Measurement of Atmospheric Neutrino Oscillations with a High-Density Detector

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Abstract

We propose an experiment to test the hypothesis that the reported anomaly on atmospheric neutrino fluxes is due to $\nu_\mu \to \nu_x$ oscillations. It will rely both on a disappearance technique, exploiting the method of the dependence of the event rate on L/E, which was recently shown to be effective for detection of neutrino oscillation and measurement of the oscillation parameters, and on an appearance technique, looking for an excess of muon-less events at high energy produced by upward-going tau neutrinos. The detector will consist of iron planes interleaved by limited streamer tubes. The total mass will be about 30 kt. The possibility of recuperating most of the instrumentation from existing detectors allows to avoid R&D phases and to reduce construction time. In four years of data taking, this experiment will be sensitive to oscillations $\nu_\mu \to \nu_x$ with $\Delta m^2 > 10^{-4}\ eV^2$ and a mixing near to maximal, and answer the question whether ν_x is a sterile or a tau neutrino.

1 Introduction

Recent Super-Kamiokande data [1] confirm the existence of an anomaly in the atmospheric muon neutrino fluxes, which is best interpreted as a $\nu_\mu \to \nu_x$ oscillation, with a mixing near to maximal and Δm^2 in the range $10^{-3} - 10^{-2}$ eV^2. The non observation of a corresponding anomaly in the electron neutrino fluxes and data from reactor experiments, indicate that the oscillation either concern the muon and tau neutrino or the muon and a new sterile neutrino. This result, given its relevance, should be tested by an independent experiment. We believe that an experiment planned with this goal should have, in itself, enough redundancy to be able to prove, or disprove, that an observed anomaly in atmospheric neutrino fluxes be due to neutrino oscillations.

It has recently been shown [2] that the study of the atmospheric ν_μ event rate as a function of the ratio L/E, between the neutrino path length and its energy, is an effective method for the detection of an atmospheric ν_μ deficit, if the deficit is due to oscillations. Moreover this method provides a clean measurement of the oscillation parameters if the mixing angle is large and $10^{-4} < \Delta m^2 < 5 \times 10^{-3}$ eV^2. In order to apply this method one should be able to measure, on an event by event basis, both the energy E and the direction of the neutrino, from which the flight length L is obtained.

For higher values of Δm^2 the modulation becomes too fast to be detected by this method, but ν_μ oscillations would result in a detectable deficit of upward muon events with respect to the downward ones.

In this paper we shall also discuss a different and independent method which can be used to detect an appearance of muon-less events produced by upward-going ν_τ, and we shall show how it can distinguish between oscillation to tau or sterile neutrino.

2 Choice of the Detector

A water cherenkov is best suited for events with simple topologies, in the quasi-elastics and resonances region, and has a high efficiency for electron identification. A detector suitable for the application of the methods outlined above should instead be efficient on high energy events, in the region of deep inelastic scattering, and have a high capability of distinguishing muons from pions. Moreover, having no interest in the study of oscillations involving electron neutrinos, a detector filtering the electro-magnetic component can be effectively chosen. These considerations favour the choice of a high-density tracking calorimeter.

In a tracking calorimeter the muon energy can be measured either by means of a magnetic field (magnetised iron), or from the range for muons stopping in the detector. We believe that the use of a magnetic field becomes too complex in an apparatus of the size needed for atmospheric neutrinos, since the requirements of a magnetic field over a large volume and of several high precision points along the track, raise the costs and conflicts with high density. The measurement of muon energy by range is instead free of intrinsic difficulties, apart the requirement that the muon stops inside the detector, which becomes critical for detectors of low density.

There remains to be solved the problem of the identification of the direction of flight of the incoming neutrino. In this respect a tracking calorimeter is in general weaker than a cherenkov. In the specific case of the events in which we are interested, the problem can be solved as follows. In interactions producing muons with energy above $\simeq 1$ GeV stopping in the detector, the direction of the incoming neutrino can be identified either by means of a visible event vertex, marked by hadronic activity at one extreme of the muon track, or, when no vertex is clearly visible, by increasing residuals, due to multiple scattering, in the muon track fit. For high-energy muon-less events the direction, upward or downward, of the incoming neutrino is recognised when the topology of the event allows to identify the vertex. The efficiency of this method increases for finer samplings. A fine sampling, however, raises the cost and reduce the detector density, thus limiting the detector mass and reducing the stopping power for muons. We found that an overall optimisation of event rates and efficiencies is obtained for a relatively coarse sampling.

In conclusion a detector, suitable for the method of analysis that we propose, should be designed according to the following guidelines:

- total mass around 30 kt;
- structure of a high-density tracking calorimeter, capable of measuring muon energy up to several GeV from its range;
- precision of $\simeq 1\ mm$ on points along an isolated track, for the measurement of multiple scattering.

Moreover we would like to keep within reasonable limits the cost and the construction time; therefore we believe that a well tested technique requiring no R&D should be adopted.

3 The Detector Structure

The detector will consist of 3 identical super-modules of $12 \times 12 \times 13.2\ m^3$ each. Each super-module will consist of a stack of 120 iron planes 8 cm thick interleaved by planes of limited streamer tubes (LST). The LST will be of the same size as those used in MACRO [3], that is 12 m long and $3 \times 3\ cm^2$ cross section. They will provide two coordinates by means of the read out of anodes and of diagonal strips, as in MACRO. The read-out and acquisition chain will be the same as adopted by MACRO. Moreover the anode signals will also be sent to TDC's with 15 ns resolution, thus providing a resolution on the x-coordinate better than 1 mm. Since each neutrino event will hit only a limited part of the detector, several anode outputs will be latched to a single TDC channel, thus limiting the number of TDC channels. The total area of LST planes will be 51840 m^2, about half of which could be recuperated from MACRO. The total mass of the detector will exceed 30 kt.

4 Detection of Atmospheric Neutrino Oscillations

Detection of oscillation of atmospheric neutrinos and measurement of their parameters will rely on two main techniques:

- disappearance of events with a high-energy muon pointing upward;
- comparison of rates upward and downward muon-less events of high energy.

We point out that while the first technique will test the hypothesis of ν_μ oscillations, and measure Δm^2 provided it is smaller than $5 \times 10^{-3}\ eV^2$, the second one will be used to discriminate between oscillations to a sterile or a tau neutrino.

4.1 Disappearance of high-energy muons

It has been shown [2, 4] that an effective method to test whether the anomaly in the atmospheric neutrino flux reported by Super-Kamiokande [1] is due to ν_μ oscillation, consists in searching for a modulation in the ν_μ rate plotted versus L/E. The modulation would be produced by a disappearance probability given by:

$$P(\nu_\mu \to \nu_x) = \sin^2(2\Theta)\sin^2(1.27\Delta m^2 L/E) \tag{1}$$

the modulation period would thus be inversely proportional to Δm^2. It has also been shown that by this method a measurement of Δm^2 in the range between 10^{-4} and 5×10^{-3} eV^2 is affordable. Moreover the method has the advantage of being practically insensitive to the precise knowledge of the atmospheric neutrino flux, since the oscillation pattern is found by dips in the L/E distribution, while the atmospheric neutrino interaction spectrum is known to be a slowly varying function of L/E. The experimental requirement is that L/E is measured with an error much smaller than the modulation period, which decreases for increasing values of Δm^2. This translates into requirements on energy and angular resolution of the detector, which become more stringent for higher Δm^2 values.

The detector that we propose has a hadronic energy resolution of $\sigma(E)/E = 150\%/\sqrt(E)$, and essentially no capability of reconstructing the hadron direction.

In the experiment simulation we reject all the events that are not fully contained in the detector. The muon energy, obtained from range with errors due to straggling and to the uncertainty on range measurement, and the muon direction, obtained by a straight line fit to the first meter of the muon track, are measured with high precision.

The condition of a good precision on L/E thus translates in the request that the muon direction and the total reconstructed energy reproduce, within the quoted errors, the neutrino direction and energy.

The request on the muon direction is simply satisfied by the selection of events in which the hadronic energy is only a small fraction of the total deposited energy. This request can change with increasing neutrino energy; in fact the Lorentz boost in the interaction is such that in high energy events the muon keeps the original neutrino direction even if its fractional energy is low. We have implemented this requirement imposing a cut on the hadronic fractional energy proportional to the total measured energy.

We present, as examples, the L/E distributions obtained with this method for several values of Δm^2: 5×10^{-3} eV^2 (fig. 1), 10^{-3} eV^2 (fig. 2), 5×10^{-4} eV^2 (fig. 3), 10^{-4} eV^2 (fig. 4). We recall that in order to compare the upward going neutrino sample with the downward going one as a function of L/E, we have assigned to the downward going neutrinos (zenith angle $\theta < \pi/2$) the distance they would have traveled if $\theta = \pi - \theta$. The ratio of the two distributions is thus approximately flux independent and the oscillating pattern is then put in evidence.

For Δm^2 larger than 5×10^{-3}, the precision on L/E is no more sufficient to resolve the narrow oscillation pattern, thus the value of Δm^2 cannot be measured. Still the oscillations can be identified by a deficit of upward with respect to downward events, which will result in an average ratio of 0.5 in the case of maximal mixing.

4.2 Appearance of high-energy muon-less events

Because of the large deficit of upward with respect to downward muon events, for $\Delta m^2 > 10^{-3}$ there is a simple method to measure the ν_τ appearance and/or distinguish between $\nu_\mu \to \nu_\tau$ oscillation and $\nu_\mu \to \nu_{sterile}$ oscillation (we assume that a sterile neutrino interacts neither via charged currents nor via neutral currents).

The method consists in measuring the up/down ratio of the high energy muon-less events, with the vertex clearly identified, as a function of the visible energy.

An event is considered to be muon-less if it does not contain non-interacting tracks longer than 1 m (equivalent to 0.9 GeV for a m.i.p.); the visible energy is defined as the quadratic sum of the digital hits in two orthogonal views; the up/down direction is determined by the shape of the hadronic shower development.

The energy spectra of the ν_μ and ν_e CC events integrated over the full solid angle are shown in fig. 5. This spectra have been provided by Lipari et al. [5] as a function of E and $\cos(\theta)$, where θ is the zenith angle, and have been extensively used in our simulation. The ν_τ CC interaction spectrum is also shown in fig. 5 in the hypothesis of full ν_μ conversion.

For sake of clarity, in table 1 we give the integrated values of the neutrino CC events rates for a detector exposure of 30 $kt \cdot 4\ y$ and $0 < \cos(\theta) < 1$; in table 2 we give the same rates but for $0.5 < \cos(\theta) < 1$.

$E_{min}(GeV)$	ν_μ	ν_e	ν_τ
1.	3767	1654	266
3.	1470	505	266
10.	453	107	179
30.	121	20	71

Table 1: Neutrino + anti-neutrino integrated CC event rate for a detector exposure of 30 $kt \cdot 4\ y$ and $0 < \cos(\theta) < 1$; full ν_μ conversion is assumed for the ν_τ case. The integrated NC event rate is about one third of the $\nu_\mu + \nu_e$ CC event rate.

$E_{min}(GeV)$	ν_μ	ν_e	ν_τ
1.	1677	612	111
3.	623	157	111
10.	187	27	74
30.	49	4	29

Table 2: Same as table 1 but for $0.5 < \cos(\theta) < 1$.

Given a specific set of oscillation parameters, the unoscillated ν_μ event distribution is obtained simply multiplying the spectrum in fig. 5 by $(1 - P)$, where P is given by equation (1), the ν_τ events distribution is obtained multiplying the ν_τ spectrum of fig. 5 by P. The ν_e spectrum is assumed to be unaffected by oscillations.

From these spectra it is clear that, in order to enhance the ν_τ contribution to muon-less events, one has to select candidates with high visible energy.

The ν_μ CC events rejection is good at high energy because of the cut of muon with energy larger that 0.9 GeV (due to the flat y distribution of the CC interaction).

The ν_e CC events rejection is due to the characteristic feature of the detector to filter off the electro-magnetic component of the interaction. As a consequence the visible energy is only due to the residual hadronic component as in the case of neutral current events.

A very important feature of this detector that helps in reducing the uncertainty on the up/down muon-less ratio is the non isotropy of the detector. The reason is the following: the horizontal events are of little use in the up/down ratio, in fact they do not oscillate enough, their hemisphere is uncertain and the ν_e background is larger. The fact that the detector has a vertical development and a thick sampling causes the rejection of most of horizontal NC events and ν_e CC, because their limited vertical development prevents the identification of their direction.

We have performed extensive simulations of the detector performance with various thicknesses of the absorber layers, from 2 cm up to 10 cm. The simulated sample corresponds to a detector exposure of 30 $kt \cdot 4\ y$. The analysis of the simulated data has been performed first through visual scanning to optimise the selection cuts, then in an automated way where the best selection cuts have been implemented.

We analysed the ratio of up to down events which produce a number of hits above a given value and satisfy the above criteria. In fig. 6 we show these integral ratios as a function of the lower bound on hits for a value of Δm^2 equal to $5 \times 10^{-3}\ eV^2$ and several thicknesses of the iron absorber. Both the cases of $\nu_\mu \to \nu_\tau$ oscillation and $\nu_\mu \to \nu_{sterile}$ oscillation are shown. The same results are obtained for larger values of Δm^2.

The choice for the best iron thickness is determined by the separation between the two oscillation hypothesis. From a visual inspection of the various plots it turns out that any thickness between 4 cm and 8 cm is acceptable. In fact, while for small thicknesses the tracking ability is slightly enhanced, the electro-magnetic filtering capability is strongly reduced mainly in the high energy region (where the ν_τ events occur). It follows that for our purpose a layer thickness of several radiation length is preferred. We believe that 8 cm is the best solution because it allows to minimise the surface of the active elements (i.e. streamer tubes).

In fig. 7 we show again the up/down integral ratio defined above for a thickness of the iron absorber of 8 cm and for two values of Δm^2. The statistical separation between the two oscillation cases amounts to several standard deviations for $\Delta m^2 > 3 \times 10^{-3}$. In the $\nu_\mu \to \nu_\tau$ case there is an excess of muon-less events with high visible energy from the bottom hemisphere due to the semileptonic decay of the tau lepton ($BR \simeq 0.7$) that produce neutral current like events; in the $\nu_\mu \to \nu_{sterile}$ case there is a lack of neutral currents from the bottom hemisphere at all visible energies because the sterile neutrino does not interact via neutral currents.

5 Conclusions

We have demonstrated that a high density detector of 30 kt with rough sampling and good tracking capability is well suited to solve the atmospheric neutrino puzzle as stated by the Super-Kamiokande experiment.

This is performed both with appearance and disappearance methods; the oscillation parameters are measured over a wide range of Δm^2 values and for the mixing parameter larger that 0.6.

The detector is easily built in a short delay because it does not require R&D phases. For the construction one could use the same technique of the MACRO detector, its infrastructures and active elements could be recycled.

This experiment, completely devoted to the atmospheric neutrino study, is complementary to those designed for long base line neutrino detection [6, 7, 8].

Its cost is limited (a rough but safe estimate is around 30 GLit half of which is for the iron). It occupies half of the area taken by MACRO at present.

We believe that this experiment together with the LBL beam will put Italy in fore-line in the fascinating quest of the neutrinos' nature.

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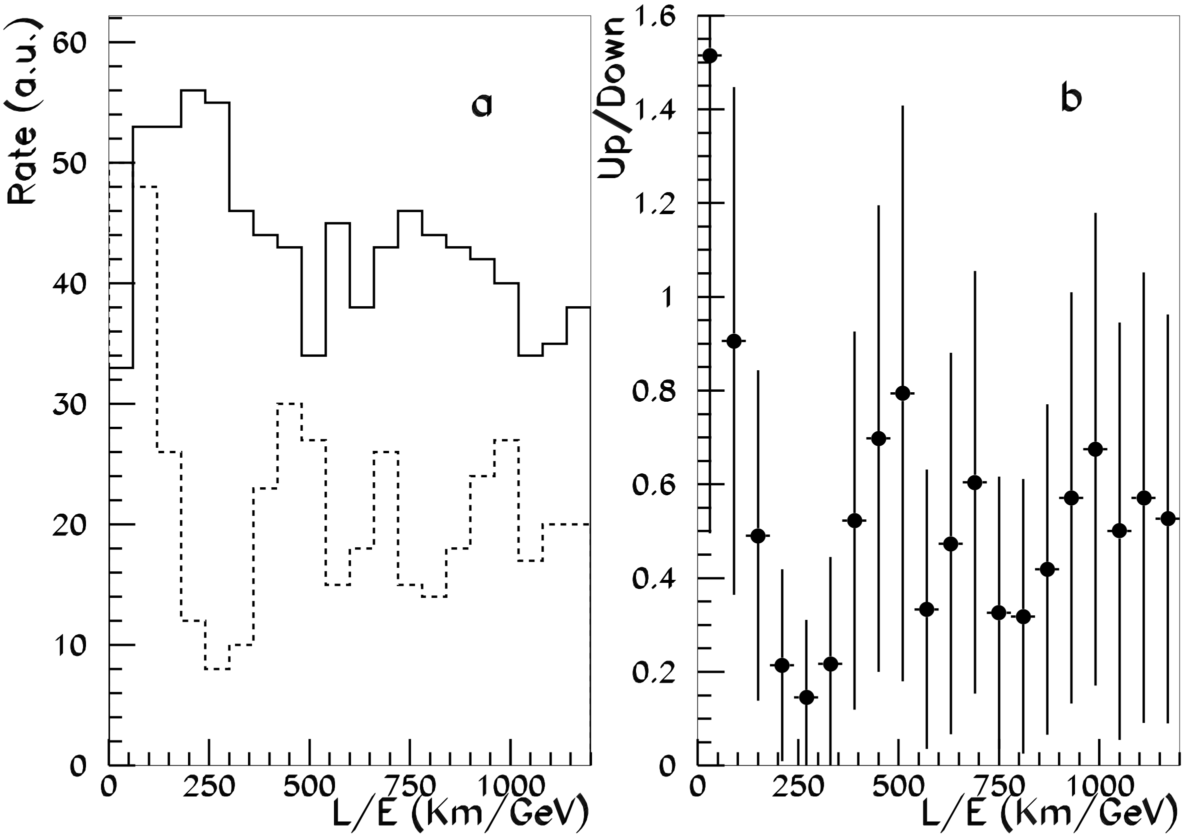

Figure 1: Measured L/E distribution in presence of $\nu_\mu \rightarrow \nu_x$ oscillations, with parameters $\Delta m^2 = 5 \times 10^{-3}\ eV^2$ and $\sin^2(2\Theta) = 1.0$ for upward muon events (dashed line) and downward ones (continuous line) (a) and their ratio R (b). Events have been generated with high statistics, error bars corresponding to the statistical uncertainty after 4 years of running are shown. In order to compare the upward going neutrino sample with the downward going one as a function of L/E, we have assigned to the downward going neutrinos (zenith angle $\theta < \pi/2$) the distance they would have traveled if $\theta = \pi - \theta$. The ratio of the two distributions is thus approximately flux independent and the oscillating pattern is then put in evidence.

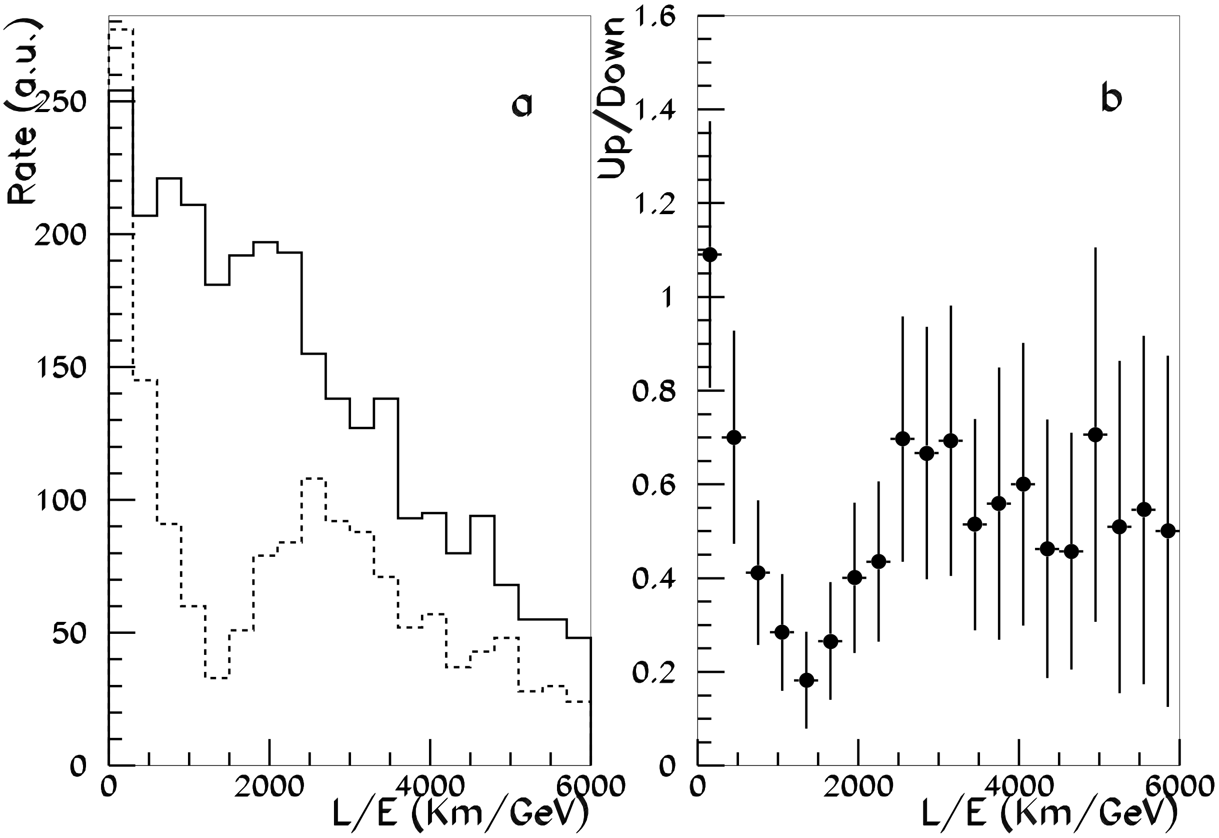

Figure 2: As fig. 1, $\Delta m^2 = 10^{-3}\ eV^2$

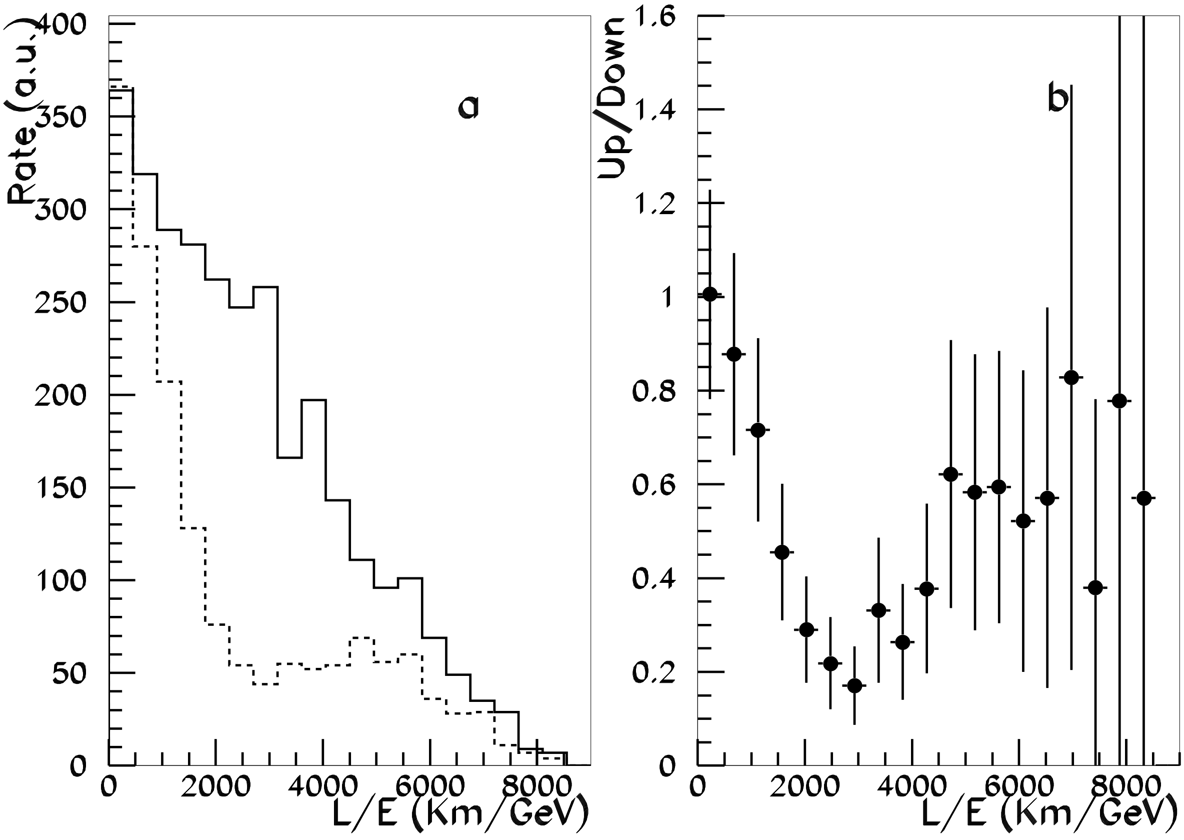

Figure 3: As fig. 1, $\Delta m^2 = 5 \times 10^{-4}\ eV^2$

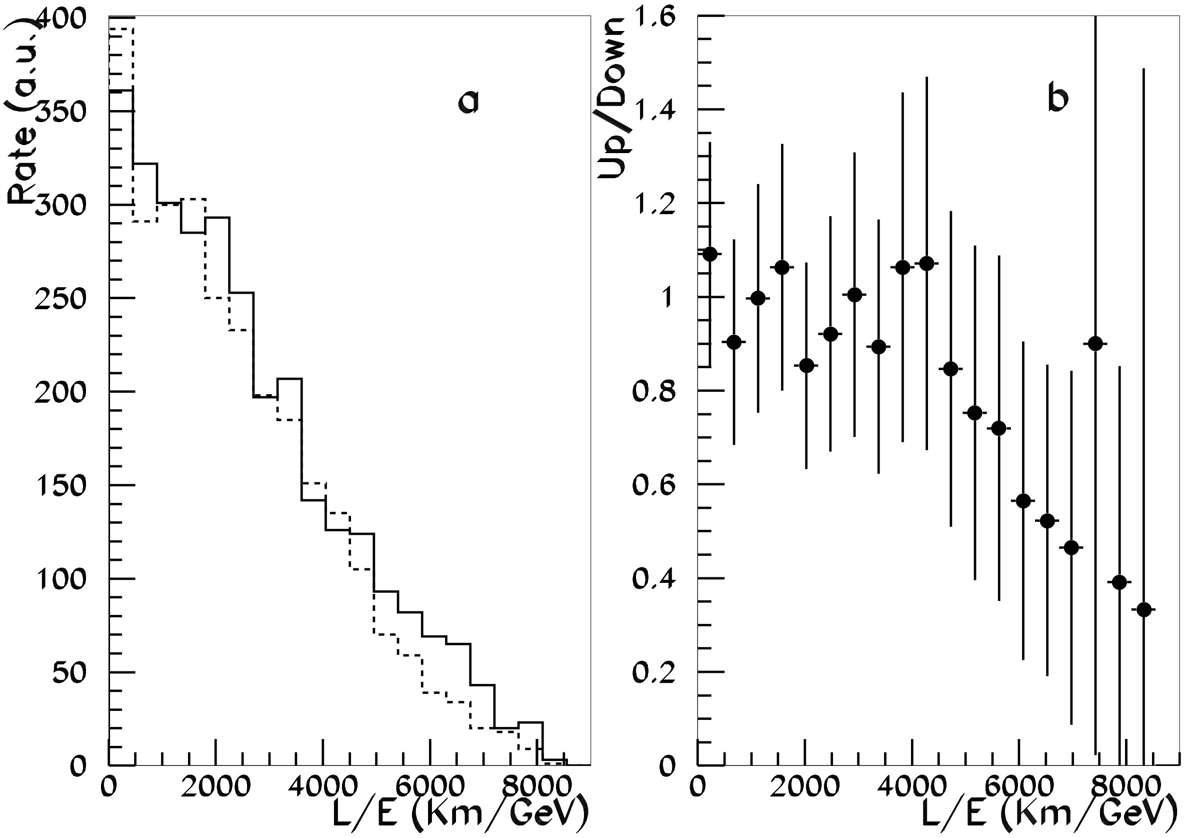

Figure 4: As fig. 1, $\Delta m^2 = 10^{-4}\ eV^2$

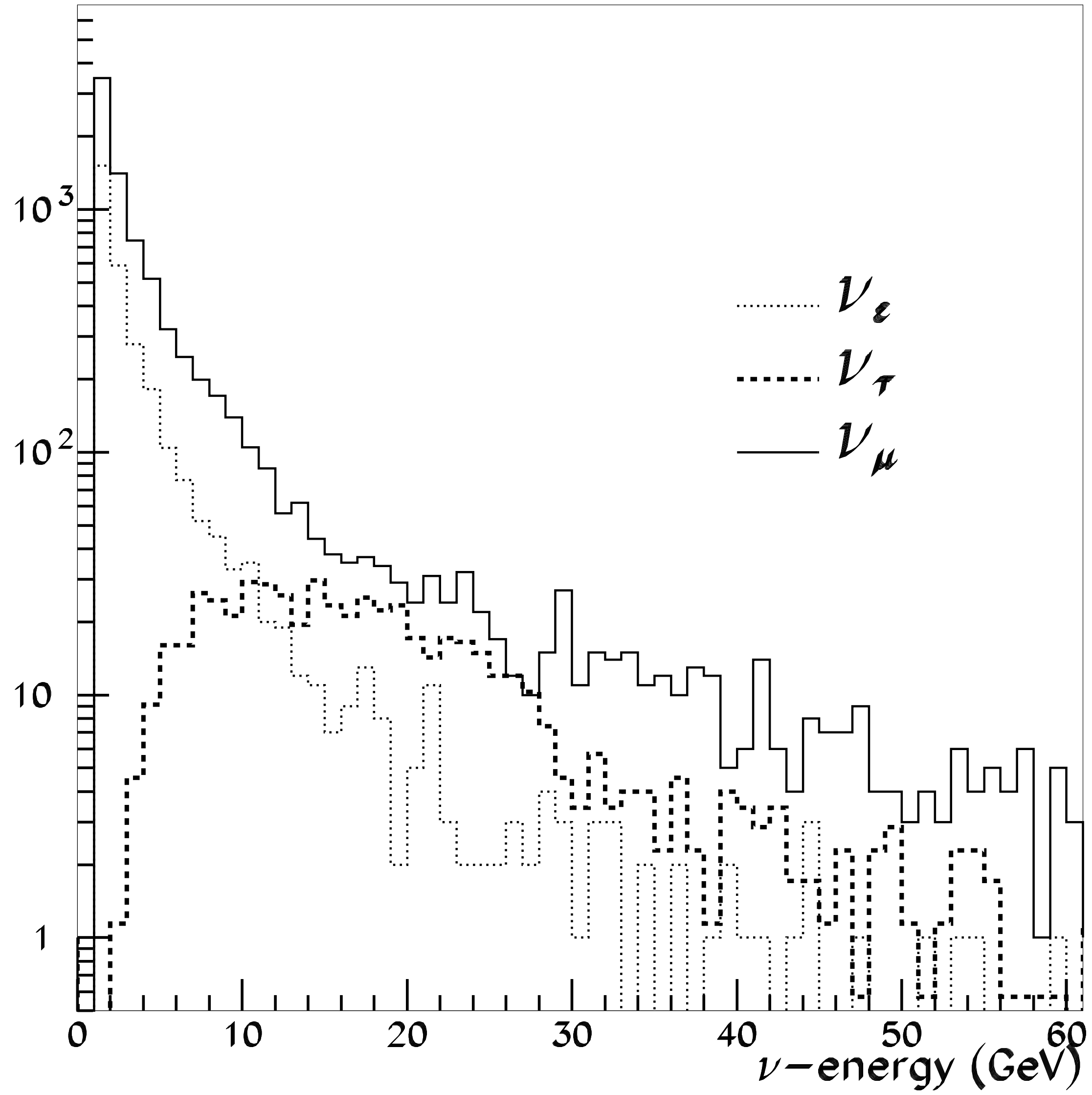

Figure 5: Energy spectra for CC interactions produced by neutrinos of different flavours integrated over the full solid angle. The spectrum of ν_τ events is obtained in the hypothesis of full ν_μ into ν_τ conversion.

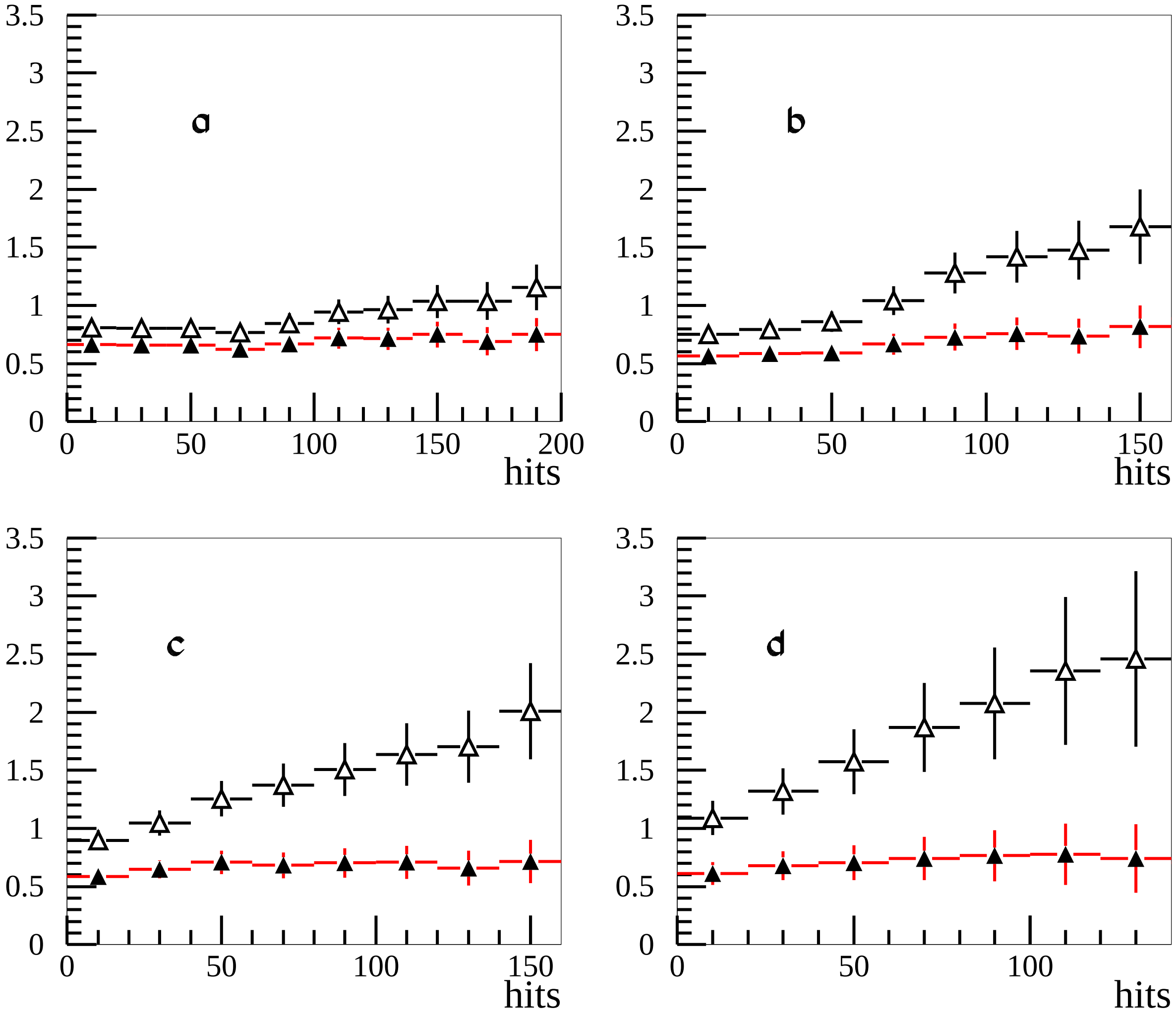

Figure 6: Up/down integral ratios for muon-less events, selected as explained in text, for ν_μ oscillation to a sterile neutrino (full triangles) and to tau neutrino (open triangles), for $\Delta m^2 = 5 \times 10^{-3}$ eV^2 and various thicknesses of the absorber layers: *fig. a 2 cm, fig. b 4 cm, fig. c 6 cm, fig. d 8 cm.* Error bars correspond to 4 years of data taking.

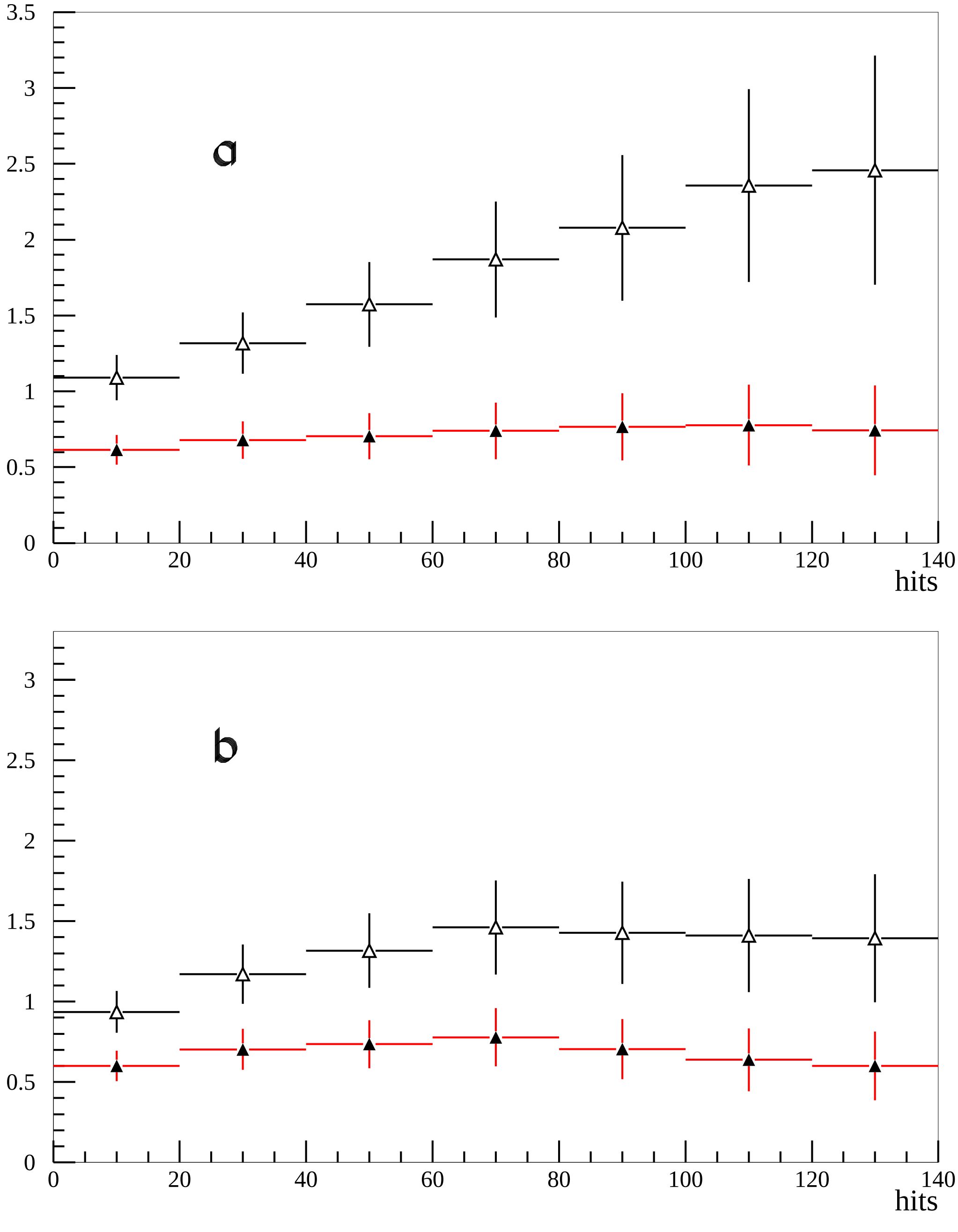

Figure 7: Up/down integral ratios for muon-less events, for ν_μ oscillation to a sterile neutrino (full triangles) and to tau neutrino (open triangles), for a thickness of the iron absorber of 8 cm. *Fig. a:* $\Delta m^2 = 5 \times 10^{-3}$ eV^2; *fig. b:* $\Delta m^2 = 3 \times 10^{-3}$ eV^2. Events have been generated with high statistics, error bars correspond to 4 years of data taking.