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Search for fractionally charged particles in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is presented for free heavy long-lived fractionally charged particles produced in pp collisions at $\sqrt{s} = 7\,\text{TeV}$. The data sample was recorded by the CMS detector at the LHC and corresponds to an integrated luminosity of $5.0\,\text{fb}^{-1}$. Candidate fractionally charged particles are identified by selecting tracks with associated low charge measurements in the silicon tracking detector. Observations are found to be consistent with expectations for background processes. The results of the search are used to set upper limits on the cross section for pair production of fractionally charged, massive spin-1/2 particles that are neutral under $SU(3)_C$ and $SU(2)_L$. We exclude at 95% confidence level such particles with electric charge $\pm 2e/3$ with masses below 310 GeV, and those with charge $\pm e/3$ with masses below 140 GeV.

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1 Introduction

The reasons for expecting physics beyond the standard model to manifest itself in pp collisions at the Large Hadron Collider (LHC) are as compelling as ever. As suggested in Ref. [1], one example of physics beyond the standard model that may have eluded previous searches is a new particle with an electric charge less than that of the electron. Owing to their lower ionization energy loss, the trajectories of such fractionally charged particles may not pass typical track quality requirements and a dedicated analysis is required.

While fractionally charged particles are common in some theoretical scenarios (e.g., superstrings [2, 3]), a variety of searches for these objects in bulk matter, cosmic rays and accelerator based experiments have reported null results [4]. Strong constraints on models with fractionally charged states come from astrophysics and cosmology [5]. These constraints, however, do not apply if the reheating temperature of the universe after the last stage of inflation is much lower than the mass of the fractionally charged particle such that there is no thermal relic from freeze-out [6]. We search for such particles, using as a benchmark the scenario considered in [5], namely a model with new, fractionally charged, massive spin-1/2 particles that are neutral under $SU(3)_C$ and $SU(2)_L$ and therefore couple only to the photon and the Z. We denote such particles with fractional charge $\pm qe$, where e is the charge of the electron, as L_q, and assume they have a lifetime sufficiently long such that they do not decay within the detector volume.

An interesting possibility is that these L_q could also be charged under a new asymptotically free gauge group $SU(N)$ with a confinement scale Λ. This would make them a variant type of "quirk", which are quark-like, naturally fractionally charged particles [7]. For $\Lambda \lesssim 100$ eV, the confining string between the quirk-antiquirk pair would have a negligible impact on their trajectories over distances typical of collider-detector dimensions. Thus such quirks would have the same kinematic properties and experimental signature as the benchmark model considered in this paper. However, the existence of this string would cause eventual annihilation of any pairs formed in the early universe resulting in a negligible relic abundance [6], thereby evading the constraints cited by Ref. [5] irrespective of cosmological history.

We search for $L_q, \overline{L}_q$ particles in a sample of tracks with a muon-like signature. We identify fractionally charged particle candidates by their anomalously low ionization energy loss in the inner tracker. This study complements Compact Muon Solenoid (CMS) searches for heavy stable charged particles with anomalously high ionization energy loss [8, 9].

2 Signal simulation

Pair production of $L_q\overline{L}_q$ at the LHC proceeds via a modified Drell–Yan mechanism with weak isospin $t_{3L} = 0$, which has L_q-Z axial coupling $g_A = 0$ and vector coupling $g_V = -2q\sin^2\theta_W$. We have performed Monte Carlo simulations of this signal using PYTHIA v6.422 [10], with $q = 1/3, 2/3$, and 1, and with masses of 100, 200, 300, 400, 500, and 600 GeV. The cross sections are calculated to leading order with the CTEQ6L1 parton distribution functions. The detector response is modeled with a simulation based on GEANT4 [11].

3 Detector and data sample

The central feature of the CMS apparatus [12] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead-tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Of particular importance to this search is the inner tracker [13], which consists of 1440 silicon pixel and 15 148 silicon strip detector modules. The inner tracker records 16 measurements on average per track.

The analysis is performed on the pp collision data sample recorded by the CMS detector at $\sqrt{s} = 7\,\text{TeV}$ in 2011, corresponding to an integrated luminosity of $5.0\,\text{fb}^{-1}$.

The data are selected with a single-muon trigger that requires a track reconstructed in both the inner tracker and muon detectors with transverse momentum $p_{\mathrm{T}} > 40\,\text{GeV}$ and pseudorapidity $|\eta| < 2.1$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle. The radius of curvature of a fractionally charged particle in a magnetic field is larger than that of a particle of unit charge with the same momentum, so the reconstructed p_{T} is larger than the true p_{T} by the inverse of the particle's charge. The trigger requirement that unit charge particles have $p_{\mathrm{T}} > 40\,\text{GeV}$ corresponds to a requirement of $p_{\mathrm{T}} > 27\,\text{GeV}$ for $L_{2/3}$ and $p_{\mathrm{T}} > 13\,\text{GeV}$ for $L_{1/3}$.

The trigger efficiency for $L_{2/3}$ is in the range 67–74% per event, which is very similar to the efficiency for unit charge particles simulated with the same mass. By contrast, the $L_{1/3}$ trigger efficiency is between 8% and 18%. The lower trigger efficiency for $L_{1/3}$ results from the fact that many of the energy deposits in the tracker and muon detectors are below the threshold required to record a measurement. The trigger efficiency for $L_{1/3}$ depends on the particle's velocity β, since $\mathrm{d}E/\mathrm{d}x \propto 1/\beta^2$ [14]. The reconstruction efficiency for slower-moving $L_{1/3}$ particles is larger because the energy deposits are more likely to be above threshold. As a result, the reconstructed velocity distribution is very different from the generated distribution. For $L_{2/3}$ the larger overall efficiency means that the velocity distribution is less affected by the reconstruction, but slower moving $L_{2/3}$ particles fail the signal region requirement since their recorded $\mathrm{d}E/\mathrm{d}x$ measurements are too large.

4 Selection

In a pre-selection step, candidates for fractionally charged particles are defined as tracks reconstructed in the inner tracker and matched to a track in the muon detectors. The pre-selection criteria, which are described below, are chosen to obtain well-reconstructed tracks and to suppress background from cosmic ray muons. We consider candidate muon tracks with large reconstructed transverse momenta, $p_{\mathrm{T}} > 45\,\text{GeV}$, as measured in the inner tracker, in the range $|\eta| < 1.5$. A loose requirement on the track fit quality, $\chi^2/\text{dof} < 10$, rejects very poorly reconstructed tracks. We also require at least six $\mathrm{d}E/\mathrm{d}x$ measurements from the tracker, where a $\mathrm{d}E/\mathrm{d}x$ measurement is the signal amplitude recorded in an inner detector module divided by the particle's path length through the module. To ensure that the track is isolated, the sum of the p_{T} of all other tracks within a cone of $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$, where ϕ is the azimuthal angle, around the candidate must be less than 0.1 times the p_{T} of the candidate. The sum of the electromagnetic and hadronic calorimeter energy recorded within this cone, including that deposited by the candidate, must be less than 5 GeV.

Muons from cosmic rays are found in only a small fraction of the triggered events, but because they typically arrive out of coincidence with the bunch crossing, the charge is sampled away from the signal's maximum, and the resulting low $\mathrm{d}E/\mathrm{d}x$ measurement can be indistinguishable from that of a fractionally charged particle. Several requirements help to suppress the cosmic ray background. The primary vertex with the smallest distance to the point of closest approach of the candidate track is required to be a well reconstructed vertex [15]. The track must also have at least two $\mathrm{d}E/\mathrm{d}x$ measurements in the pixel tracker. The candidate track is required to satisfy $|d_z| < 0.5$ cm and $|d_{xy}| < 0.1$ cm, where d_z and d_{xy} are the longitudinal and transverse impact parameters with respect to the primary vertex. Based on the time of flight measurement [9] by the muon detectors, we determine the time the candidate particle was at the interaction point (IP) under the assumptions that the particle had velocity $\beta = 1$ and was moving outward from the IP. This time must not be earlier than the nominal bunch crossing that triggered the event, a requirement that rejects over half of the background from pp collisions and cosmic rays. We require $\alpha_{\mathrm{max}} < 2.8$ rad, where α_{max} is the maximum 3-dimensional opening angle between the candidate track and any high-momentum ($p_{\mathrm{T}} > 35$ GeV) track reconstructed in either the inner tracker or in the muon system alone.

The combined efficiency of the trigger and the pre-selection for signal events generated with mass 100 GeV is 45% per event for $L_{2/3}$ and 4.4% for $L_{1/3}$. The largest efficiency loss is at the trigger stage for $L_{1/3}$, where a signal track may fail to be reconstructed. The pre-selection requirements reduce the signal efficiency by roughly a factor of two.

After the pre-selection, events with two L_q candidates are rejected from the search sample if the invariant mass of the two candidates m_{LL} is in the range $80 < m_{LL} < 100$ GeV. This ensures that the search sample is independent of a control sample, defined below, that is used to estimate the collisions background. Although in the considered signal model, $L_q\overline{L}_q$ are produced in pairs, events containing a single candidate track are retained after the pre-selection. Events containing more than two candidates, which make up less than 0.1% of the search sample, are excluded.

We isolate the signal using a technique that imposes few assumptions on any particular model but nonetheless has the power to suppress the large standard model backgrounds from pp collisions. A fractionally charged particle is most clearly distinguished from a standard model particle by its lower rate of energy loss in the detector since $\mathrm{d}E/\mathrm{d}x \propto q^2$ [14]. Figure 1 shows the distribution of $\mathrm{d}E/\mathrm{d}x$ measurements associated with tracks passing the pre-selection, for the search sample, a control sample, and the 100 GeV $L_{2/3}$ and $L_{1/3}$ simulated signal samples. The measured values from data lie predominantly in the region above 2 MeV/cm. We therefore define low-ionizing measurements to be those with $\mathrm{d}E/\mathrm{d}x < 2$ MeV/cm. By requiring a number of such low $\mathrm{d}E/\mathrm{d}x$ measurements, standard model backgrounds can be suppressed while most of the signal events that pass the pre-selection are retained. Tracks that intersect a sensor close to its edge or near the boundary between two sensor modules can result in low $\mathrm{d}E/\mathrm{d}x$ measurements because of the partial collection of the deposited charge, so these track measurements are not considered in the analysis. The distance to the sensor edge for which $\mathrm{d}E/\mathrm{d}x$ measurements are excluded is between 0.5% and 5% of the distance to the center of the module, depending on the tracker subsystem.

A signal region is determined by maximizing the expected mass limit on the production cross section of fractionally charged particles while varying the minimum number of low $\mathrm{d}E/\mathrm{d}x$ measurements. The signal region optimization is performed for simulated samples with a L_q mass of 100 GeV and 400 GeV, and for both samples the optimum signal region is defined with the requirement that events contain a track with at least six low $\mathrm{d}E/\mathrm{d}x$ measurements. For the 100 GeV signal events passing the pre-selection, 75% of $L_{2/3}$ events are in the signal region, and 93% of $L_{1/3}$ events are in the signal region.

5 Background estimate

We use control samples of data to estimate the background contribution from cosmic ray muons and from particles produced in pp collisions. The data-driven method provides a background estimate without the use of simulation.

To estimate the cosmic ray background, we use a sample of muons obtained with the nominal pre-selection except for two inverted requirements, $0.1 < |d_{xy}| < 1.1\,\mathrm{cm}$ and $0.5 < |d_z| < 50\,\mathrm{cm}$. The yield in the signal region of this sample is scaled by a weight factor to obtain the cosmic ray background for the nominal pre-selection. This weight factor is the product of two weights, each determined from a cosmic ray enriched sample as the ratio of the yield in the nominal selection region to the yield after inverting a single requirement. This scaled yield gives a cosmic ray background estimate of 0.007 events.

A Z-peak control sample is used to estimate the pp collision background. This sample is selected by relaxing the transverse momentum requirement to $p_{\mathrm{T}} > 35\,\mathrm{GeV}$, requiring $80 < m_{LL} < 100\,\mathrm{GeV}$, and applying all other pre-selection requirements. Figure 1 shows the distributions of $\mathrm{d}E/\mathrm{d}x$ measurements associated with selected tracks for both the search sample and the Z-peak control sample. The two distributions agree within the statistical uncertainties over the full $\mathrm{d}E/\mathrm{d}x$ range. The ratio of the number of tracks passing the pre-selection in the search sample to the number of tracks passing the pre-selection in the Z-peak control sample is 10.5. The control sample is scaled by this ratio to model the distribution in the search sample.

The simulation of the control sample is also shown in Fig. 1. This simulation is used only to assess the uncertainty in the signal efficiency, since the background estimate is entirely data-driven. The inset in Fig. 1 is an enlargement of the region of low $\mathrm{d}E/\mathrm{d}x$, plotted on a semi-logarithmic scale. This inset also shows the results of a modified simulation, which includes the effect of a possible source of anomalously low $\mathrm{d}E/\mathrm{d}x$ hits not reproduced in the nominal simulation. The background simulations are discussed in the next section.

To estimate the background in the signal region, we extrapolate from the background-dominated region of events containing a pre-selected track with zero to five low $\mathrm{d}E/\mathrm{d}x$ measurements. For a muon from a Z decay, the $\mathrm{d}E/\mathrm{d}x$ measurements associated with the track are expected to be uncorrelated, and the number of measurements below a given $\mathrm{d}E/\mathrm{d}x$ value can be described by a generalized binomial function,

$$N_{\mathrm{evts}} = N_0 \binom{\mu}{n} p^n (1-p)^{\mu-n},$$
$$\binom{\mu}{n} = \frac{\Gamma(\mu+1)}{\Gamma(n+1)\Gamma(\mu-n+1)},$$

where N_{evts} is the number of events containing at least one track with n low $\mathrm{d}E/\mathrm{d}x$ measurements, μ is the average number of measurements per track, p is the probability for a single measurement to be low $\mathrm{d}E/\mathrm{d}x$, N_0 is a normalization factor, and $\Gamma(n)$ is the gamma function. The fit of the binomial function to the background-dominated region of the Z-peak control sample is shown in Fig. 2. The fitted parameters are $\mu = 17.5 \pm 1.7$, $p = 0.0125 \pm 0.0013$, and $N_0 = (5.03 \pm 0.03) \times 10^6$; the values of μ and p are close to those expected based on the number of measurements per track and the fraction of low $\mathrm{d}E/\mathrm{d}x$ measurements. This function describes the distribution in the control sample well, with $\chi^2/\mathrm{dof} = 0.07/1$, corresponding to a χ^2 probability of 79%. This is strong support for the hypothesis that the data are distributed binomially and therefore that the $\mathrm{d}E/\mathrm{d}x$ measurements are uncorrelated. Extrapolation of the fitted binomial function into the signal region yields a pp background estimate of 0.005 events.

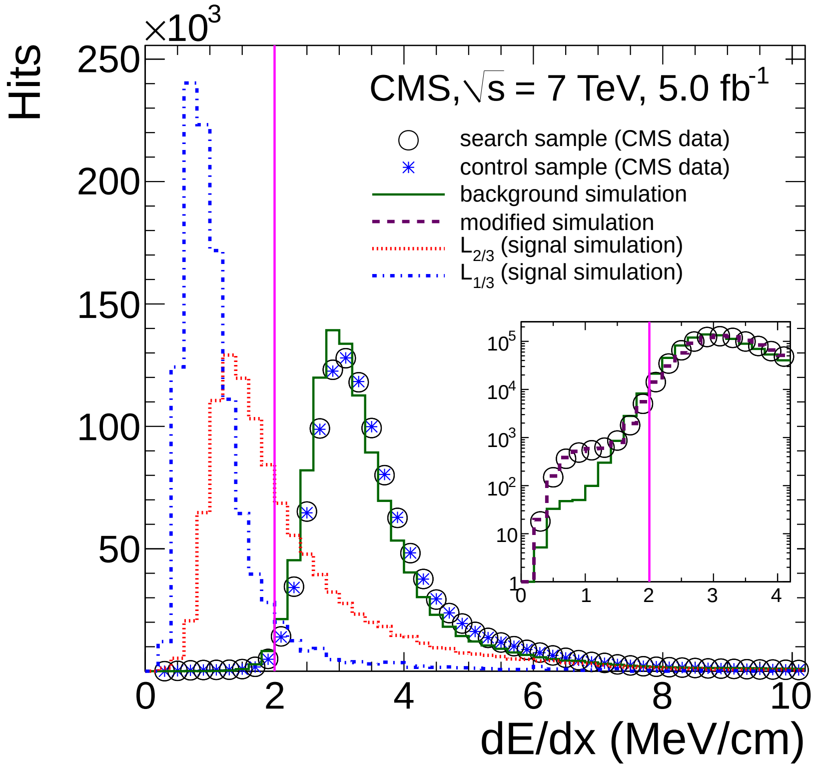

Figure 1: Distribution of dE/dx measurements associated with tracks passing the pre-selection in the search sample and the Z-peak control sample. Simulated $L_q\overline{L}_q$ signal samples for a mass of 100 GeV are shown for $q = 2/3$, $1/3$. The distributions are normalized to the area of the search sample. The magenta vertical line at dE/dx = 2 MeV/cm indicates the upper limit of the range of measurements considered to be low-ionizing. The inset is an enlargement of the region of low dE/dx, plotted on a semi-logarithmic scale.

6 Systematic uncertainties

The systematic uncertainties that significantly impact the results are the uncertainties in the integrated luminosity, the background estimate, and the signal efficiency. The uncertainty in the integrated luminosity is 2.2% [16].

The cosmic ray background estimate has a statistical uncertainty of 71% that arises from the relatively small size of the sample with inverted d_{xy} and d_z requirements used for its determination. The statistical uncertainties in the weighting factors are 1% and 24% for the d_{xy} and d_z requirements, respectively. The systematic uncertainty associated with the assumption that the d_{xy} and d_z variables are uncorrelated is assessed by examining a sample defined by replacing the inverted d_z selection with an inverted α_{max} requirement. This sample, obtained by requiring $0.1 < |d_{xy}| < 1.1$ cm, $\alpha_{\text{max}} > 2.8$ rad, and all other pre-selection criteria, provides a second estimate of the comsic ray background, which differs from the nominal estimate by 42%. The statistical and systematic uncertainties are summed in quadrature; the total cosmic ray background estimate is 0.007 ± 0.006 events.

We assess three potential sources of uncertainty in the pp background estimate in the signal region. The first source is from the choice of the function used to fit the control sample. While this is often a large source of uncertainty in many a posteriori fits to data, our hypothesis that a binomial function describes the distribution of the number of low dE/dx measurements is mo-

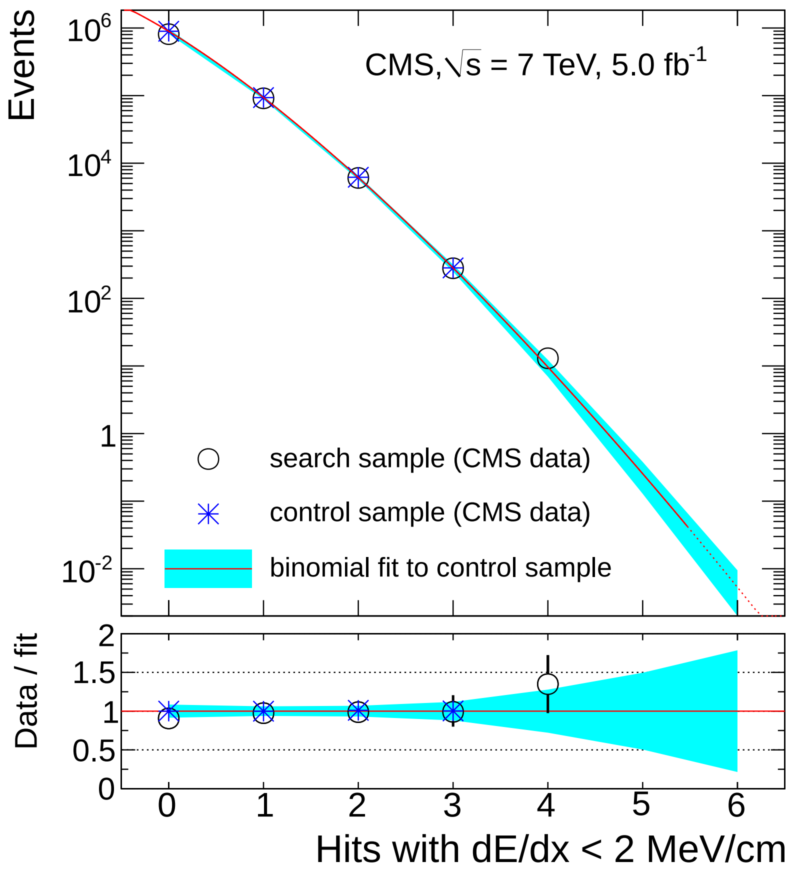

Figure 2: Number of events with at least one track with the given number of low $\mathrm{d}E/\mathrm{d}x$ measurements, for search data and the scaled Z-peak control sample background estimate. The binomial function fit to the control sample is shown, with the band representing its uncertainty. The ratio of the data to the binomial fit is also presented. No tracks in the search sample have five or more low $\mathrm{d}E/\mathrm{d}x$ measurements.

tivated a priori, from first principles. We do not expect a large uncertainty from this source. For completeness, however, other functions are also compared to the data. Fits of several modified exponential, power-law, and polynomial functions fail to converge or have very low χ^2 probabilities. One function that does fit the distribution reasonably well is $N_{\text{evts}} = p_0 n^{p_1 + p_2 n}$, where p_i are free parameters. The difference between the background estimate from this function and nominal background estimate is 0.001 events.

The second potential source of uncertainty in the pp background estimate arises from the statistical uncertainties in the fitted parameters of the binomial function. The propagation of these uncertainties results in an uncertainty in the background estimate of ± 0.0004 events.

A third source of uncertainty arises from the small disagreement between the distribution of low $\mathrm{d}E/\mathrm{d}x$ measurements from the control sample and that from the search sample. In the background-dominated region, the largest statistically-significant discrepancy between the two samples is 9%, for zero low $\mathrm{d}E/\mathrm{d}x$ measurements. To assess the resulting systematic uncertainty, the control sample fit is repeated for a large number of trials, in each case setting the value of the distribution in each bin randomly, according to a Gaussian distribution with a mean of the original value and width of 9% of the original value. The RMS of the background estimates from all of these trials is 0.004 events, which is taken as the uncertainty due to the accuracy with which the control sample models the search sample.

The three sources of uncertainty in the pp background estimate are summed in quadrature giving a total estimate of 0.005 ± 0.004 events. The high precision of this estimate is due to the large statistics of the control sample, which leads to small statistical uncertainties in the fitted parameters. Likewise, the high degree of accuracy of the background estimate is reflected in the relatively small systematic uncertainty assigned. This is a direct consequence of the somewhat unusual aspect of this analysis that the functional form with which the data would be distributed under the background only hypothesis was derived from first principles.

The sum of the pp and cosmic ray backgrounds gives a total background estimate of 0.012 ± 0.007 events.

This search uses the data itself to estimate all backgrounds, so the uncertainties in the simulation only impact the determination of the efficiency of the benchmark signal model. The systematic uncertainties in the signal efficiencies are summarized in Table 1.

The simulation of the trigger efficiency for a fractionally charged particle is sensitive to the accurate modeling of the muon detectors' electronics and gas gain as well as the threshold for recording a hit, because it has less ionization energy loss and thus the peak of its Landau distribution is closer to the threshold than that of a muon. We assess the impact on the signal region efficiency of a variation in the simulated gain of the muon system by a conservative estimate of its uncertainty. The impact of such a variation on $L_{2/3}$ is small, since the charge distributions are typically far above the threshold. However, for $L_{1/3}$, the probability to record a hit degrades significantly as the gain decreases. The impact of this variation for $L_{2/3}$ is 1%, and for $L_{1/3}$ is 8.5%. The systematic uncertainty in the offline global muon identification requirement is negligible by comparison.

The modeling of the tracker $\mathrm{d}E/\mathrm{d}x$ measurements impacts the simulated signal efficiency by affecting the efficiency of track reconstruction and signal region selection. Larger tracker energy deposits are more likely to be above the threshold required to record a measurement, and the track reconstruction efficiency increases with more measurements. Larger $\mathrm{d}E/\mathrm{d}x$ measurements also reduce the fraction of reconstructed tracks that are in the signal region, since fewer measurements are below the 2 MeV/cm limit. To evaluate the accuracy of the simulation of the $\mathrm{d}E/\mathrm{d}x$ measurements, we compare the $\mathrm{d}E/\mathrm{d}x$ distributions of the Z-peak control sample in simulation and in data, as shown in Fig. 1. The agreement in the low-$\mathrm{d}E/\mathrm{d}x$ region is evaluated as the shift of all $\mathrm{d}E/\mathrm{d}x$ measurements required to obtain the same fraction below 2 MeV/cm in both samples. For the nominal selection, the simulated $\mathrm{d}E/\mathrm{d}x$ distribution must be shifted by 2.6% to obtain the same fraction below 2 MeV/cm as in the data. For a larger sample obtained with looser selection criteria, the required shift is 5%. We use the larger of these values, 5%, as an estimate of the agreement between simulation and data. To assess the resulting uncertainty in the signal efficiency, we vary the amplitude of the $\mathrm{d}E/\mathrm{d}x$ measurements by $\pm 5\%$ before re-simulating the trigger emulation, track reconstruction, and full selection. A variation of $+5\%$ in the $\mathrm{d}E/\mathrm{d}x$ measurements changes the signal efficiency by $+16\%$ for $L_{1/3}$ particles and -7.5% for $L_{2/3}$. The efficiency changes in opposite directions because for $L_{1/3}$ the increased reconstruction efficiency is the dominant effect, while for $L_{2/3}$ the smaller signal region efficiency has a greater impact. These variations in the signal efficiency are taken as the systematic uncertainties associated with the modeling of the tracker $\mathrm{d}E/\mathrm{d}x$ measurements.

Potential causes of incorrect modeling of $\mathrm{d}E/\mathrm{d}x$ in our simulation that could produce a disagreement at low $\mathrm{d}E/\mathrm{d}x$ have been examined. The most likely possibility is a residual source of low dE/dx hits that are not removed by the sensor-edge fiducial cuts. Such a source could be accommodated by the control sample data if, at most, 0.06% of all measurements are affected. A simulation assuming a mismeasurement rate at this level reproduces the observed data distribution, as shown in the inset of Fig. 1. Such an effect would impact less than 1% of all tracks and change the signal efficiency by an even smaller amount. Furthermore, the likelihood of a track to have six such anomalous measurements is extremely small, so the effect on the background estimate would be negligible.

The uncertainty associated with the track momentum scale is less than 1%. The impact of the uncertainty in the muon timing measurements is 2%. This is assessed by varying the timing measurements according to the measured discrepancy between the data and simulation, as described in [9].

Table 1: Systematic uncertainties (in %) in the signal efficiency.

Source	$L_{1/3}$	$L_{2/3}$
Muon trigger	8.5	1
Tracker dE/dx measurements	16	7.5
Track momentum scale	<1	<1
Muon timing	2	2
Total	18	8

7 Results

The numbers of expected background and observed events are summarized in Table 2. We observe zero events in the data search sample in the signal region, which is consistent with the background estimate of 0.012 ± 0.007 events. The $L_q\overline{L}_q$ signal efficiency and average β for different signal masses and charges are listed in Table 3. Ninety-five percent confidence level (CL) upper limits on the $L_q\overline{L}_q$ production cross section are calculated using the CL_s criterion [17, 18]. Expected and observed 95% CL limits are shown in Fig. 3. These limits vary from 1.7 to 2.3 fb, for $q = 2/3$, and from 14 to 5.4 fb, for $q = 1/3$, for masses between 100 and 600 GeV. We exclude the production of $L_{2/3}$ with a mass below 310 GeV and the production of $L_{1/3}$ with a mass below 140 GeV at 95% CL.

8 Conclusion

A search has been performed for heavy, long-lived, lepton-like fractionally charged particles, using the signature of at least six low dE/dx measurements. The search is based on a pp collision sample recorded by the CMS detector at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5.0 fb^{-1}. Zero events are observed in the signal region, consistent with the background estimate. Upper limits on the production cross section of pair produced, spin-1/2 par-

Table 2: Numbers of events in the signal region, containing a track with at least six dE/dx measurements with $dE/dx < 2$ MeV/cm, estimated from the background and observed in the search data.

Cosmic rays	0.007 ± 0.006
pp collisions	0.005 ± 0.004
Total background	0.012 ± 0.007
Observed events	0

Table 3: The signal efficiency and average velocity $\langle\beta\rangle$ of events in the signal region for different mass points and charge hypotheses.

Mass	$L_{2/3}$		$L_{1/3}$	
(GeV)	Signal eff.	$\langle\beta\rangle$	Signal eff.	$\langle\beta\rangle$
100	0.341 ± 0.026	0.84	0.041 ± 0.007	0.52
200	0.357 ± 0.027	0.83	0.060 ± 0.011	0.51
300	0.337 ± 0.026	0.82	0.074 ± 0.013	0.51
400	0.314 ± 0.024	0.80	0.091 ± 0.016	0.51
500	0.265 ± 0.020	0.79	0.104 ± 0.019	0.51
600	0.251 ± 0.019	0.78	0.109 ± 0.019	0.51

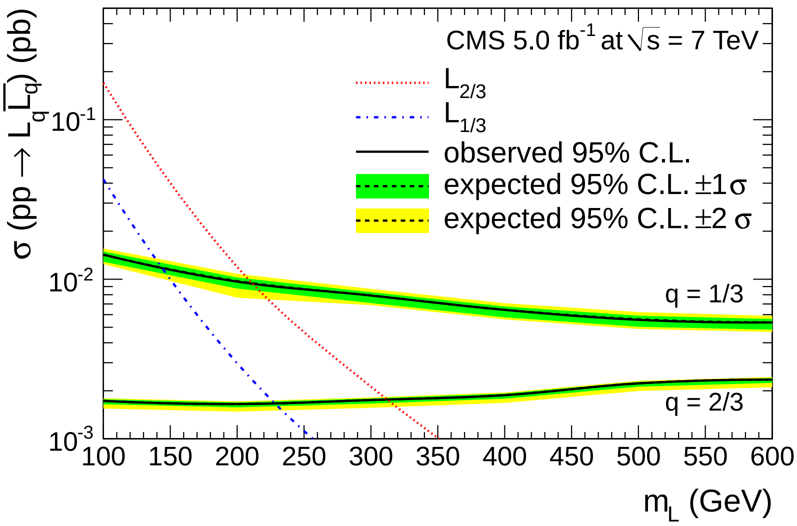

Figure 3: Expected and observed limits on the cross section of $L_q\overline{L}_q$ for $q = 2/3$ and $1/3$. The theoretical prediction of modified Drell–Yan production with $t_{3L} = 0$ is shown. The lines for the expected and observed limits are overlapping.

ticles that are neutral under $SU(3)_C$ and $SU(2)_L$ exclude at 95% confidence m_L below 310 GeV for particles with $q = 2/3$ and m_L below 140 GeV for particles with $q = 1/3$.

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