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The Compact Muon Solenoid Experiment

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Measurement of the charge ratio of atmospheric muons with the CMS detector

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Abstract

We present a measurement of the ratio of positive to negative muon fluxes from cosmic-ray interactions in the atmosphere, using data collected by the CMS detector both at ground level and in the underground experimental cavern at the CERN LHC. The excellent performance of the CMS detector allowed detection of muons in the momentum range from 5 GeV/c to 1 TeV/c. The surface flux ratio is measured to be 1.2766 ± 0.0032 (stat.) $\pm$ 0.0032 (syst.), independent of the muon momentum, below 100 GeV/c. This is the most precise measurement to date. At higher momenta the data are consistent with an increase of the charge ratio, in agreement with cosmic-ray shower models and compatible with previous measurements by deep-underground experiments.

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Measurement of the charge ratio of atmospheric muons with the CMS detector.

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Abstract.

We present a measurement of the ratio of positive to negative muon fluxes from cosmic ray interactions in the atmosphere, using data collected by the CMS detector both at ground level and in the underground experimental cavern at the CERN LHC. Muons were detected in the momentum range from 5 GeV/c to 1 TeV/c. The surface flux ratio is measured to be 1.2766 ± 0.0032 (stat.) ± 0.0032 (syst.), independent of the muon momentum, below 100 GeV/c. This is the most precise measurement to date. At higher momenta the data are consistent with an increase of the charge ratio, in agreement with cosmic ray shower models and compatible with previous measurements by deep-underground experiments.

1 Introduction

Cosmic-muon charge ratio is the ratio of the number of positive to negative-charge atmospheric muons arriving at the Earth's surface, which originate from the showers produced by interactions of high-energy cosmic-ray particles with air nuclei in the upper layers of the atmosphere. Measurements from previous experiments [1-5] show this ratio to be constant up to a vertical muon momentum of about 200 GeV/c, and then to increase significantly at higher momenta, due to the additional contribution of muons from kaon decays. These measurements are used to constrain parameters relevant to hadronic interactions and to better predict the atmospheric neutrino flux. The Compact Muon Solenoid (CMS) [6] is one of the detectors installed at the Large Hadron Collider (LHC) [7] at CERN. The main goal of the CMS experiment is to search for signals of new physics in proton-proton collisions at centre-of-mass energies from 7 to 14 TeV [8]. The CMS detector is installed in an underground cavern, with the center of the detector 89 m below Earths surface, and 420 m above sea level. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass-scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yokes. In the barrel there is a Drift Tube (DT) system interspersed with Resistive Plate Chambers (RPCs), and in the endcaps there is a Cathode Strip Chamber (CSC) system, also interspersed with RPCs. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. A detailed description of CMS can be found in [6].

CMS collected cosmic ray data in several runs during the final years of detector construction and commissioning. Data from the Magnet Test and Cosmic Challenge in 2006 (MTCC) [9] and the Cosmic Run At Four Tesla in 2008 (CRAFT08) [10] are used in the analysis reported here. In August 2006 the CMS detector was pre-assembled on the surface before being lowered into the cavern. In this configuration no material above the detector was present and a small fraction of each of the subdetectors was instrumented and operating at the time. About 25 million cosmic-muon events were recorded with the magnet at a number of field values ranging from 3.67 to 4.00 T. The details of the MTCC setup are described in [9, 11]. The CRAFT08 campaign was a sustained data-taking exercise in October and November 2008 with the CMS detector fully assembled in its final underground position. The full detector, ready for collecting data from LHC, participated in the run, with the magnet at the nominal field of 3.8 T. Approximately 270 million cosmic-muon events were recorded [10, 12].

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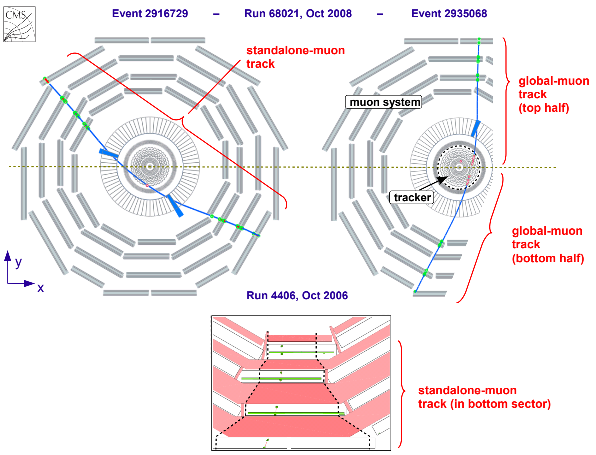

Fig. 1. Cosmic-ray muons crossing the CMS detector. The upper two pictures display muons from 2008 underground data, leaving signals in the muon system, tracking detectors and calorimeters. A standalone track (top left) and a pair of global half-tracks (top right) are shown. The bottom plot depicts a muon from 2006 surface data crossing the muon chambers at the bottom of CMS.

2 Event selection and analysis

Three types of muon-track reconstruction were designed for cosmic muons not originating from an LHC proton-proton collision [13]: a standalone-muon track includes only hits from the muon detectors; a tracker track includes only hits from the silicon tracker; and a global muon track combines hits from the muon system and the silicon tracker in a combined track fit. For a cosmic muon that crosses the whole CMS detector, illustrated in Fig. 1 (top), each of the above types of tracks can be fitted separately in the top and bottom halves of CMS. Alternatively, a single track fit can be made including hits from the top and bottom halves of CMS. The direction of the muon is assumed to be downwards, and the muon charge is defined accordingly.

The cosmic-muon charge ratio was measured by CMS for the first time using MTCC data [11], based on standalone muons. The reduced detector setup used in the MTCC was just a fraction of the bottom half of the complete detector. Having the detector on the surface, however, permitted the collection of a large number of low-momentum muons, down to a momentum of 5 GeV/c, allowing for a precise measurement of the charge ratio in the low-momentum range. Selection accepts only muons triggered and reconstructed in a perfectly left-right symmetric fiducial volume with respect to the vertical axis, emphasized in Fig. 1 (bottom), ensuring a charge-symmetric acceptance. About 330 000 events pass the fiducial-volume and track-quality selections. The probability of charge misassignment is small for low-momentum muons. At high momenta, resolution effects increase the chance of charge misassignment thus lowering the measured value of the charge ratio. Only muons with a measured momentum below 200 GeV/c are included in the analysis.

Two analyses based on the 2008 CRAFT08 underground data are performed, one using standalone muons and the other using global muons. The underground global-muon analysis (GLB) profits from the excellent momentum resolution and charge determination of global muon tracks, but requires that the muon passes through the silicon tracker. The underground standalone-muon analysis (STA) profits from the larger acceptance of the muon chambers and yields approximately eight times as many muons as the global-muon analysis. In a standalone cosmic-muon fit spanning the whole diameter of the muon detector (Fig. 1), the momentum resolution is significantly improved compared to a standalone fit using only half the detector.

The redundancy of the different tracking systems in the complete CMS detector allows the determination of the momentum resolution and rate of charge misassignment (the fraction of muons reconstructed with incorrect charge) directly in data. In the global-muon analysis, the half-difference of the track curvatures measured in the top half and the bottom half of the detector is used to measure the resolution of the half-sum.

In the underground standalone-muon analysis, an independently reconstructed tracker track is available in 40% of the selected events. In this case, the analysis relies on the simulation to correct for charge misassignment and momentum resolution effects, using the data with both a standalone and a tracker track in the event. The muon momentum scale and resolution are determined by comparing the transverse momentum of the standalone-muon track to that of the associated tracker track, and are accurately modeled by the simulation. Therefore the momentum unfolding, which provides an estimate of the true momentum of the muon tracks from the measured momentum, can be based on the simulation.

3 Corrections for energy loss and resolution

In order to express the charge ratio measurement as a function of the true momentum at the surface of the Earth, the measured momentum inside the CMS detector has to be corrected for energy lost between the surface of the Earth and the point of measurement. Furthermore, corrections need to be applied for migration of entries from bin to bin due to momentum resolution and for possible misassignment of the muon charge.

In the MTCC analysis the measured muons are propagated back to the top of CMS, correcting for expected momentum loss and bending in the magnetic field. In addition, the effect of charge misassignment is estimated using simulated events, and a bin-by-bin correction is applied to the measured charge ratio. For the muons selected in the global and standalone-muon analyses of the 2008 underground data, the average expected energy loss depends strongly on the path followed through the Earth. The underground measurements are corrected for this effect by propagating the trajectory of individual muons back to the Earths surface, using the same material model as in the simulation. Energy loss in matter is about 0.15% higher for $\mu+$ than for $\mu-$ due to slightly larger ionization losses. This difference is taken into account in the energy-loss correction, but affects the measured charge ratio by less than 0.3% over the entire momentum range.

In the underground data analyses, momentum resolution effects in the detector are corrected using an unfolding technique, applied to the charge-signed inverse momentum C = q/p. In this procedure p represents the measured momentum extrapolated to the Earth's surface, where the correlation with the true muon momentum is highest. The momentum measured at the center of CMS is propagated first to the top of CMS, accounting for the magnetic field and the amount of material traversed, and then to the surface of the Earth, following a straight line. Only muons with an estimated momentum above 30 GeV/c after this correction are kept in the analyses. Variations of the energy loss around the expected value are taken into account in the unfolding procedure by applying an additional 10% Gaussian smearing of the energy-loss correction to the measured momentum when forming the migration matrix. This approximation is based on simulation studies using GEANT4.

4 Systematic uncertainties

For the MTCC analysis, the uncertainty on the detector alignment is the main limiting factor, at around 2%, increasing with muon momentum to around 10%. Much smaller uncertainties due to charge mis- identification and knowledge of the magnetic field also contribute. For the CRAFT08 analyses, systematic were assessed due to the uncertainty on the material above the CMS cavern and any charge-dependent effect on the muon rate, the impact of the event selection and trigger, and knowledge of the magnetic field. However, the largest single source of uncertainty was the understanding of the detector alignment, which rises to 3-4% at high momentum. The detector was aligned using cosmic muons during the MTCC and CRAFT08 runs, however as well as uncertainties on this alignment, there remains the possibility of weak modes: deformations of the detector which do not change the fitted track χ^2 but do affect the measured track momenta. As these weak modes are χ^2 invariant, the standard alignment procedure is to some level blind to them, and the main concern for this analysis is the class of weak modes which induce a (signed) offset in the measured curvature, therefore shifting the measured momentum for positive and negatively charged muons in opposite directions. To constrain such weak modes, the end- point test was developed. The number of measured muons should fall to zero as the measured momentum goes to infinity, or as q/p_T goes to zero. Fitting the measured q/p_T distribution can test for any shift of this minimum away from zero, and set limits on the size of any weak modes. In the CRAFT08 analysis, an offset of $0.043 \pm 0.022\, TeV^1$ was found, the dominant uncertainty at high momentum. It is worth noting that such weak modes will be further constrained by LHC collision data, as more alignment techniques become possible.

5 Results

The fully corrected MTCC, global and stand-alone analyses were combined using a standard prescription [14]. Previous measurements have shown that the charge ratio is a constant in the range 5-100 GeV, so in a first combination all data points below p = 100 GeV are combined into a single measurement. This involves 6 points from the MTCC and 3 points from each of the global and stand-alone analyses and a full treatment of correlations between data points and analyses. This yields a charge ratio of 1.2766±0.0032(stat.)±0.0032(syst.), with a $\chi^2/ndf = 7.3/11$, in good agreement with previous measurements [2-5] and representing a significant improvement in precision.

Then, the data points from different analyses in each bin were combined, again keeping track of all correlations. The combined data points are shown in Fig. 2 as a function of p, and in Fig. 3 as a function of $p{\cdot}cos\theta_z$. Considering the full $p{\cdot}cos\theta_z$ range measured, a rise in the charge ratio is seen, as shown in Fig. 3. Comparing to previous measurements in the same momentum ranges, the CMS results agree well where there is overlap: with the L3+C measurement [3] below 400 GeV/c, and with the UTAH [1], MINOS [4] and OPERA [5] measurements above 400 GeV/c.

Models of cosmic ray showers provide an explanation for the rise in charge ratio at higher momentum. Based on the quark content of protons, and on the observation that primary cosmic ray particles are mostly positive, the ratio p+/p- is predicted to be around 1.27 [15]. Due to the phenomena of associated production, the charge ratio of strange particles such as kaons is expected to be even higher. The expected muon spectrum has been parametrized [16] based on the interactions of primary cosmic ray particles and on the decays of secondary particles, and from this parametrization, the charge ratio can be extracted [17] as a function of the fractions of all pion and kaon decays that yield positive muons, f_π and f_κ, respectively. These constants are not known a priori, and must be inferred from data. A fit performed to the combined CMS charge ratio measurement in the entire $p{\cdot}cos\theta_z$ region, with a fixed relative amount of kaon production [18], yields $f_\pi = 0.553 \pm 0.005$, and $f_\kappa = 0.66 \pm 0.06$, with a $\chi^2/ndf = 7.8/7$. Fig. 3 shows the fit to CMS data only, together with a fit performed on some previous measurements by L3+C and MINOS [17].

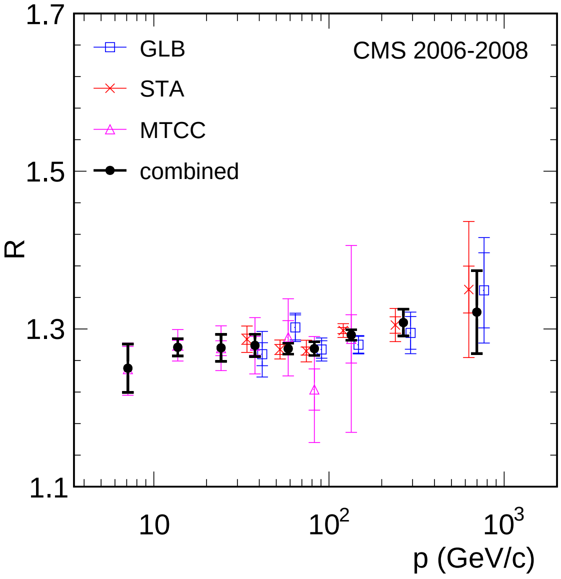

Fig. 2. The three CMS results, and their combination, as a function of the muon momentum. Data points are placed at the bin average, with the points from the standalone and global-muon analyses offset horizontally by $\pm10\%$ for clarity.

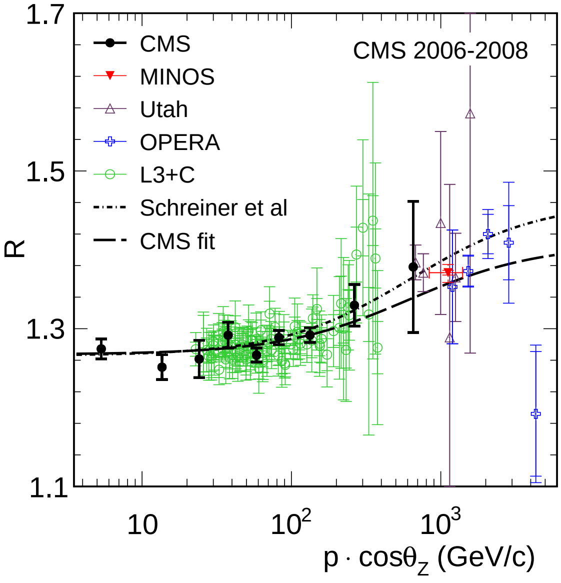

Fig. 3. The CMS result, as a function of the vertical component of the muonmomentum, together with some previous measurements and a fit of the pion-kaon model to the CMS data.

6 Conclusions

We have measured the flux ratio of positive- to negative-charge cosmic ray muons, as a function of the muon momentum and its vertical component, using data collected by the CMS experiment in 2006 and 2008. The result is in agreement with previous measurements by underground experiments. This is the most precise measurement of the charge ratio in the momentum region below 0.5 TeV/c. It is also the first physics measurement using muons with the complete CMS detector.

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