The OPERA Experiment: Latest Results

Annika Hollnagel[1] on behalf of the OPERA Collaboration

[1]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 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 $4.2\,\sigma$.

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 τ leptons from ν_τ CC interactions on an event-by-event basis, the goal of OPERA[1] [3] is to provide the first direct observation of ν_τ appearance via $\nu_\mu \to \nu_\tau$ 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 $\nu_\mu \to \nu_e$ oscillations has also been studied.

2 The OPERA Experiment

2.1 Detector and neutrino beam

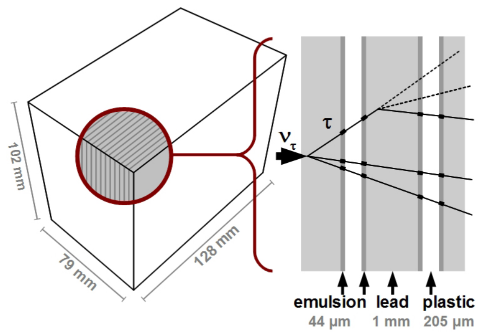
Due to the low cross sections involved, the detection of neutrino interactions in general requires a large target mass, while on the other hand, micrometric precision is needed for the observation of the short-lived τ leptons. The OPERA detector was designed as a hybrid apparatus to fulfill both requirements.

High-resolution ($\mathcal{O}$ (μm)) 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)

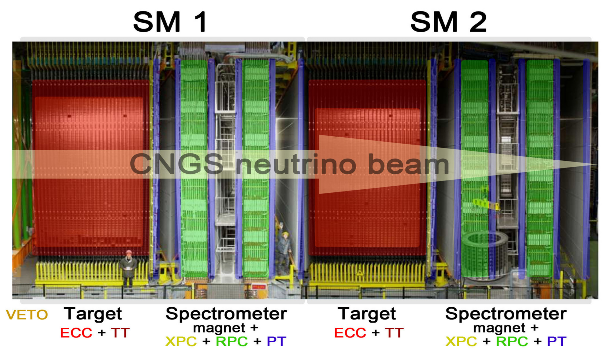
[1]**OPERA: O**scillation **P**roject with **E**mulsion **T**r**a**cking **A**pparatus.

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.



(a) ECC brick module.



(b) Lateral view (whole detector).

Figure 1: The OPERA detector.

The CNGS[2] ν_μ beam [5, 6] is a conventional neutrino beam, using 400 GeV-p from the CERN-SPS[3], a graphite target, and a magnetic horn focusing system. The resulting average ν_μ energy is $\sim$ 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 $\overline{\nu}_\mu$ and 1 % for $\nu_e + \overline{\nu}_e$, 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 $\nu_\mu \to \nu_\tau$ 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]: 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 **Gr**an **S**asso.
[3] **SPS: S**uper **P**roton **S**ynchrotron.
[4] **LNGS: L**aboratori **N**azionali del **G**ran **S**asso.

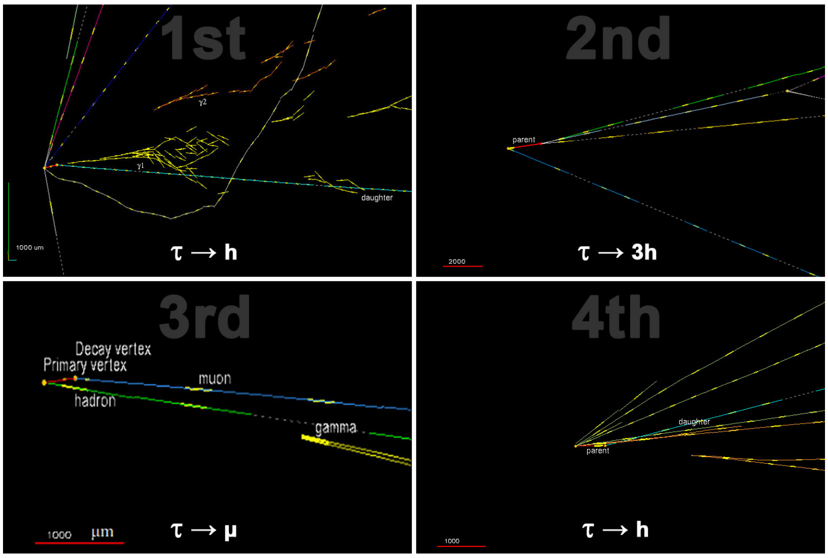


Figure 2: ECC reconstructions of the four confirmed ν_τ candidates.

With an expected signal of 2.11 ± 0.42 events[5] 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 $4.2\,\sigma$ for the first observation of ν_τ appearance. A measurement of Δm^2_{23} 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 ν_τ candidate events, and the backgrounds can be found in [8, 9, 10].

3.2 $\nu_\mu \rightarrow \nu_e$ oscillations

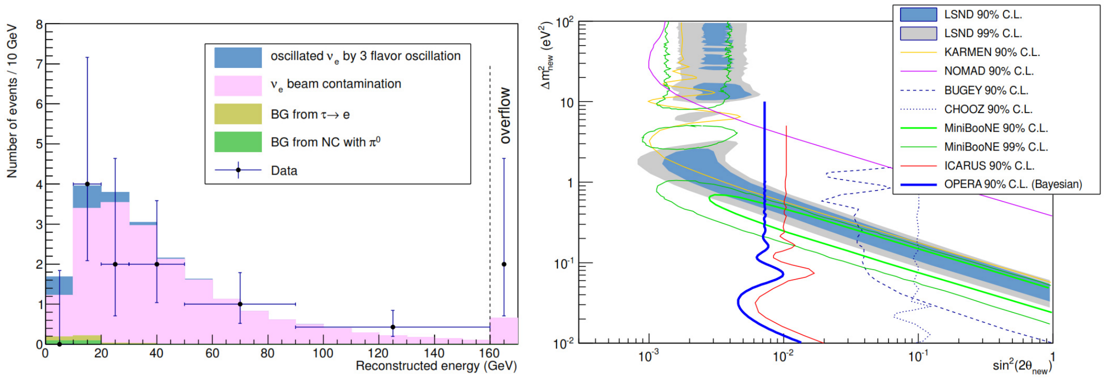
With the possibility of electron identification, OPERA is also able to perform an appearance search in the sub-leading channel of $\nu_\mu \rightarrow \nu_e$ [11].

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 $< 20\,\mathrm{GeV}$ 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 $\Delta m^2_{new} > 0.1\,\mathrm{eV}^2$ suggested by the LSND and MiniBooNE experiments, new limits could be derived by introducing a cut of $E_{\nu,rec} < 30\,\mathrm{GeV}$, reducing the number of observed ν_e candidate events to 6. With an expected

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

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^2_{new} vs. $\sin^2(2\theta_{new})$ plane.



(a) Reconstructed energy of the ν_e candidates.

(b) Exclusion plot (non-standard scenario).

Figure 3: $\nu_\mu \to \nu_e$ 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 $\nu_\mu \to \nu_\tau$ 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 $4.2\,\sigma$ significance.

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

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