Detection of cosmogenic neutrinos with the KM3NeT telescope

R. Shanidze *, B. Herold, D. Stransky, for the KM3NeT Consortium**

Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany

Abstract

Cosmogenic neutrinos are produced during the propagation of ultra high energy cosmic rays (UHECR) through the cosmological microwave background radiation. The extragalactic origin of UHECR guarantees generation of high energy cosmogenic neutrinos, however the flux depends on the currently unknown properties of UHECR, for example the chemical composition and distribution of the sources and their evolution with redshift. Estimations of cosmogenic neutrino fluxes, which are constrained by UHECR observations, include a range of models in which a detectable signal could be produced in a very large volume high-energy neutrino telescope. In particular the favorable scenarios are based on the models with a pure proton composition. The possible event rate of cosmogenic neutrinos in the KM3NeT telescope for the different flux models is discussed in this paper.

Keywords: KM3NeT, cosmogenic neutrino, neutrino telescope
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1. Introduction

The search for a cosmogenic neutrino flux is among the main goals of current and future high energy neutrino telescopes. This extragalactic diffuse neutrino flux is expected to be formed during the propagation of ultra high energy cosmic rays (UHECR) through the extragalactic photon fields. Energy loss of UHECR particles above the charged pion photo-production threshold is known as a GZK mechanism. It was first studied by Greisen [1], and Zatsepin and Kuzmin [2], soon after the discovery of CMB radiation. This mechanism predicts a strong suppression of an extragalactic UHECR spectrum above about 5×10^{19} eV, which is known as GZK cut-off. It effectively reduces the event horizon for UHECR particles to about 100 Mpc and "guarantees" the existence of the diffuse flux of cosmogenic neutrinos. Cosmogenic neutrinos could also be produced at lower cosmic ray energies, through interactions with extragalactic infrared(IR), optical(Opt) and ultraviolet(UV) background photons.

Detection of a faint flux of high energy cosmic neutrinos requires a neutrino telescope with an instrumented volume of 1 km^3 or above. The first telescope of km^3 size, the IceCube at South Pole, is taking data in its final configuration since 2011. The current most stringent limit on the high energy astrophysical neutrinos (above PeV energy) was obtained from the data of the half-completed IceCube detector [3].

The future Mediterranean deep-sea neutrino telescope KM3NeT [4], which was developed in EU commission supported design study project, is expected to have a multi-km^3 instrumented volume. In this paper we present a first estimation of contained neutrino event rates in the KM3NeT telescope for different models of cosmogenic neutrino fluxes.

2. Cosmogenic neutrino flux

The cosmogenic neutrino flux is defined by the UHECR characteristics and the energy distribution and density of extragalactic photons. Flux estimations require the knowledge of the UHECR energy spectrum, the maximum acceleration energy (E_{max}) in the source, the composition of the UHECR particles, transition energy between galactic and extragalactic cosmic rays and the spatial distribution of the sources and their cosmological evolution.

Starting from the first estimation by Berezinsky and Zatsepin [5], several groups have calculated the cosmogenic neutrino flux, assuming different sets of input parameters, constrained by the available UHECR data. For example the IceCube collaboration is using the flux models developed in the papers [6–8].

In our study we have used the cosmogenic neutrino fluxes obtained in [9] for a large set of parameters. A power law spectrum was assumed for cosmic rays between 10^{16} eV and $Z \times E_{\max}$, where Z is the charge of the UHECR nuclei. The sources were distributed between redshifts(z) of 10^{-3} and 8 and their emission was weighted according

*Corresponding author; phone: +49-9131-85-270-91 fax: +49-9131-85-28-774
**URL: www.km3net.org
Email addresses: shanidze@physik.uni-erlangen.de (R. Shanidze), Bjoern.Herold@physik.uni-erlangen.de (B. Herold), Dominik.Stransky@physik.uni-erlangen.de (D. Stransky)

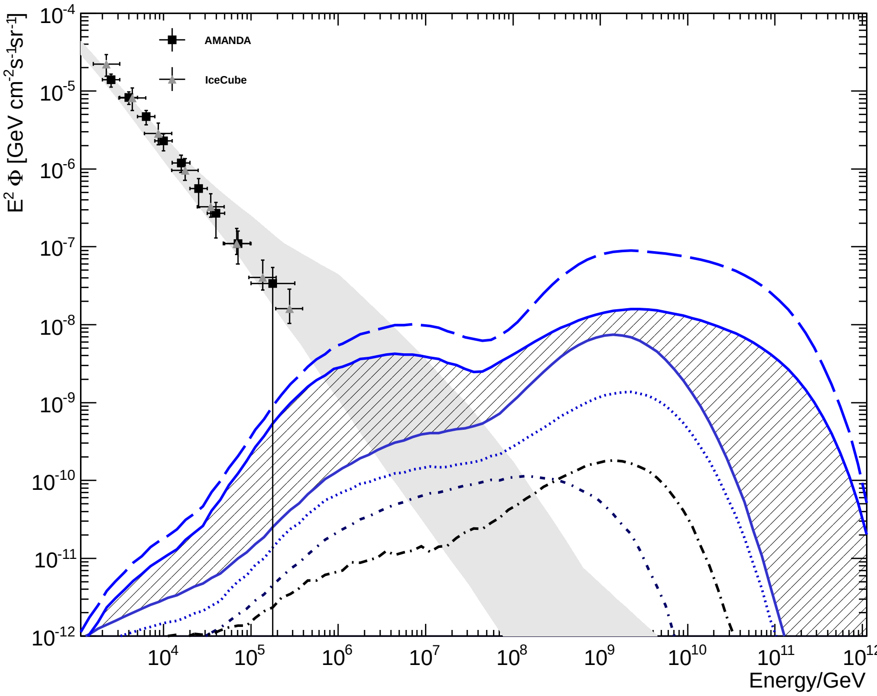

Figure 1: Cosmogenic neutrino flux (see text for description) calculated for the different parameters of UHECR together with atmospheric flux models (presented as a gray shaded area) and flux measurements for ν_μ at the South Pole.

to the different source evolution models. The particle composition was varied from pure proton to pure iron composition, including galactic mixed and iron rich composition models. For the galactic to extragalactic transition, two models have been considered: the so called "ankle" transition and "dip" models. For cosmogenic neutrino flux models, the calculations were adjusted to the UHECR data obtained in the Auger experiment [12]. The cosmogenic neutrino flux, obtained for the different sets of UHECR parameters and source evolution models are presented in Fig. 1. The shown flux includes all neutrino flavors. During the propagation over cosmological distances, the neutrino flavors are fully mixed: $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

The largest cosmogenic neutrino flux (long dashed line) is obtained in a case of pure proton composition with $E_{\mathrm{p,max}} = 10^{21.5}$eV, dip transition model and strong source FRII (Faranoff-Riley type II galaxies) evolution. The least favorable (pessimistic) cases for the cosmogenic flux correspond to iron rich compositions, low $E_{\mathrm{p,max}}$ and an uniform evolution of UHECR sources. These fluxes are given in Fig. 1 as dotted-dashed lines. Between these extreme cases are the cosmogenic flux models included in the dashed area corresponding to a wide range of parameters: all transition and source evolution models (other than the uniform and FRII models and the pure proton and mixed composition models.

Figure 1 also includes the different models for atmospheric neutrino fluxes indicated by the gray shaded area and the experimental measurements of the ν_μ flux at the South Pole [10, 11]. The atmospheric neutrino flux models considered in this study include so called "conventional" [13–15]. and "prompt neutrino" components [16]. The high energy part of the atmospheric flux (above about 100 TeV), is expected to be dominated by a "prompt" neutrino contribution. The prompt neutrinos are produced from the weak decays of short lived charmed particles and are expected to consists of about equal amounts of ν_e and ν_μ. The contribution of ν_τ is expected to be negligible. The prompt neutrino flux, which was used in this study, was obtained from the different models of charm particle production in the hadronic interactions, including pQCD, QGSM (Quark Gluon String Model), RQPM (Recombination Quark Parton Model) models. As Fig. 1 indicates, the predictions of atmospheric neutrino events above PeV energies could differ by an order of magnitude. The unknown prompt flux is one of the main sources of uncertainty in the search for cosmic neutrinos.

3. The KM3NeT neutrino telescope

The next Mediterranean deep sea neutrino observatory KM3NeT is expected to host a multi-km^3 size Cherenkov detector, which is essentially a three dimensional array of photo multipliers (PMT), mounted in pressure resistant

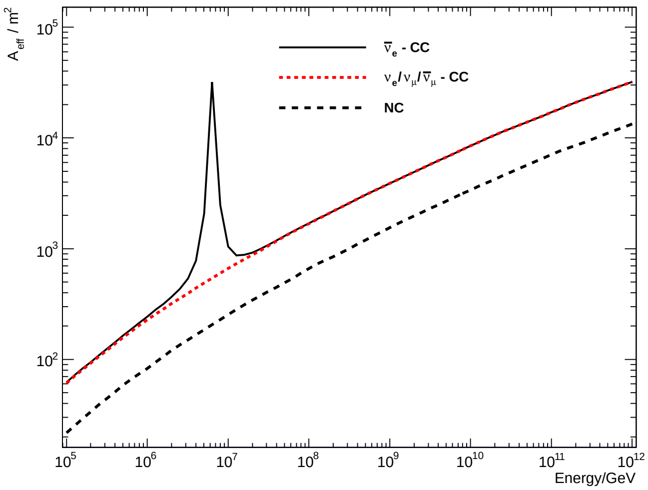

Figure 2: The KM3NeT effective area for the contained events. Solid line indicates the effective area for charged current(CC) electron anti-neutrino events, where Glashow resnance is clearly visble. Dotted line is an effective area for the CC-events of other neutrino flavors. The dashed line correspond to the KM3NeT effective area for the neutral current events.

optical modules (OM). Main building block of KM3NeT is a deployable vertical structure (tower), with 20 storeys, where each storey is a bar of 6 m length and holds 2 multi-PMT digital optical modules (DOM), each equipped with 31 PMTs of 3" diameter. The adjacent storeys are orthogonal to each other and the distance between them is 40 m. The first storey is mounted at 100 m from the seabed and the total length of the detection unit, including the top part with a buoy, is about 900 m.

The final configuration and location of the KM3NeT neutrino telescope at the time of completion of this paper (February, 2012) had not been fixed. In our study, a KM3NeT configuration with 154 detection units was used with average inter-unit distances of about 150 m. The instrumented volume of this configuration is about 3 km^3.

4. Expected rate of cosmogenic neutrinos

The search for a diffuse flux of astrophysical neutrinos explores the difference in the energy spectrum with the irreducible background of atmospheric neutrinos. As indicated by Fig.1 atmospheric neutrinos are characterized by a softer energy (E) distribution, which could be approximated with $E^{-3.7}$ before the "prompt" component. The estimation of neutrino energy with a relatively good accuracy is possible for so called contained events, in which the neutrino interaction vertex is inside the telescope's sensitive volume. The Cherenkov photons, which are produced in the neutrino induced showers of relativistic charged particles inside this volume, could reach the KM3NeT optical modules. The KM3NeT sensitive volume, used in this study, is a fixed cylindrical volume, of about 6 km^3. It encompasses an instrumented volume of a similar shape and extends its radius and height by 200 m, which is approximately 3 maximum absorption lengths $l_{\rm a} = 67.5$ m, for optical photons with $\lambda = 440$ nm.

The neutrino event rate (R_ν) in a neutrino telescope can be calculated as a convolution of neutrino flux $\Phi(E)$, an effective area A(E):

$$R_\nu = \int \Phi(E) A(E) dE \qquad (1)$$

The neutrino effective area A(E) is a product of the target mass in the sensitive volume, the neutrino cross-section, the survival probability after propagation in the Earth and the detection and reconstruction efficiency. As the up-going neutrino flux above PeV energy is strongly suppressed due to the short interaction length, in this paper we consider only the down-going neutrinos. Absorption of down going neutrinos is negligible up to the highest enegies (10^{12} GeV) considered in this paper. Figure 2 presents the KM3NeT effective area for down-going contained neutrino events as a function of the neutrino energy, calculated under the assumption of perfect (100%) efficiency. In this case effective area is directly proportional to the neutrino cross-section, which was obtained from [17], where a latest set of parton distributions was used. At high energies, the effective area is similar for all neutrino flavours, except electron anti-neutrinos, where a strong resonance is observed at $E = 6.3$ PeV. This so called Glashow resonance corresponds to a center of mass energy of the $\bar{\nu}_e e^-$ interactions of the weak boson mass $m_W = 80.4$ GeV.

The cumulative number of contained cosmogenic neutrino events in the KM3NeT telescope obtained as a function of neutrino energy for the different flux models in a time period of 1 year is given in Fig. 3. Expected event numbers from the atmospheric neutrinos are presented in the same figure as a gray shaded area. The curves in Fig. 1 and Fig. 3 represent the same models. The maximum number of contained events for cosmogenic neutrinos is obtained when the events from the Glashow resonance are included, which is seen as a clear feature in Fig.3. However in the pessimistic scenarios of the prompt atmospheric flux, the expected number of background events for this region is larger than all cosmogenic flux models, except the model with high $E_{\rm max}$ and FRII source evolution (long dashed line). Above 10 PeV, the expected number of contained cosmogenic neutrino events is significantly reduced and amounts to of 0.4-5.1 events for the models with proton or mixed composition and all galactic to extragalactic transition and source evolution models (except uniform). These models are contained in the dashed area between two solid curves. The corresponding rate from atmospheric neutrinos is below 1 event.

It should be noted, that the study of the KM3NeT discovery potential for cosmogenic neutrinos requires detailed simulation of signal and background events, including the

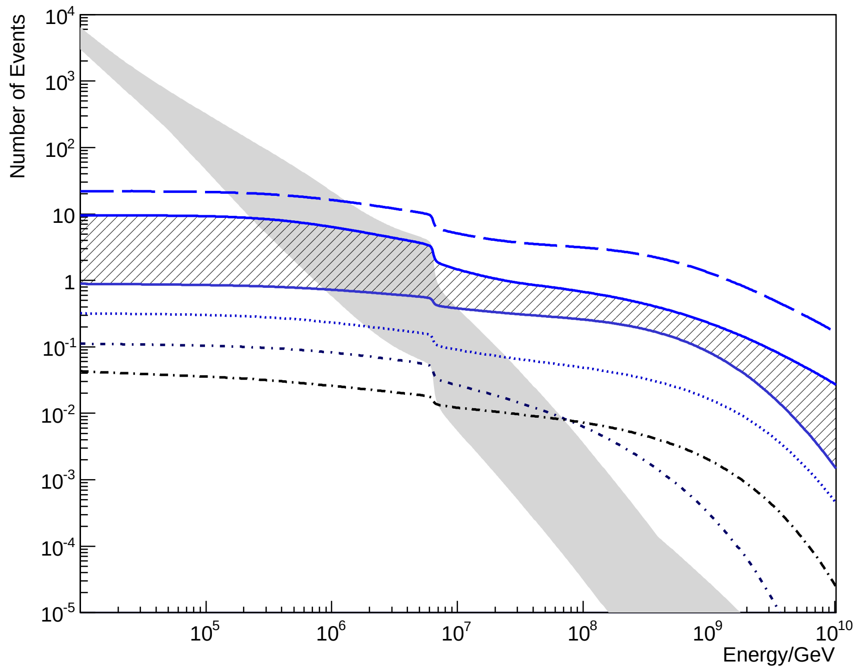

Figure 3: Cumulative number of contained events (per year) of cosmogenic neutrinos for the different flux models.

down-going atmospheric muons and is beyond the scope of this paper.

5. Conclusions

We have studied the rates of contained cosmogenic neutrino events in the next Mediterranean neutrino telescope KM3NeT. For a configuration with a fixed sensitive detection volume of about 6 km^3, the annual rate of all neutrinos above 10 PeV is in the range of 0.4-5.1 events for the favorable flux models. These models include pure proton or galactic mixed composition, all galactic to extra-galactic transition and source evolution models, except for uniform evolution models. The contribution from atmospheric neutrinos in this energy region is expected to be below 1 event/year. For the models with pure iron or iron rich composition the expected annual rates are below 0.1 events and are comparable to the atmospheric neutrino rates. The high energy threshold in this search makes the selection of down-going neutrino events necessary and correspondingly the removal of the very large atmospheric muon background. The event selection and reconstruction is a subject of ongoing studies and was not considered in this paper. Taking into account, that the sensitive volume in the final configuration could be larger by a factor of 2, the KM3NeT neutrino telescope could detect cosmogenic neutrinos for a large number of models or produce stringent limits on unknown UHECR parameters.

6. Acknowledgements

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