On neutrino oscillations searches with ANTARES

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Abstract: Although the first evidence for neutrino oscillations came from measurements on atmospheric neutrinos in underground experiments, neutrino oscillations have yet to be demonstrated in high energy neutrino telescopes, whose energy threshold is significantly higher. Recent studies have shown that a clean sample of atmospheric neutrinos with energies as low as 20 GeV can be isolated in the ANTARES neutrino telescope. Such a threshold is low enough to allow the observation of neutrino oscillation features. A robust analysis method is presented which allows the extraction of atmospheric neutrino oscillation parameters.

Keywords: neutrino oscillations, ANTARES, neutrino telescope

1 Introduction

It is now well established that neutrinos can switch from a flavour to another, neutrino flavour eigenstates for the weak interaction being different from neutrino mass eigenstates. This phenomenon, hypothesized in 1957 by Pontecorvo and described more precisely in the early sixties [1], is known as neutrino oscillations, and has been measured by a number of experiments [2].

Although part of the scientific program of the ANTARES neutrino telescope, oscillations studies have been delayed because of the difficulty to reliably reconstruct muons at a sufficiently low energy. Indeed, the granularity of ANTARES is rather coarse compared with the range of GeV muons in water : its 885 photomultiplier tubes are distributed by triplets placed 14.5 m apart along the detector lines, themselves spaced by about 60 m [3]. As a consequence, the energy range where the effect of the atmospheric neutrino oscillations should be visible is situated at the very edge of the detector sensitivity, which makes the neutrino oscillations measurement very challenging.

The topic experienced a regain of interest since the completion of the detector in 2008. As progress was steadily made in the detailed understanding of the detector and of its environment, it became clear that it should be possible to extract a clean sample of atmospheric neutrinos with energies around the first minimum in the survival probability of muon neutrinos propagating through the Earth.

Even though dedicated experiments are more sensitive for the measurements of neutrino oscillations, such an analysis is an important check for ANTARES. The analysis being very sensitive not only to the telescope efficiency but also to the quality of the angular and energy reconstruction, it becomes a benchmark for the understanding of the detector.

2 Purpose

Neutrinos oscillations are commonly described in terms of E/L dependence, where E is the neutrino energy and L its oscillation path length [2]. For a neutrino telescope such as ANTARES, detecting neutrinos crossing the Earth, L can be translated as $2R\sin\theta$, R being the Earth radius and θ the anti-elevation (that is, the angle between the neutrino direction and the horizontal axis : $\theta = \pi/2$ for a vertical upgoing neutrino). Within the two-flavour approximation, the ν_μ survival probability can then be written

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(2.54 R \Delta m^2_{32} \frac{\sin\theta}{E}\right),$$

θ_{23} and Δm^2_{32} being respectively the mixing angle and the squared mass difference of the involved mass eigenstates (with R in km, E in GeV and Δm^2_{32} in eV^2).

According to recent results from the MINOS experiment [4], the first minimum in the muon neutrino survival probability $E/\sin\theta$ spectrum occurs at about 24 GeV (figure 1). This interesting region is in principle accessible for ANTARES. Indeed, Monte-Carlo simulations have shown that it is possible to extract clean samples of atmospheric neutrinos with energies in this range, which should enable the observation of the first minimum.

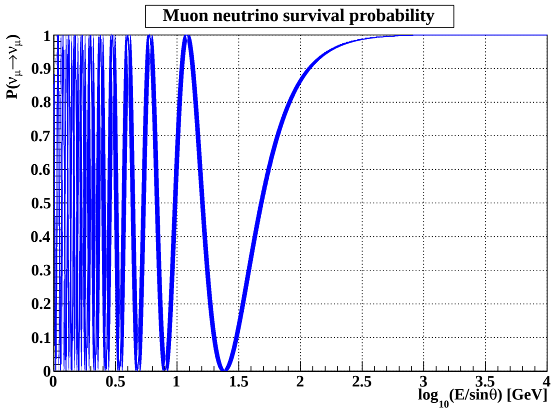

Figure 1: Survival probability of muon neutrinos as a function of $E/\sin\theta$ in the two-flavour approximation, with $\sin^2 2\theta_{23} = 1$ and $\Delta m^2_{32} = 2.32 \times 10^{-3}\,\mathrm{eV}^2$ (the line width corresponds to MINOS $1\,\sigma$ uncertainty on this parameter [4]), neglecting matter effects.

3 Method

A simple and robust method to measure neutrino oscillations in ANTARES consists in taking advantage of the different granularity of the detector along and across the detection lines. Indeed the range of muons below about 20 GeV makes them unlikely to give signal on different lines. They can be well reconstructed however using only one line, especially if they are close to the vertical. These low energy vertical tracks should be suppressed in the current oscillation scenarios compared to the more energetic and less vertical ones. Consequently, the observed ratio between the number of tracks giving signal on a single detector line (1D tracks) and the number of tracks giving signal on several detector lines (3D tracks) should differ from the expected ratio in the case of no oscillations. Many systematic effects such as the global flux normalisation or absolute detection efficiencies should cancel in this ratio, leading to a small residual systematic effect. The observed ratio can be expressed in terms of Monte-Carlo events as

$$R = \frac{N^{no\ osc}_{\mathrm{1D}} - \sin^2 2\theta_{23} \cdot f_{\mathrm{1D}}}{N^{no\ osc}_{\mathrm{3D}} - \sin^2 2\theta_{23} \cdot f_{\mathrm{3D}}}, \qquad (1)$$

where $N^{no\ osc}_{\mathrm{1D|3D}}$ is the number of expected 1D (3D) tracks without neutrino oscillations and

$$f_{\mathrm{1D|3D}} = \sum_i \sin^2\left(2.54 R \Delta m^2_{23} \frac{\sin\theta_i}{E_i}\right)$$

is summed over each event i.

For each value of Δm^2_{23} the mixing angle can be calculated analytically from the measurement of R according to equation 1. The statistical and systematic errors from R propagate directly into an error on the mixing angle, which leads to a band in the $(\theta_{23}, \Delta m^2_{32})$ plane.

Tracks are reconstructed using a fast reconstruction algorithm [5], which has the advantage of being more efficient at lower energies than other existing reconstruction strategies. A cut on the estimated quality of the fitted track and on the reconstructed angle is performed, in order to select well-defined events and to increase the upgoing neutrinos purity. The 1D tracks are required to be reconstructed using hits from at least 8 detector storeys. Lowering this cut would considerably enhance the number of 1D events and thus the sensitivity to oscillations, but would also increase dramatically the contamination from misreconstructed atmospheric muons. Such a hard cut ensures a very low contamination and leads to a minimal track length of about 100 m. The energy threshold is thus roughly 20 GeV, which is below the first oscillation minimum in the $E/\sin\theta$ spectrum.

This method is robust as it does not depend on many assumptions, nor does it rely on an energy estimator. Furthermore the reconstruction algorithm is used only to assert the quality of the selected events. Finally, assuming they affect similarly 1D and 3D events, the ratio should cancel most systematics, and in particular the large uncertainties on the atmospheric neutrino flux normalization and the uncertainties on the detector simulation. The strict hit selection criteria and the strong cut on the number of hit storeys minimize the sensitivity of the ratio to potential biases in the optical background simulation. Remaining systematic uncertainties are expected to be within a few percents, smaller than the current statistical errors.

4 Expected sensitivity

Table 1 shows, according to MINOS results [4], the number of expected events for a 170 days Monte-Carlo sample (this corresponds to 2008 active time). The atmospheric neutrino flux is weighted to match Bartol parametrization [6]. The contamination of misreconstructed downgoing atmospheric muons is negligible. The number of 1D events is suppressed by 16 % in the case of oscillations while the number of 3D events is suppressed only by 3.6 %. The effect to be observed is however small : the suppression of 1D tracks concerns only 26 events for this sample. It is clear that the $E/\sin\theta$ spectrum cannot be reliably extracted under such conditions : a larger statistics is needed.

	no osc.	osc.	contamination
1D tracks	186	160	4.7
3D tracks	522	504	1.2

Table 1: Number of expected $\nu_\mu/\bar{\nu}_\mu$ charged current events, after 170 days of lifetime, with and without oscillations, for 1D and 3D tracks, and number of misreconstructed atmospheric muons surviving the cuts.

The sensitivity after 1000 days, which may be achieved after 4 or 5 years of real data taking depending on various external conditions, is presented in figure 2, extrapolating

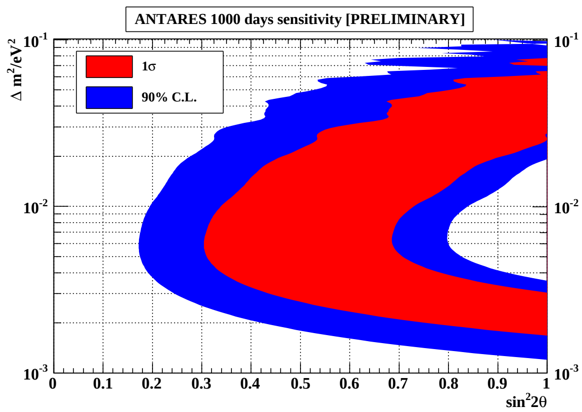

Figure 2: ANTARES expected sensitivity to atmospheric neutrino oscillations after 1000 days.

from the numbers given in table 1. The number of expected 1D events is roughly one per day, which leads for 1000 days to a statistical error of about 3 % ($\sim$30 events). Studies where PMT and water parameters have been varied within their tolerance have shown that a 3 % systematic error on R is realistic. Consequently, a total standard deviation of about 5 % on R has been used to draw the measurement contours of figure 2.

According to these results, although not competitive with dedicated experiments, ANTARES should be sensitive to neutrino oscillation parameters through disappearance of atmospheric muon neutrinos with the simple and robust analysis presented here. Current preliminary results using a restricted data sample are compatible with world oscillation data. Processing of the whole ANTARES data set is foreseen.

5 Prospects

Several directions are currently being investigated to improve ANTARES sensitivity to neutrino oscillations. In a near future, it should be possible to increase significantly the number of low energy reconstructed muons thanks to a dedicated reconstruction algorithm coupled to an optimized hit selection, which would reduce statistical uncertainties using the same amount of data. Furthermore the use of a different reconstruction algorithm would be an important cross-check of such an analysis. Additionally, the proportion of low energy events can be improved by selecting events contained in the detector.

Such improvements should enhance ANTARES sensitivity to neutrino oscillation parameters. They might also allow the extraction of the $E/\sin\theta$ spectrum, which would be a great opportunity to cross-check the understanding of the detector.

6 Conclusions

A robust method to extract atmospheric muon neutrino oscillation parameters from ANTARES data has been presented. Although not competitive with dedicated experiments, ANTARES should be able to reach some sensitivity to these parameters, which would be a demonstration of the understanding of the ANTARES detector. Preliminary analysis of a restricted data sample is compatible with existing constraints on neutrino oscillation parameters. The complete analysis of ANTARES data is ongoing.

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