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The Sensitivity of KM3NeT to Potential Neutrino Signals from Extragalactic Gamma-Ray Sources

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Abstract: The proposed northern-hemisphere, cubic-kilometre underwater neutrino detector, KM3NeT, promises unprecedented sensitivity to potential fluxes of neutrinos from southern-hemisphere, gamma-ray counterparts. Gamma-ray observations of AGN are used to set upper limits on the neutrino production rate in these potential extragalactic cosmic-ray engines. Absorption of gamma rays by the extragalactic background light is taken into account and estimates of both signal and background neutrino fluxes within KM3NeT over 5 years of observing are presented. A *melted-IceCube* benchmark design is used for the KM3NeT detector geometry and photo-detection scheme. Both the integral and differential sensitivity of the detector are discussed. It is found that the brightest, most distant gamma-ray sources may produce neutrinos detectable above the atmospheric background in KM3NeT at energies greater than 1 TeV. The feasibility of a differential detection, resulting in a measurement of the neutrino spectrum, is less likely though not excluded.

Introduction

An increasing population of VHE blazars are emerging as the gamma-ray horizon is pushed to higher redshifts by the latest generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) operating at ever lower energy thresholds. Southern-hemisphere gamma-ray sources detected by H.E.S.S., such as the blazars PKS2155-304 [1], PKS2005-489 [2], H2356-309 [3], and 1ES1101-232 [11] are also potential targets for a deep-sea neutrino detector in the northern hemisphere. The proposed cubic kilometre underwater neutrino detector, KM3NeT, offers the best opportunity yet of providing a neutrino counterpart to these violent extragalactic phenomena. Currently in a 3 year design study, KM3NeT will be based in the Mediterranean at a depth of at least 2.5 km. A three dimensional array of photo-detectors will record flashes of Cherenkov light produced by ultra-relativistic muons as they traverse the detector volume. Whilst these muons may be due to astrophysical neutrinos they may also be due to the overwhelming background of atmospheric neutrinos produced isotropically in cosmic-ray initiated air showers. The direction and energy of both muon and neutrino are reconstructed after the application of offline trigger criteria, used to discern background from source. KM3NeT will cover a volume of at least 1 km^3 and contain in the region of 10,000 photo-detectors. A neutrino angular resolution of $< 0.5°$ is desired across the accessible energy range of $\sim$200 GeV to over 200 TeV and neutrinos will be reconstructed to within a factor of two of their true energy. Optimisation of the detector design to achieve the desired performance at an affordable cost is a key goal of the KM3NeT design study [4]. The performance of a given design, including the geometric layout, the choice of detector elements and the readout scheme to a set of scientific cases must be assessed and a set of benchmark fluxes are obtained. These include the sensitivity to potential galactic sources of neutrinos [5], dark matter annihilations, the diffuse galactic and extragalactic emission and, as considered here, the sensitivity to extragalactic point sources of neutrinos. A KM3NeT benchmark architecture, constituting the same geometric make up and photo-detection scheme as a *melted-IceCube* [6] has been declared to compare benchmark fluxes and normalise simulations prior to optimisation and will be used here.

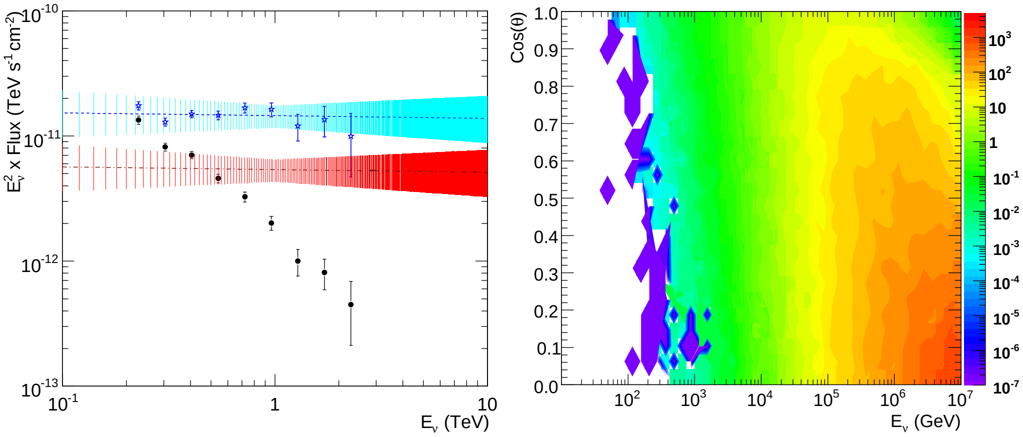

Figure 1: (a) Spectra of PKS2155-304: the measured gamma-ray spectrum (black circles), the estimated intrinsic gamma-ray spectrum (blue stars) fitted according to Eq. 1 (blue short-dashed line) with error region (cyan area) and the upper limit on the neutrino spectrum (red dashed line) with error region (red area). (b) The effective area (in m^2) of KM3NeT to neutrinos as a function of zenith angle for the *melted-IceCube* KM3NeT benchmark geometry requiring at least 6 detector storeys to be hit by photons from the muon.

Obtaining the Neutrino Spectrum

The gamma-ray spectrum measured at Earth is not equivalent to that at the source due to extragalactic background light (EBL) absorption. A prediction for the intrinsic spectrum is given following the low-SFR model obtained by Kneiske [9]. As an example the black, circular, data points in Figure 1(a) show the measured spectrum of PKS2155-304 obtained by H.E.S.S. The effect of the EBL is energy dependent and the resulting intrinsic spectrum, shown in blue stars, is hardened. As the amount of EBL absorption depends on the redshift of the source the spectra of distant blazars are most significantly altered.

The most effective gamma-ray production mechanisms within blazars by protons are photomeson interactions and synchrotron radiation of protons. Whilst the first mechanism does not provide many neutrinos at energies below 10^{16} eV, the second one does not lead to neutrino production at all. The purpose of this work is to produce upper-limits on the neutrino production. The maximum number of neutrinos are produced if the gamma-ray emission is dominated by the decay of neutral pions produced in *pp* interactions. Following the parameterisation of the pion and secondary particle production in hadronic interactions in [8] the gamma-ray spectrum may be related to the neutrino spectrum via the formulation in [7] given, in the absence of an energy cut-off by:

$$\frac{dN_{\gamma/\nu}}{dE_{\gamma/\nu}} = \kappa_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1TeV} \right)^{-\Gamma_{\gamma/\nu}}, \qquad (1)$$

where the parameters κ and Γ describe the normalisation and spectral index respectively. Eq. 1 represents the muon neutrino spectrum on Earth assuming full mixing of the electron and muon neutrinos, produced at the source in the ratio $\nu_e : \nu_\mu = 1 : 2$ and arriving at the Earth as $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. The parameters of the gamma-ray spectrum are related to those of the neutrino spectrum by: $\kappa_\nu \approx [0.71 - 0.16(\Gamma_\gamma + 0.1)]\kappa_\gamma$ and $\Gamma_\nu \approx \Gamma_\gamma$. The intrinsic gamma-ray spectral points are fitted using Eq. 1 as shown by the blue, dashed, line in Figure 1(a). The fit parameters are then used to obtain an upper limit for the muon neutrino spectrum, indicated by the red long-dashed line in Figure 1(a). The 1 σ systematic uncertainties are shown in the shaded regions for both the gamma-ray and neutrino spectra.

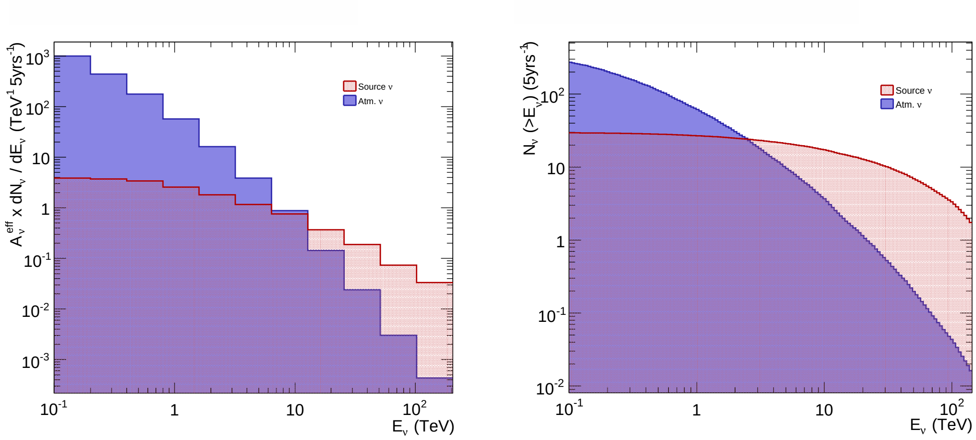

Figure 2: Upper limits on the differential (a) and integral (b) number of neutrinos observable in KM3NeT from PKS2155-304 after 5 years of operation (red) and the expected atmospheric neutrino background (blue). Differential results have been calculated assuming a bin size equal to the energy resolution of the detector. Where it is taken that neutrinos will be reconstructed to within a factor of two of their true energy. The reduction in integral flux at high energies is steepened due to the finite range of the differential plot (from which the summed number of events is obtained).

Source	z	f_o	ν Param.		$> 1TeV$			$> 5TeV$		
			κ	Γ	N_ν^s	N_ν^{atm}	σ	N_ν^s	N_ν^{atm}	σ
1ES1101-232	0.186	63.21	4.91	1.11	599	53.5	39.9	586	8.08	48.7
H2356-309	0.165	68.47	2.47	1.34	126	62.2	12.0	121	9.7	18.3
PKS2155-304	0.0117	68.14	5.38	2.02	26.9	61.7	3.04	21.0	9.59	5.00
PK2005-489	0.0710	100.0	0.0930	3.30	0.0715	90.7	0	0.0145	14.4	0

Table 1: Upper limits for the integral event rate from candidate blazars above 1 TeV and 5 TeV including the expected atmospheric neutrino rate and the statistical significance of source over the background for 5 years of observing with the *standard* KM3NeT geometry.

The Neutrino Event Rate in KM3NeT

The number of observed events in KM3NeT, N_ν^s, from a differential flux of neutrinos at the Earth's surface, dN_ν/dE_ν, between E_{min} and E_{max} is given by:

$$N_\nu^s = T_o f_o f_c \int_{E_1}^{E_2} A_\nu^{eff}(E_\nu,\theta)\frac{dN_\nu}{dE_\nu}dE_\nu, \quad (2)$$

where T_o is the total exposure time, taken here to be 5 years, and f_o is the fraction of the day for which the source is visible to KM3NeT, 68% in the case of PKS2155-304. $A_\nu^{eff}(E_\nu,\theta)$ is the energy and zenith angle, θ, dependent effective area of KM3NeT to neutrinos. Figure 1(b) shows the effective area as a function of neutrino energy and the cosine of the zenith angle of the source, where *0* is horizontal and *1* is directly down towards the Earth. At most zenith angles the effective area increases steadily before reaching a plateau, but when looking directly downwards the Earth begins to become opaque to neutrinos above $\sim 10^6$ GeV and the effective area drops. In the energy range encompassed by the measured TeV gamma-ray spectrum the effective area does not vary significantly with zenith angle and the dependence is accounted for by calculating a daily average effective area for each source. f_c represents the fraction of events contained within a cone of size ϕ placed around the source on the sky, which in turn depends on the angular resolution, $\sigma_{ang.res.}$, of the detector. Here the angular resolution is taken as 0.5° across all energies. It can be shown that the optimum cone opening angle for a point source is then given by $1.585 \times \sigma_{ang.res.}$.

The number of expected atmospheric background neutrinos, N_{ν}^{atm}, is calculated in a similar way to the number of source neutrinos, where the differential atmospheric background flux is given by the parameterisation in Volkova [12] and the zenith angle dependence is accounted for by computing the daily averaged atmospheric neutrino flux.

Results and Conclusions

The upper limit differential and integrated event rates for neutrinos from PKS2155-304 and the atmospheric background are shown in Figure 2. Upper limits on the integral flux are shown in Table 3 for the four candidate blazars. The statistical significance of the detection has been estimated using Eq.17 in [10], where the total expected background is estimated by choosing 10 background regions of the equivalent size to the cone placed around the source and at the same zenith angle.

The most distant blazars are the most promising neutrino candidates. These are most effected by the EBL. The effect of EBL absorption also increases with energy, and as no cut-off is observed in any of the candidate gamma-ray spectra detection is most likely at high energies ($> 5TeV$). However, this distant, high energy regime is extremely susceptible to inaccuracies in the EBL model. Furthermore any predictions above a few TeV exceed the range of the measured gamma-ray spectra and are therefore speculative. The intrinsic spectral index of the most distant blazar here, 1ES1101-232 at $z = 0.186$, is found to be *-1.1*. This is extremely hard and physically unlikely. A differential detection of any of the candidate blazars seems unlikely at all but perhaps the highest energies, even assuming the optimistic upper limits presented here. The question of whether a KM3NeT design optimised for high energies could reach the sensitivity required for spectral reconstruction remains open.

This work provides a benchmark for comparing KM3NeT detector designs, but the susceptibility of the results to the EBL model is clear and the best fit Kneiske model appears to over estimate the effect of the EBL. In the event of lower EBL limits (currently under consideration), the upper limits shown here will drop. The assumption that the neutrino flux results from a *pp* dominated gamma-ray production mechanism is optimistic. Photomesson interaction will be taken into account in the near future. The *melted-IceCube* benchmark design used for the KM3NeT detector geometry and photo-detection scheme is not optimised for an underwater enviroment. As other detector architectures become available this work will be repeated. Finally note that the strong variability of the TeV gamma-ray emission from blazars creates an inherent uncertainty in the expected neutrino flux. Longterm monitoring of blazars in TeV gamma-rays over several years is required to more stringently constrain the neutrino flux.

Acknowledgements

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