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Final results from the OPERA experiment in the CNGS neutrino beam

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The OPERA experiment at the Gran Sasso Laboratory was designed to study $\nu_\mu \to \nu_\tau$ oscillations in appearance mode in the CERN-to-Gran Sasso neutrino beam. We report on the final analysis of the full data sample based on looser selection criteria than in previous analyses and multivariate approach. Oscillation parameters have been determined with a reduced statistical uncertainty, and the discovery of tau neutrino appearance is confirmed with an improved significance level. Moreover, the search for electron neutrino events has been extended to the full dataset exploiting an improved method for the electron neutrino energy estimation. New limits have been set in the framework of the $3+1$ neutrino model.

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1. The OPERA experiment

The OPERA experiment [1] was designed to study $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode. The OPERA detector, located at the underground Gran Sasso Laboratory (LNGS), was exposed to the CERN to Gran Sasso (CNGS) muon neutrino beam [2, 3] produced at a distance of 730 km. The average neutrino energy was about 17 GeV, the $\bar{\nu}_\mu$ fraction was 2.1% in terms of expected CC interactions, the sum of ν_e and $\bar{\nu}_e$ was below 1%, while the prompt ν_τ contamination was negligible.

The detector was a hybrid apparatus made of an emulsion and lead target with a total mass of about 1.25 kt, complemented by electronic detectors. The general structure consisted of two identical supermodules (SM). Each SM was made of a target section, composed of 31 target walls, and a muon spectrometer. Each target wall was an assembly of horizontal trays loaded with target units, hereafter called bricks. Each brick consisted of 57 emulsion films, 300 μm thick, interleaved with 56 lead plates, 1 mm thick, with a 12.7×10.2 cm^2 cross section, a thickness of 7.5 cm corresponding to about ten radiation lengths and a mass of 8.3 kg. Downstream of each target wall, two orthogonal planes of scintillator strips (target tracker detector) recorded the position and the energy deposition of charged particles [4]. Finally, a magnetic spectrometer instrumented with resistive plate chambers and high-resolution drift tubes was used to identify muons and measure their charge and momentum [1]. A detailed description of the OPERA detector can be found in [1].

2. Tau neutrino appearance

The appearance of the ν_τ was identified by the detection of characteristic decay topologies of the tau lepton produced in the CC interactions. Kinematical selection criteria were applied to reduce the background coming from the processes that mimic the τ decay topologies, which are (i) the decays of charmed particles produced in ν_μ CC interactions; (ii) reinteractions of hadrons from ν_μ events occurring in lead plates; (iii) the large-angle scattering of muons produced in ν_μ CC interactions. A sample corresponding to 17.97×10^{19} protons on target has been collected from 2008 to 2012 and resulted in 19505 neutrino interactions in the target fiducial volume. In 2015, five ν_τ candidates were reported with an expected background of 0.25 ± 0.05 events. Candidates were selected by applying defined cuts on kinematical and topological parameters. The discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations was assessed with a significance of 5.1σ [6].

In 2018 a new analysis based on a multivariate approach for event identification, fully exploiting the expected features of ν_τ events was performed [7]. It was applied on candidate events preselected with looser cuts than those applied in the previous cut-based approach. Ten tau neutrino candidates were identified in the full OPERA dataset with an expected number of background events of 2.0 ± 0.4. The significance of the discovery increased to 6.1σ.

Assuming maximal mixing and ν_τ CC interaction cross section as in default implementation provided by GENIE v2.6 [8, 9], an interval of $\left|\Delta m^2_{32}\right| = \left(2.7^{+0.7}_{-0.6}\right) \times 10^{-3}$ eV^2 was derived at 68% C.L. using the Feldman-Cousins method [10]. This is the first result obtained in appearance mode and it is consistent with the disappearance results from different experiments, including the global best-fit value [11]. Alternatively, by fixing $\left|\Delta m^2_{32}\right|$ at the global best-fit value $\left(2.50 \times 10^3 \text{eV}^2\right)$ and

maximal mixing $\sin^2 2\theta_{23} = 1$, the ν_τ CC cross section on the lead target can be estimated [12]. The total flux integrated cross section was estimated to be $\langle\sigma\rangle_{meas} = \left(5.1^{+2.4}_{-2.0}\right) \times 10^{-36}$ cm^2.

3. Electron neutrino search

The OPERA nuclear emulsion granularity allowed the reconstruction of electromagnetic showers and thus the identification of ν_e CC interactions. A dedicated procedure [14], balancing computation time and detection efficiency, was defined to systematically search for ν_e events. A total of 35 ν_e events were observed. The number is compatible with the expected ν_e from the beam contamination (30.7 ± 3.2), together with two main sources of background: π^0's misidentified electrons in neutrino interactions without a reconstructed muon (0.5 ± 0.5) events and ν_τ CC interactions with τ decaying into an electron (0.7 ± 0.2) events.

Using the global best-fit values [11] for θ_{13}, θ_{23} and Δm^2_{atm}, assuming $\delta_{CP} = 0$ and neglecting matter effects, a total of 34.3 ± 3.5 ν_e candidate events were expected in the whole energy range. The number of observed events is compatible with the three flavors oscillation model and an upper limits on $\sin^2 2\theta_{13} < 0.43$ was set at 90% C.L. in the optimized neutrino energy range $[0-40]$ GeV.

4. Constraints on $3+1$ model

Some experimental results [15, 16, 17, 18] may hint to oscillations involving additional sterile neutrinos with a mass of O(1 eV^2). In presence of a fourth sterile neutrino ($3+1$ model), the oscillation probability is a function of a 4×4 mixing matrix U and of three squared mass differences. OPERA can exploit jointly tau and electron neutrino observed events to constrain combinations of the sterile neutrino parameters. The predictions of the $3+1$ model was evaluated using the GLoBES software [19, 20]. The parameter Δm^2_{21} was fixed to the gobal best-fit value [11], a Gaussian external constraint on Δm^2_{31} was set using mean and sigma from a global fit [11], while only positive values of Δm^2_{41} were considered since negative values are disfavoured by results on the sum of neutrino masses from cosmological surveys [22]. Matter effects were taken into account with the Earth density approximated by a constant value estimated with the PREM [20, 21] onion shell model.

The systematic uncertainty on the expected number of tau neutrino candidates is largely dominated by the limited knowledge of ν_τ interaction cross section and the detection efficiency. It is conservatively set to 20%. The systematic error on the expected number of electron neutrino candidates, due to beam normalization and efficiency uncertainties is 10% (20%) for events with neutrino energy larger (smaller) than 10 GeV.

The profile likelihood ratio was used as test statistic and the Wilks' theorem was used to extract a preliminary exclusion regions on $\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2|U_{\tau 4}|^2$ and Δm^2_{41} plane (Fig. 1a) comparing the visible energy distribution of the observed ν_τ events with the expected one. For $\Delta m^2_{41} \gtrsim 1$ eV^2, the 90% C.L. upper limit on $\sin^2 2\theta_{\mu\tau}$ is 0.099. Furthermore an exclusion regions on $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ and Δm^2_{41} plane (Fig. 1b) was preliminarily evaluated comparing the reconstructed energy distribution of the observed ν_e events with the expected one. At large $|\Delta m^2_{41}|$ values, the 90% C.L. upper limit on $\sin^2 2\theta_{\mu e}$ is 0.019.
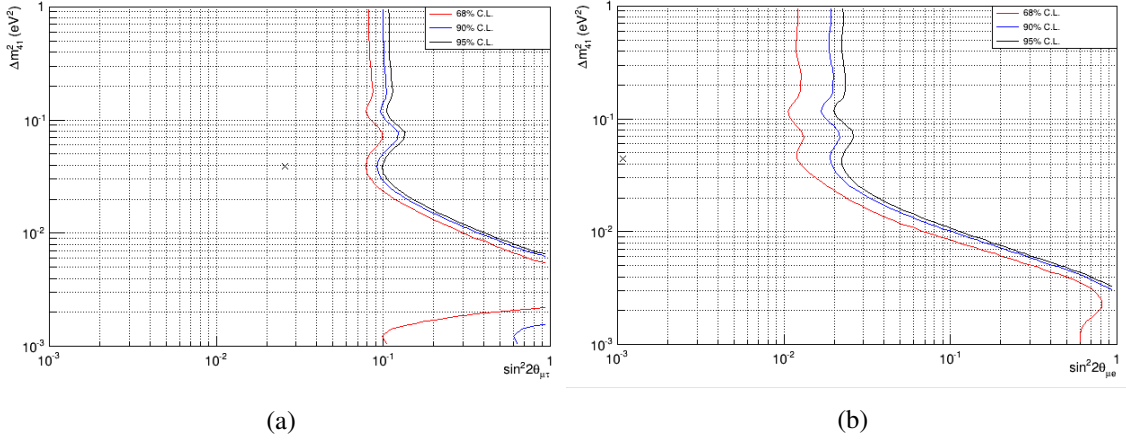
Figure 1: Preliminary exclusion regions on $\sin^2 2\theta_{\mu\tau} = 4\left|U_{\mu 4}\right|^2 \left|U_{\tau 4}\right|^2$ and Δm^2_{41} plane (a) and on $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2 |U_{e4}|^2$ and Δm^2_{41} plane (b) at 68% (red), 90% (blue) and 95% (black) C.L.

5. Conclusions

The OPERA experiment was taking data from 2008 to 2012. Five ν_τ candidates were observed applying a selection on specific kinematical and topological parameters. The non-null observation of $\nu_\mu \to \nu_\tau$ oscillations was excluded with a significance greater than 5σ. In a subsequent analysis based on looser selection criteria, a sample of ten events was collected. Using a multivariate approach the significance of the observation increased to 6.1σ and the Δm^2_{32} measurement was improved. Moreover a systematic search for ν_e events lead to a number of observed ν_e interactions compatible with the expectations in the three flavors neutrino model. Finally, the ν_e and ν_τ samples were jointly used to derive limits on oscillation parameters in the $3+1$ neutrino model.

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