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Neutrino Triggered Target of Opportunity (NToO) test run with AMANDA-II and MAGIC

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Abstract: Kilometer scale neutrino telescopes are now being constructed (IceCube) and designed (KM3NeT). While no neutrino flux of cosmic origin has been discovered so far, the first weak signals are expected to be discerned in the next few years. Multi-messenger (observations combining different kinds of emission) investigations can enhance the discovery chance for neutrinos in case of correlations. One possible application is the search for time correlations of high energy neutrinos and established signals. We show the first adaptation of a Target of Opportunity strategy to collect simultaneous data of high energy neutrinos and gamma-rays. Neutrino events with coordinates close to preselected candidate sources are used to alert gamma-ray observations. The detection of a positive coincidence can enhance the neutrino discovery chance. More generally, this scheme of operation can increase the availability of simultaneous observations. If cosmic neutrino signals can be established, the combined observations will allow time correlation studies and therefore constraints on the source modeling. A first technical implementation of this scheme involving AMANDA-II and MAGIC has been realized for few pre-selected sources in a short test run (Sept. to Dec. 2006), showing the feasability of the concept. Results from this test run are shown.

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. Neutrino telescopes are ideal instruments to monitor the sky and look for the origin of cosmic rays because they can be continuously operated. The detection of cosmic neutrinos is however very challenging because of their small interaction cross-section and because of a large atmospheric background. Parallel measurements using neutrino and electromagnetic observations (multi-messenger) can increase the chance to discover the first signals by reducing the trial factor penalty arising from observation of multiple sky bins and over different time periods. In a longer term perspective, the multi-messenger approach also aims at providing a scheme for the phenomenological interpretation of the first possible detections. The Antarctic Muon and Neutrino Detector Array (AMANDA) was built with the aim to search for extraterrestrial high energy neutrinos [1]. The Major Atmospheric Gamma Imaging Cherenkov telescope (MAGIC) is a current generation γ-ray telescope that operates in the northern hemisphere at a trigger energy threshold of 60 GeV [2].

Neutrino Target of Opportunity test run

The neutrino target of opportunity (NToO) test run described here was defined as a cooperation between the AMANDA (neutrinos) and MAGIC (γ-

rays) collaborations [3]. Each time a neutrino event was detected from the direction of a predefined list of objects, a trigger was sent to the γ-ray telescope. MAGIC then tried to observe the object within a predefined time window after the neutrino trigger. The primary goal of the NToO approach is to achieve simultaneous neutrino/γ-ray observations. This can be realized by triggering follow-up observations of interesting neutrino events, such as multiplets within a short time window or very high energy events, therewith assuring γ-ray coverage for these neutrino events. Multiplets are very seldom in AMANDA-II observations (low statistics). We therefore implemented a test run based on single high energy neutrino events from predefined directions. These events are most likely due to atmospheric neutrino background. The test run took place between 27th of September and 27th of November 2006 and its purpose was to test the technical feasability of the NToO strategy. The AMANDA-II DAQ data at the South Pole passed through an online reconstruction filter that selected up-going muon tracks and provided a monitoring of the data quality. Whenever a neutrino event was reconstructed within a few degrees of one of the selected sources and passed the data quality criteria, a message was sent via e-mail to the MAGIC shift crew. The message contained the time of the event, the source name and the reconstructed angular distance from the source. If possible (day/night duty cycle), the object was then observed with the MAGIC telescope within 24 hours for a duration of 1 hour. A coincidence is counted when a γ-ray high state (flare) is measured in these observations. A γ-ray flare can be defined as an observation above a predefined threshold flux F_{thr}. The individual thresholds were chosen either based on the MAGIC sensitivity or in case of Mrk 421 to a conservatively low value for which the probability to observe a high state as defined above would be of the order of few percent.

An example analysis: Blazars

A stand-alone neutrino analysis can only yield a significant result if an excess above the expected atmospheric background is observed. In the multi-messenger framework, the observation of a number of neutrino events in coincidence with gamma-ray high states can be an indication for a neutrino/γ-ray correlation. If this correlation is incompatible with the chance probability for coincidence with atmospheric neutrinos such an observation would be evidence at the same time for a cosmic origin of the neutrino events and a hadronic nature of the gamma-ray signal. In this scheme for the interpretation of data a statistical test was defined before the measurements. Under the hypothesis that all the neutrinos detected from the direction of the source are atmospheric, the chance probability of detecting at least $n_{\rm obs}$ neutrinos and observing at least n_γ coincident gamma-ray flares is given by:

$$P=\sum_{i=n_{\rm obs}}^{+\infty} \frac{(n_{\rm bck})^i}{i!} \mathrm{e}^{-\mathbf{n}_{\rm bck}} \sum_{j=n_\gamma}^{i} \frac{i!}{j!(i-j)!} p_\gamma^j (1-p_\gamma)^{i-j} \quad (1)$$

where the first term describes the Poisson probability of observing at least $n_{\rm obs}$ neutrinos with $n_{\rm bck}$ expected background events, and the second term describes the probability of observing at least n_γ coincident gamma-ray flares out of the $j \geq n_{\rm obs}$ triggers. p_γ is the probability to observe a gamma-ray high state above a certain threshold F_{thr} within a given time window. P defines the post-trial significance of a set of coincidences observed from one source. Trial factors to account for the number of sources considered can be easily included using Binomial statistics. For illustration of Equation 1, let us assume that we observe $n_{\rm obs}$ = 10 neutrinos with a background expectation of $n_{\rm bck}$ = 10. In itself this measurement would not be significant. However, if coincidences with γ-ray high-states are observed the significance increases as shown in Figure 1 for different γ-ray probabilities. So far, limited knowledge is available on p_γ. Efforts are on-going to address the issue of estimating an upper limit on p_γ for a few interesting sources, from a compilation of gamma-ray observations [4] and from random or long term monitoring observations (e.g. performed by the VERITAS and the MAGIC telescopes). We notice that a compilation of existing data is likely biased from the availability of measurements triggered by high states of emission observed at different wavelengths, which would tend to give an overestimation of p_γ and therefore an underestimation of the significance of the coincidences. The probability p_γ is, on average, equal to the average high-state rate of an object. One method for the estimation

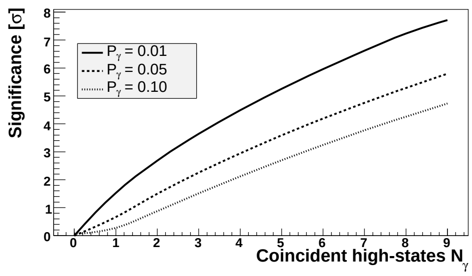

Figure 1: Significance of simultaneous neutrino/gamma-ray observations vs. the number of observed coincidences, given for different values of p_γ (Equation 1). Here, $n_{\rm obs}$ = $n_{\rm bck}$ = 10 was assumed.

of the high-state rate is based on the flux frequency distribution of the object, shown in Figure 2 for Mrk 421. This distribution can be interpreted as a stochastic flux-state distribution and can be well fit by an exponential. The high-state rate $R_{HS}(F_{thr})$ above a threshold F_{thr} is then given by

$$R_{HS}(F_{thr}) = \frac{\int_{F_{thr}}^{\infty} e^{bx} dx}{\int_{F_0}^{\infty} e^{bx} dx} = \frac{e^{bF_{thr}}}{e^{bF_0}} \qquad (2)$$

where F_0 is the baseline flux of the object and b is the slope of the flux distribution. The relative high-state rate of Mrk 421 as derived from this formula is shown in Figure 3 as a function of the chosen threshold F_{thr}. Due to the bias to high states of the available Mrk 421 observations, the high state rate is systematically overestimated here. These results will be described in detail in [4]. The estimation for p_γ can be used in Equation 1 in the case of Blazars, for which γ-ray data exist and long-term lightcurves have been compiled. The expected background rate is the rate of atmospheric neutrinos in the sky bins around the selected sources. Depending on the source declination and on the choice of the bin size, this rate ranges from about 1 to 4 events per year and per source based on the AMANDA-II event information and according to the current scheme of event reconstruction and selection [5].

List of selected sources

The first criterion for the selection of sources for the NToO test run is their variability. Only sources

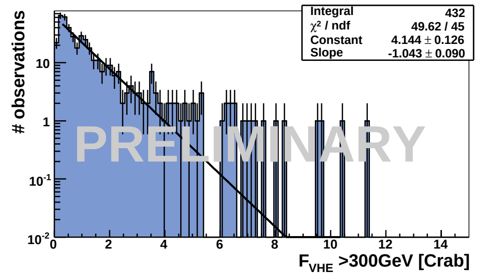

Figure 2: Distribution of flux states above 300 GeV of 15 years of VHE observations of Mrk 421 [4].

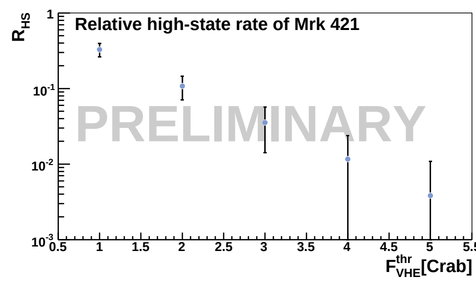

Figure 3: High-state rate calculated by applying equation 2 to the fit of the distribution of fluxstates in Figure 2.

known or expected to be variable were chosen for the test run. Other criteria are the minimal impact on the scientific plans of MAGIC and the possibility to efficiently organize the independent observation plans. Target sources are therefore preferably selected among those which are already included in the scheduled observation program (MAGIC). Further criteria are their potential for high-energy neutrino emission, good visibility for MAGIC during the time period of the test run (September–December) and previous detections at high-energy γ-rays or high probability for γ-ray emission. Sources meeting these requirements are Blazars and X-ray binaries. For these sources the level of correlation between high energy neutrinos and gamma-rays can be different under different scenarios (see for example the cases discussed in [6]).

	LSI+61 303	GRS 1915+105	1ES 2344+514	1ES 1959+650	Mrk 421
n_{bck}	0.86	1.26	0.99	0.92	1.51
n_{obs}	0	1	1	0	3
Follow ups	0	0	1	0	1
n_γ	–	–	0	–	0
F_{thr} [C.U.]	0.2	0.2	0.5	1.0	4.0
p_γ	–	–	–	< 0.15	< 0.05
P_ν	1.0	0.7	0.6	1.0	0.2

Table 1: List of selected sources for the NToO test run. Given are preliminary numbers for expected (n_{bck}) and observed (n_{obs}) neutrino triggers, the number of observed coincidences (n_γ), the γ-ray high-state probability and the probability P_ν for observing n_{obs} neutrinos or more. The error on n_{bck} is typically 0.1.

Results and Interpretation

During the two months of data taking for the NToO program a total of 5 neutrino event triggers were initiated by AMANDA-II and sent to the MAGIC observatory. In two cases follow-up observations were performed with the MAGIC telescope lasting for 1 hour each. For the remaining 3 triggers, the source was not observable with MAGIC within 24 h following the trigger due to unfavourable astronomical, moon or weather conditions. In Table 1 the individual neutrino event counts n_{obs} are given along with the number of expected neutrino background events n_{bck}, the number of coincident observations with MAGIC, the number n_γ of observed coincident γ-ray flares (as defined above) and the γ-ray flare probability p_γ derived from Equation 2. The MAGIC follow up observation data has been analyzed with the standard MAGIC analysis chain [7]. The sensitivity of MAGIC is sufficient to detect a γ-ray flux level of 30% Crab Units (C.U.) with 5 sigma significance within 1 hour. It is therefore enough to determine whether the 2 triggered sources Mrk421 and 1ES2344 were in flaring state (according to the definition of flaring state in Table 1) during the NToO observations. The analysis yielded an upper limit for 1ES2344 (16% C.U.) and a low flux state for Mrk421 (30$\pm$10% C.U.). No coincident γ-ray flaring state has thus been observed.

Discussion and Perspectives

The NToO strategy was implemented in a test run involving the AMANDA-II and the MAGIC telescope for a time period of two-months. No coincident events have been observed during this test run. However, the technical feasibility of a NToO strategy was successfully tested. The neutrino trigger information sent via e-mail has initiated follow-up observations, whenever the sources were visible and the weather and astronomical (moon/sun) conditions allowed the operation of the MAGIC telescope. At the end of the test run, a different communication infrastructure was also implemented, based on a test client/server connection, which allows the queuing of follow-up observations using a similar pipeline as that already used by MAGIC to follow-up GRB alerts. Perspectively, different event selections will be developed for IceCube. A search for multiplets with pre-defined significances will provide a means for the selection of flare-like neutrino events. Furthermore, work is in progress for the analysis of high-energy neutrino events with the IceCube 22-string detector (2007) and with extensions in subsequent years. These analyzes will possibly be implemented in an IceCube NToO program in 2008.

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