Measurement of the cosmic ray muon charge ratio with the OPERA detector

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Abstract
The OPERA detector at the Gran Sasso underground laboratory (LNGS) was used to measure the cosmic ray muon charge ratio $R_\mu = N_{\mu^+}/N_{\mu^-}$ in the TeV energy region. We analyzed 403069 cosmic ray muons corresponding to 113.4 days of livetime during the 2008 CNGS run. We computed separately the muon charge ratio for single and for multiple muon events in order to select different energy regions of the primary cosmic ray spectrum and to test the R_μ dependence on the primary composition. R_μ is also shown as a function of the "vertical surface energy" $\mathcal{E}_\mu \cos\theta$. A fit to a simplified model of muon production in atmosphere allowed the determination of the pion and kaon charge ratios weighted by the cosmic ray energy spectrum.

1 Introduction

OPERA [1, 2] is a long baseline neutrino experiment located in the Gran Sasso underground laboratory (LNGS). It is aimed at detecting for the first time the appearance of tau neutrinos from the oscillation of muon neutrinos in the CERN to Gran Sasso beam-line (CNGS). The detector is located at an average depth of 3800 m.w.e., where only high energy cosmic ray muons (and neutrinos) can arrive: the minimum surface energy threshold is $\sim$1 TeV (1.4 TeV averaged over all the directions and rock depths). OPERA, as a cosmic ray detector, provides the capability to measure the charge and momentum of cosmic muons with large statistics. Cosmic ray data are collected in the OPERA detector together with CNGS beam data: CNGS neutrino induced events are removed from the sample using the coincidence with the CERN data timing system.

The cosmic ray muon charge ratio R_μ is an important observable to shed light on the physics of cosmic ray interactions in atmosphere: its measurement will help to better understand the features of high energy hadronic interactions in the forward region and to improve Monte Carlo models of interactions, constraining the predictions at high energy (above 1 TeV).

Cosmic ray muons are produced when primary cosmic ray nuclei (mainly protons) impinge on the Earth's atmosphere, producing showers of secondary particles. Most of the interaction products are π and K mesons, which decay into muons. Since the cosmic ray primaries are positively charged, there are more positive than negative pions and kaons in the hadronic showers. At high energies, several competing processes can affect the charge ratio. As energy increases, the fraction of muons coming from kaon decays also increases, and since strong interaction production channels lead to a K^+/K^- ratio higher than for π^+/π^-, R_μ is expected to rise. At even higher energies it is expected that the muon prompt contributions (muons from the decay of charmed particles) could influence the charge ratio value. We also expect a dependence of R_μ on the underground muon multiplicity M_μ, which is related to the energy of the primary cosmic rays and to their chemical composition. For primaries different from protons, the charge excess is reduced and so is the muon charge ratio.

2 The OPERA detector

The OPERA detector is a hybrid apparatus composed of two identical parts, called supermodules (SM), each consisting of a target section and a magnetic spectrometer. It is equipped with passive detectors, the Emulsion Cloud Chamber (ECC) units, called "bricks", and with electronic detectors. In the target section, the bricks are arranged in 29 vertical "walls", transverse to the beam direction, interleaved with Target Tracker (TT) walls. Each TT wall consists of a double layered plane of 64 long scintillator strips.

The target section is followed by a magnetic spectrometer. A large dipolar iron magnet is instrumented with Resistive Plate Chambers (RPC). The magnetic field intensity is 1.53 T, directed along the vertical axis. The RPC planes are inserted between the iron slabs: they provide the tracking inside the magnet. The deflection of charged particles in the magnet is measured by six stations of vertical drift tubes, the High Precision Trackers (HPT). Each HPT station is formed by four staggered layers of aluminum tubes, 8 m long, with 38 mm outer diameter. The spatial resolution of a HPT station is better than 500 μm in the bending (horizontal) plane.

A muon crossing the spectrometer is deflected in the horizontal plane: the charge and momentum reconstruction is performed for tracks crossing at least one magnet arm using the bending angle information ($\Delta\phi$) coming from HPT stations.

2.1 Data Analysis

The results here presented are based on data recorded during the CNGS Physics Run, from June 18 until November 10, 2008. The total number of events is 403069 corresponding to 113.4 days of livetime.

For this analysis, the basic information required for the charge-momentum measurement is at least one reconstructed $\Delta\phi$ angle in each event (*acceptance cut*). A second cut removes noisy events in HPT stations, potentially dangerous for the muon charge determination (*clean PT cut*). This typically occurs when some drift tubes are fired by secondary particles (δ-rays, showers etc.). Finally, we selected tracks whose deflections are above the experimental resolution: we require $\Delta\phi/\sigma_{\Delta\phi} >$3 (*deflection cut*). After the application of this cut, the charge-misidentification η (defined as the fraction of tracks reconstructed with wrong charge sign) is reduced from 0.080$\pm$0.002 to 0.030$\pm$0.001.

The muon charge ratio has been computed separately for single muon events and multiple muon events. Single muon events are selected requiring single tracks in each projected view, well merged in 3D. Multiple muon events are selected by requiring a muon multiplicity $\geq$ 2 in both views, with tracks identified and merged in 3D.

For this kind of measurement, the main sources of systematic error are due to the HPT alignment accuracy and to the determination of the η value. For both sources, we considered all muon tracks crossing both arms of each spectrometer, thus providing two deflection values $\Delta\phi$ for the same muon track. To evaluate the misalignment contribution, we used the difference $\delta\Delta\phi = \Delta\phi_{arm_1} - \Delta\phi_{arm_2}$, that with perfect alignment should be peaked at zero. Given the peak values for the two spectrometers, we propagated the offset in the charge ratio calculation, obtaining $\delta R_\mu \simeq$ 0.015. To evaluate the systematic uncertainty on η, we computed the fraction of tracks with two opposite deflection angle signs, finding η_{real}. The difference between experimental and Monte Carlo misidentification is one-sided (since $\eta_{real} \geq \eta_{MC}$), and corresponds to δR_μ = 0.007. Systematic errors are combined quadratically.

In order to provide a result independent from the detector features, we unfolded the charge ratio measured value using the charge-misidentification η, computed by Monte Carlo.

Table 1: Primary cosmic ray information for single and multiple muon events obtained with Monte Carlo. In the last column the measured R_μ values for single and multiple muon events are given.

N_μ	$\langle A \rangle$	$\langle E/A \rangle_{primary}$	H fraction	N_p/N_n	R_μ^{unf}
=1	3.35$\pm$0.09	(19.4$\pm$0.1) TeV	0.667$\pm$0.007	4.99$\pm$0.05	1.377$\pm$0.014
$>$1	8.5$\pm$0.3	(77$\pm$1) TeV	0.352$\pm$0.012	2.09$\pm$0.07	1.23$\pm$0.06

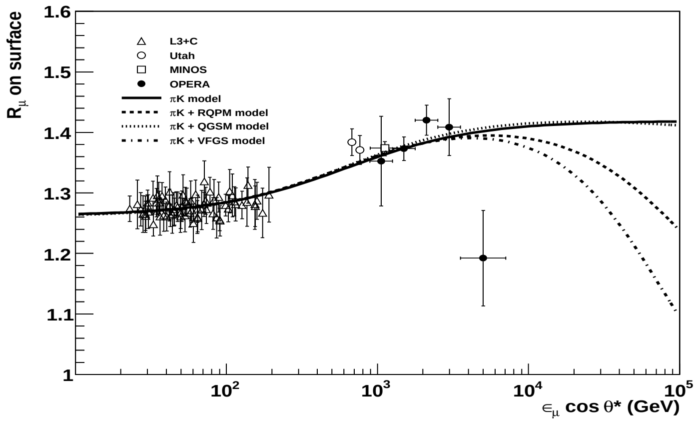

Fig. 1: R_μ values measured by OPERA in bins of $\mathcal{E}_\mu \cos\theta^*$ (black points) and by other experiments in the low and high energy region. Data were fitted to model predictions with only π and K contributions (continuous curve) and with prompt component included (dashed, dotted and dash-dotted lines) as predicted by different models.

The unfolded single-muon charge ratio is

$$R_{unf}(M_\mu = 1) = \frac{\eta - (1-\eta)R_{meas}}{\eta R_{meas} - (1-\eta)} = 1.377 \pm 0.014\,(\text{stat.})^{+0.017}_{-0.015}\,(\text{syst.}) \tag{1}$$

The unfolded charge ratio for multiple-muon events is

$$R_{unf}(M_\mu > 1) = 1.23 \pm 0.06\,(\text{stat.})^{+0.017}_{-0.015}\,(\text{syst.}) \tag{2}$$

This value is 2.4 σ away from the value for single muon events, consistent with the hypothesis of dilution of R_μ due to the neutron enhancement in the primary nuclei. Tab. 1 gives information obtained with Monte Carlo on some variables of single muon events and muon bundles and the corresponding measured R_μ (last column).

Finally, in Fig. 1 the muon charge ratio as a function of the vertical muon energy at surface is reported. In the same plot data in the low and high energy region from past experiments are considered. Data were fitted to model predictions with only π and K contributions to derive information on the spectrum-weighted moments Z_{ij}, namely the meson-nucleon inclusive cross sections weighted with the primary spectrum. The result is $R_\pi = Z_{N\pi^+}/Z_{N\pi^-}$ = 1.229±0.001 and $R_K = Z_{NK^+}/Z_{NK^-}$ = 2.12±0.03. The inclusion of the prompt muon component does not modify the fit results.

3 Conclusions

The atmospheric muon charge ratio was measured at an average depth of 3800 km w.e. Experimental values were provided separately for single and multiple muon events. Data suggest a dependence of R_μ on the primary species. Data were also reported as a function of the vertical muon energy at surface and fitted to a simplified muon production model to provide the corresponding π and K charge ratios. This experimental result will be helpful to constrain phenomenological hadronic interaction models in the very forward region.

References

[1] R. Acquafredda *et al.* [OPERA Collaboration], 2009 JINST **4** P04018.

[2] N. Agafonova *et al.* [OPERA Collaboration], 2009 JINST **4** P06020.