Point source searches with the ANTARES neutrino telescope

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Abstract

Neutrino telescopes may detect astrophysical point-like sources of high energy neutrinos as an excess of events above the atmospheric neutrino background. The sensitivity therefore depends on the pointing accuracy of the detector, which is expected to be better than 0.3° for neutrino energies above 10 TeV for the ANTARES detector. Methods based on binning or clustering algorithms have been developed, together with a method which does not require any binning. This method is based on a likelihood ratio test and uses the information on the neutrino angular resolution as a function of energy. The expected exclusion limits and discovery potential will be presented.

1. Introduction

The discovery of high energy neutrinos from cosmic sources would provide an important clue to the origin of high energy cosmic rays. In cosmic ray sources, neutrinos may be produced through decays of mesons produced by accelerated protons colliding with matter or photon targets. In this work we consider point-like sources, while in [3] results concerning diffuse fluxes are presented.

Searches for point-like sources of neutrinos can be performed by dividing the celestial sphere into angular bins and counting the events falling inside them or by looking for clusters of events. A highly populated bin or cluster compared to the expected background distribution due to atmospheric neutrinos would represent an indication for point-like sources. In addition to such widely used methods, a different method, based on a likelihood ratio test has been developed within the ANTARES collaboration. The methods are discussed in section 2.

The ANTARES collaboration is building a water Cherenkov neutrino telescope in the Mediterranean Sea at a depth of 2.4 km [2]. It will consist of 12 strings, each equipped with 75 10" photomultiplier tubes (PMTs). The arrival times of the Cherenkov photons on the PMTs will be measured with an accuracy of about 1 ns, which allows accurate reconstruction of the muon trajectory despite the optical background from decaying ^{40}K and bioluminescence. The resulting angular resolution is typically a few tens of a degree for high energy neutrinos (see Fig. 1). The effective area and angular resolution of the detector determine its

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sensitivity for point-like sources, since the signal to noise ratio depends on these quantities.

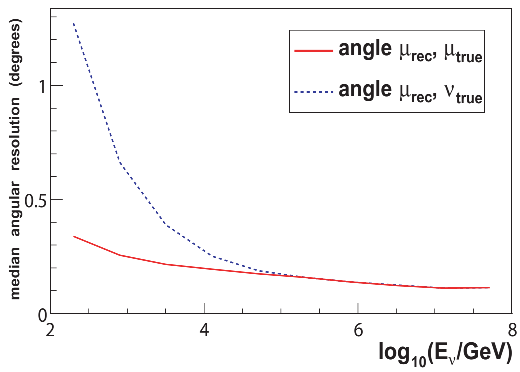

Fig. 1. The angular resolution of the ANTARES detector, estimated from a full simulation. Dashed line: median angle between the simulated parent ν and the reconstructed muon directions vs. E_ν. Solid line: median angle between the directions of the simulated and reconstructed muon.

2. Methods

Grid and cluster methods have been developed in ANTARES. The grid method divides the celestial sphere in bins. The detector area, and hence the background, depends on declination. The size of the bins was varied with declination in order to keep constant the average number of background events per bin. The bin sizes have been optimised in order to obtain the best discovery potential and exclusion limits for a source with a spectrum proportional to E^{-2}. The corresponding value for the average number of background events per bin is 0.3. The cluster method looks for events within a cone centered around measured events. The optimal cluster size for E^{-2} sources has been estimated to be 1.0°.

In these methods, the significance of a possible excess can be calculated analytically from the data itself. Moreover, even though the methods can take advantage of energy reconstruction to further reject atmospheric ν's, given their softer spectrum than E^{-2}, they do not rely on it.

A method not relying on any binning has been developed to look for sources anywhere in the sky. The likelihood ratio (LR) method operates by finding the position p_0 and flux ϕ_0 of the most likely source candidate by maximising the probability $P(\text{data}|\mathbf{s}(p,\phi)+\mathbf{b})$ under the assumption that amongst the background ($\mathbf{b}$) there is a signal ($\mathbf{s}$) from a neutrino point source at some location in the observable sky. Expressions for $P(\text{data}|\mathbf{s}+\mathbf{b})$ have been derived that can be evaluated quickly enough for its optimisation to be feasible. These expressions rely on parametrisations of the (energy dependent) effective area and angular resolution of the detector and of the probability of finding a muon with a given reconstructed energy as a function of neutrino energy. Taking this information into account without losing information due to binning effects, ensures that the likelihood ratio:

$$\lambda = \frac{P(\text{data}|\mathbf{s}(p_0, \varphi_0) + \mathbf{b})}{P(\text{data}|\mathbf{b})} \tag{1}$$

is a close to optimal observable for discriminating between the signal+background and background-only hypotheses. The method should therefore be nearly optimally sensitive for discovering a point source at a given confidence level. A preliminary comparison of the sensitivity to E^{-2} point sources indicates that the LR method leads to a significant ($\sim$ 30%) improvement in sensitivity compared to the grid method.

The degradation in sensitivity resulting from imperfect knowledge of the detector behaviour, in particular the angular resolution, remains to be studied for all methods. Since more of this knowledge is used in the LR method, such uncertainties are likely to have a larger impact on the sensitivity of the LR method compared to the grid and cluster methods. The methods are therefore complementary.

3. Results

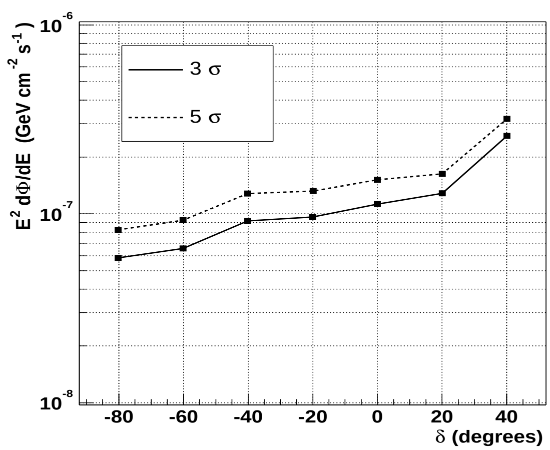

Fig. 2. Expected sensitivity (see text) of a full sky search for an E^{-2} point source of neutrinos as a function of declination. The fluxes needed for a 3σ and a 5σ discovery after one year of data taking are shown (obtained with the LR method).

The results presented are based on one year of data taking with a 10 string ANTARES detector. The final detector design was defined after the analyses were performed and comprises 12 strings. Indications are that this will improve the sensitivity by $\sim$ 10%. Conservative estimations of the atmospheric neutrino background, including prompt neutrinos, have been assumed. The full impact of the trigger, fake signals formed by the optical background and the background due to wrongly reconstructed atmospheric muon bundles remains to be studied, although the contribution of the latter has already been shown to be small compared to the atmospheric neutrino background using a simulated sample of atmospheric muon bundles equivalent to $\sim$ 10 days.

The expected sensitivity for discovering a point source with a spectrum proportional to E^{-2} anywhere in the observable sky is shown in Fig. 2 as a function of declination. This all-sky discovery sensitivity is defined as the flux that is needed to give a 50% probability of discovery at the indicated confidence levels.

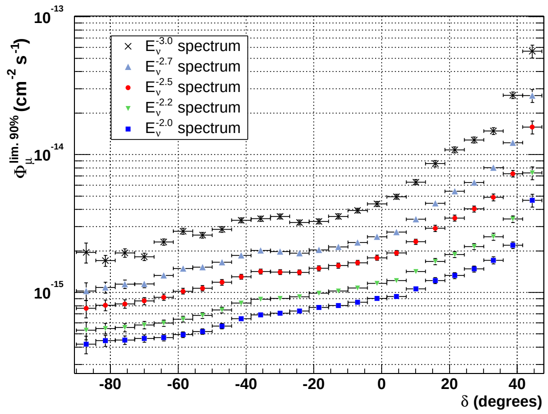

Fig. 3. Average 90% confidence level exclusion limit that may be set on the flux of muons under the assumption that the muons are produced by a point source of neutrinos with a power-law energy spectrum. Results for different values of the spectral index are given as a function of declination (obtained with the grid method).

If, in a particular direction, no source is discovered, an upper limit can be set on the flux from that direction. This limit can be expressed in terms of the muon flux that would have been produced at the detector if a neutrino source would have been present in the bin. Due to the energy dependence of the neutrino cross-section and the detector acceptance, this quantity depends on the spectrum of the hypothetical neutrino flux. The average upper limit that can be expected to be set for each individual bin after one year is given in Fig. 3 as a function of the declination.

4. Conclusions

Due to its good angular resolution, ANTARES could reach in one year a sensitivity for muon fluxes from cosmic neutrino sources lower than 10^{-15} cm^{-2}s^{-1}, which is better than the already achieved sensitivity by other experiments and comparable to what AMANDA-II expects to achieve after 600 live-days [1]. The discovery potential for sources with the generic E^{-2} spectrum has been presented in terms of the neutrino flux that can be discovered.

References

1. Barwick S. 2002, SPIE Conf., Kona, Hawaii
2. Montaruli T., *ANTARES status report*, this conference
3. Romeyer A. et al., *Muon energy reconstruction in ANTARES and its application to the diffuse neutrino flux*, this conference