Cosmic ray physics with the OPERA detector

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Abstract**. OPERA is a long-baseline neutrino experiment located in the Hall C of the underground Gran Sasso Laboratory at an average depth of 3.8 km.w.e., corresponding to muon energies at surface higher than 1.5 TeV. After a description of the main scientific goal 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, on the analysis of upgoing muons induced by atmospheric neutrinos and on the recent coincidence study between the OPERA and LVD detectors.**

Keywords**: long baseline experiments, neutrino oscillations, atmospheric muons**

I. Introduction

OPERA [1] is a long baseline neutrino experiment located in underground Hall C of the Gran Sasso 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 [2]). This would represent an unambiguous evidence of the neutrino oscillation phenomenon, so far carried out in disappearance mode in the atmospheric sector. The direct appearance search is based on the detection of tau leptons produced in the charged current interactions (CC) of tau neutrinos. Detecting prompt electrons from ν_e interactions, OPERA can also search for sub-leading transitions in the $\nu_\mu \rightarrow \nu_e$ channel.

The OPERA detector is located under an average rock overburden of 1400 meters (3.8 km of water equivalent) corresponding to $\sim$1.5 TeV muon energy threshold at surface. At LNGS the cosmic ray muon flux is reduced by a factor 10^6 with respect to the Earth's surface and the environmental radioactivity is extremely reduced. OPERA is the deepest experiment equipped with a muon spectrometer, and offers the capability to charge discriminate atmospheric muons and neutrino-induced muons and to measure the underground muon spectrum.

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 topologies of the two types of events is completely different, thus a dedicated reconstruction software was developed for cosmic events. The algorithm is based on the Hough transform to determine the event direction and on standard methods with pivot points for tracking and fitting. The code can also reconstruct multiple muon events (muon bundles).

After a short description of the OPERA detector and of its main scientific goal, we present the outcomes from the analysis of atmospheric muons, atmospheric neutrino-induced muons and on coincidence studies between the OPERA and LVD detectors.

II. The OPERA detector

The OPERA detector was designed to identify the τ lepton via the topological observation of its decay: this requires a micrometric resolution and a mass of the order of a kton, to maximize the neutrino interaction probability. To accomplish these requirements, the detector concept is based on the Emulsion Cloud Chamber (ECC) technique, combined with real-time detection techniques ("electronic detectors").

The ECC basic unit in OPERA is a "brick" made of 56 lead plates, 1 mm thick, providing the necessary mass to cope with the small neutrino cross section, interleaved with 57 nuclear emulsion films (industrially produced), providing the necessary spatial and angular resolution to identify tau decay topologies. The brick structure allows to measure charged particle momentum via multiple Coulomb scattering, to contain electromagnetic showers and to perform particle identification. In total, 150000 bricks have been assembled reaching the overall mass of 1.25 kton.

The electronic detectors are used to trigger the neutrino interactions, to locate the brick in which the interaction took place, to identify muons and measure their charge and momentum.

The detector is composed of two identical parts, called supermodules (SM), each one consisting of a target section and a magnetic spectrometer. In the target, 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 scintillator strips, one layer providing the vertical and the other one providing the horizontal coordinates. The TTs trigger the data acquisition and locate the brick in which the interaction occurred.

The target section is followed by a magnetic spectrometer: a large dipolar iron magnet instrumented with Resistive Plate Chambers (RPC). The magnetic field intensity is 1.53 T, directed along the vertical axis, transverse to the neutrino beam axis. The RPC planes are inserted between the iron slabs: they provide the tracking inside the magnet and the range measurement for stopping muons. 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 ("singlet" in the following) 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 μm in the bending (horizontal) plane: this allows the determination of the muon charge sign with high accuracy, and the momentum measurement with a resolution better than 20% for momenta <50 GeV/c. In order to remove ambiguities in the reconstruction of particle trajectories, each spectrometer is instrumented with additional RPC planes (XPC), with two crossed strip rotated by $\pm 42.6°$ with respect to the horizontal.

Two RPC planes (VETO) are placed in front of the detector, acting as a veto for charged particles originating from the upstream material (mainly muons originating from interactions in the rock).

After the successful pilot run in 2006 [3], OPERA took data in 2007 with limited statistics (38 events register in the target against 32±6 expected) and in the first CNGS physics run in 2008, when 1.78×10^{19} protons on target were delivered.

III. Atmospheric muon charge ratio

The cosmic ray muon charge ratio is an important observable to understand the physics of cosmic ray interactions in the 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 energies (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 most of the primary cosmic rays are protons, there is a positive charge excess in the hadronic showers and hence in the penetrating component. A compilation of measurements in the energy range from a few hundred MeV to 300 GeV shows a charge ratio $R_\mu = N_{\mu^+}/N_{\mu^-} \approx 1.27$ [4]. At higher energies, several 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^- higher than π^+/π^-, the muon charge ratio is expected to rise [5]. But there are other competing processes involved in the resulting charge ratio value: for instance, it is expected that as the zenith angle increases, and hence longer lived mesons have larger probability to decay in the deeper and less dense atmosphere, the fraction of muons from pion decays increases and so the muon charge ratio decreases. We also expect that muons in high multiplicity events, produced by heavier primaries and coming from small Feynman X_F, exhibit a smaller charge ratio [5].

Thus, the measurement of R_μ at high energies is an invaluable observable to constrain models of forward particle production where no experimental data exist. Air showers experiments are not sensitive to the hadroproduction at high X_F, while the interpretation of underground, underwater and underice data strongly relies on its modeling.

Recent results of the muon charge ratio measured underground with the MINOS far detector can be found in [6]. The detector is located at a depth slightly above the kaon critical energy (850 GeV) and their results suggest a smooth transition toward the energy region where kaon contribution becomes significant.

The results here presented are based on data recorded during the CNGS Physics Run, from June 18 until November 10, 2008. The detector ran in the standard configuration, with the magnetic field directed along the vertical axis in the first arm of both spectrometers, and opposite to the vertical axis in the second arm of both spectrometers. Moreover, a sample of cosmic ray muons was collected with the magnetic field switched off, in order to correct for the alignment between HPT stations and to evaluate systematic uncertainties.

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.

The first step for real data selection is the identification of good quality running periods (i.e. good quality "runs", each one lasting $\sim$12 hours). The selection is based on i) the average number of TT, RPC and HPT digits/event and ii) the absolute rate of events, defined as the number of events/livetime in each run. A run is accepted if all these parameters are within 3σ of the overall distributions. At this level, the total number of selected events is 403271 corresponding to 113.4 days of livetime. Taking into account the livetime normalization, the ratio between OPERA and Monte Carlo data is

$$\frac{\text{Rate}_{REAL}}{\text{Rate}_{MC}} = (95.9 \pm 0.3)\% \qquad (1)$$

The Monte Carlo simulation is based on a parameterized generator, which takes in input the MACRO primary composition model [7]. It is mainly used to obtain a large statistical sample of reconstructed muons in order to unfold and compare data to expectations. However, it is not predictive of the cosmic ray muon charge ratio, differently from the more detailed and physically-inspired Monte Carlo described in [5]. We stress that the residual $\sim 4\%$ mismatch in Eq. 1 is well within the systematic uncertainties related to the primary cosmic ray composition and hadronic interaction models and livetime computation.

For this analysis, the basic information required for the charge-momentum measurement is at least one reconstructed $\Delta\phi$ angle in each event. The first row in Tab. I reports the experimental and simulated event rates after this selection. A second cut removes noisy events in HPT stations, in which some drift tubes are fired due to interactions and showers in the magnet. A detailed study with Monte Carlo simulation provided the dependence of the maximum number of HPT digits allowed only from geometrical considerations. We expect that this number should increase with the ϕ angle reconstructed in each HPT station. The cut requires a number of HPT digits in each station lower than the MC average value plus 3σ. We verified by visual inspection that events rejected by this cut are characterized by a large number of noise digits in the neighbourhood of the correct ones, thus preventing fake track reconstruction. Then we select only $\Delta\phi$ angles reconstructed with a pair of singlets ("doublets"), with at least 6 HPT digits/doublet: this ensures a good angular resolution and discards some noisy events recostructed in singlet mode. Finally, we selected tracks whose deflections are above the experimental resolution: we require $\Delta\phi/\sigma_{\Delta\phi}$ >3.

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 ≥ 2 in both views, with tracks identified and merged in 3D.

Table I lists the number of events remaining at each stage in the selection.

TABLE I: Progressive reduction of the sample after cuts. The total number of real events analysed is 45691.

	REAL (events/day)	MC (events/day)
$\Delta\phi$-angle	992	1219
Good HPT digits	515 → 52%	951 → 78%
Only doublets	180 → 18%	320 → 26%
Deflection cut	161 → 16%	289 → 24%
Single muons	157 → 16%	277 → 23%
Multiple muons	4 → 0.4%	12 → 1%

For this kind of measurement, the main source of systematic error is due to the HPT misalignment. A first alignment campaign was carried out with a theodolite to calculate the position of the HPT walls in the OPERA coordinate system. Recently, profiting from the collected statistics during the 2008 run, we have been able to perform a more refined alignment using cosmic ray muons with magnet on and off. The two HPT stations forming a *doublet* were aligned with the whole data sample; to align the station doublets the one with respect to the other, being separated by the magnet arms, dedicated runs with magnet off were performed. In order to estimate the misalignment magnitude and its propagation into the charge ratio estimate, we computed, for each magnet arm, the deviation from zero of the peak of the $\Delta\phi$ distribution, as a function of the ϕ angle. We observed that this deviation is at maximum ± 0.4 mrad, with a RMS of 0.2 mrad. This value was inserted into the routine which computes the charge and we found that a systematic error of ± 0.2 mrad translates into a ± 0.001 in the charge ratio when the deflection cut is applied. When the muon charge ratio is computed separately in the four independet arms of the spectrometers, their mutal deviations are within the experimental errors, making us confindent that the systematic uncertainties related to HPT misalignment are well below the statistical accuracy of the measurement.

In order to provide a result independent from the detector features, we unfolded the charge ratio measured value using the charge mis-identification probability η, computed with Monte Carlo. We estimated for η a one-sided systematic error of 1%, to be added in quadrature with the misalignement accuracy.

The unfolded single-muon charge ratio is

$$R_{unf} = \frac{\eta - (1-\eta)R_{meas}}{\eta R_{meas} - (1-\eta)} = 1.395 \pm 0.022\,(\text{stat.})^{+0.011}_{-0.001}\,(\text{syst.}) \quad (2)$$

The unfolded charge ratio for multiple-muon events is

$$R_{unf} = 1.23 \pm 0.10\,(\text{stat.})^{+0.011}_{-0.001}\,(\text{syst.}) \quad (3)$$

Within the present statistical accuracy, we did not find any indication of charge ratio dependence on the residual underground momentum, rock depth, zenithal angle and azimuthal angle. On the other hand this result is somehow expected: using Eq. 18 of Ref. [6], we can evaluate the rock/zenith dependence of the charge ratio. Considering the parameters fitted in that work and an energy/depth relation obtained by Monte Carlo, we find that muons detected by OPERA are in the region where the kaon contribution is completely saturated. In fact, the Gran Sasso topological map has the unique rock/cos(θ) dependence for which kaon decay contribution is constant with the energy and no further rise in the charge ratio is expected. In this respect, OPERA data constitute an ultimate limit for this kind of measurement.

With the same data sample, using the bending angle information, the underground muon spectrum was measured. To reconstruct the momentum from the $\Delta\phi$ measurement, the energy loss in the iron magnet is taken into account. The MC distribution of true momentum versus reconstructed momentum shows a linear trend until $\approx$300 GeV/c, where the angular resolution starts to saturate the momentum reconstruction accuracy. The muon spectrum allows to investigate the primary chemical composition: varying the composition model in MC, the comparison with the measurement should indicate the best one. A complete unfolding procedure is on the way in order to perform such a comparison.

IV. Atmospheric neutrinos

The OPERA detector is able to measure particle time-of-flights. Therefore, it can tag and charge-discriminate atmospheric-neutrino induced muons, a powerful handle to assess CPT conservation [8]. OPERA, however, is strongly limited by its acceptance for through-going tracks, about 1/10 of that of MACRO for events crossing the spectrometer. Atmospheric neutrino tagging is performed using the TT timing system, in order to discriminate between up-going and down-going particles: up-going (and outside the CNGS spill window) particles are selected as atmospheric neutrinos.

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

$$\mathrm{speed\,side} = 1/\beta \times (\mathrm{track\ angle\ sign}) \tag{4}$$

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 $\sim 3.3°$). 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 $1/\beta$ between 0.75 and 1.25 and 20 TT planes hit. We observed 5 events recognized as atmoshperic neutrino-induced muons. In the corresponding data taking period, we expect 6.4 events as predicted with a Monte Carlo simulation based on the Honda neutrino spectrum.

V. OPERA-LVD COINCIDENCES

We attempted a first search of coincident events between the OPERA and LVD detectors (see also [9] in these proceedings). The relative position of the two detectors, separated by an average distance of ∼170 m, allows an unprecedented analysis of very large cosmic ray showers looking at their penetrating TeV component. The physics case follows the consideration that TeV muons separated by hundreds of meters are produced in high p_T interactions up in the atmosphere ($p_T >$3 GeV/c) where pQCD can be applied. One can therefore relieve the interpretation of cosmic ray data from the phenomenological models usually adopted to describe the bulk of soft processes occurring in cosmic ray showers [10].

We analysed data of 2008 CNGS run, for a total livetime - in common between the two experiments - of 131.3 days. In a time-window of 15 μs we found 145 events ontime with CNGS (beam events) and 38 events out of the CNGS spill window (cosmic events). The first sample of events have a time difference within the 10.5 μs of the CNGS spill width and is well centered around zero, probing the good inter-calibration accuracy of the detector timing systems. The cosmic ray sample, on the other hand, has a narrow distribution peaked at -573.4 ns with an RMS of 94 ns. The central value of the distribution has a simple interpretation: coincident events are due to single muon events entering horizontally from the OPERA side sticking the LVD detector after 573.4 s of flight (corresponding to 172 m). The OPERA-LVD direction lies along the so-called "Teramo valley", where the mountain profile exhibits a small rock depth even for horizonthal directions. Visual inspection using the event displays of both the experiments confirms this conclusion.

This analysis will be extended with the statistics accumulated in the forthcoming runs in order to improve the limits on high p_T events.

VI. CONCLUSIONS

We presented a list of 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 analysis of neutrino-induced atmospheric muons showed the OPERA capability to tag these kind of events, with the aim of charge discriminate the oscillation signature as soon as new statistics will be accumulated. Finally, coincident events between two LNGS experiments have been unambiguously observed, premise to observe high p_T events originated in cosmic ray showers in the forthcoming runs.

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