The $N^{O}E$ detector performances for large mixing angle long baseline neutrino oscillations

G.C.Barbarino[1], D.Campana[1], F.Guarino[1], A. Lauro[1], G.Osteria[1], U.Rubizzo[1], A.Margiotta[2], M.Spurio[2], P.Bernardini[3], G.Mancarella[3], D.Martello[3], A.Surdo[3], S.Bussino[4], E.Lamanna[4], M.De Vincenzi[4,5], A.Di Credico[6], A.Grillo[6], C.Gustavino[6], S.Mikheyev[6,7], E.Scapparone[6] G.De Cataldo[8], P.Fusco[8], N.Giglietto[8], M.N.Mazziotta[8], A.Rainó[8], P.Spinelli[8]

[1] *Dip. di Scienze Fisiche dell' Universitá di Napoli and INFN Sez. di Napoli - Italy*
[2] *Dip. Fisica dell' Universitá di Bologna and INFN Sez. di Bologna - Italy*
[3] *Dip. Fisica dell' Universitá di Lecce and INFN Sez. di Lecce - Italy*
[4] *Dip. Fisica dell' Universitá di Roma and INFN Sez. di Roma - Italy*
[5] *Dip. Fisica dell' Universitá di Roma III - Italy*
[6] *INFN, Laboratory Nazionali del Gran Sasso, Assergi - Italy*
[7] *Institute of Nuclear Research, Russian Academy of Science, Moscow, Russia*
[8] *Dip. di Fisica dell'Universitá di Bari and INFN Sez. di Bari - Italy*

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1 Introduction

One of the open and most debated problems in elementary particle physics is whether neutrinos are massless or not. Very small neutrino masses are unlikely to be measured via the classical β-decay procedure. If neutrinos have non zero mass and the mass eigenstates are mixed, the most promising way to measure their mass is through oscillation experiments, as foreseen by Bruno Pontecorvo. In the simplified hypothesis of a mixing between two neutrino families, the probability of observing $\nu_i \to \nu_j$ oscillations at a distance L is given by

$$P(\nu_i \to \nu_j) = \sin^2 2\theta \sin^2 \left[\frac{1.27\Delta m^2 L}{E_\nu}\right] \tag{1}$$

where $\Delta \mathrm{m}^2 = \mathrm{m}_\mathrm{i}^2 - \mathrm{m}_\mathrm{j}^2$ is in eV^2, L is the distance from the ν source to the detector in km and E_ν is the neutrino energy in GeV.

For maximal mixing, this probability is different from zero if $\Delta \mathrm{m}^2$ is at least $\sim \mathrm{E}_\nu/\mathrm{L}$. Solar neutrino data ($\mathrm{E}_\nu \sim$ few MeV, $L = 150 \cdot 10^6$ km) cover $\Delta \mathrm{m}^2$ regions from 10^{-5} to 10^{-10} eV^2 and existing accelerator experiments can go up to $\Delta \mathrm{m}^2 \sim 1$ eV^2. The region of $\Delta \mathrm{m}^2 = 10^{-2} \div 10^{-3}$ eV^2 can be covered with long baseline ν_μ-beams (L $\sim 10^3$ km). The $\Delta \mathrm{m}^2$ region which could be investigated by experiments for oscillation studies using long baseline ν-beams from accelerators coincides with the region of atmospheric neutrinos ($\mathrm{E}_\nu \sim$ GeV, L $= 10 \div 10^4$ km). Long baseline neutrino beams provide a unique way to study ν_μ oscillations at small $\Delta \mathrm{m}^2$ values, offering several advantages when compared with atmospheric neutrinos (high flux, known energy spectrum, known initial neutrino direction and flavour and ν_e contamination). A muon neutrino beam peaked around an energy of several GeV can be used to detect τ neutrinos appearance via ν_τ CC interactions. Long baseline projects are being discussed in various laboratories in the world (Fermilab to Soudan, CERN to Gran Sasso, KEK to SuperKamiokande) and are at different stages of approval.

2 Atmospheric neutrinos

2.1 Introduction

Atmospheric neutrinos originate mainly from the decays of charged π, K and muons, produced in cosmic-ray-induced air showers. From these decay chains one expects the ratio of the number of $\nu_\mu(\bar{\nu_\mu})$ to $\nu_e(\bar{\nu_e})$ to be approximatively equal to two at low energy (1-2 GeV). Atmospheric neutrinos can be identified in different energy ranges:

1. At low energy by means of their interaction within a massive detector. These interactions may be studied with water Čerenkov detectors (IMB [1], Kamiokande [3]), or dense tracking calorimeters (NUSEX [2], Soudan 2 [5], Frejus [4]). Neutrino interactions are then classified as fully or partially contained, depending on whether all interaction products are contained within the detector fiducial volume or high energy muons leave the detector.

2. At higher energy by means of the muons produced by ν_μ CC interactions in the rock surrounding the detector. In this case the produced muons may either cross or stop in the detector and can be studied with large area tracking detectors. The MACRO experiment measures a deficit of upward-throughgoing μ's generated by ν interactions. This result may be another clue of ν oscillation, even though it is compatible with the expectation with a 8 % confidence level [6], [7].

2.2 Contained events

The water Čerenkov experiments Kamiokande and IMB are able to separate ν_μ CC from ν_e CC interactions and find that the ratio

$$R = \frac{\left(\frac{\nu_\mu}{\nu_e}\right)_{\mathrm{data}}}{\left(\frac{\nu_\mu}{\nu_e}\right)_{\mathrm{MC}}}$$

is smaller than expected. Experimental results on contained atmospheric neutrino events are consistent with a 30-40% ν_μ deficit. Such a deficit could be the result of either $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_e$ oscillations or both. At this stage the simulation of ν_μ and ν_e fluxes favours a $\nu_\mu \to \nu_\tau$ interpretation of the atmospheric neutrino puzzle. In particular, the allowed regions in the oscillation parameter space from the Kamiokande data are: $\Delta \mathrm{m}^2 > 4 \cdot 10^{-3}$ eV^2, $\sin^2(2\theta) > 0.3$ for $\nu_\mu \to \nu_e$ and $\Delta \mathrm{m}^2 > 10^{-3}$ eV^2, $\sin^2(2\theta) > 0.4$ for $\nu_\mu \to \nu_\tau$. A similar analysis performed by calorimetric experiments (NUSEX and Frejus) are not in agreement with this result; on the contrary Soudan 2 seems to confirm Čerenkov detector results.

2.3 Partially contained events

A different analysis has been performed by the Kamiokande group in the so-called multi-GeV energy range. These events are:

1. Fully-contained events with visible energy larger than 1.33 GeV;
2. Partially-contained events which have their interaction vertex in the fiducial volume and a visible track leaving the detector.

The estimated mean energy of neutrinos is 5 GeV for fully contained e-like events, 2.5 GeV for fully contained μ-like events, and 9 GeV for partially-contained events. Also in this data sample an analogous deficit is observed. A feature of this data is the relative excess of electrons and the relatively small deficit of muon neutrinos, compared to what is expected from the $\nu_\mu \rightarrow \nu_\tau$ hypothesis. Assuming oscillation, the best fit gives the following parameters: $\Delta\mathrm{m}^2 = 1.8 \cdot 10^{-2}$ eV^2 and $\sin^2(2\theta)$=1.0 for $\nu_\mu \rightarrow \nu_e$ and $\Delta\mathrm{m}^2 = 1.6 \cdot 10^{-2}$ eV^2 and $\sin^2(2\theta)$=1.0 for $\nu_\mu \rightarrow \nu_\tau$. Thus, while the low energy sample suggests $\nu_\mu \rightarrow \nu_\tau$, the high energy sample may suggest $\nu_\mu \rightarrow \nu_e$ oscillations. Finally, combining all their data (sub-GeV and multi-GeV), the Kamiokande group finds a rather limited allowed region, both for $\nu_\mu \rightarrow \nu_\tau$ and for $\nu_\mu \rightarrow \nu_e$ with nearly full mixing and with $\Delta\mathrm{m}^2 \sim 10^{-2}$ eV^2.

3 Three-Flavour Mixing

A more general assumption making use of a three generation neutrino oscillation formalism has been recently carried out by many authors. In particular Harrison, Perkins and Scott[8] have pointed out that atmospheric and solar neutrino data could be explained in a threefold maximal mixing scheme assuming two independent mass-squared differences: $\Delta\mathrm{m}^2 = (0.72 \pm 0.18) \cdot 10^{-2}$ eV^2 and $\Delta m'^2 < 0.9 \cdot 10^{-11}$ eV^2. For L/E $< 1/\Delta\mathrm{m}^2$ the flavour survival probability formula $P(\nu_l \rightarrow \nu_l)$ returns a value equal to one, while for L/E $> 1/\Delta\mathrm{m}^2$ the value of this quantity, averaged over the neutrino spectrum, is expected to be 5/9. The two plateau regions are separated by a well localized threshold at L/E $\sim 1/\Delta\mathrm{m}^2$. The corresponding appearance probability $P(\nu_l \rightarrow \nu_{l'})$ to produce a neutrino of different flavour $l' \neq l$ is equal to 2/9 sharing the oscillation between $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ channel. A similar threshold at L/E $\sim 1/\Delta m'^2$ gives rise to the third plateau characterized by a survival probability equal to 1/3. The data from all the experiments are shown in Fig. 1 as a function of L/E: they suggest the existence of a sharp

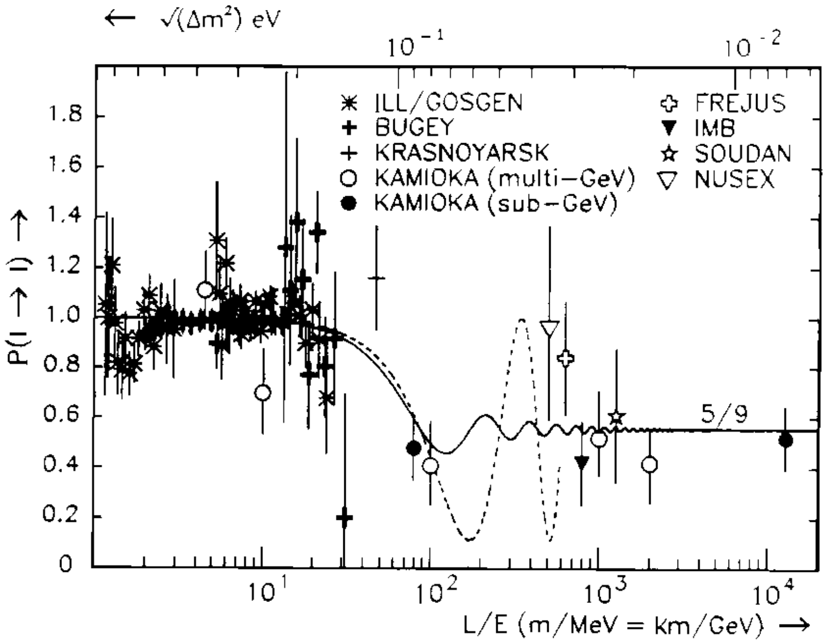

Figure 1: The first threshold of the oscillation curve and disappearance rates as a function of L/E

threshold in the region L/E = 20÷80 km/GeV corresponding to $\Delta m^2 \sim 10^{-2}$ eV^2. Beyond this threshold the data suggest a plateau close to the prediction $P(\nu_l \rightarrow \nu_l) = 5/9 \simeq 0.56$, characteristic of maximal mixing. The atmospheric anomaly could be explained in this way. The figure also shows the full oscillation curve corresponding to $\Delta m^2 \sim 0.72 \cdot 10^{-2}$ eV^2 under a maximal mixing hypothesis.

A minimum is expected for L/E = 170 km/GeV (or m/MeV). Given L and measured E one can map out the energy dependence both for the disappearance and the appearance rates $\nu_\mu \rightarrow \nu_e$ and/or $\nu_\mu \rightarrow \nu_\tau$ providing the first detailed proof of the neutrino oscillation existence. Forthcoming planned or in progress long baseline reactor and accelerator experiments, with L/E ranging from 20 to 200 km/GeV, will be able to perform these conclusive measurements. In addition it should be possible to verify directly the prediction $P(\nu_\mu \rightarrow \nu_e) = P(\nu_\mu \rightarrow \nu_\tau)$ if the detectors will prove to be able to identify τ-leptons.

A more general treatment shows that one could accomodate also LSND results. Acker et al. [9] explore the possibility that all the neutrino anomalies may be explained with three neutrino flavors. They assume two distinct values of Δm^2. The first value of $\Delta m^2 = 10^{-2}$ eV^2 is selected to take into account the atmospheric data, while the second value $\sim$ 1-2 eV^2 should explain the LSND effect. With this Δm^2 spectrum an explanation of both LSND, solar and atmospheric neutrino data can be found by an appropriate choice of mixing angles. They predict that future reactor experiments as CHOOZ and PALO VERDE (sensitive to Δm^2 down to 10^{-3} eV^2), should measure a survival probability $P(\nu_e \to \nu_e) = 0.48 \div 0.5$, while long baseline experiments (like MINOS, CERN-GS, K2K) should measure $\nu_\mu \to \nu_\tau$ oscillations with $P(\nu_\mu \to \nu_\tau) \sim 0.028 \div 0.035$, accompanied by $\nu_\mu \to \nu_e$ with $P(\nu_\mu \to \nu_e) \sim 0.46 \div 0.48$. However, in the whole scenario it is worth noting that the LSND results remain controversial, so that the case $1 \div 2$ eV^2 for Δm^2 may turn out not to be entirely correct. From the experimental point of view this means that simultaneous $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ oscillatory conversions could occur.

4 Experimental setup

4.1 Detector design

Taking into account the relative low ν-beam luminosity at long distance (the beam luminosity decreases as 1/L^2), a long baseline detector should be a very massive target. Unlike the case of short baseline experiments this constraint implies a not well specialized detector, where all parts have to be, at the same time, target, tracker, calorimeter, and μ-detector.

In this kind of experiments more than one oscillation test must be performed simultaneously. Two classes of measurements can be done:

1. Inclusive measurements:
    - ν_μ disappearance: comparing the fluxes measured in the near and in the far detector, the presence of a μ-deficit at long distance can be tested.
    - measurement of the ratio of events without muon track (apparent NC events) to those with a muon track (apparent ν_μ CC events). This measurement not only provides a clear signature of muon neutrino disappearance (muon deficit), but is also sensitive to ν_τ appearance due to hadronic decay of taus. In fact the ratio NC/CC should change in case the oscillation is in ν_e or in ν_τ. This inclusive measurement requires a large mass and, given cost constraints, poor granularity.

- comparison of the ratio NC to CC events in the near and far detector. The existence of a detector located close to the accelerator allows a comparison between neutrino interactions at different distances from the neutrino source. Also this measurement needs a large number of events and, consequently, a very massive far detector. In addition, the near detector should be very similar to the far one in order to minimize the effect of beam and detector systematics.

2. Exclusive measurements:

    - Search for tau and/or electron appearance. This analysis can be performed on an event by event basis, taking advantage of both the spatial and the topological event reconstruction. A detector devoted mainly to this measurement should have very high granularity rather than a large mass. A beam monitor, identifying ν_e beam background, could be also very useful for this kind of analysis.

The $N^{O}E$ experiment privileges the last methods. At present, the general design choice is to have a moderate but fully active mass with high granularity, allowing a fine event reconstruction.

The feasibility of exclusive measurements requires enough granularity to permit the separation between CC interaction events with or without taus in final state when $\nu_\mu \to \nu_\tau$ oscillation occurs. Such a discrimination is based on the measurement of the missing momentum in the plane transverse to the ν-beam direction as well as on the angular correlation between missing momentum, outgoing lepton and hadronic jet directions. In ν_τ CC interactions, the missing momentum is mainly due to the two neutrinos coming out from tau decay. In $\nu_\mu \to \nu_e$ oscillations an excess of e.m. showers will be looked for. Hence, general requirements for an adequate detector performing such exclusive measurements are the following:

- good sampling capability to achieve good energy resolution.
- fine topological readout to determine both shower axis and allow electron - pion discrimination by the analysis of the shower profile.
- analog readout to perform energy loss measurements in each calorimetric element

A detector with a good energy resolution can easily follow the oscillation modulation, as a function of L/E (E varying while L, the distance from the accelerator to the detector is fixed). Besides that inclusive measurements (like the NC/CC ratio) as a function of L/E complete the exploration of possible neutrino oscillation.

Given the listed features, the detection of a large mixing angle oscillation should be possible with the $N^{O}E$ detector proposed for the CERN-Gran Sasso program. In this letter the complete response of the detector to direct $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ appearance and to inclusive measurements (ratio NC/CC), necessary to claim any observation of neutrino oscillations, are described.

4.2 The $N^{O}E$ Detector

According to the previous conceptual considerations the $N^{O}E$ detector is a massive, fine grain calorimeter based on scintillating fiber technology. It consists of a 5 kton calorimeter plus a 2 kton muon detector which completes the experimental apparatus (Fig. 2).

A very preliminary detector set up has been described in the letter of intent submitted to the Gran Sasso Committee [10]. In order to improve the accuracy of shower axis determination and the reconstruction of the event topology, the ultimate design solution consists of many crossed X,Y fiber layers. Such a layout allows a very fine sampling in two views, making X and Y coordinates completely equivalent.

A detail of the detector is shown in Fig. 3 and 4. Very thin iron sheets ($\sim$ 2 mm) provide the mechanical support for two planes of fibers embedded into the absorber. Fiber planes are positioned at both sides of the iron sheet, rotated 90 degrees one respect to the other. Each plane consists self-supporting slabs made of extruded iron ore and recycled plastic. The 6.5 mm thin slab is made of two identical profiles which provide the fiber housing (Fig. 5). The iron sheets are hung to a supporting mechanical structure.

The extreme modularity of the $N^{O}E$ design allows to assemble the detector outside the tunnel, greatly improving the construction efficiency.

It is worth noting that the intrinsic granularity of the proposed detector is very high: the average distance between the fibers inside the absorber is of the order of 6 mm. At present such a granularity is limited only by the cost of the read-out electronics. This experiment wants to address the fiber read-out towards a fine configuration in order to get a better event topology and tracking information, by grouping some fibers and then by coupling them to a multianode device. In the detector fiducial volume, 5×5 cm^2 (or better) of

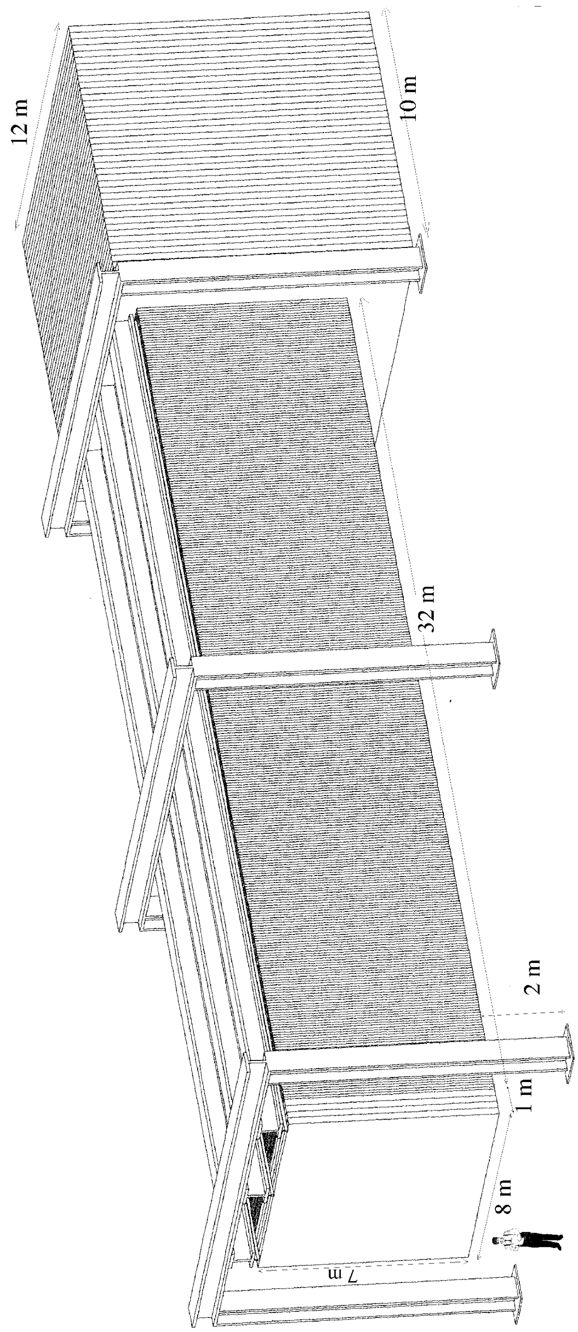

Figure 2: General layout of the $N^{O}E$ detector

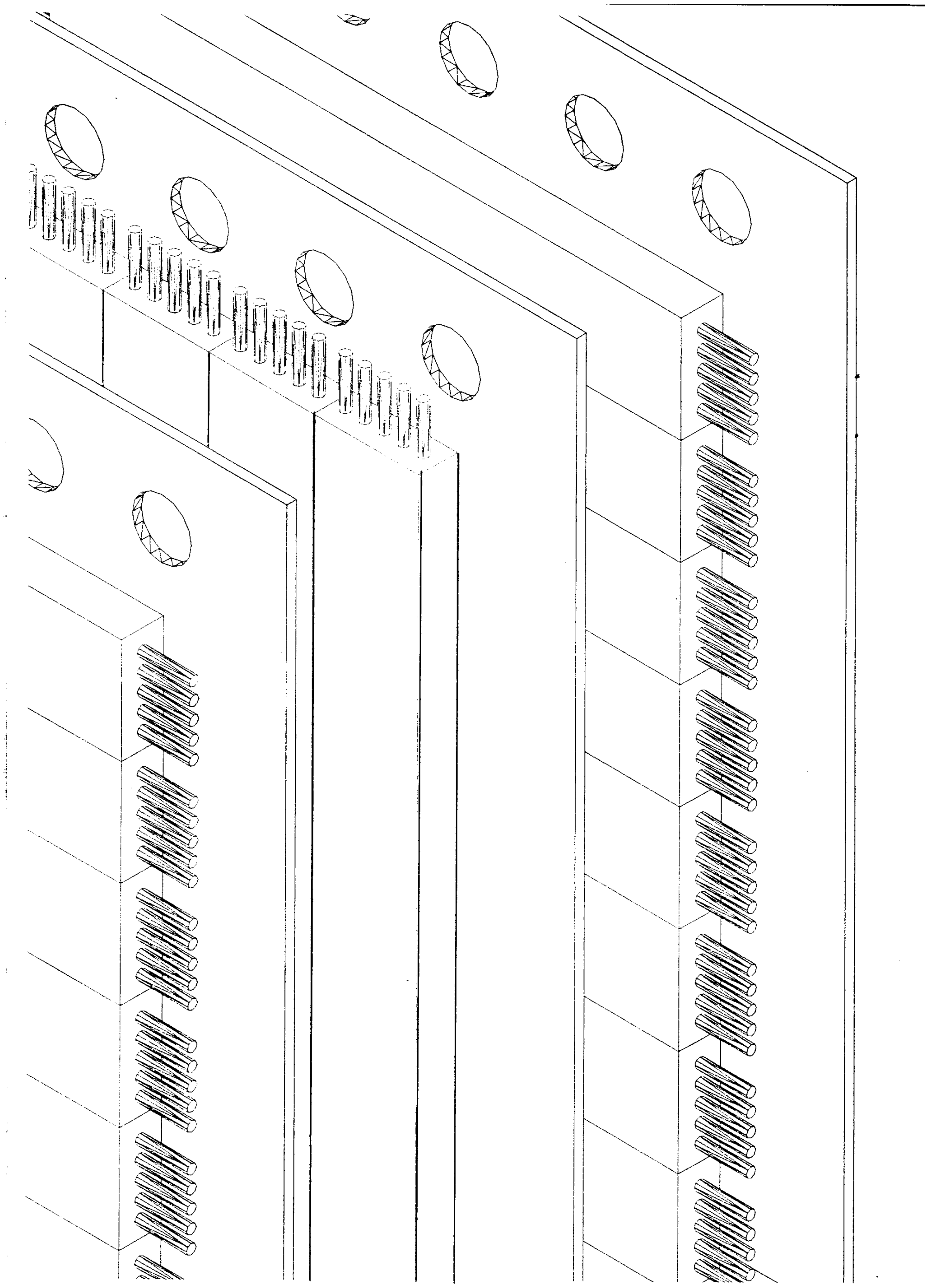

Figure 3: N^OE calorimeter details (fibers, absorber and mechanical supports)

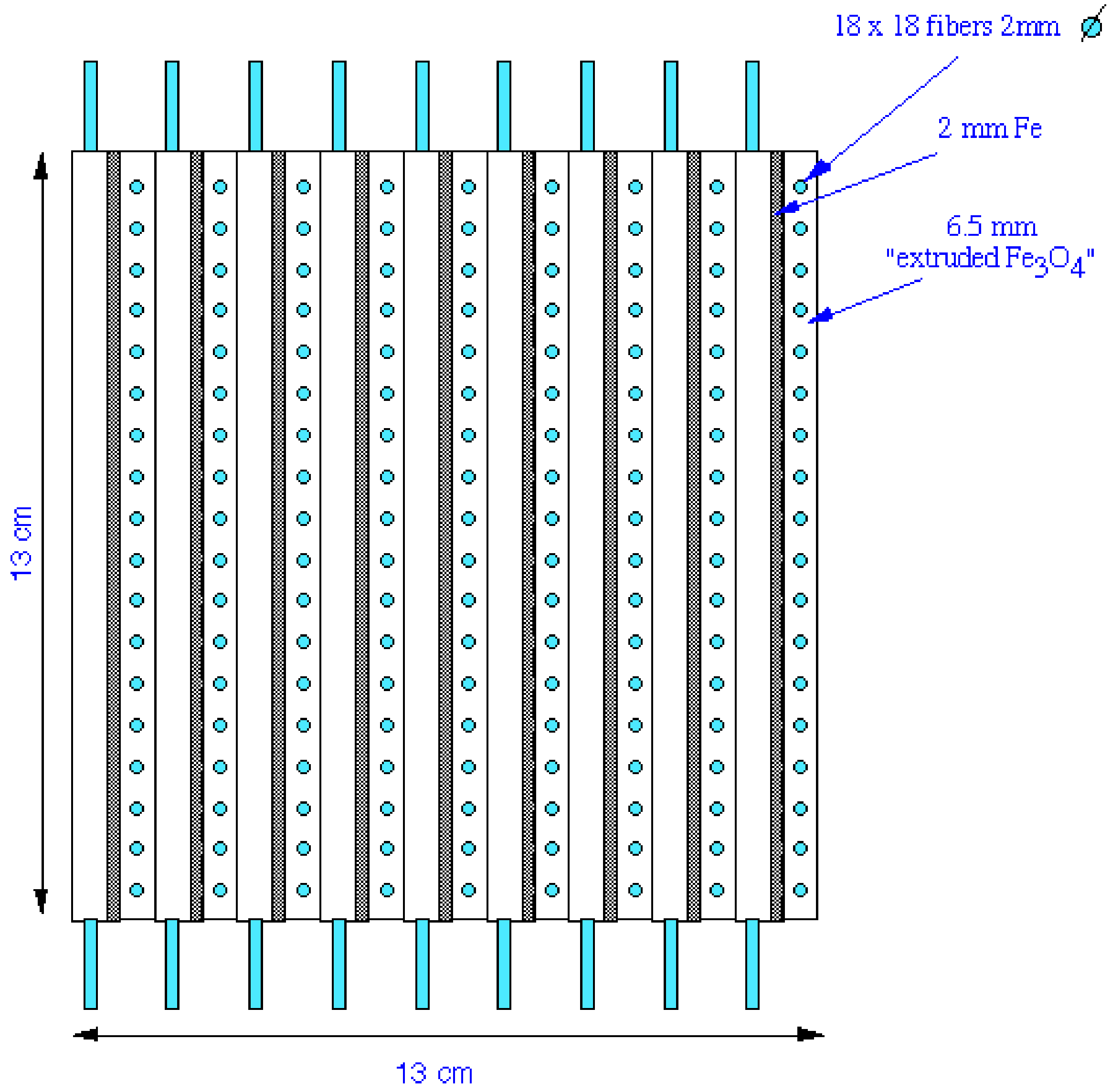

Figure 4: $N^O E$ calorimeter details (fibers, absorber and mechanical supports)

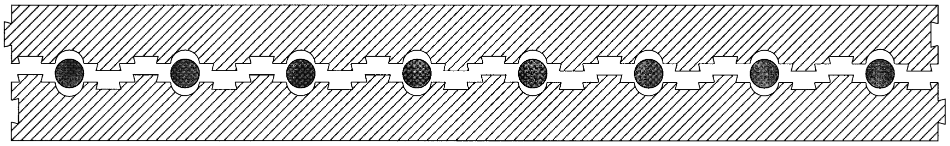

Figure 5: Self-supporting fiber housing

channel quantization in two views can be achieved in a grid read-out scheme. The grid read out hits will be sent to a shift register chain; energy loss and crossing time will be also recorded. The simulations will suggest definitively the more suitable grid read out to achieve electromagnetic and hadronic shower discrimination and good resolution on the measurement of their axis direction. To date simple and compact multianode PMT's are available, but recently many efforts have been devoted to develop a new fast light device, hybrid photodiode (HPD) with a very simple structure, high linearity and great reliability.

The capability of the experiment to measure energy loss (dE) and the path (dl) in each calorimetric element, many times along the track, allows particle identification using the dE/dl versus range method.

By using a GEANT based MonteCarlo simulation program, the energy resolution for electrons and hadrons have been evaluated in the hypothesis of ~ 300 fibers in a 13×13 cm^2 cross section square. They are, $\sigma(E)/E = 0.01 + 0.17/\sqrt{E}$ and $\sigma(E)/E = 0.08 + 0.42/\sqrt{E}$ respectively for electrons and hadrons.

The shower axis is obtained by using the center of gravity of the energy collected in each calorimetric grid element (XE,YE). The present calculations are performed on the apparatus having crossed fiber channel area of 6 cm^2. The sampling of such a topology is $\sim$ 1 radiation length. The tracking accuracy of both the muon and the hadronic axis have been determined and their resolutions are given by: $\sigma_\mu(\theta) = 1.27/\sqrt{E_\mu} + 2.27/E_\mu$ and $\sigma_h(\theta) = 10/\sqrt{E_h} + 20/E_h$ respectively.

A different possible option exists for the calorimeter set up: teflon tubes filled with liquid scintillator could be used instead of scintillating fibers. At the end of the calorimeter, a muon detector, implemented by using iron/concrete absorber and streamer tubes, helps to contain the muons when the ν_μ interaction occurs in the final part of the calorimeter.

Site	λ	ϕ	Λ	α	Distance
CERN	6.073°	46.24°	122.5°	3.283°	731 km
LNGS	13.57°	42.45°			

Table 1: Absolute coordinates (λ,ϕ) and azimuth and declination angles (Λ,α) of the direction Gran Sasso-CERN.

5 The CERN - Gran Sasso LBL project

The decay of pions and kaons produces essentially μ's and ν_μ's. Hence it is possible to generate a neutrino beam starting from the decay of secondaries (charged π and K) produced by the interactions of a primary proton beam on a target. The secondary particles are focused towards a detector and left to decay in a vacuum tunnel. A beam dump at the end of the tunnel stops muons and all remaining hadrons. It is important to remind that a small contamination of ν_e is unavoidably present in the neutrino beam, due to π, K and muon decay. The feasibility of a ν_μ beam from CERN to LNGS has been considered in the framework of the LHC project [11]. New transfer lines are required in order to bring the SPS to LHC. In the project is proposed to derive the primary proton beam from one of these lines; this beam may be deflected and directed to Gran Sasso in a 550 m transfer line, followed by a target and a focusing station (25 m). The decay tunnel is about 1 km long, with a diameter of a few meters. Tab. 1 shows absolute and relative coordinates for the two sites.

The ν-beam from CERN to LNGS will enter the present underground halls with an angle of 93.3° with respect to gallery axis. The project foresees two different extraction cycles. During the LHC construction it is possible to have a neutrino beam dedicated cycle of 7.2 s with 3 fast extractions of 6μs at a 50 ms interval. When LHC will be operating, the beam has to be shared among different projects. Then, only a cycle of 14.4 s with 2 fast extractions of 10μs at 50 ms interval for the neutrino beam will be used. Tab. 2 shows the performance of the machine in these two cases. The total number of protons on target is given for a run of 100 days (10^7 s) at 70% efficiency, which corresponds to about one year of operation. At present SPS

Operating mode	Energy (GeV)	Cycle length (s)	Proton on target per cycle	Proton on target per run
dedicated	450	7.2	$3 \times 0.8 \times 10^{13}$	2.0×10^{19}
shared	450	14.4	$2 \times 0.9 \times 10^{13}$	0.75×10^{19}

Table 2: Performances of the SPS machine for dedicated and shared mode.

Focusing	Events/10^{19}pot/kton	$< E_\nu^{-2} >^{-1/2}$(GeV)	ν_e/ν_μ (%)
H20R40 [12]	473	10.5	1.4
H40R70 [12]	722	14.2	1.1
Single horn [13]	1040	22.8	0.65

Table 3: Event rate, neutrino mean energy and ν_e contamination for a 450 GeV/c proton beam , a flux of 10^{19} protons on target and a perfectly efficient detector at Gran Sasso.

works in shared mode. Two detailed simulations of the transport beam and of the decay of secondaries have been carried out independently [12],[13],[14]. For the production target both simulations assume the same configuration now used for the short baseline at CERN, i.e. a segmented beryllium rod (1.2 m long, with a radius of 1.5 mm). Moreover the target is compatible with fluxes lower than $1.5 \cdot 10^{13}$ protons per fast extraction. Different types of target are under study for higher fluxes. Two different possibilities have been analyzed for magnetic lenses: a horn-reflector system, different configuration of the magnets, tuned to focalize different monochromatic beams have been studied. Result of the simulations are reported in Tab. 3.

Event rate, neutrino mean energy and ν_e contamination are reported assuming a 450 GeV/c primary beam energy and two different focusing systems. Improvements on the ν_μ beam intensity could be achievable increasing either the proton beam or shortening the machine cycle.

6 Oscillating event rates

As it has been stated in sect. 3 the most important question is the confirmation of the ν-survival probability and its complementary probability of different ν-flavors appearance. These measurements can be performed by looking at the depletion of ν_μ CC events and at the appearance of ν_e CC (and/or ν_τ CC) as a function of L/E. In particular at Gran Sasso, L=731 km away from CERN, in the hypothesis of three fold maximal mixing, the transition of the survival probability to the plateau value of 5/9 is expected to happen around the neutrino energy E $\sim$ 10 GeV (Fig. 1). It is noteworthy that the energy spectrum of the ν_μ-beam described in the previous section seems to be well suited for this kind of measurement. At the transition, the first full oscillation cycle will be more evident if the event energy is well measured.

In the following analysis hadronic jets with a reconstructed energy greater than about 3 GeV are considered. Moreover in order to take into account the muon identification capability of the detector, a cut on the reconstructed μ energy has been considered (E$\geq$ 1 GeV)

In what follows, three different detector configurations have been considered:

1. an ideal detector with infinite resolution
2. a N^OE like detector with a $40\%/\sqrt{E}$ resolution on hadronic showers
3. a coarse calorimeter with a $150\%/\sqrt{E}$ resolution

In absence of oscillations Fig. 6 shows the expected ν_μ CC energy distribution of the reconstructed simulated events for the three detectors.

Given an exposure of $2 \cdot 10^{19}$ proton on target per year and under the hypothesis of a "A. Ball" neutrino spectrum[12], the rate of ν_μ CC unoscillated events expected at Gran Sasso by the N^OE detector are $\sim$15000 in 3 years of operation.

In case of oscillation, the N^OE detector will be able to measure:

- ν_μ disappearance as a function of the energy, collecting ν_μ CC interaction events;
- Excess of ν_e CC events and/or ν_τ CC interactions respectively for $\nu_\mu \to \nu_e$ and/or $\nu_\mu \to \nu_\tau$ oscillations.

6.1 ν_μ disappearance test

If ν_μ oscillations exist, the rate of ν_μ CC interactions will be depleted independently of the flavour in which the neutrino has oscillated. (Fig. 7).

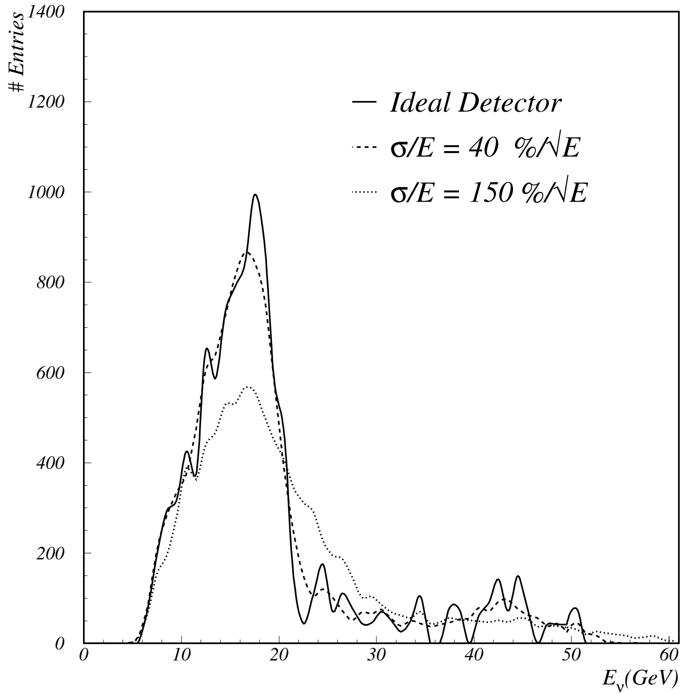

Figure 6: ν_μ CC interaction spectrum for different hadronic resolutions at Gran Sasso location.

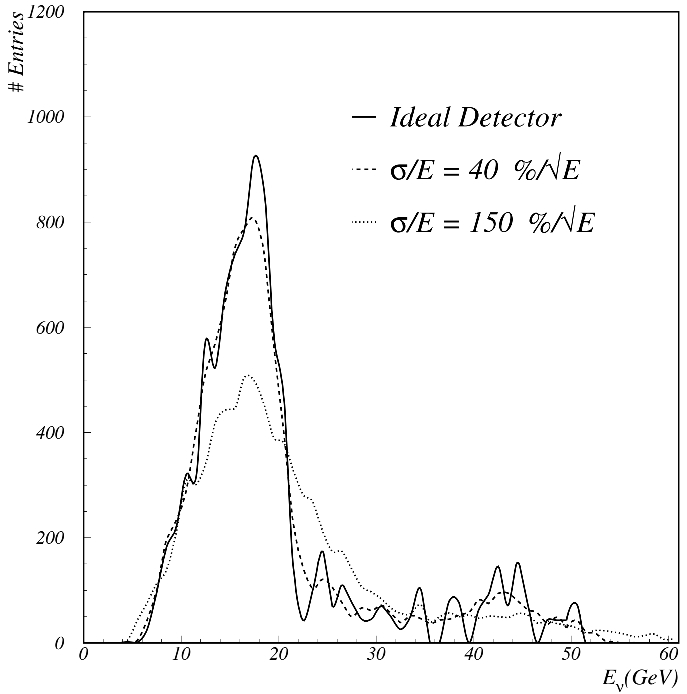

Figure 7: Residual ν_μ CC interaction spectrum for different hadronic resolution at Gran Sasso location.

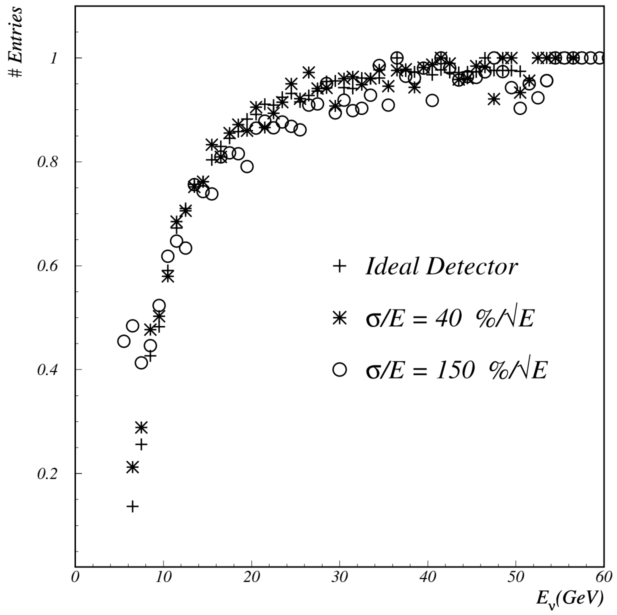

Figure 8: ν_μ survival probability curve at maximal mixing angle for different hadronic resolutions at Gran Sasso location.

Under the hypothesis of $\Delta m^2 = 0.72 \cdot 10^{-2}$ eV^2 and maximal mixing angle for the oscillation parameters (see sect. 1), a survival curve as a function of the energy can be drawn dividing residual ν_μ CC by total ν_μ CC (Fig. 8).

In both figures the effect of the reconstructed energy resolution (ideal, $N^{O}E$, very coarse calorimeter) is clearly visible. The number of oscillated events, most of them concentrated at lower energy, is 4051 under the exposure defined in the previous section. By lowering the value of $\sin^2(2\theta)$ the level of sensitivity for ν_μ disappearance as a function of the energy resolution is shown in Fig. 9, 10 and 11.

6.2 ν_e appearance test

Once that the ν_μ flux will be found depleted, the next step will be the understanding of the nature of oscillations. In principle both neutrino flavors ν_e, ν_τ are likely, hence the detector must be able to discriminate them unambiguously through the respective charge current interactions. Different predictions of the oscillation ratio into ν_e and ν_τ have been presented in sect. 1 as well as some experimental hints. Maximal transition rates in ν_e or ν_τ are respectively considered in the present calculation. On the contrary, if oscillations will be unequally divided between ν_e and ν_τ the respective rate

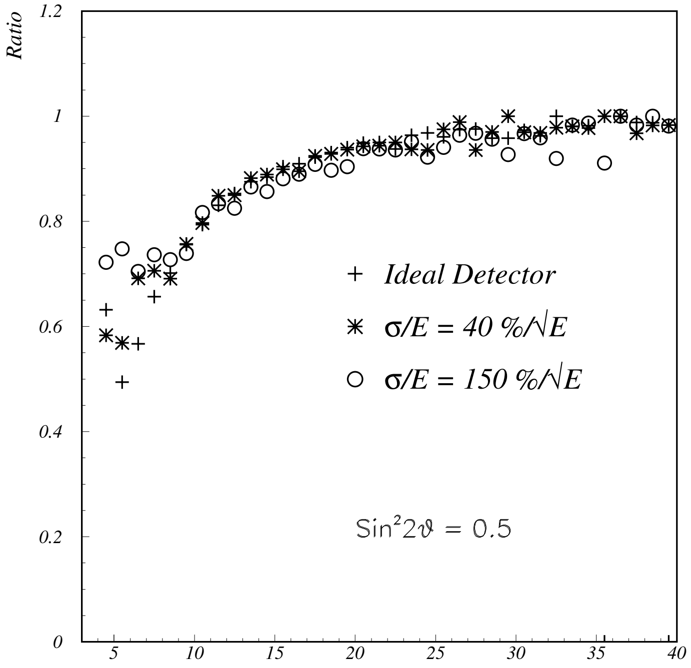

Figure 9: ν_μ survival probability curve at $\sin^2 2\theta = 0.5$ for different hadronic resolutions at Gran Sasso location.

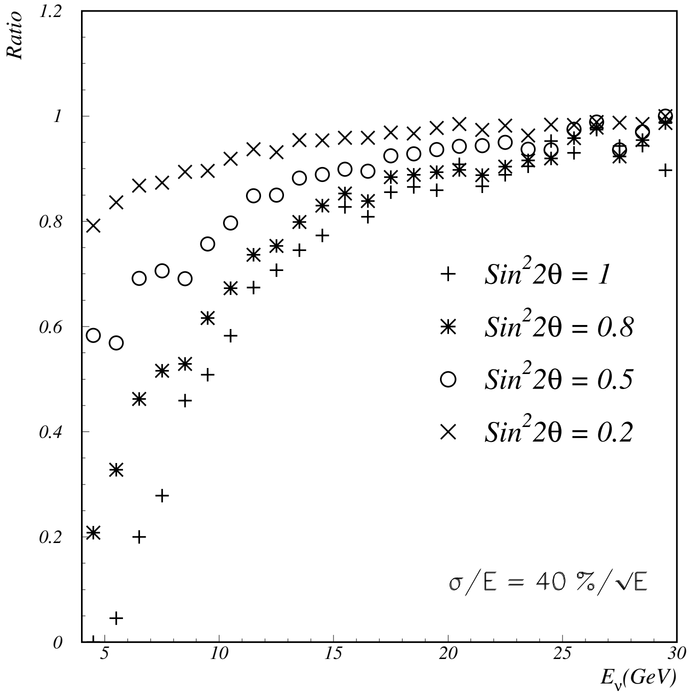

Figure 10: ν_μ survival probability curve at different mixing angle for N^OE hadronic resolutions at Gran Sasso location.

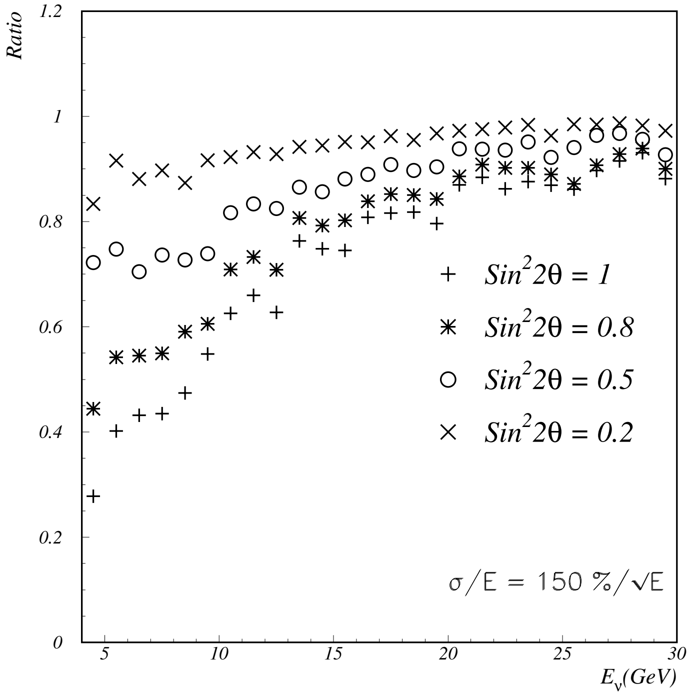

Figure 11: ν_μ survival probability curve at different mixing angle for coarse hadronic resolutions at Gran Sasso location

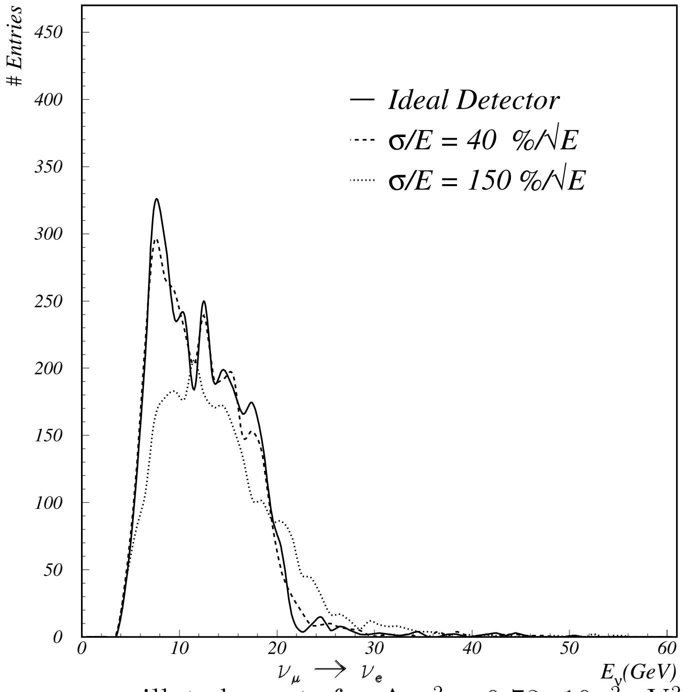

Figure 12: $\nu_\mu \rightarrow \nu_e$ oscillated events for $\Delta m^2 = 0.72 \cdot 10^{-2}$ eV^2 and maximal mixing angle at Gran Sasso location.

$\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ can be easily deduced. Always in the same exposure conditions, and in the hypothesis of a predominant mixing $\nu_\mu \rightarrow \nu_e$, with the channel $\nu_\mu \rightarrow \nu_\tau$ strongly suppressed as suggested by Acker and Pakvasa model [9], the oscillating ν_e CC and the residual ν_μ CC will be respectively 4051 and 10867 events while the energy spectra are shown in Fig. 12 and 7.

The ν_e contamination in the beam gives ~ 150 ν_e CC events rather flatly distributed over the energy, but nevertheless the signal is expected to be very large. Electrons coming from ν_e CC can be detected by studying the topology of the electromagnetic shower (maximum charge, depth, shower profile). In addition the capability of N^OE experiment to measure energy loss ΔE and the path in each calorimetric element many times along the track, contributes to the electron identification, taking advantage of the $\Delta E/\Delta L$ versus range parameter technique. "Fake" electrons could be produced by the decay of π^0 generated in the hadronic core. Cuts in event topology, energy and $\Delta E/\Delta L$ versus range in each calorimetric element, can reduce this background to a tolerable level. A simple 1.5 GeV energy cut reduces the π^0 contamination to less than 5% of the total number of ν_μ CC. In case of oscillations with large mixing, this contamination should not produce large effects.

Finally, the ratio ν_μ CC/ν_e CC = μ/e, like the parameter used to quote the atmospheric disappearance of ν_μ, can be computed to point out the existence of long base ν_e oscillations. The ν_e excess (Fig. 13) at low energy should be very large. This effect produces 1 to 2 orders of magnitude change in the ratio and makes this parameter a very attractive oscillation indicator.

6.3 ν_τ appearance test

The number of the oscillated ν_τ CC as a function of energy is shown in Fig. 14. Unlike the ν_e CC interaction rate, ν_τ CC events are depleted by a kinematical factor η, namely σ_τ/σ_μ, that suppresses the τ generation. Moreover the branching ratio of tau decaying into leptonic channels leads to 300 $\tau \rightarrow \mu$ and 300 $\tau \rightarrow e$ collected in the same exposure conditions described in last section.

In spite of these depletion factors the oscillation effect is still large and unambiguous. A proof is given in Fig. 15, where the ratio between ν_μ CC and ν_τ CC is plotted.

Kinematical identification of the τ decay, which follows the ν_τ CC interaction, requires excellent detector performances: good calorimetric features together with tracking and event topology reconstruction capabilities.

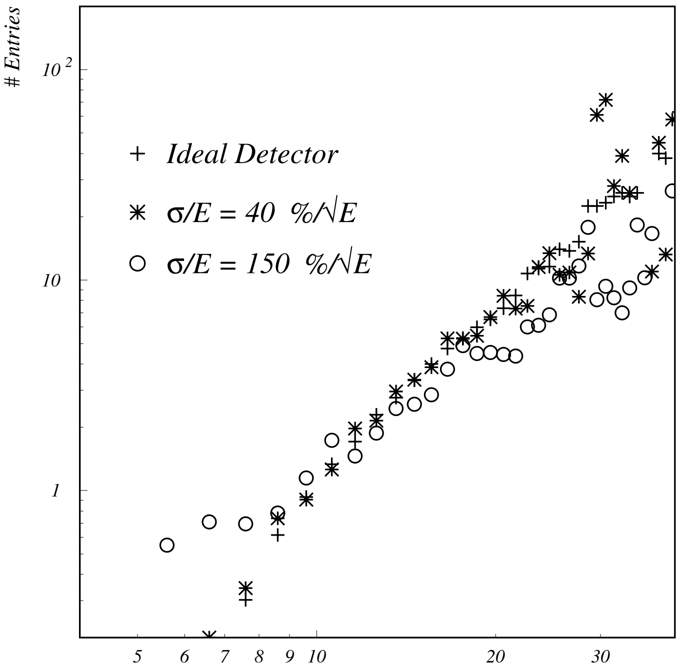

Figure 13: ν_μ CC/ν_e CC = μ/e ratio for $\Delta m^2 = 0.72 \cdot 10^{-2}$ eV^2 and maximal mixing angle at Gran Sasso location.

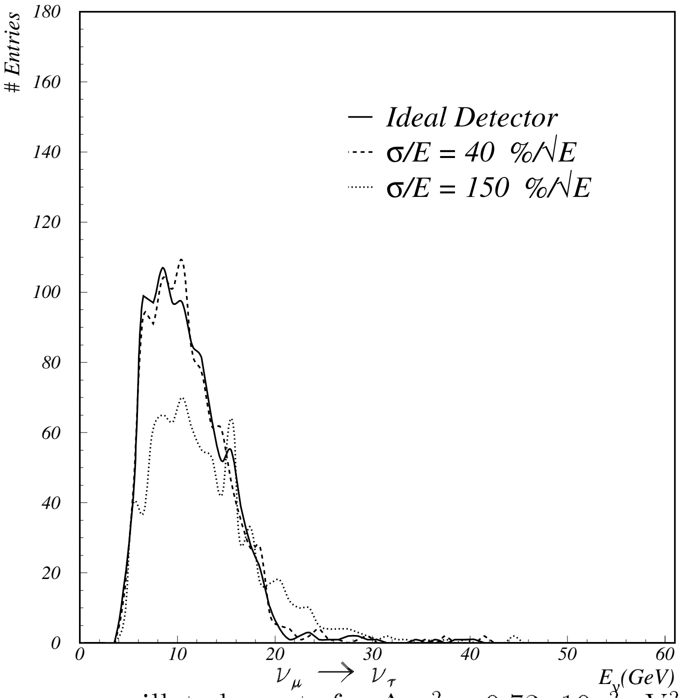

Figure 14: $\nu_\mu \rightarrow \nu_\tau$ oscillated events for $\Delta m^2 = 0.72 \cdot 10^{-2}$ eV^2 and maximal mixing angle at Gran Sasso location.

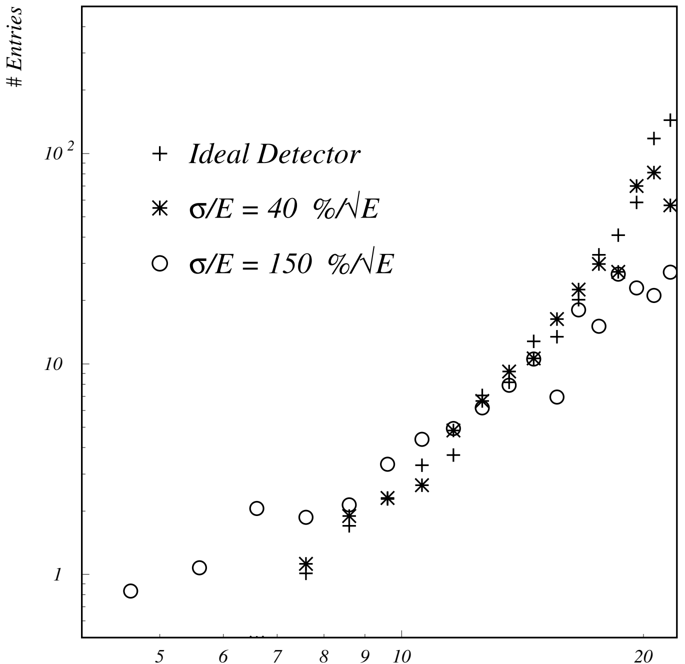

Figure 15: ν_μ CC/ν_τ CC= $\mu/\mu(\tau)$ ratio for $\Delta m^2 = 0.72 \cdot 10^{-2}$ eV^2 and maximal mixing angle at Gran Sasso location.

$N^{O}E$ ’s choice to have a high granularity but a relatively moderate mass (5 kton), compensates the loss of statistics with the ability to perform measurements in the τ decay channel. Depending on the examined decay channel , the background is constituted of ν_e CC events or ν_μ CC events. In order to separate ν_τ events from the background two basic criteria adopted mainly by short baseline experiments can be used:

1. the presence of two neutrinos from τ decay produces an unbalanced total transverse momentum;
2. the angular correlation between lepton, hadronic prong and missing momentum in the transverse plane.

For ν_μ CC events the lepton and the hadronic shower transverse momenta are opposite and the missing momentum is not correlated with either of them. For ν_τ CC events lepton and missing momentum tends to be opposite to the hadronic component making the angles between lepton-hadrons $\phi_{l \to h}$ wide and similar to that between missing p_t and hadrons $\phi_{pt \to h}$. $\phi_{l \to h}$ vs. $\phi_{pt \to h}$

Simulations of ν_μ CC and ν_τ CC events have been performed in order to reconstruct both the unbalanced total transverse momentum and the angular

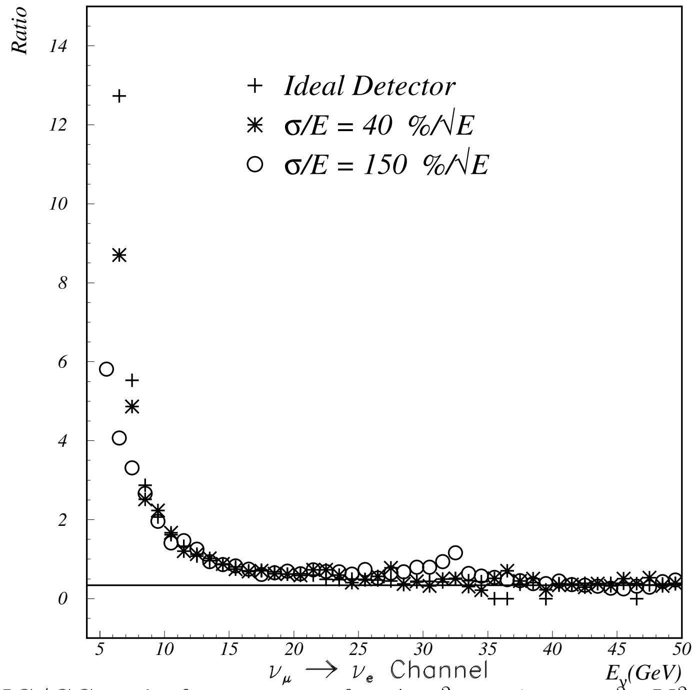

Figure 16: NC/CC ratio for $\nu_\mu \rightarrow \nu_e$ for $\Delta\mathrm{m}^2 = 0.72 \cdot 10^{-2}$ eV^2 and maximal mixing angle at Gran Sasso location.

correlation plots $\phi_{l\rightarrow h}$ versus $\phi_{pt\rightarrow h}$. Our preliminary results show that is possible to define cuts allowing to reduce the ν_μ CC background of a factor 10^{-2}. Such a modest rejection factor permits an high τ detection efficiency. Taking into account also cuts in fiducial volume to ensure containment, and in muon energy to have clear ν_μ CC identification, we obtain 48 μ's from τ decay and 11 residual μ's from ν_μ CC interactions.

7 Inclusive measurements

A further experimental evidence of the modulation curve (Fig.1) of the neutrino oscillations will come from the analysis of the classic inclusive NC/CC ratio measurement. In Fig. 16 and 17 the behaviour of this parameter as a function of the energy for $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ is shown.

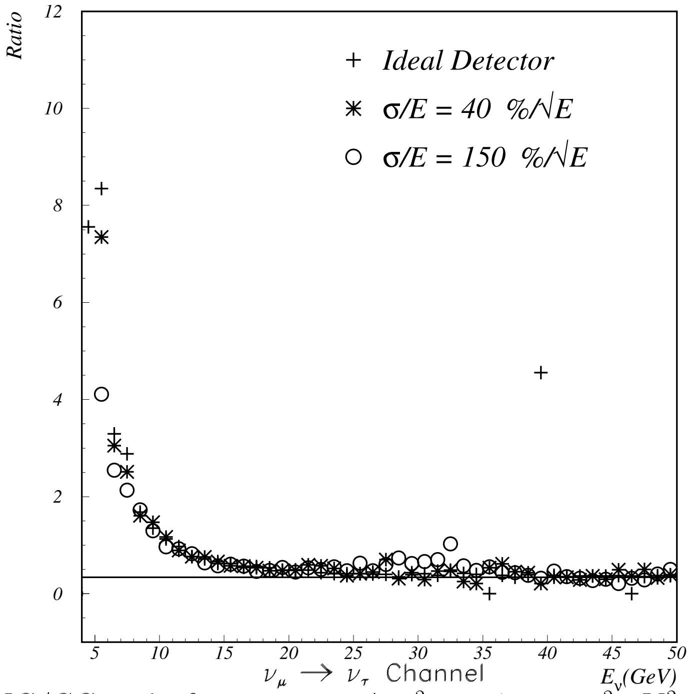

Figure 17: NC/CC ratio for $\nu_\mu \rightarrow \nu_\tau$ $\Delta m^2 = 0.72 \cdot 10^{-2}$ eV^2 and maximal mixing angle at Gran Sasso location.

8 Conclusions

The analysis presented in this article simulates the response of the N^OE long-base experiment when it is looking at the large mixing angle in the parameter space. At present both experimental hints (atmospheric anomaly) and the theoretical models accomodating all the existing experimental results (LSND, atmospheric and solar data) make this region especially attractive to the exploration.

In absence of signal in the large mixing region the sensitivity limits of the N^OE detector are shown in Fig. 18.

In general a long-base detector, having in this region an excellent ratio signal over background, is a very powerful tool to investigate large mixing angle. Hence, the measurements at Gran Sasso could clarify unambiguously the oscillation models checking both disappearance and ν_e, ν_τ appearance tests. Tables 4 and 5 summarize the expected number of events at the Gran Sasso location with and without oscillation parameters. It has been shown that the design of the N^OE detector is able to explore the whole spectrum of oscillations. In particular a good balance between mass and granularity

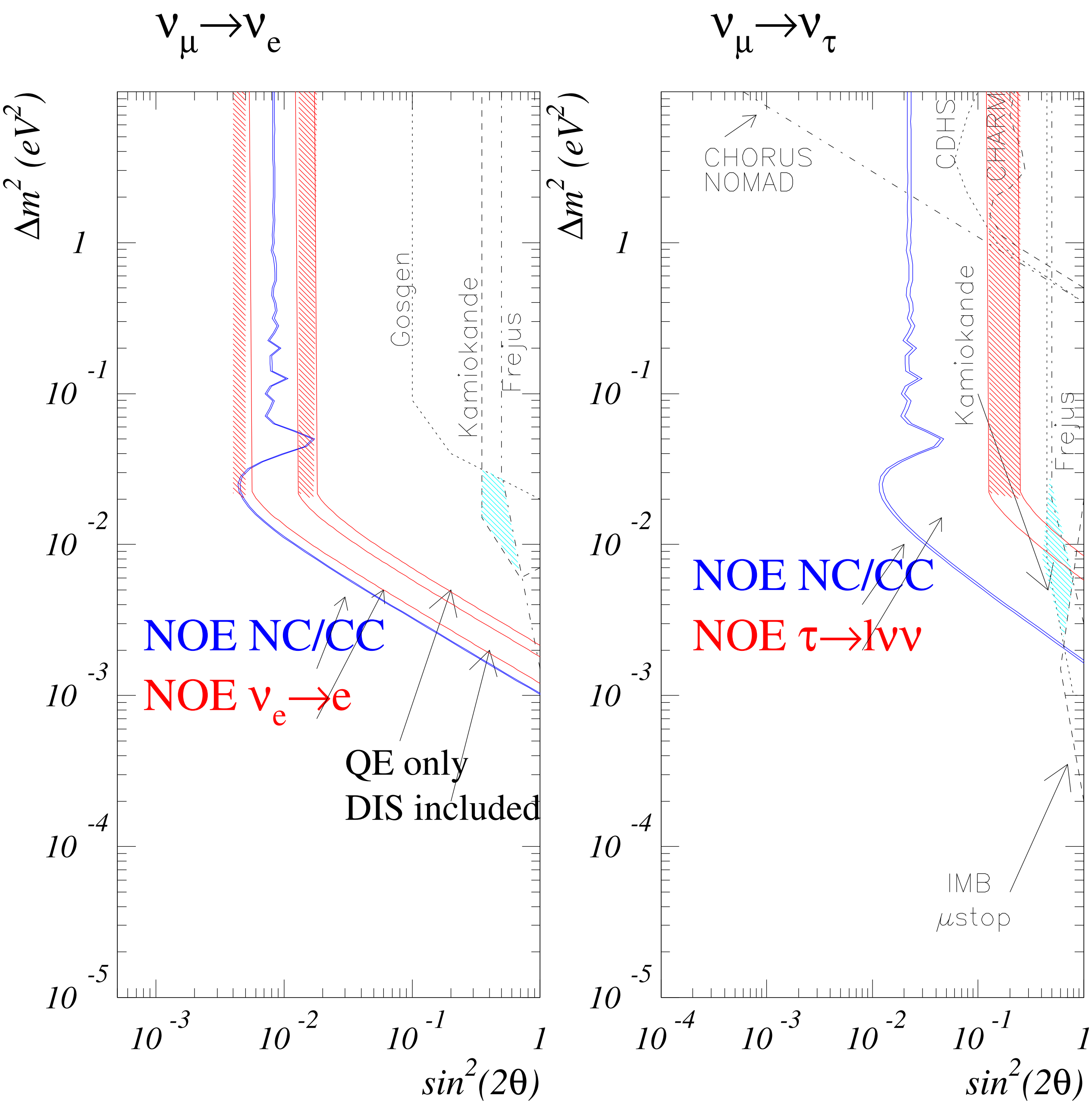

Figure 18: The N^OE sensitivity for long baseline neutrino oscillation measurements. The shaded regions show the present uncertainty due to the spread of ν_e beam contamination values and to the still preliminary background estimates.

No Oscillation

Processes	**# of Events**
ν_μ CC DIS	15000
ν_μ CC Q.E.	845
ν_μ CC RES	1056
ν_e CC DIS beam contamination	150
ν_e CC Q.E. beam contamination	9
ν_e CC RES beam contamination	10

Table 4: Expected number of events at the Gran Sasso location without oscillation (DIS= Deep Inelastic Scattering, Q.E.= Quasi Elastic scattering, RES= Baryon RESonance production).

allows to detect a large and clear effect in the energy modulation both in the disappearance rate $\nu_\mu \rightarrow \nu_x$ and in the appearance one $\nu_\mu \rightarrow \nu_e$ and/or ν_τ.

Oscillations

Processes	# of Events
ν_μ CC DIS (residual)	10807
ν_μ CC Q.E. (residual)	612
ν_μ CC RES (residual)	765
$\nu_\mu \to \nu_e$ CC DIS	4051
$\nu_\mu \to \nu_e$ CC Q.E.	228
$\nu_\mu \to \nu_e$ CC RES	285
$\nu_\mu \to \nu_\tau$ CC DIS	1561
(Branching Ratio $\tau \to \mu$)	300
(Branching Ratio $\tau \to$ e)	300
$\nu_\mu \to \nu_\tau$ CC Q.E.	
(Branching Ratio $\tau \to \mu$)	18
(Branching Ratio $\tau \to$ e)	18
$\nu_\mu \to \nu_\tau$ CC RES	
(Branching Ratio $\tau \to \mu$)	20
(Branching Ratio $\tau \to$ e)	20

Table 5: Expected number of events at the Gran Sasso location with oscillation. Used parameters are $\Delta \mathrm{m}^2 = 0.72 \cdot 10^{-2}$ eV^2, $\sin^2 2\theta = 1$ (max mixing); (DIS= Deep Inelastic Scattering, Q.E.= Quasi Elastic scattering, RES= baryon RESonance production).

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