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Experimental results on the atmospheric muon charge ratio

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Abstract. The atmospheric muon charge ratio, defined as the number of positive over negative charged muons, is a highly informative observable both for cosmic rays and particle physics. It allows studying the features of high-energy hadronic interactions in the forward region and the composition of primary cosmic rays. In this review results from underground experiments measuring the charge ratio around 1 TeV are discussed. The measurements in the TeV energy region constrain the associated kaon production, which is particularly important e.g. for the calculation of the atmospheric neutrino flux.

1. Introduction

The atmospheric muon charge ratio is an important observable to shed light on the physics of cosmic ray interactions in atmosphere. Its measurement allows to better understand the features of high energy hadronic interactions in the forward region and to improve Monte Carlo predictions of the atmospheric neutrino flux.

Atmospheric muons constitute the penetrating charged remnants of cosmic rays under the Earth's surface. They are produced when primary cosmic rays, mainly protons, impinge on the Earth's atmosphere producing a particle cascade, in which secondary particles decay into muons. In the energy range up to $\sim$100 GeV atmospheric muons come mostly from the decay of secondary pions. At higher energies, the kaon contribution to the muon flux become significant, reaching the asymptotic value of 27% at about 10 TeV [1]. At even higher energies, at $O(100)$ TeV, also charmed hadrons are expected to contribute (*prompt* muons). In the pion dominated energy region ($E_\mu \lesssim 100$ GeV), the muon charge ratio R_μ has been measured by several experiments on surface, by balloon-borne detectors and at shallow depths [2]. It results to be constant, $R_\mu \simeq 1.27$, as expected assuming the validity of Feynman scaling in the fragmentation region [1]. Since the associated production ΛK^+ has no analog for K^-, the K^+/K^- ratio is larger than the π^+/π^- ratio [1, 3]. Thus, the increasing kaon contribution from a few hundred GeV to a few TeV causes a smooth transition to a higher value of the muon charge ratio.

In this work experimental results on the muon charge ratio in the TeV energy range, fundamental to constrain the associated kaon production and test the Feynman scaling in the forward region, are reviewed. Furthermore, this measurement allows to study the chemical composition of cosmic rays near the *knee* in the primary spectrum.

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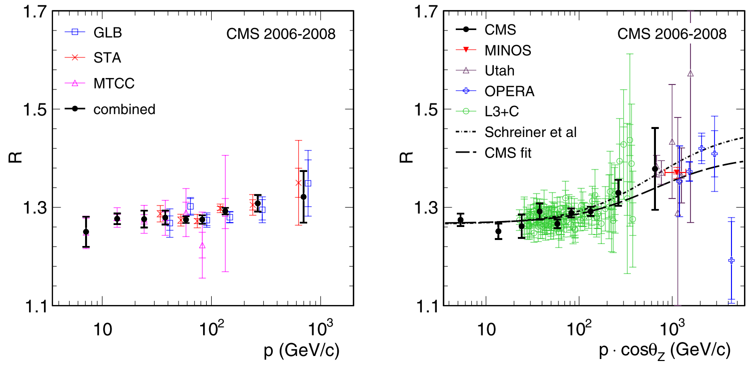

Figure 1. The atmospheric muon charge ratio measured by CMS (*black points*) as a function of (left) the muon momentum and (right) the vertical component of the muon momentum [4].

2. Underground experiments

Underground experiments naturally select high energy down-going muons, the minimum energy threshold being fixed by the rock overburden surrounding the detector. Key elements for the accurate determination of the muon charge and momentum in the O(TeV) energy range are magnetized detectors and large depth.

Recent results were obtained by the CMS [4], MINOS [5, 6] and OPERA [7, 8] experiments that measured the muon charge ratio R_μ around vertical surface energy $E_\mu \cos\theta \sim 1$ TeV. MINOS and OPERA are long-baseline neutrino experiments located deep underground, while CMS is a collider experiment located at shallow depth but provided with an intense magnetic field.

In order to disentangle the different parent components to the muon flux (π, K, charm) the correct variable to describe the evolution of R_μ is the vertical surface energy $E_\mu \cos\theta$ [9]. Taking into account the possible variation of the primary cosmic ray composition, we should consider separately the dependency on the surface muon energy E_μ and the zenith projection $\cos\theta$, see Sect. 2.3 [3].

2.1 CMS results

The CMS detector is installed in an underground cavern at the Large Hadron Collider (LHC). The experiment is located at shallow depth, with the center of the detector 89 m below the Earth's surface, corresponding to 6 to 175 m.w.e. traversed by close-to-vertical muons depending on the impact point on CMS. At the core of the apparatus, a superconducting solenoid generates a magnetic field of 3.8 T directed along the LHC beam direction (z axis). This configuration favours the reconstruction of atmospheric muons, since the bending is stronger for vertical tracks. Muon tracking in CMS is performed with the inner silicon tracker and with either three or four stations of muon chambers installed outside the solenoid. Depending on the track topology, the maximum detectable momentum ranges from 200 GeV/c up to 20 TeV/c [4].

The muon charge ratio was determined using data collected during 2006 and 2008 cosmic ray runs. The results on R_μ in the 5 GeV/c to 1 TeV/c momentum range are shown in Fig. 1. CMS provided the most precise measurement of the charge ratio below 100 GeV/c to date, $R_\mu = 1.2766 \pm 0.0032\,(stat.) \pm 0.0032\,(syst.)$. The measurements lie in the transition region between the pion dominated muon flux ($p\cos\theta < 100$ GeV/c), where R_μ is consistent

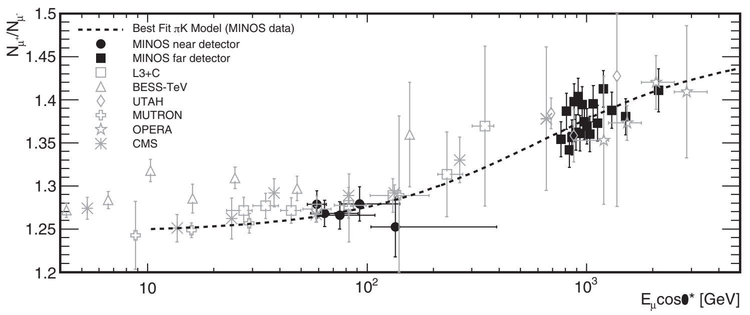

Figure 2. The atmospheric muon charge ratio measured by MINOS (*black points* for the Near Detector, *black squares* for the Far Detector) as a function of $E_\mu \cos\theta^*$ [6].

with a flat charge ratio, and the plateau corresponding to the asymptotic kaon contribution, above some TeV. CMS data are consistent with an increase of the charge ratio. Using the parameterization described in [9], the fit on stand-alone CMS data yields the fractions of charged pions and kaons decaying into positive muons, $f_{\pi^+} = 0.553 \pm 0.005$ and $f_{K^+} = 0.66 \pm 0.06$.

2.2 MINOS results

The MINOS Near and Far Detectors (ND and FD, respectively) are two functionally identical magnetic calorimeters placed in the NuMI neutrino beam. They are composed by magnetized steel planes instrumented with scintillator strips and located under a flat overburden of 94 m (ND) and 710 m (FD), corresponding to 225 m.w.e. and 2070 m.w.e., respectively. The toroidal magnetic field is stronger near the coil hole along the longitudinal z-axis (1.8 T for the FD, 2.1 T for the ND) and weaker near the edges (1 T at FD, 0.2 T at ND), with an average value of 1.3 T. This configuration focus toward the center of the detector positive muons coming from one direction and negative muons coming from the opposite direction, giving rise to a different acceptance for μ^+ and μ^-. During the data taking period, the coil current was periodically reversed in order to invert the direction of the magnetic field. Data recorded with the two magnetic field configurations, referred to as forward and reverse, were combined to cancel the acceptance bias [5, 6].

Due to the approximately flat overburden at both sites, the highest energy muons are at large zenith angles. Since the median surface energy increases as $\cos\theta$ decreases, the $E_\mu \cos\theta$ distribution is much narrower than the E_μ distribution. Due to this compensation muon events with the highest $E_\mu \cos\theta$ are those with the highest reconstructed momentum at the detector. The maximum detectable momentum is around $\sim$ 300 GeV/c.

The results on the muon charge ratio were obtained with the FD, using data collected between 2003 and 2006 [5], and with the ND, using data collected between 2006 and 2009 [6]. R_μ is shown as a function of $E_\mu \cos\theta^*$ in Fig. 2, where θ^* is the zenith angle at the production point taking into account the Earth's curvature. The ND charge ratio is given in the 50−130 GeV vertical energy range, while the FD data are in the 800 GeV−2 TeV range. Using only MINOS Near and Far Detector data the best fit to the parameterization of R_μ [9] over (f_{π^+}, f_{K^+}) gives the result $f_{\pi^+} = 0.55$ and $f_{K^+} = 0.70$ and it is also plotted in Fig. 2.

MINOS observed an increase in the charge ratio, from $R_\mu = 1.266 \pm 0.001\,(stat.)^{+0.015}_{-0.014}\,(syst.)$ at the ND shallow depth to $R_\mu = 1.374 \pm 0.004\,(stat.)^{+0.012}_{-0.010}\,(syst.)$ at the FD large depth, consistent with an increase in the fraction of observed muons arising from kaon decays.

2.3 OPERA results

The OPERA experiment is a hybrid electronic detector/emulsion apparatus exposed to the CNGS neutrino beam from 2007 up to 2012. It is located in the underground Gran Sasso laboratory, at an average depth of 1400 m of rock corresponding to 3800 m.w.e. OPERA is the deepest experiment able to measure charge-separated atmospheric muons. The minimum surface muon energy threshold is $\sim$1 TeV (1.4 TeV averaged over all the directions and rock depths). The detector is composed of two identical parts, called supermodules, each consisting of a target section and a magnetic spectrometer. The target consists of scintillator strips interleaved with Emulsion Cloud Chambers, the spectrometer is a large dipole iron magnet instrumented with Resistive Plate Chambers. The magnetic field is almost uniform, with intensity 1.53 T, and directed along the vertical axis with opposite orientations in the two magnet arms. A muon crossing the spectrometer is deflected in the horizontal plane. The deflection is measured by six stations of vertical drift tubes, the Precision Trackers (PT), grouped in 3 pairs placed upstream of the first arm, in between the two arms and downstream of the second arm. The charge and momentum reconstruction is performed for tracks crossing at least one magnet arm using the angle $\Delta\phi$ in the bending plane, i.e. the difference between the track directions reconstructed by two PT stations before and after each magnet arm. For nearly horizontal muons up to four bending angles can be measured in the two dipole magnets.

Different muon reconstruction procedures are used for CNGS neutrino and cosmic ray induced events. Atmospheric events with single and multiple muon tracks (*muon bundles*) were reconstructed. Due to the charge-symmetry of the dipole magnet, the acceptance for μ^+ and μ^- is the same and, depending on the track topology, the maximum detectable momentum varies from a few hundred GeV/c up to 1 TeV/c [8, 10]. Data were collected with both magnetic field polarities in order to minimize systematic errors due to misalignment.

OPERA reported a first measurement of the atmospheric muon charge ratio using the 2008 Run data [7] and the final results using the complete statistics from 2008 up to 2012 [8]. In the latter analysis the two data sets collected with opposite magnet polarities were combined reaching the most accurate measurement to date of R_μ in the TeV energy region. The muon charge ratio was computed separately for single muons, $R_\mu(n_\mu = 1) = 1.377 \pm 0.006\,(stat.)^{+0.007}_{-0.001}\,(syst.)$, and for muon bundles, $R_\mu(n_\mu > 1) = 1.098 \pm 0.023\,(stat.)^{+0.015}_{-0.013}\,(syst.)$. This is the first observation of a decrease in the charge ratio of high multiplicity events with respect to single muon events. The dilution effect in R_μ is expected since the multiple muon sample selects events generated by heavier primary cosmic rays and secondaries with a low value of Feynman-x, coming from the central region [10].

Because of the Gran Sasso orography, the amount of rock crossed by muons is not directly related to the zenith angle, and the high energy tail is not completely suppressed by the $\cos\theta$ factor. OPERA presented results on R_μ (for single muons) as a function of the vertical surface energy $E_\mu \cos\theta^*$, where θ^* is the zenith angle at the muon production point, fitting data to the parameterized model described in Ref. [9]. The atmospheric muon charge ratio was measured in a large $E_\mu \cos\theta^*$ range, from 500 GeV up to $\sim$ 10 TeV, and plotted in Fig. 3. With an average value $\langle E_\mu \cos\theta^* \rangle \simeq 2$ TeV, OPERA is the magnetized experiment measuring the charge ratio at the largest vertical surface energy. The fit of OPERA and L3+C data, shown in Fig. 3, yields the fractions of charged mesons decaying into positive muons $f_{\pi^+} = 0.5512 \pm 0.0014$ and $f_{K^+} = 0.705 \pm 0.014$. The prompt muon component does not significantly contribute to R_μ up to $E_\mu \cos\theta^* \lesssim 10$ TeV.

Taking into account the primary cosmic ray composition requires to disentangle the energy and zenith angle dependencies [3]. The fit in two dimensions $(E_\mu, \cos\theta^*)$ yields

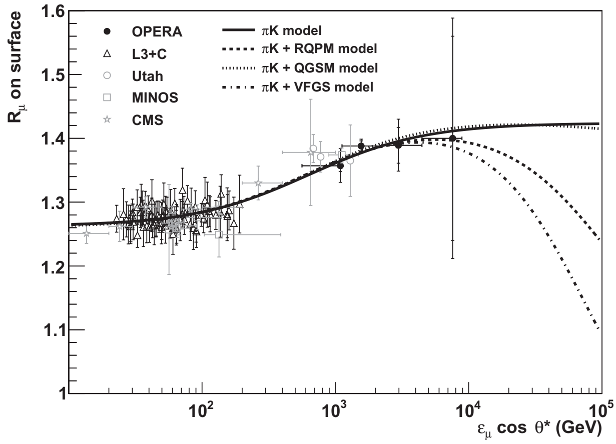

Figure 3. The atmospheric muon charge ratio measured by OPERA (*black points*) as a function of $E_\mu \cos\theta^*$.

the proton excess in primary cosmic rays $\delta_0 = 0.61 \pm 0.02$ at primary energy $\langle E_N \rangle \approx$ 20 TeV/nucleon, and the factor related to the associated kaon production, $Z_{pK^+} = 0.0086 \pm 0.0004$, determined for the first time.

3. Conclusions

The results on the atmospheric muon charge ratio from the CMS, MINOS and OPERA experiments show an increase of R_μ as a function of the vertical surface energy $E_\mu \cos\theta^*$ in the range between a few hundred GeV and a few TeV. The measurements are compatible with a simple parametric model where the rise is due to the increasing kaon contribution to the muon flux. No significant contribution from charm decay is observed up to energies $\sim$ 10 TeV. A future experimental measurement of R_μ in the region $E_\mu \cos\theta^* > 10$ TeV, with a new detector at very large depths, could shed light on the prompt component even before the crossover between conventional and prompt muons.

The OPERA measurement of R_μ in the TeV energy range determined for the first time the spectrum weighted moment Z_{pK^+}, fundamental to accurately predict the atmospheric $\bar{\nu}/\nu$ ratio. No similar results on the associated kaon production cross section are available to date from accelerator experiments. The Z_{pK^+} factor was extracted together with the primary proton excess δ_0, which is consistent with direct measurements of the primary composition [3]. The energy behaviour of R_μ measured by OPERA above a few TeV, compatible with the plateau corresponding to the asymptotic kaon contribution, supports the validity of Feynman scaling in the fragmentation region up to primary energies/nucleon around 200 TeV.

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