Neutrino triggered high-energy gamma-ray follow-up with IceCube

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: We present the status of a program for the generation of online alerts issued by IceCube for gamma-ray follow-up observations by Air Shower Cherenkov telescopes (e.g. MAGIC). To overcome the low probability of simultaneous observations of flares of objects with gamma-ray and neutrino telescopes a neutrino triggered follow-up scheme is developed. This mode of operation aims at increasing the availability of simultaneous multi-messenger data which can increase the discovery potential and constrain the phenomenological interpretation of the high energy emission of selected source classes (e.g. blazars). This requires a fast and stable online analysis of potential neutrino signals. We present the work on a significance based alert scheme for a list of phenomenologically selected sources. To monitor the detector and the alert system reliability, monitoring systems have been implemented on different levels. We show data from the first weeks of running this system.
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1 Introduction

The major aim of neutrino astrophysics is to contribute to the understanding of the origin of high energy cosmic rays. A point-like neutrino signal of cosmic origin would be an unambiguous signature of hadronic processes, unlike γ-rays which can also be created in leptonic processes. The detection of cosmic neutrinos is however very challenging because of their small interaction cross-section and because of a large background of atmospheric neutrinos. Parallel measurements using neutrino and electromagnetic observations (the so-called ”multi-messenger” approach) can increase the chance to discover the first neutrino signals by reducing the trial factor penalty arising from observation of multiple sky regions and over different time periods. In a longer term perspective, the multi-messenger approach also aims at providing a scheme for a phenomenological interpretation of the first possible detections.

The search of occasional flares with a high-energy neutrino telescope is motivated by the high variability which characterizes the electromagnetic emission of many neutrino candidate sources. Recent results obtained by the IceCube Collaboration [1] indicate that high-energy neutrino telescopes have reached a sensitivity to neutrino fluxes comparable to the observed high energy gamma-ray fluxes of Blazars in the brightest states (e.g. the flares of Markarian 501 in 1997 [2] and Markarian 421 in 2000/2001 [3]). With the assumption that the possibly associated neutrino emission would be characterized by a flux enhancement comparable to what is observed in gamma-rays in such states, neutrino flares could be extracted from the sample of neutrino-like events with a reasonable significance.

These astrophysical neutrinos can be searched for in several ways. Here we present a methods for a neutrino point source search that looks for events coming from a restricted angular region, which could be identified with a known astrophysical object. Finding neutrino point sources in the sky means to locate an excess of events from a particular direction over the background of cosmic-ray induced atmospheric neutrinos and muons. These events might present additional features that distinguish them from background, for example a different energy spectrum or time structure. For sources which manifest large time variations in the emitted electromagnetic radiation, the signal-to-noise ratio can be increased by searching for periods of enhanced neutrino emission (a time-dependent search). Of special interest is the relation of these periods of enhanced neutrino emission with periods of strong high-energy γ-ray emission. However, as Imaging Air Cherenkov Telescopes (IACTs) have a small field-of-view and are not continuously operated such correlation studies are not always possible to do after the fact. Therefore it is desirable to ensure the availability of simultaneous neutrino and high-energy γ-ray data for periods of interests. This is achieved by an online neutrino flare search that alerts a partner IACT experiment when a possible neutrino flare from a monitored source is detected.

Such a Neutrino Triggered Target of Opportunity program (NToO) using a list of pre-defined sources was developed already in 2006 using the AMANDA array to initiate quasi-simultaneous gamma-ray follow-up observations by MAGIC [4]. We present here a refined and enhanced implementation using the IceCube neutrino detector.

IceCube is a one cubic kilometer neutrino detector operating in the glacial ice at the geographical South Pole. It consists of 86 strings equipped with 5160 digital optical modules (DOMs). Each DOM contains a photomultiplier tube to detect Cherenkov light of charged ultra-relativistic particles.

2 Neutrino event selection

The basis for the neutrino event selection is an on-line filter that searches for high-quality muon tracks. The full-sky rate of this filter is about 35 Hz for IceCube in its 2010/2011 configuration with 79 deployed strings. This rate is strongly dominated by atmospheric muons. As the computing resources at the South Pole are limited one can not run more elaborate reconstructions at this rate, so a further event selection has to be done. This so called Online Level2 filter selects events that were reconstructed as upgoing ($\theta > 80°$, $\theta = 0°$ equals vertically down-going tracks) with a simple likelihood reconstruction that only takes into account the arrival time of the first photon at each Digital Optical Module. By requiring a good reconstruction quality the background of misreconstructed atmospheric muons is reduced. The parameters used to assess the track quality are the likelihood of the track reconstruction, the number of unscattered photons with a small time residual w.r.t. the Cherenkov cone and the distribution of these photons along the track. The reduced event rate of approximately 3.6 Hz can then be reconstructed with more time intensive reconstructions, like a likelihood fit seeded with different tracks (iterative fit) and a likelihood-fit that takes into account the total number of photo-electrons registered in each module (multi-photoelectron fit). Based on this reconstruction the final event sample is selected by employing a zenith angle cut of $\theta > 90°$ for the multi-photoelectron fit and further event quality cuts based on this reconstruction. These cuts are optimized to achieve a good sensitivity for flares of different time durations. The event selection results in a median angular resolution of $0.48\,°$ for an E^{-2} signal neutrino spectrum, the median resolution for events with $E > 10^6$ GeV is $< 0.4\,°$. For each event an angular uncertainty estimate is calculated.

The resulting event rate compared to the rate of atmospheric neutrinos as predicted by Monte Carlo as a function of zenith angle can be seen in Figure 1.

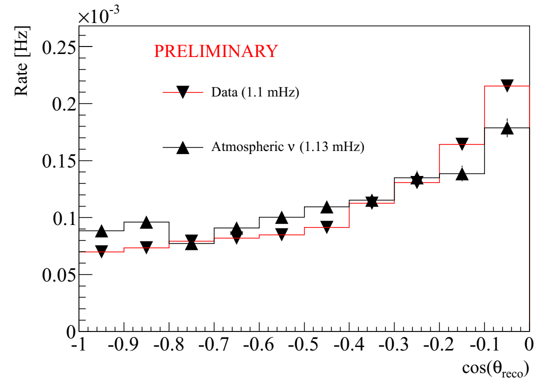

Figure 1: Comparison of the rate of selected events to the predicted rate of atmospheric neutrinos based on Monte-Carlo for IceCube in its 2010/2011 configuration with 79 deployed strings. The atmospheric neutrino prediction is based on the Bartol conventional flux model and the Naumov prompt flux model.

3 The time-clustering algorithm

The timescale of a neutrino flare is not fixed a-priori and thus a simple rolling time window approach is not adequate to detect flares. The time clustering approach that was developed for an unbiased neutrino flare search [6] looks for any time frame with a significant deviation of the number of detected neutrinos from the expected background. The simplest implementation uses a binned approach where neutrino candidates within a fixed bin around a source are regarded as possible signal events. To exploit the information that can be extracted from the estimated reconstruction error and other event properties like the energy an unbinned maximum-likelihood method is under development.

If a neutrino candidate is detected at time t_i around a source candidate the expected background $N^{i,j}_{\text{bck}}$ is calculated for all other neutrino candidates j with $t_j < t_i$ from that source candidate. To calculate $N^{i,j}_{\text{bck}}$ the detector efficiency as a function of the azimuth angle and the uptime has to be taken into account. The probability to observe the multiplet (i, j) by chance is then calculated according to:

$$\sum_{k=N^{i,j}_{\text{obs}}-1}^{\infty} \frac{(N^{i,j}_{\text{bck}})^k}{k!} e^{-N^{i,j}_{\text{bck}}} \qquad (1)$$

where N_{obs} is the number of detected on-source neutrinos between t_j and t_i. It has to be reduced by 1 to take into account the bias introduced by the fact that one only does this calculation when a signal candidate is detected. As typical flares in high energy gamma-rays have a maximal duration of several days we constrain our search for time clusters of neutrinos to 21 days.

If the cluster with the highest significance exceeds a certain threshold (e.g. corresponding to $3\,\sigma$) the detector stability

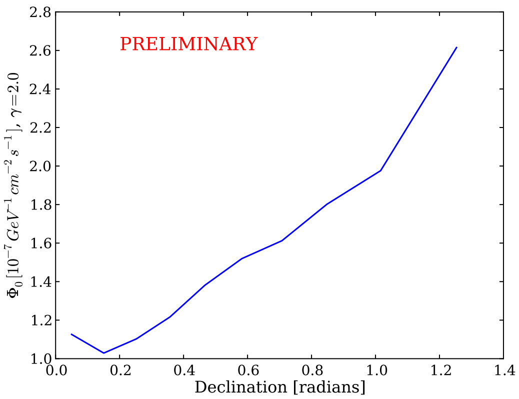

Figure 2: Neutrino flux needed from a given source declination to trigger a flare with a significance of $3\,\sigma$ with a probability of 50%. The neutrino spectrum is assumed to be an unbroken power law with a spectral index of -2.

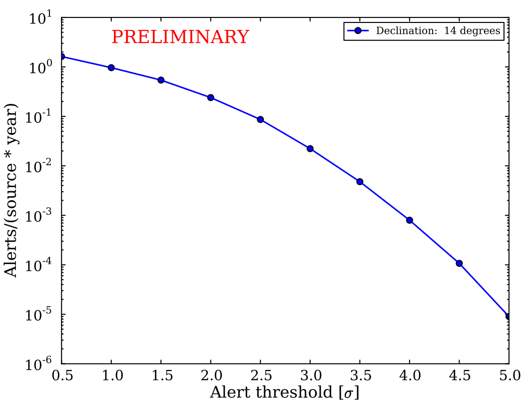

Figure 3: Expected number of accidental background alerts per year for a source at a declination of 14° as a function of the alert threshold expressed in units of standard deviations corresponding to a one-sided p-value.

will be checked and an alert will be sent to a Cherenkov telescope to initiate a follow-up observation. Figure 2 shows the flux needed as a function of declination for a neutrino spectrum with a spectral index of -2 to trigger a flare with a significance of $3\,\sigma$ with a probability of 50 %.

To not overwhelm the partner experiment with follow-up requests one has to know the number of accidental background alerts caused by atmospheric neutrinos. This is shown in Figure 3 as a function of the alert threshold.

4 Stability monitoring

Data quality is very important for any online alert program to minimize the rate of false alerts due to detector or data aquisition (DAQ) instabilities. IceCube has a very extensive monitoring of the DAQ system and South Pole on-line processing. However, most of the information is only available with a certain delay after data-taking and thus not useful for a follow-up program which requires fast alerts. To ensure that alerts are triggered by neutrino multiplets that were detected during stable running conditions a simple but powerful stability monitoring scheme has been developed. It is based on a continuous measurement of the relevant trigger and filter rates in time bins of 10 minutes. These rates are inserted into an SQL database at the South Pole and are generally accessible a few minutes after the respective time bin ended. The rates and ratios of rates relevant for the selection of good quality neutrino-induced muon tracks are compared to an exponential running average of these rates to detect significant deviations. The running average is necessary as slow seasonal changes in the atmosphere and faster weather changes influence the rate of atmospheric muons which dominate the Level-2 rate. This system was tested off-line on data from IceCube in its 59-string configuration and proved to correlate very well with the extensive off-line detector monitoring. The fraction of data that has to be discarded because it was flagged as bad by this method was about 1.6 %.

To generate a sufficient number of alerts to monitor the alert generation and forwarding itself we add 2000 so-called monitoring sources to the sourcelist (see Section 5). They are randomly distributed over the northern sky. To guarantee blindness for these sky locations the alerts for the monitoring sources are generated from blinded data events. The blindness is achieved by using the previous event time in the transformation from detector to sky coordinates for the current event instead of its own time. Due to the low event rate on the order of 10^{-3} Hz this results in a sufficient random shift of the event right ascension.

5 Sources

For a test run of this program we used selection criteria based on FERMI measurements [5]. For the galactic sources we choose sources that were observed in TeV and had a FERMI variability index > 15. Blazars were chosen according to the following criteria:

- Redshift < 0.6
- Fermi variability index > 15
- Spectral index as observed with FERMI < 2.4 (BL Lacs only)
- FERMI flux $1 - 100$ GeV $> 1 \cdot 10^{-9}$ph cm^{-2} s^{-1} (BL Lacs only)
- FERMI flux $0.1 - 1$ GeV $> 0.7 \cdot 10^{-7}$ph cm^{-2} s^{-1} (FSRQs only)

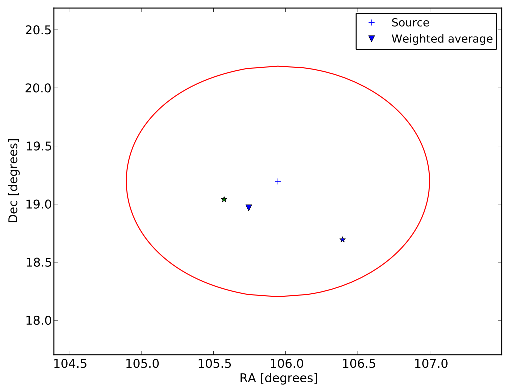

Figure 4: Angular distribution of events (star symbols) for one of the alerts that were generated during a test run of this follow-up program from March, 21st 2011 till May, 13th 2011 (see Section 7). The events contributing to this alert were blinded using the procedure described in this paper. The weighted average of the contributing events is calculated using an event-by-event angular resolution estimator. The circle indicates the size of the on-source bin.

These criteria are motivated by a compilation of different hadronic models that provide the guidelines to identify the most promising neutrino candidate sources. 22 sources (one galactic source, three FSRQs and 18 BL Lac objects) were selected according to these criteria in the northern hemisphere ($\delta > 0$).

6 Technical design of the alert system

After the alerts for this follow-up program are generated at the South Pole they are sent to the University of Wisconsin via the Iridium satellite communication system. This low bandwidth connection allows to send short messages from the South Pole without any significant delay. Once the message arrives in the North it is checked to see whether it represents a real alert or a test alert from a monitoring source. If it is a real alert, the alert is forwarded to the partner experiment. Depending on the technical setup this can happen e.g. via email or a dedicated socket connection.

All alerts (real and test) are filled into a database and a monitoring web page is updated. Each alert can be reviewed and basic information like the coordinates of the contributing events can be inspected. This allows a fast human inspection of alerts, even before the full IceCube event data arrives in the North. For each generated alert the time and space distribution of the contributing events can be inspected (see Figure 4). Furthermore global properties of the alerts, like their rate, significance and time length distribution are plotted and monitored.

The total time delay between the time the (latest) neutrino event is detected by IceCube and the moment it is forwarded to the partner experiment is on the order of several minutes (~ 10 min). This time is dominated by the delay until the detector rate is available in the database and the event processing time in the South Pole system.

7 Testrun results and Outlook

The system described here was tested online with the IceCube 79-string configuration from March, 21st 2011 till May, 13th 2011. During the test run neutrino triggers were generated online but not forwarded to any IACT. 199 alerts were generated during this test run for all sources combined, including the monitoring sources, while 219 where expected for a 52 day period. Besides statistical fluctuations, part of the discrepancy is also due to the limited event history available during the first days of running the program.
We plan to run this neutrino triggered high-energy gamma follow-up program using IceCube in its final 86-string configuration. Several enhancements are possible and planned. A maximum-likelihood based significance calculation taking into account an event-by-event angular reconstruction uncertainty estimation and an energy estimation of the event will further improve the sensitivity to neutrino flares.

References

[1] J.L. Bazo Alba *et al.* for the IceCube Collaboration, Proc. 31st ICRC, 2009, arXiv:0908.4209
[2] F. Aharonian *et al.* , A&A, 1999, **349**: 11-28
[3] F. Aharonian *et al.* , A&A, 2002, **393**: 89-99
[4] M. Ackermann *et al.* , Proc. 29th ICRC, 2005, arXiv:astro-ph/0509330.
[5] The Fermi LAT Collaboration, Astrophys.J.Suppl., 2009, **183**: 46-66
[6] K. Satalecka *et al.* for the IceCube collaboration, Proc. 30th ICRC, 2007