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OPERA neutrino oscillation search: Status and perspectives

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Summary. — OPERA is a long-baseline neutrino experiment at the Gran Sasso laboratory (LNGS) designed to search for $\nu_\mu \to \nu_\tau$ oscillations in a direct appearance mode on an event by event basis. OPERA took data in 2008–2012 with the CNGS neutrino beam from CERN. The data analysis is ongoing, with the goal of establishing ν_τ appearance with a high significance. Complementary studies of the $\nu_\mu \to \nu_e$ oscillations and atmospheric muons fluxes were performed as well. Current results of the experiment are presented and perspectives discussed.

PACS 14.60.Pq – Neutrino mass and mixing.

1. – The OPERA detector and the neutrino beam

The OPERA experiment [1] was designed in late 90 s to study the neutrino oscillations in atmospheric sector following the definite results on this effect by SuperKamiokande collaboration [2] which left still open question about the mechanism of those oscillations. To confirm a most popular model of $\nu_\mu \to \nu_\tau$ transition as the mechanism underlying the disappearance of atmospheric muon neutrinos, the OPERA project was aiming at a direct observation of the appearance of τ neutrinos in a ν_μ beam. The OPERA setup [3] has the capability of detecting the ν_τ charged-current (CC) interactions on an event-by-event basis and with an extremely high signal-to-noise ratio.

To accomplish this task, several ingredients were required: a high-energy muon-neutrino beam, a long baseline and a kt-scale detector with sub-micrometric resolution. In 1999–2006, the CERN Neutrinos to Gran Sasso (CNGS) [4] beam has been designed to deliver muon neutrinos with an average energy of 17 GeV to the Gran Sasso underground laboratory (LNGS) of INFN where in 2004–2006 the detector [3] (fig. 1) was installed at a distance of 730 km. A contamination of $\overline{\nu}_\mu$ and $\nu_e + \overline{\nu}_e$ CC interactions at LNGS, relative to the number of ν_μ CC interactions, were respectively 2.1% and 0.9%. The contamination from prompt ν_τ was negligible. The identification of the short-lived τ lepton ($c\tau = 87.11\,\mu$m) via the topological observation of its decay was achieved by means of a hybrid apparatus that combines real-time "electronic detectors" (ED) and the target part made of 150000 blocks (bricks) of lead and nuclear emulsion layers which provide a

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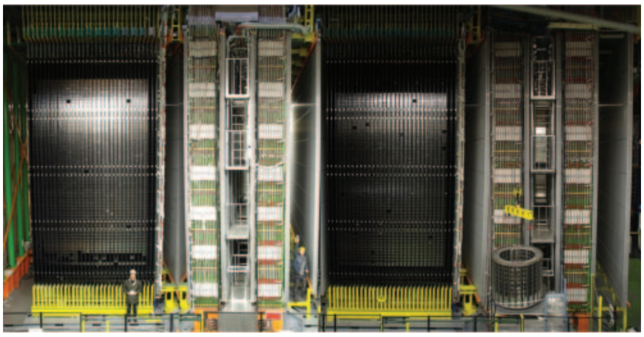

Fig. 1. – Detector OPERA.

sufficient resolution to recognize the ν_τ interaction by topology of the τ-lepton decays. Each brick consists of 56 lead plates of 1 mm thickness (passive material) interleaved with 57 nuclear emulsion films [5] and can be selectively extracted, developed, and analyzed soon after the interaction has occurred. Each film is composed of two 44 μm thick emulsion layers on both sides of a 205 μm thick plastic base. The transverse dimensions of the brick are $12.8 \times 10.2\,\mathrm{cm}^2$ and the thickness along the beam direction is 7.9 cm (about 10 radiation lengths). The detector has two identical Super Modules (SM). Each SM includes $\sim$ 75000 bricks with the overall mass of 0.6 kton arranged in walls interleaved with planes of scintillator strips forming the Target Tracker (TT) [6] and a muon spectrometer composed of the Precise Tracker (PT) (the planes of drift tubes), and a magnet instrumented with the Resistive Plate Chambers (RPC). Muon spectrometers are to recognize muons and to measure their momentum and the charge.

2. – Data analysis chain

When neutrino interacts in the detector, the charged particles, produced in the reaction, leave signals in the ED providing the real-time registration of the neutrino event. The signals, related to the same event, are combined together according to their similar time stamps which are known with a 10 ns resolution. The time-tags of the signals related to the neutrino beam must be in coincidence with CNGS spills (on-time events). Those signals are combined and analyzed offline to determine the target element (brick) where the interaction occurred. Other events are considered to be caused by cosmic rays. For neutrino events, a 3D track reconstruction and a muon identification procedures are performed in order to classify events as being either charge current (CC)-like or neutral current (NC)-like ones. About 60% of events of the on-time sample results from neutrino interactions in the rock in front of the detector typically producing long passing-through muon tracks, while the rest are from interactions occurring in the detector (contained events). ED data of the contained events are then analyzed by a brick-finding (BF) procedure [7] aiming to identify the bricks most probably containing the neutrino interaction vertex. Event topology and energy deposition in the TT scintillator strips, as well as muon track or hadronic shower information are used to define a 3D probability density map for the vertex position. The bricks with highest probability are extracted from the detector by a dedicated robot for analysis at the emulsion level, performed with help of automatic optical scanning microscopes [8] at LNGS and the participating institutions in Europe and Japan. With those microscopes, the 3D information on the tracks in the emulsion is read with a speed of 20–70 cm^2/h. So one can consider the emulsions as raw data storage media, while the automatic microscopes as readers providing data processing and track reconstruction. After this step the event analysis is similar to one of any other experiment. To save the analysis time and to preserve the detector mass, the analysis of the brick is performed only in case when the tracks from ED are confirmed in the 2 separate emulsion layers serving as an interface (Changeable Sheets doublet, CSd). After a brick has been validated, it is brought to the surface to be exposed to high-energy cosmic-rays for further precise (with an accuracy of a few μm) film-to-film alignment. The brick emulsion films are then developed and dispatched to one of the various scanning laboratories of the Collaboration. All tracks measured in the CSd are sought in the most downstream films of the brick and followed back until they are not found in three consecutive films. The stopping point is considered as the signature either for a primary or a secondary vertex. The vertex is then confirmed by scanning a volume with a transverse size of 1 cm^2 in 15 films in total, 5 upstream and 10 downstream of the stopping point. All track segments collected in the scanned volume are analyzed by off-line algorithms which perform precise alignment, tracking and vertexing. A further phase of analysis is applied to located vertices, called decay search procedure, to detect possible decay or interaction topologies on tracks attached to the primary vertex. It is also searched for additional tracks from neutral decays, interactions and γ-ray conversions. When secondary vertices are found in the event, a kinematical analysis is performed. This analysis uses the values of the angles measured in the emulsion films, of the momenta determined by multiple Coulomb scattering measured in the brick, of the momenta measured by the magnetic spectrometers, and of the total energy deposited in the instrumented target acting as a calorimeter. The detection of decay topologies is triggered either by the observation of a daughter track with a large impact parameter with respect to the primary vertex, or by the presence of a significant kink/trident topology.

3. – Main sources of background

The background evaluation is performed by means of a full simulation which includes the beam properties, the physics processes and the detector structure. Three main sources of backgrounds are: charmed particle decays, hadronic re-interactions and large-angle muon scattering (LAS). Given the similar masses and lifetimes of charmed particles and the τ lepton, charm production and decay event topologies have a great importance in OPERA. On one hand they constitute the most significant background source for all τ-decay modes, in particular, if a muon at the primary vertex is not identified. On the other hand the charm control sample is used to verify the understanding of the τ detection efficiency up to the decay search level. A main tool for the charm event recognition is a detection of a muon in the primary vertex. The background from the re-interactions of the hadrons originated from the primary vertex, was estimated by a FLUKA-based MC simulation [9]. Several data-driven checks of the FLUKA description of hadronic interactions in the OPERA bricks were performed demonstrating a good agreement between data and simulation for different data-sets [10]. The occurrence of LAS of muons in thin lead plates is, at present, conservatively estimated by a value for the rate of $\sim 10^{-5}$ per 2 mm of lead for angles larger than 20 mrad, obtained as an upper limit from extrapolation of measurements on copper or nuclear emulsions, is used for the present analysis. More experimental activities to measure this number are in progress as well as justification of the simulation.

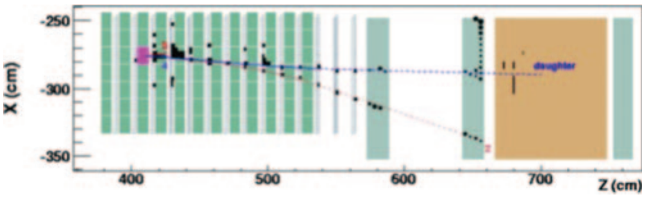

Fig. 2. – Electronic detectors view of the 4th candidate event.

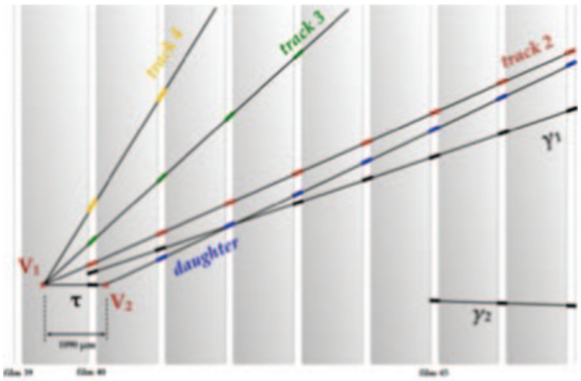

Fig. 3. – The vertex view of the 4th candidate event in the emulsion.

4. – Current results: expectation and statistical significance

A total sample of 16879 events corresponding to 17.97×10^{19} protons on target has been registered by the detector since the beginning of the program. The current sample of 6148 fully analyzed events is expected to contain ν_τ signal (background) in all decay channels of 2.1 (0.23 ± 0.04) events, taking into account $\Delta m^2_{23} = 2.32 \times 10^3\,\mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 1$. The systematic uncertainties are estimated to be 20% on the signal, 20% on the charm background, 30% on the hadronic background, and 50% on the large-angle muon scattering background, *i.e.* muon scatterings mimicking $\tau \to \mu$ decays. So far, four ν_τ candidate events have been observed: the first in the 2009 run data ($\tau \to h$ decay channel) [11], the second in the 2011 run data ($\tau \to 3h$ decay channel) [12], the third in the 2012 run data ($\tau \to \mu$ decay channel) [13] and the fourth in $\tau \to h$ decay channel again found in the sample of 2012 [14]. The last registered candidate event can be seen in fig. 2, where the event display of the ED and in fig. 3 where the view of the event at microscopic level are presented. The significance of the observation of the four ν_τ candidate events is estimated by considering the confidence for excluding the null hypothesis. A hypothesis test employing a likelihood-based approach [15] was performed. The likelihood function is $L(\mu) = \prod_{i=1}^{4} \exp^{-(\mu s_i + b_i)}(\mu s_i + b_i)^{n_i}/n_i!$. The index i runs over decay channels, the parameter μ determines the strength of the signal process ($\mu = 0$ corresponds to the background-only hypothesis), s_i and b_i are the numbers of expected signal and background events, n_i is the number of observed events. The systematic uncertainties of the backgrounds were taken into account in a similar way as above. A p-value of 1.03×10^5 corresponding to a significance of 4.2 σ for the exclusion of the null hypothesis is obtained.

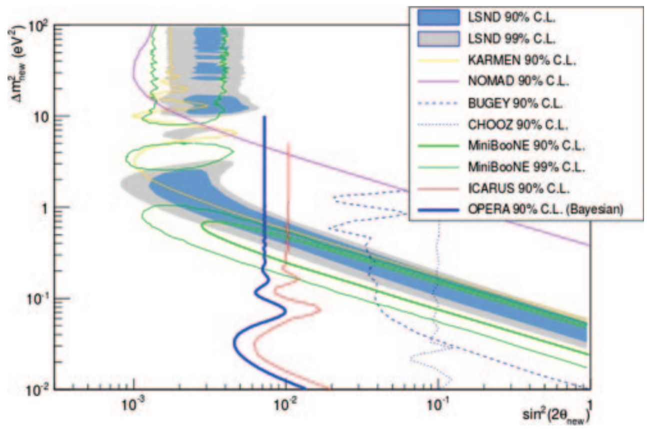

Fig. 4. – The exclusion plot for the parameters of the non-standard $\nu_\mu \to \nu_e$ oscillations obtained from the present analysis.

5. – The study of $\nu_\mu \to \nu_e$ oscillations

Profiting of the excellent tracking capabilities of the OPERA emulsions, it is possible to detect ν_e and, therefore, to study the $\nu_\mu \to \nu_e$ oscillations in the CNGS beam. Since the beam originally contains a small fraction of the ν_e and anti-ν_e, the deviation from the expected number of electron neutrinos in dependence of their energy will indicate the oscillation process. To recognize the electrons produced in the primary vertex as a signature of the nu e CC interaction, the dedicated procedure was elaborated [16]. Out of fully analyzed data sample collected in 2008–2009 (5255 registered triggers), 2853 events have a located and reconstructed vertex in bricks. Out of these sample, 505 events were not classified as ν_{mu} CC events. Amoung them, 19 ν_e candidates were recognized. The energy of the primary electron neutrino for those events was reconstructed making use of a total energy deposited in the TT with an accuracy which can be expressed as $\Delta E/E = 0.37+0.74/\sqrt(E)$, (E in GeV). The background one deal with when looking for the appearance of oscillated ν_e events, is composed of the primary beam contamination (mentioned above), misidentification of γ s from π^0 produced in the primary vertex of the ν_μ with muon not identified, and events of the ν_τ CC interactions with τ decay to electron. The estimated total number of the background events for the sample of the 2008–09 is 19.8 ± 2.8(syst.) which is consistent with the 19 events observed. The details of the background calculation are available in [16]. The lack of the oscillated ν_e observed at the restricted sample of 2008–09 allows us to put limits on the parameters of the $\nu_\mu \to \nu_e$ oscillations, the standard three-flavor mixing as well as non-standard exotic mixing indicated by LSND and MiniBoonE experiments [17, 18]. If the results for standard mixing are not compatible with the recent achievements of the reactor experiments as well as T2K and MINOS, the restrictions one can put on the exotic scenario are quite interesting. In fig. 4 we present the exclusion plot for exotic oscillation extracted from our sample. Given the under fluctuation of the data, the Bayesian approach was chosen for the bound estimation. The results of the other experiments though working in the different L/E region, are shown as well. One can see the OPERA results put a serious constraint on parameter space still available for the non-standard ν_e appearance oscillations. The further details of the analysis are available in [16].

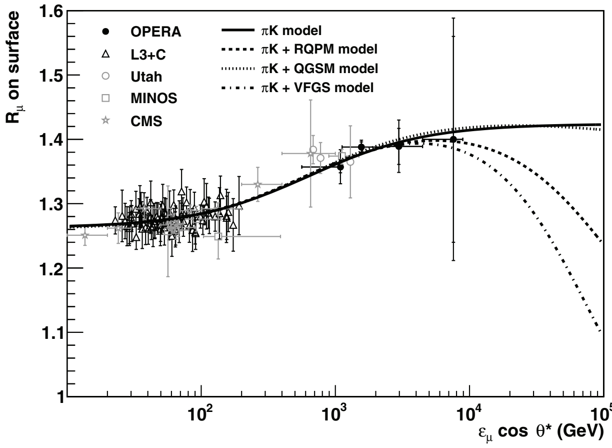

Fig. 5. – The muon charge ratio measured by OPERA as a function of the vertical surface energy $E_\mu \cos\theta^*$ (black points). Our data are fitted together with the L3 + C [19] data (open triangles). The fit result is shown by the continuous line. The dashed, dotted and dash-dotted lines are, respectively, the fit results with the inclusion of the RQPM [20], QGSM [20] and VFGS [21] models for prompt muon production in the atmosphere. The vertical inner bars denote the statistical uncertainty, the full bars show the total uncertainty. Results from other experiments, MINOS Near and Far Detectors [22, 23], CMS [24] and Utah [25], are shown for comparison.

6. – Study of the atmospheric muons charge ration the TeV region

As was described, the OPERA detector is equipped with the magnetic spectrometers to identify the muons produced in the neutrino interactions, and to measure their momenta and the charge. The detector was registering large amount of the cosmic muons as well. The muon charge ratio $R_\mu \equiv N_{\mu^+}/N_\mu$, defined as the number of positive over negative charged muons, is studied by experiments since many decades. It provides an understanding of the mechanism of multiparticle production in the atmosphere in kinematic regions not accessible to accelerators, as well as information on the primary cosmic ray composition. A charge ratio larger than unity reflects the abundance of protons over heavier nuclei in the primary cosmic radiation. The charge asymmetry is preserved in the secondary hadron production, and consequently in the muon fluxes, due to the steepness of the primary spectrum which enhances the forward fragmentation region [26]. The kaon contribution to the muon flux increases with the muon energy. Since the production of positive kaons is favored by the associated production K^+, the muon charge ratio is expected to rise with energy. Assuming the hypothesis of complete scaling, an energy independent charge ratio is expected above the TeV energy region at sea level [26]. Once the kaon contribution to the muon flux reached its asymptotic value [27] at higher energies, around $O(100)$ TeV, the heavy flavor contribution, as well as changes in the primary composition, may become significant.

Given the large overburden of the LNGS (~ 3000 m.w.e.), the average energy of muons registered by OPERA is ~ 280 GeV. During the data taking period between 2008 and 2012 more than 3 million atmospheric muon events were detected and reconstructed, among which about 110000 multiple muon bundles. The charge ratio R_μ was measured separately for single and for multiple muon events. The analysis exploited the inversion of the magnet polarity which was performed on purpose during the 2012 Run. The combination of the two data sets with opposite magnet polarities allowed minimizing systematic uncertainties and reaching an accurate termination of the muon charge ratio. Data were fitted to obtain relevant parameters on the composition of primary cosmic rays and the associated kaon production in the forward fragmentation region. In the surface energy range 120 TeV investigated by OPERA, R_μ is well described by a parametric model including only pion and kaon contributions to the muon flux, showing no significant contribution of the prompt component. The energy independence supports the validity of Feynman scaling in the fragmentation region up to 200 TeV/nucleon primary energy. The charge ratio of single muons impinging on the apparatus was computed combining the two polarity data. After the correction for charge misidentification and detector misalignment, the final measurement with the complete 5-year statistics yields the result: $R_\mu(n_\mu = 1) = 1.377 \pm 0.006(\text{stat.})^{+0.007}_{-0.001}(\text{syst.})$ The charge ratio of multiple muon events was computed using all the muon charges reconstructed in events with $n_\mu > 1$. The result after polarity combination and correction for misidentification is significantly lower than the single muon value: $R_\mu(n_\mu > 1) = 1.098 \pm 0.023(\text{stat.})^{+0.015}_{-0.013}(\text{syst.})$ The smaller value of the charge ratio for multiple muon events originates from two effects. First, as pointed out in [28], multiple muon sample naturally selects heavier primaries, thus a neutron enriched primary beam ($\langle A \rangle \simeq 3.4$ for single muons, $\langle A \rangle \simeq 8.5$ for bundles). Second, the selection of muon bundles biases the Feynman-x distribution towards the central region ($x_F \simeq E_{secondary}/E_{primary} \to 0$), in which the sea quark contribution to secondary particle production becomes relevant processes cause a decrease in the charge ratio. The single muon charge ratio was projected at the Earth surface using a Monte Carlo based unfolding technique for the muon energy E_μ [29]. This approach does not yet consider any energy dependence of the proton excess in the primary composition. In this case the muon flux and charge ratio depend on the vertical surface energy $E_\mu \cos\theta^*$, where θ^* is the zenith angle at the muon production point [30]. The results are shown in fig. 5, together with data from other experiments. The observed behavior of R_μ as a function of the surface energy from 1 TeV up to 20 TeV (about 200 TeV/nucleon for the primary particle) shows no deviations from a simple parametric model taking into account only pions and kaons as muon parents, supporting the hypothesis of limiting fragmentation up to primary energies/nucleon around 200 TeV.

7. – Conclusions

The OPERA experiment moves to the completion of the data analysis. So far $4\nu_\tau$ appearance candidates were detected which provides the significance of the 4.2 σ given the estimated background of 0.23 events. The Collaboration is continuing the data analysis as well as further exploring the background sources aiming to reach the 5 σ significance level. In parallel with the main analysis, interesting results on the complementary process on $\nu_\mu \to \nu_e$ were also presented as well as the measurement of the atmospheric muons charge ratio in the highest energy region was performed. More results are expected soon.

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