Physics Letters B 692 (2010) 83–104

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

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ARTICLE INFO

Article history:
Received 29 May 2010
Received in revised form 7 July 2010
Accepted 14 July 2010
Available online 23 July 2010
Editor: M. Doser

Keywords:
CMS
Physics
Muon
Cosmic rays
Charge ratio

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 $1.2766 \pm 0.0032\,(\text{stat.}) \pm 0.0032\,(\text{syst.})$, 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

The muon charge ratio R is defined as the ratio of the number of positive- to negative-charge atmospheric muons arriving at the Earth's surface. These muons arise from showers produced in interactions of high-energy cosmic ray particles with air nuclei in the upper layers of the atmosphere. The magnitude and the momentum dependence of R are determined by the production and interaction cross sections of mesons (mainly pions and kaons), and by their decay lengths. As most cosmic rays and the nuclei with which they interact are positively charged, positive meson production is favoured, hence more positive muons are expected. Previous measurements from various experiments [1–8] showed the muon charge ratio to be constant up to a momentum of about 200 GeV/c, and then to increase at higher momenta, in agreement with the predicted rise in the fraction of muons from kaon decays. Measurements of the charge ratio can be used to constrain hadronic interaction models and to predict better the atmospheric neutrino flux.

The Compact Muon Solenoid (CMS) [9] is one of the detectors installed at the Large Hadron Collider (LHC) [10] 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 [11].

Cosmic rays were used extensively to commission the CMS detector [12,13]. These data can also be used to perform measurements of physical quantities related to cosmic ray muons. This Letter presents a measurement of the muon charge ratio using CMS data collected in two cosmic ray runs in the years 2006 and 2008. More details of the analyses can be found in [14,15].

2. Experimental setup, data samples, and event simulation

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 [16], the crystal electromagnetic calorimeter and the brass-scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yokes [17]. 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 [9].

The CMS detector is installed in an underground cavern, with the center of the detector 89 m below Earth's surface, and 420 m above sea level. The location is $46^\circ\,18.57'$ north latitude and $6^\circ\,4.62'$ east longitude. The upper 50 m of the material above CMS consists of moraines, followed by 20 m of molasse rock. A large access shaft with a diameter of 20.5 m rises vertically to the surface, and is offset from the center of CMS by 14 m along the beam direction. It is covered by a movable concrete plate of 2.25 m

☆☆ Date submitted: 2010-05-29 08:19:58.
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doi:10.1016/j.physletb.2010.07.033

Table 2
The muon charge ratio R from the combination of all three CMS analyses, as a function of p and $p\cos\theta_z$, in GeV/c, together with the combined statistical and systematic relative uncertainty, in %.

p range	$\langle p \rangle$	R	Uncertainty	$p\cos\theta_z$ range	$\langle p\cos\theta_z \rangle$	R	Uncertainty
5–10	7.0	1.250	2.45	2.5–10	5.3	1.274	0.99
10–20	13.7	1.277	0.85	10–20	13.6	1.251	1.26
20–30	24.2	1.276	1.34	20–30	24.1	1.262	1.88
30–50	37.8	1.279	1.10	30–50	37.7	1.292	1.27
50–70	58.5	1.275	0.54	50–70	58.4	1.267	0.71
70–100	82.5	1.275	0.68	70–100	82.4	1.289	0.70
100–200	134.0	1.292	0.52	100–200	133.1	1.292	0.72
200–400	265.8	1.308	1.29	200–400	264.0	1.330	1.99
> 400	698.0	1.321	3.98	> 400	654.0	1.378	6.04

ment [5] below 400 GeV/c, and with the UTAH [1], MINOS [6] and OPERA [8] measurements above 400 GeV/c. Measurements by other experiments in the range 5–20 GeV/c [2–5,31] are not shown in the plot; they are consistent with the constant value fitted in the CMS data.

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 π^+/π^- is predicted to be around 1.27 [32]. 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 [33] 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 [7] as a function of the fractions of all pion and kaon decays that yield positive muons, f_π and f_K, 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 $p\cos\theta_z$ region, with a fixed relative amount of kaon production [33], yields $f_\pi = 0.553 \pm 0.005$, and $f_K = 0.66 \pm 0.06$, with a $\chi^2/\mathrm{ndf} = 7.8/7$. Fig. 6(b) shows the fit to CMS data only, together with a fit performed on some previous measurements by L3 + C and MINOS [7].

8. 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.

Acknowledgements

We thank the technical and administrative staff at CERN and other CMS institutes. This work was supported by the Austrian Federal Ministry of Science and Research; the Belgium Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport; the Research Promotion Foundation, Cyprus; the Estonian Academy of Sciences and NICPB; the Academy of Finland, Finnish Ministry of Education, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules/CNRS, and Commissariat à l'Énergie Atomique, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz–Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Office for Research and Technology, Hungary; the Department of Atomic Energy, and Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Korean Ministry of Education, Science and Technology and the World Class University program of NRF, Korea; the Lithuanian Academy of Sciences; the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Pakistan Atomic Energy Commission; the State Commission for Scientific Research, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); the Ministry of Science and Technologies of the Russian Federation, and Russian Ministry of Atomic Energy; the Ministry of Science and Technological Development of Serbia; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the National Science Council, Taipei; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie IEF program (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; and the Associazione per lo Sviluppo Scientifico e Tecnologico del Piemonte (Italy).

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