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Time-dependent search of neutrino emission from bright gamma-ray flaring blazars with the ANTARES telescope

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The ANTARES telescope is well suited for detecting astrophysical transient neutrino sources as it can observe with high duty cycle an instantaneous field of view of 2π sr. The background due to atmospheric muons and neutrinos can be drastically reduced, and the point-source sensitivity improved, by selecting a narrow time window around possible neutrino production periods. Blazars, radio-loud active galactic nuclei with their jets pointing almost directly towards the observer, are particularly attractive potential neutrino point sources, since they are among the most likely sources of the very high-energy cosmic rays. Neutrinos and gamma rays may be produced in hadronic interactions with the surrounding medium. Blazars generally show high time variability in their light curves at different wavelengths and on various time scales. Using ANTARES data a time-dependent analysis has been carried out searching for neutrino events from a selection of flaring gamma-ray blazars previously observed by the FERMI/LAT experiment and by TeV imaging Cherenkov telescopes. The results of these searches will be presented. If no signal will be discovered upper limits on neutrino fluxes, their comparisons with the published gamma-ray spectral energy distribution and with prediction from astrophysical models will also be reported.

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1. Introduction

Active galactic nuclei (AGN) are among the most likely sources of the very high-energy cosmic rays. High-energy neutrino detection from them would confirm such hypothesis [1]. The debate is still open if AGN gamma-ray emission is due by leptonic [2, 3, 4, 5] or hadronic processes [6, 7]. In the second scenario, neutrinos are expected to be produced in correlation with gamma-rays from pion-decays.

Blazars are among the best candidates for being the source of the very high-energy cosmic rays [8, 9]. Several neutrino emission models are proposed [10, 11, 12, 13, 14, 15, 16], characterised by different spectral indexes and normalisation constants. While E^{-2} is among the most commonly proposed spectrum, in certain cases harder spectral indexes up to one are proposed [17, 18]. In analogy to what has been observed for several gamma-ray sources also for the neutrino spectra is possible to conceive a high energy cutoff. For the present analysis is considered the following neutrino spectra: E^{-1}, E^{-2}, $E^{-2} \times exp(\sqrt{-E/10\,\mathrm{TeV}})$ and $E^{-2} \times exp(\sqrt{-E/1\,\mathrm{TeV}})$.

We report here about results obtained analysing a data sample, collected by the ANTARES telescope [19, 20], searching for neutrinos, with energy dependences as the ones described above and from a selection of flaring gamma-ray blazars. The search is performed in restricted time windows under the hypothesis of a time-correlation between neutrino and gamma fluxes. Searching for neutrinos in a limited time interval around the gamma flare time, increases the Signal/Background ratio and, if compared with analogous time integrated searches elsewhere reported by ANTARES [21, 22], reduces by a factor 2–3 the number of signal events required for a discovery. This approach has been carried out in previous similar analyses [23, 24] where, in order to test the blazar source hypothesis, a correlation between the most energetic observed gamma-ray flares of the brightest blazars with neutrino emission has been studied (see Sec. 3). The main update with respect to the previous analyses is the inclusion of the shower channel in addition to the track one from the ANTARES data taken from 2008 to 2016 with ∼2413 days of live-time.

2. Time-dependent analysis

The analysis is done evaluating a test statistic built from an unbinned extended likelihood maximised ratio. The likelihood ($\mathscr{L}$) treats the ANTARES data as a composition of background ($\mathscr{N}_{bk}$) and signal ($\mathscr{N}_{sg}$) events, properly weighted by their different probability density functions (PDFs, $P_{sg/bk}$):

$$\ln \mathscr{L}_{sg+bk} = \sum_{ch} \sum_{i} \ln \left[\mathscr{N}_{sg}^{ch} \cdot P_{sg}^{ch} + \mathscr{N}_{bk}^{ch} \cdot P_{bk}^{ch} \right] - \left[\mathscr{N}_{sg} + \mathscr{N}_{bk} \right]$$

The likelihood is extended over all the events (i) for both considered channels (ch), i.e. tracks and showers.

The P_{sg} for the track channel is defined as the product of three probability functions: one related to the neutrino direction (the point spread function probability, PSF, $PSF_{sg}^{tr}(\alpha)$, with α the angular distance to the source), the second related to the energy ($P_{sg}^{tr}(dE/dX)$, being dE/dX the energy estimator used in the track channel) and the third related to the time ($P_{sg}(t)$):

$$P_{sg}^{tr} = PSF_{sg}^{tr}(\alpha, \delta_S) \cdot P_{sg}^{tr}(dE/dX) \cdot P_{sg}(t + lag)$$

The PSF is estimated for each source declination (δ_S) and both $PSF^{tr}_{sg}(\alpha)$ and $P^{tr}_{sg}(dE/dX)$ are function of the assumed neutrino energy spectrum. Additionally, a lag of ± 5 days is allowed on the neutrino signal arrival time t in order to allow possible offsets between the neutrino and gamma-ray emission at leaving the source.

The neutrino time probability is obtained directly by the observed gamma-ray light curve assuming the correlation between gamma-rays and neutrinos, i.e. the neutrino time probability follows the gamma-ray detection time, PDF extracted from the gamma ray emission of the studied source (see Sec. 3). This time PDF is the same for both track and shower channels.

The P_{sg} for the shower channel is the product of the shower PSF, the energy and the time PDF:

$$P^{sh}_{sg} = PSF^{sh}_{sg}(\alpha, \delta_S) \cdot P^{sh}_{sg}(n_{hits}) \cdot P_{sg}(t + lag)$$

where the number of hits used in the shower reconstruction, n_{hits}, is used as the energy estimator and again both $PSF^{sh}_{sg}(\alpha)$ and $P^{sh}_{sg}(n_{hits})$ are function of the assumed neutrino energy spectrum.

The P_{bk} for each channel is the corresponding product of the background PDF at a certain declination ($P^{tr}_{bk}(\delta)$), the background energy estimator PDF and the background time PDF:

$$P^{tr}_{bk} = P^{tr}_{bk}(\delta) \cdot P^{tr}_{bk}(dE/dX, \delta) \cdot P_{bk}(t)$$

$$P^{sh}_{sg} = P^{sh}_{bk}(\delta) \cdot P^{sh}_{bk}(n_{hits}) \cdot P_{bk}(t)$$

These probabilities are derived from data using, respectively, the observed declination distribution of selected events in the sample, the measured distribution of the energy estimator, and the observed time distribution of all the reconstructed events.

The amount of signal for each channel is determined by the ratio contribution of each channel to the global acceptance of the detector at source declination:

$$\mathcal{N}^{ch}_{sg} = \mathcal{N}_{sg} \cdot (A^{ch}_{cc}(\delta_S)/A^{TOTAL}_{cc}(\delta_S))$$

and the total signal or background is the sum of each channel:

$$\mathcal{N}_{sg/bk} = \mathcal{N}^{sh}_{sg/bk} + \mathcal{N}^{tr}_{sg/bk}$$

The likelihood is maximised by varying the $\mathcal{N}_{sg}$ and lag parameters and the test statistic $\mathcal{Q}$ is built from the ratio of this maximised likelihood with the null hypothesis:

$$\mathcal{Q} = \log \mathcal{L}^{max}_{sg+bk} - \log \mathcal{L}_{bk}$$

The significance of this test statistic is evaluated via pseudo-experiment simulation. Cut optimisation is realised for each source and for each assumed energy spectrum in order to optimise the track quality parameter cut on the track-like event selection and to improve the analysis model discovery potential at 3σ. Well established quality cuts used in previous analyses, and in point source analyses for the shower channel, are kept.

3. Source and gamma-ray flare selection

Potentially interesting blazars are selected from the 3FHL FermiLAT high-energy catalogue [25, 26], where are listed all sources significantly detected in the 10 GeV−2 TeV range during the first 7 years of the Fermi mission using the Pass 8 event-level analysis. From this list, the following sources are selected:

- Blazars of the flat spectrum radio quasars (FSRQ) type or BL Lac objects (BLL).
- Blazars with a detection significance above 10.
- Blazars with more than one Bayesian block emission, which implies to be variable at 99% of confidence level.
- The brightest sources, with a flux above 10^{-10} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
- Sources with declination below 35°, i.e. visible in the track channel of ANTARES.

This criteria results in a preliminary selection of 46 BLLs and 32 FSRQs. A subsequent selection of sources is done regarding they flare or not in the light curves (LCs) described below.

The time PDF to be used for each source is build from the 2nd FAVA catalogue [27], the Fermi all-sky variability analysis done with 7.4 years of Fermi mission, from 2008/08/04 to 2016/01/04. LCs with weekly time bin and in two energy bands (100−800 MeV and 0.8−300 GeV) are analysed. The detection threshold for a source to be include in the catalogue is of 6σ pre-trial. Sources from the preliminary selection showing more than one flare in the FAVA catalogue with more than a 5σ excess over the baseline emission are selected for the analysis: 17 BLLs and 23 FSRQs (see Table 1). The time PDFs are build up with the flares above a 5σ significance from the LCs of the FAVA catalogue, complemented with the online FAVA search. Each flare is weighted by its significance in the time PDF.

4. Results

Preliminary sensitivities for the track only channel considering a E^{-2} spectrum have been presented at the conference (see some specific cases in Table 2). Sensitivity to the neutrino flux during the flares is improved by a factor of ∼2 on average with respect to the previous analysis upper limits. In function of the source declination, shower channel inclusion would improve neutrino limits even a 10%. The corresponding neutrino fluence estimate is also provided in the tables according to its definition:

$$\mathscr{F} = \iint E \frac{\mathrm{d}N}{\mathrm{d}E}\,\mathrm{d}E\,\mathrm{d}t = \phi_0\,\Delta t \int_{5\%}^{95\%} E\,E^{-2}\,\mathrm{d}E$$

with ϕ_0 the spectrum normalisation, Δt the flaring livetime and the integral performed in the 5−95% ANTARES sensibility energy range of each source.

Table 1: List of the 40 blazars selected for the analysis. For each source are given its coordinates, flaring days and average daily significance.

Name	R.A. (°)	δ (°)	Flaring days	Ave. sig.
1ES 1215+303	184.5	30.1	21.0	7.5
3C 279	194.0	−5.8	231.0	9.9
3C 454.3	343.5	16.1	336.0	15.6
4C +14.23	111.3	14.4	70.0	8.7
4C +21.35	186.2	21.4	133.0	13.5
4C +28.07	39.5	28.8	77.0	7.7
AO 0235+164	39.7	16.6	217.0	8.2
B2 0716+33	109.9	33.1	49.0	7.0
B2 1520+31	230.5	31.7	49.0	8.1
CTA 102	338.2	11.7	616.0	11.4
MG1 J021114+1051	32.8	10.9	7.0	8.2
MG2 J043337+2905	68.4	29.1	14.0	7.3
OJ 287	133.7	20.1	56.0	8.7
ON 246	187.6	25.3	119.0	10.0
PKS 0301−243	45.9	−24.1	21.0	11.5
PKS 0426−380	67.2	−37.9	273.0	6.7
PKS 0454−234	74.3	−23.4	147.0	7.2
PKS 0507+17	77.5	18.0	63.0	15.8
PKS 0537−441	84.7	−44.1	98.0	7.3
PKS 0727−11	112.6	−11.7	7.0	8.1
PKS 0805−07	122.1	−7.9	56.0	10.0
PKS 0829+046	128.0	4.5	14.0	7.5
PKS 1124−186	171.8	−19.0	126.0	6.5
PKS 1441+25	221.0	25.0	399.0	8.4
PKS 1502+106	226.1	10.5	259.0	8.1
PKS 1510−08	228.2	−9.1	287.0	11.1
PKS 1717+177	259.8	17.8	112.0	7.5
PKS 1730−13	263.3	−13.1	84.0	8.0
PKS 2142−75	326.8	−75.6	105.0	7.6
PKS 2155−304	329.7	−30.2	14.0	8.4
PKS 2233−148	339.1	−14.6	98.0	10.2
PKS B1424−418	217.0	−42.1	728.0	9.5
PMN J0531−4827	83.0	−48.5	63.0	10.6
PMN J0622−2605	95.6	−26.1	21.0	6.8
PMN J1802−3940	270.7	−39.7	70.0	6.5
PMN J2345−1555	356.3	−15.9	182.0	7.9
RX J1754.1+3212	268.5	32.2	28.0	8.2
Ton 599	179.9	29.2	49.0	9.1
TXS 0518+211	80.4	21.2	70.0	6.8
TXS 1530−131	233.2	−13.3	140.0	9.0

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Table 2: Preliminary sensitivities for some specific blazars for the track only channel assuming a E^{-2} spectrum. For each source are given the neutrino flux sensitivity during the flare (ϕ_0, in $10^{-8}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$), the flare livetime ($\Delta t$, in days), the integral in the 5−95% ANTARES sensibility energy range ($I_{5\%}^{95\%} = \int_{5\%}^{95\%} E^{-1}\,\mathrm{d}E$) and the fluence ($\mathscr{F}$, in $\mathrm{GeV\,cm}^{-2}$).

Name	ϕ_0	Δt	$I_{5\%}^{95\%}$	$\mathscr{F}$	Name	ϕ_0	Δt	$I_{5\%}^{95\%}$	$\mathscr{F}$
3C 279	10	182	7.0	11	PKS 0426−380	6.4	191	7.4	8
4C +14.23	52	41	7.0	13	PKS 1441+25	6.2	383	7.0	14
CTA 102	4.0	526	7.0	13	PKS 1510−08	8.3	219	7.0	11
OJ 287	55	41	7.0	14	PKS B1424−418	1.9	594	7.3	7

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