Search for neutrino emission of gamma-ray flaring blazars with the ANTARES telescope

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Abstract: The ANTARES telescope is well suited to detect neutrinos produced in astrophysical transient sources as it can observe a full hemisphere of the sky at all the times with a duty cycle close to unity. The background and point source sensitivity can be drastically reduced by selecting a narrow time window around the assumed neutrino production period. Radio-loud active galactic nuclei with their jets pointing almost directly towards the observer, the so-called blazars, are particularly attractive potential neutrino point sources, since they are among the most likely sources of the observed ultra high energy cosmic rays and therefore, neutrinos and gamma-rays may be produced in hadronic interactions with the surrounding medium. The gamma-ray light curves of blazars measured by the LAT instrument on-board the Fermi satellite reveal important time variability information. A strong correlation between the gamma-ray and the neutrino fluxes is expected in this scenario.

An unbinned method based on the minimization of a likelihood ratio was applied to a subsample data collected in 2008 (61 days live time). By looking for neutrinos detected in the high state periods of the AGN light curve, the sensitivity to these sources has been improved by about a factor 2 with respect to a standard time-integrated point source search. First results on the search for ten bright and variable Fermi sources are presented.

Keywords: ANTARES, Neutrino astronomy, Fermi transient sources, time-dependant search, blazars

1 Introduction

The production of high-energy neutrinos has been proposed for several kinds of astrophysical sources, such as active galactic nuclei, gamma-ray bursters, supernova remnants and microquasars, in which the acceleration of hadrons may occur. Neutrinos are unique messengers to study the high-energy universe as they are neutral and stable, interact weakly and travel directly from their point of creation in the source without absorption. Neutrinos could play an important role in understanding the mechanisms of cosmic ray acceleration and their detection from a source would be a direct evidence of the presence of hadronic acceleration in that source.

Radio-loud active galactic nuclei with their jets pointing almost directly towards the observer, the so-called blazars, are particularly attractive potential neutrino point sources, since they are among the most likely sources of the observed ultra high energy cosmic rays and therefore, neutrinos and gamma-rays may be produced in hadronic interactions with the surrounding medium [1]. The gamma-ray light curves of blazars measured by the LAT instrument on-board the Fermi satellite reveal important time variability information on timescale of hours to several weeks, with intensities always several times larger than the typical flux of the source in its quiescent state [2]. A strong correlation between the gamma-ray and the neutrino fluxes is expected in this scenario.

In this paper, the results of the first time-dependent search for cosmic neutrino sources in the sky visible to the ANTARES telescope are presented. The data sample used in this analysis is described in Section 2, together with a discussion on the systematic uncertainties. The point source search algorithm used in this time-dependent analysis is explained in Section 3. The results are presented in Section 4 for a search on a list of ten selected candidate sources.

2 ANTARES

The ANTARES collaboration has completed the construction of a neutrino telescope in the Mediterranean Sea with the connection of its twelfth detector line in 2008 [3]. The telescope is located 40 km on the southern coast of France (42°48’N, 6°10’E) at a depth of 2475 m. It comprises a three-dimensional array of photomultipliers housed in glass spheres (optical modules), distributed along twelve slender lines anchored at the sea bottom and kept taut by a buoy at the top. Each line comprises up to 25 storeys of triplets of optical modules (OMs), each housing a single 10” PMT. Since lines are subject to the sea current and can change...
shape and orientation, a positioning system comprising hydrophones and compass-tiltimeters is used to monitor the detector geometry. The main goal of the experiment is to search for neutrinos of astrophysical origin by detecting high energy muons (>100 GeV) induced by their neutrino charged current interaction in the vicinity of the detector.

The arrival time and intensity of the Cherenkov light on the OMs are digitized into hits and transmitted to shore, where events containing muons are separated from the optical backgrounds due to natural radioactive decays and bioluminescence, and stored on disk. A detailed description of the detector and the data acquisition is given in [3] [4]. The arrival times of the hits are calibrated as described in reference [5]. The online event selection identifies triplets of OMs that detect multiple photons. At least 5 of these are required throughout the detector, with the relative photon arrival times being compatible with the light coming from a relativistic particle. Independently, events were also selected which exhibit multiple photons on two sets of adjacent, or next to adjacent floors.

The data used in this analysis corresponds to the period from September 6th to December 31st, 2008 (54720-54831 modified Julian day), taken with the full detector. Some filtering has been applied in order to exclude periods in which the bioluminescence-induced optical background was high. The resulting effective life time is 60.8 days. Atmospheric neutrinos are the main source of background in the search for astrophysical neutrinos. These neutrinos are produced from the interaction of cosmic rays in the Earth’s atmosphere. Only charged current interactions of neutrinos and antineutrinos were considered. An additional source of background is due to the mis-reconstructed atmospheric muons. The track reconstruction algorithm derives the muon track parameters that maximize a likelihood function built from the difference between the expected and the measured arrival time of the hits from the Cherenkov photons emitted along the muon track. This maximization takes into account the Cherenkov photons that scatter in the water and the additional photons that are generated by secondary particles (e.g. electromagnetic showers created along the muon trajectory). The algorithm used is outlined in [6]. The value of the log-likelihood per degree of freedom ($\Lambda$) from the track reconstruction fit is a measure of the track fit quality and is used to reject badly reconstructed events, such as atmospheric muons that are mis-reconstructed as upgoing tracks. Neutrino events are selected by requiring that tracks are reconstructed as upgoing and have a good reconstruction quality. In addition, the error estimate on the reconstructed muon track direction obtained from the fit is required to be less than 1°.

The angular resolution cannot be determined directly in the data and has to be estimated from simulation. However, the comparison of the data and Monte Carlo simulations from which the time accuracy of the hits has been degraded has yielded a constrain on the uncertainty of the angular resolution of the order of 0.1° [8]. Figure 1 shows the cumulative distribution of the angular difference between the reconstructed muon direction and the neutrino direction with an assumed spectrum proportional to $E_\nu^{-2}$, where $E_\nu$ is the neutrino energy. For this period, the median resolution is estimated to be 0.4 ± 0.1 degree.

3 Time-dependent search algorithm

This time dependent point source analysis is done using an unbinned method based on a likelihood ratio maximization. The data is parameterized as a two components mixture of signal and background. The goal is to determine, at a given point in the sky and at a given time, the relative contribution of each component and to calculate the probability to have a signal above a given background model. The likelihood ratio $\lambda$ is the ratio of the probability density for the hypothesis of background and signal ($P_{bkg}(\alpha,t)$) over the probability density of only background ($P_{bkg}$): 

$$
\lambda = \sum_{i=1}^{N} \frac{P_{bkg}(\alpha_i, t_i) + (1 - \frac{n_{sig}}{N}) P_{bkg}(\alpha_i, t_i)}{P_{bkg}(\alpha_i, t_i)}
$$

where $n_{sig}$ and $N$ are respectively the unknown number of signal events and the total number of events in the considered data sample. $P_{bkg}(\alpha_i, t_i)$ and $P_{bkg}$ are the probability density function (PDF) for signal and background respectively. For a given event $i$, $t_i$ and $\alpha_i$ represent the time of the event and the angular difference between the coordinate of this event and the studied source.

The probability densities $P_{bkg}$ and $P_{bkg}$ are described by the product of two components: one for the direction and one for the timing. The shape of the time PDF for the signal event is extracted directly from the gamma-ray light curve assuming the proportionality between the gamma-ray and the neutrino fluxes. For the signal event, this directional
PDF is described by the one dimension point spread function, which is the probability density of reconstructing an event at an angular distance from the true source position. The directional and time PDF for the background are derived from the data using respectively the observed declination distribution of selected events in the sample and the observed time distribution of all the reconstructed muons. Figure 2 shows the time distribution of all the reconstructed events and the selected upcoming events for this analysis. Once normalized to an integral equal to 1, the distribution for all reconstructed events is used directly as the time PDF for the background. When data is at 0, it means that there are no data taken during those periods (i.e., detector in maintenance) or data with a very poor quality (high bioluminescence or bad calibration).

The null hypothesis is given with \( \lambda_{\text{data}} = 0 \). The obtained value of \( \lambda_{\text{data}} \) on the data is then compared to the distribution of \( \lambda \) given the null hypothesis. Large values of \( \lambda_{\text{data}} \) compared to the distribution of \( \lambda \) for the background only reject the null hypothesis with a confident level equal to the fraction of the scrambled trials above \( \lambda_{\text{data}} \). This fraction of trials above \( \lambda_{\text{data}} \) is referred to as the p-value. The discovery potential is then defined as the average number of signal events required to achieve a p-value lower than 5\( \sigma \) in 50% of trials. Figure 3 shows the average number of events required for a 5\( \sigma \) discovery (50% C.L.) produced in one source located at a declination of -40\( ^\circ \) as a function of the width of the flare period. These numbers are compared to the one obtained without using the timing information.

Fermi LAT catalogue [9] and in the LBAS catalogue (LAT Bright AGN sample [10]). The sources located in the visible part of the sky by Antares from which the averaged 1 day-binned flux in the high state is greater than 20 \( 10^{-8} \) photons.cm\(^{-2}.s^{-1} \) above 300 MeV in the studied time period and with a significant time variability are selected. This list includes six flat spectrum radio quasars (FSRQ) and four BLlacs. Table 1 lists the characteristics of the ten selected sources.

<table>
<thead>
<tr>
<th>Name</th>
<th>OFGL name</th>
<th>Class</th>
<th>redshift</th>
<th>( F_{300} )</th>
</tr>
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<tr>
<td>PKS0208-512</td>
<td>J0210.8-5100</td>
<td>FSRQ</td>
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<tr>
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<tr>
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<tr>
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<td>J2138.8-3014</td>
<td>BLLac</td>
<td>0.116</td>
<td>7.89</td>
</tr>
</tbody>
</table>

Table 1: List of bright variable Fermi blazars selected for this analysis. \( F_{300} \) is the gamma-ray flux above 300 MeV (10\(^{-8} \) photons.cm\(^{-2}.s^{-1} \)).

The light curves published in Fermi web page for the monitored sources [11] for the observed sources are used for this analysis. These light curves correspond to the one-day binned time evolution of the average gamma-ray flux above a threshold of 100 MeV from August 2008 to August 2010. The high state periods are defined using a simple and robust method based on three main steps. First, the baseline is determined with an iterative linear fit. After each fit, the points where the flux is above a given threshold are suppressed. When the baseline is computed, all the points (green dots) where the flux minus its error are above the baseline plus two times its fluctuation and the flux is above the baseline plus three times its fluctuation are used as priors from which the flares are defined. The last step consists on, for each selected point, adding the adjacent points for which the emission is com-

Figure 2: Time distribution of the reconstructed events. Black: distribution for all reconstructed events. Red filled: distribution of selected upcoming events (\( \lambda > -5.4 \) and \( \beta < 1^\circ \)).

Figure 3: Average number of events required for a 5\( \sigma \) discovery (50% C.L.) produced in one source located at a declination of -40\( ^\circ \) as a function of the width of the flare period. These numbers are compared to the one obtained without using the timing information.

4 Search for neutrino emission from gamma-ray flare

This time-dependent analysis has been applied to bright and variable Fermi blazar sources reported in the first year
patible with the flare. Finally, an additional delay of 0.5 day is added before and after the flare in order to take into account that the precise time of the flare is not known (1-day binned LC). With this definition, a flare has a width of at least two days. Figure 4 shows the time distribution of the Fermi LAT gamma-ray light curve of 3C454 for almost 2 years of data and the determined high state periods (blue histogram). With the hypothesis that the neutrino emission follows the gamma-ray emission, the signal time PDF is simply the normalized de-noise light curve.

The most significant source is 3C279, which has a pre-trial p-value of 1.03%. The unbinned method finds one high-energy neutrino event located at 0.56° from the source location during a large flare in November 2008. Figure 5 shows the time distribution of the Fermi gamma-ray light curve of 3C279 and the time of the coincident neutrino event. This event has been reconstructed with 89 hits spread on 10 lines with a track fit quality Λ = −4.4 and an error estimate β = 0.3°. The post-trial probability is computed taking into account the ten searches. The final probability, 10% is compatible with background fluctuations.

5 Summary

This paper discusses the first time-dependent search for cosmic neutrinos using the data taken with the full 12 lines ANTARES detector during the last four months of 2008. Time-dependent searches are significantly more sensitive than standard point-source search to variable sources thanks to the large reduction of the background of atmospheric muons and neutrinos over short time scales. This search has been applied to ten very bright and variable Fermi LAT blazars. The most significant observation of a flare is 3C279 with a p-value of about 10% after trials for which one neutrino event has been detected in time/space coincidence with the gamma-ray emission. Limits have been obtained on the neutrino fluence for the ten selected sources. The most recent measurements of Fermi in 2009-11 show very large flares yielding a more promising search of neutrinos [12].

6 Acknowledgments

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References

[8] Bogazzi C., this conference