IceCube/AMANDA combined analyses for the search of neutrino sources at low energies

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***Abstract*. During the construction of IceCube, the AMANDA neutrino telescope has continued to acquire data and has been surrounded by IceCube strings. Since the year 2007, AMANDA has been fully integrated for data acquisition and joint IceCube/AMANDA events have been recorded. Because of the finer spacing of AMANDA phototubes, the inclusion of AMANDA significantly extends the detection capability of IceCube alone for low energy neutrinos (100 GeV to 10 TeV). We present the results of two analyses performed on the 2007-2008 Icecube (22 string) and AMANDA data. No evidence of high energy neutrino emission was observed; upper limits are reported.In 2008-09, IceCube acquired data in a 40 string configuration together with the last year of operation of AMANDA. Progress on the analysis of this new combined IceCube/AMANDA sample are presented as well. In addition, a novel method to study an extended region surrounding the most active parts of Cygnus with these datasets is described here.**

***Keywords*: Neutrino astronomy, galactic sources, IceCube, AMANDA, DeepCore**

I. Introduction

Recent detections by Cherenkov telescopes provide evidence of particle acceleration up to TeV energies in astrophysical sources [1]. The TeV γ-ray emission from these sources could arise from the acceleration of electrons (production of γ-rays via inverse Compton scattering) or the acceleration of hadrons (production of γ-rays through the decay of neutral pions produced in pp/pγ interactions). In the later scenarios, the γ-ray production would be accompanied by the neutrino production since charged pions, like neutral pions, would be generated and decay within the source. The detection of high-energy neutrinos would thus be an unambiguous proof for the acceleration of hadrons in these sources. In particular, galactic TeV γ-ray sources present the bulk of their γ-ray emission at energies lower than a few TeV. The spectrum from these sources is soft with a typical spectral index ($|\Gamma| > 2$) and often exhibits an exponential cut-off at a few TeV. Both observations suggest a break in the neutrino spectrum below 100 TeV. Accordingly, the flux from these sources would differ from the standard spectral index of -2 for neutrino sources. Additionnaly, they represent “low energy” sources (TeV) for IceCube and would be challenging to detect. To enhance the sensitivity to this type of sources, an analysis comprising both the IceCube and the AMANDA detector has been performed. The higher density of optical modules in AMANDA than in IceCube provides a sufficient increase in the number of hits that reconstruction of low energy, neutrino-induced events is possible. This increase in statistics particularly benefits searches for sources with steeply falling spectra (see Sec. III and Sec.IV). A first analysis has been made using the 22 string configuration of IceCube in combination with the AMANDA detector; the results are presented in this proceeding. A new sample of data has been collected with IceCube-40 and AMANDA and is under analysis. We present here the general scheme for this analysis, with particular emphasis on a specific development to enhance the detection sensitivity for extended active regions in the galactic plane.

II. Galactic sources : the γ-ν connection

Since neutrino and γ-rays are expected to be produced together in hadronic acceleration processes, the neutrino spectrum can be inferred from the observed γ-ray spectrum of the source by a two-step procedure:

1 - The γ-ray spectrum from a source is fitted assuming a pp interaction model obtained using the parametrizations given in [4]. Possible γ-ray absorption is estimated and corrected for before the fit.

2 - With the obtained proton distribution and the target density, the expected neutrino spectrum is estimated.

The Crab Nebula γ-ray energy spectrum has been measured in details by the H.E.S.S. experiment [8]. It is described by a power law with spectral index (Γ) of -2.4 and has a γ-ray energy cutoff at $\sim$14 TeV. Although numerous arguments attribute the γ-ray production from this source to e^+/e^- acceleration, its status as a standard candle argues for its use as a reference for neutrino astronomy. Moreover, the establishment of sufficiently low upper limits by IceCube on the neutrino emission could bring new constraints on the possible hadron acceleration at this source. Assuming that γ-rays from the Crab Nebula originate from hadronic processes (decay of π^0 mesons generated from pp interactions at the source) and that their absoption is negligible, the ν spectrum obtained is:

$$\Phi = 3 \times 10^{-7} e^{-E/7\mathrm{TeV}} (E/\mathrm{GeV})^{-2.4} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1} \quad (1)$$

In the following, we use this computed spectrum as a reference ("Crab Nebula spectrum") to estimate the sensitivity of analyses to low energy sources.

III. ICECUBE-22/AMANDA: RESULTS

During the two deployment seasons 2003-2004 and 2004-2005 at the South Pole, the data acquisition system (DAQ) of AMANDA was significantly upgraded to provide nearly deadtime-less operation and full digitization of the electronic readout [2]. This was achieved by using Transient Waveform Recorders (TWR). The new DAQ system allowed for the reduction of the multiplicity trigger threshold and, consequently, of the energy threshold to $\sim$50 GeV. By being optimally sensitive to neutrinos under 1 TeV, AMANDA thus complements IceCube well and was integrated into the full IceCube analysis starting in January 2006.

A. Data sample and methods

The IceCube 22-string run represents 276 days taken between May 2007 and April 2008. Within this period, the AMANDA detector was taking jointly with IceCube for 143 days. Nevertheless, since the 2006-07 deployment season, every time the AMANDA detector is triggered, a readout request is sent to the IceCube detector. Events are then merged for processing. The trigger rates are strongly dominated by downgoing, atmospheric muons produced in cosmic ray air showers above the detector. They outnumber atmospheric neutrinos by a factor $\sim 10^6$. This background is largely eliminated by limiting the analysis to upgoing muons using a fast reconstruction algorithm which is applied to all of the data. The selected events are then further pared down by applying a cpu-intensive, likelihood-based reconstruction algorithm that accounts for the properties of the ice and then cutting on the fit direction and fit quality parameters. In this analysis, these cuts were optimized to obtain the best discovery potential for a source with a "Crab Nebula" spectrum (Eqn. 1). As low energy events are mainly due to the dominant atmospheric neutrino background, a significantly larger number of events is obtained with this selection than with other IceCube-22 point source searches [12].

In total, 8727 events are selected, of which 3430 are combined IceCube/AMANDA events. Despite the smaller size of AMANDA (1/6 of the volume of IceCube-22) and its shorter livetime (less than 60% wrt. IceCube-22), the contribution of AMANDA to the combined detector sample, particularly at low energies, is clearly visible in the energy distribution simulated atmospheric neutrinos retained at the final event selection in the analysis (Fig. 1). As a consequence, the sensitivity achieved with this approach for a source with a spectrum similar to the one expected for the Crab Nebula (Γ=-2.4; cut-off at 7 TeV) is better than the one achieved with the IceCube only analysis (Fig. 2). Even though, for a harder spectrum (Γ=-2;no cutoff), the standard IceCube only analysis remains better adapted.

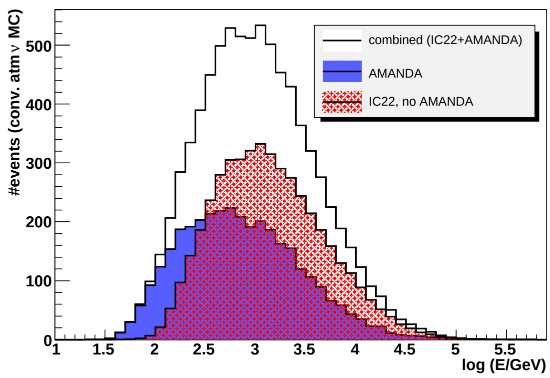

Fig. 1. Event energy distribution for simulated atmospheric neutrinos at the final level of the galactic point source analysis normalized to the livetime of the IceCube 22 strings data taking (276 days) for IceCube only events and to the combined IceCube+AMANDA livetime (143 days) for the AMANDA and combined events.

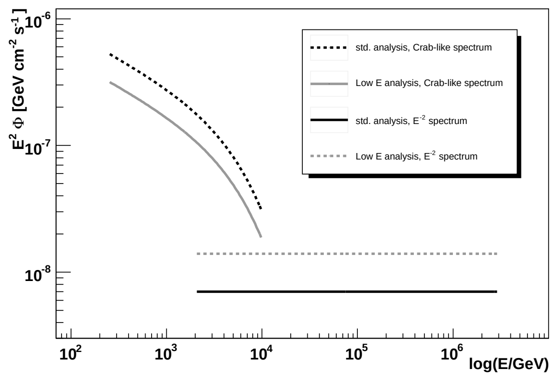

Fig. 2. Sensitivity for a source spectrum with Γ=-2 and a "Crab" spectrum (Γ=-2.4; cut-off at 7 TeV). This analysis (gray) is compared to the standard IceCube only analysis (black).

B. Search on an a priori selected list of point sources

With this dataset, a search for neutrino emission was performed for a list of four, preselected sources: the Crab Nebula, Cas A, SS 433 and LS I +61 303. For three of them, the γ-ray spectrum is known ([8]-[11]), so we optimized the analysis for the expected corresponding neutrino spectrum (for SS 433, which has no measured γ-ray spectrum, the optimisation was made with respect to a test spectrum with a spectral index Γ=-2.4 and a cut-off at 7 TeV). The test-statistic for the analysis is the log likelihood ratio of the signal hypothesis with best fit parameters to the pure background hypothesis. This method is widely used in IceCube [7]. This test-statistic provides an estimate for the significance of a deviation from background (pre-trial p-value) at a position in the sky. The post-trial p-value is then determined by applying the analysis to randomized samples. With this method, the lowest pre-trial p-value (p=0.14) was obtained for the Crab Nebula. This p-value or a lower one can be achieved in 37% of randomized samples. This excess is therefore not significant. The number of signal events detected and their associated pre-trial p-values are summarized in the table below. Based on the γ-ray observations, the expected neutrino spectral index and possible cut-off energies have been calculated using the method described in Sec. II and are indicated in the same table.

Source	Γ_ν	ν cut-off	Nb. of signal events	p-value (pre-trial)
Crab Nebula	-2.39	7 TeV	3.3	0.14
Cas A	-2.4	-	-1.9	0.65
SS433	-	-	-0.9	0.67
LSI+61 303	-2.8	-	-0.4	0.47

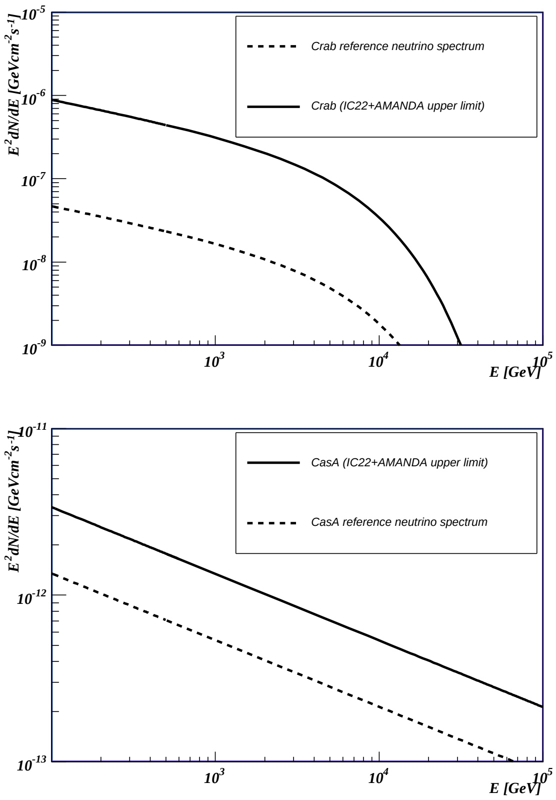

Fig. 3. *Top:* Crab upper limit obtained for this study compared to the reference neutrino spectrum computed for the Crab as in section II using [4] for modeling. *Bottom:* Cas A upper limit obtained for this study compared to its reference neutrino spectrum.

Upper limits on the neutrino flux were derived from the number of events observed in the direction of the different sources with this analysis. The limits obtained for the Crab Nebula and Cas A are presented in Fig. 3 and compared to their expected neutrino spectrum. The limit that can be set by this IceCube-22/AMANDA analysis is for example for the Crab Nebula a factor 18.9 above the expected reference spectrum. This calculation was also made for the case of Cas A (Fig. 3, bottom). This source was detected by HEGRA up to 10 TeV without evidence of high energy cut-off [9]. We extrapolate the power-law γ-ray spectrum given in [10] up to higher energies.

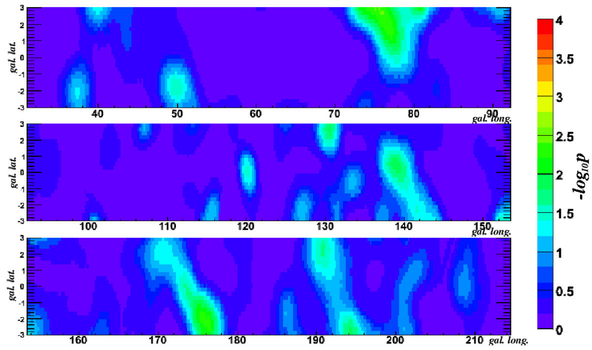

Fig. 4. Galactic plane scan (longitude : 31.5° $<$ l $<$ 214.5°, latitude : -3° $<$ b $<$ 3°) pretrial significance map for IceCube-22/AMANDA. The strongest excess at l=75.875°, b=2.675° (pre-trial p-value = 0.0037). 95% of randomized datasets yielded a more significant excess.

C. Galactic plane scan

In addition to these sources, we performed an unbinned point source search of the galactic plane in the nominal field of view of IceCube (longitude : 31.5°<l<214.5°, latitude -3°<b<3°). The result of this search is shown Fig. 4. The most significant deviation from background observed in this galactic plane unbiased search is seen at l=75.875°, b=2.675° in galactic coordinates. The pre-trial p-value at this location is 0.0037. For 95% of the randomized datasets (reproducing a pure background hypothesis) an equal or lower probability is found and thus the observed excess is not significant.

IV. ICECUBE-40/AMANDA: EXPECTATIONS

A. Data sample

For the dataset acquired between April 17, 2008 and February 2nd 2009 with the IceCube 40 strings configuration, the total livetime of the IceCube was 268.7 days, and the AMANDA sub-detector performed much better than for the 2007/8 season with a total livetime of 240 days on the same period, corresponding to almost 90% of the IceCube livetime. As a consequence, even with the doubling of the size of IceCube, the relative number of combined IceCube-40/AMANDA events compared to the IceCube-40 only events remain comparable to the ratios obtained with the IceCube-22/AMANDA dataset. The data is still under processing for the selection of neutrino candidates and final exploitation will be made in the near future. Beyond replicating the galactic plane scan and the search for the same list of *a priori* selected sources with these new data, we will search for multiple unresolved sources in the Cygnus region applying a new analysis strategy.

B. Extended sources: Multi-Point Source analysis

A particular interest is given to active regions of the galactic plane, where several accelerators might contribute to a possible neutrino signal. The Cygnus region is a very active star-forming region located at

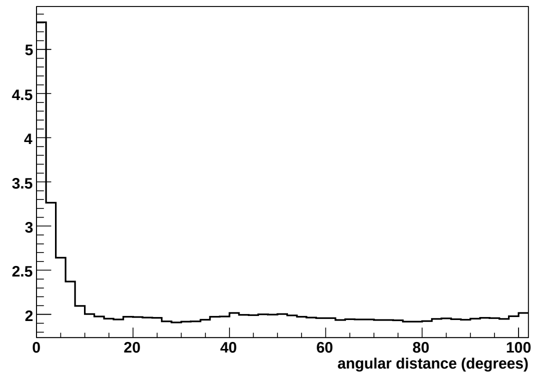

Fig. 5. Number of event pairs (distant of less than 2°) for the signal case divided by the average histogram of random cases with the MPS method for a simulated case presenting 3 sources (yielding each 8 events in the detector) randomly distributed in a region of 11°x7°.

galactic longitude 65° < l < 85°. Recently, the Milagro collaboration measured both a diffuse TeV γ-ray emission and a bright, extended TeV source [5]. These observations suggest the presence of cosmic rays sources which accelerate hadrons that subsequently interact with the local, dense interstellar medium to produce γ-rays and possibly neutrinos through pion decay. Estimates of the neutrino emission from the zone of diffuse γ-ray emission are reported in [6].

The current point source search method is optimized for resolveable sources. However, to study extended regions like the Cygnus region, this method is not optimal. A better analysis for these cases takes advantage of the possibility of clustering of neutrino events in the totality of the region to improve the detection probability. In this multi-point source (MPS) analysis, we construct a two-point correlation function in which each neutrino candidate that pointed inside the region of study is paired with all other neutrino candidates. A test statistic is then obtained from the number of "close" pairs for which the angular separation is at most 2 degrees, the bin size for achieving the best signal to noise ratio (for IceCube-22/AMANDA data). An excess in the number of these close pairs would indicate an emission from astrophysical sources in the chosen region. This method is sensitive not only to clustered signal that would come from a single source, but also would take advantage of the presence of a diffuse signal.

To illustrate the potential of this method, we give an example of its performance for the IceCube-22/AMANDA configuration. Using the point-spread function obtained from the data (median value: 1.5°), we inserted simulated neutrino events from three possible sources in the IceCube-22/AMANDA dataset. Each simulated source yielded eight events in the detector and was positioned randomly within a region of 11°x7° centered around Cygnus. Fig. 5 shows the histogram of event pairs for the signal case divided by the average histogram of random cases. The first bin thus corresponds to the excess of "close pairs". In order to evaluate the significance associated with this excess, the number of close pairs in 10^7 scrambled sky maps is used. The excess obtained in this example has a p-value of 3×10^{-7}, corresponding to a 5σ detection. For the same configuration, the standard point source analysis [12] is less sensitive as it would require 11 events from each of the sources to reach a detection at the 5σ level (instead of just 8). This analysis will be applied to the unblinded data for IceCube-22/AMANDA and IceCube-40/AMANDA in the near future. For IceCube-22/AMANDA, we will use a region surrounding the most active sources observed by Milagro on Cygnus to define our primaries (72° < l < 83°; -3° < b < 4°).

V. CONCLUSION AND OUTLOOK

Numerous galactic sources observed with γ-rays present a soft spectrum and possibly a cut off at an energy E <100 TeV. Under the hypothesis that acceleration of hadrons explains the γ-ray emission, the associated neutrino spectrum should exhibit a similar cut-off. The merging of the AMANDA and IceCube detector offers an enhancement in sensitivity for the search for these sources. The results of the IceCube-22/AMANDA configuration show no significant excess either for a systematic galactic plane scan on the parts visible for IceCube or for a list of *a priori* selected sources. The data acquired with the IceCube-40/AMANDA configuration are under study and an additional analysis allowing the investigation of the extended Cygnus region will be added. The AMANDA detector, which was shut down on May 15, 2009 as part of the startup of the physics run for the IceCube 59-string configuration detector, paved the road for the development of a nested, higher granularity detector array within IceCube. A new detector array of this type, called "IceCube DeepCore", is under construction [13]. It will consist of at least six strings instrumenting the deep ice (below 2100m) deployed in the center of IceCube and will be completed during the 2009-2010 deployment season.

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