PROCEEDINGS OF SCIENCE

# OPERA, Emulsion Scanning, Analysis And Recent Results On $\nu_\mu \rightarrow \nu_e$ Oscillations

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The OPERA detector in the underground Gran Sasso Laboratory (LNGS) has been designed to detect $\nu_\mu \rightarrow \nu_\tau$ oscillations in the appearance mode. The hybrid apparatus consists of an emulsion/lead target and of electronic detectors. Runs with the CNGS neutrino beam from CERN were carried out from 2008 to 2012. Thanks to the high spatial resolution of nuclear emulsion that allows the detection of electrons produced in $\nu_e$CC interaction, a search for a $\nu_e$ appearance in the CNGS neutrino beam can be performed in the experiment. A first result of the search for $\nu_\mu \rightarrow \nu_e$ oscillations in the OPERA experiment is presented using the data collected in 2008 and 2009. Data are compatible with the non-oscillation hypothesis in the three-flavour mixing model. A further analysis of the same data constrains the non-standard oscillation parameters $\theta_{new}$ and $\Delta m^2_{new}$ suggested by the LSND and MiniBooNE experiments. For large $\Delta m^2_{new}$ values ($> 0.1 eV$) , the OPERA 90% C.L. upper limit on $sin^2(2\theta_{new})$ based on a Bayesian statistical method reaches the value $7.2 \times 10^{-3}$.

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## 1. Introduction

The OPERA experiment is designed to perform an appearance search for the $\nu_\mu \to \nu_\tau$ oscillations in the CNGS $\nu_\mu$ beam produced at CERN and directed towards the OPERA detector at the Gran Sasso Underground Laboratory (LNGS), 730 km away. A charged-current (CC) $\nu_\tau$ interaction in the lead-emulsion target can be identified by detecting the decay of the short-lived $\tau$ lepton in the high-resolution nuclear emulsions. The observation of two $\nu_\tau$ candidate events has recently been reported [1, 2]. The tracking capabilities of emulsions also allow to identify electrons produced in $\nu_e$CC interactions and therefore to search for $\nu_e$ appearance from $\nu_\mu \to \nu_e$ oscillations.

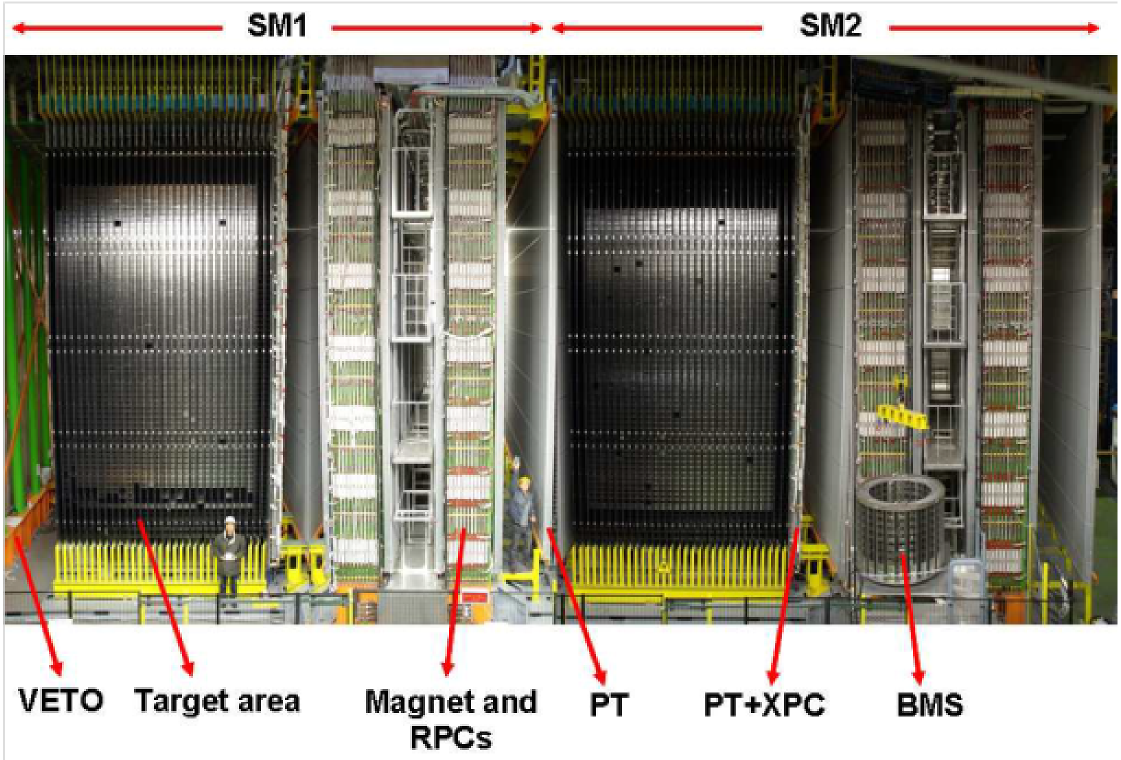

**Figure 1:** View of the OPERA detector; the neutrino beam enters from the left. The upper horizontal lines indicate the two identical super-modules (SM1 and SM2). The target area is made of walls filled with lead/emulsion bricks interleaved with 31 planes of plastic scintillators (TT) per SM. The VETO detector and a magnet with its inserted RPC planes are indicated by arrows, as well as some precision drift tubes planes (PT) and RPC planes with inclined readout strips (XPC). The Brick Manipulator System (BMS) is also visible[3].

## 2. The OPERA Experiment and Data Taking

In OPERA, neutrinos interact in a large mass target made of lead plates interspaced with nuclear emulsion films acting as a high accuracy tracking device [4, 5]. This kind of target is historically called Emulsion Cloud Chamber (ECC). The detector [4] is composed of two identical super-modules (SM) as shown in Figure 1. Each of them has a target section composed by target walls filled with lead/emulsion bricks interleaved with walls of scintillator strips that constitute the Target Tracker (TT). Each target wall contains about 2830 bricks.

A brick is a mechanical unit which contains 57 emulsion films interleaved with 56, 1 mm thick lead plates. The transverse size of the brick is $12.8 \times 10.2\ cm^2$. Each emulsion film has two 44 $\mu m$ thick emulsion layers deposited on a 205 $\mu m$ thick plastic base. Tightly packed removable doublets of emulsion films, called Changeable Sheets (CS) [6], are placed on the downstream face of each brick. They serve as interfaces between the TT planes and the bricks to facilitate the location of the neutrino interactions. Charged particles from a neutrino interaction in a brick cross the CS and produce signals in the scintillator strips of the TT. These signals are used to trigger the read-out and identify the brick where the interaction occurred. The brick is then extracted by an automated brick manipulator. After development, the emulsion films are sent to the scanning laboratories [7]. The CNGS beam, to which the OPERA detector is exposed, contains a small contamination of $\overline{\nu}_\mu$, $\nu_e$ and $\overline{\nu}_e$. The contamination of $\nu_e$ and $\overline{\nu}_\mu$ CC interactions at Gran Sasso relative to the number of $\nu_\mu$ CC interactions is 0.88% and 0.05%, respectively [9]. OPERA collected data corresponding to $17.97 \times 10^{19}$ protons on target (p.o.t.) by December 2012 with 18941 events recorded. The analysis reported in this paper uses the data collected in 2008 and 2009, corresponding to $5.25 \times 10^{19}$ p.o.t. ($1.73 \times 10^{19}$ and $3.52 \times 10^{19}$ p.o.t., respectively) and to 5255 events recorded. The details of data taking and a comparison with Monte Carlo (MC) simulations for the 2008 and 2009 runs have been reported [4, 3].

## 3. Emulsion scanning and search for $\nu_e$ interactions

Bricks that are candidates for containing neutrino interactions are analysed following a procedure that has been described in detail [1, 8]. Here we just recall the main steps of the analysis. The TT predictions are used for a large area scan of the corresponding CS films. If candidate tracks corresponding to the TT predictions are found in the CS, the 57 films contained in the brick are developed, and sent to the scanning labs. The tracks found in the CS are then followed upstream from film to film (scan-back) to find the neutrino interaction vertex. Once the vertex is found, the scanning of a volume around the vertex (1 $cm^2$ in area and at least 7 films; 3 downstream and 4 upstream) is performed in order to reconstruct all the tracks connected to the vertex and to search for decay topologies. The main goal is the observation of the decay of a $\tau$ lepton, as a signature for a $\nu_\tau$ CC interaction. Moreover, the scanning also allows identifying electrons, hence looking for $\nu_e$ CC interactions. The identification of an electron is essentially based on the detection of the associated electromagnetic shower. Since the size of the standard scanned volume is too short in the beam direction to contain the electromagnetic shower, the search for electrons is performed using an extended scanning volume defined by a dedicated procedure sketched in Figure 2. All primary tracks emerging from the interaction vertex are extrapolated to the CS. The tracks with angles similar ($\Delta\theta < 150\ mrad$) to that of the corresponding primary track (Figure 2b) are searched in the CS region within 2 mm around the projected point. If three or more tracks are found in the CS, corresponding to a given primary track, an additional volume along the candidate track is scanned, aiming at the reconstruction of an electromagnetic shower (Figure 2c) [7].

If a shower is found, the corresponding primary track becomes an electron candidate. The candidate track is then carefully inspected in the first two emulsion films following the interaction

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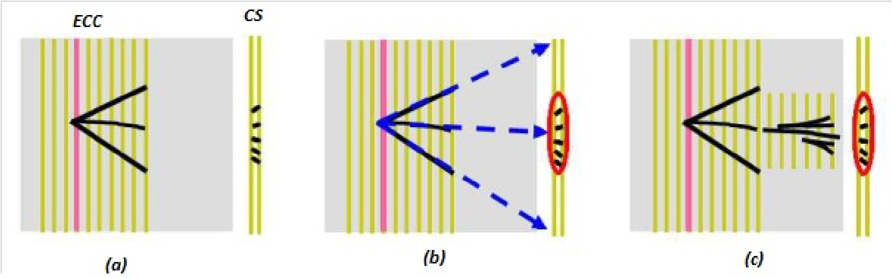

**Figure 2:** Sketch for the procedure of a systematic search for $\nu_e$ candidates. After the reconstruction of tracks in the standard volume (a), all tracks emerging from the interaction vertex (the pink film) are extrapolated to the CS (b). If 3 or more tracks are found in the CS, corresponding to a given track, an additional volume along the full track length is scanned, leading to the detection of the electromagnetic shower (c)[7].

vertex. The aim is to check whether the track is due to a single particle (an electron) or to an $e^+e^-$ pair and so to reject electromagnetic showers initiated by the early conversion of a gamma from a $\pi^0$ decay. Once the presence of an electron track is confirmed at the neutrino interaction vertex, the event is classified as a $\nu_e$ interaction candidate. The energy of the $\nu_e$ candidates is estimated from the calorimetric measurement in the TT [3] and the estimated energy resolution for an energy range up to 100 GeV can be parametrized as:

$$\Delta E/E = 0.37 + 0.74/\sqrt{E} \text{ (E in GeV )}$$

During the 2008 and 2009 runs, 5255 candidate neutrino interactions collected. Among them 2853 vertices were localized in the bricks, out of which 505 did not have a muon identified by the electronic detectors, i.e. were not classified as $\nu_\mu$ CC interactions.Out of those 505 events 19 $\nu_e$ candidate events were found, 17 events were found with the procedure illustrated in Figure 2. The other 2 remaining events were found with the scan-back procedure. To illustrate the typical pattern of $\nu_e$ candidates, Figure 3 shows the reconstructed image of a $\nu_e$ candidate event, with the track segments observed along the showering electron track.

## 4. Results of the search for $\nu_\mu \to \nu_e$ oscillations

The observation of 19 $\nu_e$ candidate events is compatible with the non-oscillation expectation of $19.8 \pm 2.8$ events. This result in the framework of the three-flavour neutrino oscillations yields an upper limit of $sin^2(2\theta_{13}) < 0.44$ (90% C.L.). The parameter space available for a non-standard $\nu_e$ appearance suggested by the results of the LSND and MiniBooNE experiments is limited by the OPERA experiment. It further constrains the still allowed region around $\Delta m^2_{new} = 5 \times 10^{-2} eV^2$. For large $\Delta m^2_{new}$ values, the 90% C.L. upper limit on $sin^2(2\theta_{new})$ reaches $7.2 \times 10^{-3}$.

The 90% C.L. upper limit on $sin^2(2\theta_{new})$ was computed by comparing the expectation from oscillation plus backgrounds, with the observed number of events. Since we observed a smaller number of events than the expected background, we computed both the Feldman and Cousins F&C confidence intervals [10] and the Bayesian bounds, setting a prior to zero in the unphysical region and to a constant in the physical region [11]. Uncertainties on the background were incorporated

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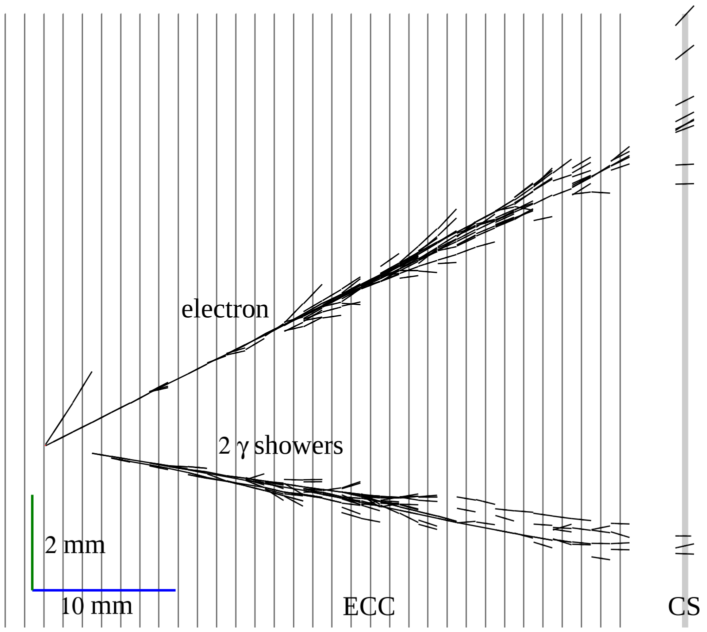

**Figure 3:** Display of the reconstructed emulsion tracks of one of the $\nu_e$ candidate events. The reconstructed neutrino energy is 32.5 GeV. Two tracks are observed at the neutrino interaction vertex. One of the two generates an electromagnetic shower and is identified as an electron. In addition, two showers from gamma conversions are observed (overlapping in this projection), starting from 2 and 3 films downstream of the vertex[7].

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using prescriptions provided [12]. The results obtained by the two methods for the different C.L. are reported in table 1. Given the underfluctuation of the data, the curve with the Bayesian upper limit was chosen for the exclusion plot shown in Figure 4 [7].

| | C.L. | Upper Limit | | Sensitivity | |
|---|---|---|---|---|---|
| | | F&C | Bayes | F&C | Bayes |
| Number of oscilatted $\nu_e$ events | 90% | 3.1 | 4.5 | 6.1 | 6.5 |
| | 95% | 4.3 | 5.7 | 7.8 | 7.9 |
| | 99% | 6.7 | 8.2 | 10.7 | 10.9 |
| $sin^2(2\theta_{new})$ at large $\Delta m^2$ | 90% | $5\times10^{-3}$ | $7.2\times10^{-3}$ | $9.7\times10^{-3}$ | $10.4\times10^{-3}$ |
| | 95% | $6.9\times10^{-3}$ | $9.1\times10^{-3}$ | $12.4\times10^{-3}$ | $12.7\times10^{-3}$ |
| | 99% | $10.6\times10^{-3}$ | $13.1\times10^{-3}$ | $17.1\times10^{-3}$ | $7.2\times10^{-3}$ |

**Table 1:** Upper limits on the number of oscillated $\nu_e$ CC events and $sin^2(2\theta_{new})$, obtained by the F&C and Bayesian methods, for C.L. 90%, 95%, 99%. The sensitivity is computed assuming that the number of observed events is 9, which is the closest integer to the 9.4 expected background events[7].

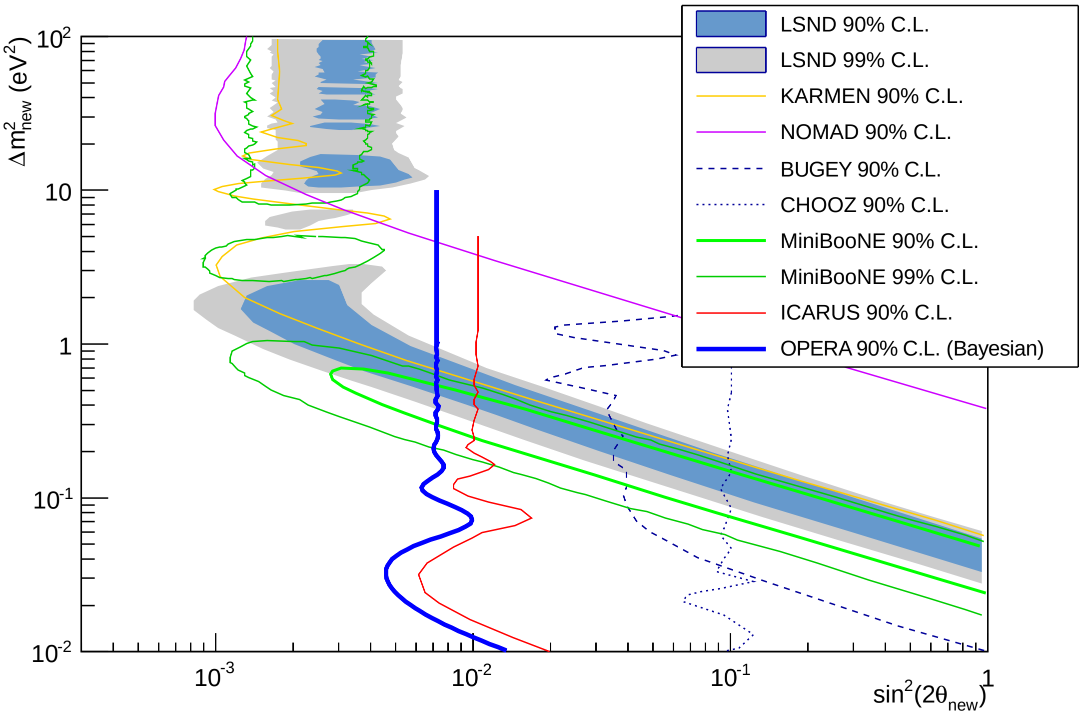

**Figure 4:** The exclusion plot for the parameters of the non-standard $\nu_\mu \rightarrow \nu_e$ oscillation, obtained from the analysis using the Bayesian method, is shown. The other limits shown, mostly using frequentist methods, are from KARMEN ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$[13]), BUGEY ($\bar{\nu}_e$ disappearance [14]), CHOOZ ($\bar{\nu}_e$ disappearance [15]), NOMAD ( $\nu_\mu \rightarrow \nu_e$ [16]) and ICARUS ( $\nu_\mu \rightarrow \nu_e$ [17]). The regions corresponding to the positive indications reported by LSND ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ [18]) and MiniBooNE ( $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ [19]) are also shown[7].

## 5. Conclusion

First results of a search for $\nu_\mu \rightarrow \nu_e$ oscillations with the OPERA experiment have been presented. The experiment searched for the appearance of $\nu_e$ in the CNGS neutrino beam using the data collected in 2008 and 2009, corresponding to an integrated intensity of $5.25x10^{19}$ p.o.t. The result is still affected by the statistical underfluctuation, the sensitivity corresponding to the analysed statistics being $10.4\times10^{-3}$. Therefore, to determine the upper limit, a Bayesian statistical treatment has been adopted. The improvements in the analysis and with the increase in sample size the effect of a possible statistical underfluctuation of the background will be reduced and OPERA should then be able to access the parameter region comparable to its sensitivity below $sin^2(2\theta_{new}) = 5.0\times10^{-3}$ [7].

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