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A low energy optimization of the CERN-NGS neutrino beam for a θ_{13} driven neutrino oscillation search

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Abstract: The possibility to improve the CERN to Gran Sasso neutrino beam performances for θ_{13} searches is investigated. We show that by an appropriate optimization of the target and focusing optics of the present CNGS design, we can increase the flux of low energy neutrinos by about a factor 5 compared to the current τ optimized focalisation. With the ICARUS 2.35 kton detector at LNGS and in case of negative result, this would allow to improve the limit to $\sin^2 2\theta_{13}$ by an order of magnitude better than the current limit of CHOOZ at $\Delta m^2 \approx 3 \times 10^{-3}\,\mathrm{eV}^2$ within 5 years of nominal CNGS running. This is by far the most sensitive setup of the currently approved long-baseline experiments and is competitive with the proposed JHF superbeam.

Keywords: Quark Masses and SM Parameters, Beyond Standard Model, Neutrino Physics, Weak Decays.

*On leave of absence from INFN Milano.

Contents

1. Introduction

The firmly established disappearance of muon neutrinos of cosmic ray origin [1, 2] strongly points toward the existence of neutrino oscillations.

The approved first generation long baseline (LBL) experiments — K2K [3], MINOS [4], ICARUS [5] and OPERA [6] — will search for a conclusive and unambiguous signature of the oscillation mechanism. They will provide the first precise measurements of the parameters governing the main muon disappearance mechanism. In particular, the CERN-NGS beam [7, 8], specifically optimized for tau appearance, aims to directly confirm the hints for neutrino flavor oscillation.

The physics program of ICARUS will start with the installation of the 600 ton prototype at the Gran Sasso Laboratory (LNGS) and will allow the observation of atmospheric neutrinos, the detection of solar and supernovae neutrinos and the search for proton decay. An extension of the mass of argon is foreseen with the goal of reaching a total mass of about 3000 tons.

In addition to the dominant $\nu_\mu \to \nu_\tau$ oscillation, it is possible that a sub-leading transition involving electron-neutrinos occur as well. In the "standard interpretation" of the 3-neutrino mixing, the $\nu_\mu \to \nu_e$ oscillations at the $\Delta m^2 \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$ indicated by atmospheric neutrinos is driven by the so-called θ_{13} angle. Indeed, given the flavor eigenstates $\nu_\alpha(\alpha = e, \mu, \tau)$ related to the mass eigenstates $\nu'_i(i = 1, 2, 3)$, where $\nu_\alpha = U_{\alpha i}\nu'_i$, the mixing matrix U is parameterized as:

$$U(\theta_{12}, \theta_{13}, \theta_{23}, \delta) = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \tag{1.1}$$

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

The best sensitivity for this oscillation is expected for ICARUS at the CERN-NGS. Limited by the CNGS beam statistics at low energy, this search should allow to improve by roughly a factor 5 (see ref. [5]) the CHOOZ [9] limit on the θ_{13} angle for $\Delta m^2 \approx 3\times10^{-3}\,\mathrm{eV}^2$. Beyond this program, new methods will be required in order to improve significantly the sensitivity.

At present, the only well established proposal in this direction is the JHF-Kamioka project [10]. In its first phase, 5 years of operation with the Super-K detector, it aims to a factor 20 improvement over the CHOOZ limit.

In this paper, we investigate the possibility to perform θ_{13} searches with a CERN to Gran Sasso beam optimized for Low Energy (L.E.) neutrino production. This is meant to be *alternative* to the CNGS τ program, in order to be competitive with JHF.

FLUKA [11, 12] Monte Carlo simulations are employed to calculate neutrino yields with specific target and focusing configuration.

Simulated neutrino fluxes are employed to derive exclusion plots in the Δm^2 vs $\sin^2(2\theta_{13})$ plane for the ICARUS detector.

2. The neutrino energy range

In order to maximize the probability of an oscillation, we must choose the energy of the neutrino $E_{\max}$ and the baseline L such that

$$1.27\frac{L(\mathrm{km})}{E_{\max}(\mathrm{GeV})}\Delta m^2(\mathrm{eV}^2) \simeq \frac{\pi}{2}\,. \tag{2.1}$$

However, in order to *observe the oscillation*, we must at least see the maximum preceded by a minimum, given by

$$1.27\frac{L(\mathrm{km})}{E_{\min}(\mathrm{GeV})}\Delta m^2(\mathrm{eV}^2) \simeq \pi\,. \tag{2.2}$$

At the CERN-LNGS baseline (730 Km), with Δm^2 in the range indicated by Super Kamiokande ($1 \times 10^{-3} < \Delta m^2 < 4 \times 10^{-3}\,\mathrm{eV}^2$), the maxima and minima of the oscillation lie between 0.3 GeV and 2.4 GeV (See table 1).

3. The present CERN-LNGS configuration

The present CNGS design [7] is optimized for ν_τ appearance, thus for a relatively high-energy neutrino beam. The 400 GeV/c SPS beam will nominally deliver 4.5×10^{19} protons per year on a graphite target, made of spaced rods to reduce the re-interaction rate within

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	Δm^2(eV ^{2})							
L	1×10^{-3}		2×10^{-3}		3×10^{-3}		4×10^{-3}	
(km)	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV
730	590	295	1180	590	1771	885	2361	1180

Table 1: Neutrino energies E_{max} and E_{min} (see text for definition) corresponding to the maximum and minimum of the $\nu_\mu \to \nu_x$ oscillation for the CERN-LNGS baseline and the Δm^2 range indicated by Superkamiokande.

the target. The two magnetic horns (horn and reflector) are tuned to focus 35 and 50 GeV/c mesons, with an acceptance of the order of 30 mrad. The present shielding and collimator openings would not allow more than 100 mrad even in perfect focusing. The decay tunnel length is 1 km, and the baseline for neutrino oscillation is 732 km.

4. The CNGS L.E. option

To improve particle yield at low energies, we re-designed the focusing system, and changed the target dimensions and shortened the effective decay tunnel length. The main differences wit the present (τ) design are summarized in table 2.

The L.E. target is still made of graphite, but the spaces have been eliminated. A more compact target (1 meter full length) allows for a better focusing and increases the low-energy yield as will be discussed in the next section.

The decay tunnel length in the present calculations has been set at 350 meters. This corresponds to about two decays lengths for pions producing 2.5 GeV neutrinos.

The neutrino energy of interest correspond to pions in the range 0.7–5.5 GeV. To focus these pions, we adopt a standard double-horn system (following the CNGS tradition, we call *horn* the first magnetic lens and *reflector* the second). Both have to be placed near to or even around the target, to capture particles emitted at relatively large angles. The average transverse momentum of secondary particles is around 300 MeV/c, with a sizable number of events up to 600 MeV/c, corresponding to 750 mrad for 1 GeV/c pions. These particles have to be bent before they travel too far away in radius, therefore the horn magnetic field has to be high enough. This also means that the horn should be shorter than the ones used to focus high energy beams, because the particles should not travel in the magnetic field for a distance longer than their curvature radius.

We obtained good focusing capability with two four meter long horns. The horn current has been set at 300 kA, the reflector one at 150 kA. The horn starts 25 cm after the target entrance face, the reflector starts just two meters after the horn end. Horn and reflector shapes has been computed to focus 2 GeV/c and 3 GeV/c particles, respectively. We are aware that these (parabolic) horn shapes are derived in the approximation of point-like source, that is not verified in the present case. However, the Monte Carlo calculations verified the good focusing capabilities of this system. The focusing efficiency in the range of interest is around 50%.

	CNGS τ	CNGS L.E.
Target		
Material	Carbon	Carbon
Total target length	2 m	1 m
Number of rods	13	**1**
Rod spacing	first 8 with 9 cm dist.	none
Diameter of rods	first 2 5 mm, then 4 mm	**4 mm**
Horn		
Distance beginning of target-horn entrance	320 cm	**25 cm**
Length	6.65 m	**4 m**
Outer conductor radius	35.8 cm	80 cm †
Inner conductor max. radius	6.71 cm	11.06 cm
Inner conductor min. radius	1.2 cm	0.2 cm
Current	150 kA	300 kA
Reflector		
Distance beginning of target-reflector entrance	43.4 m	**6.25 m**
Length	6.65 m	**4 m**
Outer conductor radius	55.8 cm	90 cm †
Inner conductor max. radius	28 cm	23.6 cm
Inner conductor min. radius	7 cm	5 cm
Current	180 kA	150 kA
Decaytunnel		
Distance beginning of target-tunnel entrance	100 m	50 m
Length	992 m	350 m
Radius	122 cm	350 cm †

Table 2: Parameter list for the present CNGS design and the "new" beam for low energy ν. For the parameters flagged with a †, a full optimization has not been performed and possible improvements have not been studied yet.

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5. Neutrino fluxes and rates

With the standard CNGS parameters, the low-energy neutrino flux is low, as can be seen from the entries flagged by † in table 3, even assuming perfect focusing: we expect 0.9 ν_μ CC events per kton per 10^{19} pots for the tau focusing. Even if ideal focusing is assumed, the rate is only improved by a factor 2.

The more compact target, and a wider acceptance, give about a factor five higher rate in the 0.–2.5 GeV range, or about 4.5 ν_μ CC events per kton per 10^{19} pots for the real focusing and up to 9.0 ν_μ CC events per kton per 10^{19} pots for the ideal focusing.

While in both cases the focusing introduces an efficiency factor of about 50% with respect to the ideal focusing, our improvement comes from the ability to capture more wide angle, soft pions. The interplay of target configuration and angular acceptance can be

E_p GeV	focus	decay tunnel length (m)	ν_μ flux ν/cm^2	ν_e flux	10^{19} p.o.t. ν_μ CC ev/kton	ν_e CC	$< E_\nu >$, CC ν_μ GeV	ν_e	ν_e/ν_μ CC
400	p.f	350	$1.3 \cdot 10^{-13}$	$2.6 \cdot 10^{-15}$	**9.0**	0.12	1.8	1.8	1.3%
400	horn	350	$1.0 \cdot 10^{-15}$	$9.0 \cdot 10^{-16}$	**4.5**	$4.2 \cdot 10^{-2}$	1.8	1.4	0.9%
400	p.f †	CNGS	$1.6 \cdot 10^{-14}$	$3.2 \cdot 10^{-16}$	**1.8**	$2.2 \cdot 10^{-2}$	2.1	1.7	1.2%
400	$\tau^\dagger$	CNGS	$1 \cdot 10^{-14}$	$9.4 \cdot 10^{-17}$	**0.9**	$8.7 \cdot 10^{-3}$	1.8	1.8	0.9%

Table 3: Neutrino beam parameters for the CNGS baseline, with $E_\nu < 2.5\,\mathrm{GeV}$. The † cases correspond to the *present CNGS design* for target, acceptance and focusing system.

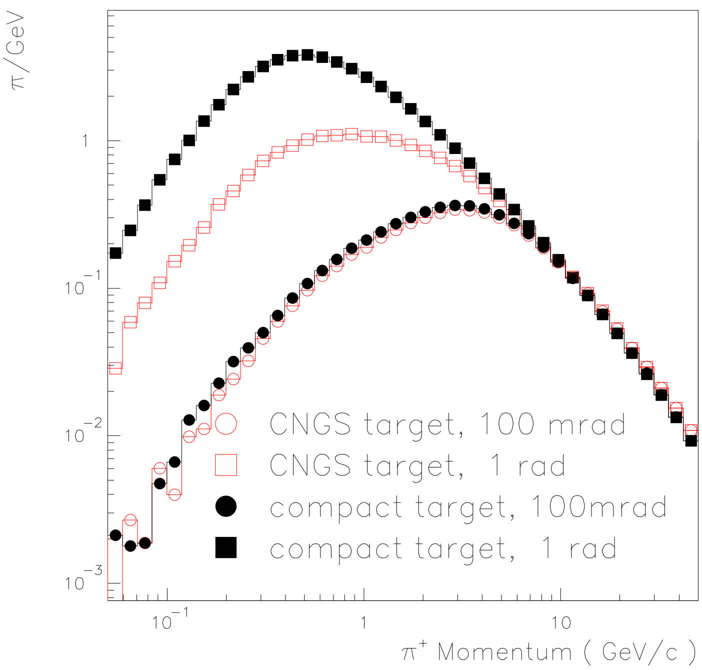

Figure 1: Pion production at 400 GeV, for the CNGS target within 100 mrad acceptance, for a compact target (the one of this study) within 100 mrad acceptance and within 1 rad acceptance.

seen clearly from figure 1: the low-energy part of the produced pion spectrum is enhanced due to the higher re-interaction probability in a compact target, at the expenses of the medium-high energy part, the one of interest for τ appearance. This enhancement is small in the forward direction (100 mrad acceptance), but it grows at larger angles (up to 1 rad), where it reaches an average factor of 1.5 for pions in the 1–5 GeV energy range. The real boost in low energy pion production comes however from the angular acceptance of the system, which accounts for a factor 3.3 in the case of a compact target and a factor 2.3 in the case of the CNGS target. The difference in acceptances (1 rad in the low-energy option vs. 100 mrad for CNGS in perfect focusing) is therefore the dominant factor.

Even after focusing, the L.E. option produces five times more low energy ν_μ than the standard one. The difference can be appreciated by eye in figure 2, where we show the ν_μ

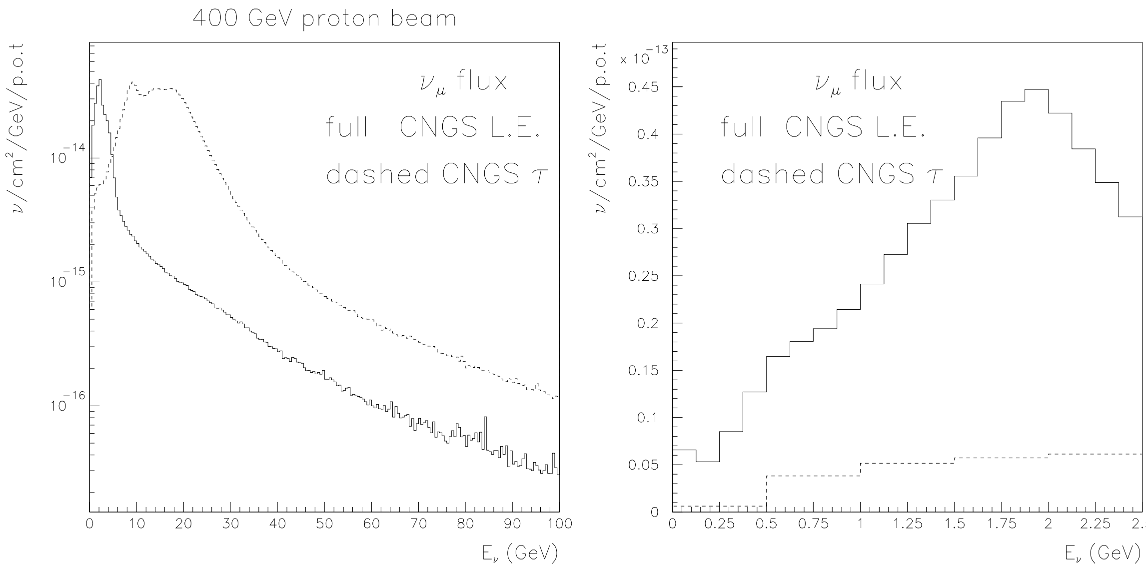

Figure 2: Muon neutrino fluxes at Gran Sasso, for the present CNGS design and for the new target/optics configuration. Whole spectra (left) and low-energy (right) are shown.

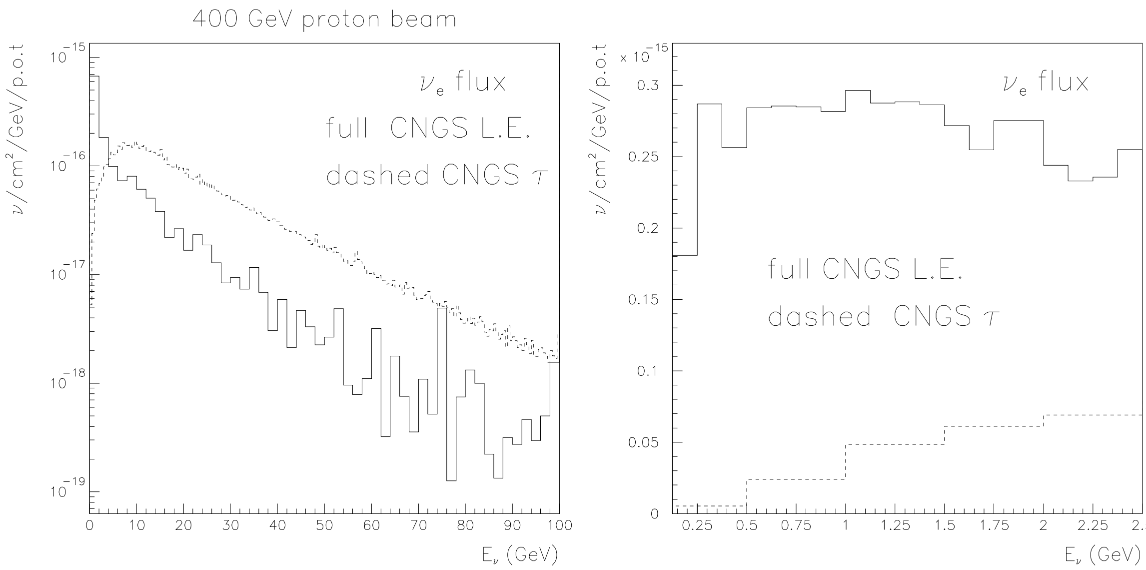

Figure 3: Electron neutrino fluxes at Gran Sasso, for the present CNGS design and for the new target/optics configuration. Whole spectra (left) and low-energy (right) are shown.

fluxes at Gran-Sasso for the two configurations. The electron neutrino contamination is of the same order of magnitude (around 1%) for the τ and L.E. options. Electron neutrino spectra are plotted in figure 3.

6. A near detector?

During the optimization for low energy pions, it came natural to reduce the "used" length of the decay tunnel from the available 1 km of the CNGS, in order to reduce the high energy neutrino tail.

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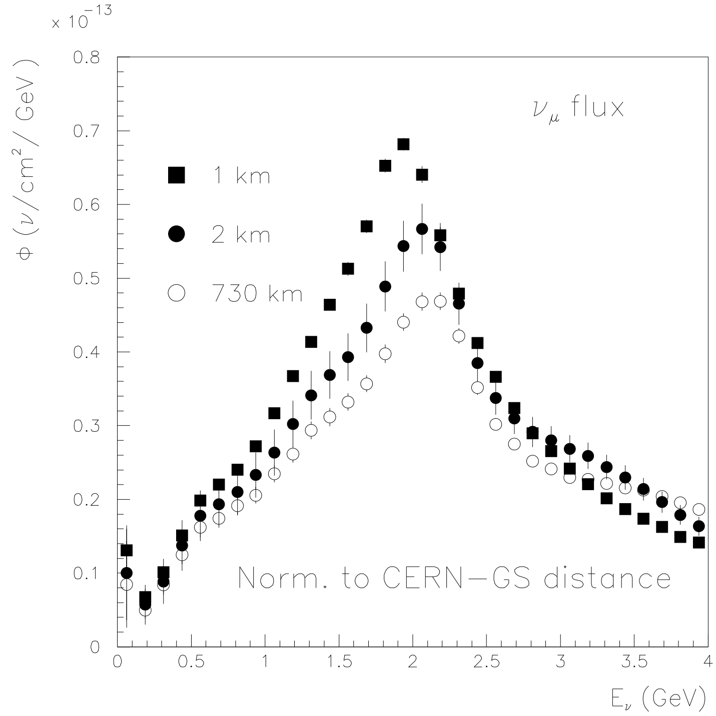

Figure 4: Muon neutrino fluxes at Gran Sasso and at "near" positions, one and two kilometers from the target. For direct comparisons, the flux for the near detectors have been rescaled according to the square of (target-near)/(target-Gran Sasso) distances.

The reduction of the actual effective decay length could be accomplished by relocating some of the graphite and iron blocks of the currently planned CNGS beam dump within the decay tunnel. We are aware that this operation is technically not as trivial as it might sound, however, we want to point out that it is not necessary to fill the entire decay tunnel but simply to stop the hadrons at the given point of the decay tunnel in order to achieve our wanted result.

The reduced use of the decay tunnel leaves the room for an eventual "near" detector to be placed in the present beam dump position, that is at about 1 km from the target. This would allow us to monitor the beam in absence of oscillations and to predict the beam spectrum at the far position.

As is well known however [3, 4, 10], the neutrino spectra at the near position are different from the "far" ones, mainly because they feel the finite size of the decay tunnel. We have simulated for the L.E. beam the ν_μ fluxes as a function of ν energy at 1 and 2 km from the target. The 1 km distance would correspond to the current "beam dump area" while the 2 km corresponds to the originally planned location of the TOSCA detector. We have rescaled our results according to the square of the baseline ratio, such that the spectra are directly comparable. As shown in figures 4 and 5, the low energy part of the spectrum is enhanced with respect to the one at Gran Sasso, with differences up to 60% in the case of the very near detector.

Therefore, the ν_e beam contamination at Gran Sasso cannot be directly evaluated from the measurement at the near detector, but has to be "propagated" through Monte Carlo

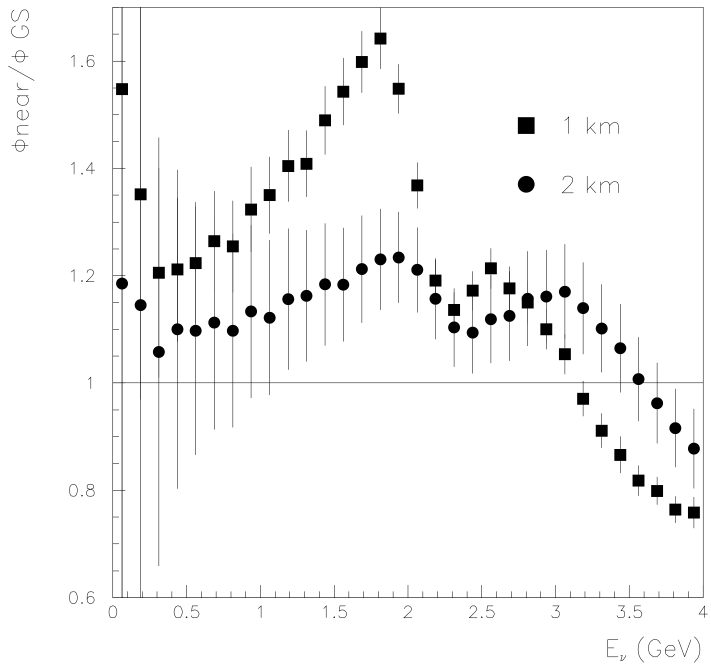

Figure 5: Ratio of near/far muon neutrino fluxes.

simulations. Hence, the need of the near detector is not fundamental, however, it would allow to cross-check the beam simulation in the region of no oscillations which can then be extrapolated at far distance. The resulting systematic error has not been estimated yet, however, we point out in next section that our results will be limited by statistics.

7. Oscillated events and limits

Figure 6 shows the exclusion plots for $\sin^2 2\theta_{13}$ at the 90% C.L. for the CNGS τ and our optimized CNGS L.E. options, compared with the CHOOZ limit, the SuperK allowed region and other proposed experiments. These contours have been derived from ν_e appearance, assuming 5 years of operation at the nominal CNGS intensity, and an ICARUS fiducial volume of 2.35 kton. For MINOS we assume an exposure of 10 kton $\times$ year [14] and we quote the JHF limit according to the proposal of the OAB beam [10]. Three neutrino formalism and maximal $\nu_\mu - \nu_\tau$ mixing have been assumed, i.e. $\theta_{23} = 45^o$, so that the usual "appearance factor" $P(\nu_\mu \to \nu_e) = 0.5 \times P(\nu_e \to \nu_\mu/\nu_\tau)$ has been taken into account.

Only the intrinsic ν_e beam contamination has been considered here for the background evaluation; other background sources, such as π^0 production in neutral current events, have been extensively studied in the past [5] and found to be negligible given the excellent granularity of the ICARUS detector. They will nonetheless be precisely re-addressed in a forthcoming paper [15]. We however do not expect any significant changes in sensitivity introduced by other sources of backgrounds.

The integrated number of background and oscillated ν_e events in the hypothesis $\Delta m^2 = 3 \times 10^{-3}\,\mathrm{eV}^2$ are listed in table 4. The oscillation maximum in the case of $\Delta m^2 =$

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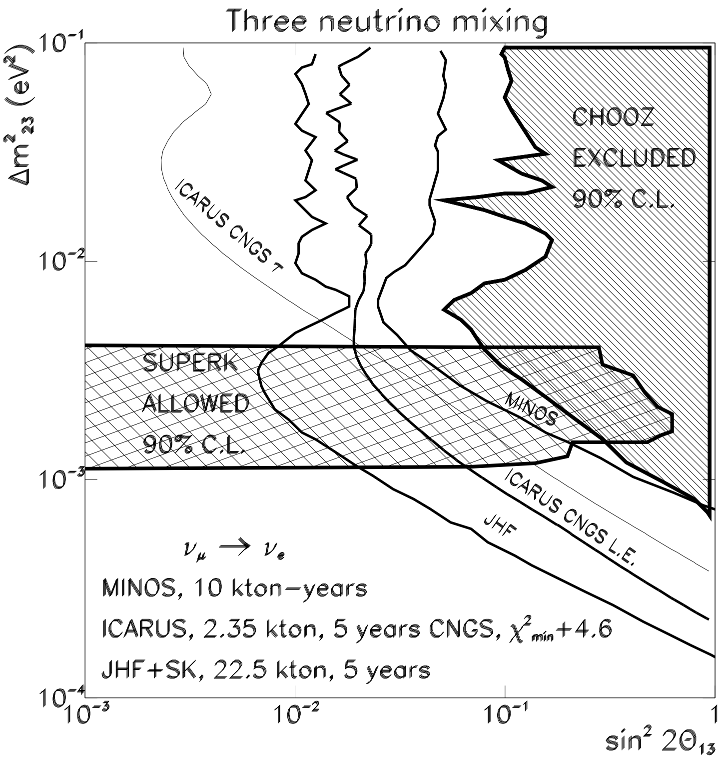

Figure 6: Expected sensitivity to $\sin^2 2\theta_{13}$ mixing angle at nominal CNGS intensity, compared to existing results from CHOOZ [9] and SuperK [13] and expected results from MINOS [4] and JHF-SK [10].

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC $E_\nu < 4\,\mathrm{GeV}$	ν_e CC $E_\nu < 50\,\mathrm{GeV}$	$\nu_\mu \to \nu_e$ $E_\nu < 4\,\mathrm{GeV}$	$\nu_\mu \to \nu_e$ $E_\nu < 50\,\mathrm{GeV}$
9	0.095	5	44	16	22.
8	0.076	5	44	13	18.
7	0.059	5	44	10	13
5	0.030	5	44	5	7
3	0.011	5	44	1.8	2.5
2	0.005	5	44	0.8	1.1
1	0.001	5	44	0.2	0.3

Table 4: Events from the CNGS L.E. beam, assuming $\Delta m^2_{23} = 3 \times 10^{-3}\mathrm{eV}^2$, $\theta_{23} = 45°$, 5 years of operation and 2.35 kton fiducial mass.

$3 \times 10^{-3}\,\mathrm{eV}^2, \sin^2 2\theta_{13} = 0.1$ is evident from the event spectra shown in figure 8. For comparison, we also quote the numbers for the CNGS τ optimization in table 5.

The CNGS L.E. options represents an increase of roughly a factor 2 in sensitivity with respect to the CNGS τ beam, within the SuperK allowed region. For $\Delta m^2 = 2.5 \times 10^{-3}\,\mathrm{eV}^2$, we find:

$$\left(\sin^2 2\theta_{13}\right)_{\mathrm{CNGS},\tau} < 0.04\,, \qquad \text{or} \qquad \theta_{13} < 6^o\,, \tag{7.1}$$

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC		$\nu_\mu \to \nu_e$	
		$E_\nu < 4\,\mathrm{GeV}$	$E_\nu < 50\,\mathrm{GeV}$	$E_\nu < 4\,\mathrm{GeV}$	$E_\nu < 50\,\mathrm{GeV}$
9	0.095	1.5	150	4	42
8	0.076	1.5	150	3.1	34
7	0.059	1.5	150	2.4	26
5	0.030	1.5	150	1.2	14
3	0.011	1.5	150	0.4	5
2	0.005	1.5	150	0.2	2.2
1	0.001	1.5	150	0.1	0.5

Table 5: Events from the CNGS τ beam, assuming $\Delta m^2_{23} = 3 \times 10^{-3}\,\mathrm{eV}^2$, $\theta_{23} = 45°$, 5 years of operation and 2.35 kton fiducial mass.

$$\left(\sin^2 2\theta_{13}\right)_{\mathrm{CNGS,L.E.}} < 0.02\,, \qquad \text{or} \qquad \theta_{13} < 4^o\,. \tag{7.2}$$

The improvement over the CHOOZ limit is almost tenfold [9], and the performances are three times better than those foreseen by MINOS [14]:

$$\left(\sin^2 2\theta_{13}\right)_{\mathrm{CHOOZ}} < 0.14\,, \qquad \text{or} \qquad \theta_{13} < 11^o\,, \tag{7.3}$$

$$\left(\sin^2 2\theta_{13}\right)_{\mathrm{MINOS}} < 0.06\,, \qquad \text{or} \qquad \theta_{13} < 7^o\,. \tag{7.4}$$

Finally, the JHF proposal with the OAB beam gives [10]

$$\left(\sin^2 2\theta_{13}\right)_{\mathrm{JHF,OAB}} < 0.006\,, \qquad \text{or} \qquad \theta_{13} < 2.2^o\,. \tag{7.5}$$

The comparison with the first phase (5 years) of the superbeam JHF is still slightly unfavourable, however we point out the possible time schedule and the probable SPS proton beam intensity upgrades.

- The JHF-Kamioka experiment will start one or two years later than the CNGS beam;[1] this allows to set at 7 years the CNGS L.E. data taking.

- As for proton intensity, it is expected that PS and SPS upgrades [16] will bring the accelerated intensity from 4.8×10^{13} to 7×10^{13} protons per cycle. This represents an increase of $\approx 50\%$ in the p.o.t. per year. This intensity upgrade is already taken into account in all the design specifications for the CNGS facility [17]. We call this CNGS1.5.

Accordingly, the sensitivity contour for 7 years data taking at CNGS1.5 nominal intensity is shown in figure 7. This gives for $\Delta m^2 = 2.5 \times 10^{-3}\,\mathrm{eV}^2$

$$\left(\sin^2 2\theta_{13}\right)_{\mathrm{CNGS1.5,L.E.}} < 0.015\,, \qquad \text{or} \qquad \theta_{13} < 3.5^o\,. \tag{7.6}$$

[1] We assume the starting dates of 2007 for CNGS and 2009 for JHF.

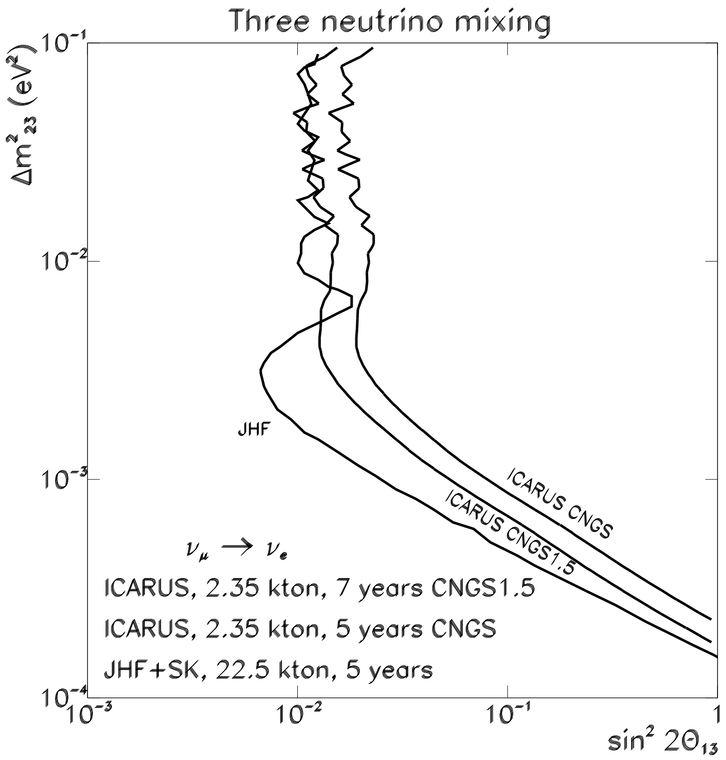

Figure 7: Comparison of expected sensitivity to $\sin^2 2\theta_{13}$ mixing angle with an improved CNGS$\times$1.5 [16] and 7 years of running.

Since we are limited by the intrinsic ν_e background, the sensitivity scales with the square of the exposure and one would need to increase the intensity of the CNGS and/or the total mass of ICARUS by a factor

$$\left(\frac{(\sin^2 2\theta_{13})_{\mathrm{CNGS1.5,L.E.}}}{(\sin^2 2\theta_{13})_{\mathrm{JHF,OAB}}}\right)^2 \approx 6 \tag{7.7}$$

in order to reach exactly the level of sensivity of the JHF superbeam.

8. Conclusions

The CERN-NGS has been originally optimized and coupled to high quality detectors in order to unambiguously give evidence for the $\nu_\mu \to \nu_\tau$ flavor oscillation mechanism.

However given the CERN financial situation, the CERN-NGS programme, approved in 1999, is now foreseen to start with full intensity in the year 2007. Given these delays, it is worth wondering if the priority of the program should be tau appearance ("a confirmation of the oscillation mechanism") or electron appearance ("a potential discovery of a new flavor transition").

In this paper, we have studied a different optimization of the CNGS beam optics that is optimized for $\nu_\mu \to \nu_e$ oscillation searches at the Δm^2 indicated by the atmospheric

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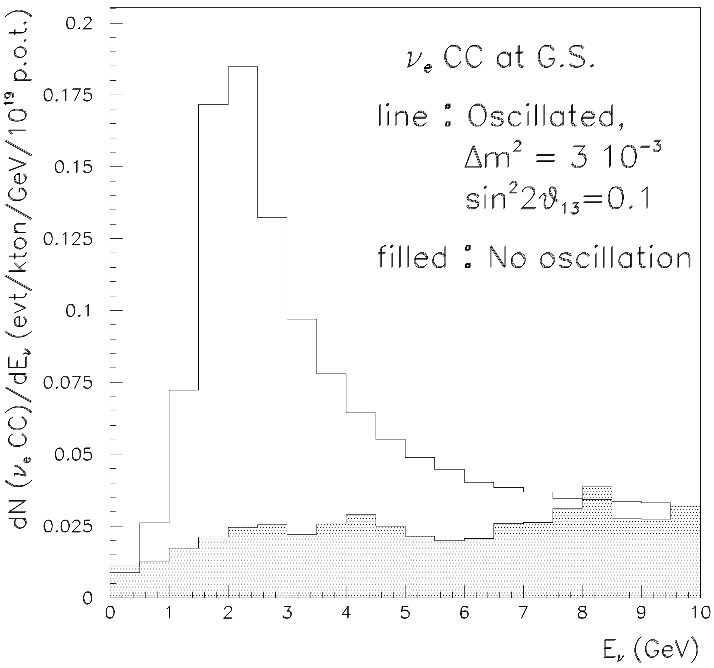

Figure 8: Comparison of ν_e CC spectra at Gran Sasso, in presence and in absence of oscillation.

neutrinos. We find that this beam coupled with the approved ICARUS T3000 experiment at LNGS would offer great opportunities to find neutrino oscillations driven by θ_{13} on the same time scale as that of the proposed JHF superbeam.

To reach a sensivity $\sin^2 2\theta_{13} < 0.006$, the total exposure should be increased by a factor 6 compared to what we have assumed here. This would require a big increase in beam intensity or a substantial increase of the liquid argon mass. The cost of multiplying the mass of ICARUS by a factor six is interestingly on the scale of the price of a new superbeam.

Acknowledgments

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