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Sensitivity to the Glashow resonance with KM3NeT ARCA detector

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The Glashow resonance, expected to occur in the interaction of high energy electron antineutrinos with electrons in the Earth's matter, was postulated in the late 1960s but still remains unobserved. The biggest challenge for the observation of this phenomena is reaching the capability to detect neutrinos with an enormous energy (about 6.3 PeV). The KM3NeT-ARCA (Astroparticle Research with Cosmics in the Abyss) detector, currently under construction in the Mediterranean deep sea, is optimized to observe very high energy neutrinos of astrophysical origin. In this work the sensitivity of the KM3NeT-ARCA for the Glashow resonance detection is reported. Preliminary results show that the discovery of the Glashow resonance can be possible with KM3NeT-ARCA after 15 years of operation. However, the final prediction depends very strongly on the astrophysical neutrino flux model, which is still not well constrained.

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1. Introduction

Because of the extremely low astrophysical neutrinos flux at the PeV region, the observation of the Glashow resonance requires a huge detection volume. Currently the only detector capable of catching these rare neutrinos is IceCube. One event with a reconstructed energy of around 5.9 PeV was observed by IceCube and it can be viewed as a first Glashow resonance event candidate [1]. In the near future KM3NeT-ARCA will enter the area of very large neutrino telescopes complementing the IceCube field of view. This paper investigates the timescale required to prove the Glashow resonance existence with reliable significance using the KM3NeT-ARCA detector.

2. KM3NeT-ARCA detector

KM3NeT is a pan-European project, which, in the near future, will become one of the flagship experiments in neutrino astronomy worldwide [2]. The KM3NeT-ARCA detector, designed to investigate the astrophysical neutrino sources and the highest neutrino energies, will bring new opportunities to the astroparticle physics research. ARCA is located at a depth of 3400 m, 80 km off-shore the Italian town Portopalo di Capo Passero on the south-eastern coast of Sicily. Once completed, ARCA will consist of two separate blocks, each one with an active volume of about 0.5 km^3. Each building block will consist of 115 strings (Detection Units) sparsely placed (grid pitch around 90 m) on a circle plane forming a cylindrical volume. Each DU comprises 18 Digital-Optical Modules (DOM) that detect the Cherenkov light produced by neutrinos interacting in the sea water. The vertical space between DOMs is 36 meters.

3. Glashow resonance theory and detection principle

The Glashow resonance is the production of a W^- on the mass shell in an interaction of an electron antineutrino with an electron [3]. Assuming the electron at rest, the energy of the incoming neutrino E_ν has to reach

$$E_\nu = \frac{M_W^2 - m_e^2}{2m_e} \simeq 6.32\text{PeV}, \tag{3.1}$$

where M_W^2 is the mass of W boson and m_e is the electron mass. These events are expected to be extremely rare, so one has to be ensure that the Glashow resonance signal is well separated from the background. A dedicated event selection is required for this analysis.

The theoretical model used for the Glashow resonance implementation in the simulation software is described in Ref. [4]. According to the model, the total Glashow resonance cross section at the peak energy is expected to be around 300 times larger than the one of Deep Inelastic Scattering. For this reason, electron antineutrinos with energies close to the Glashow resonance region are strongly absorbed when crossing the Earth. The experimental signature is a peak in the reconstructed energy distribution and is possible for fully contained hadronic decays of the W boson (67% branching ratio).

Considering the above limitations, only fully contained, downgoing shower events are considered in this analysis. Figure 1 shows the true neutrino energy distribution of contained down going showers only (no atmospheric muons and $\nu_\mu/\bar{\nu}_\mu$ events in the sample). All the tracks and upgoing events are excluded to show the physical limit for detectable excess in the Glashow resonance region, which can be reached with perfect energy and direction reconstruction and track exclusion. The rate of Glashow resonance signal events is 0.25/year. The distribution can not be obtained for the data, but it shows that, even with perfect event selection, the observation of Glashow resonance needs timescale of at least a decade.

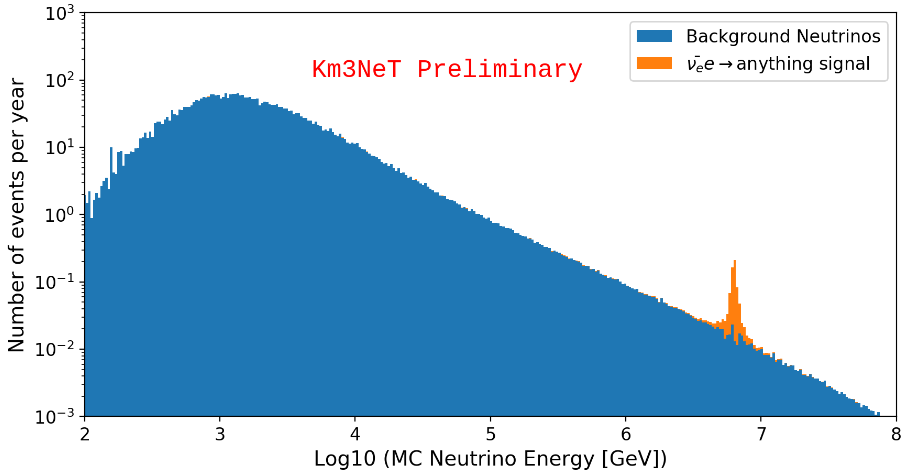


Figure 1: Expected event rate in one block of KM3NeT-ARCA after one year of observation. The sample is weighed with the astrophysical neutrino flux model from [5] and atmospheric flux from Honda [8] and Enberg [9]. Orange histogram corresponds to $\bar{\nu}_e$ Glashow resonance events only. Blue histogram contains all the interactions induced by the other neutrino flavours.

4. KM3NeT-ARCA sensitivity

4.1 Monte Carlo sample

For the purpose of this analysis a Monte Carlo production for 1 block of KM3NeT-ARCA detector was generated. The simulation chain is divided into 4 main steps [2]

1. Event generation - neutrinos and atmospheric muons,

2. Cherenkov light generation and detector response (PMT hits),

3. On shore-triggering,

4. Event reconstruction.

Each event is weighted to obtain absolute event rate equivalent to one year of data taking. The simulated number of events was the same for every investigated snapshot in observation timescale, but the weights and their errors were scaled to the corresponding observation time.

4.2 Event selection

The analysis requires an effective selection of very high energy, down-going and fully contained shower events. The atmospheric background (atmospheric neutrinos and muons) is expected to be much smaller than signal [2]. However, atmospheric muons may initiate showers, and therefore they can by identified by the shower reconstruction algorithms. Moreover, badly reconstructed events can have their energy highly overestimated. Because of this, a strong suppression of atmospheric background based on the use of machine learning algorithms and strict quality cuts has been applied. The background for this analysis is considered to be every interaction (including $\bar{\nu}_e$ induced ones), which is not of Glashow resonance origin. The event selection procedure was originally developed in the KM3NeT Collaboration to search for HESE (High Energy Starting Events) induced showers [6].

4.3 Astrophysical neutrino flux model

This analysis assumes a single component unbroken power law spectrum for the astrophysical neutrino flux:

$$\Phi_\nu = \phi \cdot \left(\frac{E}{100\text{TeV}}\right)^{-\gamma}. \tag{4.1}$$

Parameters of the astrophysical neutrino flux model were taken from the IceCube results [5] [7]. Two different sets of the flux parameters were tested:

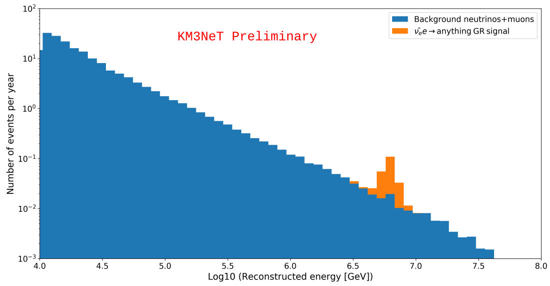
- $\gamma = 2.49, \phi = 2.33 \cdot 10^{-18} \frac{1}{\text{GeV}\, s\, cm^2\, sr}$ - results published in [5]. Originally the fit was performed up to 2 PeV, but in this analysis it's extrapolated to 10 PeV,
- $\gamma = 2.87, \phi = 1.86 \cdot 10^{-18} \frac{1}{\text{GeV}\, s\, cm^2\, sr}$ - preliminary results presented in [7]. The fit was initially performed up to 10 PeV.

The energy spectrum fits were performed with an assumption of equal flavour contribution. Both models are compatible within 2σ. For the atmospheric background, the atmospheric neutrino flux model was taken from Honda et al. [8] for the conventional component and Enberg et al. [9] for the prompt component. Event rates for the reconstructed energy after applying the HESE event selection are shown in Fig 2.

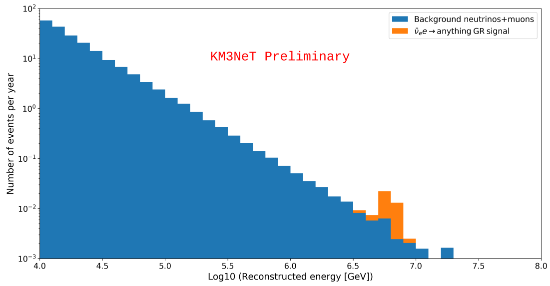
4.4 Analysis method

Non parametric PDFs for the signal+background and background-only models were created based on an unbinned Monte Carlo sample using adaptive Gaussian kernel estimation [10]. This method was chosen to reduce the influence of statistical fluctuations occurring in the used sample in the very high energy regime. The example obtained functions for the spectrum with spectral index $\gamma = 2.49$, together with the sample binned for visualization purpose, are shown in Fig. 3.

The discovery significance is derived using the approach described in Ref. [11]. Due to a very low absolute event rate, the final result is extremely sensitive to the assumed astrophysical neutrino flux parameters. Results for the two astrophysical neutrino flux models are presented in Fig 4. The model with spectral index ($\gamma = 2.87$) very strongly suppresses energies in the Glashow resonance window and makes the detection impossible in a reasonable timescale. The model ($\gamma = 2.49$) yields a 3σ discovery significance in approximately 15 years of data.



(a) Astrophysical neutrino flux model based on Eq 4.1 and the best fit parameters from [5].



(b) Astrophysical neutrino flux model based on Eq 4.1 with the best fit parameters [7].

Figure 2: Reconstruced event energy after applying the HESE event selection.

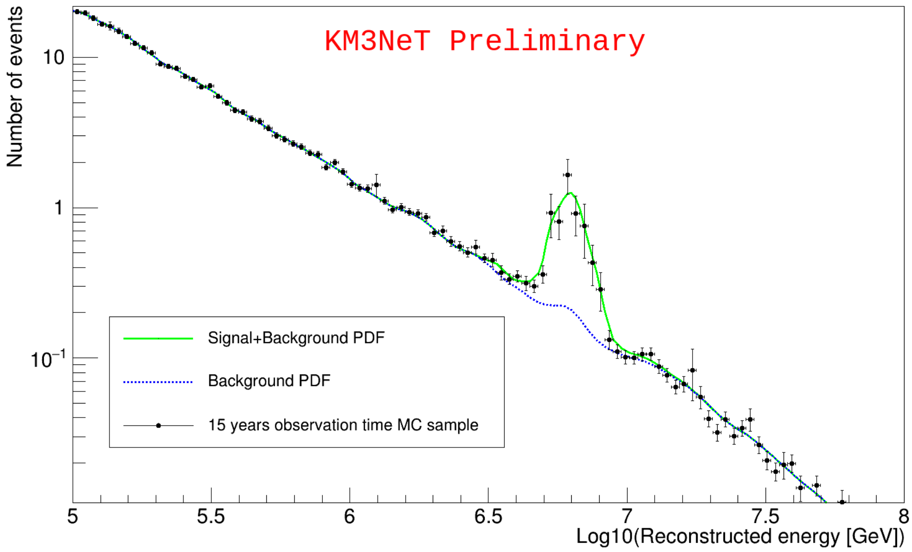


Figure 3: Expected HESE selected event rate for 2 blocks of KM3NeT-ARCA detector after 15 years of data. Rates are weighted with a single flavour flux $\Phi_\nu = 2.33 \cdot 10^{-18} \cdot \left(\frac{E}{100\text{TeV}}\right)^{-2.49} \frac{1}{\text{GeV}\, s\, cm^2\, sr}$.

5. Summary

It was shown that the KM3NeT-ARCA detector can be capable of detecting Glashow resonance after at least 15 years of observation. On the other hand, the astrophysical neutrino flux is still not well constrained and its parameters very strongly affect the final result. What was not investigated and expected to have an impact on the analysis is the uncertainty of the flavour composition and complete lack of $\nu/\bar{\nu}$ ratio measurement for the neutrinos of astrophysical origin. Because of a very low expected event rate in the Glashow resonance energy region, a predominance of electron antineutrinos in the flux composition can increase the sensitivity by a significant factor. In the end, it might be the case that for the high confidence observation of the Glashow resonance, it will be necessary to build a much bigger detector or count on the combined effort of all the large neutrino telescopes operating around the world.

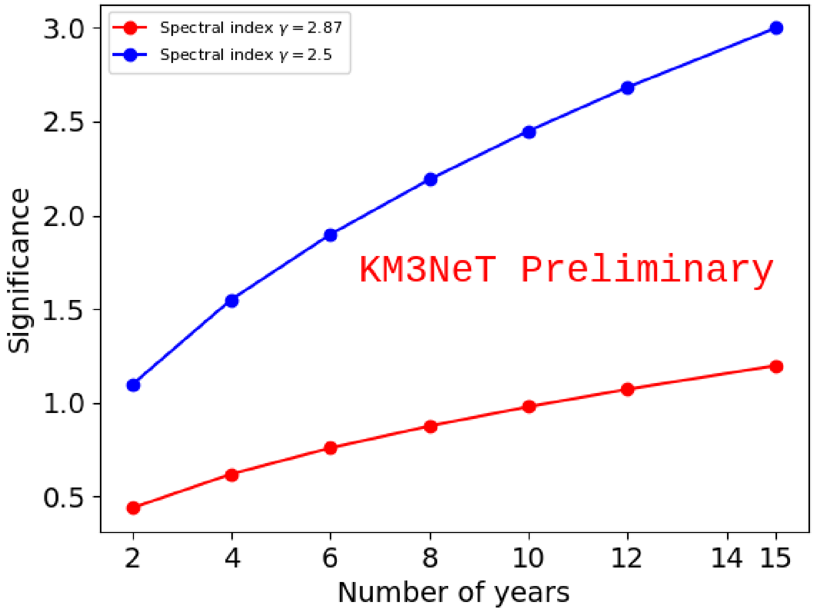


Figure 4: Discovery significance vs time of observation for 2 blocks or KM3NeT-ARCA detector.

Recently more precise theoretical calculations were done for ultra high energy neutrino interactions cross sections including the Glashow resonance [12]. Based on these calculations, a new high energy extension GENIE-HEDIS for GENIE neutrino generator was prepared and is going to be used in KM3NeT Collaboration, potentially giving new insights into the astrophysical neutrino interactions. It is planned to repeat the analysis with the new models in the near future.

Acknowledgements

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