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Search for $\nu_\mu \to \nu_e$ oscillations with the OPERA experiment in the CNGS beam

M. Tenti[*]

University of Bologna and INFN, viale B. Pichat 6/2, Bologna (BO) 40127, Italy

Abstract

The OPERA hybrid detector, designed to prove neutrino oscillations in the $\nu_\mu \to \nu_\tau$ channel, was exposed to the CNGS ν_μ beam at a distance of 730 km from the neutrino source. Profiting of the tracking capabilities of its Emulsion Cloud Chamber system, OPERA can perform also a search for $\nu_\mu \to \nu_e$ oscillations. Current results are compatible with the non-oscillation hypothesis in the three flavour mixing model. The same data allow to constrain the non-standard oscillation parameters θ_{new} and Δm^2_{new} indicated by the LSND and MiniBooNE experiments.

Keywords: Electron Neutrino, Neutrino Oscillations, OPERA, Sterile Neutrino

1. The OPERA detector

The OPERA (Oscillation Project with Emulsion-tRacking Apparatus) experiment at the Gran Sasso Laboratory [1] aims at the observation of the $\nu_\mu \to \nu_\tau$ oscillations in appearance mode, looking for the direct detection of the τ lepton in ν_τ-charged current interactions. Recently the collaboration reported the observation of $\nu_\mu \to \nu_\tau$ appearance [2, 3]. The τ lepton is identified through its decay topology exploiting the tracking capabilities of the Emulsion Cloud Chamber (ECC) modules, called bricks. Each brick is composed of 56 1-mm-thick lead plates (target) interleaved with 57 nuclear emulsion films (tracker). Each film is made of two 44-μm-thick emulsion layers on both sides of a 205-μm-thick plastic base. At the downstream face of the brick, two additional emulsion films (Changeable Sheets, CS) [4] act as interface between the electronic detectors and the emulsions. The detector is arranged in 2 identical SuperModules (SM). In each SM the target section is formed by about 75000 bricks, for a mass of about 625 tons, arranged in vertical structures transverse to the beam direction (called walls) interleaved with planes of scintillator strips (the target tracker, TT). The target

section is followed downstream by a muon spectrometer, composed of a dipole magnet instrumented with Drift Tubes and Resistive Plate Chambers. The apparatus was exposed to the CNGS neutrino beam, from CERN to Gran Sasso [5], at a distance of 730 km from the neutrino source. The CNGS was an almost pure ν_μ beam and the electron neutrinos component in terms of expected charged current interactions relative to ν_μ at Gran Sasso amounts to 0.88% and 0.05% for ν_e and $\bar{\nu}_e$ respectively [6].

2. Search for $\nu_\mu \to \nu_e$

Bricks that are candidates for containing neutrino interactions are analysed following a procedure described in detail in [7]. Here only the main steps of the analysis are recalled. Based on TT predictions a large area of the corresponding CS films is scanned. If tracks consistent with the TT predictions are found in the CS, the brick's emulsion films are developed, and sent to the scanning labs. Tracks found in the CS are followed upstream from film to film (scan-back) in order to locate the neutrino interaction vertex. If the vertex is found, a volume scan around its position (over 1 cm^2 area in at least 3 foils downstream and 4 foils upstream) is performed in order to reconstruct every track attached

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[*]for the OPERA Collaboration (members and institutions as in [3])
Email address: matteo.tenti@bo.infn.it (M. Tenti)

to the vertex and to search for decay topologies. The main goal of this search is the observation of the τ lepton decay, as a signature of the ν_τ CC interactions. In addition, electrons and their associated electromagnetic shower can be identified, thus allowing the search for ν_e events. Since the size of a standard scanned volume along the beam direction is too short to contain the electromagnetic shower, an extended volume scan triggered by a defined CS track pattern is performed, as described in the following. All primary tracks from the interaction vertex are extrapolated to the CS. Tracks with angle difference smaller than 150 mrad with respect to the corresponding primary track are searched for in the CS in a 2 mm wide area around the projected point. If three or more tracks are found in the CS that can be associated to a given primary track (*shower hint*), an additional volume scan along the candidate tracks is done, aiming at the reconstruction of the electromagnetic shower. If a shower is found, a careful inspection is performed around the primary track in the first two foils downstream the interaction vertex. The aim is to establish whether the primary track is from a single particle (an electron) or from an e^+e^- pair (and so to be able to reject electromagnetic showers initiated by the early conversion of a γ from a π^0 decay). In addition, a scan-back procedure along the electromagnetic shower, as described in [1], is applied. Such procedure, which was implemented to increase the detection efficiency for $\tau \to e$ decay, is also beneficial for the detection of ν_e CC interactions. Events with an electron track associated with the neutrino interaction vertex are ν_e candidates and their energy is estimated from the calorimetric measurement in the TT section [8]. The analysis described in this paper uses data collected in 2008 and 2009, corresponding to 5.25×10^{19} proton on target (pot). 2853 vertices were localized in the bricks, out of which 505 with no muon identified by the electronic detectors. Out of those 505 events, 19 ν_e candidates were found: 17 events applying the procedure described above and 2 events with the scan-back procedure. The ν_e detection efficiency, estimated with a GEANT3 based MC simulation and averaged over the ν_e energy spectrum (the beam contamination component), is $\epsilon_{det} = (53 \pm 5)\%$. For neutrino energies smaller than 30 GeV (20 GeV) $\epsilon_{det} = (43 \pm 5)\%$ ($(35 \pm 4)\%$). An irreducible background in $\nu_\mu \to \nu_e$ oscillations search arises from CC interactions of ν_e and $\bar{\nu}_e$ primary beam components. The estimated number of such background events is 19.4 ± 2.8 (syst). The systematic error is related to the ν_e beam contamination (10%) and detection efficiency, 20% for $E_{\nu_e} < 10$ GeV and 10% for $E_{\nu_e} > 10$ GeV. Two other main sources of background are considered

in this search: (a) π^0 misidentified as an electron in neutrino interactions without a reconstructed muon; (b) ν_τ CC interactions with the τ decaying into an electron. The former was evaluated by counting the number of γs converting in the second and third lead plate after the interaction vertex, in events with a *shower hint* and a reconstructed electromagnetic shower. This number was converted into an estimated background of 0.2 ± 0.2, taking into account the radiation length. Background (b) was computed by MC simulation assuming three-flavour $\nu_\mu \to \nu_\tau$ oscillations at maximal mixing and $\Delta m^2 = 2.32 \times 10^{-3}$ eV^2 [9]; in our sample it amounts to 0.3 ± 0.1 events. Overall the background in the ν_e CC interactions search is 0.4 ± 0.2 events. The expected number of CC interaction from the intrinsic ν_e component of the beam is 19.8 ± 2.8 (syst) events. In the following we analyse two possible oscillation scenarios.

3. Results

Using the oscillation parameters [9]: $\sin^2 2\theta_{13} = 0.098$, $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{32} = \Delta m^2_{31} = 2.32 \times 10^{-3}$ eV^2, also assuming $\delta_{CP} = 0$ and neglecting matter effects, 1.4 oscillated ν_e CC events are expected in the whole CNGS beam energy range. Fig. 1 shows the reconstructed energy distribution of candidate events compared to the energy spectra of the ν_e beam intrinsic component, the oscillated ν_e from the three-flavour oscillation and the previously mentioned background (a) and (b) (stack histogram). The cut on the reconstructed energy ($E < 20$ GeV) is applied to maximize the sensitivity to θ_{13}. With this cut, 4.8 events (from ν_e beam contamination and the backgrounds) are expected, while 4 events are observed. The number of observed events is compatible with the non-oscillation hypothesis and an upper limit on $\sin^2 2\theta_{13} < 0.44$ is derived at 90% Confidence Level (CL). Beyond the three-neutrino paradigm, possible hints for non-standard oscillations have been reported, in particular by the LSND [10] and MiniBooNE [11] experiments. OPERA data were used to set an upper limit on non-standard $\nu_\mu \to \nu_e$ oscillations. In the one mass scale dominance approximation for the $\nu_\mu \to \nu_e$ oscillation probability (with new oscillation parameters θ_{new} and Δm_{new}) 1.4 ν_e events from three-flavour mixing scenario have to be taken into account in the background expectation. The optimal cut on the maximum reconstructed energy is at 30 GeV. We observe 6 events below 30 GeV, while the expected number of events from background is 9.4 ± 1.3 (syst). Since a smaller number of events than the estimated background was observed, we determined, the Feldman and Cousins (F&C) confidence interval [12] and also the
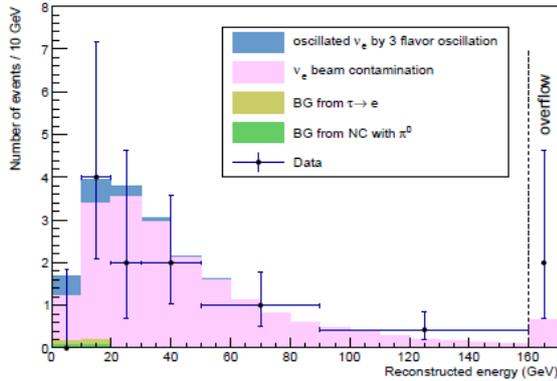
Figure 1: Distribution of reconstructed energy of the ν_e events, and the expected spectrum from different sources in a stack histogram, normalized to the number of pot.

	$\sin^2 2\theta_{new}$ at large Δm^2_{new}	
	F&C	Bayes
90% CL Upper Limit	5×10^{-3}	7.2×10^{-3}
90% CL Sensitivity	9.7×10^{-3}	10.4×10^{-3}

Table 1: 90% CL upper limit and sensitivity on $\sin^2 2\theta_{new}$ at large Δm^2_{new} using F&C and Bayesian methods.

Bayesian bounds, setting a prior to zero in the unphysical region and to a constant in the physical region [13]. The results obtained from the two methods are reported in Tab. 1; the OPERA sensitivity, calculated assuming 9 observed events, is also quoted. Given the underfluctuation of the data, the curve with the Bayesian upper limit was chosen for the exclusion plot shown in Fig. 2. For large Δm^2_{new} values the OPERA 90% upper limit on $\sin^2 2\theta_{new}$ is 7.2×10^{-3}, while the sensitivity corresponding to the number of pot used for this analysis is 10.4×10^{-3}.
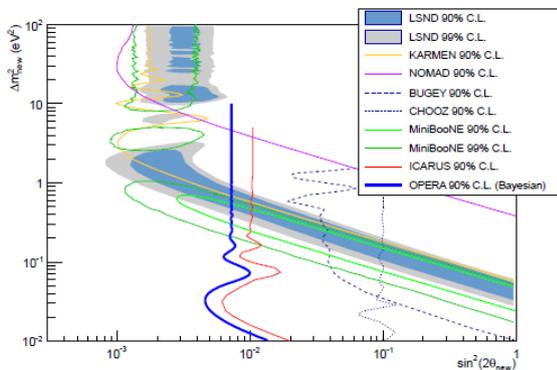

Figure 2: The exclusion plot for the parameters of the non-standard $\nu_\mu \rightarrow \nu_e$ oscillation, obtained using Bayesian method, is shown.

4. Conclusions

The OPERA experiment searched for the appearance of ν_e in the CNGS neutrino beam using data collected in 2008 and 2009 runs. The observation of 19 ν_e candidate events, to be compared with 19.8 ± 2.8 events from the intrinsic ν_e component of the CNGS beam, is compatible with the non-oscillation hypothesis. The derived upper limit on the mixing angle θ_{13} in the three-flavour neutrino oscillation scenario is at $\sin^2 2\theta_{13} < 0.44$ (90% CL). OPERA limits the parameter space available for non-standard ν_e appearance suggested by the result of the LSND and MiniBooNE experiments. For large Δm^2_{new} values, the 90% CL upper limit on $\sin^2 2\theta_{new}$ is 7.2×10^{-3}. This result is still affected by the statistical underfluctuation, the sensitivity corresponding to the analysed statistics being 10.4×10^{-3}. A Bayesian statistical treatment has therefore been adopted in determining the upper limit.

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