Muon production due to neutrino interaction with Earth matter

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Introduction

Atmospheric neutrinos constantly bombard the Earth's surface, propagate through it, and interact with nuclei of the Earth (rock), producing muons via various charge-current (CC) weak interaction processes

$$\nu_\mu(\bar{\nu}_\mu) + A \rightarrow \mu^{\pm} + A'. \quad (1)$$

In this study, the calculation is performed to estimate the upgoing muon distributions produced from the atmospheric neutrino (ν_μ) charge-current (CC) interaction with the Earth's rock. Preliminary results are presented here for the neutrino energy range from $E_\circ = 1$ GeV to $E_{\max} = 50$ GeV which constitutes bulk of the atmospheric neutrino flux at the Earth's surface.

Model Calculations

High-energy neutrino events are uniformly generated over the Earth's surface and the plane, which is at a distance from the surface of the Earth. The neutrino energy distribution is taken from the Honda calculation [1]. The cross-section and muon momentum for various neutrino-rock (Z=11 and A=22) interaction processes that produce a muon in the final state are calculated using GENIE (version v3.0.6) [2], a neutrino event generator package. Only those neutrino interactions are considered here that produce a muon in the final state via CC processes like QES, RES, COH, and DIS, etc. Since muons loose energy while propagating through the rock, the lower-energy muons with higher propagation lengths mostly die inside the rock. Muons, that are produced near Earth's surface, at lower angles and with higher energies only survive up to Earth's surface.
A plane at several depths (target length) from the Earth's surface is considered to study the neutrinos. At the neutrino interaction vertex, muon has certain energy, zenith angle and azimuthal angle in the neutrino frame which can be obtained from the GENIE package.

The number of successful upgoing muon events were calculated by -

$$Y(p_\mu) = \phi_\mu \times \sigma_\nu(10^{-38}) \times N_t(10^{38}), \quad (2)$$

where $\phi_\mu(p_\mu)$ is the muon flux and $\sigma_\nu(E)$ is the neutrino interaction cross section, $N_{\rm t}(L)$ is the number of nucleon targets present along the neutrino path in the rock which can be calculated using $N_{\rm t} = L \times N_A \times \rho$, where N_A is the Avogadro's Number, ρ (g/cm^2) is the density of Earth's rock and L (cm) is the length of path traversed by neutrino inside rock.
Total number of successful upgoing muon events Y (/m^2/sr/year) in the momentum range $p_\circ = 1$ GeV/c to $p_{\max} = 50$ GeV/c is calculated as -

$$Y = \int_{p_\circ}^{p_{max}} Y(p_\mu)\, dp_\mu. \quad (3)$$

Results and Discussions

Figure 1 shows the neutrino and muon distributions. Neutrinos are genereted using their zenith angle distribution upgoing muons is obtained by 180°-Zenith angle. Upgoing muon distributions are weighted by neutrino interaction cross-section and the number of targets (for 400 m target length). The Blue histogram there represent the muons at the

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interaction vertex, while red histograms correspond to the successful upgoing muons.

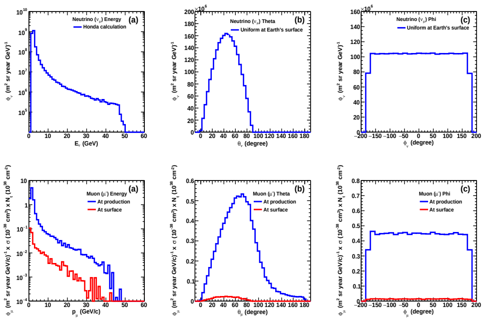

FIG. 1: (a) Energy distribution, (b) Angular distribution, and (c) Azimuthal angle distribution for neutrino(top row) and upgoing muons(bottom row).

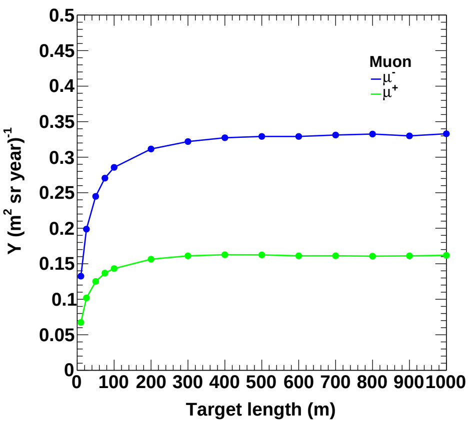

FIG. 2: Upgoing muon (μ^- and μ^+) flux as a function of target (rock) length.

Figure 2 shows the upgoing muon (μ^- and μ^+) flux as a function of target (rock) length. The upgoing muon yield Y_μ at the Earth's surface increases with the target length, reaching a saturation point (0.33 $(\mathrm{m}^2\mathrm{sr\ year})^{-1}$ for μ^- and 0.16 $(\mathrm{m}^2\mathrm{sr\ year})^{-1}$ for μ^+) of around 400 meters. Prior to reaching this length, the increase in muon yield can be attributed to the greater thickness of nuclear targets for neutrino interactions, resulting in a higher production of muons in the final state of interaction. However, beyond the 400-meter target length, muons generated at larger depths will lose energy as they pass through the rock which is preventing them from reaching the surface.

Conclusions

In this work, we have calculated the upgoing muon distribution, produced from the atmospheric neutrino interaction with Earth's matter. We have generated high energy neutrino using GENIE package and allowed them to pass through the Earth. After they interact with the Earth's matter, they produce muons and some of these muons with sufficiently high energy reach the surface. We obtained the yield of upgoing muons as the function of target length. We have neutrino interaction data up to 1 TeV energy, which can be used to examine the dependence of the maximum energy E_{max} on both the upgoing muon yield and the target length.

References

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