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The OPERA experiment

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Abstract

The OPERA experiment was designed to study $\nu_\mu \to \nu_\tau$ oscillations in appearance mode using the CERN to Gran Sasso high energy neutrino beam. From 2008 to 2012, 19505 CNGS neutrino interactions were recorded in the OPERA detector. At the present status of the analysis, 4 ν_τ candidate events have been observed, establishing the oscillation mechanism in the atmospheric sector with a significance of 4.2 σ. The oscillation analysis will be presented in detail and the candidate events will be described. The final measurement of the atmospheric muon charge ratio in the TeV region will be also reported.

1. Introduction

Over the past decades, strong evidence in favor of the hypothesis of neutrino oscillations has been provided by several experiments. In particular, the mixing of neutrino flavor states in the atmospheric sector has been mainly investigated in disappearance mode [1, 2, 3, 4]. The *Oscillation Project with Emulsion-tRacking Apparatus* (OPERA) [5] is a long baseline neutrino experiment designed to provide the first measurement of $\nu_\mu \to \nu_\tau$ oscillations at the atmospheric scale in direct appearance mode, i.e. through the detection of the τ leptons produced in charged current (CC) interactions of oscillated ν_τ's. The detector is located in the underground Gran Sasso Laboratory (LNGS, Italy) and was exposed to the CERN Neutrinos to Gran Sasso (CNGS) [6] ν_μ beam from 2008 to 2012 collecting an integrated intensity of 17.97×10^{19} protons on target. Given the mean beam energy of 17 GeV and the baseline of 730 km, the average L / E ratio of 43 km / GeV is adequate for neutrino oscillation studies at the atmospheric scale.

2. The OPERA experiment

2.1. Detector

The OPERA detector [7] consists of two identical super-modules as shown in Fig. 1. Each super-module has a target section followed by a muon spectrometer. Each target section is arranged in 31 vertical walls, filled with lead/emulsion bricks and followed by pairs of tracker planes made of plastic scintillator strips (Target Tracker, TT). The overall target mass is about 1.2 kt. The brick is the basic target unit and consists of 57 nuclear emulsion films, interleaved with 1 mm thick lead plates, with a total volume of $(7.9 \times 10.2 \times 12.8)\,\mathrm{cm}^3$ and a mass of 8.3 kg. OPERA emulsion films are made of two 45 μm-thick sensitive layers deposited on each side of a 205 μm plastic base. On the downstream face of the brick, a pair of additional emulsion films in a separate envelope (Changeable Sheets, CS [8]) acts as an interface between the brick and the TT. The TT identifies the brick where the neutrino interaction occurred. The brick is promptly removed from the target and the emulsion films are developed and analysed by means of automated high-speed scanning systems [9, 10]. Each spectrometer consists of a dipolar magnet instrumented with planes of Resistive Plate Chambers (RPC) and drift tube detectors in order to identify muons and measure their momentum and charge. The charge sign misidentification probability is about 0.3% up to 50 GeV/c; the momentum resolution is about 20% in the same kinematical range. A veto system, consisting of planes of glass RPCs, is placed in front of the first super-module in order to tag the interactions occurring in the upstream rock.

2.2. ν_τ detection signature

The challenge of OPERA is the separation, on an event-by-event basis, of CC interactions induced by oscillated ν_τ's from dominant ν_μ interactions.

The experimental signature consists in the detection of the τ lepton decaying in one prong (muon, single hadron or electron) or in three hadrons over typical distances of a few hundred microns.

The use of nuclear emulsion films, acting as submicrometric tracking devices, allows resolving the neutrino interaction and the τ lepton decay vertices with adequate background rejection power. Moreover, the combined use of nuclear emulsions and high-density material plates makes it possible to measure particle momenta by multiple Coulomb scattering (MCS) [11] and reconstruct electromagnetic showers initiated by γ's and π^0's.

3. Physics results

Table 1 shows the details of the five CNGS runs. The total number of neutrino interactions recorded in the OPERA detector is 19505. For runs 2008 and 2009, all predicted events have been searched for in the two bricks with the highest probability of containing the neutrino interaction. Only the most probable brick has been analysed so far for runs 2010 – 2012. In the

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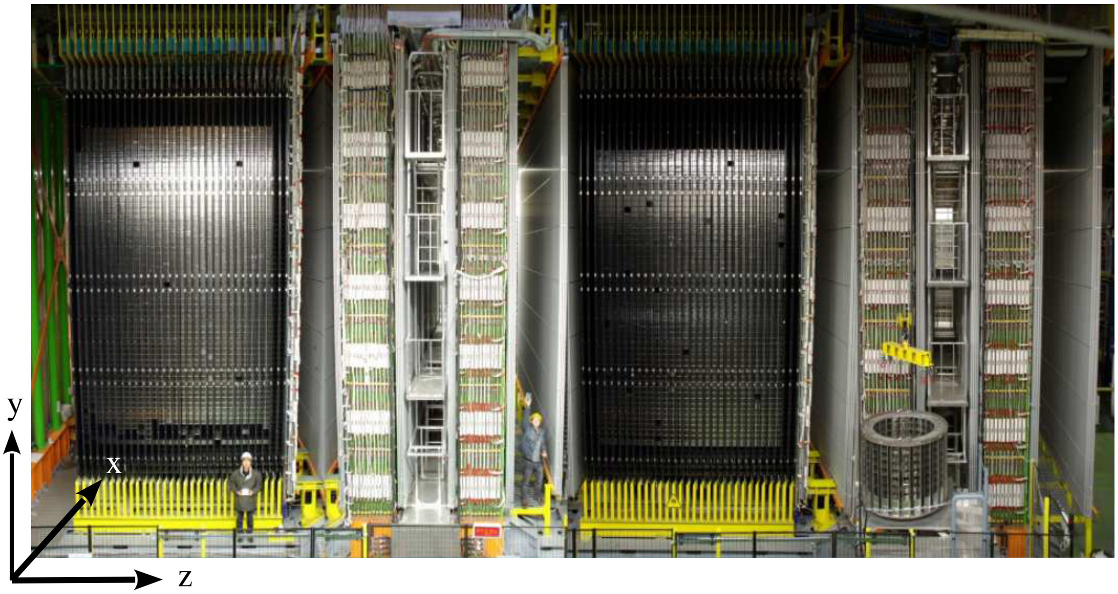

Figure 1: The OPERA detector in the hall C of Gran Sasso Laboratory.

Table 1: Details of the CNGS runs: beam intensity, efficiency and run duration are reported, as well as the number of recorded neutrino interactions in OPERA.

Run	2008	2009	2010	2011	2012	Total
p.o.t ($\times 10^{19}$)	1.7	3.53	4.09	4.75	3.86	17.97
SPS efficiency	61%	73%	80%	79%	82%	77%
Beam days	123	155	187	243	257	965
ν interactions	1931	4005	4515	5131	3923	19505

Table 2: Numbers of events used for the present $\nu_\mu \to \nu_\tau$ oscillation analysis.

Run	2008	2009	2010	2011	2012	Total
0μ events	148	250	209	223	149	979
1μ events ($p_\mu \leq 15\,\mathrm{GeV/c}$)	534	1019	814	749	590	3706
Total number of events	682	1269	1023	972	739	4685

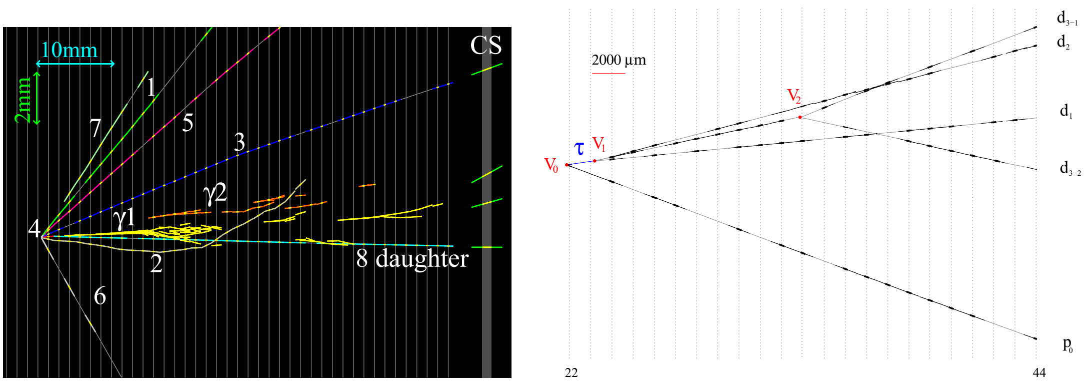

Figure 2: Sketch of the first (left) and second (right) ν_τ candidate events detected by OPERA.

present analysis, the whole sample of events without a reconstructed muon in the electronic detectors ($0\,\mu$) have been considered. A cut on the muon momentum ($p_\mu < 15\,\mathrm{GeV/c}$) has been applied for $1\,\mu$ events to improve the signal to noise ratio. Details on the dataset are summarised in Table 2. The total number of fully analysed neutrino interactions is 4685.

3.1. Oscillation analysis

In the data sample shown in Table 2, four ν_τ candidate events have been observed [12, 13, 14, 15].

The first OPERA ν_τ candidate is shown in Fig. 2 left. The primary neutrino interaction consists of seven tracks. One of them exhibits a visible kink of 41±2 mrad, after a path length of 1335±35 μm. Two electromagnetic showers, initiated by γ-rays and associated with the decay vertex, have been reconstructed. Their invariant mass is (120 ± 20 (stat.) ± 35(syst.)) MeV/c^2, supporting the hypothesis that they originate from a π^0 decay. The observed decay topology and kinematics are compatible with the tau lepton decay mode $\tau \to h(n\pi^0)\nu_\tau$.

Figure 2 right shows a display of the second ν_τ candidate event. The primary vertex consists of two tracks forming an angle of (167.8 ± 1.1)° in the beam transverse plane. In addition, a forward-going nuclear fragment has been detected. One of the two primary particles (the τ lepton candidate) decays after 1466 ± 10 μm in three charged hadrons. One of the daughter tracks interacts in the same brick containing the neutrino vertex, about 1.3 cm downstream (V2 in Fig. 2). The final state is composed of two charged tracks and four backscattered nuclear fragments.

The third ν_τ candidate is depicted in Fig. 3 left. The neutrino vertex is formed by two tracks: the τ lepton and a hadron. An electromagnetic shower produced by a γ-ray and pointing to the primary vertex has also been observed. The τ lepton decays into a single prong at a distance of (376 ± 10) μm from the neutrino interaction point. The daughter particle appears as an isolated, penetrating track traversing 24 planes of the TT and six RPC planes before stopping in the spectrometer. The track is reconstructed as a muon by the electronic detectors with a momentum 2.8 ± 0.2 GeV/c, compatible with the measurement obtained by MCS in emulsion of $3.1^{+0.9}_{-0.5}$ GeV/c. The sign of its charge has been measured to be negative by the bending of the track in the magnetized iron, thus rejecting the hypothesis of a neutrino-induced charmed particle production with subsequent muonic decay.

Figure 3 right shows a display of the fourth candidate event as reconstructed in the brick, in the view transverse to the neutrino direction. The primary vertex consists of four tracks. One of them (track 1) exhibits a kink topology after 1090 μm. The measured kink angle is 137 mrad. The decay daughter track was analysed in all traversed downstream bricks and was found to stop in the spectrometer after leaving a signal in three RPC planes. The track was identified as a hadron. Two electromagnetic showers initiated by the conversion of γ's and pointing to the neutrino vertex were also reconstructed.

The procedure developed to detect τ lepton decays in OPERA is described in detail in [16] and has been validated by studying its application to the search for charmed particle production in a subsample of data collected in runs 2008-2010. In this sample, 50 ν_μ CC interactions with a charmed hadron in the final state were observed, while 54 ± 4 were expected.

Table 3 reports the estimated numbers of signal and background events for the data sample shown in Table 2, assuming $\Delta m^2_{23} = 2.32\,\mathrm{eV}^2$ and maximal mix-

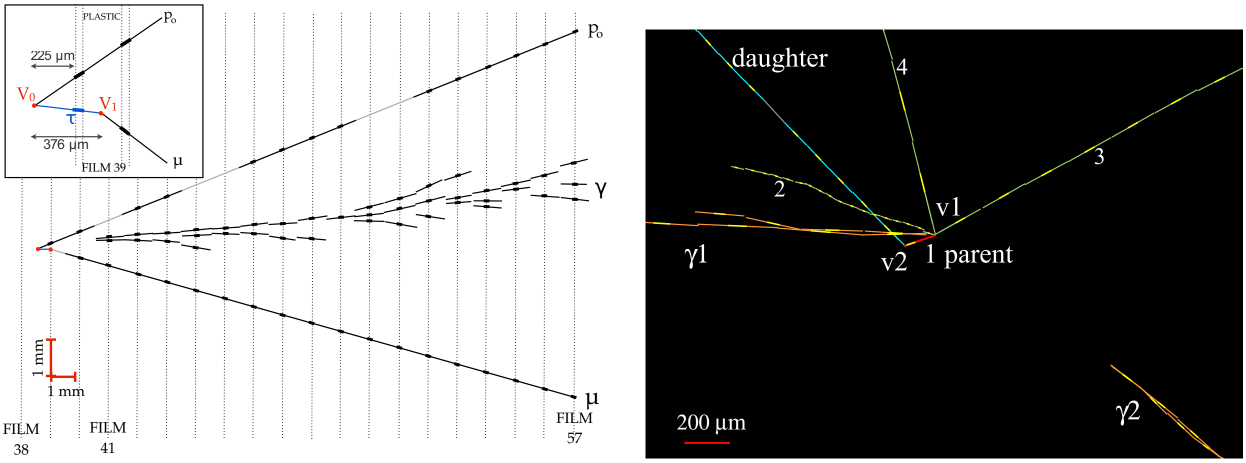

Figure 3: Sketch of the third (left) and fourth (right) ν_τ candidate events detected by OPERA.

ing. In total, four candidate events are detected while 2.11 ± 0.42 events are expected with an estimated background of 0.233 ± 0.041 events. The observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode is thus estabilished at $4.2\,\sigma$ level. The number of observed ν_τ events is also used to compute the 90 % confidence interval for Δm^2_{23}. The estimated interval with the Feldman - Cousins method [17] is $[1.8, 5.0] \times 10^{-3}\,\mathrm{eV}^2$.

In OPERA, the use of nuclear emulsion films as tracking devices allows the identification of electrons produced in ν_e CC interactions. Therefore, OPERA is suited to the investigation of ν_e appearance from $\nu_\mu \rightarrow \nu_e$ oscillations. A systematic search for ν_e interactions was applied to the full data sample collected in 2008 and 2009, consisting of 505 0 μ neutrino events. The number of reconstructed ν_e candidate events is 19, in agreement with the expectation of 19.8±2.8 (syst). To increase the signal to background ratio, a cut on the neutrino energy can be applied. If only events with an energy value lower than 20 GeV are selected, 4 events are detected while 4.6 are expected. The number of observed events is compatible with the non-oscillation hypothesis and yields an upper limit of $\sin^2 2\theta_{13} < 0.44$ (90% C.L.) [18]. The analysis is being extended to all runs and 40 ν_e candidate events have been observed so far.

OPERA has also set an upper limit for non-standard ν_e appearance in the parameter space suggested by the LSND [19] and MiniBooNE [20] experiments. In the approximation of one mass scale dominance, 9.4±1.3 (syst) events with a neutrino energy lower than 30 GeV are expected at large mass squared difference, while 6 events are found in the data. The corresponding exclusion plot in the oscillation parameters θ_{new} and Δm^2_{new} is shown in Fig.4. For large Δm^2_{new} values, the 90% C.L. upper limit on $\sin^2 2\theta_{new}$ reaches 7.2×10^{-3}. For comparison, results from other experiments with different L/E ranges are also reported in this figure.

3.2. Atmospheric muons

The underground Gran Sasso laboratory is a privileged location to study TeV-scale cosmic rays. Between 2008 and 2012, OPERA collected more than 3 million atmospheric muon events, out of them about 110000 multiple muon bundles were detected. Profiting of the inversion of the magnet polarity that was performed on purpose during 2012 run, the atmospheric muon charge ratio $R_\mu = N_{\mu+}/N_{\mu-}$ in the TeV region was measured both for single and for multiple muon events. The combination of the two data sets collected with opposite magnet polarities allowed minimizing the systematic uncertainties, thus reaching the most accurate measurement in the high energy region to date [21]:

$$R_\mu\,(n_\mu = 1) = 1.377 \pm 0.006(\mathrm{stat.})^{+0.007}_{-0.001}(\mathrm{syst.})$$

$$R_\mu\,(n_\mu > 1) = 1.098 \pm 0.023(\mathrm{stat.})^{+0.015}_{-0.013}(\mathrm{syst.})$$

As shown in Fig. 5, in the surface energy range between 1 and 20 TeV investigated by OPERA, R_μ is well described by a simple parametric model including only pion and kaon contributions to the muon flux, showing no significant contribution of the prompt component. The observed behaviour supports the validity of Feynman scaling in the fragmentation region up to 200 TeV/nucleon primary energy.

Table 3: Estimated signal and background events for the analysed sample. Numbers are reported separately for each of the four τ decay channels. Observed events in each channel are also reported.

Decay channel	Expected signal ($\Delta m^2_{23} = 2.32\,\mathrm{eV}^2$)	Total background	Observed events
$\tau \to h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \to \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \to e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

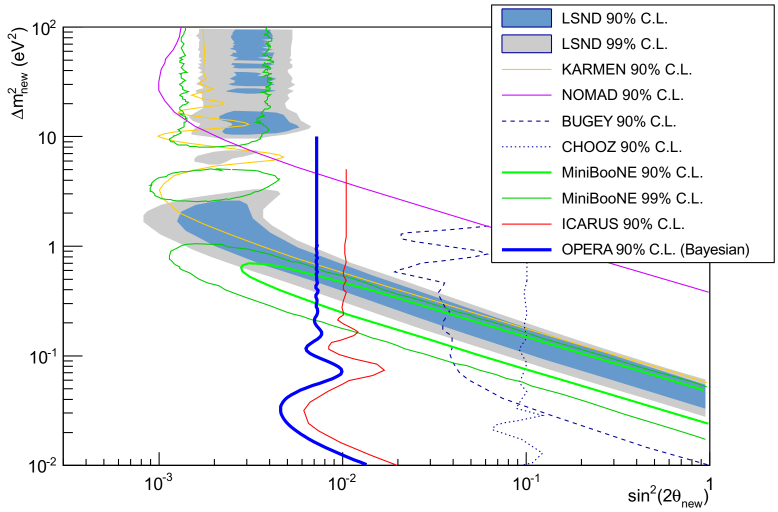

Figure 4: Exclusion plot in the parameter space ($\sin^2 2\theta_{new}$, Δm^2_{new}) for the non-standard $\nu_\mu \to \nu_e$ oscillation analysis.

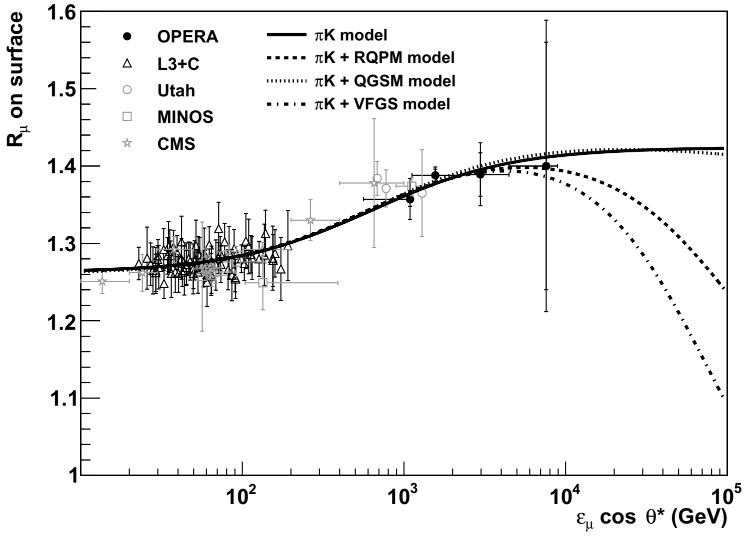

Figure 5: Muon charge ratio measured by OPERA as a function of the vertical surface energy. The fit result is shown as a continuous line.

4. Conclusions

The OPERA experiment has collected data in the CNGS neutrino beam from 2008 to 2012, integrating about 18×10^{19} protons on target. Four ν_τ candidate events have been detected so far, leading to the observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric scale in appearance mode. The non-oscillation hypothesis is excluded at 4.2 σ level.

From the systematic search for sub-leading $\nu_\mu \rightarrow \nu_e$ oscillations in the 2008-2009 data sample, 19 electron neutrino candidates were detected while 19.8 ± 2.8 (syst) were expected.

The analysis of the full data sample of atmospheric muon events provided the most accurate measurement of the muon charge ratio R_μ in the high energy region, confirming the validity of a simple parametric model which includes only pion and kaon contributions to the muon flux.

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