RESEARCH NOTES FROM COLLABORATIONS

Sensitivity to θ_{13} of the CERN to Gran Sasso neutrino beam

M Komatsu[1], P Migliozzi[2] and F Terranova[3]

[1] Nagoya University, Japan
[2] INFN, Napoli, Italy
[3] INFN, Laboratori Nazionali Frascati, Italy

Abstract
The sensitivity of the present CNGS beam to the sub-dominant $\nu_\mu \leftrightarrow \nu_e$ oscillations in the region indicated by the atmospheric neutrino experiments is investigated. In particular, we present a revised analysis of the OPERA detector and discuss the sensitivity to θ_{13} of ICARUS and OPERA combined. We show that the CNGS beam optimized for ν_τ appearance will improve significantly (about a factor of 5) the current limit of CHOOZ and explore most of the region $\sin^2 2\theta_{13} \simeq \mathcal{O}(10^{-2})$.

1. Introduction

There are currently intense efforts to confirm and extend the evidence for neutrino oscillations in the atmospheric and solar sectors. In particular the disappearance of muon neutrinos originating from cosmic ray interactions [1, 2] provides a strong hint in favour of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. This indication will be tested in a conclusive manner at the next generation of long baseline experiments. In a simple two-flavour mixing scheme the atmospheric neutrino experiments constrain the mixing parameter in the region around $(\Delta m^2, \sin^2 2\theta) = (2.5 \times 10^{-3}, 1)$. Recently, the SNO experiment gave an unambiguous signature of the solar neutrino oscillations, excluding the sterile neutrino hypothesis [3, 4].

In addition to the dominant $\nu_\mu \leftrightarrow \nu_\tau$ component, sub-dominant oscillations involving also ν_e could be observed. In this three-flavour scenario the gauge eigenstates ν_a ($\alpha = e, \mu, \tau$) are related to the mass eigenstates $\nu_i'(i = 1, 2, 3)$ through the leptonic mixing matrix $U_{\alpha i}$. This matrix can be parametrized as

$$U(\theta_{12}, \theta_{13}, \theta_{23}, \delta) = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,\mathrm{e}^{-\mathrm{i}\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}\,\mathrm{e}^{\mathrm{i}\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}\,\mathrm{e}^{\mathrm{i}\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}\,\mathrm{e}^{\mathrm{i}\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}\,\mathrm{e}^{\mathrm{i}\delta} & c_{13}c_{23} \end{pmatrix} \quad (1)$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$.

Here the leading $\nu_\mu \leftrightarrow \nu_\tau$ transitions are driven by the angle $\sin^2 2\theta_{23}$ and the squared mass difference Δm_{23}^2. Sub-dominant $\nu_\mu \leftrightarrow \nu_e$ oscillations at the atmospheric scale

Table 1. Nominal performance of the CNGS reference beam [10].

$\nu_\mu (\mathrm{m}^{-2}/\mathrm{pot})$	7.78×10^{-9}
ν_μ CC events/pot/kton	5.85×10^{-17}
ν_e/ν_μ	0.8%
$\bar{\nu}_\mu/\nu_\mu$	2.1%
$\bar{\nu}_e/\nu_\mu$	0.07%

Table 2. Number of ν_τ charged-current interactions at Gran Sasso per kton and per year (shared mode) for different values of Δm^2 and $\sin^2(2\theta) = 1$ [10].

Δm^2	ν_τ CC interactions/kton/year
1×10^{-3} eV^2	2.53
3×10^{-3} eV^2	22.8
5×10^{-3} eV^2	63.3

$\left(\Delta m_{23}^2 \simeq 2.5 \times 10^{-3}\right)$ are driven by the mixing angle θ_{13}. This angle is constrained by the CHOOZ experiment to be small ($\sin^2 2\theta_{13} < \mathcal{O}(10^{-1})$) [5].

The next generation of long baseline experiments—MINOS [6], ICARUS [7] and OPERA [8]—will search for a conclusive evidence of the oscillation mechanism at the atmospheric scale. In particular, the CNGS beam [9, 10] will directly confirm the indication for neutrino oscillations through tau appearance.

Although the precision that will be achieved on the parameters driving the dominant $\nu_\mu \leftrightarrow \nu_\tau$ after this first generation of long baseline experiments is well established [11], the sensitivity to the sub-dominant $\nu_\mu \leftrightarrow \nu_e$ channel deserves further investigation, in particular for what concerns CNGS. This is due to the fact that only recently the baseline configuration of the CNGS detectors (ICARUS [7] and OPERA [12]) has been established. Moreover, a full $\nu_\mu \leftrightarrow \nu_e$ analysis with the OPERA experiment has not been carried out yet.

In this note we discuss the sensitivity of the ICARUS and OPERA experiments is searching for θ_{13} by using the present CNGS neutrino beam. The sensitivity of ICARUS to θ_{13} has been evaluated in [7]. For OPERA, whose primary aim is the direct detection of ν_τ appearance, a preliminary estimate of the sensitivity to $\nu_\mu \leftrightarrow \nu_e$ oscillations has been given in the 1999 Letter of Intent [13] and is evaluated here in more detail. The paper is organized as follows: in section 2 we briefly describe the present CNGS neutrino beam, the ICARUS and OPERA experimental set-ups and their features, in section 3 we discuss the ICARUS and OPERA sensitivity to θ_{13} and finally in section 4 we draw our conclusions.

2. The present CNGS experimental programme

2.1. The CNGS neutrino beam

In November 2000 a new version of the CNGS beam design was released [14]. In tables 1 and 2, the performance of the beam is given.

The possibility of an increase of the neutrino beam intensity at moderate cost is being studied by the CNGS design group [14] and other groups working on the PS and SPS machines [15]. The SPS and its injectors have a crucial role for the LHC accelerator and considerable efforts and investment are going into the upgrade of these accelerators to meet the requirements of the LHC. Most of the efforts are also directly beneficial to CNGS: for example, it is

expected that the maximum intensity accelerated in the SPS will be 7×10^{13} rather than 4.5×10^{13} pot/cycle [16]. Moreover, it has been recently pointed out [15] that, taking into account that all the accelerators (LINAC, PSB, PS and SPS) are close to their limits, an increase in the proton beam intensity can be reached—pending further accelerator machine development studies—by reducing the beam losses between two sequential accelerators. These improvements could, at a moderate cost, increase the proton flux by as much as a factor of 1.5.

Other scenarios for a further increase of the SPS extracted beam intensity has been outlined in [15], but those are much more expensive and might turn out to be technically unrealistic. It is therefore prudent to state that an intensity increase for CNGS of a factor 1.5 is within reach.

The CNGS energy spectrum has been optimized for ν_τ appearance and the prompt ν_τ contamination (mainly from D_s decays) is negligible. On the other hand, in the CNGS beam, the expected ν_e contamination is relatively small compared to the dominant ν_μ component, see table 1 and allow search for the sub-dominant oscillation $\nu_\mu \leftrightarrow \nu_e$ seeking after an excess of ν_e charged-current (CC) events.

The systematic error associated with the ν_e contamination plays an important role for the $\nu_\mu \leftrightarrow \nu_e$ oscillation search, the statistical fluctuation of this ν_e component being the irreducible limiting factor. In turn, this uncertainty depends on the knowledge of the K yield. For the sake of consistency with [11, 19], we assume for this study a 5% systematic error on the overall ν_e flux. However, as we will show in section 3.1 due to the small number of selected events, especially in OPERA, a more conservative estimate of the systematics (up to 10%) would not change appreciably the experimental sensitivity.

2.2. The ICARUS experiment

The aim of the ICARUS Collaboration [17] is the construction of a liquid argon time projection chamber (TPC) detector with a space resolution comparable to that of bubble chambers.

In an ICARUS module, a large liquid argon volume is contained in a cryostat equipped with wire readout planes and a high voltage plane at the centre giving a long drift length. Ionization electrons produced by charged particles crossing the liquid argon are collected at the readout planes. The arrival time of the different electrons allows the reconstruction of the particle track trajectory by the time projection technique. Each readout plane has three coordinates at $60°$ from each other and wire pitch of 3 mm. This corresponds to a *bubble* diameter of about 3 mm.

The detector is a homogeneous tracking device capable of dE/dx measurement. Its high dE/dx resolution allows good momentum measurement and particle identification of soft particles. Electromagnetic and hadronic showers are, in fact, identified and fully sampled. This gives the energy resolution for electromagnetic showers of $\sigma(E)/E = 3\%/\sqrt{E(\text{GeV})} \oplus 1\%$ and for hadronic contained showers of $\sigma(E)/E = 16\%/\sqrt{E(\text{GeV})} \oplus 1\%$. ICARUS features excellent electron identification and e/π^0 separation.

The physics programme of the ICARUS experiment as described in the Proposal [17] has been derived assuming a 'baseline configuration' consisting of one T600 plus two T1200 modules for a total fiducial mass of 2.35 kton [7].

2.3. The OPERA experiment

The OPERA experiment [8, 18] is meant for a long baseline search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the CNGS beam [14]. The experiment uses nuclear emulsions as high resolution tracking devices for the direct detection of the τ produced in the ν_τ CC interactions with the target.

Due to its excellent electron identification capability exploited for the reconstruction of the $\tau \to e$ decay, OPERA is able to perform also a $\nu_\mu \leftrightarrow \nu_e$ oscillation search.

OPERA is designed starting from the emulsion cloud chamber (ECC) concept (see references quoted in [8]) which combines the high precision tracking capabilities of nuclear emulsions and the large mass achievable by employing metal plates as a target. The basic element of the ECC is the cell which is made of a 1 mm thick lead plate followed by a thin emulsion film. The film is made up of a pair of emulsion layers 50 μm thick on either side of a 200 μm plastic base. Charged particles give two track segments in each emulsion film. The number of grain hits in 50 μm (15–20) ensures redundancy in the measurement of particle trajectories.

For details on the event reconstruction both with the nuclear emulsions and the electronic detector, and the OPERA sensitivity to $\nu_\mu \leftrightarrow \nu_\tau$ we refer to [8, 18]. The mass of the OPERA 'baseline configuration' is 1.77 kton [12]. In the following an effective mass of 1.65 kton has been assumed to account for the brick removal during data taking.

Thanks to the dense ECC structure and the high granularity provided by the nuclear emulsions, the OPERA detector is also suited for electron and γ detection [8]. The resolution in measuring the energy of an electromagnetic shower in the energy range relevant to CNGS is approximately constant and is about 20%. Furthermore, the nuclear emulsions are able to measure the number of grains associated with each track. This allows an excellent two tracks separation (better than 1 μm). Therefore, it is possible to disentangle single-electron tracks from tracks produced by electron pairs coming from γ conversion in the lead. These features are particularly important for the $\nu_\mu \leftrightarrow \nu_e$ analysis.

The outstanding position resolution of nuclear emulsions can also be used to measure the angle of each charged track with an accuracy of about 1 mrad. This allows momentum measurement by using the multiple Coulomb scattering with a resolution of about 20% and the reconstruction of kinematical variables characterizing the event (i.e. the missing transverse momentum at the interaction vertex p_T^{miss} and the transverse momentum of a track with respect to hadronic shower direction Q_T).

3. Sensitivity to θ_{13}

3.1. Event selection

In this section we discuss the event selection in OPERA and the expected number of signal and background events in both ICARUS and OPERA.

The overall rate is defined as

$$R\left(\Delta m_{23}^2, \sin^2 2\theta_{23}, \sin^2 2\theta_{13}\right) = S + B^{(\tau \to e)} + B^{(\nu_\mu \mathrm{CC} \to \nu_\mu \mathrm{NC})} + B^{(\mathrm{beam})} + B^{(\mathrm{NC})}, \tag{2}$$

where the signal, S, is the convolution of the ν_μ flux $\left(\phi_{\nu_\mu}(E)\right)$ with the ν_e charged-current cross section $\left(\sigma_{\nu_e}^{\mathrm{CC}}(E)\right)$, the $\nu_\mu \leftrightarrow \nu_e$ oscillation probability $\left(P_{\nu_\mu \leftrightarrow \nu_e}(E)\right)$ and the signal efficiency $\left(\epsilon^{\mathrm{signal}}\right)$

$$S = A \int \phi_{\nu_\mu}(E) P_{\nu_\mu \leftrightarrow \nu_e}(E) \sigma_{\nu_e}^{\mathrm{CC}}(E) \epsilon^{\mathrm{signal}} \, \mathrm{d}E. \tag{3}$$

The normalization A takes into account the effective target mass. The background coming from the dominant $\nu_\mu \to \nu_\tau$ oscillation channel where the produced τ decays in one electron is

$$B^{(\tau \to e)} = A \int \phi_{\nu_\mu}(E) P_{\nu_\mu \leftrightarrow \nu_\tau}(E) \sigma_{\nu_\tau}^{\mathrm{CC}}(E) \epsilon^{(\tau \to e)} \, \mathrm{d}E, \tag{4}$$

where $\epsilon^{(\tau \to e)}$ is the efficiency and $\sigma_{\nu_\tau}^{\mathrm{CC}}$ is the ν_τ charged-current cross section. This background includes mainly taus decayed in the same lead plate as the primary vertex ('short decays') plus a small (4%) contribution from 'long decays' where the kink has not been detected.

The background from ν_μ events with the primary muon not identified is given by

$$B^{(\nu_\mu \mathrm{CC} \to \nu_\mu \mathrm{NC})} = A \int \phi_{\nu_\mu}(E) P_{\nu_\mu \leftrightarrow \nu_\mu}(E) \sigma_{\nu_\mu}^{\mathrm{CC}}(E) \epsilon^{(\nu_\mu \mathrm{CC} \to \nu_\mu \mathrm{NC})} \, dE, \tag{5}$$

where $\epsilon^{(\nu_\mu \mathrm{CC} \to \nu_\mu \mathrm{NC})}$ is the probability for a $\nu_\mu \mathrm{CC}$ to be identified as a $\nu_\mu \mathrm{NC}$ and with another track mimicking an electron.

The background coming from the ν_e beam contamination is

$$B^{(\mathrm{beam})} = A \int \phi_{\nu_e}(E) P_{\nu_e \leftrightarrow \nu_e}(E) \sigma_{\nu_e}^{\mathrm{CC}}(E) \epsilon^{(\mathrm{beam})} \, dE, \tag{6}$$

where $\epsilon^{(\mathrm{beam})}$ is the efficiency for CC events from the ν_e beam contamination.

The last background included, $B^{(\mathrm{NC})}$, from the decay of neutral pions created by neutral-current (NC) interactions, is

$$B^{(\mathrm{NC})} = A \int \phi_{\nu_\mu}(E) \sigma_\nu^{(\mathrm{NC})}(E) \epsilon^{(\mathrm{NC})} \, dE, \tag{7}$$

where $\epsilon^{(\mathrm{NC})}$ is the reduction efficiency. Further background from charge exchange process is negligible [8].

The OPERA analysis for $\nu_\mu \leftrightarrow \nu_e$ oscillation quoted in the 1999 Letter of Intent [13] has been revised. The major improvements are the following:

- the muon identification is improved from 80% to 95% [8]. This means that the contribution to the background from $\nu_\mu \mathrm{CC}$ events can drastically be reduced;
- γ's produced at the primary vertex (π^0 decays) and converting into the lead plate where the interaction occurred are identified if at least one of the below conditions is fulfilled

  1. if the $e^+ e^-$ pair has an opening angle larger than 3 mrad. This cut is fixed by the angular resolution achievable by the emulsion films;
  2. if the $e^+ e^-$ pair has an opening angle smaller than 3 mrad, we exploit the nuclear emulsion capability in measuring the number of grains associated with a reconstructed track. The rejection power of this cut has been computed by assuming for a minimum ionizing particle 30 grains per emulsion sheet, while 60 grains are assumed for the $e^+ e^-$ pair with opening angle smaller than 3 mrad. A reconstructed track is classified as an $e^+ e^-$ pair if the associated number of grains is larger than $(30 + 3 \times \sqrt{30})$. Conservatively we consider only the emulsion film downstream from the vertex lead plate. Note, however, that a significant improvement could be obtained including the grains in the subsequent emulsion sheets, crossed by the electrons before showering;

- since neutrino oscillations create an excess of $\nu_e \mathrm{CC}$-induced events at low neutrino energies, a cut on the visible energy is applied.

Hence, the OPERA $\nu_\mu \leftrightarrow \nu_e$ dedicated analysis seeks for neutrino interactions with a candidate electron from the primary vertex with energy greater than 1 GeV (this cut reduces the soft γ component) and a visible energy of the event smaller than 20 GeV (this cut reduces the prompt ν_e component of the background). Moreover, we also apply a cut on the number of grains associated with the track of the candidate electron. The latter has a strong impact on the reduction of the background from $\nu_\mu \mathrm{CC}$ and $\nu_\mu \mathrm{NC}$ events and allowed for a softer cut on the electron energy. Finally, a cut on missing transverse momentum at the primary vertex p_T^{miss} of the event is applied $\left(p_T^{\mathrm{miss}} < 1.5 \, \mathrm{GeV}\right)$ to further reduce NC contaminations and suppress $\tau \to e$ background.

Table 3. Signal and background efficiencies for the $\nu_\mu \leftrightarrow \nu_e$ oscillation search with OPERA. Note that the $\tau \rightarrow e$ efficiency includes the $\tau \rightarrow e\nu\bar{\nu}$ branching ratio.

	ν_eCC signal	$\tau \rightarrow e$	ν_μCC $\rightarrow \nu_\mu$NC	ν_μNC	ν_eCC beam
ξ	0.53	0.53	0.52	0.48	0.53
ϵ	0.31	0.032	0.34×10^{-4}	7.0×10^{-4}	0.082

Table 4. Expected number of signal and background events for both ICARUS and OPERA assuming 5 years' data taking with the nominal CNGS beam and oscillation parameters $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV^2, $\theta_{23} = 45°$ and $\theta_{13} \in [3° \div 9°]$.

| θ_{13}	$\sin^2 2\theta_{13}$	ν_eCC signal	$\tau \rightarrow e$	ν_μCC $\rightarrow \nu_\mu$NC	ν_μNC	ν_eCC beam
ICARUS						
9°	0.095	27	24	–	–	50
8°	0.076	21	24	–	–	50
7°	0.058	16	24	–	–	50
5°	0.030	8.4	25	–	–	50
3°	0.011	3.1	25	–	–	50
OPERA						
9°	0.095	9.3	4.5	1.0	5.2	18
8°	0.076	7.4	4.5	1.0	5.2	18
7°	0.058	5.8	4.6	1.0	5.2	18
5°	0.030	3.0	4.6	1.0	5.2	18
3°	0.011	1.2	4.7	1.0	5.2	18

For the brick finding, the vertex finding, the trigger efficiencies and the fiducial volume cut, we used the numbers quoted in the Status Report [18]. The product of these efficiencies is shown in table 3 and is indicated by ξ.

The final efficiencies (ϵ) for both the signal and the background channels are shown in the second row of table 3, and the expected number of events is shown in table 4.

The search for $\nu_\mu \leftrightarrow \nu_e$ oscillations does not increase the emulsion scanning load by a large amount. Indeed, once the events have been located, the time needed to search for interesting topologies around the reconstructed vertex is small compared with the time needed to locate the events. On the other hand, for events identified as NC produced in the downstream half of the brick one should always remove the following brick to perform the electron identification. It implies that 13% more bricks have to be removed and scanned. Note that in the preliminary estimate quoted in the 1999 Letter of Intent only half of the ECC mass has been used.

If we assume that both $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_e$ oscillations occur simultaneously with oscillation parameters $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV^2, $\theta_{23} = 45°$ and $\theta_{13} \in [3° \div 9°]$, the expected number of signal and background events both in ICARUS and OPERA are given in table 4. The rates are normalized to 5 years' data taking and assuming the nominal intensity of the CNGS beam.

The ICARUS rates at CNGS from $\nu_\mu \leftrightarrow \nu_e$ oscillations and from background sources have been taken from table 5.9 of [7] and scaled at the different oscillation parameters $\left(\Delta m_{32}^2, \sin^2 2\theta_{23}, \sin^2 2\theta_{13}\right)$. Here a cut on the electron energy ($E_e > 1$ GeV) and the visible energy ($E_{\text{vis}} < 20$ GeV) have been applied. In table 4 the background from π^0 production in NC events is negligible for ICARUS as assumed in [7]. This is not true for OPERA being the lead radiation length much shorter than the one of liquid argon. Nevertheless, this background can be further suppressed by a kinematical analysis, see section 3.2. On the
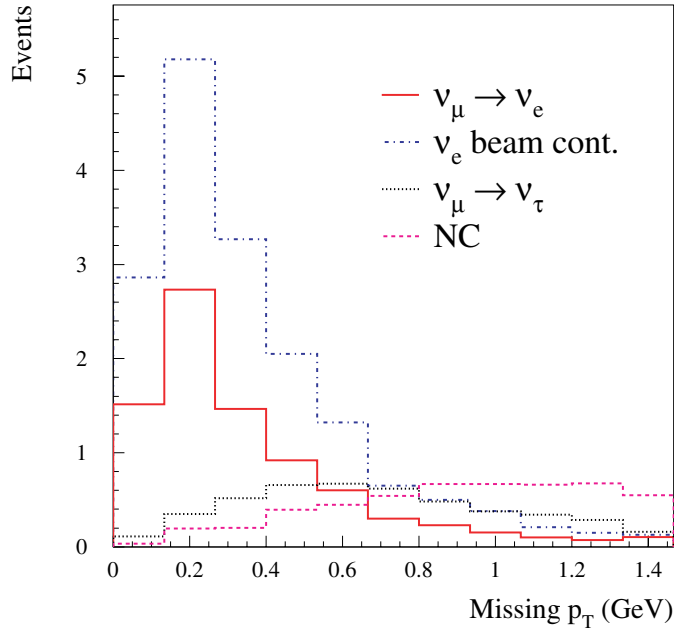
Figure 1. p_T^{miss} distribution for signal and background channels assuming $\theta_{13} = 8°$, $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$ and $\theta_{23} = 45°$.

other hand, the $\tau \to e$ background in OPERA is suppressed by the capability of this detector to reconstruct exclusively the τ decay topology. Finally, note that in both experiments the dominant background reamins the ν_e contamination of the beam.

3.2. Kinematical analysis

An increase of sensitivity to $\nu_\mu \leftrightarrow \nu_e$ oscillations can be obtained by fitting the kinematical distributions of the selected events. As an example the OPERA P_T^{miss} distribution for signal and background channels is given in figure 1.

In order to disentangle $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, the ICARUS Collaboration considered the transverse missing momentum. The $\nu_\mu \leftrightarrow \nu_e$ events are balanced, while $\nu_\mu \leftrightarrow \nu_\tau$ show a sizable transverse momentum due to the presence of two neutrinos in the final state. The visible energy and the missing transverse momentum are combined into a binned χ^2-fit, in which the three oscillation parameters are allowed to vary.

By using the information contained in the figures 5.9 and 5.10 of [7], we have performed a binned χ^2-fit of these distributions and reproduced the results reported by the ICARUS Collaboration in [7]. The sensitivity at 90% CL to θ_{13}, corresponding to $\chi^2 = \chi_{\text{min}}^2 + 4.6$, has been evaluated under the assumption $\theta_{23} = 45°$. The exclusion plot is reported in figure 2.

In the case of OPERA, the kinematical variables have been obtained starting from true quantities and applying a smearing according to the OPERA experimental resolutions, see section 2.3. By fitting simultaneously the E_{vis}, E_e and p_T^{miss} distributions, we obtained the exclusion plot at 90% CL shown in figure 3 under the assumption $\theta_{23} = 45°$.

The use of differential distributions improves the sensitivity to $\sin^2 2\theta_{13}$ of both ICARUS and OPERA by about 20%. The combined sensitivity at 90% CL of the ICARUS and OPERA

CNGS 5 years nominal beam
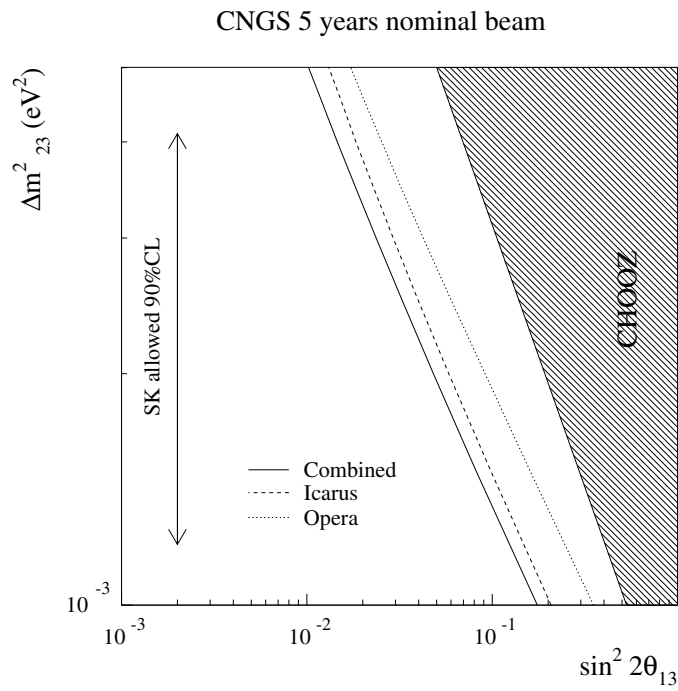
Figure 2. Sensitivity to the parameter θ_{13} to 90% CL in a three family mixing scenario, in presence of $\nu_\mu \leftrightarrow \nu_\tau$ with $\theta_{23} = 45°$.
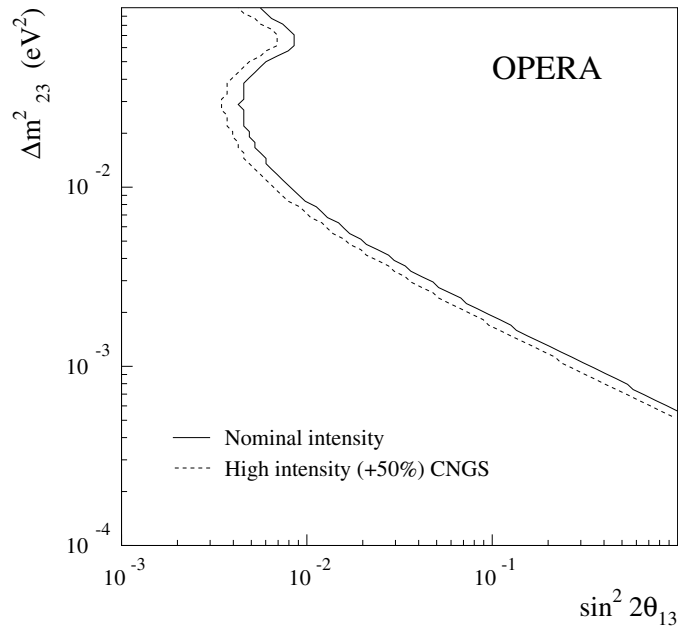
Figure 3. OPERA sensitivity to the parameter θ_{13} at 90% CL in a three family mixing scenario, in the presence of $\nu_\mu \leftrightarrow \nu_\tau$ with $\theta_{23} = 45°$. The sensitivity with the higher intensity CNGS beam is also given.

Table 5. Limits at 90% CL on $\sin^2 2\theta_{13}$ and θ_{13} for various experiments.

Experiment	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	<0.14	<11°
MINOS	<0.06	<7.1°
ICARUS	<0.04	<5.8°
OPERA	<0.06	<7.1°
ICARUS and OPERA combined (CNGS)	<0.03	<5.0°
ICARUS and OPERA combined (CNGS $\times$ 1.5)	<0.025	<4.5°
JHF [20]	<0.006	<2.5°

experiments is obtained by minimizing the χ^2 defined as $\chi^2 = \chi^2_{e(\text{icarus})} + \chi^2_{e(\text{opera})}$ and is also shown in figure 2.

3.3. Results

In the previous sections we discussed the sensitivity achievable in searching for θ_{13} with the present CNGS beam by combining the ICARUS and OPERA experiments. The improvements on $\sin^2 2\theta_{13}$ over the CHOOZ limit in the region indicated by atmospheric neutrinos is about a factor 5 assuming 5 years data taking with the nominal CNGS beam. The limits at 90% CL on $\sin^2 2\theta_{13}$ and θ_{13} for various experiments are given in table 5. The limits achievable with an improved CNGS beam (1.5 times more proton) are also shown.

It is worth noting that the sensitivity of the combined experiments running with the present high energy CNGS beam is comparable to the one achievable with a dedicated low energy configuration running below the kinematical threshold for τ production [21] and is obtained 'for free', as a by-product of the search for ν_τ appearance.

Clearly, we expect JHF phase 1 to significantly improve the sensitivity to $\sin^2 2\theta_{13}$ with respect to the CNGS programme in case of a negative result.

4. Conclusion

The OPERA experiment was designed and optimized for the direct observation of the τ decay topology and to search for ν_τ appearance at the Δm^2 atmospheric scale. Nevertheless, given the good electron identification, it turned out to be sensitive to the sub-dominant $\nu_\mu \leftrightarrow \nu_e$ oscillations in the region indicated by atmospheric results. Exploring the region of $\sin^2 2\theta_{13} \simeq \mathcal{O}(10^{-2})$ is particularly interesting in connection with the discovery of CP violation in the leptonic sector [20]. Hence, an observation of $\sin^2 2\theta_{13}$ in the region of $\mathcal{O}(10^{-2})$ would place future CP violation searches such as JHF phase 2 and the neutrino factories on firmer ground. We showed that by using the present CNGS beam and combining the ICARUS and OPERA experiments a sensitivity in $\sin^2 2\theta_{13}$ down to 0.03 ($\Delta m^2_{23} = 2.5 \times 10^{-3}\,\text{eV}^2$ and $\theta_{23} = 45°$) can be achieved. It can be further improved if a higher intensity (6.8×10^{19} pot/year) will be reached.

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