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Time-Dependent Sensitivity and Discovery Potential for the KM3NeT-ARCA detector

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The blazar TXS 0506+056 underwent a major gamma-ray flare in 2017, lasting more than a year. The continuous gamma-ray data available during the flare and the long duration of the flare are advantageous to study the neutrino emission potential of the source, assuming correlation between the observed gamma flux and the neutrino flux. KM3NeT-ARCA is an upcoming km^3 Cherenkov Telescope in the Mediterranean Sea, capable of studying astrophysical point-sources of neutrinos with a median angular resolution of upto 0.1°.

In this contribution, the sensitivity and discovery potential of the KM3NeT-ARCA detector to TXS 0506+056 are reported as a function of time during its flare. For a gamma-ray flare with the same luminosity as that of 2017-18, we find that KM3NeT-ARCA would need six months or less to detect the source, depending on the model assumed. Assuming a constant average flux, the source would be detectable with a significance $> 5\sigma$ in 2 years of observation.

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1. Introduction

IceCube found evidence for a neutrino event spatially and temporally correlated with an astrophysical point-source. The blazar TXS 0506+056, lying within the error-radius of an IceCube EHE event (IC170922A) dated 22nd Sept. 2017, with energy ~ 290 TeV, was found to be in a flaring state by Fermi-LAT during this period. Subsequently, the MAGIC telescope also observed activity from the source in the energy range of 80-400 GeV between September 28^{th} to October 4^{th} [1]. The analysis of this BL-Lac by the IceCube Collaboration, using the data collected in the last 8 years, also showed a 3.5σ excess in the sample of reconstructed muonic neutrino events, suggesting this BL-Lac to be the first identified source emitting very high energy (VHE) neutrinos. The gamma-ray flare from this source lasted for more than one year. With the Fermi-LAT collecting data continuously during this period, it is possible to study the gamma-ray emission from this source during the flaring state and correlate it with the neutrino emission assuming a lepto-hadronic model. TXS 0506+056, thus, presents an interesting case study in the multi-messenger context.

The KM3NeT experiment is a next generation deep-sea Cherenkov neutrino detector under-construction in the Mediterranean Sea. Its main objectives are (i) the discovery and subsequent observation of high-energy neutrino sources in the Universe with the **ARCA** (Astroparticle Research with Cosmics in the Abyss) telescope, and (ii) the determination of the mass hierarchy of neutrinos with the **ORCA** (Oscillation Research with Cosmics in the Abyss) detector [2]. ARCA will be devoted to neutrino astronomy, with its primary objective being the detection of high-energy cosmic neutrinos. When completed, it will consist of two building blocks, with a total volume of $\sim 1\ km^3$. By virtue of its location in the Northern hemisphere, it will provide a complementary field of view to the Icecube observatory, and upon completion, in combination with IceCube and the Baikal Deep Underwater Neutrino Telescope, will form a global network of neutrino telescopes (GNN).

At a declination of 5.69°, TXS 0506+056 lies at a good position to be observed by ARCA. We can take advantage of the long duration of its flare to study the sensitivity of the detector to this source as a function of time, with varying time-bin sizes. For this analysis, Fermi-LAT [3] gamma-ray data between 1-300 GeV is used, and correlated with the neutrino flux at TeV - PeV scale using two different models ([4], [5]). These extrapolated neutrino fluxes are then compared with the sensitivity and discovery potential of the ARCA detector in time-bins of different sizes in and around the flare of 2017-18.

2. Estimation of neutrino flux from the source

To estimate the neutrino flux from the source, two models have been utilized. The first is the model proposed by Petropoulou et al. in their 2015 paper [4], and the second is the parameterization from Kelner & Aharonian [5].

The Petropoulou model assumes that the observed gamma-rays are produced by synchrotron emission of pion cascade products in the jets of the blazars. The neutrino flux at 100 TeV is pro-

Table 1: Time ranges and normalization constants (Φ_0) for the different time bins as per the Petropoulou model

Time Bin	Time Range (Julian)	Fermi-Mission Elapsed Time	Φ_0 ($TeV^{-1}cm^{-2}s^{-1}$)
2 year	01.01.2017 - 31.12.2018	504921604 - 567907205	1.85×10^{-11}
1 year	16.04.2017 - 16.04.2018	513993605 - 545529605	2.47×10^{-11}
6 months	01.07.2017 - 31.12.2017	520560005 - 536371205	2.70×10^{-11}
1 month	26.06.2017 - 25.07.2017	520128005 - 522633605	3.79×10^{-11}

portional to the gamma-ray flux observed at 100 GeV. The model is applicable to blazars with a relatively high luminosity.

Kelner & Aharonian provide a parameterization for the energy spectra of gamma-rays, electrons and neutrinos produced in p-π interactions. For a source emitting with an E^{-2} spectrum, the total ν-flux is $\sim$ 0.45 times the gamma-ray flux at a given energy. The flux for muonic neutrinos can be obtained by dividing by three the total gamma flux at GeV energies.

The neutrino fluxes for the two models were obtained by looking at the gamma-ray emission of TXS 0506+056 in the Fermi-LAT data. Light curves of the source were obtained for the bins of 2 years, 1 year, 6 months and 1 month in the energy range of 1-300 GeV, and the flux for each bin was then extrapolated to the corresponding muonic neutrino flux as per the two models. The time bins were chosen such as to maximally contain the flare, and/or the peak of the flare. The values of the normalization fluxes for the 4 time bins are shown in Table 1 . Fig. 1 shows a Fermi-LAT light curve of TXS 0506+056 over 10 years of observation, with a binning of 6 months. The gamma-ray flare, spanning over 3 bins of 6 months can be seen towards the end of the lightcurve.

3. Analysis Overview

For the analysis presented in this work, the sensitivity calculation is based on the Cut&Count method described in [6]. The signal to background ratio is increased by imposing cuts on variables related to the fit quality and direction of the reconstructed tracks. The signal here refers to the events from the source, while the background consists of the atmospheric neutrinos and muons. After applying all the cuts, the remaining signal and background events are summed up, and the value of sensitivity and discovery potential of the detector are evaluated. More details on the event selection is provided in Section 3.2.

The Cut&Count method is a relatively quick and efficient method to obtain the sensitivity and discovery potential, although an improvement can be obtained by employing machine learning and statistical approaches, as in [7].

3.1 Monte-Carlo Sample

Monte-Carlo (MC) simulated events are used to describe the detector response to atmospheric

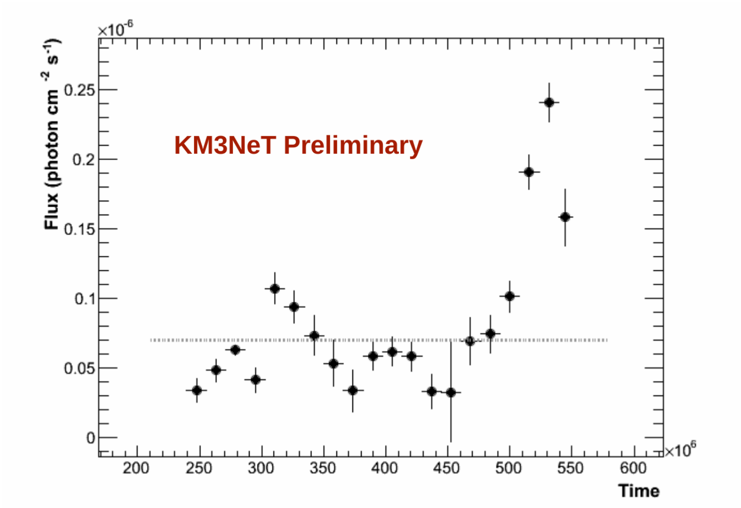

Figure 1: The Fermi-LAT light curve for the blazar TXS 0506+056 in the range 1-300 GeV over 10 years of observation. The X-axis is in MET (Fermi-Mission Elapsed Time in seconds), with a binning of 6 months, and the flux is given in photons/cm^2/s. The last 3 bins constitute the gamma-ray flare.

neutrinos and atmospheric muons, and a dedicated simulation for the source declination in point-like mode is used for the signal events. Only track-like events are used for the analysis. Both CC and NC interactions of (*anti-*)ν_μ and (*anti-*)ν_e are considered for atmoshpheric neutrinos while for the source only ν_μ and (*anti-*)ν_μ events are simulated. The MC event-generation, detector response and reconstruction strategies for the muon and neutrino files, as well as the weights used for the atmospheric neutrinos and muons, are described in [6], and the references therein. An energy spectrum $\propto E^{-2}$ is considered for the signal events, with the normalization constant obtained from the gamma-ray data as per the models described in Section 2.

3.2 Event selection

A pre-selection of events was done from the signal and background MC files by cutting on the following key variables, which are output by the track reconstruction code:

1. $\boldsymbol{\theta}$: The reconstructed zenith distribution of the source and background

2. $\boldsymbol{\alpha}$: The angular distance of the reconstructed track from the nominal source position

3. $\boldsymbol{\lambda}$: Likelihood given by the track reconstruction procedure, correlated with the quality of reconstruction

4. $\log_{\mathbf{10}}(\boldsymbol{\beta})$: Logarithm of the error estimate on the fit, calculated as $\sqrt{((err_{vx})^2 + (err_{vy})^2)}$, where err_{vx} and err_{vy} are the errors estimated for the versors x and y of the reconstructed track in the reference system where the track is on the z axis

Table 2: Final cut values for the discovery potential calculation in one year

Parameter	Range/Value
θ	$\theta < 100°$
α	$\alpha < 1°$
λ	$\lambda > 125$
$\beta 0$	$\log_{10}(\beta) > -2.0$
E_{rec}	$\log_{10}(E_{rec}) > 2.90$

5. $\mathbf{\log_{10}(E_{rec})}$: Logarithm of the reconstructed energy

The distribution of the reconstructed energy before any cuts is shown in Fig. 2 for MC signal and background events. The Petropoulou model has been used for source normalization.

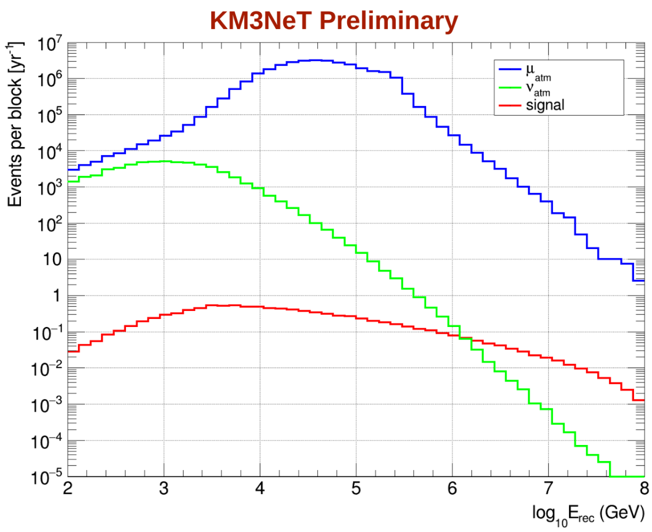

Figure 2: Distribution of reconstructed energy for signal and background from MC, without any cuts. The source has been normalized using the Petropoulou model flux in one year.

Background events are rejected by selecting up-going events and by requiring the reconstructed track to be compatible with the nominal source position. The λ and β are used to reject the poorly reconstructed tracks. The event selection criteria for the case of discovery potential calculation in one year are shown in Table 2. Fig. 3 shows the E_{rec} distribution of signal and background events after the event selection, using the Petropoulou model [4] for source normalization. All the atmospheric muons are rejected after applying the selection criteria.

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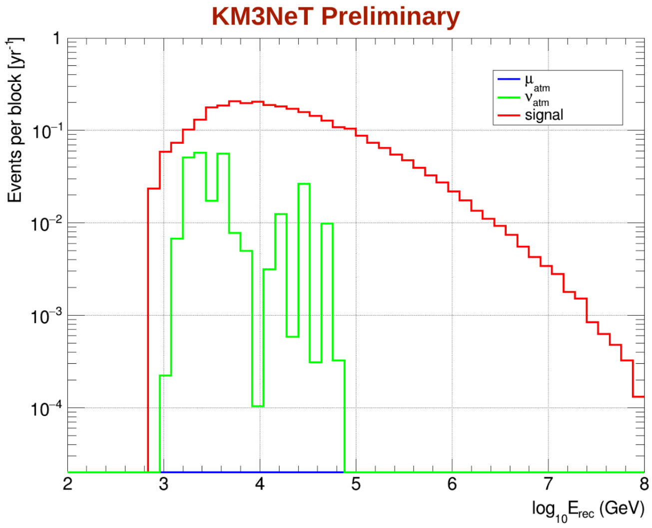

Figure 3: Distribution of reconstructed energy for signal and background from MC, with cuts on zenith ($\theta < 100°$), α ($\alpha < 1°$), λ ($\lambda > 125$), β ($log_{10}(\beta) > -2$) and E_{rec} ($log_{10}(E_{rec}) > 2.90$)

4. Sensitivity and Discovery Potential

Applying the Cut&Count method, with the selection criteria from Table 2, the time-dependent sensitivity at 90% C.L.and 5σ discovery potential with 50% probability are calculated for the full ARCA detector for 2 years, 1 year, 6 months and 1 month of observation time. In Fig. 4, the sensitivity and DP are compared to the expected fluxes from the two models considered ([4], [5]). Both models predict a discovery of over 5σ in six months or less, for a gamma-ray flare with a similar luminosity as that of 2017-18. The Petropolou model provides a more optimistic picture than the Kelner model.

Also shown in Fig. 5 is the time-averaged muonic neutrino flux expected from TXS 0506+056 (averaged over 10 years of Fermi data) derived from the Kelner parameterization. A source with an equivalent average flux will be visible to ARCA in 1 year, and should be detectable with a significance of $> 5\sigma$ in 2 years.

The discovery potential is minimized for the parameter values provided in Table 2. The expected signal to background ratio for one year of observation is 3.05 source events to a background of 0.25 atmospheric neutrinos and 0 atmospheric muons, assuming Petropoulou normalization. For the same time period, ARCA is sensitive to a minimum flux of $3.58 \times 10^{-12}\ TeV cm^{-2} s^{-1}$ from the source TXS 0506+056, and a flux of $7.3 \times 10^{-12}\ TeV cm^{-2} s^{-1}$ is required for a 5σ discovery in 50% of equivalent experiments. These values can be further improved by adopting a more sophisticated approach, like in [7].

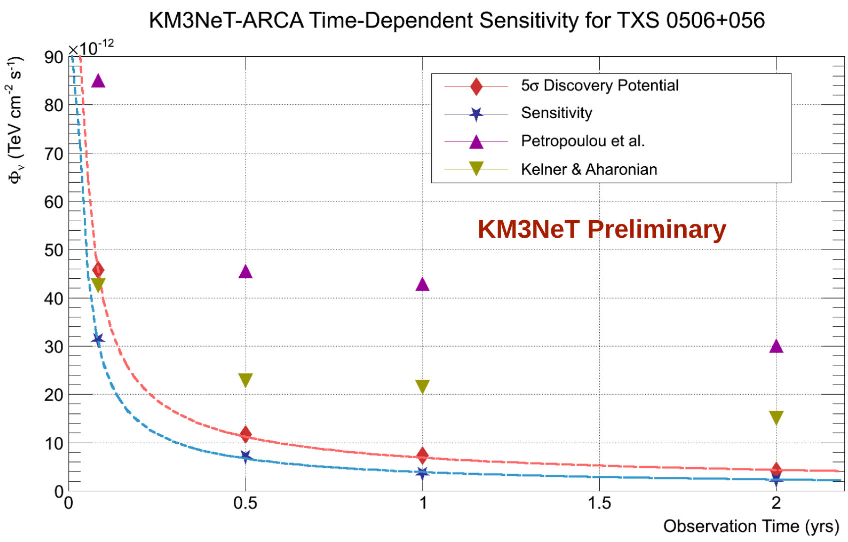

Figure 4: The 90% C.L. sensitivity and 5σ discovery potential with 50% probability for 2 blocks of KM3NeT-ARCA to the blazar TXS 0506+056, shown with the expected neutrino fluxes from TXS 0506+056 during its gamma-ray flare, derived with the Petropoulou and the Kelner models

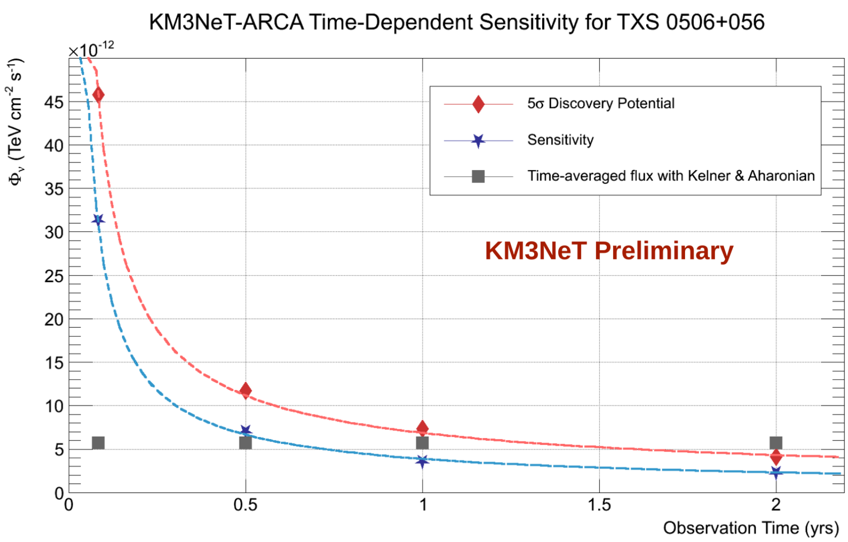

Figure 5: The 90% C.L. sensitivity and the 5σ discovery potential with 50% probability for 2 blocks of KM3NeT-ARCA to the blazar TXS 0506+056, shown with the expected neutrino flux from TXS 0506+056 over a long observation period (derived using the Kelner parameterization)

5. Discussion

It is important to note that the results obtained here for the estimated flux from TXS 0506+056, and the expected number of events in the detector from this source, are strongly model dependent, and will differ with different assumptions. For instance, while applying the Kelner parameterization and the Petropoulou model, we have assumed a 100% hadronic origin of the gamma-ray flux, although for most of the blazars, including TXS 0506+056, lepto-hadronic, instead of purely hadronic models are favored. The time period for observation and a 5-sigma discovery will go up significantly, depending upon the percentage of gamma-flux that is hadronic.

6. Conclusion

The sensitivity and discovery potential for 2 building blocks of ARCA have been evaluated for the blazar TXS 0506+056, by applying the Cut&Count approach. Neutrino flux from the source is estimated from the observed gamma-rays in the range 1-300 GeV using the Petropoulou and Kelner models. For the flare of 2017-18, ARCA would need 6 months or less of observation to detect the source with a significance $> 5\sigma$. If a constant time-averaged flux from the source is assumed, it should still be detectable within 2 years of observation.

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