A Test of $\nu_{\mu} \rightarrow \nu_x$ Oscillations and determination of the $\Delta m^2$ parameter of Atmospheric Neutrinos using the $L/E$ method

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Abstract

We point out that the measurement of the $L/E$ distribution of atmospheric neutrino events with sufficient resolution in order to observe the characteristic modulations of neutrino oscillations would provide a unique way to test the $\nu_{\mu} \rightarrow \nu_x$ oscillations nature of the atmospheric neutrino anomaly[1] in the parameter range $5 \times 10^{-4} < \Delta m^2 < 2 \times 10^{-3}$ eV$^2$. With an integrated exposure of a few tens of kiloton-year, this method can cover the lower part of the $\Delta m^2$ region of the currently allowed atmospheric neutrino solution[2] and is therefore complementary to the one explorable with planned long-baseline neutrino beam experiments (e.g. Refs. [3, 4]). We stress that experimentally this method relies on the ability to measure high energy muons ($E_\mu > 5$ GeV). A large magnetized calorimeter of several kilotons would be ideally suited for this measurement. The existing LEP detectors augmented with atmospheric neutrino triggers could also be used to perform such a study.

1 Introduction

Recent SuperKamiokande data show an asymmetry in the rate of upward and downward atmospheric muon-like events[1, 2]. In order to verify that this phenomenon is really due to neutrino oscillations, an effective method consists in observing the $\sin^2(1.27\Delta m^2 L/E)$ modulation characteristic of a given $\Delta m^2$ when the event rate is plotted as a function of the reconstructed $L/E$ of the events. Such a method, capable of measuring $\Delta m^2$ in the range between $5 \times 10^{-4}$ and $2 \times 10^{-3}$ eV$^2$ exploiting atmospheric neutrino events, has been advocated in a recent note[5]. 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 striking dips in the $L/E$ distribution while the neutrino interaction spectrum is known to be a slowly varying function of $L/E$. It was shown that the main experimental requirement is that the error on $L/E$ is the following:

$$\delta(L/E) \ll \pi/(1.27\Delta m^2)$$ (1)

This implies that precise measurements of energy and direction of both the muon and hadrons are needed in order to reconstruct precisely the neutrino $L/E$. Note that all past and present large scale underground atmospheric neutrino experiments are unable to determine accurately the momentum of high energy muons (e.g. $E_\mu > 5$ GeV). This implies that the capability to study the $L/E$ distribution is currently quite limited. The ability to measure high momentum muons requires the construction of a magnetized calorimeter with a mass of several kilotons in order to have enough of an event interaction rate.

In section 2, we define a set of selection cuts that improve the reconstruction of the $L/E$ distribution of events which do not strongly rely on the hadronic energy resolution. In section 3 we show how the oscillation can be found and the oscillation parameters determined in a generic magnetized calorimeter. In section 4 we argue that the existing LEP detectors — able to measure muon momentum and direction with a coarse hadronic energy resolution — could fulfill the required criteria to observe the $L/E$ modulations.
2 Optimizing the $L/E$ resolution

The atmospheric neutrino interaction energy spectrum for $E > 1$ GeV has roughly a $E^{-1.7}$ dependence. The basic idea to satisfy Eq. 1 consists in selecting only the neutrino events where the muon direction is close to that of the incoming neutrino. Given the energy dependence of the atmospheric neutrinos, the events with high energy muons are more likely to fulfill the condition. Therefore, there is a cut on the muon momentum for which the total event rate and the $L/E$ resolution are optimized. Moreover, the effective cut in the neutrino energy removes the smearing due to the Fermi motion of the target nucleon.

On a sample of simulated atmospheric neutrino interactions, we placed a cut on the muon energy at 2.5 GeV to select a sample of events where an 80% fraction has the opening angle smaller that $10^\circ$. The remaining 20% is mainly due to high-$y$ high neutrino energy events and is small due to the $E^{-1.7}$ dependence of the neutrino interaction spectrum. It can be further reduced requiring small hadronic energy deposition; a cut of $E_{\text{had}} < 0.5 \times E_\mu$ satisfies the above requirements. We point out that for this purpose a good hadronic energy resolution is not needed. The neutrino energy is reconstructed using both muon and hadron energy but the neutrino energy resolution is only partially affected by the rough hadronic energy resolution because of the applied selection criteria.

Another important cut is applied on the incoming neutrino zenith angle $\theta$; in order to minimize the error on $L$, only the events with $\theta < 75^\circ$ or $\theta > 105^\circ$ should be retained (see Ref. [5]) to well define the sets of upward and downward events. The selection efficiency of this method is close to 15% for events in the detector with neutrino energy above 1.0 GeV. The selection efficiencies for neutrinos and antineutrinos are summarized in Table 1. The efficiency for antineutrinos is higher due to $d\sigma/dy \propto (1 - y)^2$ compared to the flat $d\sigma/dy$ for neutrinos.

### Oscillation parameters determination

To illustrate the method, we consider a generic calorimetric detector with muon identification and measurement capability. The assumed resolutions are listed in Table 2.

The oscillation parameters $\Delta m^2$ and $\sin^2 2\theta$ of interest, we expect that the downward atmospheric neutrinos above 2.5 GeV will not have oscillated while the upward going neutrinos will show the oscillation signal. The sensitivity to oscillations is therefore obtained by comparing the measured $L/E$ distributions of upward and downward going neutrino events. For upward going events, the distance $L$ is obtained from the cos $\theta$ with the expression $L = \sqrt{R^2 - (R - d)^2 \sin^2 \theta} - (R - d) \cos \theta$ where $R$ is approximately the earth radius and $d$ is the depth of the atmosphere. For downward going events, the mirror-distance $L'$ is calculated replacing in the expression $\theta \rightarrow -\theta$, in order obtain an “unoscillated” upward going $L'/E$ spectrum. This method only relies on the fact that the angular distribution of atmospheric neutrinos is symmetric in $\cos \theta$ for energies above 5 GeV and below 5 GeV the geomagnetic effect and the solar activity perturbances are small. In the considered $\cos \theta$ region (see section 2), the geomagnetic correction is even smaller. The $\nu_\mu \rightarrow \nu_x$ conversions are extracted by searching for the characteristic pattern of oscillations in the $L/E$ distribution normalized by the $L'/E$ distribution ($R = (L/E)/(L'/E)$).

In Figures 2 we show the measured $L/E$ distribution in presence of $\nu_\mu \rightarrow \nu_x$ oscillations with parameters $\Delta m^2 = 1 \times 10^{-3}$ and $\Delta m^2 = 5 \times 10^{-4}$ and $\sin^2 2\theta = 0.9$ after an exposure of 30 kt-year for upward going and downward going muons. The oscillation parameters are extracted by comparing the two distributions. For simplicity, we show the ratio $R$ of the two distributions

| Selection | $\nu_\mu$ Fraction(%) | $\bar{\nu}_\mu$ Fraction(%) | $\delta(L/E)$ RMS (Km/GeV) |
|-----------|----------------------|-----------------------------|--------------------------|
| All ($E_\nu > 1$ GeV) | 100 | 100 | 765 |
| $E_\mu > 2.5$ GeV | 31.7 | 45.1 | 560 |
| $E_{\text{had}} < 0.5 E_\mu$ | 13.7 | 27.0 | 350 |
| $\theta < 75^\circ$ or $\theta > 105^\circ$ | 11.2 | 21.9 | 345 |

Table 1: Neutrino and anti-neutrino event selections.
Table 2: Resolutions assumed for a generic calorimetric detector with muon identification and measurement capability.

|                  | Muons | Hadrons |
|------------------|-------|---------|
| $\delta E/E$     | 5%    | 80%/\sqrt{E} |
| $\delta \theta$  | 10 mrad | not used |

where we have assumed symmetric errors. The position of the first minimum in the R distribution (corresponding to an $(L/E)_{min}$) yields an estimate of the oscillation parameter $\Delta m^2$ through the oscillation formula. The best estimate of the parameters in the $(\Delta m^2, \sin^2 2\theta)$ plane are obtained by fitting the oscillation formula to the observed R distribution. The confidence levels (see Figures [12]) for the determination of the mass difference and mixing angle at the 90, 95 and 99% shows the power of this method.

4 Atmospheric Neutrinos in LEP detectors

The existing LEP detectors (ALEPH\cite{7}, DELPHI\cite{8}, L3\cite{9} and OPAL\cite{10}), equipped with some additional apparatus, could fulfill the required criteria; namely:

- large mass (several kt);
- magnetized muon spectrometer;
- segmented hadron calorimeter;
- very precise tracking chambers (TPC’s and L3 MUCH).

We note that for our purpose the three detectors ALEPH, DELPHI and OPAL have very similar characteristics with most of their mass concentrated in their hadronic calorimeters acting as return yokes for their inner magnetic field. The L3 detector has a large mass in its iron magnet surrounding completely the large precise muon chambers and the inner sub-detectors. We estimate that a useful mass of $\approx 3$ kt can be obtained with the iron of the L3 detector magnet; the hadron calorimeters of ALEPH, OPAL and DELPHI amount to 9 kt; about one more kt can be added if one includes the electromagnetic calorimeters.

For the events occurring in the hadronic calorimeters the neutrino energy is estimated as the total visible energy and an appropriate cut on the hadronic activity will be used to improve the correlation between neutrino and muon direction. We stress the importance of the magnetic field available in all LEP detectors in order to obtain a reliable muon momentum measurement:

- In the case of ALEPH, the acceptance for the muon to traverse the inner tracking detector is large since the hadron calorimeter was built to completely cover the inner tracker. In this case a very precise determination of the muon momentum is available; for the events with this topology the measurement error is dominated by the error of the backward extrapolation into the hadron calorimeter. For the muons that do not cross the inner tracker, the fine segmentation of the hadron calorimeter should permit the momentum to be measured by curvature (using the residual magnetic field) or by range-out.
- For the events in the L3 magnet, the hadronic energy cannot be reliably estimated. Nevertheless, we recall that the cut on muon momentum suppresses topologies with large hadronic energy and a further reduction can be obtained by requiring no other activity that the muon in the muon chambers. So we expect that the muon momentum vector will be a good estimator of the incoming neutrino energy and direction. To efficiently veto cosmic ray muon backgrounds, we expect that the L3 magnet will have to be covered with active large area detectors (e.g. RPC’s).

We deduce from the technical reports of the LEP experiments\cite{7, 8, 9, 10} that the resolutions for reconstructing the events in the topologies described above are well matched with the one
Figure 1: Measured $L/E$ distribution in presence of $\nu_\mu \rightarrow \nu_x$ oscillations with parameters $\Delta m^2 = 1 \times 10^{-3}$ and $\sin^2 2\theta = 0.9$ after an exposure of 30 kt-year for a) upward going muons; b) downward going muons; c) the ratio $R$; d) the confidence levels for the determination of the mass and mixing angle.

hypothesized for the generic calorimeter of section 3. A more precise description and discussion on the use of the LEP detectors will be given after detailed simulations will have been performed.

5 Conclusions

In this note we have shown that the neutrino oscillation parameter, $\Delta m^2$, can be precisely determined through the measure of atmospheric neutrino flux as a function of $L/E$ in the search region between $5 \times 10^{-4}$ and $2 \times 10^{-3}$ eV$^2$ even with a large mass detector with rough hadronic resolution in the GeV range. The four LEP detectors have a total mass of about 10 kt and resolutions matching the requirements to use the $L/E$ method. It could be very interesting to explore their capabilities as atmospheric neutrino detectors.

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Figure 2: Measured $L/E$ distribution in presence of $\nu_\mu \rightarrow \nu_x$ oscillations with parameters $\Delta m^2 = 5 \times 10^{-4}$ and $\sin^2 2\theta = 0.9$ after an exposure of 30 kt-year for a) upward going muons; b) downward going muons; c) the ratio $R$; d) the confidence levels for the determination of the mass and mixing angle.

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