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The OPERA Experiment and Recent Results

Serhan TUFANLI, on behalf of the OPERA Collaboration[1,a]

[1] *Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Siddlerstrasse 5 CH-3012 Bern*

Abstract. OPERA (Oscillation Project with Emulsion tRacking Apparatus) is a long-baseline neutrino experiment, designed to perform the first direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode. The OPERA detector is placed in the CNGS long baseline ν_μ beam, 732 km away from the neutrino source. The detector, consisting of a modular target made of lead - nuclear emulsion units complemented by electronic trackers and muon spectrometers, has been conceived to select ν_τ charged current interactions through the observation of the outcoming tau leptons and their subsequent decays. Runs with CNGS neutrinos were carried out from 2008 to 2012. In this paper results on $\nu_\mu \rightarrow \nu_\tau$ oscillations with background estimation and statistical significance are reported.

1 Introduction

In last decades data from solar, atmospheric, reactor and accelerator neutrino experiments have established a framework of 3-flavor neutrino oscillations through the mixing of three mass eigenstates.

In the atmospheric sector, the disappearance of muon neutrinos was first established by the Super-Kamiokande experiment [1] and then confirmed with accelerators by K2K [2] and MINOS [3] long-baseline experiments. Although the $\nu_\mu \rightarrow \nu_\tau$ oscillation channel seems to be the dominant one, no explicit observation of tau neutrino appearance has been confirmed so far.

The OPERA experiment [4], located at the Gran Sasso underground laboratory, aims to perform the $\nu_\mu \rightarrow \nu_\tau$ appearance observation in order to confirm unambiguously the neutrino oscillation model. The detection is accomplished by detecting ν_τCC interactions, observing τ-lepton decay products. Although the neutrino beam is not optimized for it, OPERA is also aiming to perform a search for subleading $\nu_\mu \rightarrow \nu_e$ oscillations at atmospheric and high Δm^2.

2 The Neutrino Beam and the OPERA Detector

The OPERA experiment used the CERN neutrinos to Gran Sasso (CNGS) ν_μ beam [5]. The 400 GeV CERN-SPS proton beam hits a graphite target to create pions and kaons. The π^+s and K^+s are focused into the 1000 m decay pipe and decay in μ^+ and ν_μ. The μ^+s are absorbed by the earth rock while neutrinos continue to travel towards Gran Sasso. As a result of this process, a ν_μ beam with ~17 GeV mean energy, 2.1% $\bar{\nu}_\mu$ contamination, ~ 1% ν_e and $\bar{\nu}_e$ contaminations is produced. During the 2008

[a] e-mail: serhan.tufanli@lhep.unibe.ch

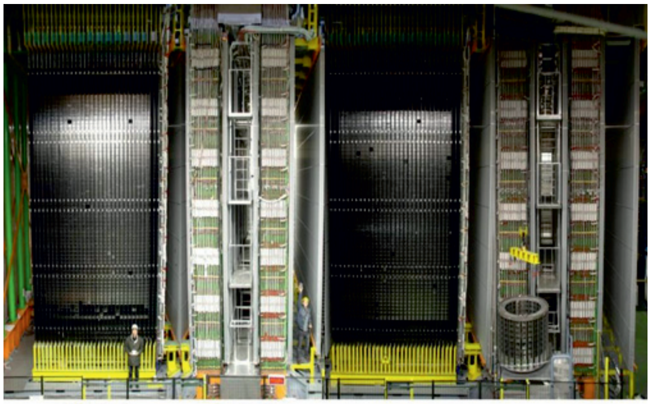

Figure 1. The OPERA detector with two super modules. Each super module has a target area and a spectrometer at the end of the target area. The CNGS neutrinos travel from left to right.

to 2012 runs OPERA collected 18×10^{19} p.o.t.(protons on target) which correspond to 80% of the forseen design value.

The challenge of the experiment is the detection of the short lived τ lepton ($c\tau$ =87 μm, decay length $\sim$1 mm at the average CNGS beam energy) produced in the ν_τCC interaction. In order to fulfill this goal, the OPERA Collaboration designed a detector of large target mass to collect enough statistics, very high spatial resolution to observe the τ lepton and high rejection power to minimize background contamination. The target unit is the so-called Emulsion Cloud Chamber(ECC) brick. A brick is a sandwich of 57 nuclear emulsion films and 56 lead plates, 1mm thick. Emulsion films provide micrometric spatial resolution while lead acts as target material.

The OPERA detector has an hybrid set up made of two identical Super Modules (SM1 and SM2). Each SM has a target section composed of $\sim$75k ECC bricks followed by a spectrometer which is used to reconstruct and identify muons from ν_μCC interactions and measure their momentum and charge. Each target section is organized in 31 vertical walls transverse to the beam direction. Walls are filled with ECC bricks and followed by Target Tracker(TT) double layered scintillator planes. The TT is used for locating the neutrino interaction brick in the target. In figure 1, a picture of the detector is shown. More details about the apparatus and experimental techniques are discussed in [4].

3 Event Analysis in the OPERA

Charged particle tracks produced in a neutrino interaction generate signals in the TT and in the spectrometer. These signals are used to classify the events (either as Charged Current-like or 0-muon) and locate the neutrino interaction brick. The most probable brick that may contain the neutrino interaction vertex is selected by an automatic algorithm and is extracted from the detector by the automatic Brick Manipulator System.

Validation of the extracted brick is done using the Changeable Sheets (CS) [6], namely two emulsion films attached downstream of the brick. CS doublet films are scanned by high speed automatic microscopes [7] [8]. If tracks compatible with the electronic detector prediction are found on the CS, the brick is exposed to the cosmic rays, disassembled, then its films are developed and sent to one of the scannning laboratories for the analysis. If the CS analysis result is negative, the brick is re-inserted in the apparatus with a new CS doublet.

All tracks found on the CS are followed back(scan-back) film by film inside the brick until no track is found anymore in three consecutive films. The lead plate upstream of the last detected track segment is defined as the stopping plate. In order to confirm the interaction vertex, a general scanning is performed in a volume with a transverse area of 1×1 cm^2 in 5 films upstream and 10 films downstream of the stopping point.

A further analysis, called decay search, is applied to detect possible τ decays or interaction topologies for the tracks attached to the primary vertex. In so-called short decays, the τ lepton decays in the same lead plate where the neutrino interaction occurs and its main signature is a track with large impact parameter relative to the neutrino interaction vertex. For long τ decays, for which the neutrino interaction vertex plate is not the same as the τ decay vertex plate, a candidate is selected on the basis of the existence of a clear ı*kink*ȷ or secondary vertex from the decay in flight of a particle emerging from the primary vertex.

The identification of electrons is based on the detection of the associated electromagnetic shower. Once the electromagnetic shower is reconstructed, the track initiating the shower is investigated. If a single track in the vertex emulsion film is found, the event is classified as a ν_e candidate event.

The so-called scan forth (SF) is the last step of the OPERA analysis chain. Event tracks are followed from the vertex to the CS films. In each emulsion plate, the track position and slope are measured automatically. If a track is not found automatically, manual measurements of position and slope are performed. The particle *reconstructed momentum* is obtained using angular deviations due to Multiple Coulomb Scattering (MCS) in lead [9]. By this method a momentum resolution better than 33% is obtained for particles crossing the brick with momentum lower than 12 GeV/c.

When a kink topology or a secondary vertex is found, a kinematical analysis based on track angles and reconstructed momentum is performed. At the neutrino interaction vertex kinematical parameters are the missing transverse momentum, $P_t - missing$, and the angle ϕ between the parent and the vectorial sum of hadronic primaries in the plane perpendicular to the CNGS axis. At the secondary vertex, the kinematical parameters are the daughter momentum, P_{dau}, the kink angle θ_{kink} between the parent and daughter track, the decay point position D_z along the longitudinal axis, the transverse momentum at the decay vertex, P_t^{2ry}, the invariant mass m and the minimum invariant mass m_{min}. These parameters are used in the selection of ν_τ candidates described in Section 4.

4 Neutrino Oscillation Results

The OPERA experiment took data from 2008 to 2012. 3 ν_τ candidate were observed in the analyzed sub-sample.

4.1 $\nu_\mu \rightarrow \nu_\tau$ Oscillation:

4.1.1 The First ν_τ Candidate Event:

The first ν_τ candidate in OPERA is in the $\tau \rightarrow h$ decay channel [11]. The schematic view of the event is shown in top left picture of figure 2. The candidate neutrino interaction has seven prongs at the primary vertex. None of the primary tracks is a muon or an electron. The parent track exhibits a kink topology and the daughter track is identified as a hadron through its interaction. At the τ decay vertex, in addition to the daugher track, there are two γ-rays with 120 ± 20(stat) ± 35(syst) MeV/c invariant mass, supporting the hypothesis that they are produced by a π^0 decay. The invariant mass at the decay vertex of the state composed by the two γ-rays and the charged hadron, assumed to be a π^-,

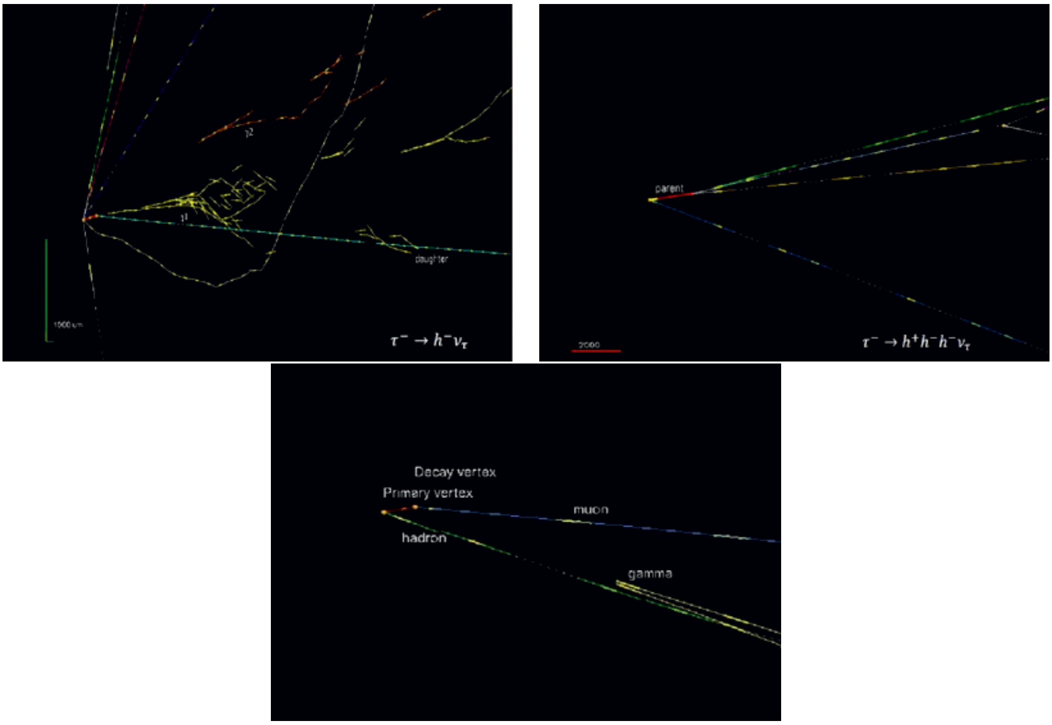

Figure 2. Schematic representation of the three OPERA ν_τ candidates. Top left: The first OPERA candidate in the $\tau \to 1h$ channel. Top right: The second OPERA candidate in the $\tau \to 3h$ channel. Bottom: The last OPERA candidate in the $\tau \to \mu$ channel. The parent *tau*-lepton is indicated by the red coloured track in all three pictures.

Table 1. Kinematical parameters of the first ν_τ candidate for the $\tau \to$ *hadron* decay channel.

Variable	Measured value	Selection Criteria
ϕ angle(deg)	173 ± 2	>90
$P_T$missing(MeV/c)	570^{+320}_{-170}	<1000
θ_{kink}(mrad)	42 ± 2	>20
Decay Length(μm)	1335 ± 35	<2600
$P_{daughter}$ (GeV/c)	12^{+6}_{-3}	>2
P_T at secondary (MeV/c)	470^{+230}_{-120}	>300(γ attached)

is $640^{+125}_{-80}(stat)^{+100}_{-90}(syst)\ MeV/c^2$ which is compatible with the $\rho(770)$ mass. Therefore, the decay mode of the candidate is consistent with the hypothesis $\tau \to \rho^- \nu_\tau$.

All the measured and required values of the kinematical parameters of the event can be seen in Table 1. More details about the first ν_τ candidate can be found in [11].

4.1.2 The Second ν_τ Candidate Event:

The second ν_τ candidate found in the OPERA is in the $\tau \to 3h$ channel [12]. The schematic view of the event is shown in the top right picture of figure 2. At the primary vertex there is the short

Table 2. Kinematical parameters of the second ν_τ candidate for the $\tau \to 3$ *hadrons* decay channel.

Variable	Measured value	Selection Criteria
ϕ angle(deg)	167.8 ± 1.1	>90
$P_T$missing(MeV/c)	310 ± 11	<1000
$Average\theta_{kink}$(mrad)	87.4 ± 1.5	<500
Decay Length(μm)	1335 ± 35	<2600
P_{total}at decay vertex (GeV/c)	8.4 ± 1.7	>3
Mininum invarian mass(GeV/c)	0.96 ± 0.13	[0.5,2]
Invariant mass GeV/c	0.80 ± 0.12	[0.5,2]

Table 3. Kinematical parameters of the third ν_τ candidate for the $\tau \to \mu$ decay channel.

Variable	Measured value	Selection Criteria
θ_{kink}(mrad)	245 ± 5	>20
Decay Length(μm)	151 ± 10	<2600
P_μ(GeV/c)	2.8 ± 0.2	[1,15]
P_T^{2ry}(MeV/c)	690 ± 50	>250

lived particle that is the τ-lepton candidate and another track identified as a hadron. This track has a measured $2.8^{+2.1}_{-2.5}$ GeV/c momentum which is a very unlikely value for a muon of the observed range.

The candidate τ-lepton decays into three hadrons after a 1.54 mm flight length. One of the daughters re-interacts after 10 lead plates producing two charged hadrons and four back-scattered highly ionizing particles. The two other daughters are also identified as hadrons on the basis of momentum-range consistency checks. The event satisfies all the required kinematical selection criteria summarized in Table 2 and is compatible with the $\tau \to 3$ *hadrons* decay. More details about the second ν_τ candidate can be found in [12].

4.1.3 The Third ν_τ Candidate Event:

The third ν_τ candidate is in the $\tau \to \mu$ decay channel [13]. A schematic view of the event can be seen in the bottom picture of figure 2. At the primary vertex there are two tracks, the τ lepton candidate and a hadron track. An electromagnetic shower produced by a γ-ray and pointing to the primary vertex was also observed.

The τ lepton candidate decays into a μ^- after a flight length of $376 \pm 10\mu m$. The sign of the muon charge was measured to be negative with a 5.6σ significance. The sign of the muon is important to reject the background from ν_μCC interactions with the production of a charmed particle decaying to a μ^+ if the primary μ^- goes undetected.

The daughter μ^- crosses 24 planes of TT and 6 planes of RPC before stopping in the spectrometer. Its momentum estimation is 2.8 ± 0.2 GeV/c using the electronic detectors and $3.1^{0.9}_{-0.5}$ GeV/c using the Multiple Coulomb Scattering method [9]. The candidate satisfies all the kinematical requirements summarized in Table 3 for the $\tau \to \mu$ decay channel.

4.1.4 Statistical Significance:

The method used for the estimation of signal and background was discussed in [12]. For the analyzed data sample, the expected signal and background are reported in [13]. With a signal expectation of

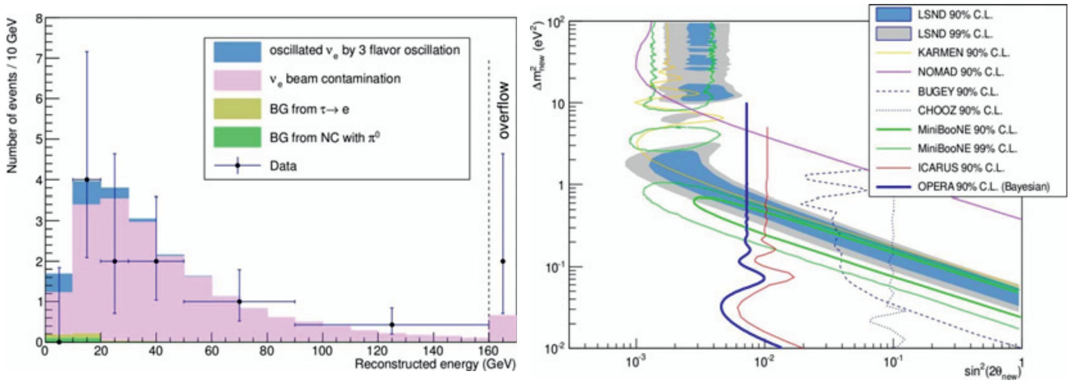

Figure 3. Left: Distribution of the reconstructed energy of the ν_e events and expected spectrum from different sources. Right: The exclusion plot for the parameters of the non-standard $\nu_\mu \to \nu_e$ oscillation(see text).

1.7 and a total background expectation of 0.184, the procedure described in [12] allows excluding the absence of a $\nu_\mu \to \nu_\tau$ oscillation signal with a significance of 3.4 σ (p-value = 2.9×10^{-4}).

4.2 $\nu_\mu \to \nu_e$ Oscillation:

The OPERA experiment has also performed a $\nu_\mu \to \nu_e$ oscillation search [14] thanks to its good electron identification capability. On a sample of 505 NC-like located events from the 2008 and 2009 data, 19 ν_e candidate events were detected with an expectation of 19.8±2.8 (syst) events from the beam contamination and 1.4 event from standard three-flavour oscillations. The reconstructed energy distribution of the observed ν_e events is shown in figure 3.

In order to increase the signal to background ratio, events with reconstructed energy lower than 20 GeV were selected. 4 events were observed with an expectation of 4.2 from beam contamination and 0.4 from background. The number of observed events is compatible with the non-oscillation hypothesis and an upper limit $sin^2 2\theta_{13} < 0.44$ (90% C.L.) was derived.

OPERA sets an upper limit also on non-standard $\nu_\mu \to \nu_e$ oscillations at large $\Delta m^2_{new} (> 0.1 eV^2)$ as suggested by the results of the LSND [15] and MiniBooNE [16] experiments. With an energy cut < 30 GeV, 6 events were observed while the expectation was 9.4±1.3. By using a Bayesian approach, the 90% C.L. upper limit on large $sin^2 2\theta_{new}$ is 7.2×10^{-3}. The exclusion plot in the Δm^2_{new}, $sin^2 2\theta_{new}$ plane is shown in figure 3.

5 Conclusions

The OPERA experiment took data from 2008 to 2012. In total 18×10^{19} p.o.t. were collected. So far 5272 events have been fully analyzed. 3 ν_τ candidates were observed in the analyzed sample corresponding to a 3.4σ statistical significance.

A systematic search for ν_e CC interactions was performed searching for sub leading $\nu_\mu \to \nu_e$ oscillations. In the analysis of the 2008-2009 data, 19 ν_e candidates were observed while the expectation was 19.8±2.8. The result is compatible with the non-oscillation hypothesis. Using the same data sample, OPERA set an upper limit in the parameter space available for a non-standard ν_e appearance indicated by the LSND and MiniBooNE experiments.

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