The OPERA Experiment: Latest Results

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The long-baseline neutrino oscillation experiment OPERA has been designed for the direct observation of ν_{τ} appearance in the CNGS ν_{μ} 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 ν_{τ} appearance at 4.2 σ .

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 τ leptons from ν_{τ} CC interactions on an event-by-event basis, the goal of OPERA¹ [3] is to provide the first direct observation of ν_{τ} appearance via $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations in a long-baseline beam of ν_{μ} . Although the detector is not optimised for other purposes, ν_e appearance in the sub-leading channel of $\nu_{\mu} \rightarrow \nu_e$ 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 τ leptons. The OPERA detector was designed as a hybrid apparatus to fulfill both requirements.

High-resolution ($\mathcal{O}(\mu m)$) 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 **P**roject with **E**mulsion Tracking **A**pparatus.

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 μ 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.



Figure 1: The OPERA detector.

The CNGS² ν_{μ} beam [5, 6] is a conventional neutrino beam, using 400 GeV-*p* from the CERN-SPS³, a graphite target, and a magnetic horn focusing system. The resulting average ν_{μ} energy is ~ 17 GeV - well-above the threshold for τ lepton production in ν_{τ} CC interactions. While negligible for ν_{τ} , the contaminations with other flavours are 2.1% for $\bar{\nu}_{\mu}$ and 1% for $\nu_{e} + \bar{\nu}_{e}$, respectively. Between 2008 and 2012, a total of 17.97×10^{19} p.o.t. have been delivered.

With the detector location at the $LNGS^4$ underground laboratory, the baseline of the experiment, is 730 km.

3 Neutrino oscillation results

3.1 $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations

The data sample used for the present results on $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations consists of 4685 fully analysed neutrino interactions with predefined selection criteria [7]: 0μ events and 1μ events with μ momentum of less than 15 GeV were searched for ν_{τ} 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 ν_{τ} candidate events have been confirmed, their ECC reconstructions are shown in Figure 2.

²**CNGS: C**ERN **N**eutrinos to **G**ran **S**asso.

³SPS: Super Proton Synchrotron.

⁴LNGS: Laboratori Nazionali del Gran Sasso.



Figure 2: ECC reconstructions of the four confirmed ν_{τ} candidates.

With an expected signal of 2.11 ± 0.42 events⁵ and a background of 0.233 ± 0.041 , the 4 observed events correspond to a p-value of 1.24×10^{-5} (Fisher method) or 1.03×10^{-5} (likelihood analysis) for the no-oscillation hypothesis, both giving a significance of 4.2σ for the first observation of ν_{τ} appearance. A measurement of Δm_{23}^2 has also been performed, resulting in intervals of $[1.8, 5.0] \times 10^{-3} \text{ eV}^2$ (Feldman-Cousins) and $[1.9, 5.0] \times 10^{-3} \text{ eV}^2$ (Bayes) at 90 % C.L., respectively.

Further details on the analysis procedure, the kinematics of the ν_{τ} candidate events, and the backgrounds can be found in [8, 9, 10].

3.2 $\nu_{\mu} \rightarrow \nu_{e}$ oscillations

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

In the unbiased 2008 + 2009 data sample of 5255 located ν CC interactions (corresponding to 5.25×10^{19} p.o.t.), 19 ν_e candidate events have been found, while 19.8 ± 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 $E_{\nu,rec}$ of the ν_e candidates at < 20 GeV to increase the signal-to-noise ratio results in 4 remaining ν_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. 6

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 $E_{\nu,rec} < 30 \,\text{GeV}$, reducing the number of observed ν_e candidate events to 6. With an expected

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⁵Assumptions: $\Delta m_{23}^2 = 2.32 \times 10^{-3} \,\mathrm{eV}^2$, $\sin^2(2\theta_{23}) = 1$. ⁶Assumptions: $\sin^2(2\theta_{13}) = 0.098$, $\sin^2(2\theta_{23}) = 1$, $\Delta m_{23}^2 = \Delta m_{31}^2 = 2.32 \times 10^{-3} \,\mathrm{eV}^2$, $\delta_{CP} = 0$.

background of 9.4 events (incl. 1.3 events from 3-flavour oscillations), the Bayesian upper limit on large $\sin^2(2\theta_{new})$ is 7.2×10^{-3} . Figure 3(b) shows the exclusion plot in the Δm_{new}^2 vs. $\sin^2(2\theta_{new})$ plane.



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 17.97×10^{19} p.o.t.

In the main analysis of $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations, 4 ν_{τ} interactions have been confirmed within the current data sample of 4685 fully analysed events. Using statistical methods, this result constitutes the first observation of ν_{τ} appearance in a ν_{μ} beam at 4.2 σ 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.

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