The OPERA Experiment: Latest Results

Annika Hollnagel on behalf of the OPERA Collaboration

Hamburg University, Luruper Chaussee 149, D-22761 Hamburg, Germany

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The long-baseline neutrino oscillation experiment OPERA has been designed for the direct observation of $\nu_\tau$ appearance in the CNGS $\nu_\mu$ beam. The OPERA detector is located at the LNGS underground laboratory, with a distance of 730 km from the neutrino source at CERN. It is a hybrid detector, combining the micrometric precision of emulsion cloud chambers with electronic detector elements for online readout.

While CNGS beam data taking lasted from 2008 to 2012, the neutrino oscillation analysis is still ongoing. Updated results with increased statistics are presented, including the recent observation of $\nu_\tau$ appearance at 4.2 $\sigma$.

1 Introduction

During the last decades, neutrino oscillations have been studied by many experiments, and a standard picture of 3-flavour oscillations via the mixing of neutrino mass eigenstates has emerged. However, most experiments - such as the first observation of atmospheric neutrino oscillations by Super-Kamiokande [1] - work in disappearance mode. The observation of neutrino oscillations in appearance mode is required to firmly establish this 3-flavour framework.

Similar to DONuT [2] in its capability to identify $\tau$ leptons from $\nu_\tau$ CC interactions on an event-by-event basis, the goal of OPERA [3] is to provide the first direct observation of $\nu_\tau$ appearance via $\nu_\mu \rightarrow \nu_\tau$ oscillations in a long-baseline beam of $\nu_\mu$. Although the detector is not optimised for other purposes, $\nu_\tau$ appearance in the sub-leading channel of $\nu_\mu \rightarrow \nu_\tau$ oscillations has also been studied.

2 The OPERA Experiment

2.1 Detector and neutrino beam

Due to the low cross sections involved, the detection of neutrino interactions in general requires a large target mass, while on the other hand, micrometric precision is needed for the observation of the short-lived $\tau$ leptons. The OPERA detector was designed as a hybrid apparatus to fulfill both requirements.

High-resolution ($O(\mu m)$) AgBr nuclear emulsions on plastic bases are interleaved with Pb plates to form Emulsion Cloud Chamber (ECC) modules called bricks - see Figure 1(a) for a schematic view and dimensions. At the downstream side of each brick, extra Changeable Sheet (CS) emulsion doublets act as an interface between ECC and Electronic Detector (ED).

$^1$OPERA: Oscillation Project with Emulsion Tracking Apparatus.
components [4]. Altogether, the detector comprises about 150,000 bricks, resulting in a total target mass of 1.25 kt.

The bricks are arranged in two target regions of 31 vertical walls, perpendicular to the neutrino beam direction. Each wall is followed by planes of horizontal and vertical Target Tracker (TT) scintillator strips, allowing the location of neutrino interactions within the target, i.e. the identification of the respective brick. Downstream of each target region, a magnetic spectrometer - made from iron core dipole magnets, Resistive Plate Chamber (RPC & XPC) detectors, and Precision Tracker (PT) drift tubes - is used for the identification of $\mu$ momentum and charge. Upstream of these two identical Super Modules (SM), a RPC VETO system is installed. Figure 1(b) shows a lateral view of the detector.

![ECC brick module and Lateral view of the detector](image)

Figure 1: The OPERA detector.

The CNGS$^2$ $\nu_\mu$ beam [5, 6] is a conventional neutrino beam, using 400 GeV-$p$ from the CERN-SPS, a graphite target, and a magnetic horn focusing system. The resulting average $\nu_\mu$ energy is $\sim 17$ GeV - well-above the threshold for $\tau$ lepton production in $\nu_\tau$ CC interactions. While negligible for $\nu_\tau$, the contaminations with other flavours are 2.1% for $\overline{\nu}_\mu$ and 1% for $\nu_e + \overline{\nu}_e$, respectively. Between 2008 and 2012, a total of $1.797 \times 10^{19}$ p.o.t. have been delivered.

With the detector location at the LNGS underground laboratory, the baseline of the experiment is 730 km.

## 3 Neutrino oscillation results

### 3.1 $\nu_\mu \to \nu_\tau$ oscillations

The data sample used for the present results on $\nu_\mu \to \nu_\tau$ oscillations consists of 4685 fully analysed neutrino interactions with predefined selection criteria [7]: 0$\mu$ events and 1$\mu$ events with $\mu$ momentum of less than 15 GeV were searched for $\nu_\tau$ appearance in the 1st and 2nd most probable bricks of 2008 + 2009 data, as well as in the 1st most probable bricks of 2010 + 2011 + 2012. In this sample, 4 $\nu_\tau$ candidate events have been confirmed, their ECC reconstructions are shown in Figure 2.

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$^2$CNGS: CERN Neutrinos to Gran Sasso.

$^3$SPS: Super Proton Synchrotron.

$^4$LNGS: Laboratori Nazionali del Gran Sasso.
With an expected signal of $2.11 \pm 0.42$ events and a background of $0.233 \pm 0.041$, the 4 observed events correspond to a $p$-value of $1.24 \times 10^{-5}$ (Fisher method) or $1.03 \times 10^{-5}$ (likelihood analysis) for the no-oscillation hypothesis, both giving a significance of $4.2 \sigma$ for the first observation of $\nu_\tau$ appearance. A measurement of $\Delta m_{23}^2$ has also been performed, resulting in intervals of $[1.8, 5.0] \times 10^{-3} \mathrm{eV}^2$ (Feldman-Cousins) and $[1.9, 5.0] \times 10^{-3} \mathrm{eV}^2$ (Bayes) at 90% C.L., respectively.

Further details on the analysis procedure, the kinematics of the $\nu_\tau$ candidate events, and the backgrounds can be found in [8, 9, 10].

### 3.2 $\nu_\mu \to \nu_e$ oscillations

With the possibility of electron identification, OPERA is also able to perform an appearance search in the sub-leading channel of $\nu_\mu \to \nu_e$ [11].

In the unbiased 2008+2009 data sample of 5255 located $\nu$ CC interactions (corresponding to $5.25 \times 10^{19}$ p.o.t.), 19 $\nu_e$ candidate events have been found, while $19.8 \pm 2.8$ background events are expected from beam contamination and 1.4 events from standard 3-flavour oscillations (see Figure 3(a)). A cut on the reconstructed energy $E_{\nu,\mathrm{rec}}$ of the $\nu_e$ candidates at $< 20 \mathrm{GeV}$ to increase the signal-to-noise ratio results in 4 remaining $\nu_e$ candidates, with an expected signal of 1 event and a background expectation of 4.6. The number of observed events is compatible with the no-oscillation hypothesis, allowing to derive an upper limit of $\sin^2(2\theta_{13}) < 0.44$ at 90% C.L.\footnote{Assumptions: $\Delta m_{23}^2 = 2.32 \times 10^{-3} \mathrm{eV}^2$, $\sin^2(2\theta_{23}) = 1$.}

For non-standard oscillations in the parameter space of large $\Delta m_{new}^2 > 0.1 \mathrm{eV}^2$ suggested by the LSND and MiniBooNE experiments, new limits could be derived by introducing a cut of $E_{\nu,\mathrm{rec}} < 30 \mathrm{GeV}$, reducing the number of observed $\nu_e$ candidate events to 6. With an expected signal

\footnote{Assumptions: $\sin^2(2\theta_{13}) = 0.098$, $\sin^2(2\theta_{23}) = 1$, $\Delta m_{31}^2 = \Delta m_{32}^2 = 2.32 \times 10^{-3} \mathrm{eV}^2$, $\delta_{CP} = 0$.}
background of 9.4 events (incl. 1.3 events from 3-flavour oscillations), the Bayesian upper limit on large \( \sin^2(2\theta_{\text{new}}) \) is \( 7.2 \times 10^{-3} \). Figure 3(b) shows the exclusion plot in the \( \Delta m^2_{\text{new}} \) vs. \( \sin^2(2\theta_{\text{new}}) \) plane.

![Reconstructed energy of the \( \nu_e \) candidates.](image1)

![Exclusion plot (non-standard scenario).](image2)

Figure 3: \( \nu_\mu \rightarrow \nu_e \) oscillation analysis.

4 Conclusion

OPERA is a long-baseline neutrino oscillation experiment. Data taking in the CNGS beam lasted from 2008 to 2012, with a total exposure of \( 17.97 \times 10^{19} \) p.o.t.

In the main analysis of \( \nu_\mu \rightarrow \nu_\tau \) oscillations, 4 \( \nu_\tau \) interactions have been confirmed within the current data sample of 4685 fully analysed events. Using statistical methods, this result constitutes the first observation of \( \nu_\tau \) appearance in a \( \nu_\mu \) beam at 4.2 \( \sigma \) significance.

In the sub-leading channel of \( \nu_\mu \rightarrow \nu_e \) oscillations, new limits could be derived in the parameter space of non-standard neutrino oscillations.

References