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Characterizing the High-Energy Activity of Blazars Possibly Correlated with Observed Astrophysical Neutrinos

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Since IceCube's announcement of TXS 0506+056 as a candidate for astrophysical neutrino emission, there has been a strong interest in the multi-messenger study of blazars to characterize their potential for high-energy neutrino emission. Identifying their most active periods with Fermi-LAT data and correlating the high-energy γ-ray luminosity and flare duration of these sources with potential hadronic scenarios can be a useful way to approach this problem.
In this study, we build a sample of blazars in spatial coincidence with IceCube astrophysical muonic neutrinos (med. error $<= 1.3^{\circ}$), and look at their long-term γ-ray light curves to identify long-duration flares. The level of high-energy activity of the sources is quantified by calculating their γ-ray duty cycles. For the sources with relevant flares, we assume a lepto-hadronic model to obtain neutrino light-curves with different time binnings, and compare with the discovery potential of IceCube, obtaining the minimum flare duration for detecting very high-energy neutrinos from these blazars.

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†A footnote may follow.

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1. Introduction

IceCube recently provided strong evidence for a neutrino signal of astrophysical origin [1]. It has also been shown that the galactic contribution to this flux cannot exceed 10% of the all sky astrophysical excess [2], [3]. Most of this galactic emission comes from the interaction of diffuse cosmic rays with dense molecular clouds, with the galactic point sources (like SNRs) being sub-dominant [4]. The spectral energy distribution (SED) of the muonic neutrino events observed from the Northern hemisphere showed a spectrum with index $\alpha \sim$2.2, harder than the SED of the full sky HESE (High Energy Starting Events) events observed in 7 years [5]. It is also not yet clear which class of extragalactic population contributes more to the remaining $\sim$90% of the observed astrophysical neutrino flux, with GRBs and Star Forming Galaxies (SFGs) having already been excluded as dominant contributors [6].

Identifying electromagnetic counterparts for the IceCube astrophysical neutrino signal and characterizing their behavior can provide an answer to this question. The focus of this work has been to investigate the neutrino emission from blazars through a multi-messenger approach. We limit our study to gamma-ray activity of blazars, due to availability of continuous gamma-ray data through the Fermi-LAT [7] which allows us to probe the temporal correlation between the IceCube neutrino events and the periods of activity in the sources.

2. Source Selection

In this work we study the Fermi-LAT blazars that are spatially connected with the IceCube track-like events. In particular, EHE and HESE events (being part of the AMON alerts [8]) and muonic neutrino events reconstructed with a 50% containment error $\leq 1.5^\circ$ from [5], [9] were considered. We select the blazars of 3FHL and 3FGL catalogs [10] that satisfy the condition $|FermiLAT_{centroid} - IceCube_{centroid}| \leq 1.3^\circ$ and hence are strictly spatially connected with these neutrino events. This condition ensures the position of reported blazars within ~ 5 sq. deg. around the reconstructed astrophysical neutrino events. The list of blazars that satisfy this condition are reported in Table 1 with their corresponding redshifts, and source types. For each of them, we obtain the maximal gamma-ray luminosity reached during the 9.5 years of Fermi-LAT observation, considering different time binning and search for possible gamma-ray activity temporally correlated to a neutrino event. We report a particular study of the long term activity for TXS 0506+056 (the EM counterpart of IC170922A [11])and OP 313, a flat spectrum radio quasar (FSRQ) present in our sample of selected blazars. Markarian 421 is used just as a reference candle for the duty cycle (DC) study, being one of the most studied and closest BL-Lacs.

3. Analysis of γ-ray Data

We extracted data in the energy range 0.1 - 300 GeV within a 10° cone around the Region of Interest (ROI) of each source. The data reduction was made using Enrico, a community-developed Python package to simplify Fermi-LAT analysis [12], using the LAT analysis software

Table 1: Sample of blazars in spatial coincidence with selected IceCube ν_μ events

S.no.	Source Name	RA (deg)	Dec.(deg)	Source Class	z
1	OP 313	197.649	32.351	fsrq	0.998
2	SDSS J085410.16+275421.7	133.532	27.8826	bll	0.494
3	1RXS J064933.8-313914	102.386	-31.6491	bll	≥ 0.563
4	GB6 J1040+0617	160.147	6.3023	bll	0.7351
5	GB6 J1231+1421	187.866	14.368	bll	0.256
6	PKS 1454-354	224.382	-35.6478	fsrq	1.424
7	PMN J1505-3432	226.25	-34.5472	bll	1.554
8	PMN J2227+0037	336.972	0.6101	bll	-
9	PKS 2021-330	306.108	-32.9047	fsrq	1.47
10	TXS 0506+056	77.3636	5.7066	bll	0.3365

ScienceToolsv10r0p5 and including all known gamma-ray sources within each ROI reported in the third Fermi-LAT catalog [10] as well as the isotropic and Galactic diffuse emission components (iso_P8R2_SOURCE_v6_v06.txt and gll_iem_v06.fits). The Franceschini EBL absorption model was adopted throughout [13].

3.1 Gamma-Ray Duty Cycle

The duty cycle (DC) of a blazar is defined as the fraction of time the source spends in a high-activity state. Combined with the maximum luminosity achieved in gamma-rays, the range of DC values for blazars can provide information useful in identifying candidate sources for very high-energy neutrino emission, by correlation of gamma-flux with neutrinos through a lepto-hadronic model. The definition of a high-activity phase varies through literature, and the DC can be expressed by,

$$DC = \frac{T_{HE}}{T_{HE} + T_{bl}} \tag{3.1}$$

where T_{HE} is the total time in a high-energy phase and T_{bl} is the total time in the baseline state. Following [14], the DC can also be expressed as,

$$DC = \frac{\overline{F} - F_{bl}}{\langle F_{flare} \rangle - F_{bl}} \tag{3.2}$$

where $\overline{F}$ is the average flux in the observation period and in the energy range used for the selection of the data, F_{bl} is the baseline flux and $\langle F_{flare} \rangle$ is the average flux of flaring states. To infer the baseline flux we obtained the distribution of flux states for the observation period, considering 1 week bins, and as [15] reported for Mkn 421, it was best fit by a function consisting of a sum of a Gaussian plus a LogNormal distribution. The mean of the Gaussian function represents the upper limit for F_{bl} and the log-normal function is associated to the flaring states. Fig. 1 shows the distribution of the photon flux of TXS 0506+056 from Fermi-LAT over the period of 9.5 years.

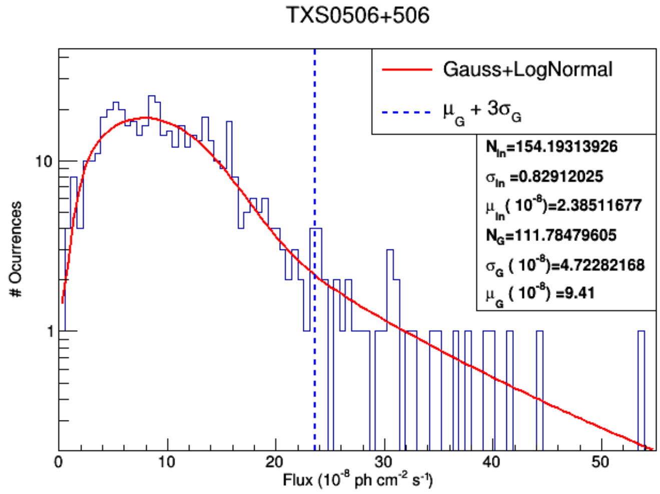

Figure 1: The flux state distribution for TXS 0506+056, with a Gaus+LogNormal fit

We defined the active state as the baseline flux (peak of Gaussian) + 3 times the σ of the Gaussian. EBL absorption was also considered. $\overline{F}$ for TXS 0506+056 was calculated to be 8.82 $\times$ 10^{-8}, with an error of 1.09 $\times$ 10^{-9}, and $\langle F_{flare} \rangle$ had a value of 2.896 $\times$ 10^{-7} (all fluxes are in ph cm^{-2} s^{-1}). Duty cycles were then calculated after determining these parameters for both the sources. As in seen from Fig. 2, duty cycles of the two sources are at the same level as each other and comparable to that of Mkn 421 on average. This puts them in the category of a select few very active blazars, and the high level of activity can present more chances of possible hadronic emission products being observed.

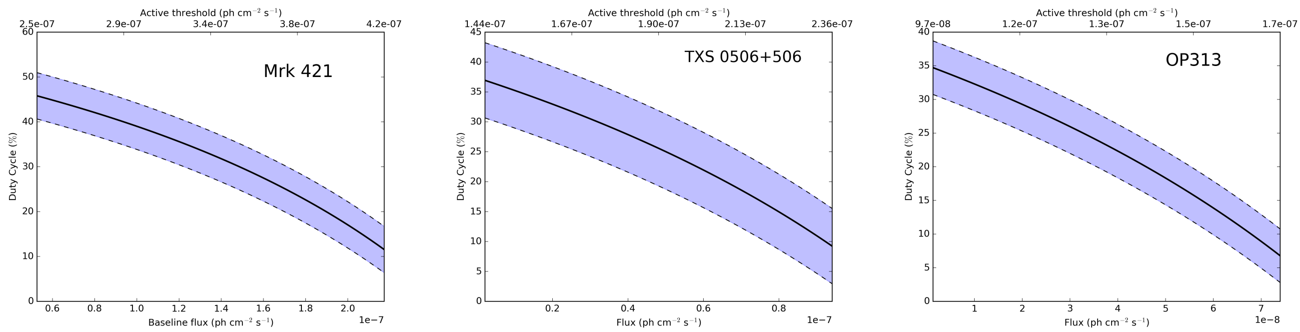

Figure 2: The gamma-ray duty cycles, left to right: Mkn 421, TXS 0506+056, OP 313

Since we assumed a lepto-hadronic emission from these sources with the same emitting region for gamma rays and neutrinos, we used the gamma-ray DC calculated through Fermi-LAT data to set also the DC of neutrino emission. It should be noted that the Gaus+LogNormal fit of [15] is only valid for sources that have well defined flare(s)/active states. Other than TXS 0506+056, OP 313 was the only other source in our sample that could be fit with this method to obtain a meaningful DC value, possibly due to its high average flux and a well defined flare. For the other sources with no prominent active periods, DC was calculated using a slightly modified approach from the one

Table 2: Isotropic γ-ray luminosities of the three blazars during their major flares. Average values of the duty cycles are also indicated

S.no.	Source Name	z	Luminosity (erg/s)	Duty Cycle (avg.)
1	Mkn 421	0.031	9.03×10^{44}	$\sim 29\%$
2	TXS 0506+056	0.3365	6.70×10^{46}	$\sim 23\%$
3	OP 313	0.998	6.81×10^{47}	$\sim 21\%$

described in [16]. The mean flux was calculated including the upper limits, and the threshold for active state was set to mean + 1σ. Only the bins whose errors bars lied entirely above the threshold were considered for the calculatin of active states. With this approach, only TXS 0506+056, OP 313 and PKS 1454-354 were found to have a DC of more than a few percent.

3.2 Luminosity during flaring period

Isotropic γ-ray luminosities between 0.1 - 300 GeV were calculated for the two blazars, TXS 0506+056 and OP 313 during their major flares. The cosmological parameters: H_0 = 67.8, Ω_m = 0.308, Ω_λ = 0.692 were assumed for calculation, and redshifts of the sources were taken from the text above. Flux values above the threshold of $3\sigma_G$ (derived by fitting the observations with a Gaussian+LogNormal distribution) were included in the calculation and an integrated luminosity over the thus obtained period was computed for each source.

Table 2 summarizes the luminosity values for each of these sources. It is immediately evident that even for its longest and brightest flare, Mkn 421, a rather bright local source, is outshone by TXS 0506+056 and OP313 by a factor of $\sim$ 75. Among the two farther away sources, OP 313 is more than 5 times luminous than TXS 0506+056 during its flare of April 2014 [17], thus presenting a strong case for its potential to produce very high energy (VHE) neutrinos if we consider the observed gamma-rays to be related to hadronic processes. The luminosity of TXS 0506+056, accounting for the different periods of integration, is compatible with the one obtained by [11]. It is worth pointing out that this result is strongly dependent on the redshift values of the sources through their luminosity distance.

4. Neutrino Observations

Both BL-Lacs and FSRQs can be considered VHE neutrino emitter candidates since their jets can accelerate protons up to ultra high energies (UHE). In this work we follow the [18] approach to estimate the expected neutrino flux from the source. We consider the gamma-ray data recorded by Fermi-LAT observatory between 1 - 300 GeV during the flaring period to be mainly produced by the synchrotron emission of pion cascade products inside the jet of the blazars considered. Different proportionality constants $K_{\nu\gamma}$ were considered to link this synchrotron emission measured between 1 - 300 GeV (L_γ) and the corresponding neutrino expectations between 100 TeV - 1 PeV (L_ν):

$$K_{\nu\gamma} = \frac{L_\nu}{L_\gamma}. \tag{4.1}$$

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The calculated neutrino fluxes $F_{\nu_\mu+\bar{\nu}_\mu}$ reported in Fig. 3 are obtained considering two different values for $K_{\nu\gamma}$, 1 and 0.4. In the following part we will refer to $K_{\nu\gamma}$ using simply a K. In this context, we assume low values of opacity caused by the interaction of photons of $\mathscr{O}(10^2)$ GeV with the Broad Line Region (BLR) photons [19].

4.1 Neutrino Observability during flare

We apply the scenario in [18] for different time bins, assuming a SED described by a power law with exponential cutoff. The neutrino flux obtained for the entire period of Fermi-LAT data taking (upto July 2018) is then compared to the discovery potential of IceCube telescope for the same time period. The position of the source as well the energy of expected neutrinos are also considered. This analysis is aimed at finding the minimum activity period needed to observe a possible EHE track-like event correlating the emission of 100 GeV photons with the one of 100 TeV neutrinos in the jet of the blazar. In Fig.3 we report the two cases of $K = 1.0$ and $K = 0.4$ for two of the blazars that we report in the sample: TXS 0506+056 and OP 313. We report two different discovery potentials for the IceCube experiment, [20] and [21] respectively.

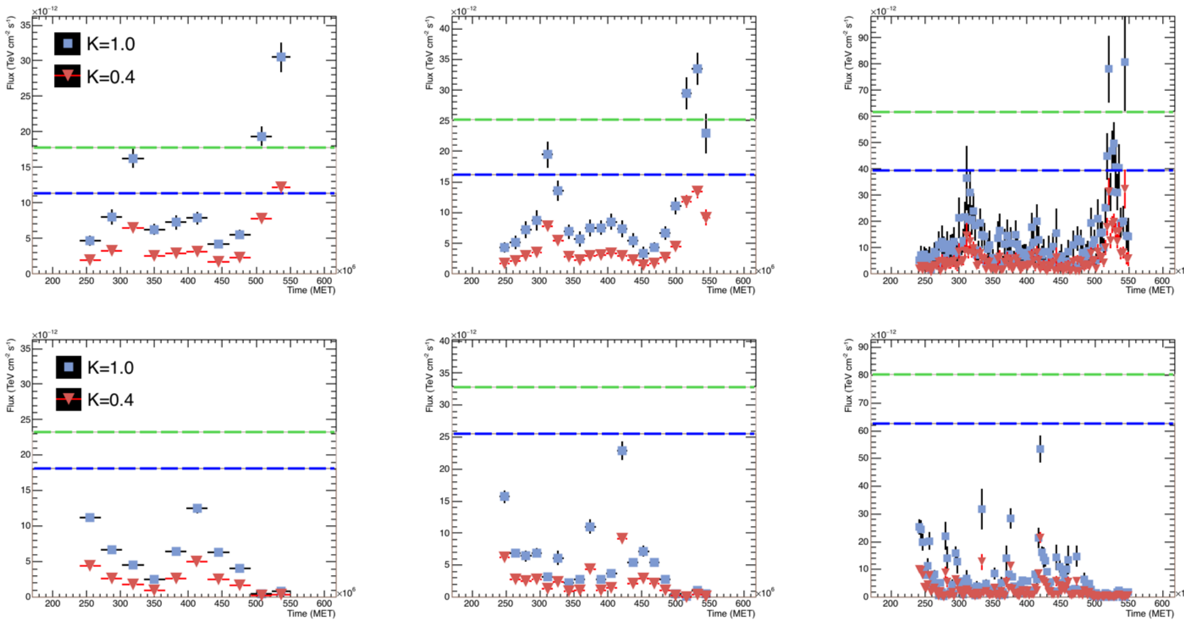

Figure 3: Neutrino LC of OP 313 and TXS 0506+056, On the upper part the neutrino light curve expected from TXS 0506+056 (on the left) and OP 313 (on the right) considering 1 year binning while on the lower part the same neutrino light curves with 6 months binning. The green and blue dotted lines correspond to the IceCube discovery potential with 50% confidence level from [20] and [21] respectively, scaled with time.

5. Discussion

For this work, we perform a more detailed study of the high-energy activity of two of the brightest blazars in our obtained sample: TXS 0506+056 and OP 313. This study shows that among the sample of selected blazars, only TXS 0506+056 presents a significant coincidence between the

EHE neutrino event and a long gamma-ray flaring activity. Neutrino light-curves are obtained with different time binning, assuming the Fermi-LAT data above 1 GeV to be mainly produced through the synchrotron emission from pion cascade products. A comparison with the IceCube discovery potential shows that the minimal flaring time needed to observe with IceCube telescope an integrated neutrino flux above 100 TeV requires the order of several months even for a very luminous BL-Lac like TXS 0506+056. From among the sample of blazars built, the other objects which show a higher level of gamma-ray activity and a long flare duration are the FSRQs PKS 1454-354 and OP 313, however only TXS 0506+056 has a computed neutrino flux above the IceCube discovery potential level, when a time bin of one year or six months is selected. This can partly be attributed to the important role played by EBL absorption at energies above 100 GeV at the high redshifts of these FSRQs, and for the case of PKS 1454-354, also to the fact that its major flare was in the initial years of IceCube, when the detector was still not operating in its full configuration.

In this analysis we take into account also the Duty Cycle estimated with the 9.5 years of Fermi-LAT data. Quite similar DC is obtained for the BL-Lac TXS 0506+056 (avg. DC $\sim 23\%$) and for the FSRQ OP 313 (avg. DC $\sim 21\%$) using the [14] definition. We also calculated the DC for the sample (wherever possible) using the modified [16] approach described in 3.1. Both the approaches suggest that TXS 0506+056, OP 313 and PKS 1454-354 have the higher DC values among the sample, but TXS 0506+06 and OP 313 are found to have a higher flux on average.

In [22] the KM3NeT collaboration has reported the 90% C.L. sensitivity and 5σ discovery potential of the upcoming KM3NeT-ARCA detector to TXS 0506+056 during its gamma-ray flare. For one year of observation time, the 5σ discovery potential is found to be $\sim 7.3\times10^{-12}$ $TeV\,cm^{-2}s^{-1}$. For a flare with the same gamma-ray intensity as that of 2017-18, KM3NeT-ARCA would need six months or less to detect the source with a significance $> 5\sigma$, assuming $K = 1$ in the [18] approach for neutrino flux estimation. Even for $K = 0.4$, the KM3NeT-ARCA should be able to detect the source in 1 year of observation.

6. Conclusion

We construct a sample of blazars with enhanced gamma-ray emission spatially and temporally correlated with some selected neutrino events reconstructed by IceCube. With the built sample we compare the time dependent high-energy activity of the BL-Lac TXS 0506+056 with one of the other possible VHE neutrino sources, OP 313. The FSRQ OP 313 was able to fulfill the criteria of spatial correlation with an EHE, but without the time correlation between the event and the gamma-ray flare. Its high average flux, and the DC comparable to TXS 0506+056, highlight its capability of being considered another important candidate for VHE neutrino emission. In this work, two important aspects of blazars are examined: the Duty Cycle, and the minimum flare duration required to be observable with a kilometric neutrino telescope. We show that the minimum activity expected from the more luminous BL-Lacs (the most luminous 3% of the 3FHL catalog) should be of the order of a few months to be observable through a kilometric neutrino telescope. The DC parameter, at the level of $\sim 23\%$ on average for the more luminous blazars in the sample, suggests that the first possible multi-messenger observation with IC170922A and the gamma-ray flare of TXS0506+056 might not be ununsual given the infrequent flares combined with the long periods of low activity in blazars. With these considerations we have to conclude that the preferential way to reach a 5σ confidence in the future with multi-messenger observations for blazars, will be the simulataneous data taking of a Global Neutrino Network comprising several km^3 spread around the word. This will soon be possible with the upcoming KM3NeT and Baikal-GVD telescopes.

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