sauvan [5], J.B. Sauvan [115], P. Savard [158,f], V. Savinov [123],
D.O. Savu [30], L. Sawyer [25,n], D.H. Saxon [53], J. Saxon [120], C. Sbarra [20a], A. Sbrizzi [20a,20b], D.A. Scannicchio [163],
M. Scarcella [150], J. Schaarschmidt [115], P. Schacht [99], D. Schaefer [120], A. Schaelicke [46], S. Schaepe [21],
S. Schaetzel [58b], U. Schäfer [81], A.C. Schaffer [115], D. Schaile [98], R.D. Schamberger [148], A.G. Schamov [107],
V. Scharf [58a], V.A. Schegelsky [121], D. Scheirich [87], M. Schernau [163], M.I. Scherzer [35], C. Schiavi [50a,50b],
J. Schieck [98], M. Schioppa [37a,37b], S. Schlenker [30], E. Schmidt [48], K. Schmieden [21], C. Schmitt [81],
S. Schmitt [58b], B. Schneider [17], U. Schnoor [44], L. Schoeffel [136], A. Schoening [58b], A.L.S. Schorlemmer [54],
M. Schott [81], D. Schouten [159a], J. Schovancova [125], M. Schram [85], C. Schroeder [81], N. Schroer [58c],
M.J. Schultens [21], J. Schultes [175], H.-C. Schultz-Coulon [58a], H. Schulz [16], M. Schumacher [48],
B.A. Schumm [137], Ph. Schune [136], A. Schwartzman [143], Ph. Schwegler [99], Ph. Schwemling [78],
R. Schwienhorst [88], R. Schwierz [44], J. Schwindling [136], T. Schwindt [21], M. Schwoerer [5], F.G. Sciacca [17],
G. Sciolla [23], W.G. Scott [129], J. Searcy [114], G. Sedov [42], E. Sedykh [121], S.C. Seidel [103], A. Seiden [137],
F. Seifert [44], J.M. Seixas [24a], G. Sekhniaidze [102a], S.J. Sekula [40], K.E. Selbach [46], D.M. Seliverstov [121],
B. Sellden [146a], G. Sellers [73], M. Seman [144b], N. Semprini-Cesari [20a,20b], C. Serfon [98], L. Serin [115],
L. Serkin [54], R. Seuster [159a], H. Severini [111], A. Sfyrla [30], E. Shabalina [54], M. Shamim [114], L.Y. Shan [33a],
J.T. Shank [22], Q.T. Shao [86], M. Shapiro [15], P.B. Shatalov [95], K. Shaw [164a,164c], D. Sherman [176], P. Sherwood [77],
S. Shimizu [101], M. Shimojima [100], T. Shin [56], M. Shiyakova [64], A. Shmeleva [94], M.J. Shochet [31], D. Short [118],
S. Shrestha [63], E. Shulga [96], M.A. Shupe [7], P. Sicho [125], A. Sidoti [132a], F. Siegert [48], Dj. Sijacki [13a],
O. Silbert [172], J. Silva [124a], Y. Silver [153], D. Silverstein [143], S.B. Silverstein [146a], V. Simak [126], O. Simard [136],
Lj. Simic [13a], S. Simion [115], E. Simioni [81], B. Simmons [77], R. Simoniello [89a,89b], M. Simonyan [36],
P. Sinervo [158], N.B. Sinev [114], V. Sipica [141], G. Siragusa [174], A. Sircar [25], A.N. Sisakyan [64,*],
S.Yu. Sivoklokov [97], J. Sjölin [146a,146b], T.B. Sjursen [14], L.A. Skinnari [15], H.P. Skottowe [57], K. Skovpen [107],
P. Skubic [111], M. Slater [18], T. Slavicek [126], K. Sliwa [161], V. Smakhtin [172], B.H. Smart [46], L. Smestad [117],
S.Yu. Smirnov [96], Y. Smirnov [96], L.N. Smirnova [97,aj], O. Smirnova [79], B.C. Smith [57], D. Smith [143],
K.M. Smith [53], M. Smizanska [71], K. Smolek [126], A.A. Snesarev [94], S.W. Snow [82], J. Snow [111], S. Snyder [25],
R. Sobie [169,l], J. Sodomka [126], A. Soffer [153], D.A. Soh [151,w], C.A. Solans [167], M. Solar [126], J. Solc [126],
E.Yu. Soldatov [96], U. Soldevila [167], E. Solfaroli Camillocci [132a,132b], A.A. Solodkov [128], O.V. Solovyanov [128],
V. Solovyev [121], N. Soni [1], A. Sood [15], V. Sopko [126], B. Sopko [126], M. Sosebee [8], R. Soualah [164a,164c],
P. Soueid [93], A. Soukharev [107], S. Spagnolo [72a,72b], F. Spanò [76], R. Spighi [20a], G. Spigo [30], R. Spiwoks [30],

M. Spousta [127,ak], T. Spreitzer [158], B. Spurlock [8], R.D. St. Denis [53], J. Stahlman [120], R. Stamen [58a], E. Stanecka [39], R.W. Stanek [6], C. Stanescu [134a], M. Stanescu-Bellu [42], M.M. Stanitzki [42], S. Stapnes [117], E.A. Starchenko [128], J. Stark [55], P. Staroba [125], P. Starovoitov [42], R. Staszewski [39], A. Staude [98], P. Stavina [144a,*], G. Steele [53], P. Steinbach [44], P. Steinberg [25], I. Stekl [126], B. Stelzer [142], H.J. Stelzer [88], O. Stelzer-Chilton [159a], H. Stenzel [52], S. Stern [99], G.A. Stewart [30], J.A. Stillings [21], M.C. Stockton [85], K. Stoerig [48], G. Stoicea [26a], S. Stonjek [99], P. Strachota [127], A.R. Stradling [8], A. Straessner [44], J. Strandberg [147], S. Strandberg [146a,146b], A. Strandlie [117], M. Strang [109], E. Strauss [143], M. Strauss [111], P. Strizenec [144b], R. Ströhmer [174], D.M. Strom [114], J.A. Strong [76,*], R. Stroynowski [40], B. Stugu [14], I. Stumer [25,*], J. Stupak [148], P. Sturm [175], N.A. 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