Cosmic ray studies with the OPERA detector at Gran Sasso

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Abstract. OPERA is a long-baseline neutrino experiment located in the Hall C of the Gran Sasso underground Laboratory at an average depth of 3.8 km w.e., corresponding to average muon energies at surface higher than 1.4 TeV. After a brief description of the main scientific goals of the experiment, we focus on the potentialities of OPERA used as a cosmic ray detector. In particular, we report on the measurement of the atmospheric muon charge ratio \( R_\mu = N_\mu^+/N_\mu^- \) and on the analysis of upgoing muons induced by atmospheric neutrinos.

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 under 1400 meters of rock overburden, where only high energy cosmic ray muons 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 (“on time” flag).

After a short description of the OPERA detector, we present the results obtained from the analysis of atmospheric neutrino induced muons and of the atmospheric 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 aluminium tubes, 8 m long, with 38 mm outer diameter. The spatial resolution of a HPT station is better than 500 $\mu$m 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.

3. Atmospheric neutrinos
Atmospheric neutrino interactions in the rock surrounding the LNGS underground laboratory produce muons. In OPERA, the TT timing system measures particle time-of-flights, thus it is used to discriminate between up-going and down-going particles: up-going muons (not within the CNGS spill window) with a restricted speed range are selected as atmospheric neutrinos.

This analysis classifies events in terms of the “speed side”, a composition of velocity and direction informations:

$$\text{speed side} = \left(1/\beta\right) \times (\text{track angle sign})$$

The track angle sign is positive for positive slopes in the $yz$ plane (side view), negative for negative slopes. The $(1/\beta)$ sign is given by the time difference between the last and first TT planes. With this convention, upward-going and downward-going particles have positive and negative speed side, respectively. Given the slope of the CNGS beam and the muon angular resolution, almost all on-time events have a positive speed side (exit angle $\sim 3.3^\circ$). Off-time upgoing events, with a cut $0.75 < (1/\beta) < 1.25$, are selected as atmospheric neutrino events.

For this first analysis, the total livetime is 254 effective days, with the detector running also with the magnetic spectrometer off. The up-going muon sample was selected applying two levels of cuts: the first level cut requires a track unambiguously detected in at least three consecutive TT planes along both projections. The second level cut requires $0.75 < (1/\beta) < 1.25$ and 20 TT planes hit. From a full Monte Carlo simulation based on the Honda flux calculations, 6.4 up-going muons were expected for the analysed period. The OPERA detector observed 5 events recognized as muon neutrino induced.

4. Cosmic ray muon charge ratio
The cosmic ray muon charge ratio $R_\mu$ 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 $\pi$ 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 $\pi^+/\pi^-$, $R_\mu$ is expected to rise. But there are other competing processes involved in the resulting charge ratio value. We also expect a dependence of $R_\mu$ on the underground muon multiplicity $m_\mu$, 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.
4.1. 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). 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 $\eta$ (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 $\eta$ 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 $\delta \Delta \phi = \Delta \phi_{\text{arm}1} - \Delta \phi_{\text{arm}2}$, 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 $\eta$, we computed the fraction of tracks with two opposite deflection angle signs, finding $\eta_{\text{real}}$. The difference between experimental and Monte Carlo misidentification is one-sided (since $\eta_{\text{real}} \geq \eta_{\text{MC}}$), and corresponds to $\delta R_{\mu} = 0.007$. The final systematic error is the quadratic sum of its contributions.

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

The unfolded single-muon charge ratio is

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

(2)

The unfolded charge ratio for multiple-muon events is

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

(3)

This value is $2.4 \sigma$ away from the value for single muon events, consistent with the hypothesis of dilution of $R_{\mu}$ due to the neutron enhancement in the primary nuclei.

5. Conclusions

We presented results on two cosmic ray physics items carried out in parallel to the oscillation physics program of the OPERA experiment. We reported the measured value of the atmospheric muon charge ratio, integrated over all directions, at an average depth of 3800 km w.e. This experimental result will be helpful to constrain phenomenological hadronic interaction models in the very forward region. The first upgoing atmospheric neutrinos were observed; since this item needs a large livetime the analysis is still in a preliminary phase.

References

[1] R. Acquafredda et al. [OPERA Collaboration], 2009 JINST 4 P04018.
[2] N. Agafonova et al. [OPERA Collaboration], 2009 JINST 4 P06020.