PROCEEDINGS OF SCIENCE

Neutrino oscillation results of the OPERA experiment in the CNGS beam

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The OPERA experiment was designed to observe the appearance of tau neutrinos in the muon neutrino CNGS beam. This goal was successfully reached by observing a high purity sample of ν_τ charged current (CC) interaction candidate events. Additionally, it was possible to isolate samples of ν_e and ν_μ CC candidates, as well as neutral current candidate events. These four samples were used to put additional constraints on parameters of both the standard neutrino mixing model and the $3+1$ sterile model. This poster will review the methodology of measuring neutrino interactions using the OPERA apparatus and give an overview of all results on neutrino oscillations produced by the experiment. In particular, a joint analysis of ν_τ and ν_e samples will be shown which excludes a significant fraction of the sterile neutrino phase space allowed by MiniBooNE appearance analysis.

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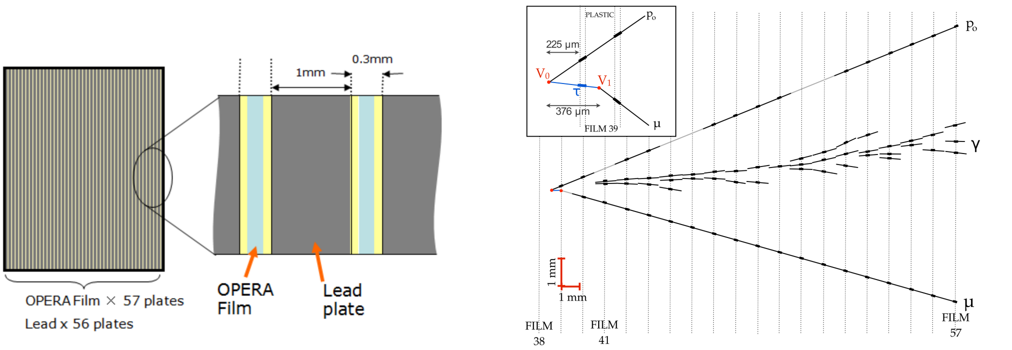
1. The OPERA experiment

The OPERA experiment [1] was designed to discover tau neutrino appearance in the predominantly muon neutrino CNGS beam [2, 3]. The OPERA detector target consisted of about 150 000 stacks of lead plates and emulsion films, called Emulsion Cloud Chamber (ECC) elements (Fig. 1), embedded between scintillator planes. The detector also featured two muon spectrometers, used for momentum reconstruction of charged particles (Fig. 2).



(a) Schematic view of an ECC element.

(b) Tau neutrino candidate reconstructed in the OPERA ECC. Figure taken from [4].

Figure 1: Emulsion cloud chamber.

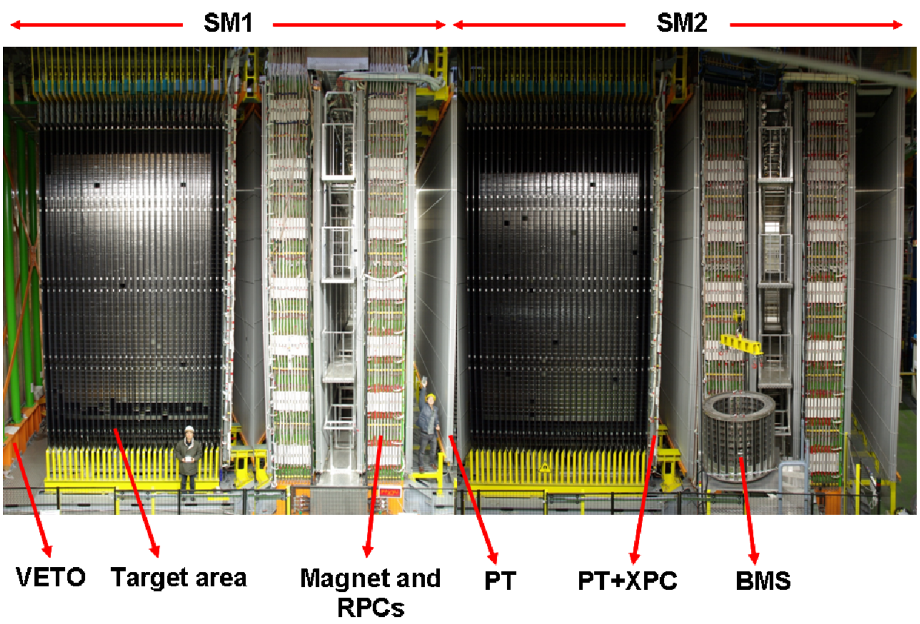


Figure 2: Side view of the OPERA detector.

Scintillator planes were used to predict the ECC element in which neutrino interaction occurred. Selected ECCs were then extracted and analysed by automatic scanning microscopes. The data taking run lasted from 2008 to 2012 with an exposure of 17.97×10^{19} protons on target, in which 19505 events were recorded in the target, of which 5603 were fully reconstructed in the ECCs. The discovery of ν_τ appearance was first published in 2015 [5], with 5 observed tau candidate events and an expected background of 0.25 ± 0.05 events, corresponding to a significance of 5.1 σ.

2. Neutrino oscillation results

Final results on the $\nu_\mu \to \nu_\tau$ appearance channel were published in 2018 [6]. Using looser selection cuts, ten ν_τ candidates were observed with an expected background of 2.0 ± 0.4 events (Fig. 3), corresponding to a significance of 6.1 σ. Assuming maximal mixing, OPERA measured the atmospheric mass splitting in ν_τ appearance mode to be $\left|\Delta m^2_{32}\right| = \left(2.7^{+0.7}_{-0.6}\right) \times 10^{-3}$ eV^2.

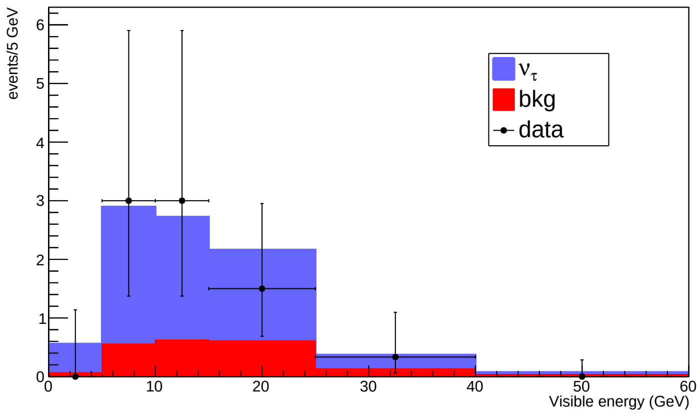


Figure 3: Energy distribution of the final sample of 10 ν_τ candidates (bullets) compared to the Monte Carlo prediction (histogram). Figure taken from [7].

The OPERA detector was also capable of measuring ν_e CC interactions, which allowed it to probe $\nu_\mu \to \nu_e$ oscillations in the CNGS beam. The expected number of ν_e candidate events is 31.9 ± 3.2 in case of no oscillations, and 34.3 ± 3.4 for standard oscillations. 35 events were observed, consistent with both cases [7].

A joint fit using ν_τ and ν_e appearance was done assuming both the standard neutrino oscillations and the sterile $3+1$ model. In the standard model, a constraint was made on the parameters θ_{13} and θ_{23} (Fig. 4). In the sterile model, constraints on parameter pairs $\left(\sin^2 2\theta_{\mu\tau} - \Delta m^2_{41}\right)$ and $\left(\sin^2 2\theta_{\mu e} - \Delta m^2_{41}\right)$ were made (Fig. 5), which exclude recent MiniBoone result [8] with a significance of 3.3 σ [9].

Finally, a search for $\nu_\mu \to \nu_\mu$ disappearance signal has been performed. Due to the lack of a near detector, the measured NC/CC event rate ratio was used to search for the disappearance signal. Assuming all other oscillation parameters fixed, an upper limit on atmospheric mass splitting (Fig. 6) was obtained to be $\left|\Delta m^2_{32}\right| < 4.1 \times 10^{-3}$ eV^2 @ 90% C.L.

3. Conclusions

OPERA is the only experiment which was able to directly study all three channels of ν_μ

oscillations: $\nu_\mu \to \nu_\tau$, $\nu_\mu \to \nu_e$, and $\nu_\mu \to \nu_\tau$. Apart from the primary ν_τ analysis, a joint fit of ν_τ and ν_e has been performed in both standard and sterile hypothesis. Additionally, a search to ν_μ disappearance has been performed.

References

[1] OPERA collaboration, *The OPERA experiment in the CERN to Gran Sasso neutrino beam*, *JINST* **4** (2009) P04018.

[2] G. Acquistapace et al. CERN-98-02, INFN/AE-98/05 http://proj-cngs.web.cern.ch/proj-cngs/.

[3] R. Baldy et al. CERN-SL-99-034-DI, INFN-AE-99-05 (1999). Addendum to report CERN-98-02, INFN/AE-98/05.

[4] OPERA collaboration, *Evidence for $\nu_\mu \to \nu_\tau$ appearance in the CNGS neutrino beam with the OPERA experiment*, *Phys. Rev.* **D89** (2014) 051102 [1401.2079].

[5] OPERA collaboration, *Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment*, *Phys. Rev. Lett.* **115** (2015) 121802 [1507.01417].

[6] OPERA collaboration, *Final Results of the OPERA Experiment on ν_τ Appearance in the CNGS Neutrino Beam*, *Phys. Rev. Lett.* **120** (2018) 211801 [1804.04912].

[7] OPERA collaboration, *Final results of the search for $\nu_\mu \to \nu_e$ oscillations with the OPERA detector in the CNGS beam*, *JHEP* **06** (2018) 151 [1803.11400].

[8] MiniBooNE collaboration, *Significant Excess of ElectronLike Events in the MiniBooNE Short-Baseline Neutrino Experiment*, *Phys. Rev. Lett.* **121** (2018) 221801 [1805.12028].

[9] OPERA collaboration, *Final results on neutrino oscillation parameters from the OPERA experiment in the CNGS beam*, *Phys. Rev.* **D100** (2019) 051301 [1904.05686].

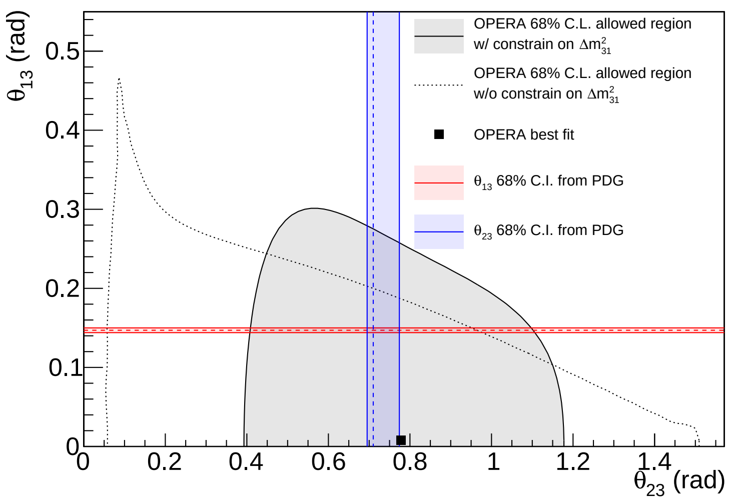
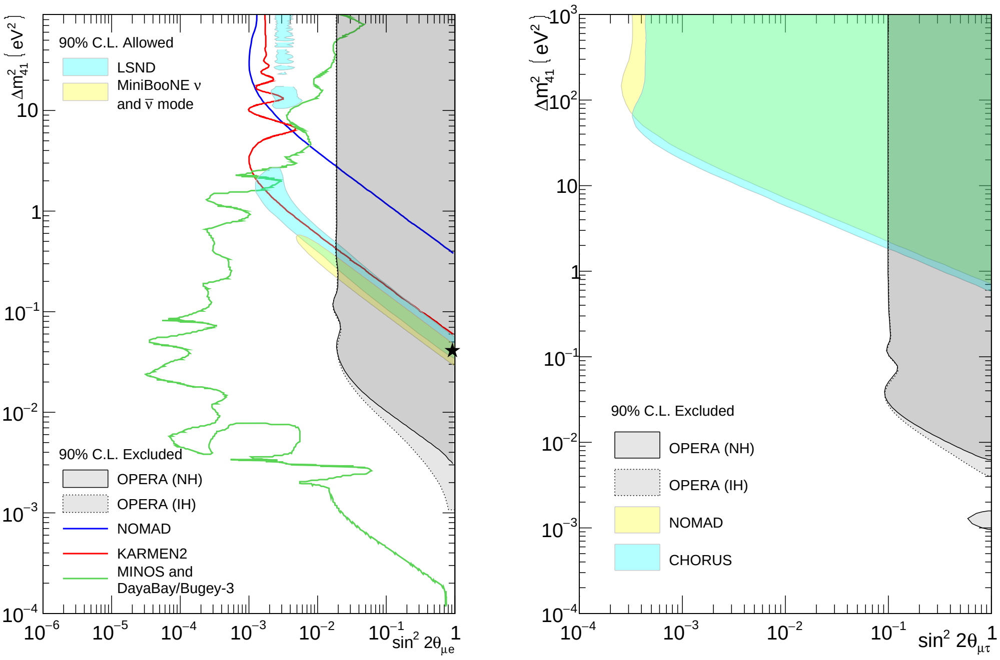


Figure 4: OPERA 68% C.L. allowed region in the θ_{13} and θ_{23} parameter space for the normal hierarchy (NH) of the three standard neutrino masses; assuming a prior on Δm^2_{32} (filled area), and treating Δm^2_{32} as a free parameter (dashed line).



(a) The 90% C.L. exclusion region in the Δm^2_{41} and $\sin^2 2\theta_{\mu e}$ parameter space. The best fit of MiniBooNE [8] is excluded by 3.3 σ.

(b) The 90% CL exclusion region in the Δm^2_{41} and $\sin^2 2\theta_{\mu\tau}$ parameter space.

Figure 5: Sterile 3+1 model oscillation parameter constraints assuming NH and inverted neutrino mass hierarchy (IH). Figures taken from [9].

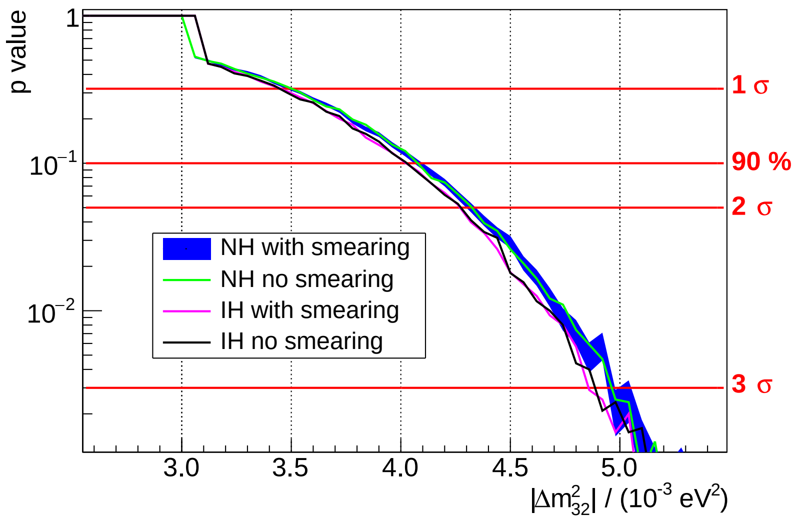


Figure 6: p-values as a function of $\left|\Delta m^2_{32}\right|$ obtained from the ν_μ disappearance analysis, with all other oscillation parameters fixed to global fit central values. Figure taken from [9].