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

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***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 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 minimize the rate of false alerts due to detector instabilities a fast online monitoring scheme based on IceCube trigger and filter rates was implemented.**

***Keywords*: IceCube neutrino gamma-ray follow-up**

I. Introduction

A Neutrino Triggered Target of Opportunity program (NToO) was developed already in 2006 using the AMANDA array to initiate quasi-simultaneous gamma-ray follow-up observations by MAGIC. The aim of such an approach is to increase the chance to discover cosmic neutrinos by on-line searches for correlations with established signals (e.g. flares in high-energy gamma-rays) triggered by neutrino observations. For sources which manifest large time variations in the emitted radiation, the signal-to-noise ratio can be increased by limiting the neutrino exposures to most favorable periods. The chance of discovery can then be enhanced (the so called ”multi-messenger approach”) by ensuring a good coverage of simultaneous data at a monitoring waveband (e.g. gamma-rays). The first realization of such an approach led to two months of follow-up observations of AMANDA triggers by MAGIC, focused on a selected sample of Blazars as target sources [1]. An extension of this program to IceCube and also to optical follow-up observations has been later realized with the ROTSE network of optical telescopes, addressing possible correlations between neutrino multiplets and either GRBs or Supernovae [2].

Multi-messenger studies can be accomplished off-line, searching for correlations between the measured intensity curves in the electromagnetic spectrum and the time of the detected neutrinos. The major limitations encountered so far were due to the scarce availability of information on the electromagnetic emission of the objects of interest, which typically are not observed continuously. Whenever data is available, such an a-posteriori approach is however very powerful, and it is part of the research plans of the IceCube Collaboration. We emphasize that a neutrino telescope at the South Pole is continuously and simultaneously sensitive to all objects located in the northern hemisphere. The investigation of the correlation between the observed properties of the electromagnetic emission and the detected neutrinos is therefore at any time feasible once the relevant electro-magnetic information is available. In other words, on-line and off-line approaches have to be seen as complementary and not mutually exclusive.

In case of variable objects like Blazars, FSRQs as well as Galactic systems like microquasars and magnetars, hadronic models describing the very high energy gamma-rays emission also predict simultaneous high energy neutrinos. Absorption processes might attenuate the gamma-ray luminosity when the objects are brightest in neutrinos, so that an anti-correlation or time-lag might be predicted as well. In all cases, the availability of simultaneous data on high energy gamma-ray emission and (possibly) neutrinos is mandatory to test different scenarios and shed light on the emission mechanisms (e.g. extract information on the optical depth and on other astrophysical source parameters).

II. Selection of target sources

The most interesting objects as a target for gamma-ray follow-up observations of IceCube events are promising sources of TeV neutrinos, which are either known to exhibit a bright GeV flux in gamma-rays and show extrapolated fluxes detectable by Imaging Air Cherenkov Telescopes, or are already detected by IACTs and are variable. Candidates currently being considered are AGNs (HBL, LBL, FSRQs), Microquasars and Magnetars (SGRs). A preliminary source list based on observations with the FERMI [6] and EGRET [3] experiments is based on the following criteria:

- Source is present in both the third EGRET(3EG) and Fermi catalogues;
- Source is classified as variable in the Fermi catalogue;
- Variability Index > 1 in the 3EG catalog (taken from [5]);
- Maximum 3EG flux $> 40 \cdot 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}, E > 100\,\mathrm{MeV}$;

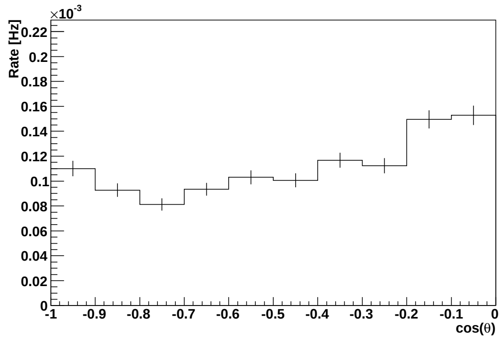

Fig. 1. Predicted rate of atmospheric neutrinos based on Monte-Carlo for IceCube in its 2009/2010 configuration with 59 deployed strings.

- Average 3EG flux $> 15 \cdot 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}, E > 100\,\mathrm{MeV}$;
- Difference between the maximum 3EG flux and the minimum 3EG flux $> 30 \cdot 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}, E > 100\,\mathrm{MeV}$.

The sources that were selected according to these criteria can be found in Table I.

III. EVENT SELECTION

The basis for the event selection is an on-line filter that searches for up-going muon tracks. The rate of this filter is about $24\,\mathrm{Hz}$ for IceCube in its 2009/2010 configuration with 59 deployed strings. 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 Level-2 filter searches events that were reconstructed with a zenith angle $\theta > 80^\circ$ ($\theta = 0^\circ$ equals vertically down-going tracks) with a likelihood reconstruction. By requiring a good reconstruction quality the background of misreconstructed atmospheric muons is further reduced. The parameters used to assess the track quality are the likelihood of the track reconstruction and the number of unscattered photons with a small time residual w.r.t. the Cherenkov cone. The reduced event rate of approximately $2.9\,\mathrm{Hz}$ can then be reconstructed with more time intensive reconstructions, like a likelihood fit seeded with ten different tracks (iterative fit). The fit with the best likelihood is used for further cuts. Based on this reconstruction the final event sample is selected by employing a zenith angle cut of $\theta > 90^\circ$ for the iterative reconstruction and further event quality cuts based on this reconstruction. In addition to the already mentioned parameters we also employ a cut on the longest distance between hits with a small time residual compared to their expected arrival time calculated from the track geometry when projected on the reconstructed track. The resulting rate of atmospheric neutrinos as predicted by Monte Carlo as a function of zenith angle can be seen in Figure 1.

IV. 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 [7] 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 $N_{\mathrm{bck}}^{i,j}$ is calculated for all other neutrino candidates j with $t_j < t_i$ from that source candidate. To calculate $N_{\mathrm{bck}}^{i,j}$ 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

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

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 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 three weeks.

If the cluster with the highest significance exceeds a certain threshold (e.g. corresponding to $5\,\sigma$) the detector stability will be checked and an alert will be send to an Cherenkov telescope to initiate a follow-up observation.

V. DATA QUALITY

Data quality is very important for any online alert program to minimize the rate of false alerts due to detector or DAQ instabilities. IceCube has a very extensive monitoring of the DAQ 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 follow-up program which requires fast alerts. To ensure that alerts are only sent for neutrino multiplets that where 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 and their respective ratios in time bins of 10 minutes. These values are then compared to a running average of these rates over approximately four days 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. An example of this behaviour

TABLE I
PRELIMINARY CANDIDATE SOURCE LIST FOR NEUTRINO TRIGGERED FOLLOW-UP OBSERVATIONS. THE TYPE OF AGN HAS BEEN TAKEN FROM [4]

Source name	Blazar type	Dec. [°]	RA [°]	max. 3EG flux [10^{-8} cm^{-2}s^{-1}]	min. 3EG flux [10^{-8} cm^{-2}s^{-1}]	avg. 3EG flux [10^{-8} cm^{-2}s^{-1}]
3C 273	FSRQ	2.0	187.3	48.3	8.5	15.4
CTA 102	FSRQ	11.7	338.1	51.6	12.1	19.2
GEV J0530+1340	FSRQ	13.5	82.7	351.4	32.4	93.5
3C 454.3	FSRQ	16.1	343.5	116.1	24.6	53.7
GEV J0237+1648	LBL	16.6	39.7	65.1	11.6	25.9

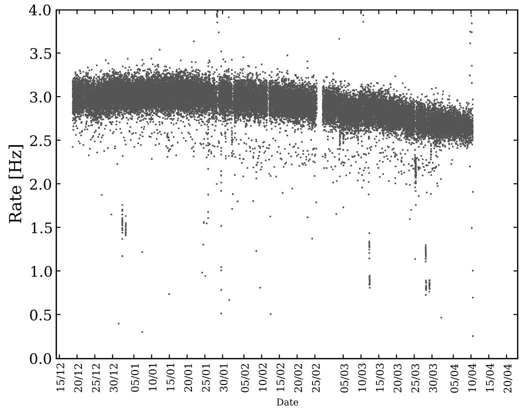

Fig. 2. Rate of the Level-2 online filter for four months (December 2008 till April 2009) in 10-minute bins with IceCube in its 2008/2009 configuration with 40 deployed strings. The Level-2 filter is an online filter that is used for different follow-up observation programs. The slow change in the rate is due to seasonal variations in the atmospheric muon background rate caused by pressure changes in the atmosphere.

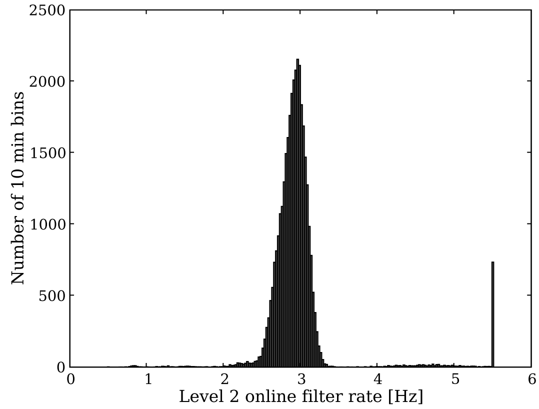

Fig. 3. Histogram of the rates of the online Level-2 filter of IceCube in its 2008/2009 configuration with 40 deployed strings for the four months shown in figure 2. The bin at a value of 5.5 Hz contains all entries bigger than 5.5 Hz.

can be seen in Figures 2 and 3. This system was tested off-line on data from IceCube in its 40-string configuration and proved to correlate very well with the extensive off-line detector monitoring. The fraction of data that has to be discarded due to detector or software problems was about 6 %, which includes all periods in Figures 2 and 3 that significantly deviate from the average. This method will be implemented online for IceCube in its 2009/2010 configuration with 59 deployed strings.

VI. SIGNIFICANCE CALCULATION

Under the hypothesis that all the neutrinos are of atmospheric origin, the probability of observing at least N_{obs} multiplets above the significance threshold and detecting at least N_{coinc} coincident gamma-ray flares is given by:

$$\sum_{m=N_{\text{obs}}}^{+\infty} \frac{(N_{\text{bck}})^m}{m!} e^{-N_{\text{bck}}} \sum_{j=N_{\text{coinc}}}^{m} \frac{m!}{j!(m-j)!} (p_{\text{gam}})^j (1-p_{\text{gam}})^{m-j} \quad (2)$$

where the first term describes the Poisson probability of observing at least N_{obs} neutrino multiplets with N_{bck} background expected, and the second term describes the probability of observing at least N_{coinc} out of m – the running number of observed multiplets, larger or equal to N_{obs} – each with a probability of p_{gam}. We note that this probability can be calculated anytime a-posteriori, once a realistic knowledge of the probability p_{gam} to detect a gamma-ray flare in a time window Δt is available. In order to avoid statistical biases it is mandatory, however, that the statistical test is defined a-priori, i.e. that the conditions to accept an observation and defining a coincidence are previously fixed. Methods on how the to reliably estimate the probability p_{gam} of detecting a gamma-ray flare in a time window Δt, which is influenced by the source elevation and weather conditions, from the frequency of the observed gamma-ray flares are under development. The significance calculated above also does not account for the trial factor correction due to the selection of three or more objects, which can however be calculated as the product of the individual terms corresponding to each source. The probability of having at least one coincidence in any of the proposed sources is, for example:

$$P = 1 - \prod_{i=1}^{N_{\text{Sources}}} P_i^0 \quad (3)$$

where ${P^0}_i$ is the probability of having zero coincidences at the source i.

VII. THE GAMMA-RAY FOLLOW-UP OBSERVATION SCHEME

We propose an observation scheme as follows:

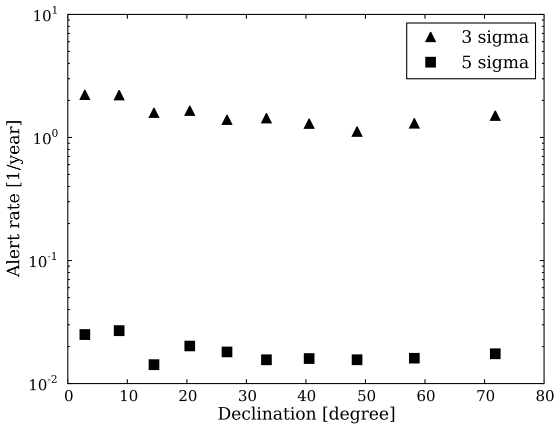

Fig. 4. Preliminiary alert rate from atmospheric neutrino background for IceCube in its 2009/2010 configuration with 59 deployed strings for an alert threshold for the multiplet significance corresponding to 3σ (upper points) and 5σ (lower points) and a bin size of $2°$.

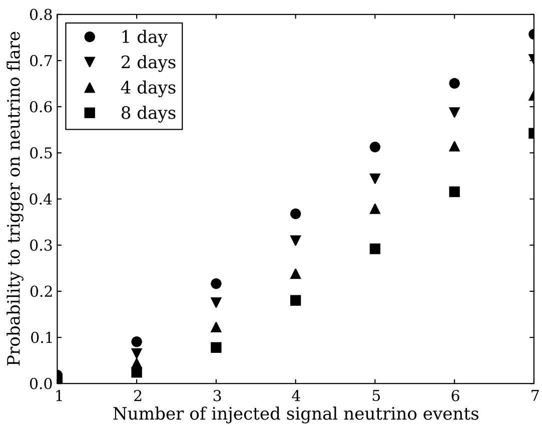

Fig. 5. Preliminary discovery probability for a certain number of injected on-source neutrino events for different flare durations for a source at a declination of $26°$. The discovery probability is defined here as the probability to detect a $5\,\sigma$ deviation with the time-clustering method. This does not contain the probability of the gamma-ray observation.

- Up to 1 day after receiving an IceCube alert from one of the pre-defined directions, the source is scheduled to be observed as soon as visible and observation conditions allow.
- If the gamma-ray observation is possible, it will continue for one hour.
- The results of the on-line analysis will be checked and, if there is a positive hint (above 3 σ) the gamma-ray observations may be extended. In case of a positive observation (i.e. a gamma-ray flux trespassing the pre-defined threshold defining a flare), the opportunity to trigger multi-wavelength observations should then be considered. Due to the irreducible background of atmospheric neutrinos (Figure 1) one can estimate the alert rate for different zenith regions (Figure 4) for thresholds corresponding to 3σ and 5σ. The on-source bin has been preliminarily chosen to have a radius of $2°$.

Based on a simple Monte Carlo simulation that does not take into account detector features like the azimuth dependent efficiency we calculated the discovery probabilities for different numbers of injected on-source events (see Figure 5) at a declination of $26°$. The discovery probability is defined here as the probability to detect a $5\,\sigma$ deviation with the time clustering method.

VIII. Status

The event selection and software to calculate the significance of a neutrino cluster are implemented and ready to be deployed at the South Pole. As IceCube in its 2009/2010 configuration with 59 deployed strings is considerably bigger than the previous detector configuration the stability monitoring needs to be checked with the first weeks of physics data. Pending the approval of the follow-up program by a Cherenkov telescope collaboration we then aim for a timely implementation of this program.

IX. Outlook

Besides enhancing the chance to discover point sources of neutrinos, the gamma-ray follow-up approach here discussed can increase the chance of detecting unusual gamma-ray emission of the selected objects. It also can provide an important contribution to the understanding of the flaring behavior of a few emitters of high energy gamma-rays in a way complementary to X-ray observations. Most relevant, it can provide a series of coincidences and therefore represent an important input to dedicated multi-wavelength follow-up observations, which will assess in more details the phenomenology of the potential sources. In fact – thanks to the existing communication infrastructures of multi-wavelength campaigns – the observation of gamma-ray flares can start a monitoring of the objects at other wavelengths (e.g. X-ray) that would further complement the information that are discussed here.

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