NOE, a Neutrino Oscillation Experiment at Gran Sasso Laboratory

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Abstract

The project of a large underground experiment (N^OE) devoted to long baseline neutrino oscillation measurement is presented. The apparatus is composed by calorimetric modules interleaved with TRD modules and has been optimized to be sensitive in the region of $\sin^2 2\theta$ and Δm^2 suggested by the atmospheric neutrino oscillation signal.

1 Introduction

The first version of the N^OE proposal has been submitted to the Gran Sasso Scientific Committee in February 1996 [1]. From that time on, many efforts (technical design, tests, simulations and so on) have been done to improve the project, in terms of scientific goals, detector performances and granularity, safety and reduction in costs [2, 3, 4]. Here a brief progress report is presented, mainly devoted to describe the latest developments with respect to [5].

The scientific goal of N^OE long baseline (LBL) experiment is the measurement of neutrino masses looking for $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations. The philosophy of N^OE design is to have oscillation sensitivity by looking for the τ decay ($\nu_\mu \rightarrow \nu_\tau$ oscillation) or for an electron excess ($\nu_\mu \rightarrow \nu_e$ oscillation) and by measuring a deficit of muons in apparent NC/CC ratio.

The major experimental hint for the ν oscillation search in the region of low Δm^2 ($10^{-2} \div 10^{-3}\ eV^2$) comes from the muon deficit observed in atmospheric neutrino flux measurements [6, 7, 8]. Recent results from LBL reactor neutrino experiment (CHOOZ) exclude neutrino oscillation in $\bar{\nu}_e$ disappearance mode, up to $\sin^2 2\theta > 0.18$ for large Δm^2 [9].

Given the confirmations of the atmospheric neutrino anomaly and the negative CHOOZ result, a LBL experiment has to fulfill the following requirements:

1. ν_τ **tagging.** The search for ν_τ appearance becomes fundamental in order to confirm the oscillation phenomenon. This search requires detector high performances to reveal the τ decay in different channels.

2. **Measurement of the ratio NC/CC.** This robust and unambiguos test is mandatory to investigate on the existence of a neutrino oscillation signal. Moreover in a scenario, never ruled out, in which a neutrino oscillates in a sterile neutrino the oscillation can be discovered only by measuring a deviation from expected NC/CC ratio. There is no doubt that this measurement can be done only with a massive detector.

3. **Atmospheric neutrinos.** After the last results which suggest smaller values of Δm^2, the interest for the atmospheric neutrinos is raised up. It would be interesting to test this effect using a massive apparatus based on a different technique with respect to the water Čerenkov detectors.

4. **Fast response.** If a beam from CERN to Gran Sasso will be available in the next years, a strong competition with American and Japanese LBL programs is foreseen: at present, the 7 kton N^OE project can adequately compete with the 8 kton MINOS detector and with K2K.

According to these remarks the N^OE program can be summarized in this way:

- Direct ν_τ appearance by kinematical τ decay reconstruction and inclusive (NC/CC) ν_μ disappearance.

- Investigation of $\nu_\mu \rightarrow \nu_e$ oscillation in a mixing angle region two orders of magnitude beyond the CHOOZ limit.

- Atmospheric neutrino studies.

In order to improve the ν_τ search, the apparatus has been implemented with Transition Radiation Detector (TRD) interleaved between calorimetric modules (CAL). The combination of TRD and CAL information strongly enforces e, μ, and π identification, thus permitting the study of the τ decay. In particular the $\tau \rightarrow e\nu\nu$ channel is detectable with a clean signature because of the low background (residual ν_e beam). Moreover the good electron identification in the TRD and the low π^o background allow to reach high $\sin^2 2\theta$ sensitivity looking for $\nu_\mu \rightarrow \nu_e$ oscillation, thus considerably enlarging the region investigated by CHOOZ.

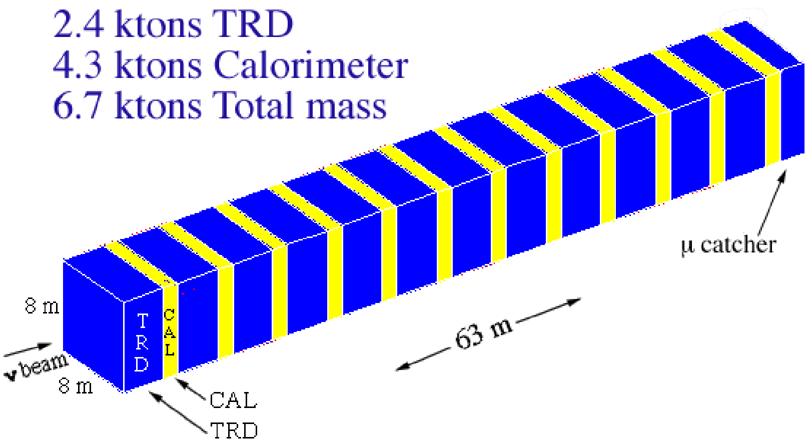

Figure 1: Schematic view of the N^OE detector

2 The N^OE detector

The detector (Fig. 1) is a classical fixed target apparatus consisting of a sequence of 12 modules. Each one is composed by a lighter part (TRD target) in which vertex, e-identification and kinematics are defined, followed by a fiber scintillating calorimeter devoted to absorb the event and to measure the energy. The Basic Module (BM) is shown in Fig. 2. Appearance measurement is performed on the events generated in TRD (2.4 $kton$), disappearance measurement on all events (generated in ~ 7 $kton$ of target).

The calorimetric element is an 8 meter long bar having iron ore and scintillating fibers[1] suitably distributed inside and parallel to the axis. The calorimetric module is made by alternate planes of crossed bars. The calorimetric bar consists of more logical cells with square cross section, the iron/iron-ore volume ratio is 0.3. The iron ore is radiopure and practically cost free.

At present the latest production developments of 2 mm diameter scintillating fibers provides an attenuation length of 4.5 m and an increase in light yield of $10\div15$ %. These figures allow to build 8 m long bars. Further investigations to improve fiber features are in progress because longer fibers shall permit to enlarge the N^OE cross section (9×9 m^2) and mass (8 $kton$). It is worth noting the very high intrinsic granularity of the proposed calorimeter : the average distance between the fibers inside the absorber is of the order of 3 mm. In a simple and often used way, all fibers are grouped together at each side of the calorimetric bar and sent to single or multipixel photodetector.

The TRD module consists of 32 vertical layers of 8×8 m^2 area, each made by polyethylene foam radiator ($\rho \sim 100$ mg/cm^3) and 256 proportional tubes (3×3 cm^2 cross section), filled with an Ar (60%) - Xe (30%) - CO_2 (10%) mixture, already tested in MACRO experiment. Consecutive layers have tubes rotated of 90°.

A graphite wall of 5 cm thickness is set in front of each of the first 24 layers of the TRD module acting as a 174 ton target for ν_e and ν_τ interactions, to be identified in the following layers. The last target wall is followed by 8 TRD layers in order to identify the secondary particles. Each target wall corresponds to 0.25 X_0 while the

[1] Extruded scintillator strips with wavelength shifter fibers have been also studied.

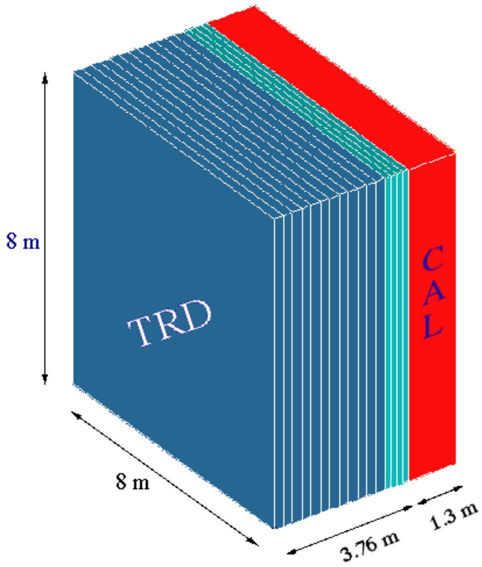

Figure 2: The Basic Module of the N^OE detector

entire TRD basic module corresponds to about 7 X_0 and 3.5 λ_I. The total length is about 3.76 m.

So many layers of proportional tubes permit to determine the muon energy by means of multiple measurements of energy loss dE/dx. Combining informations coming from both subdetectors (TRD and CAL) the discrimination between e, μ and π is largely enforced allowing the study of several neutrino oscillation channels.

3 ν_τ appearance and requirements about ν beam

The rate of ν_τ CC events is given by

$$R_\tau = A \int \sigma_\tau P_{osc} \Phi dE, \qquad (1)$$

where E is the energy, σ_τ the ν_τ CC cross section, P_{osc} the oscillation probability, Φ the muon neutrino flux and A the number of target nucleons in the detector. The search for ν_τ requires that the term $\sigma_\tau P_{osc}\Phi$ is large. Therefore a dedicated ν-beam has to provide most of its flux in the energy range where the factor $\sigma_\tau P_{osc}$ is larger.

Assuming the mixing of two neutrinos, the oscillation probability results

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E), \qquad (2)$$

where $L = 731$ km is the distance CERN - Gran Sasso. CC cross section as a function of energy is shown in Fig. 3 for ν_μ and ν_τ. We have to note that the τ cross section grows slowly with energy above a threshold of about 3.5 GeV. The factor $\sigma_\tau P_{osc}$ is shown in Fig. 4 for different values of Δm^2. The optimal energy is about 15 GeV for $\Delta m^2 = 0.01$ eV^2 and decreases gently with Δm^2 towards a limiting value of about 10 GeV.

As an example the number of ν_τ CC interactions per 10^{19} protons on target per kton has been calculated for different proposed beams [10, 11, 12] whose spectra are shown in Fig. 5. The rate of ν_τ CC interactions is shown in the first plot of Fig. 6 as a function of Δm^2. The highest τ yield is obtained with a beam like that proposed by

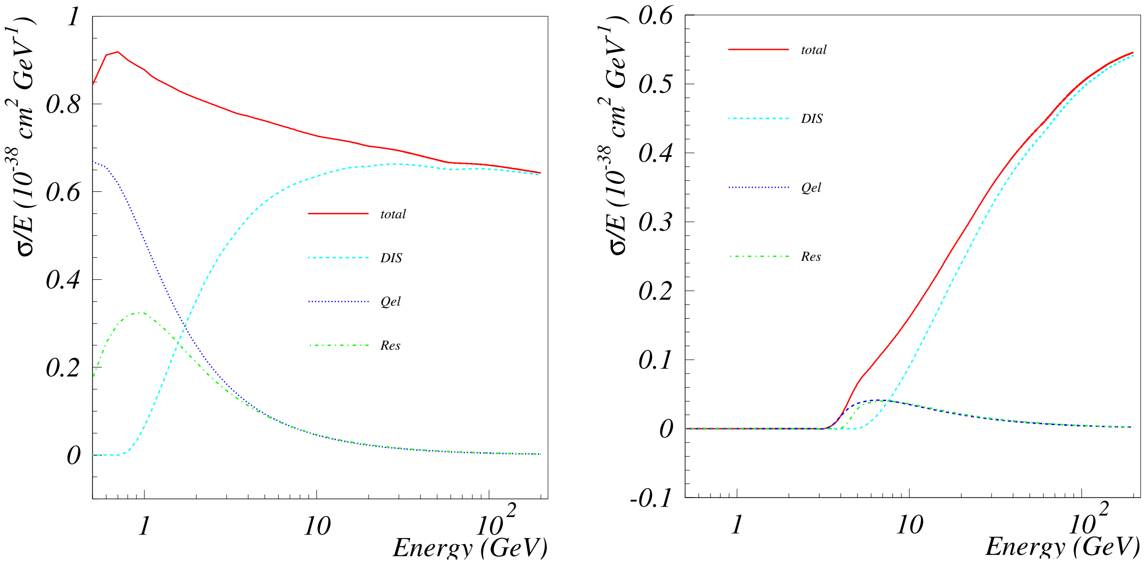

Figure 3: Ratio of ν_μ and ν_τ CC cross section over energy.

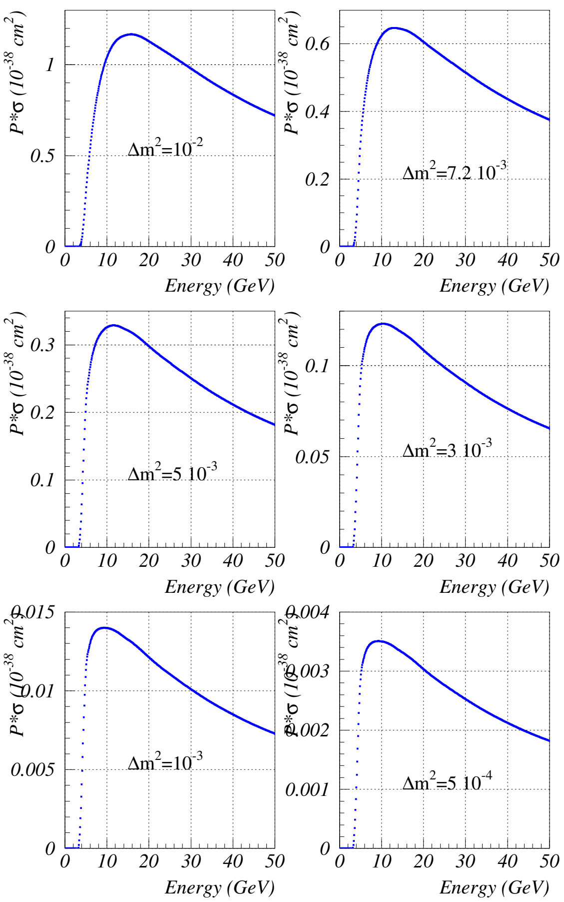

Figure 4: ν_τ CC cross section multiplied by the oscillation probability for different values of Δm^2.

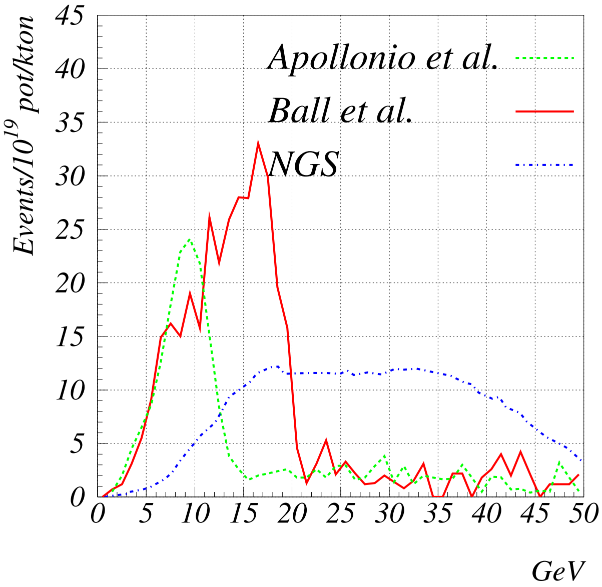

Figure 5: ν_μ CC interaction spectra for different proposed beams.

Ball *et al.* [10], narrowly peaked around an energy that better matches the appearance requirements.

Fig. 6 shows also the rate of residual ν_μ CC interactions. From comparison of the plots in Fig. 6 we observe that the beam of Ref. [10] has a higher ratio of oscillated to unoscillated events (the best signal to noise ratio) when compared to that of Ref. [11]. Moreover the event rate of Ref. [10] above ~ 20 GeV is about 25 % of that of Ref. [11] (see Fig. 5). Therefore the background of π^o due to NC will be reduced by the same amount, looking for $\tau \to e\nu\nu$ decay.

In the following, the beam from Ref. [10] and 5 years of data taking are assumed.

4 τ appearance searches

Tau appearance search is performed on the basis of kinematical identification of the τ decay. The $\tau \to e\nu\nu$ is the channel favourite for this search due to the low background level and the the good electron identification capabilities of the TRD. It is worth noting that in the region of atmospheric anomaly the oscillation probability is $50 \div 100$ times higher than expected in NOMAD, as a consequence a much lower background rejection power is required.

In order to check the overall N^OE performances, a complete chain of event simulation and analysis has been performed. Event generators that include Fermi motion, τ polarization and nuclear rescattering inside the nucleus have been used to simulate deep inelastic, quasi elastic and resonance events.

Generated events are processed by a GEANT based MonteCarlo in which calorimeter and TRD geometrical set-up are described in great detail, down to a scale of a few mm. Fiber attenuation length, Birks saturation, photoelectron fluctuations and readout electronics non linearities for both TRD and calorimeter have been taken into account. DST of processed events ($\tau \to e\nu\nu$, ν_μ NC and ν_e CC) have been produced and analysed.

Electron identification is performed by looking for high energy releases in the TRD

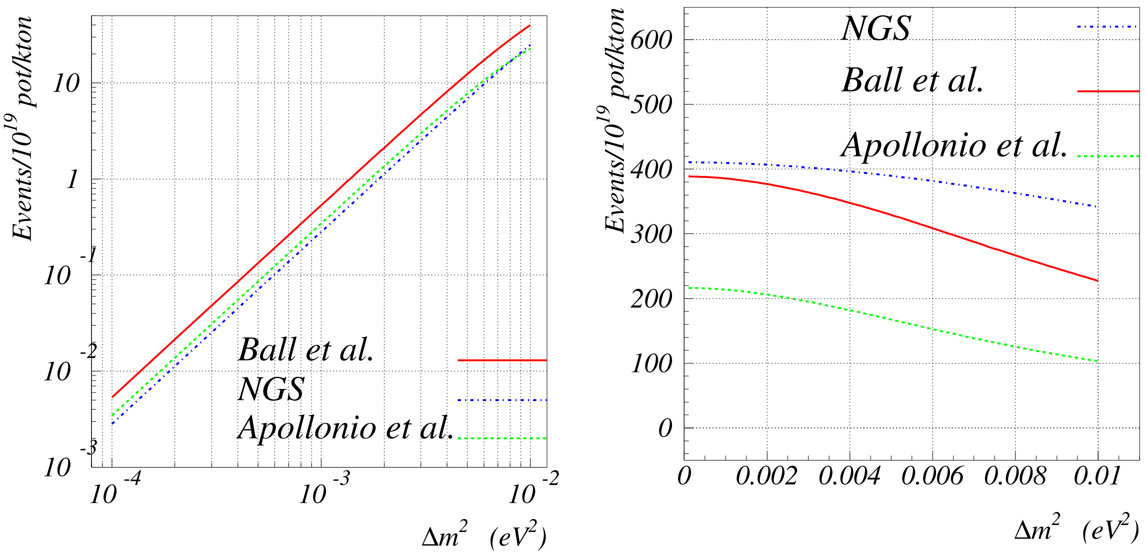

Figure 6: First plot - ν_τ CC interactions for different beams vs Δm^2. Second plot - residual ν_μ CC interactions for different beams vs Δm^2.

and in the calorimeter readout elements in fully contained events. The electron candidate is the one that maximizes collected energy in a 5° cone centered at the interaction vertex. Electron direction is reconstructed by weighting hits position by collected energy. With present algorithms an angular resolution of 0.6° and a 180 MeV/c resolution on the measurement of transverse momentum are achieved.

The remaining part of the event is used to reconstruct the hadronic component. The obtained resolution on the measurement of transverse momentum is 420 MeV/c.

Topological cuts on the electromagnetic shower are applied to reject ν_μ NC events with π^o faking electrons. Work is in progress to improve the reconstruction efficiency and ν_μ NC rejection. Additional cuts are performed to reduce the background:

- total reconstructed energy $< 15\ GeV$,
- electron energy $> 1.5\ GeV$,
- the component of electron momentum perpendicular to the hadronic jet direction $Q_{lep} > 0.75\ GeV/c$,
- transverse mass $M_T = \sqrt{4 p_T^e p_T^m \sin^2(\phi_{e-m}/2)} < 2\ GeV$,
- ϕ_{e-h} ϕ_{m-h} correlation as shown in Fig. 7.

Resulting efficiencies and residual backgrounds are reported in Table 1.

5 Neural network for the ratio NC/CC

The procedure to perform this measurement is well known [5]. The identification of charged and neutral current events has been improved by means of a neural network. The algorithm uses 24 topological, geometrical and calorimetric event parameters as input. The network has been trained with ν_μ CC and NC MonteCarlo events with a

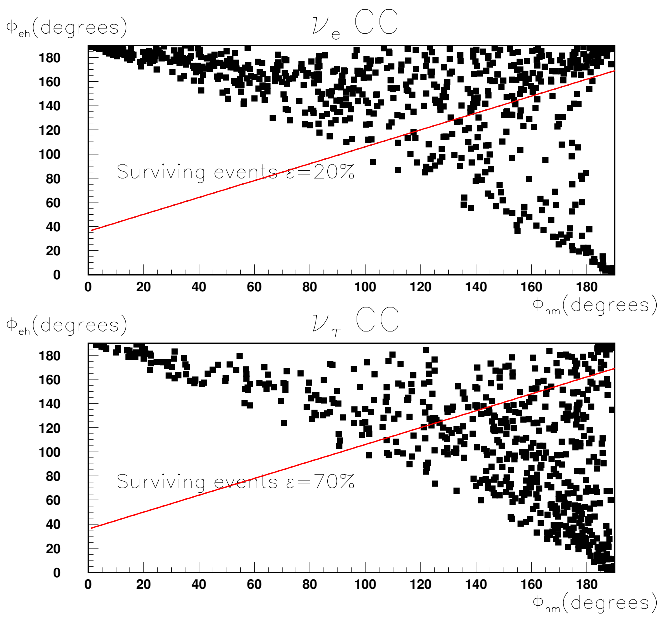

Figure 7: Effects of ϕ_{e-h} ϕ_{m-h} cut on background (ν_e) and signal (ν_τ).

■ **event containement**

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
1	79%	67%	79%

■ **high released energy track in two views: Ey = Ez**

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
2	19%	88%	91%

■ **compact shower, starting from the vertex, topology.**
(π^0 without initial conversion)

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
3	11%	88%	89%

■ **E_{Tot} < 15 GeV**

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
4	94%	45%	97%

■ **$E_{e.m.} \geq 1.5$ GeV**

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
5	55%	90%	84%

■ **$Q_{Lep} \geq 0.75$ GeV/c**

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
6	25%	75%	70%

■ **$M_{T\tau}$ < 2 GeV**

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
7	57%	89%	87%

■ **$\phi_{e,h}$ $\phi_{ptm,h}$ correlation**

Cut	Res. NC	Res.ν_e beam	eff. $\tau \to e\nu\nu$
8	35%	20%	70%

■ **for 1.5x10^{20} pot and 14000 ν_μCC (TRD) 5 years :**

Δm^2= 5x10^{-3} eV^2	2.7ν_eCC + 1.6NC = 4.3 evs.	19 τ evs.
Δm^2= 3x10^{-3} eV^2	2.7ν_eCC + 1.9NC = 4.6 evs.	7 τ evs.
no oscillation	2.7ν_eCC + 2.0NC = 4.7 evs.	0 τ evs.

Table 1: Details of analysis cuts, efficiency and rejection power for main background sources.

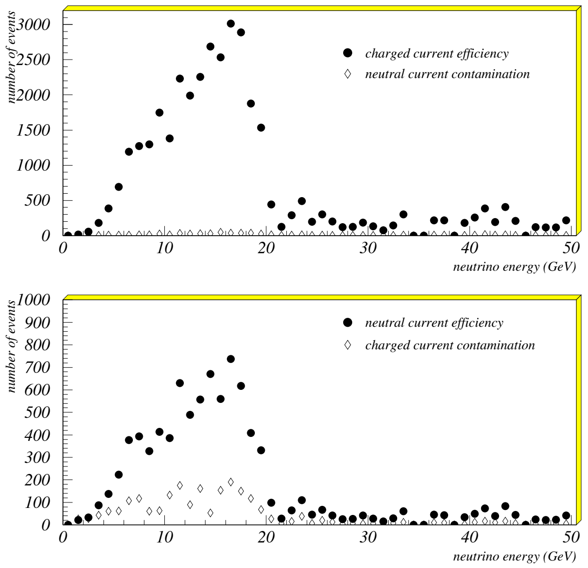

Figure 8: CC and NC signal. The contamination is also shown.

neutrino energy uniformly distributed in the range $0 \div 50$ GeV. The results of this analysis are shown in Fig. 8.

The μ event recognition is mainly dependent on the track length and the NC signal is still affected by a significant CC contamination. We hope to improve the recognition efficiency by tuning the neural network and the input parameters.

6 Conclusions

The combined use of two subdetectors (TRD and CAL) allows to search for τ appearance signal for events generated in the 2.5 $kton$ TRD target where electron identification, vertex and kinematics reconstruction are performed at best. Nevertheless the whole 8 $kton$ mass can be exploited for disappearance oscillation tests.

Such measurements can be carried out at the same time by using an appropriate neutrino beam. A full analysis has recently been performed to demonstrate the feasibility of both measurements. In Fig. 9 the sensitivity of N^OE experiment to ν oscillations is shown.

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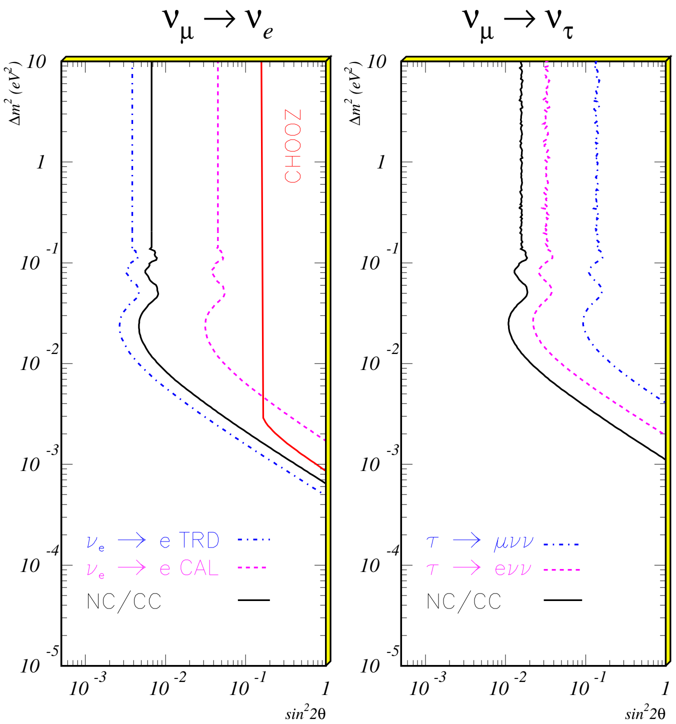

Figure 9: N^OE sensitivity to ν oscillations.

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