NEUTRINO PROPERTIES FROM LARGE NEUTRINO TELESCOPES

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We discuss new analysis for neutrinos from neutrino telescopes and the new physics that could be extracted from them. We show that high statistics atmospheric neutrino measurements in the IceCube Deep Core Array can provide useful information about neutrino oscillation parameters and other neutrino properties.

1 Introduction

Over the last decade, neutrino oscillations have provided the first confirmed particle physics experimental evidence for physics beyond the Standard Model. We are now at the point where we have learned enough about neutrinos to be able to use them as a tool for learning about other new phenomena. A large number of neutrino telescopes have recently started taking data or are presently under construction, looking for extraterestrial sources of neutrinos. Several different techniques are presently used in order to look for high energy neutrinos: Cerenkov light in ice (AMANDA/IceCube), in water (ANTARES, NEMO, NESTOR); radio Cerenkov emission in ice (RICE, ANITA) and air shower experiments (Pierre Auger observatory). These experiments are looking for high energy neutrinos from astrophysical objects, cosmic ray interactions, dark matter annihilation, etc.. Both diffuse fluxes and point sources are expected to be observable in the next few years and this data could possibly correlate with other observations of cosmic rays, gamma rays, etc. For most of these searches, atmospheric neutrinos constitute a background. The atmospheric neutrino flux is decreasing very fast with energy, but is very large at the lowest energies accessible in neutrino telescopes. We explore the possibility of using this high statistics atmospheric neutrino data for neutrino oscillation studies.

2 Neutrino Oscillations from the IceCube Deep Core Detector

Recently, a low energy extension of the IceCube detector, the IceCube Deep Core array (ICDC), has been built [1]. It consists of 6 densely instrumented strings (7m DOM spacing) in the deep center region of the IceCube detector and the 7 nearest standard IceCube strings. Its goal is to significantly improve the atmospheric muon rejection and to extend the IceCube neutrino detection capabilities in the low energy domain, possibly to muon energies as low as 5 GeV. The instrumented volume is of about 15 Mton. Such a low threshold array buried deep inside IceCube opens up a new energy window on the universe. It searches for neutrinos from sources in the Southern hemisphere, in particular from the galactic center region, as well as for neutrinos from WIMP annihilation, as originally motivated.

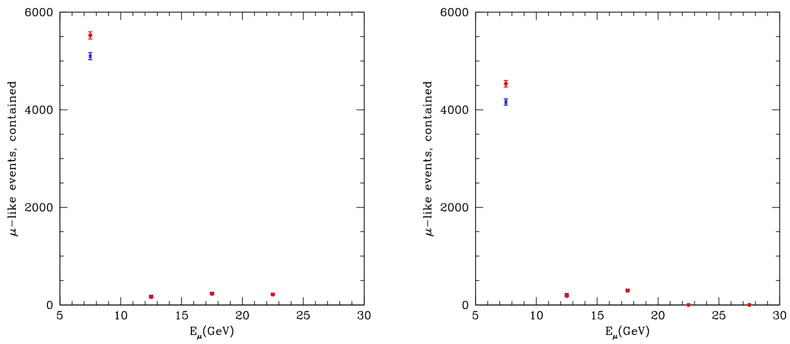

Figure 1: From left to right, number of contained μ-like events in a 5000 kton detector after 10 years exposure, within the $(-0.9, -0.8)$ and $(-0.8, -0.7)$ c_ν bin, assuming $\sin^2 2\theta_{13} = 0.1$, $\delta = 0$ and an energy bin size of 5 GeV, with a muon energy threshold for detection of 5 GeV. We show the 1σ statistical errors. The blue crosses (red circles) denote positive (negative) hierarchy.

2.1 Mass hierarchy

We have provided an additional and independent motivation for building such an array ?, namely to explore neutrino oscillation physics. In particular, we have shown that it is possible to use atmospheric neutrinos detected by the Deep Core Array to determine the neutrino mass hierarchy. This is extremely important given that long baseline experiments with comparable sensitivity might take a very long time to build and collect data, while the IceCube Deep Core will accumulate high statistics relatively fast. Our study indicates that for a total mass of the instrumented volume times exposure of 100 Mt yr (roughly equivalent to a 10 year running of the Deep Core Detector), neutrino mass hierarchy can be determined at least with 90% confidence level assuming the current best-fit values of the oscillation parameters, and for θ_{13} close to the present bounds.

We have considered μ-like *contained* events produced by the interactions of atmospheric upward going neutrinos in deep ice. Formally, the expected number of muon neutrino-induced contained events in the i- and j-th energy and cosine of the nadir angle (c_ν) bins is:

$$N_{i,j,\mu} = \frac{2\pi N_{\rm T}\, t}{V_{\rm det}} \int_{E_i}^{E_i+\Delta_i} dE_\nu \int_{c_{\nu,j}}^{c_{\nu,j}+\Delta_j} dc_\nu V_\mu \quad \times \quad \Big(\frac{d\phi_{\nu_\mu(\nu_e)}}{dE_\nu d\Omega}\, \sigma^{\rm CC}_{\nu_\mu(\nu_e)} P_{\nu_\mu(\nu_e)\to\nu_\mu} + \frac{d\phi_{\bar\nu_\mu(\bar\nu_e)}}{dE_\nu d\Omega}\, \sigma^{\rm CC}_{\bar\nu_\mu(\bar\nu_e)} P_{\bar\nu_\mu(\bar\nu_e)\to\bar\nu_\mu} \Big) \,, \qquad (1)$$

where Δ_i and Δ_j are respectively the energy and c_ν bin widths, $N_{\rm T}$ is the number of available targets, $V_{\rm det}$ is the total volume of the detector, t is the exposure time, $d\phi_\nu$'s are the atmospheric (anti)neutrino differential spectra, $\sigma^{\rm CC}$ is the CC (anti)neutrino cross section and V_μ is the effective detector volume.

Figure 1 shows the number of contained μ-like events within three different angular bins: $c_\nu \in (-0.9, -0.8)$ and $(-0.8, -0.7)$ for $\sin^2 2\theta_{13} = 0.1$ and best fit values for the other oscillation parameters. We have assumed an energy bin size of 5 GeV, with a muon energy threshold for detection of 5 GeV.

A finer angular bin than $\Delta c_\nu \sim 0.1$ is not possible because the reconstruction of primary neutrino direction is expected to be poor in this energy range due to the intrinsic spread in charged lepton-neutrino scattering angle. The resonance is expected to be located at low energies and the maximum difference between normal and inverted hierarchies is observed in the $(5, 10)$ GeV energy bin. In higher energy bins, the effect is negligible.

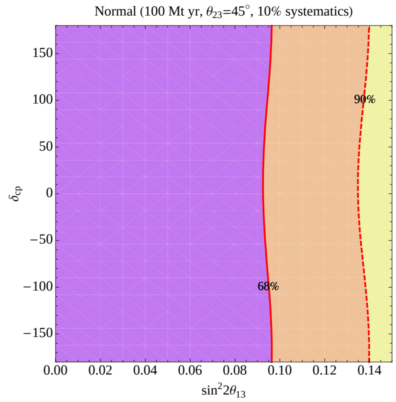

Figure 2: Rejection regions of the "wrong" hierarchy model in the $(\sin^2\theta_{13}, \delta_{cp})$ plane Different lines correspond to rejection regions of the "wrong" hierarchy at 68%, 90%, 95% and 99% CL (2 d.o.f.) using the muon-like contained events in a detector of mass times exposure of 100 Mt yr.

We performed a minimum χ^2 analysis in the $(\sin^2 2\theta_{13}; \delta)$ parameter space. For a particular hierarchy (h) and $(\sin^2 2\theta_{13}; \delta)$ parameters chosen by nature, we consider the number of μ-like events $N^{\rm ex}_{ij,h}(\sin^2 2\theta_{13}; \delta)$ measured by an experiment in the i- and j-th muon energy and c_ν bins (see Eq. (1)). These events include the ν_μ and $\bar{\nu}_\mu$ signal, as well as the background secondary muons from ν_τ and $\bar{\nu}_\tau$'s.

The χ^2 statistics, for a "theoretical" model of hierarchy (h') and parameters $(\sin^2 2\theta'_{13}; \delta')$ is then defined as

$$\chi^2_{h'}(\sin^2 2\theta'_{13}; \delta') = \sum_{i=1,2}\sum_{j=1,3} \left[\frac{N^{\rm ex}_{ij,h}(\sin^2 2\theta_{13}; \delta) - N^{\rm th}_{ij,h'}(\sin^2 2\theta'_{13}; \delta')}{\sigma^{\rm ex}_{ij,h}(\sin^2 2\theta_{13}; \delta)}\right]^2 . \quad (2)$$

Here $N^{\rm th}_{ij,h'}(\sin^2 2\theta'_{13}; \delta')$ is the expected event number from both signal ν_μ's and background ν_τ's given a "theoretical" model. The variance $\sigma^{\rm ex}_{ij,h}(\sin^2 2\theta_{13}; \delta)$ is calculated from experimental events with or without systematic uncertainties. We minimize χ^2 in Eq. (2) for $(\sin^2 2\theta'_{13}; \delta')$ parameters (i.e. 2 d.o.f). When nature's choice or "true" hierarchy is h (normal for example), then the "wrong" theoretical model of hierarchy $h' \neq h$ (inverted in this case) is rejected if

$$\min\left(\chi^2_{h'\neq h}\right) - \min\left(\chi^2_{h'=h}\right) \geq \alpha \quad (3)$$

in the $(\sin^2 2\theta_{13}; \delta)$ parameter space. The 68%, 90%, 95% and 99% confidence levels (CL) are defined for $\alpha = 2.3$, 4.61, 5.99 and 9.21 respectively, for 2 d.o.f statistics [3]. Note that our choice of 2 d.o.f statistics is rather conservative as explained in the Appendix of Ref. [4]. Our 90% CL translate into the 97% CL for 1 d.o.f statistics.

Figure 2 shows the regions of parameter space where the correct hierarchy can be distinguished from the wrong one if the normal hierarchy is the one present in nature, also takes into account a 10% systematic error in addition to the statistical ones.

2.2 Tau neutrinos

The IceCube detector and its Deep Core extension are optimized for detecting muon tracks from the charged current interactions of ν_μ. It is, however, possible to also detect cascades. While these type of events provide poor directional information, their energy can be measured quite precisely. We analyzed [5] the cascade rate in the ICDC array. There are many contributions

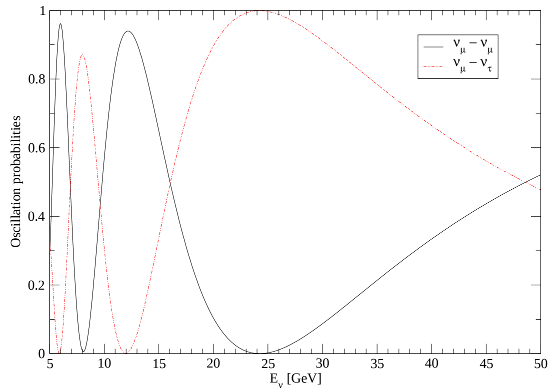

Figure 3: ν_μ survival probability and $\nu_\mu \to \nu_\tau$ oscillation probability for $c_\nu = -1$, $\sin^2 2\theta_{13} = 0.1$

to this signal: charged current interactions of ν_e, neutral current interactions of all neutrino flavors and electromagnetic and hadronic decays of tau leptons produced in charged current interactions of ν_τ. There are several important observations which suggest that the ν_τ signal can be significant and can provide evidence for ν_τ appearance from oscillations of ν_μ. First, the atmospheric electron neutrino flux at the relevant energies is significantly lower than the muon neutrino flux, such that the ν_e charged current interactions provide only a small contribution to the event rates. In addition, the energy range covered by ICDC corresponds to a maximum of $\nu_\mu \to \nu_\tau$ oscillations (minimum of ν_μ survival), as can be seen in Figure 3. The large flux of atmospheric muon neutrinos can thus lead to a large flux of tau neutrinos. This has already been noted [2], when we showed that $\nu_\mu \to \nu_\tau \to \tau \to \mu$ provides a non-neglibile contribution to the muon track rate. It is also important to note that, unlike for Super-Kamiokande, which is sensitive at much lower energies, tau threshold production effects are relatively small, only affecting the lowest energy events detected by ICDC.

We investigate the neutrino energy range between 10 GeV and 100 GeV. Cascades have very little directional information, especially at these low energy, so we integrate over all upgoing directions. The downgoing neutrinos are largely unaffected by oscillations, so they can be used for determining the atmospheric neutrino flux and thus the contribution of the ν_e charged current interactions to the overall cascade rate. In our numerical calculations we have taken into account full three flavor oscillations. It is however straightforward to see that solar parameters do not play an important role in the analysis due to the rather high energy threshold of ICDC. Also, θ_{13} effects, while in principle obaservable for values of θ_{13} close to the present bound, do not affect any conclusions regarding ν_τ rates, which are determined by the (maximal) atmospheric mixing angle θ_{23}. Fig. 4 shows the number of tau-neutrino induced cascades for one year of data from the ICDC detector. While the background is still large, a statistically significant detection of tau-neutrino appearence from neutrino oscillations is clearly possible.

3 Outlook

The IceCube detector and its Deep Core extention provide a great opportunity for studies of atmospheric neutrinos. Being the largest existing neutrino detector, it will accumulate a huge number of atmospheric neutrino events over an enormous energy range, thus allowing for detailed studies of oscillation physics, Earth density, atmospheric neutrino fluxes and new physics. In order to extract all this information it is necessary to use energy and angular distribution information, as well as flavour composition, all possible to obtain with the IceCube detector.

In the "low" energy region, below about 40 GeV, neutrino oscillation effects can be significant. Matter effects inside the Earth are very important in this energy range and for non-zero

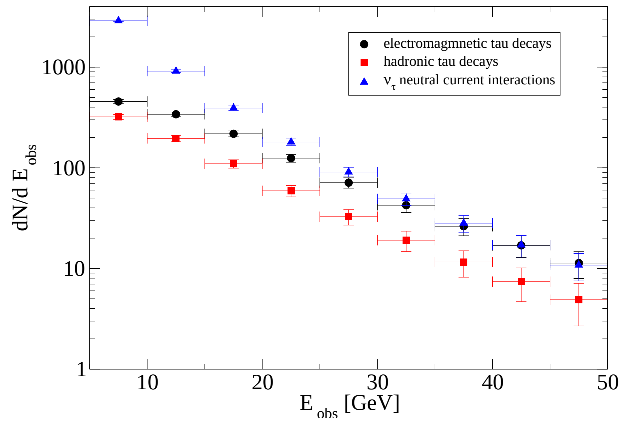

Figure 4: ν_τ event rate in the ICDC

values of θ_{13} resonance effects can strongly enhance/reduce oscillation probabilities. Straight-up-going neutrinos ($c_\theta \leq -0.7$) pass through the core of the Earth and are most sensitive to resonant matter oscillations and thus to all sub-dominant neutrino oscillation effects (θ_{13}, mass hierarchy, CP violation). Up-going neutrinos at shallower angles are still sensitive to the "main" oscillation effects (Δm^2_{31}, θ_{23}), while the other, sub-dominant contributions become smaller, due to the lower matter densities and shorter pathlengths.

The IceCube Deep Core array, with muon energy detection thresholds of $\sim 5-7$ GeV, could provide the first measurement of the neutrino mass hierarchy if $\sin^2 2\theta_{13}$ is not very small. It also has the unique capability of detecting large numbers of tau neutrinos.

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1. O. Schulz [IceCube Collaboration], AIP Conf. Proc. **1085**, 783 (2009); C. Wiebusch and f. t. I. Collaboration, arXiv:0907.2263 [astro-ph.IM].
2. O. Mena, I. Mocioiu and S. Razzaque, arXiv:0803.3044 [hep-ph].
3. W. M. Yao *et al.*, Journal of Physics, G 33, 1 (2006).
4. O. Mena, H. Nunokawa and S. J. Parke, Phys. Rev. D **75**, 033002 (2007).
5. G. Giordano, O. Mena, I. Mocioiu, "'Atmospheric neutrino oscillations, tau neutrinos in ice and non-standard neutrino interactions"', arXiv:1004.3519 [hep-ph].