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Atmospheric neutrinos in a large Liquid Argon Detector

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Abstract

In view of the evaluation of the physics goals of a large Liquid Argon TPC, evolving from the ICARUS technology, we have studied the possibility of performing precision measurements on atmospheric neutrinos. For this purpose we have improved existing Monte Carlo neutrino event generators based on FLUKA and NUX by including the 3–flavor oscillation formalism and the numerical treatment of Earth matter effects. By means of these tools we have studied the sensitivity in the measurement of θ_{23} through the accurate measurement of ν_e's. The updated values for Δm^2_{23} from Super–Kamiokande and the mixing parameters as obtained by solar and KamLand experiments have been used as reference input, while different values of θ_{13} have been considered. An exposure larger than 500 kton yr seems necessary in order to achieve a significant result, provided that the present knowledge of systematic uncertainties is largely improved.

1 Introduction

In the framework of the design study for a very large Liquid Argon TPC evolving from the present status of the ICARUS project[1], it is important to start the discussion of the different physics goals that should be addressed by a multipurpose detector of this kind. The topic of atmospheric neutrinos is certainly one of the relevant chapters. Indeed, after the results coming mostly from Super–Kamiokande[2], there is still a scientific interest in continuing the study of atmospheric neutrinos. First of all it is necessary to confirm the results from SK with a technology capable of a large reduction of experimental systematics with respect to water Čerenkov. In second place, many authors have pointed out the possibility of exploring subleading contributions in the oscillation matrix. This would allow, in particular, a possible precision measurement of θ_{23} and the discrimination of the normal vs. the inverted hierarchy in the neutrino mass scale. These are tiny effect, and a very large Liquid Argon TPC with a sensitive mass of the order of several tens of kilotons seems necessary to reach the exposure necessary for these proposed analyses.

The preliminary work here presented aims to investigate quantitatively the attainable performance of such a large LAr detector in the field of atmospheric neutrinos

In section 2 we describe in more detail the motivations of physics for this study and provide a general discussion of the effects we are going to discuss. In section 3, we present the model implemented in our simulation to include three flavor oscillations and matter effects. Then, in section 4 we discuss the possible results with atmospheric neutrinos in the limit of a very high exposure.

2 Atmospheric neutrinos and 3–F oscillations

A large number of results regarding atmospheric[2], solar[3], reactor[4, 5] and accelerator neutrinos can be accounted for assuming that the ordinary 3 neutrinos have mass and mix among them [6]. In this framework, flavor oscillations are fully described by assigning 3 mixing angles and 1 CP violating phase. We do not know the type of mass hierarchy, and 3 of these quantities are still unmeasured: The size of θ_{13}, the deviation of θ_{23} from maximal mixing, and the CP violating phases δ (see sect. 3 for their definitions). The first unknown quantity is particularly important, for θ_{13} controls the size of three flavor oscillations. Although there are little doubts that such a 3ν framework is appropriate to describe these data, it is also fair to say that any experimental indication that we have is appropriately described by 2 flavor (2F) oscillations and 3 flavor (3F) effects have been not yet seen.

We recall that there are several theoretical approaches to understand neutrino masses, and possibly to predict unknown quantities as θ_{13}. The problem of fermion masses is known to be a difficult one, and caution is necessary in interpreting any prediction or theoretical expectation. However, several models suggest that θ_{13} is not undetectably small (see e.g., [7] for SO(10) models); rather, θ_{13} often happens to be close to the experimental limit of about 10°. Similarly, there are several models where deviations of θ_{23} from maximal mixing amount to several degrees. Presumably, these expectations can be considered in agreement with the common sense: in absence of any strong reasons to assume the contrary, θ_{13} and $\theta_{23} - 45^\circ$ should be not too small. Certainly, experimental investigations of θ_{13} and the search of 3F effects in oscillations are among the most important goals still to be achieved and will have a profound impact on what we know about neutrinos.

One of the most important results emerging from the 2F analysis of atmospheric neutrino experiments is that the θ_{23} mixing angle, which is defined in the range 0-$\pi/2$, is found to be compatible with the full mixing value of $\pi/4$. The measurement of this mixing angle comes from the up-down asymmetry of muon–like events, and in particular of the higher energy events, as the Multi–GeV selection in Super–Kamiokande, where the direction correlation between neutrino and lepton is strong. Actually, such up/down ratio, which in the average results very close to 1/2, gives a measurement of $sin^2 2\theta_{23}$ and therefore it is not possible in this way to distinguish the octant of θ_{23}. The present result is $sin^2 2\theta_{23} = 1 \pm 0.01$, which corresponds to $sin^2 \theta_{23} = 0.5 \pm 0.05$ In order to achieve a better understanding of the properties of neutrino mixing, it is of the utmost importance to measure precisely the value of θ_{23} and to measure its deviation from the full mixing value.

The possibility of performing a different measurement emerges in the framework of the 3-flavor oscillation scenario. Beside the main part due to $\nu_\mu - \nu_\tau$ oscillations certainly we have further small effects of ν_e oscillations with “solar frequency” and possibly, other

ν_e oscillations with "atmospheric frequency" due to θ_{13}. On top of these two effects, essentially of 2F character, there are also genuine 3F effects due to the interference between the various amplitudes of transition.

The following analytical considerations help to understand the underlying physics. In general, one can write the formal solution for the amplitude $\mathcal{A}_\nu$ of neutrino propagation as

$$\mathcal{A}_\nu = \mathrm{Texp}[-i\int dt\mathcal{H}_\nu(t)] = R_{23}\Delta \cdot \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \Delta^* R_{23}^t \tag{1}$$

where R_{23} are rotations by the angle $\theta_2 3$ in the 23 plane. The elements a_{ij} form an unitary matrix that depends on θ_{13} and θ_{12} but not on θ_{23} or on δ (of course, it depends also on Δm^2's and on the 'kinematical variables' E, L and θ_Z). From the explicit form of the hamiltonian $\mathcal{H}_\nu$ one easily shows that in the limit $\theta_{13} = 0$, one has $a_{13} = a_{23} = 0$, so the effects due to θ_{12} are described by a_{12} ('θ_{12}-driven' or 'solar frequency' oscillations). Similarly, in the limit $\theta_{12} = 0$, one has $a_{12} = a_{23} = 0$, so the effects due to θ_{13} are described by a_{13} ('θ_{13}-driven' or 'atmospheric frequency' oscillations).

In general, one can get a_{ij} from a numerical calculation. In the case of vacuum oscillations, however, the equations can be integrated and give for instance:

$$\begin{cases} a_{12} = s_{12}c_{12}c_{13}(e^{-i\varphi} - 1), & \varphi = \Delta m_{12}^2 L/2E \\ a_{13} = s_{13}c_{13}[(e^{-i\Phi} - 1) - s_{12}^2(e^{-i\varphi} - 1)], & \Phi = \Delta m_{13}^2 L/2E \end{cases} \tag{2}$$

Here we are using the standard notation s_{ij}, c_{ij} for $sin\theta_{ij}$ and $cos\theta_{ij}$ respectively. It is evident that these amplitudes have properties just discussed in the limiting cases $\theta_{12} \to 0$ and $\theta_{13} \to 0$.

From eq. (1) one obtains expressions for the probabilities of survival or of conversion, e.g.:

$$\begin{cases} P_{e\to e} = |(\mathcal{A}_\nu)_{11}^2| = 1 - |a_{12}^2| - |a_{13}^2| \\ P_{\mu\to e} = |(\mathcal{A}_\nu)_{12}^2| = |c_{23}\ a_{12}\ e^{i\delta}\ +\ s_{23}\ a_{13}|^2 \end{cases} \tag{3}$$

The interference term in the latter expression is a prime example of a genuine 3 flavor (3F) effect, that disappears in the limits $\theta_{12} \to 0$ and $\theta_{13} \to 0$. It should be noted that the dependence of this interference term on a_{13} is linear, thus it depends mildly on θ_{13}. (It should be recalled that the CHOOZ or reactor limit on θ_{13}, instead, scales with θ_{13}^2.)

Using eqs. (3) and following the discussion in [8], let us introduce the flavor ratio $r = F_\mu^0/F_e^0$. The variation of the electron neutrino flux $F_e = P_{e\to e}F_e^0 + P_{\mu\to e}F_\mu^0$ reads:

$$\frac{F_e}{F_e^0} - 1 = (rc_{23}^2 - 1)|a_{12}^2| + (rs_{23}^2 - 1)|a_{13}^2| + 2rs_{23}c_{23}\mathrm{Re}[a_{13}^* a_{12} e^{i\delta}] \tag{4}$$

The first two contribution are small for low energy neutrinos, since $r \sim 2$ and the θ_{23} mixing is close to maximal: $c_{23} \sim s_{23} \sim 1/\sqrt{2}$. It should be noted that these two terms correspond largely to 2 flavor effects. In fact, from what told above we know that in the limit $\theta_{13} = 0$, $a_{13} = 0$ thus from the first of eqs. (3) $|a_{12}^2| = 1 - P_{e\to e}(\Delta m_{12}^2, \theta_{12})$ whereas in the limit $\theta_{12} = 0$, $a_{12} = 0$ thus $|a_{13}^2| = 1 - P_{e\to e}(\Delta m_{13}^2, \theta_{13})$. The third term is the only one that it is not suppressed by the flavor ratio $r \sim 2$. In fact, this is exactly the interference term, namely, the genuine 3F effect. Note finally that the three terms work in different ways: the first one increases the electron flux if $\theta_{23} < 45°$, the second one if $\theta_{23} > 45°$, the last, can increase or decrease depending on δ. In other words, the "solar" sector of the neutrino mixing (described by the Δm_{12}^2 and θ_{12} parameters) influence the rate of ν_e events (in particular in the SubGeV range) with respect to the no–oscillation case, with a different sign according to the value of θ_{23}, even in case θ_{13} is very small or null. The effect vanishes totally instead for the maximum mixing case $\theta_{23} = \pi/4$. Since the solar neutrino and KamLand[2, 3] experiments have obtained a remarkably precise determination of two parameters Δm^2_{12} and θ_{12}, in principle the proposed measurement is possible, provided that systematics uncertainties are kept under control.

The MSW effect[9] ("matter effects") is relevant in specific energy regions, and in particular this happens where vacuum term is comparable with the matter term. For instance, the vacuum term at $\Delta m^2 = 10^{-4}$ eV^2 and $E = 0.5$ GeV is $\Delta m^2/2E \approx 5 \cdot 10^{-4}$ eV^2/MeV while the matter term at $\rho_e = 2.5\ e^-$ moles/cc is $\sqrt{2} G_F N_e = 9 \cdot 10^{-4}$ eV^2/MeV (as usual, $N_e = N_A \rho_e$). An interesting consequence is that, due to the MSW effect, θ_{13} oscillations (driven by $\Delta m^2_{atm} \sim 2.5 \cdot 10^{-3}$ eV^2) are amplified for $E \sim 2 - 6$ GeV. This could be of particular interest in long-baseline experiments, while, for statistical reasons connected to the steeply falling energy spectrum, atmospheric neutrino experiments are less sensitive in this energy range. Therefore in this work we focus on low energy events and neglect measurements aimed to measure θ_{13} and more in general MultiGeV events. We remark here that one of the most appealing advantage offered by the Liquid Argon technology with respect to water Čerenkov detectors, is the much larger efficiency in SubGeV investigation, in conjunction to the partial possibility of a better reconstruction of their kinematics. In fact an ICARUS–like detector can reconstruct recoiling protons down to a rather low energy threshold.

There is another important measurement connected with 3F oscillations including matter effects which can be in principle performed using atmospheric neutrinos. This is the discrimination of normal from inverted mass hierarchy (the sign of Δm^2_{13}). Large matter effects occur for neutrino if $\Delta m^2_{13} > 0$ and for antineutrinos if $\Delta m^2_{13} < 0$ and this is again more significant in the MultiGeV region. As suggested in [10], a detector capable of distinguishing on an event by event basis ν_μ from $\overline{\nu}_\mu$ in the range from about 3 to 10 GeV is ideal for this purpose. Such a separation capability can be performed by means of a magnetized detector: there is not yet a convincing design of large Liquid Argon coupled to a magnet. Furthermore, a low density detector has a low containment efficiency for MultiGeV muons. Therefore we also will not further discuss this suggestion, at least in this preliminary work which concerns the possibilities of further investigation of atmospheric neutrinos with a large Liquid Argon detector.

3 The simulation code for 3F oscillations with matter effects

The discussion of the previous paragraph introduces the need of calculating predictions taking into account with the maximum possible accuracy 3F oscillation coupled with matter effects. A numerical code has been designed for this purpose and we recall here the basic formalism that has been implemented for this purpose.

The propagation of neutrinos or antineutrinos in a medium with electron density N_e that varies along the neutrino trajectory (parameterized by the time t) is described by Schrödinger-like evolution equations[9]:

$$\left\{ \begin{array}{lcl} \mathcal{H}_\nu(t) & = & U \cdot \mathrm{diag}(m_i^2) \cdot U^\dagger/(2E) + \sqrt{2} G_F N_e(t)\ \mathrm{diag}(1,0,0) \\ \mathcal{H}_{\overline{\nu}}(t) & = & U^* \cdot \mathrm{diag}(m_i^2) \cdot U^t/(2E) - \sqrt{2} G_F N_e(t)\ \mathrm{diag}(1,0,0) \end{array} \right. \quad (5)$$

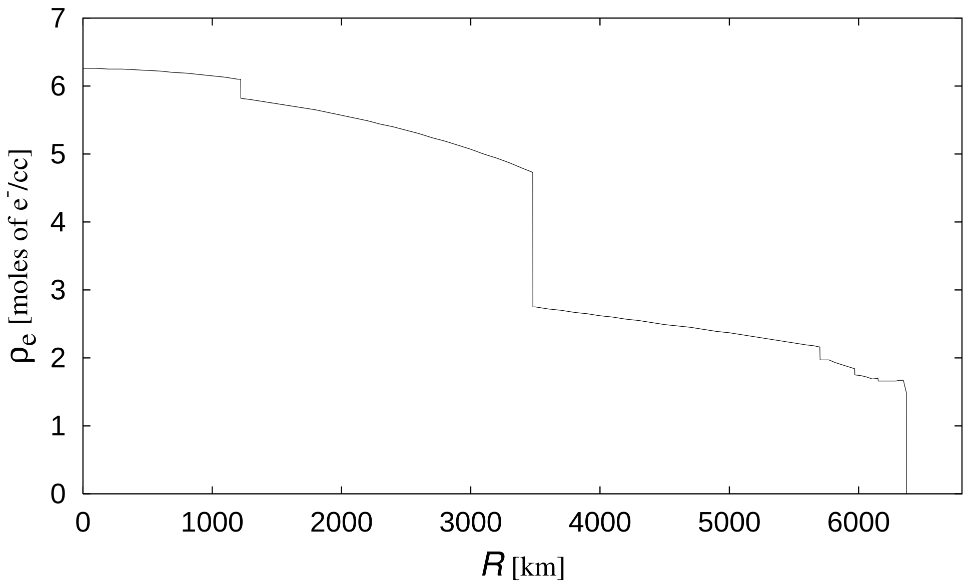

Figure 1: Density profile of the Earth according to the PREM model[11].

where the neutrino mixing matrix includes the already mentioned three rotations through the 23, 13 and 12 planes with angles θ_{23}, θ_{13} and θ_{12} and a CP violating phase δ

$$U = R_{23}\Delta R_{13}\Delta^* R_{12}, \quad \Delta = \mathrm{diag}(1, 1, e^{i\delta}) \tag{6}$$

In the following, we will discuss the case of neutrinos, however it is clear that the same discussion applies to antineutrinos inverting the sign of N_e and of the CP-violating phase δ. We use the notation $\Delta m^2_{ij} = m^2_j - m^2_i$, and adopt the convention that $\Delta m^2_{12} = \Delta m^2_{sol} > 0$, whereas $\Delta m^2_{13} = \pm\Delta m^2_{atm}$ if the mass hierarchy is normal or inverted respectively. In other terms, we declare that ν_3 is respectively the heaviest or the lightest neutrino.

In the code, the evolution equations above are solved resorting to numerical methods. Being concerned with atmospheric events, we consider neutrinos of energy E that reach a detector with zenith angle θ_Z after a path length L; if $\theta_Z > 90°$, these neutrino traverse the Earth and therefore meet a non-zero electron density N_e. We describe the Earth electron density by adopting the PREM model[11]. which gives the radial profile of the Earth's density as shown in Fig. 1

We solve the resulting evolution equations through a straightforward numerical integration.[1] Given a neutrino (or antineutrino), we calculate the probabilities that it will be detected as ν_e, ν_μ or ν_τ and finally, sort the detected flavor according to these probabilities.

This code has been coupled to a neutrino interaction generator (for both CC and NC) which makes use of the FLUKA[13] and NUX[14] libraries. Quasi-elastic (QE) and deep inelastic scattering (DIS) are considered. The QE part is managed by FLUKA and according to the physics choice of NUX, the resonance region is considered in average,

[1]We use the `ODEINT` subroutine given in Numerical Recipes[12], with the `yscal(i)` variable set to unity. We obtained a numerical precision in the determination of the oscillation probabilities much better than one part per million for all neutrinos we propagated. This tight requirement is much more than what we actually need, but the required computational time is small when compared with the time to simulate an event.

according to the duality principle, by the DIS part. FLUKA provides the nuclear environment for all reactions. Quantum and nuclear effects, including reinteractions in the nucleus, are simulated in detail. This event generator was originally developed within the ICANOE proposal[15] with the possibility of invoking 2-flavor oscillations (full mixing) in vacuum. Now the present version has been upgraded so to include the general 3-flavor oscillation code coupled to the above described numerical solution of the differential equation for the transport of neutrino amplitude through the Earth.

Oscillation parameters are provided by means of a data card file (*osc.datacards*), where Δm^2 values must be given in eV^2 and mixing angles in degrees. The CP violating phase $\delta = (0 - 360°)$ is also considered, and the user can choose the "direct" or "inverse" hierarchy. Matter effects can be switched off. A typical example of the osc.datacard file is reported below:

```
#Data cards for atm. neutrino oscillation code
# Theta12 in degrees
THETA12  32.3
# Theta13 in degrees
THETA13   0.
# Theta23 in degrees
THETA23  45.
# DeltaM12**2 in eV**2
DMSQ12   8.2D-5
# DeltaM23**2 in eV**2
DMSQ23   2.6D-3
# CP violation phase in degrees
DELTA    0.
# Hierarchy: normal: 1, inverted: -1
HIERARCHY 1.
# Activate matter effects: on: 1, off = 0
MATTER 1.
# end of data cards
END
```

These drivers require as input the neutrino fluxes. For atmospheric neutrinos we start from the "FLUKA" fluxes of 2001[16]. which are calculated for 3 specific geographic locations. For the purpose of this work, we limited ourself to the LNGS case.

As a default choice the interactions are performed against argon nuclei, but any other nucleus can be considered. The natural isotopic composition of any given nucleus is automatically provided by the FLUKA database. These generators produce in output the detailed kinematical information of the initial, intermediate and final state of the interaction and, optionally, the binary input for a full simulation of detector response as deriving from ICARUS.

4 Atmospheric neutrinos in a large Liquid Argon TPC

We have simulated a single experiment with an high exposure, simulating the statistical sample of CC interactions of atmospheric neutrinos at Gran Sasso expected in 1000 kton yr. We have considered, beyond the unoscillated case, three cases for θ_{23} well inside the present limit from atmospheric experiments: 40°, 45° and 50°. The fit results from the review of ref.[6] have been used as reference for Δm^2_{23}, Δm^2_{12} and θ_{12} (2.5 10^{-3} eV^2, 8.0 10^{-5} eV^2, 34°), while θ_{13} has been varied between 0° and 10°, (*i.e.* about the existing limit from the CHOOZ experiment[5]). For the work described here, the CP violation phase δ has been left to 0° and only the direct hierarchy of masses has been considered.

4.1 Distribution in zenith angle and L/E

Before entering into the details of the measurement of the octant of θ_{23} it is worthwhile considering the "standard" measurements with atmospheric neutrinos. For instance, Fig.2 shows the expectation for the zenith angular distribution of muon neutrino events, when only the lepton direction is measured, for SubGeV and MultiGeV regions in the case of full mixing ($\theta_{23} = 45°$). The two extreme values of θ_{13} are considered in the oscillation predictions.

This plot already gives a quantitative idea of the difficulty of measuring θ_{13} with atmospheric neutrinos. However, a Liquid Argon TPC gives the chance of performing an improved measurement of the neutrino direction. This is already possible, in part, in the SubGeV range. Notwithstanding the intrinsic smearing due to Fermi motion, a better correlation with original neutrino direction can be maintained, as shown in Fig.3, where the kinematic information of possible recoiling proton has been added, assuming a detection threshold of 50 MeV for the kinetic energy of an hadron. The expected enhancement around the horizontal direction is clearly visible. Despite the reduction in statistics, the separation between the two extreme cases of θ_{13} is slightly improved.

The above considerations suggest that the results from a large Liquid Argon TPC can be used to perform a significant identification of the oscillation pattern by means of the plot of the ratio of event rate with respect to the non oscillated prediction as a function of $\log L/E$. This is reported in Fig.4 (L is measured in km, while E is in GeV). There we have followed the usual method of mirroring the direction of downward going events to obtain a model independent prediction for upward going neutrinos. In the upper panel of Fig.4 only the lepton direction has been considered, while in the bottom panel the kinematics of the hadronic system (for particles above threshold) has been included: the significance in pattern recognition is clearly improved.

We estimate that, for this measurement, an exposure of 500 kton yr would be already sufficient to provide a very significant result.

4.2 Low energy electron events and θ_{23}

We enter now the topic of the precision measurement of θ_{23}. According to the discussion of section 2, we expect a variation of the rate of electron neutrino events (and in particular of SubGeV electron neutrinos) as a function of θ_{23}. In the simple case of vacuum oscillations and θ_{13} we expect: $\Delta N_e \propto (1 - N^0_\mu/N^0_e sin^2\theta_{23})$, where N^0_μ and N^0_e are the unoscillated μ-like and e-like event rates. The situation is slightly more complex for $\theta_{13} = 0$ and when matter effects are present. Our complete simulation gives the behavior shown in Fig. 5, where the deviation from no-oscillation prediction of event rate of SubGeV e-like events (in events/kton yr) is plotted vs $sin^2\theta_{23}$.

As expected, the relative differences in rate are very small and a very large exposure is needed. The absolute difference in rate of SubGeV e-like events is shown in Fig. 6, for

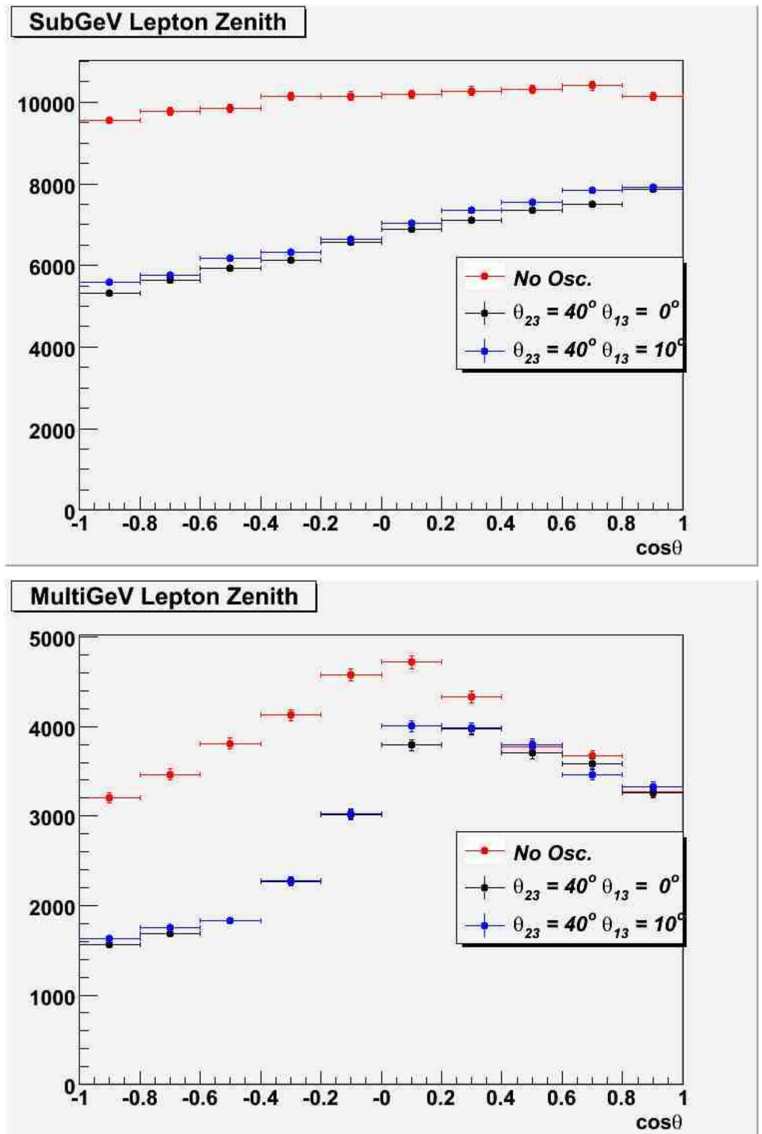

Figure 2: Zenith angle distribution for SubGeV (top) and MultiGeV (bottom) μ-like events. The non oscillated and oscillated predictions for θ_{23}=40° and two different values of θ_{13} are reported. Here only the lepton direction has been used.

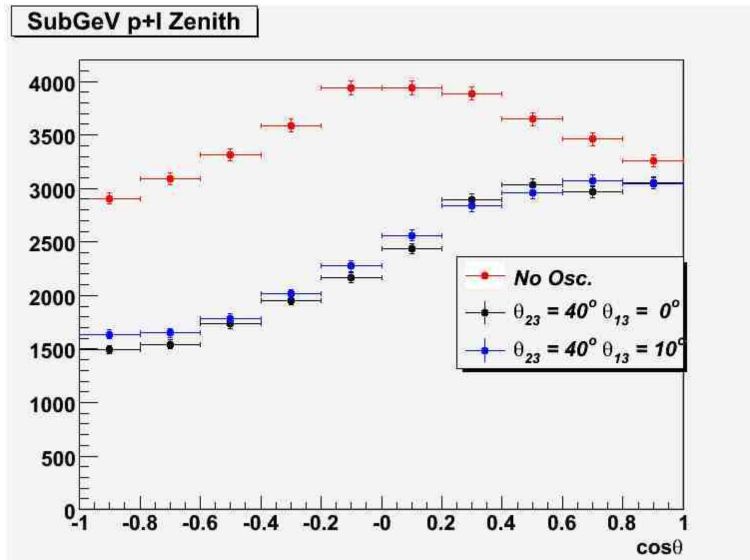

Figure 3: Zenith angle distribution for SubGeV μ-like events where both lepton and recoiling proton kinematics has been reconstructed ($E_{kin} > 50$ MeV). The non oscillated and oscillated predictions for θ_{23}=40° and two different values of θ_{13} are reported.

$\theta_{13} = 0$ and for two values of θ_{23} symmetric with respect to 45° (only the lepton direction is considered here).

If we take the ratio with respect to the non oscillated prediction, we get the result plotted in Fig.7

If we conservatively fit the SubGeV distribution with a constant (namely this is equivalent to integrating the angular distribution over the whole range of the zenith angle) the difference in the ratio N_e/N_e^0 between $\theta_{23} = 40°$ and 50° is at the level of 0.037 ± 0.006. For relatively large values of θ_{13}, the significance in the difference becomes smaller, as shown in Fig.8.

Of course it is hard to believe that one could rely on the absolute level of N_e prediction: flux normalization remains one of the most important uncertainties. A better analysis is obtained by the double ratio: $(N_e/N_\mu)/(N_e^0/N_\mu^0)$. The variation of μ-like events has the opposite trend of N_e, and in first approximation all common uncertainties contributing both to N_e and N_μ cancel out. Here the most important uncertainties concern the normalization of the primary cosmic ray flux and the knowledge of ν-Nucleus cross sections. In good approximation these affect e and μ flavor almost at the same level (there are mass dependent terms which are of course non negligible at very low energy). As an example of the possible expectation, we get the behavior as a function of the zenith angle which shown in Fig.9 (when $\theta_{13} = 0°$).

Now the important topic, as far as systematic uncertainties are concerned, is the accuracy on the prediction of the N_e/N_μ ratio. This topic has been already debated in the context of a dedicated workshop stimulated by Super–Kamiokande[17]. One of the reported conclusions was that the measurement of θ_{23} octant can be done achieving an exposure of at least 20 years of runs of Super–Kamiokande in order to distinguish (at the level of $\Delta\chi^2 \sim 2$) between the two mirror values corresponding to $\sin^2 2\theta_{23}$=0.96 ($\sim$39°$\div$ 51°), with the present level of systematics. An effort to improve the accuracy on the

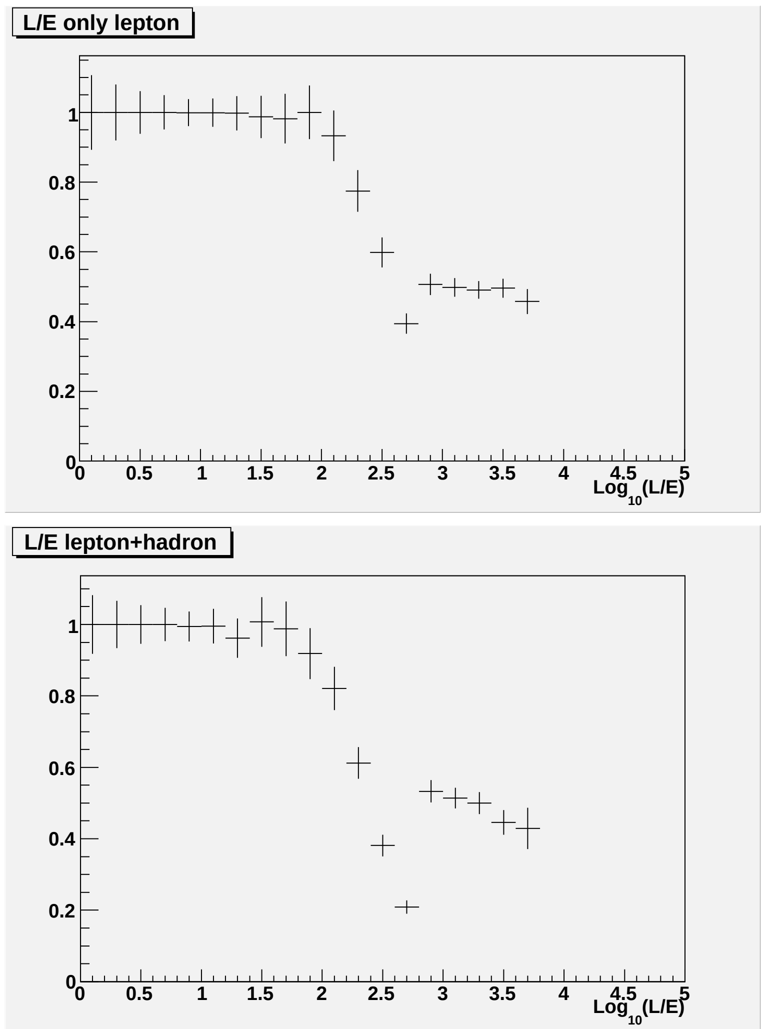

Figure 4: Ratio of event rate with respect to the non oscillated prediction as a function of $\log L/E$. L is measured in km, while E is in GeV. Top panel: only lepton direction is reconstructed. Bottom panel: both lepton and charged hadrons are reconstructed ($E_{kin} > 50$ MeV).

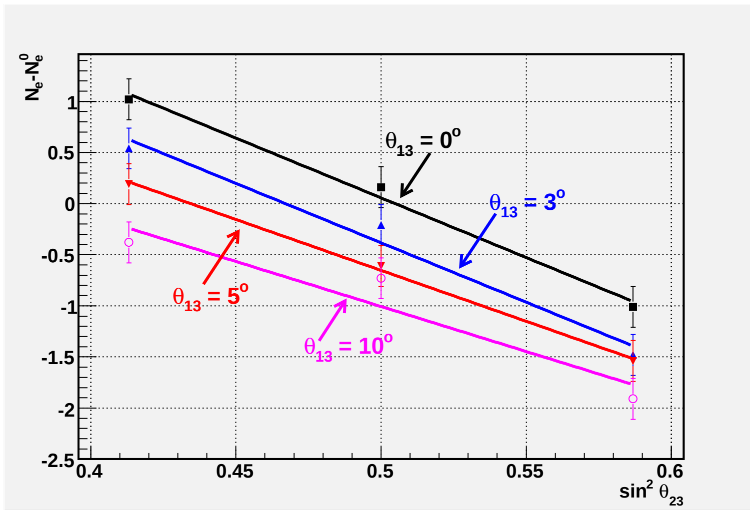

Figure 5: Deviation of the SubGeV e-like event rate (in events/kton yr) from the no-oscillation prediction as a function of $sin^2\theta_{23}$.

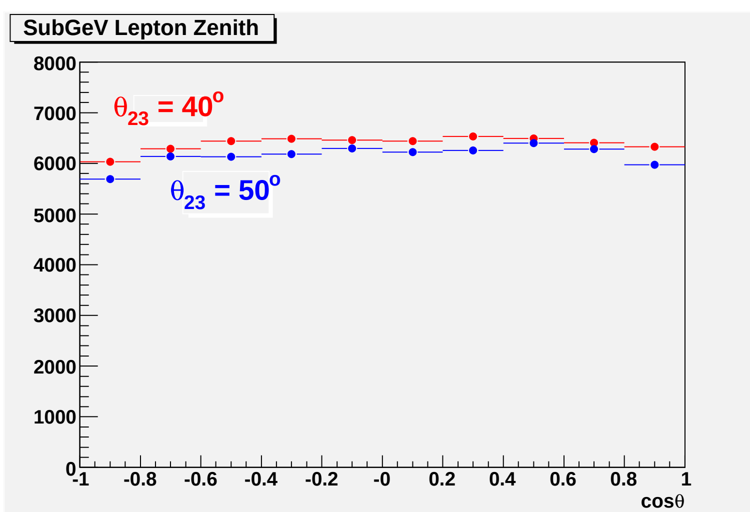

Figure 6: Absolute prediction of the zenith angular distribution of SubGeV e-like events for two different values of θ_{23} when $\theta_{13} = 0°$.

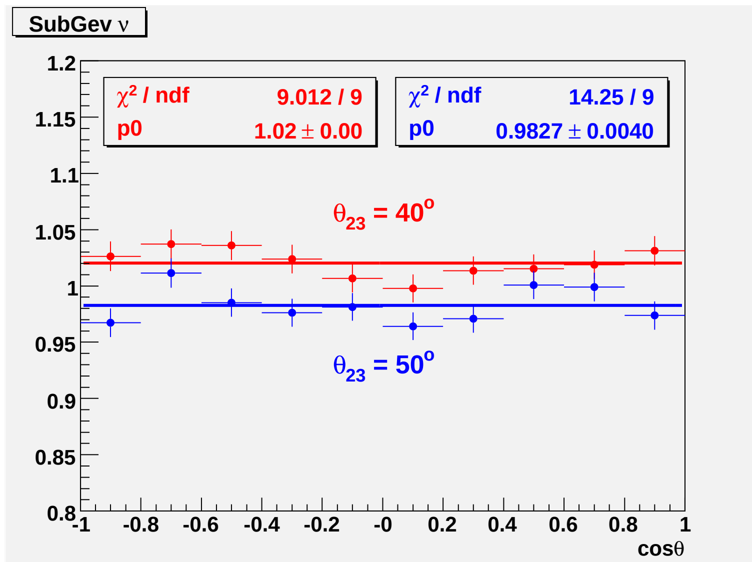

Figure 7: N_e/N_e^0 ratio as a function of the zenith angle of SubGeV e-like events for two different values of θ_{23} when $\theta_{13} = 0°$.

prediction on N_μ/N_e at a level better than 1% would be very helpful.

5 Summary and discussion

A very large LAr TPC allows to detect low energy neutrinos (above ~ 50 MeV) with null or negligible experimental systematic error. Therefore, in principle, such a detector can give new important contributions to neutrino physics, also by means of a new investigation of atmospheric neutrinos. An exposure of at least 500 kton yr is however necessary in order to give new significant contributions. The sector of SubGeV ν_e, which is particularly suitable for an ICARUS–like detector, offers in particular the possibility of performing new precision measurements. In this work we have performed a preliminary investigation about the possibility of the measuring how close is θ_{23} to the full mixing value of 45°. In principle this measurement is affordable if two conditions are met: an exposure larger or equal to 500 kton yr and a reduction of systematic uncertainties about neutrino fluxes, where the most important item is the knowledge of the N_e/N_μ ratio.

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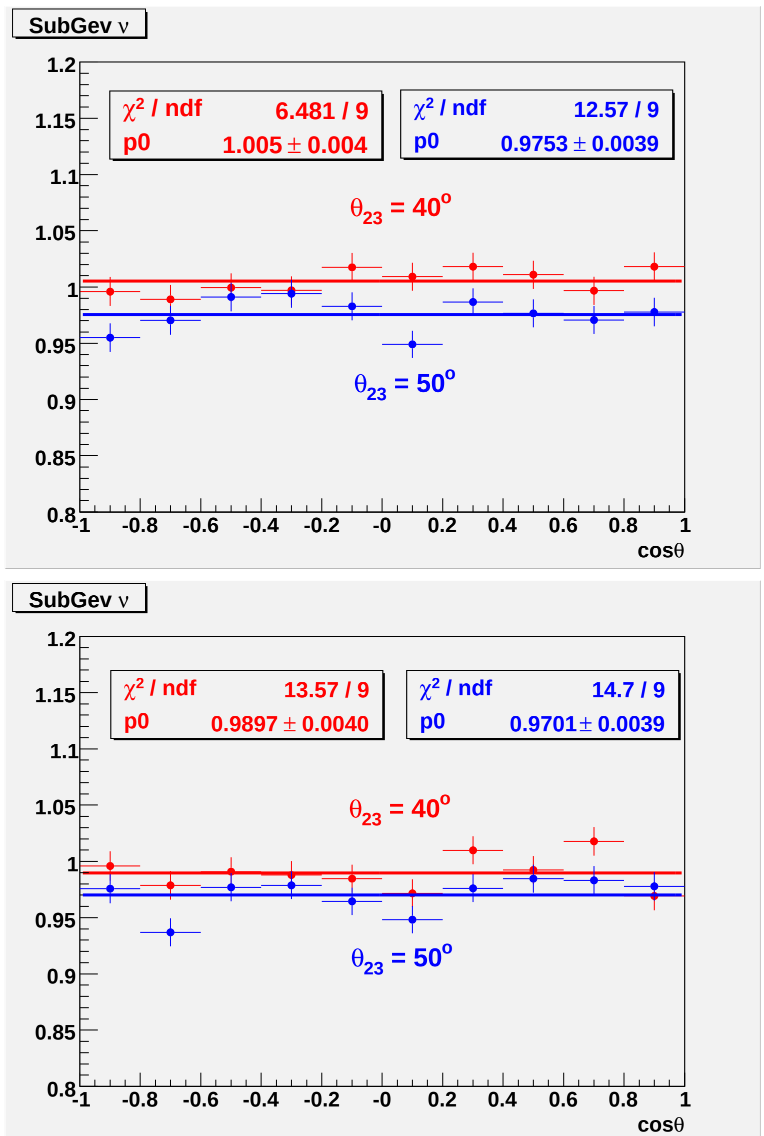

Figure 8: N_e/N_e^0 ratio as a function of the zenith angle of SubGeV e-like events for two different values of θ_{23} when $\theta_{13} = 5^\circ$ (top) and $\theta_{13} = 10^\circ$.

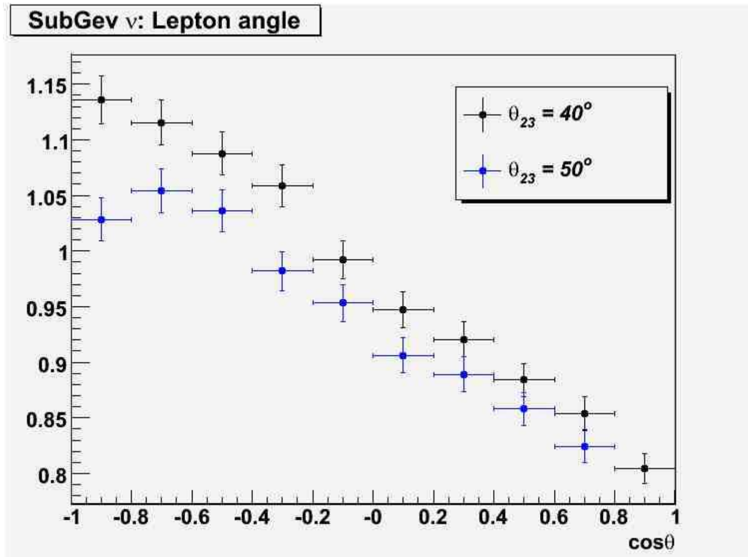

Figure 9: Double ratio $(N_e/N_e^0)/(N_\mu/N_\mu^0)$ as a function of the zenith angle of SubGeV e-like events for two different values of θ_{23} when $\theta_{13} = 0°$.

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