Mid Term Report

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Support Number:	VH-NG-205
Topic:	Multi-messenger study of point sources of cosmic rays including data from IceCube
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Search for point sources of neutrinos with IceCube

1. **Up-going searches (Northern Sky – energy range from TeV to PeV)**

IceCube is half-way constructed. Nine in-ice strings (IC-9) recorded data in 2006-2007 and the first 22 in-ice strings (IC-22) from May 2007 to April 2008. Forty strings (half array) are operational since May 2008 and the next season, 56 are expected.

Last year, the YIG worked on the analysis of data collected with 22 strings (hereafter called IC-22). In particular, delivered a neutrino selection and a search for point sources, based on a so called "binned" method, in which data is compared with background expectation within angular search bins of fixed size. An independent analysis was performed in Madison, based on an un-binned method (maximum likelihood approach). Due to binning, the former is expected to exhibit lower discovery potential, at the advantage of higher robustness against the systematic uncertainties (a modeling of signal properties if required by un-binned analyses). The two analyses were carried out in parallel and independently, in order to gain most benefit for mutual cross-check and stability of the results. 256 days of data were used (after data quality selection). The neutrino effective area and the sensitivity for the two analyses (binned and un-binned) are shown in Fig. 1. 2956 and 5114 events were selected, respectively buy the binned and un-binned analysis.

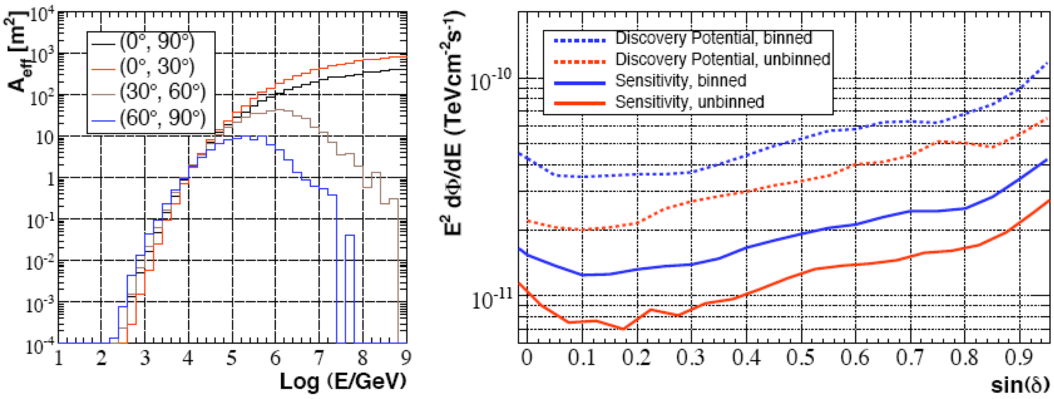

FIGURE 1: Left: Effective area of IceCube with 22 strings versus energy and declination. The decrease at high energies for vertical tracks is due to absorption of neutrinos in the Earth. Right: Sensitivity (average flux upper limit in case of no signal, at 90% CL) and discovery potential (minimum flux delivering a 5σ detection with 50% probability) for the binned (blue) and un-binned (red) analysis. The latter shows better performance, due to event weighting including the angular reconstruction error and a simple energy estimator, at the expenses of higher model dependency. The systematic uncertainty is not included.

Two tests were performed: a search for excesses on a list of pre-selected directions (source catalog including 28 objects, mostly Blazars) and an un-biased scan of the entire Northern Sky. In either case a significant deviation from the background expectation was found. Details of the test of pre-selected sources are given in Table 1 and the significance maps from the Northern Sky are shown in Fig. 2 (binned analysis) and Fig. 3 (un-binned analysis). The largest deviation was found by the un-binned analysis, with a pre-trial p-value of 0.7%. After correcting for trial factors arising from multiple tests (catalog and un-biased scan), the background probability of a similar or higher deviation is 1.3%, consistent with no signal.

A third independent analysis was carried out within the IceCube Collaboration using the IC-22 data set and including events triggered by the AMANDA array. This analysis was optimized for low-energy spectra (i.e. more suitable for testing galactic sources) and a scan of the portion of the Galactic Plane visible in the Northern Sky was performed. Also in this case no excess due to cosmic neutrinos was found. From the results of these three analyses, we conclude that no indication of cosmic signal was found on IC-22 data [C. Finley et al, TevPa08, Beijing/China (2008), J. Bazo et al. arXiv:0811.4110, E. Bernardini et al. arXiv:0901.1049].

TABLE 1. Pre-trial p-values from the binned and un-binned analysis of a pre-defined catalog of 28 sources (preliminary). Sources were selected based on evidence for non-thermal emission. In bold are marked the respective highest excesses.

	binned	un-binned*
MGRO J2019+37	0.51	0.25
MGRO J1908+06	0.90	*
TeV J2032+4130	0.81	*
SS 433	0.66	0.32
Cyg X-1	1.00	*
LSI +61 303	0.80	*
GRS 1915+105	0.20	*
XTE J1118+480	1.00	0.08
GRO J0422+32	0.15	*
Geminga	0.51	*
Crab Nebula	**0.10**	*
Cas A	0.54	*
Mrk 421	0.82	*
Mrk 501	0.48	*
1ES 1959+650	0.57	**0.07**
1ES 2344+514	0.19	*
H 1426+428	1.00	*
1ES 0229+200	0.81	*
Bl Lac	0.80	0.37
S5 0716+71	0.62	0.31
3C66A	0.77	0.31
3C454.3	0.13	*
4C38.41	0.51	*
PKS 0528+134	1.00	*
3C 273	0.88	0.37
M87	0.68	*
NGC 1275	0.49	0.21
Cyg A	0.19	*

* Negative excesses not treated by the un-binned analysis.

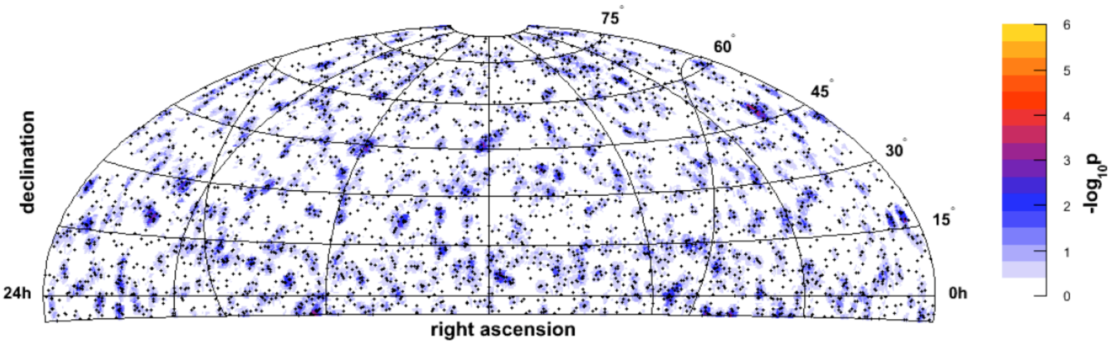

FIGURE 2. Pre-trial significance sky map from the binned analysis (preliminary).

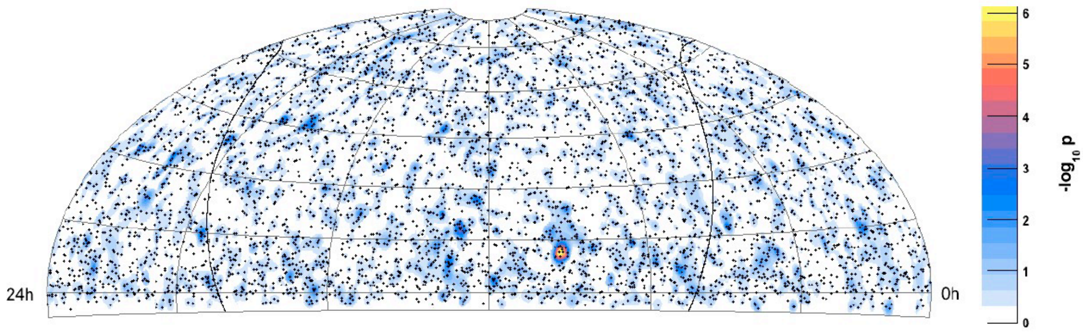

FIGURE 3. Pre-trial significance sky map obtained with the un-binned analysis (preliminary).

2. Extended search for point sources (All Sky – energy range from TeV to EeV)

Last year, the YIG group worked on the establishment of a new approach, able to extend the sensitivity of IceCube to point sources of neutrinos in the Southern Sky. This analysis is challenged by the overwhelming background of muons produced in interactions of cosmic rays in the Earth's atmosphere ("atmospheric muons"). $O(10^9)$ events per year are collected from atmospheric muons, while only $O(10^3)$ are stemming from atmospheric neutrinos. This compares to a few events per year at most, expected from a neutrino point source. In order to cope with such a high background rate, this analysis focused at the highest energy (above few PeV) where this background is expected to drop-off. On the other-hand only neutrinos from the Sourthern sky can be detected at these high energies, due to the very large cross-section, which makes the Earth opaque to multi-PeV neutrinos. Both aspects combined (background rate and neutrino interaction probability) make it possible to extend the window of sensitivity of IceCube to the Southern Sky by selecting multi-PeV neutrinos.

In addition to developing a new event reconstruction and selection adequate to multi-PeV neutrinos, we worked out an analysis approach able to combine both energy and angular window in one single analysis. The method was very successful and allowed us to test regions previously un-accessible (including the Galactic Center and a region, around the AGN Centaurus A, of high density of cosmic rays as detected by Auger). The sensitivity of this analysis is shown in Fig. 4. 1885 events were selected.

Also in this case two tests were performed: a search for excesses from a catalog of pre-selected objects (29 sources) and a scan of the full-sky. The source pre-selection was based mostly on source luminosity at GeV energies as detected by EGRET and Fermi, and was motivated by the Proton Blazar Model (A. Muecke et al 2003). No significant deviation from the background expectation was found on data collected with 22 strings (details in Fig. 5).

No similar work had been attempted before to extend the region of sensitivity of IceCube, beside the prototype analysis developed in 2007 by the YIG on AMANDA data. The results obtained with 22 strings of IceCube represent a very encouraging success: not only is the feasibility of one combined all-sky analysis proven, but the best limits to point source are extracted also for the Southern Sky, before the advent of the Mediterrenean array (Antares). The Sky visibility was extended to -40 deg in declination (40 degrees more compared to previous analyses) and a further extension will be attempted with data collected with 40 strings.

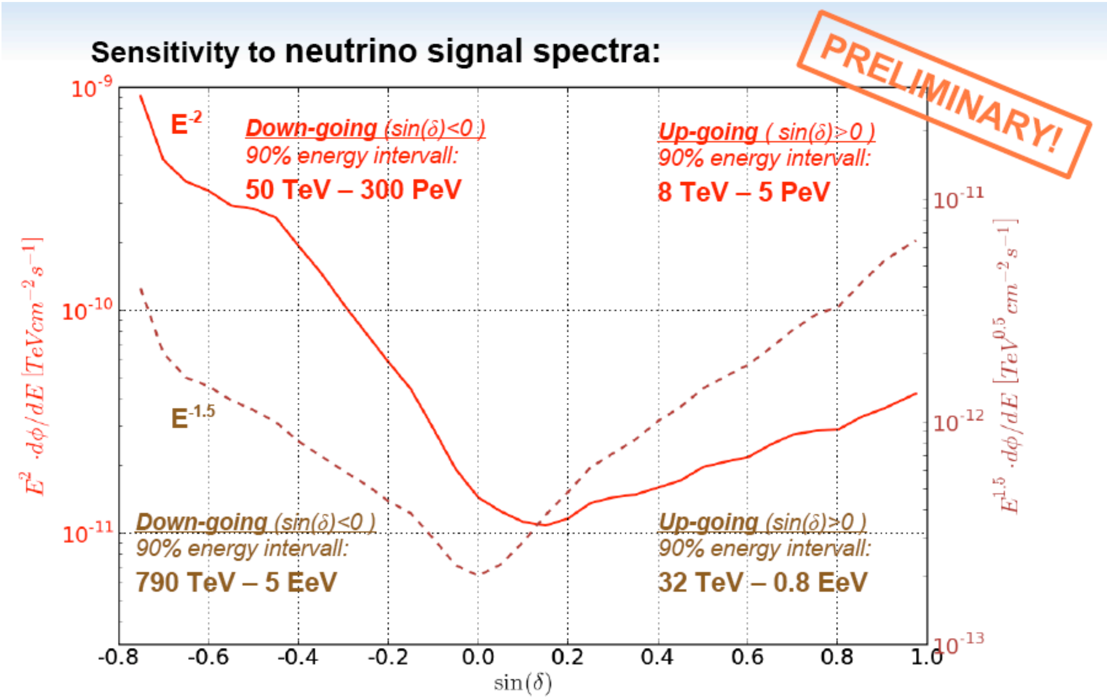

FIGURE 4: Sensitivity to point sources of neutrinos with 22 strings of IceCube, obtained by the multi-PeV analysis, for power-law energy spectra with index 2 (red, continuous line) and 1.5 (brown, dashed line) respectively. The sensitivity to the Northern sky obtained with spectral index 2 (marked "Up-going" on this figure) is comparable to the other two analyses reported here. Totally innovative is the extension of the sensitivity to the Southern Sky (marked "Down-going" on this figure) and to multi-PeV energies.

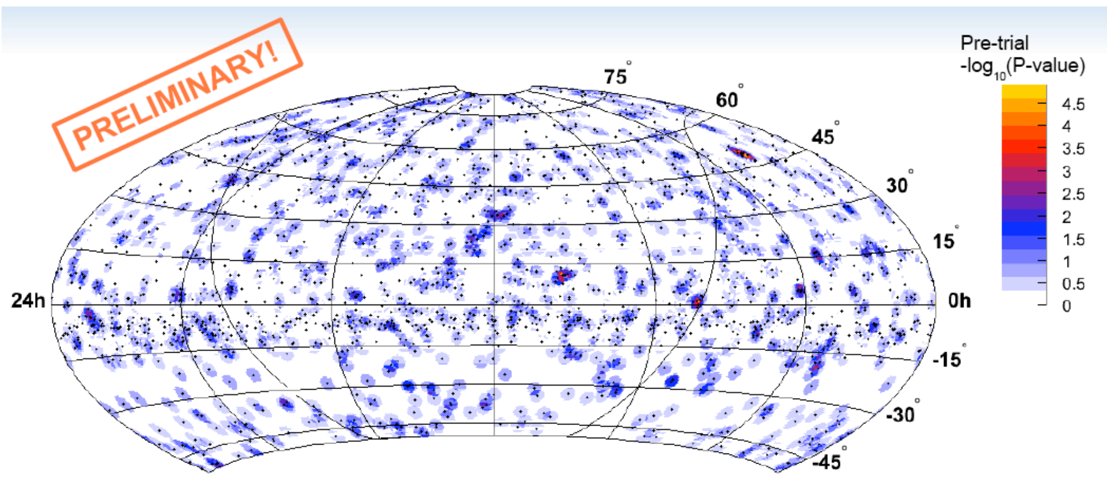

FIGURE 5: Significance map, given as $-\log_{10}$(p-value), obtained by the extended search for point sources of neutrinos. The maximum deviation from the expected background has a pre-trial p-value of 2.9 10^{-5}, corresponding to a post-trial probability of 35%. This map is consistent with background fluctuations.

3. On-line neutrino selection for gamma-ray follow-up

An independent work of the YIG is dedicated to the development of on-line analyses aiming at providing a prompt selection of neutrinos to trigger gamma-ray follow-up observations (by MAGIC) of interesting neutrino events. In the year 2008, the YIG group developed a system to monitor on-line the stability of the detector, based on trigger and event filtering data rates. The system has proven to be very stable and also capable of providing a preliminary prompt data quality selection. Compared to off-line data quality selection of data with 40 strings, the algorithms developed showed very high efficiency in identifying periods of malfunctioning of the detector. The system will be fully integrated in the data processing chain installed at the South Pole and deliver results from data collected with the latest IceCube configuration.

In collaboration with Humboldt University, working in parallel on the development of an optical follow-up system, we designed an event-filter, aiming at selecting neutrino candidates at the South Pole (on-line "level 2").

Gamma-ray Astrophysics with MAGIC

The YIG group contributed to the Cycle IV of MAGIC observations with several proposals, mostly on Blazars, a sub-class of Active Galactic Nuclei (details of such are non-public information). Analysis of data collected so far is in progress. Results already published or presented at conferences are listed below.

1. **Analysis of monitoring observations of Blazars**

The YIG group was involved in the analysis of AGN monitoring data (Markarian 421, Markarian 501 and 1ES1959+650). Part of the data set on Markarian 421 contributed to a multi-wavelength campaign including soft X-rays (Swift and RXTE), hard X-ray and low energy gamma-rays (AGILE) and high energy gamma-rays (MAGIC and VERITAS).
A hard X-ray flare flare of Mrk 421 was detected by Super-AGILE on 2008 June 10 (Costa et al. 2008). This detection was later followed by detection in gamma-rays (Pittori et al. 2008) by the AGILE/GRID (Gamma Ray Imaging Detector) and prompted a ToO observation by Swift/XRT, complementing the ongoing multi-frequency observing campaign of Mrk 421 with WEBT (optical), MAGIC and VERITAS (TeV). This data was also complemented by the public data from RossiXTE/ASM (2-12 keV) and Swift/BAT (15-50 keV). The light-curves are shown in Fig. 6 (I. Donnarumma et al., Astrophys. J. 691 (2009) L13). Taking advantage of the overlapping MAGIC and VERITAS observations, a combined VHE light curve could be derived.

Mrk 421 showed a very interesting broad-band activity during the first half of 2008 June as derived from AGILE data combined with those of WEBT, Swift, MAGIC and VERITAS. Using this data it was possible to derive time-resolved Spectral Energy Distribution (SEDs). The source shows a very interesting time-variable broad band emission that appears to be in overall agreement with a "Self-Syncrotron-Compton" (SSC) model (Ghisellini et al. 1998).

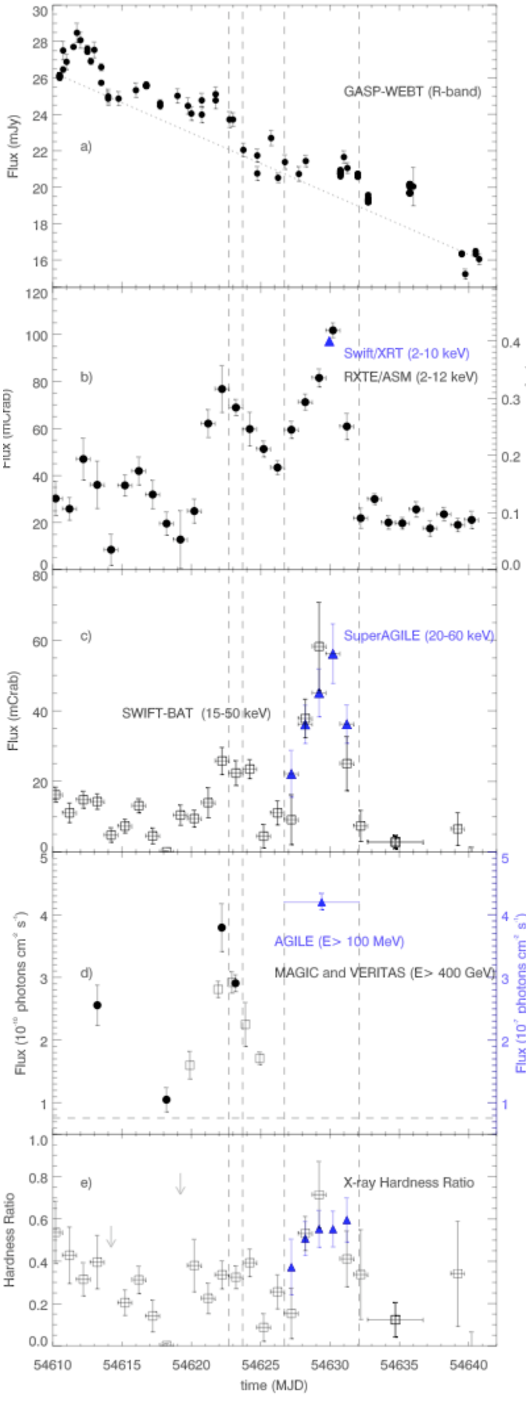

FIGURE 6: a) R-band optical light curve from GASP-WEBT (May 24–June 23); b) ASM (2-12

keV) light curve (bin size is 1 day) and XRT (2-10 keV) flux (blue triangle); c) SuperAGILE (20-60 keV, blue triangles; 1 Crab = 0.2 ph cm−2 s−1) and BAT (15-50 keV, empty black squares; 1 Crab = 0.29 ph cm−2 s−1); d) MAGIC and VERITAS (>400 GeV, empty black squares and black circles, respectively), the Crab flux > 400 GeV (horizontal dashed line), AGILE (> 100 MeV, blue triangle); e) the hardness ratio computed by using the SuperAGILE and ASM data for each day (I. Donnarumma et al., Astrophys. J. 691 (2009) L13).

The YIG also worked on the analysis of Markarian 501 data (monitoring observations and multi-wavelength campaigns). Preliminary light-curves (Fig. 7) were presented at Scineghe 08 (Satalecka et al., AIP Conf. Ser. in press).

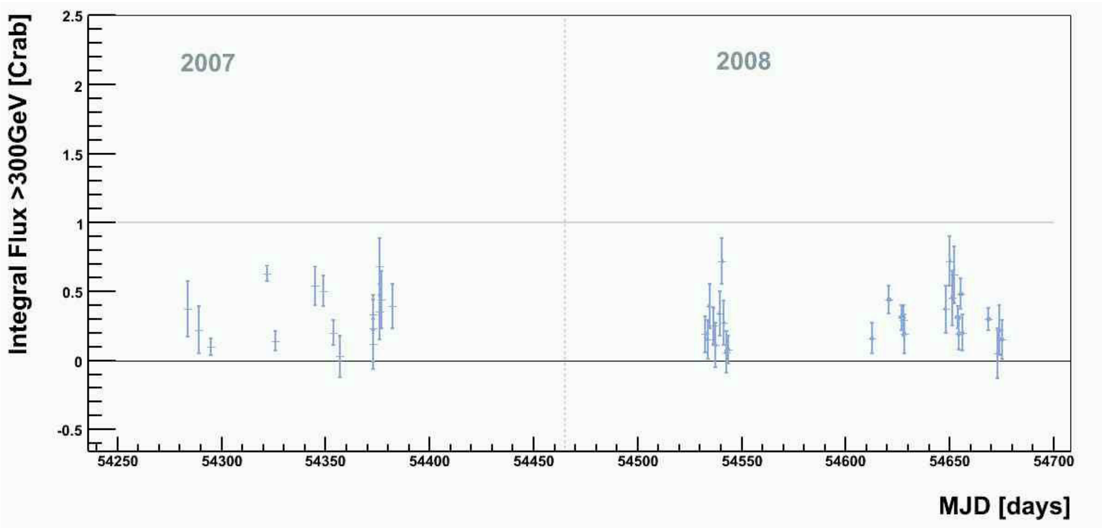

FIGURE 7: a) R-band optical light curve from GASP-WEBT (May 24–June 23); b) ASM (2-12

2. **Historical light-curve collection and analysis for selected Blazars**

Finally, the group continues the activity on the collection and analysis of historical gamma-ray data on selected Blazars ("light-curve collection"). A study of a generalized modeling of the frequency of different states of emission was carried out. Data can be successfully fitted with a gamma-function, with a reasonably stable error estimate. A probability can be now associated to different states of emission (and a statistical confidence level) and this information can used to interpret correlations with neutrinos (for "Neutrino-triggered Target of Opportunity" applications).