A study on JEM-EUSO's trigger probability for neutrino-initiated EAS

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Abstract: Neutrinos at ultra high energies (UHE) are expected as by-products of the interaction UHE Cosmic Rays (UHECRs). Whether these interactions happen in astrophysical sources or whilst their propagation, UHE neutrinos retain valuable information about the origin and propagation of UHECRs and about their sources. Those elusive particles can be detected by very large exposure observatories that are currently being operated or, as is the case of JEM-EUSO, designed. Currently designed to be hosted on-board the International Space Station, the JEM-EUSO mission will pioneer the observation of the Extensive Air Showers (EAS) fluorescent light from space. Hence, specific studies tailored to address all the peculiarities of such mission are necessary to assess JEM-EUSOs capabilities. In this paper we perform a simulations study of the trigger probability for neutrino-initiated EAS. The simulations are carried out within the EUSOs Simulation and Analysis Framework (ESAF), which is a software tool specifically developed bearing space borne missions in mind and in particular EUSO-like observatories. The shower longitudinal profiles are produced by a combination of the PYTHIA interaction code and CONEX shower simulator. The resulting EAS are then integrated to ESAFs simulation chain and subsequent triggering conditions analyzed.

Keywords: UHECR, neutrinos, JEM-EUSO, detectors

1 Introduction

Neutrinos can be generated as by-products of the interaction of cosmic rays during their propagation through the intergalactic medium or by interactions in the acceleration sites [1]. The showers initiated by ultra high energy(UHE) neutrinos can be observed by orbital detectors like the Extreme Universe Space Observatory, on-board the Japanese Experimental Module (JEM-EUSO)[2]. The identification of the events initiated by UHE neutrinos is based on the different characteristics of the longitudinal profiles of the Extensive Air Shower(EAS) generated by these primaries. In this work we present the response of the JEM-EUSO telescope to these type of showers and discuss the trigger probability for horizontal neutrino showers.

1.1 JEM-EUSO

JEM-EUSO is a space based UV telescope devoted to the observation of ultra high energy cosmic ray induced air showers in the Earth's atmosphere. It will be mounted on board the Japanese Module of the International Space Station (ISS), orbiting the Earth at an altitude of ~ 400 km. JEM-EUSO will study the energy region around 10^{20} eV [3], allowing it to study the sources and their spectra with high precision [4]. The duration of the mission is scheduled to be a minimum of 3 years. During this time, JEM-EUSO will observe several hundreds of events with energies $> 5 \times 10^{19}$ eV [3].

The JEM-EUSO instrument consists of a refractive optics of three Fresnel lenses focusing the UV photons onto the focal surface (FS) detector. The focal surface detector is made of 137 individual photo-detector modules (PDMs) . Each PDM is formed by 36 multi-anode photomultiplier tubes (MAPMT). Each MAPMT has $(8 \times 8 =)$ 64 pixels. Two levels of trigger algorithms are operated to search each PDM for stationary and transient excesses over background. The telescope is equipped with an atmospheric monitoring system using LIDAR and IR-camera data to record the state of the atmosphere and infer the altitude of possible clouds inside the field of view (FOV) [5]. More details on the specifications of the detector can be found on [6] .

2 Neutrino shower simulations

High energy neutrinos that propagate in the Earth atmosphere can interact with protons and neutrons of the air molecules. There are two possible channels for this interaction, charged current (CC) and neutral current (NC),

$$\text{CC:} \quad \nu_\ell + N \quad \rightarrow \quad \ell + X \tag{1}$$

$$\text{NC:} \quad \nu_\ell + N \quad \rightarrow \quad \nu_\ell + X, \tag{2}$$

Here N is a nucleon (proton or neutron), ν_ℓ is a neutrino of the family ℓ, ℓ is the corresponding lepton and X is the hadronic part of the processes. For the scope of this work we shall concentrate only in the electron neutrino ν_e.

For this work, the simulation of the neutrino nucleon interaction is performed by using the PYTHIA code [7] linked with the library LHAPDF [8] to be able to use different extrapolations of the parton distribution functions. PYTHIA is an event generator, intended for high-energy processes with particular emphasis on the detailed simulation of quantum chromodynamics (QCD) parton showers and the fragmentation process. The set of PDFs used for these simulations is CTEQ66 [9].

The energy fraction taken by the leading particle after a CC or NC interaction depends on the primary energy of the incident neutrino. For example the energy fraction taken by the electron increases with the energy of the incident electron neutrino reaching values close to 0.82 at $E_\nu = 10^{20}$ eV [10].

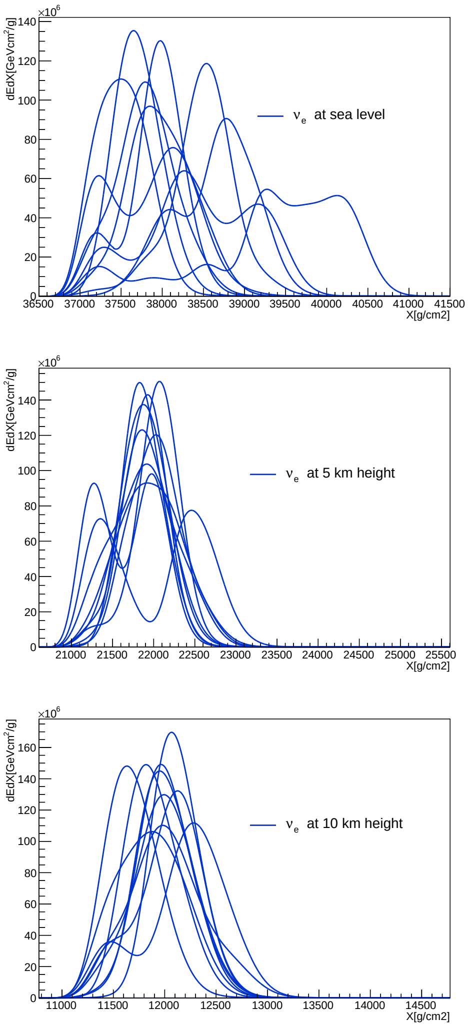


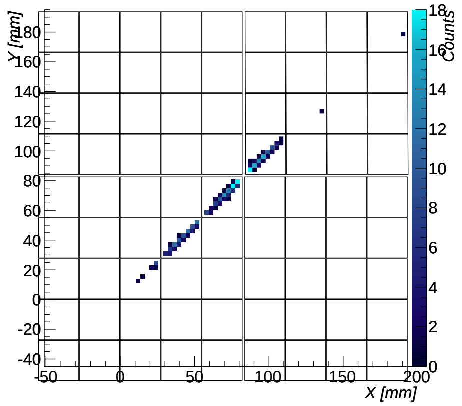
Fig. 1: Longitudinal profiles for horizontal electron neutrino showers with $E_\nu = 10^{20}$ eV. The neutrino injection point is contained on the vertical axis of JEM-EUSO in the Nadir mode. At sea level (top), at an altitude of 5km (middle) and 10 km (bottom).

Neutrinos can initiate atmospheric air showers when they interact with the nucleons of the air molecules. The CC interactions are the most important for the space observations because in the NC interactions most of the energy is taken by a secondary neutrino that could produce an observable air shower just in case it suffers a subsequent CC interaction. In this work the showers initiated by CC interactions are just considered. Note that the probability that a neutrino interacts in the atmosphere increases with the zenith angle because of the increase of the number of target nucleons.

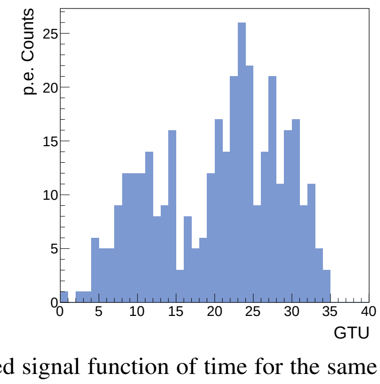
Electron neutrino showers are simulated following Ref. [10]. The secondary particles produced in the interaction are used as input in the program CONEX [11] (v2r2.3), in order to simulate the shower development. The high energy hadronic interaction model used for the shower simulations is QGSJET-II [12].

Because the mean free path of neutrinos propagating in the atmosphere is very large, they can interact very deeply, after traversing a large amount of matter. An orbital detector like JEM-EUSO can also detect horizontal showers that do not hit the ground. In particular, horizontal neutrinos can interact at higher altitudes producing a shower observable by the detector. In fig. 1 we show the energy deposit $\frac{dE}{dX}$ as a function of X, where X is the atmospheric depth in grams per square centimeter, for horizontal electron neutrino showers of $E_\nu = 10^{20}$ eV.

The profiles corresponding to low altitudes are very broad which can present several peaks and large fluctuations. This behavior is due to the Landau and Pomeranchuk [13, 14], Migdal [15] (LPM) effect, which is very important inside dense regions of the atmosphere and for electromagnetic particles, electrons in this case, which take about 82% of the parent neutrino energy. This effect can be appreciated in the longitudinal profiles shown in fig. 1. As the altitude increases the fluctuations are reduced and, on average, the profiles become thinner. This is due to the fact that the LPM effect become progressively less important with decreasing atmospheric density.



(a) Neutrino initiated EAS's fluorescence signal track on the focal surface of the detector. Height is 5 km



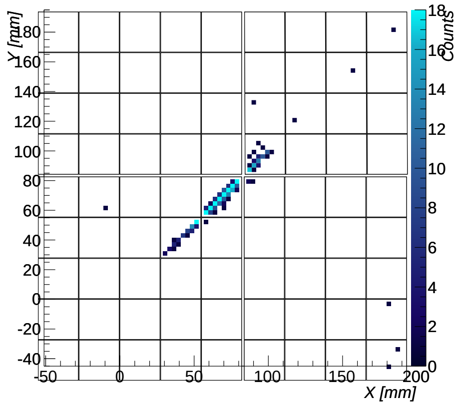
(b) Detected signal function of time for the same (above) shower. Time measured in GTU's (see text).

Fig. 2: ESAF simulated neutrino EAS with a strong LPM effect as seen by the JEM-EUSO detector. The energy of the neutrino is 10^{20}eV and the injection height is 5 km.

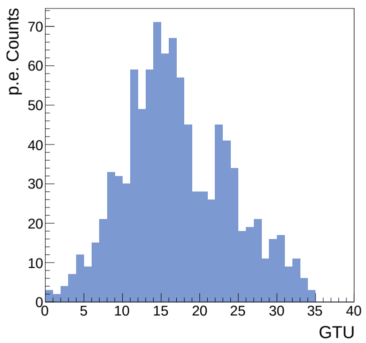
3 Detector simulations

The EUSO Simulation & Analysis Framework (ESAF) [16] is a modular software built upon the ROOT framework, designed to simulate UHECR detectors. The simulations account for the physical processes that take place during the development of an EAS. Each simulation covers the whole chain, the longitudinal development of the EAS itself, the fluorescence and Cerenkov light produced at the shower site, the atmospheric propagation of photons, as well as the processes within the detector, i.e. the propagation of photons through the optics, the response of the electronics, and the triggering algorithms. On a second stage, ESAF also provides the tools for reconstructing the simulated events based on the recorded information of the detector's response. The detector's response in time is fixed to a value of 2.5 μs, called Gate Time Unit (GTU).

In order to bring into context the main scope of the present work, we would like to explain a bit in detail the JEM-EUSO's trigger. The trigger of the detector is implemented in ESAF and consist of two levels. The first, the *Persistent Track Trigger (PTT)*, searches for groups of pixels (3×3) in which a signal appears longer than average background counts and the total count rate is higher than a preset threshold. The second trigger level, the *Linear Tracking Trigger* (LTT), looks for patterns that could be signal tracks by moving an integration box along a set of pre-defined directions. The LTT issues a triggering flag if the maximum integral along those tracks is above a preset threshold.



(a) Neutrino initiated EAS's fluorescence signal track on the focal surface of the detector. Height is 5 km



(b) Detected signal as a function of time for the signal track above.

Fig. 3: ESAF simulated neutrino EAS with a small LPM effect as seen by JEM-EUSO. The energy of the neutrino is 10^{20} eV and the injection height is 5 km.

In fig. 2 we show the expected signal track without the background, for a neutrino shower of $10^{20} eV$. This shower

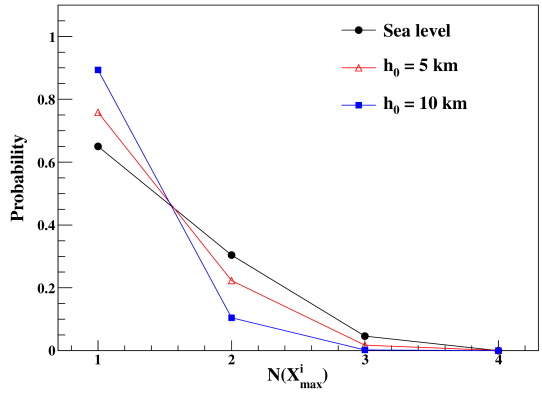


Fig. 4: Probability to find profiles with $N(X^i_{max})$ peaks for ν_e showers occurring at sea level, 5 km and 10 km height.

was injected at 5 km above sea level, but still, in this case the LPM effect diminishes the maximum of the photon counts. This is more evident if we compare fig. 2 with fig. 3. In the latter the LPM effect is not so drastic, therefore the track seems a bit shorter but brighter. In both cases the gaps between PMTs introduce artificial peaks in the light curves, whose origin should not be mistaken as multiple peaks coming from the LPM effect. We also calculated the probability of a neutrino shower having N maxima. This is shown in fig. 4. As expected from fig. 1, at lower altitudes the probability of having a shower with multiple peaks increases.

We simulated a set of ν_e initiated showers at energies between $10^{19.25}$eV and $10^{20.5}$eV. All showers were horizontal ($\Theta = 90°$) and their first interaction point was either at sea level, 3 km, 5 km or 10 km above sea level. This last statement, translates to grammages for the first interaction point of ≈ 36500 g cm^{-2} at sea level, ≈ 26139 g cm^{-2} for 3 km of altitude, ≈ 20600 g cm^{-2} for 5 km of altitude, and ≈ 10776 g cm^{-2} for 10 km of altitude.

We proceeded to set the first point of interaction randomly within JEM-EUSO's Field of View (FoV). With the aid of ESAF we can make a statistical test on how many of the injected showers actually activated the trigger mechanisms of JEM-EUSO. The trigger probability is defined as product of the ratio of the injected neutrino-EAS to the triggered ones , times the ratio of the observed area to the injection area. The trigger probability is shown in fig. 5, for injection altitudes of zero, five and ten kilometers.

The reduction in the probability for showers injected at sea level is a consequence of a diversity of factors. The atmospheric attenuation will be significantly enhanced since most of the atmospheric mass is concentrated at lower altitudes. Secondly the shower is developing farther away from the detector. And last but not least, the broadening of the longitudinal profile due to the LPM creates a longer signal track, but as a trade-off suffers from worse signal to noise ratio (see fig. 1).

4 Conclusions

In the current work we prepared neutrino simulations and injected them into the JEM-EUSO simulation framework. This allowed us to study JEM-EUSO's response to EAS initiated by UHE neutrinos. For this purpose we combined well established simulating tools. For the EAS simulator we used CONEX, for the neutrino interaction we used PYTHIA

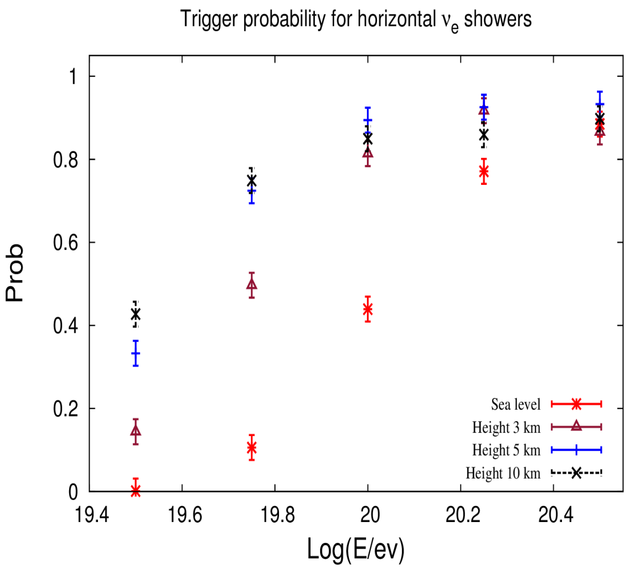


Fig. 5: Trigger probabilities as a function of energy for horizontal electron neutrino showers.

and for the rest of the chain ESAF. With these tools at hand we studied the expected trigger probability for deeply interacting neutrino showers at sea level, 3 km, 5 km and 10 km altitudes, as case studies. Though not definitive, this types of test are part of the first full end-to-end simulation studies carried out to calculate the expected number of UHE neutrino events under the current JEM-EUSO instrument's configuration.

5 Acknowledgments

The present work has been conducted under support of Deutsches Zentrum fĽuft und Raumfahrt (DLR). Moreover it has partly been funded by the European Space Agency (ESA) Topical Team Activities Fond. We wish to thank RICC, the RIKEN Integrated Cluster of Cluster in Tokyo, Japan for the allocation of computing resources and service.

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