Measurement of the atmospheric muon charge ratio with the OPERA detector at Gran Sasso

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Physics motivation

The atmospheric muon charge ratio R_μ, defined as the number of positive over negative muons, is an important observable for several features: it depends on the primary cosmic ray composition, on hadronic interactions in atmosphere and, at very high energy, on the contribution of prompt muons.

In the Gran Sasso underground laboratory (LNGS), the minimum surface energy of surviving muons is about 1.5 TeV, averaged over all directions. In this energy range, the fraction of muons from kaon decays in secondary showers increases and, since strong interaction production channels lead to a K^+/K^- ratio larger than the π^+/π^-, the muon charge ratio is expected to rise.

The muon charge ratio is also supposed to depend 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.

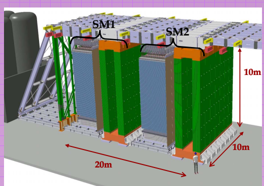
A simplified model of the atmospheric muon charge ratio is

$$\phi_{\mu^\pm} = \frac{\phi_0 \mathcal{E}_\mu^{-\gamma}}{1 - Z_{NN}} \left(\frac{a_\pi Z_{N\pi^\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta / \epsilon_\pi} + \frac{a_K Z_{NK^\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta / \epsilon_K} \right)$$

where $\mathcal{E}_\mu$ is the muon energy in atmosphere and θ is the zenith angle, $\gamma \cong 2.7$ is the primary cosmic ray spectral index, $a_{\pi/K}$ and $b_{\pi/K}$ are kinematical factors, $\varepsilon_{\pi/K}$ are the critical energies and $Z_{N\pi/K}$ are the spectrum weighted moments.

OPERA is the first large magnetized detector that can measure the muon charge ratio at the LNGS depth, where $<\mathcal{E}_\mu \cos\theta> \sim 2$ TeV, well above the kaon critical energy.

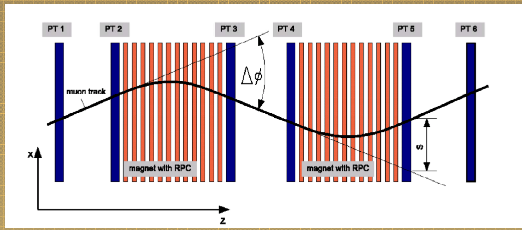
OPERA is an "hybrid" experiment, instrumented with electronic detectors and nuclear emulsions. It is composed of two identical parts, called supermodules (SM).



A supermodule is made of a target section and a magnetic spectrometer. The muon spectrometer consists of a dipolar magnet made of two iron walls. In the walls, the magnetic field intensity is 1.53 T, and RPC planes are inserted between the iron slabs for range measurement.

Charge and momentum measurement

Muon charge and momentum were reconstructed using the bending angle information Δϕ. The ϕ angle is provided by the Precision Tracker system: drift tube stations located in front and behind the magnet and between the walls.
The muon charge is determined from the sign of the Δϕ angle.



For horizontal tracks we can have up to 4 deflection angles: for each $\Delta\phi_i$, the momentum is computed using this formula →

$$p_i = \frac{l(dE/dz)}{1 - \exp[\Delta\phi_i (dE/dz)/c\bar{B}]}$$

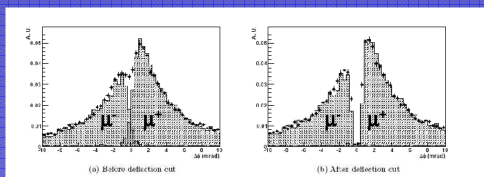
l = 0.82 m is the arm length and B = $\bar{B}d/l$ is the effective magnetic field.
In case of more than one information, the final muon momentum and charge are computed as the weighted average of the single measurements, taking $1/\sigma_\phi^2$ as weights.

Data Analysis: computation of R_μ

The results here presented are based on data recorded during the 2008 CNGS Physics Run: 403069 cosmic ray muons, corresponding to 113.4 days of livetime, were analyzed.

We used two Monte Carlo simulations: one is based on a fast parameterized generator and was used for data comparison and unfolding; the other one is a full generator based on the FLUKA code, used to link the underground to the surface physical features.

Two main analysis cuts were applied:
1) Clean PT cut: removes events with a large number of PT hits.
2) Deflection cut: rejects events with a Δϕ smaller or compatible with the experimental resolution.



Effect of the deflection cut on the Δϕ distributions: before (left) and after (right) the cut

With MC we calculated the fraction of tracks reconstructed with wrong charge sign, the charge-misidentification η.
The unfolded charge ratio is obtained according to this formula →

$$R_\mu^{unf} = \frac{(1-\eta) R_\mu^{meas} - \eta}{-\eta R_\mu^{meas} + (1-\eta)}$$

We computed separately R_μ for single and for multiple muon events, obtaining

$$R_\mu^{unf}(m_\mu = 1) = 1.377 \pm 0.014 \qquad R_\mu^{unf}(m_\mu > 1) = 1.23 \pm 0.06.$$

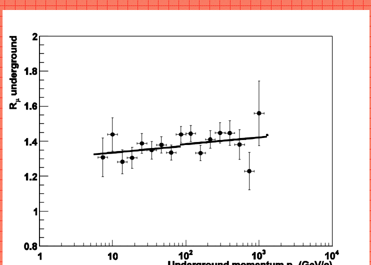
R_μ (m_μ=1) ≠ R_μ (m_μ>1) at 2.4 σ level

The main sources of systematic uncertainties on R_μ are related to the alignment accuracy and to the determination of η. Their values were evaluated using a method which exploits muon tracks crossing both magnet arms of a spectrometer. The result is:

$$\delta R_\mu^{unf}(\text{syst.}) = ^{+0.017}_{-0.015}$$

Results: underground and surface muon charge ratio

The underground muon charge ratio shows a mild increase when reported as a function of the reconstructed muon momentum:



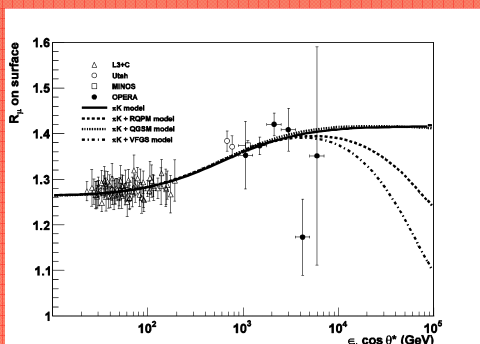
This behavior is a residual effect of the R_μ dependence on the "vertical surface energy", which is the proper variable to describe the evolution of the charge ratio in atmoshpere.

The surface muon energy $\mathcal{E}_\mu$ can be inferred from the measurement of the underground residual energy and the amount of rock crossed by the muon.
The full Monte Carlo simulation based on the FLUKA code was used to build a table:

$$<\mathcal{E}_\mu> = f(p_\mu, \text{rock})$$

The muon charge ratio was properly binned in $\mathcal{E}_\mu\cos\theta$ and fitted to the model of conventional muon production in atmosphere. The fit, which uses data from L3+C in the low energy region, yields the pion and kaon charge ratios:

$$R_\pi = Z_{N\pi+}/Z_{N\pi-} = 1.229 \pm 0.001$$
$$R_K = Z_{NK+}/Z_{NK-} = 2.12 \pm 0.03$$



Muon charge ratio as a function of the vertical surface energy. Also reported are other experimental results and four different model predictions, including the prompt muon contribution.

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