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Study of OPERA sensitivity in the $\nu_\mu \to \nu_e$ oscillation channel

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Summary. — We report on the study of the sensitivity in the $\nu_\mu \to \nu_e$ oscillation channel of the OPERA detector at the Gran Sasso Laboratory along the CNGS neutrino beamline. An identification procedure for ν_e events was defined and a full Monte Carlo simulation was used in order to simulate the detection of real events and evaluate the identification efficiency. A cut on the reconstructed neutrino energy was studied with the purpose of improving the sensitivity on the $\nu_\mu \to \nu_e$ oscillation parameters. Finally a further analysis of the OPERA sensitivity in (3+1)-neutrino mixing model was performed.

PACS 14.60.Pq – Neutrino mass and mixing.
PACS 14.60.St – Non-standard-model neutrinos.

1. – Introduction

The OPERA experiment is designed to search for $\nu_\mu \to \nu_\tau$ oscillations in a pure ν_μ beam [1]. The ν_μ beam is produced at CERN and directed to the OPERA detector located in Hall C of the LNGS underground laboratory, 732 km away. A charged-current (CC) ν_τ interaction in the lead-emulsion target can be identified by detecting, via tracking in the high-resolution photo emulsion, the decay of the short-lived τ lepton. The observation of two ν_τ candidate events has been recently reported [2, 3].

The capabilities of the emulsions for charged-particle tracking also allows to unambiguously identify the electrons produced in ν_e CC interactions. In this work we defined an identification procedure for ν_e events and by means of Monte Carlo (MC) technique we simulated all the procedure for the location and identification of ν_e events allowing us to evaluate both location and identification efficiency. Moreover a cut on the reconstructed neutrino energy was studied in order to optimize the sensitivity on $\nu_\mu \to \nu_e$ oscillation parameters. Finally we used the recent measurement of θ_{13} [4], to analyze OPERA sensitivity in a (3+1)-neutrino mixing model accommodating a fourth sterile neutrino specie.

Table I. – *CNGS beam features and interactions expected in OPERA.*

$L/\langle E_{\nu_\mu}\rangle$	43 km/GeV
ν_μ	$7.36 \times 10^{-9}\,\mathrm{m}^{-2}$ pot^{-1}
ν_e/ν_μ	0.89%
$\bar{\nu}_e/\nu_\mu$	0.06%
$\bar{\nu}_\mu/\nu_\mu$	2.1% (CC)
ν_τ/ν_μ	negligible
ν_μ CC	5.05×10^{-17} pot^{-1} kton^{-1}

2. – OPERA experiment and CNGS beam

OPERA detector is installed in Hall C of the Gran Sasso Laboratory (LNGS) under 1400 meter of rock overburden and is exposed to the CERN to Gran Sasso (CNGS) neutrino beam [5]. The CNGS is a conventional neutrino beam. It is an almost pure ν_μ beam designed and optimized for the ν_τ appearance. The high energy of the beam (the mean neutrino energy is ~ 17 GeV), well above the threshold for τ production, is chosen to maximize the number of CC interactions at Gran Sasso of ν_τ produced by the oscillation mechanism. The average L/E_ν ratio is 43 km/GeV, that makes the ν_μ spectrum "off peak" with respect to the maximum oscillation probability for $\Delta m^2 = 2.4 \times 10^3\,\mathrm{eV}^2$. During a nominal SPS cycle two extractions separated by 50 ms are performed, each one lasts 10.5 μs and contains 2.4×10^{13} protons at 400 GeV/c. The $\bar{\nu}_\mu$ contamination is 2.1% in terms of CC interactions, the $(\nu_e + \bar{\nu}_e)$ contamination is 0.95% and the prompt ν_τ is totally negligible. A summary of the CNGS features is shown in table I. Neutrino fluxes are shown in fig. 1.

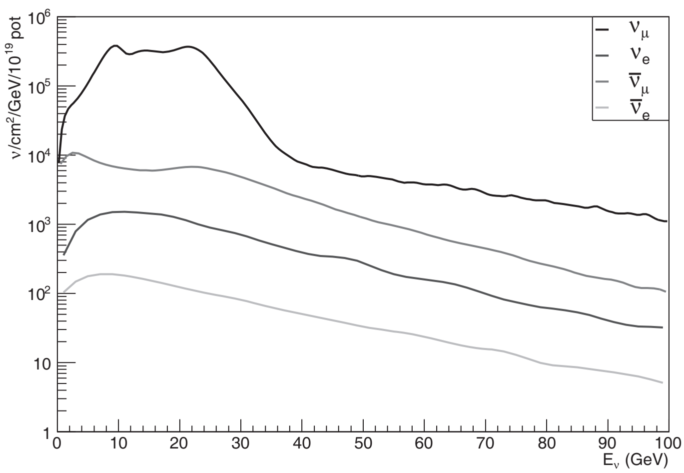


Fig. 1. – Neutrino fluxes from CNGS as expected at LNGS underground laboratory.

The OPERA detector [6, 7] is an hybrid apparatus with a modular structure and consists of a large-mass target made of lead plates interspaced with nuclear emulsion films acting as high-accuracy tracking device. This tracking detector, historically called Emulsion Cloud Chamber (ECC), is assembled in modules (*bricks*). Bricks are grouped in planar structures perpendicular to the beam direction, called *walls*. Each brick wall is followed by planes of plastic scintillators, *Target Tracker* (TT), which provides real-time detection of the outgoing charged particles. The TT main task is to trigger neutrino interactions, locate the brick in which the interaction occurred and provide calorimetric measurement of the hadronic shower energy. In addition the detector is instrumented with veto planes and two muon spectrometers.

The brick is composed by 56 lead plates of 1 mm thickness interleaved with 57 emulsion films. It has an overall dimension of $128 \times 102 \times 79\,\mathrm{mm}^3$ and its thickness along the beam direction corresponds to about 10 radiation lengths. The mass of a brick is 8.3 kg, leading to an overall target mass of ~ 1.2 kton. In order to reduce the emulsion scanning load, Changeable Sheets (CS) film interfaces were used [8]. They consist of tightly packed doublets of emulsion film glued to the downstream face of each brick. The main aim of a CS is to confirm the neutrino interaction and to provide a geometrical connection between the 1 cm resolution of scintillator and the 1 μm resolution of ECCs.

3. – Simulation and analysis

Data taking is based on a minimum bias interaction trigger from the TT scintillators. A software reconstruction program processes the electronic detector data to select the brick with the highest probability to contain the neutrino interaction vertex. An additional software is responsible for the reconstruction of the outgoing track and the identification of the candidate muon track.

Bricks selected by the finding algorithm are removed from the target wall, exposed to X-rays (to allow CS-to-brick alignment); the CS doublet is detached from the brick and developed underground. The corresponding CS films are then analyzed to validate the selected brick. Validation is achieved if at least one track compatible with tracks reconstructed in the electronic detectors is detected in the CS films. In case of validation the brick is brought to the surface to be exposed to penetrating cosmic rays for a precise film-to-film alignment. Brick emulsion films are then developed and dispatched to the various scanning laboratories.

All tracks measured in the CS are sought in the most downstream films of the brick and then followed back. This procedure is called *scanback* and consists in projecting the measured track into the upstream emulsion film and search for candidate track within spatial and angular tolerances defined using the projection of the track slope both in the x-z plane (θ_x) and in the y-z plane (θ_y), where z is the beam direction, y is the vertical axis and x the horizontal one. The tolerances are

$$\Delta x(y) = (80 + 6 \cdot \theta_{x(y)})\,\mu\mathrm{m}, \tag{1}$$

$$\Delta \theta_{x(y)} = (30 + 50 \cdot \theta_{x(y)})\,\mathrm{mrad}, \tag{2}$$

where $\theta_{x(y)}$ is measured in rad. If the candidate track if found the process is repeated until no candidates are found for three consecutive emulsion films. This is considered the signature of a possible neutrino interaction vertex. The upstream plate where the track is found is labeled *stopping plate*, its position in the stopping plate is called *stopping*

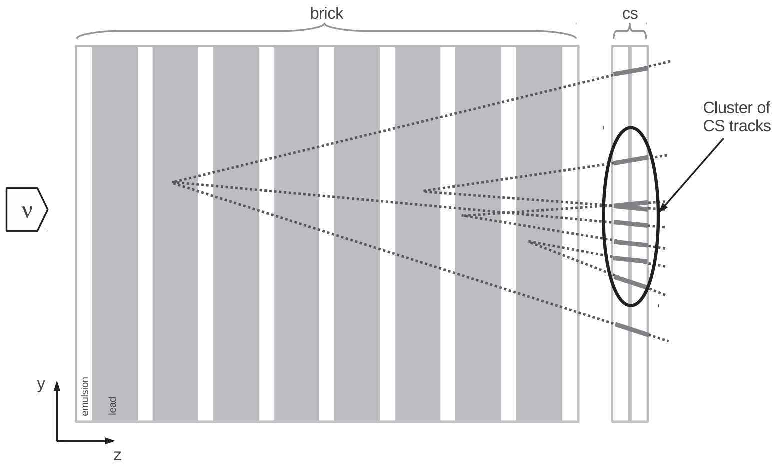


Fig. 2. – Schematic explanation of the *CS shower hint*. Three or more CS tracks, found within the tolerances, are *hint* of a possible electromagnetic shower developed in the brick.

point. A visual inspection is then performed to validate the stopping plate. In order to confirm the neutrino interaction vertex a volume of $1\,\mathrm{cm}^2$ around the stopping point for 15 consecutive films, 5 upstream and 10 downstream of the stopping plate, is scanned.

A further phase of analysis (*decay search* procedure) is applied to located vertices, to detect decay or interaction topologies along tracks attached to the primary vertex, and to search for extra tracks from neutral particle decays, interactions and γ-ray conversions.

In this work the classification of an event as candidate ν_e CC interaction is based on the identification of the associated electron. The conditions for classifying a track as electron are i) low-impact parameter w.r.t. the vertex, ii) the presence of track hits on the first upstream plate confirmed by visual inspection as single track, iii) the signature of an electromagnetic shower in the following downstream plates (by visual inspection or by a shower identification algorithm). This identification procedure is performed every time a *shower hint* is found during the location procedure. Three *shower hints* were defined:

1. *CS shower hint*: Three or more CS tracks are found to be within 2 mm and 0.15 rad of spatial and angular tolerances, respectively (fig. 2).

2. *Scanback shower hint* (fig. 3)

   (a) *Converging pattern* – Three or more scanback tracks found merging into one.

   (b) *e-pair* – An $e^+ e^-$ pair is identified during the visual inspection for the stopping point confirmation.

3. *Vertex to CS shower hint*: Three or more CS track are to be related to a primary track within 2 mm and 0.15 rad of spatial and angular tolerances, respectively (fig. 4).

The total energy of the ν_e candidate is estimated based on a calorimetric measurement of the overlapping electromagnetic and hadronic showers using the information provided by the TT scintillators (*reconstructed neutrino energy* in this paper).

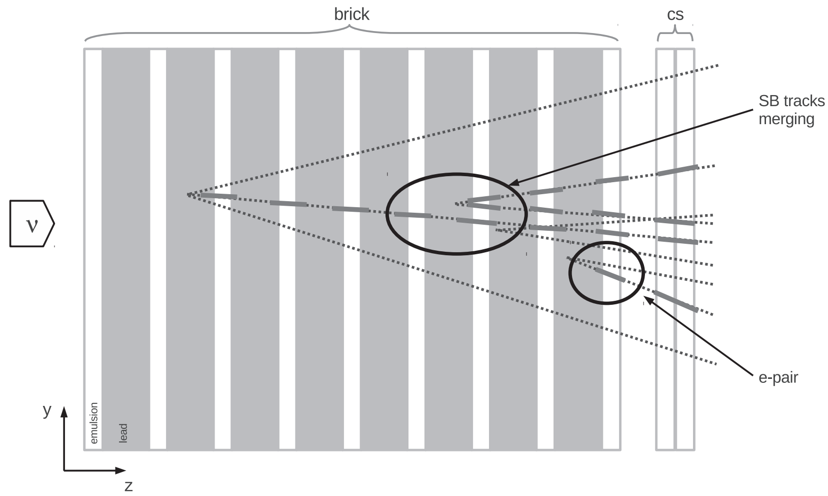


Fig. 3. – Schematic explanation of the *SB shower hint*. Three or more SB tracks, merging during the *scanback* procedure, or the identification of an e-pair, during the visual inspection for the *stopping point* confirmation, are both *hints* of an electromagnetic shower developed in the brick.

The ν_e identification efficiency was determined in the following way. ν_e CC interactions are generated and then propagated in the detector using a GEANT based simulation. All particles are propagated in the lead, in the emulsions, in the TT and in the spectrometers. This data sample is used to study the detection efficiency by applying to it the event reconstruction algorithms. We evaluated separately the efficiency to locate the interaction vertex (ϵ_{loc}) and the efficiency to identify an electron neutrino event (ϵ_{id}).

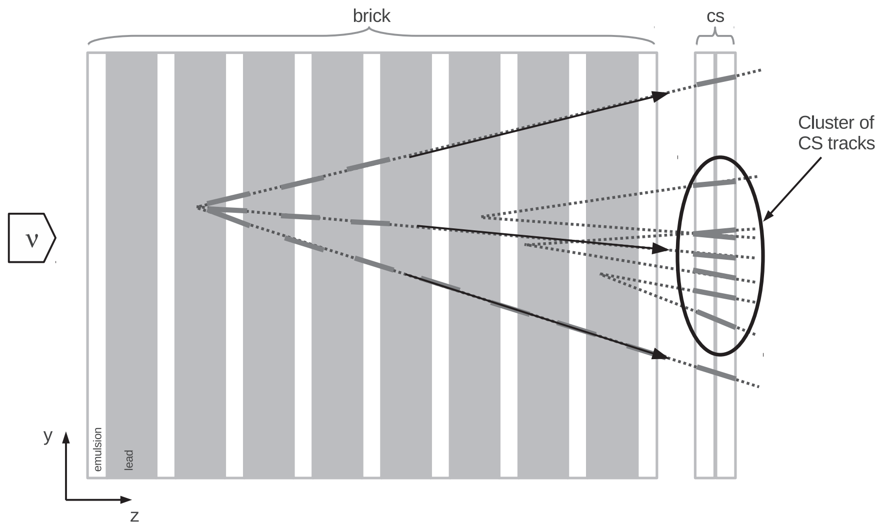
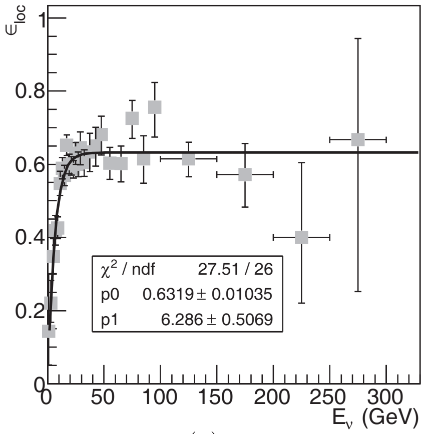
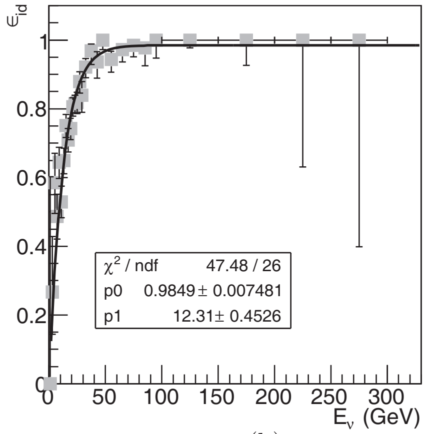


Fig. 4. – Schematic explanation of the *Vertex to CS shower hint*. All primary vertex are projected to CS. A cluster of tracks is searched within tolerances. Three or more CS tracks, belonging to the same cluster, is considered *hint* of a possible electromagnetic shower developed in the brick.



(a)



(b)

Fig. 5. – Location (a) and identification efficiency (b) for ν_e events as evaluated by MC.

The results are shown in fig. 5. They have been both parameterized with an exponential function as

$$\epsilon = k_0 \ (1 - \exp(-E/k_1)) \, . \tag{3}$$

Apart from the dominating background due to intrinsic ν_e beam contamination in this work we considered the additional background due to ν_x NC events with a π^0 misidentified as electron. This background is generated by π^0 decays originating a e^- e^+ pair by γ conversion. Such events constitute a background if the e^- e^+ appears connected to the interaction vertex and cannot be distinguished from a single particle in the first emulsion film after the vertex, or if one of the two electrons produced were outside the detection acceptance.

This background was evaluated directly from the data, analyzing 1106 events (with and without a candidate muon) and looking for a γ conversion in the second and third lead plate downstream the vertex point. A normalization factor was applied to the data sample in order to take into account the different location efficiency for events with and without a candidate muon track. The number of events with a γ conversion in the specified lead plates was then normalized in order to account for the different probability for a γ to convert in the first lead plate and in the second or third ones. The final estimation of π^0 background is $0.16 \ \pm \ 0.16$ events [3].

4. – Results

A signal of ν_e appearance originated by $\nu_\mu \to \nu_e$ oscillations would be given by an excess of events with respect to the expectation from the $\nu_e + \bar{\nu}_e$ beam contamination which can be computed according to the formula

$$N^{\nu_e(\bar{\nu}_e)}_{beam} = N_A \ N_{pot} \ m \int \Phi^{\nu_e(\bar{\nu}_e)}(E) \ \sigma^{\nu_e(\bar{\nu}_e)}_{CC}(E) \ \epsilon_{loc}(E) \ \epsilon_{id}(E) \ \mathrm{d}E, \tag{4}$$

where N_A is the Avogadro constant, N_{pot} is the number of collected proton on target assumed to be 5.3×10^{19}, $m = 1.179$ kton is the mean detector mass, Φ is the neutrino flux and σ_{CC} the neutrino CC cross action in lead.

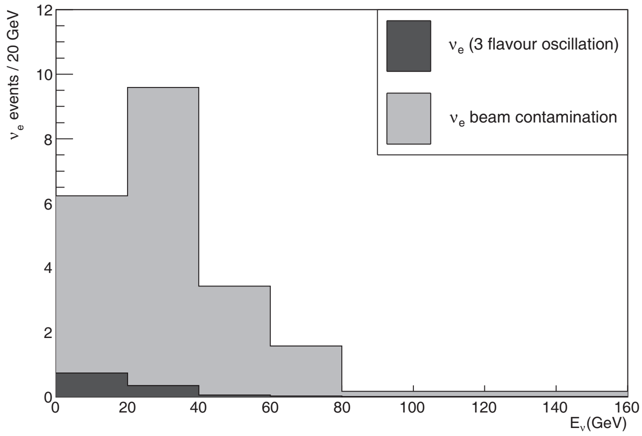


Fig. 6. – Expected reconstructed neutrino energy distribution for ν_e events from beam contamination and from 3-neutrino mixing model oscillation.

Taking into account a conservative 10% systematic uncertainty on the absolute ν_e flux [9, 10], we expect to observe $N^{\nu_e}_{beam} = 20.5 \pm 2.0$ (sys) ν_e events from the beam contamination and NC background. The number of expected ν_e events is 1.2, obtained from 3-neutrino mixing model oscillations assuming $\Delta m^2_{atm} = 2.47 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2(2\theta_{23}) = 0.97$, $\delta_{CP} = 0$ and $\sin^2(2\theta_{13}) = 0.09$ as provided by reactor experiments [4].

Figure 6 shows the expected reconstructed neutrino energy distribution for the beam contamination and the oscillated ν_e (via 3-neutrino mixing model oscillations), normalized to the pot analyzed for this paper. Different reconstructed neutrino energy cut values were studied, from 5 to 50 GeV with 5 GeV step (fig. 7); we found that the reconstructed neutrino energy cut optimizing the sensitivity to θ_{13} is $E^{rec}_\nu < 25\,\mathrm{GeV}$. Applying this cut the OPERA sensitivity to $\sin^2 2\theta_{13}$ at high value of Δm^2_{13} is $\sim 2 \times 10^{-2}$.

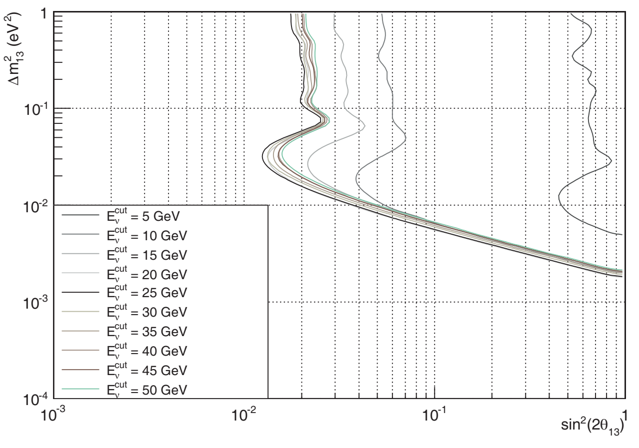


Fig. 7. – Sensitivity curves for different reconstructed neutrino energy cut values. The reconstructed neutrino energy cut that optimizes the sensitivity to θ_{13} is $E^{rec}_\nu < 25\,\mathrm{GeV}$.

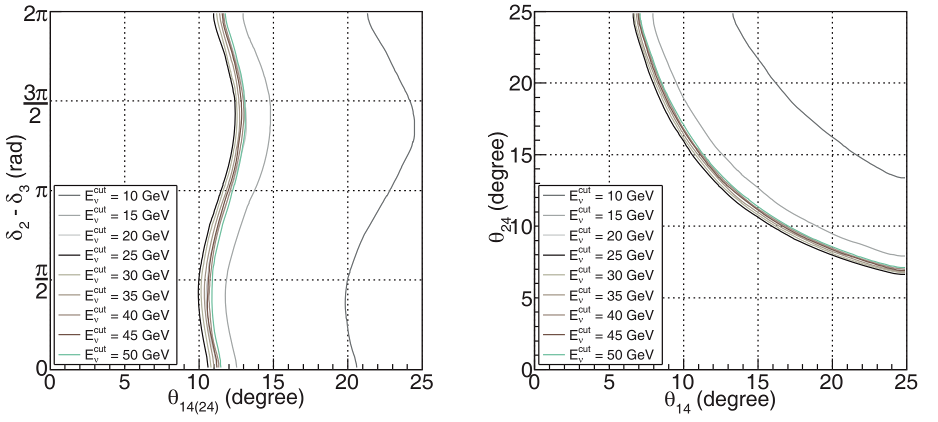
TABLE II. – *In the table two examples of the number of oscillated ν_e events in the* (3 + 1)*-neutrinos mixing model* ($N^{\nu_e}_{3+1}$) *are shown.* $N^{\nu_e}_{3+1}$ *strongly depends on the oscillation parameter* (θ_{14}*,* θ_{24} *and* $\delta_2 - \delta_3$) *values and in particular depending on the* $3 + 1$ *oscillation parameter values,* $N^{\nu_e}_{3+1}$ *could be lower or higher with respect of the number of* ν_e *events expected in the 3-neutrinos mixing model* ($N^{\nu_e}_3$).

case 1	case 2	3ν model
$\theta_{14} = 0°$	$\theta_{14} = 3°$	$\theta_{14} = 0°$
$\theta_{24} = 25°$	$\theta_{24} = 25°$	$\theta_{24} = 0°$
$\delta_2 - \delta_3 = 0\,\text{rad}$	$\delta_2 - \delta_3 = 0\,\text{rad}$	$\delta_2 - \delta_3 = 0\,\text{rad}$
$N^{\nu_e}_{3+1} = \mathbf{0.77}$	$N^{\nu_e}_{3+1} = \mathbf{2.4}$	$N^{\nu_e}_3 = \mathbf{0.94}$

Neutrino oscillations in models beyond the standard 3-neutrino mixing model, requiring the existence of one or more sterile neutrino have also been considered. Searches and possible hints for non-standard effects are reported in literature, in particular by the LSND [11] and MiniBoone [12] Collaborations. We adopted a model with one sterile neutrino separated from three active ones by an $\mathcal{O}(\text{eV}^2)$ mass-squared difference when oscillations driven by this mass-squared difference are averaged [13]. The fourth-order approximated oscillation probability is

$$(5)\quad \begin{aligned} P_{\mu e} = {} & 4\left\{s^2_{23}s^2_{13}\left[1 - s^2_{13} - s^2_{14} - s^2_{24}\right] + s_{23}s_{13}s_{14}s_{24}\cos(\delta_2 - \delta_3)\right\}\sin^2\frac{\Delta m^2_{atm}L}{4E_\nu} \\ & \pm 2s_{23}s_{13}s_{14}s_{24}\sin(\delta_2 - \delta_3)\sin\frac{\Delta m^2_{atm}L}{4E_\nu} + 2s^2_{14}s^2_{24}, \end{aligned}$$

where s_{ij} stands for $\sin(\theta_{ij})$ and δ_j are the CP violating phases. $L = 732\,\text{km}$ is the neutrino baseline and E_ν is the neutrino energy.



(a)

(b)

Fig. 8. – Sensitivity curves for different reconstructed neutrino energy cut values in the $\theta_{14(24)}$ -($\delta_2 - \delta_3$) plane (a) and in θ_{14} - θ_{24} plane (b). The reconstructed neutrino energy cut value that optimizes the sensitivity to θ_{14}, θ_{24} and ($\delta_2 - \delta_3$) is $E^{rec}_\nu < 25\,\text{GeV}$.

It is worth mentioning that the interference terms play a crucial role. In fact, the number of expected oscillated ν_e events in the (3+1)-neutrinos mixing model ($N_{3+1}^{\nu_e}$) strongly depends on the oscillation parameter (θ_{14}, θ_{24} and $\delta_2 - \delta_3$) values, as could be seen in the examples reported in table II. In particular in case 1 $N_{3+1}^{\nu_e}$ is smaller than the number of ν_e events expected in 3 neutrinos mixing model ($N_3^{\nu_e}$), while in case 2 $N_{3+1}^{\nu_e}$ is larger.

We studied different reconstructed neutrino energy cut values, from 10 to 50 GeV with 5 GeV step, as shown in fig. 8 and we found that the reconstructed neutrino energy cut which maximize the sensitivity to $\theta_{14(24)}$ is again $E_\nu^{rec} < 25\,\mathrm{GeV}$.

5. – Conclusions

In this work we studied the OPERA sensitivity in the $\nu_\mu \to \nu_e$ oscillation channel. We defined an identification procedure for ν_e events. The ν_e were identified by looking for single-electron tracks at the primary vertex. Electrons were identified searching for *shower hints*. A MC simulation of the location and identification procedures allowed to evaluate the search efficiencies. Taking into account the efficiencies we evaluated the number of ν_e events expected from beam contamination and NC background. We also optimized reconstructed neutrino energy cut in order to improve the search sensitivity; we found $E_\nu^{rec} < 25\,\mathrm{GeV}$ to be the best cut allowing OPERA to reach a sensitivity of $\sim 2 \times 10^{-2}$ for $\sin^2 2\theta_{13}$ in the high Δm_{13}^2 region. We also studied the sensitivity in the (3+1)-neutrino mixing model in the high mass-squared hypothesis The reconstructed neutrino energy maximizing the sensitivity to $\theta_{14(24)}$ is $E_\nu^{rec} < 25\,\mathrm{GeV}$.

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