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First combined search for neutrino point-sources in the southern sky with the ANTARES and IceCube neutrino telescopes

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Abstract. A search for cosmic neutrino point-like sources using the ANTARES and IceCube neutrino telescopes over the Southern Hemisphere is presented. The ANTARES data were collected between January 2007 and December 2012, whereas the IceCube data ranges from April 2008 to May 2011. An unbinned maximum likelihood method is used to search for a localized excess of muon events in the southern sky assuming an E^{-2} neutrino source spectrum. A search over a pre-selected list of candidate sources has also been carried out for different source assumptions: spectral indices of 2.0 and 2.5, and energy cutoffs of 1 PeV, 300 TeV and 100 TeV. No significant excess over the background has been found, and upper limits for the candidate sources are presented compared to the individual experiments.

1. Introduction

Neutrinos offer unique insight into the Universe due to the fact that they interact only weakly. This also implies that their detection is challenging. The high-energy field is currently led by the IceCube [1] and ANTARES [2] experiments. While the instrumented volume of ANTARES is significantly smaller than that of IceCube, its geographical location provides a better view of the southern sky for neutrino energies below 100 TeV. The complementarity of the detectors for southern sky sources allows for a gain in sensitivity by combining the analysis of data from both experiments in a joint search for point sources. The improvement with this combination depends on the details of the fluxes, in particular the energy spectrum and a possible energy cut-off of the signal.

2. Neutrino data samples

The data sample corresponds to all events from the southern sky which were included in the latest published ANTARES point-source analysis [3] combined with the events in the three-year IceCube point-source analysis [4]. The ANTARES sample corresponds to data recorded from 2007 January 29

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to 2012 December 31. The total number of events in this sample amounts to 5516, of which 4136 are from the Southern Hemisphere. The estimated contamination of mis-reconstructed atmospheric muons is of 10%. The IceCube data was recorded from 2008 April 5 to 2011 May 13, with a total number of 146 018 events in the southern sky. These data were collected within different configurations (40, 59 and 79 strings). These events are predominantly well-reconstructed atmospheric muons rather than atmospheric neutrinos, because the Earth cannot be used to filter out the muon background for down-going events.

3. Search method

An unbinned maximum likelihood has been performed to search for excesses of events. In order to estimate the significance of a cluster, the likelihood takes into account the energy and directional information of each event. The data sample to which an event belongs is also taken into account, due to the differences in detector response and background. The likelihood, as a function of the total number of signal events, n_s, can be expressed as

$$L(n_s) = \prod_{j=1}^{4} \prod_{i=1}^{N^j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j} \right) B_i^j \right], \tag{1}$$

where j indicates one of the four data samples (ANTARES, IC40, IC59 or IC79), i indicates an event belonging to the j-th sample, S_i^j is the value of the signal probability distribution function (PDF) for the i-th event in the j-th sample, B_i^j indicates the value of the background PDF, N^j is the total number of events in the j-th sample, and n_s^j is the number of signal events fitted for in the j-th sample. Since a given evaluation of the likelihood refers to a single source hypothesis at a fixed sky location, the number of fitted signal events n_s^j in each sample is related to the total fitted number of signal events n_s by the relative contribution of each sample, $n_s^j = n_s \cdot C^j(\delta, \frac{d\Phi}{dE})$, which allows us to only fit in the likelihood the total number of signal events. This contribution corresponds to the fraction of signal events expected for the j sample compared to the total for a given source spectrum and declination.

The signal and background PDFs for the IceCube and ANTARES samples have slightly different definitions. The signal PDFs are defined as

$$S^{\mathrm{ANT}} = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\Delta\Psi(\vec{x}_s)^2}{2\sigma^2} \right) P_s^{\mathrm{ANT}}(N^{hits}, \sigma), \quad S^{\mathrm{IC}} = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\Delta\Psi(\vec{x}_s)^2}{2\sigma^2} \right) P_s^{\mathrm{IC}}(\mathcal{E}, \sigma|\delta) \tag{2}$$

where $\vec{x}_s = (\alpha_s, \delta_s)$ indicates the source direction in equatorial coordinates, $\Delta\Psi(\vec{x}_s)$ is the angular distance of a given event to the source, σ is the angular error estimate, and $\mathrm{P}_s^{\mathrm{ANT}}(N^{hits}, \sigma)$ is the probability for a signal event to be reconstructed with an angular error estimate of σ and a number of hits taken in the event reconstruction N^{hits}. The number of hits is a proxy for the energy of the event [5]. In the case of the IceCube signal PDF, the main difference lies in the use of the reconstructed energy, $\mathcal{E}$, and the declination dependence of the probability for a signal event to be reconstructed with a given σ and $\mathcal{E}$.

The background PDFs are obtained from the experimental data itself. The definitions of the PDFs are:

$$B^{\mathrm{ANT}} = \frac{B^{\mathrm{ANT}}(\delta)}{2\pi} P_b^{\mathrm{ANT}}(\mathcal{N}^{hits}, \sigma), \quad B^{\mathrm{IC}} = \frac{B^{\mathrm{IC}}(\delta)}{2\pi} P_b^{\mathrm{IC}}(\mathcal{E}, \sigma|\delta), \tag{3}$$

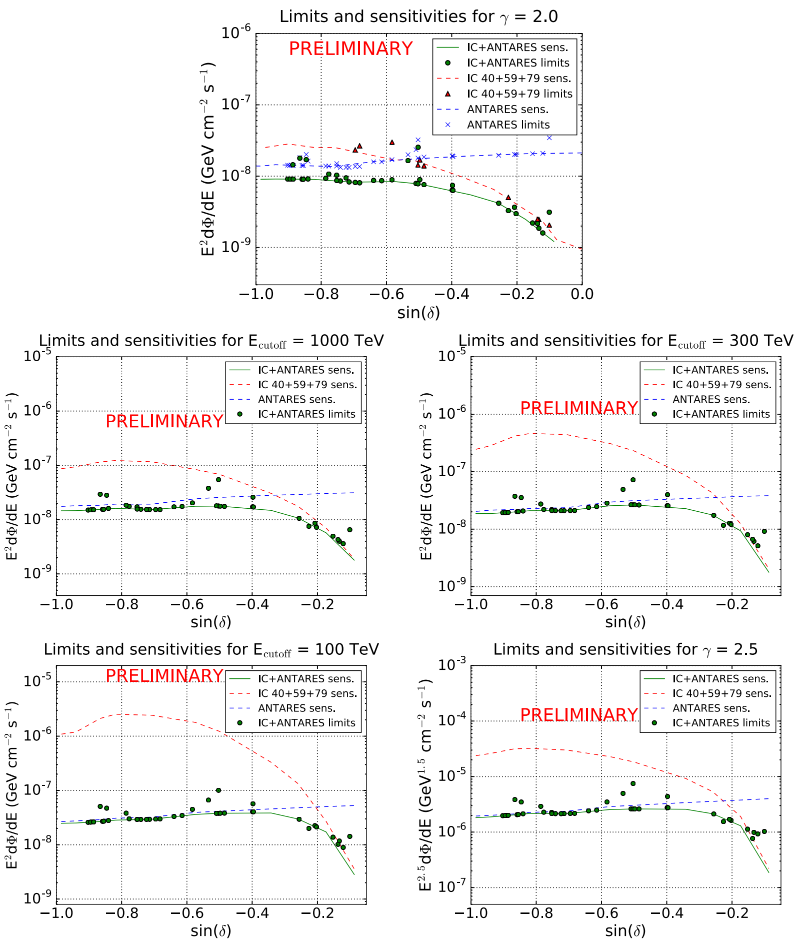

Figure 1. Point source sensitivities and limits for the following energy spectra: unbroken E^{-2} spectrum (top), E^{-2} with a square-root exponential cut-off at $E = 1$ PeV (middle left), $E = 300$ TeV (middle right), $E = 100$ TeV (bottom left) and $E^{-2.5}$ unbroken power-law (bottom right). Green points indicate the limits on the southern sky candidate sources given in Ref. [4] and [3]. The green line indicates the sensitivity for the combined search. Blue and red curves/points indicate the sensitivities for the individual IceCube and ANTARES analyses, respectively.

where B(δ) is the per-solid-angle rate of observed events as a function of the declination in the corresponding sample. $P_b^{\mathrm{ANT}}(\mathcal{N}^{hits}, \sigma)$ and $P_b^{\mathrm{IC}}(\mathcal{E}, \sigma|\delta)$ characterize the distributions for background event properties, in analogy with the definitions of P_s^{ANT} and P_s^{IC} for signal events given above.

The test statistic, *TS*, is determined from the likelihood (Eq. (1)) as $TS = \log L(\hat{n}_s) - \log L(n_s = 0)$, where $\hat{n}_s$ is the value that maximizes the likelihood. The p-value is calculated as the probability of the background to produce a TS of equal or higher value and becomes smaller for larger TS.

Two different searches for point-like neutrino sources have been performed. In the candidate list search, a possible excess of neutrino events is looked for at the location of 40 pre-selected neutrino source candidates.These candidates correspond to all sources in the southern sky considered in the previous candidate-source list searches performed in the ANTARES and IceCube point-source analyses [3, 4]. The second search is a "full sky" search, looking for a significant point-like excess anywhere in the southern sky.

4. Results

No significant event clusters are found over the expected background. The most significant cluster in the full southern sky search is located at equatorial coordinates $\alpha = 332.8^\circ, \delta = -46.1^\circ$, with best-fit $\hat{n}_s = 7.9$ and pre-trial p-value of 6.0×10^{-7}, with a post-trial significance of 24% (0.7σ in the one-sided sigma convention). The direction of this cluster is consistent with the second most significant cluster in the previous ANTARES point-source analysis (but also less significant).

No statistically significant excess is found in the candidate source list search. The most significant excess for any object in the list corresponds to HESS J1741-302 with a pre-trial p-value of 0.003. To account for trial factors, the search is performed on the same list of sources using pseudo data-sets. 11% of randomized data sets have a smaller p-value for some source than that found for the real data; the post-trial significance of the source list search is thus 11% (1.2σ in the one-sided sigma convention).

Figure 1-top shows the sensitivities and limits for this search (assuming an E^{-2} spectrum) in comparison with the previously published ANTARES and IceCube analyses of the same data. The point source sensitivity in a substantial region of the sky, centered approximately at the declination of the Galactic Center ($\delta = -30^\circ$), can be seen to have improved by up to a factor of two. Similar gains in other regions of the sky can be seen for different energy spectra in Fig. 1.

5. Conclusion

We have presented the first combined point-source analysis of data from the ANTARES and IceCube detectors. We have calculated the sensitivity to point sources and, with respect to an analysis of either data set alone, found that up to a factor of two improvement is achieved in different regions of the southern sky, depending on the energy spectrum of the source. Two joint analyses of the data sets have been performed: a search over the whole southern sky for a point-like excess of neutrino events, and a targeted analysis of 40 pre-selected candidate source objects. The largest excess in the southern sky search has a post trial p-value of 0.24 (significance of 0.7σ). In the source list search the candidate with the highest significance corresponds to HESS J1741-302, with a post-trial p-value of 0.11 (significance of 1.2σ). Both of the results are compatible with the background-only hypothesis and no significant excess is found. Flux upper limits for each of the source candidates have been calculated for E^{-2} and $E^{-2.5}$ power-law energy spectra, as well as for E^{-2} spectra with cut-offs at energies of 1 PeV, 300 TeV, and 100 TeV. Because of their complementary nature, with IceCube providing more sensitivity at higher energies and ANTARES at lower energies, a joint analysis of future data sets will continue to provide the best point-source sensitivity in critical overlap regions in the southern sky, where neutrino emission from Galactic sources in particular may be found.

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