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TauRunner: A Monte Carlo for Very-High-Energy Tau Neutrino Propagation

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The hunt for cosmogenic neutrinos is a target of next generation observatories: IceCube-Gen2, RNO, GRAND, POEMMA, and CHANT [1–5]. In a recent publication, a novel detection strategy for these neutrinos has been put forward. This new technique relies on the observation of Earth-throughgoing tau neutrinos at PeV energies. By measuring the flux at this energy, we can indirectly observe the flux at EeV energies since these two are related by the cascading down of the neutrinos. However, such a link demands an accurate simulation of the VHE tau neutrino transport. `TauRunner` is a Python Monte Carlo (MC) package developed in 2019 that was intended for such analysis, but contained some limitations. This contribution will present the newest version of this MC, which now incorporates all the neutrino flavors in the propagation as well as other features.

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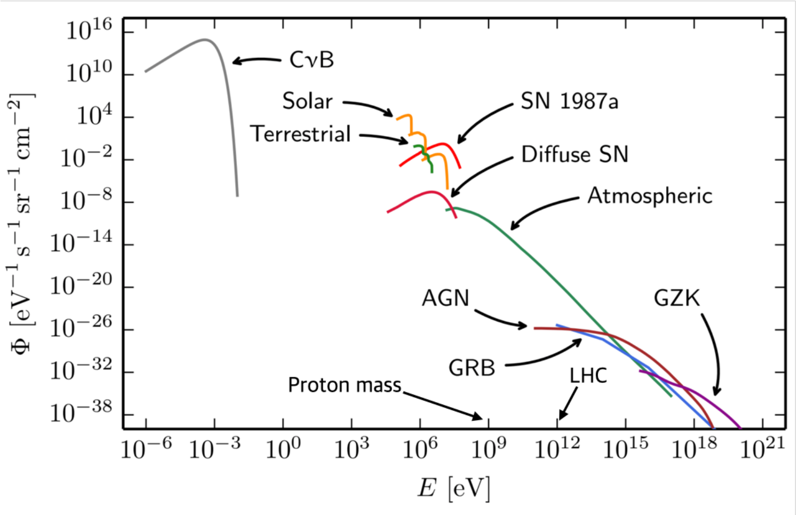

Figure 1: A collection of neutrino fluxes as a function of energy. The region of interest is $\sim 10^{18}$ eV which is six orders of magnitude larger than the energies observed at the LHC. Additionally, the GZK flux is up to 24 orders smaller than atmospherics making the former incredibly elusive. A similar plot with a more extensive discussion can be read in a publication from Vitagliano et al. [17]

1. Introduction

Neutrinos with a wide range of energies have been detected through the years and their fluxes are shown in Fig. 1, those in the ultra-high region are extremely rare and the subject of an exhaustive search that goes back more than half a century. These neutrinos are expected to be produced by cosmic-ray interactions with the cosmic microwave background (CMB). During travel, they morph from one flavor to another yielding, in the standard scenario, a democratic flavor composition at their arrival on Earth.

The observation of ultra-high energy neutrinos can be done by direct measurement of Earth-skimming events in cosmic-ray detectors such as the Pierre Auger Observatory and radio detectors such as ANITA, ARA, and ARIANNA [6–16]. An alternative strategy relies on looking at through-going tau neutrinos at PeV energies. In particular, this method takes advantage of the so-called regeneration process where a tau neutrino undergoes a Charged Current (CC) interaction and the produced tau decays quickly into a secondary tau neutrino carrying a great portion of the primary energy. As a consequence, when the neutrinos arrive on Earth they produce signatures in water Cherenkov neutrino detectors, such as IceCube, as illustrated in Fig. 2. The detection of the Earth through-going flux serves as an indirect measurement of the primary flux since these two are related by the following cascade equation,

$$\frac{d\Phi(E,x)}{dx} = -\sigma(E)\Phi(E,x) + \int_{E}^{\infty} d\tilde{E}\, f(\tilde{E},E)\Phi(\tilde{E},x) \tag{1}$$

where E is the neutrino energy, x is the target column density, $\sigma(E)$ the total neutrino cross section per target nucleon, $f(\tilde{E},E)$ is a function that encodes the migration from larger to smaller neutrino energies, and $\Phi(E,x)$ is the neutrino spectrum.

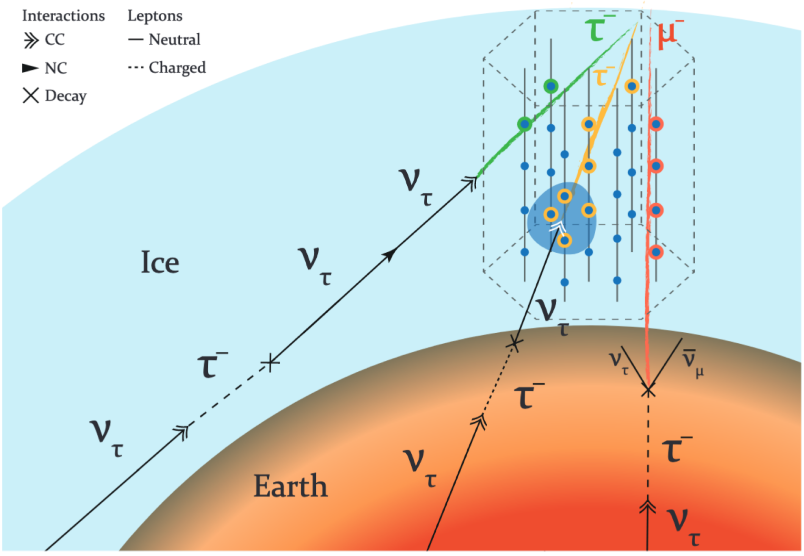

Figure 2: Schematic of neutrino propagation through Earth followed by an event signature in IceCube. EeV tau-neutrino secondaries can be detected in three possible ways, though this work focuses on the rightmost signature. Right: The tau decays before reaching the detector, producing a muon in $\sim$18% of the cases, which subsequently enters the detector. Center: The interaction vertex is contained in the fiducial volume of the detector in this case, producing a cascade from the charged-current interaction, along with an outgoing tau track. Left: A throughgoing tau track, which is possible for taus at or above 10 PeV.

2. `TauRunner`

To facilitate this search in accordance with the indirect measurement strategy, the Python Monte Carlo `TauRunner` was developed in 2019 by Safa et al. [18]. The software was initially intended to propagate VHE tau neutrinos and exploit the regeneration process in the following manner. First, the neutrino mean-free-path is calculated according to the total cross section and medium properties, then the free-streaming distance is obtained by random sampling. The target number density is also calculated using the isoscalar approximation. During an interaction, the accept/reject sampling method is used to select either a Neutral Current (NC) or CC interaction. If the neutrino experiences a NC interaction, its energy loss is sampled stochastically from the differential cross section tables and a new free-streaming distance is sampled. As for CC interactions, the produced tau is created with energy that is also sampled from the differential cross sections. The tau is propagated and once it decays the process repeats.

The code has been upgraded over the last months with the notable incorporation of antineutrino secondaries produced in some tau decay channels. Precisely, whenever such secondaries are produced, their energies are sampled via inversion using a spline based on `PYTHIA` [19] distributions, the energy is recorded alongside its position on a list. Each antineutrino on the list is then subject to the propagation algorithm with the caveat that it is is absorbed during a CC interaction since the resulting particles will lose their energy in the medium. The fraction of outgoing neutrinos to incoming monochromatic neutrinos matches the results obtained by Beacom et al. [20] as seen in Fig. 3.

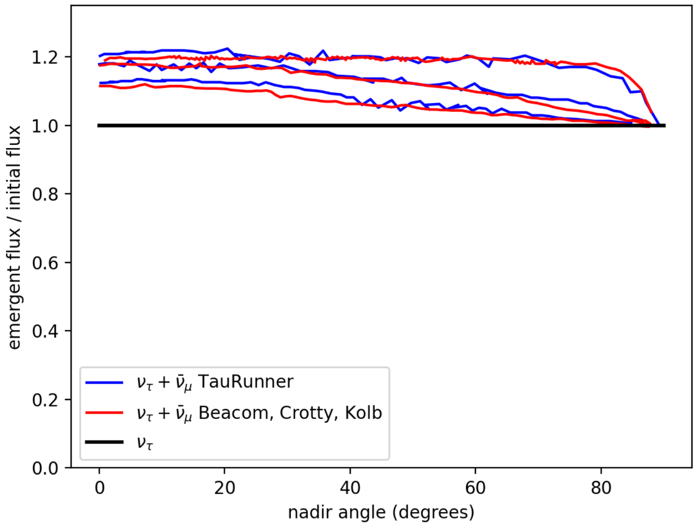

Figure 3: Neutrino fractions at a continuum of angles and initial energies of 10^5, 10^6, and 10^9 GeV (bottom to top). As expected, the secondaries will boost the yield of events by a factor of 2 and the tau neutrino fraction should always result in unity.

Other additions to `TauRunner` include the ability to use any medium with spherical symmetry (Earth was the only option and is now the default), the body is specified through an abstract data type that takes in the density profile and radius. Dependence on the neutrino oscillation software `nuSQuIDS` has been removed as a means for optimization. Additionally, we are working to replace MMC with `PROPOSAL` for the lepton energy losses. There is also a significant leap in code readability, this includes a rewrite of modules, classes, and integration of PDG identifications. mention test coverage

3. Conclusions

With this new version of `TauRunner`, we expect to have a more precise simulation of the VHE tau neutrino signal which should be of great aid for the search of the cosmogenic flux. It is essential to continue developing quality software to facilitate this effort. We seek complementarity with other propagation tools such as `NuTauSim` and `NuPropEarth` by making cross checks. We are targeting a release of `TauRunner` for the upcoming months, which will include all of the features that have been discussed as well as removal of any dependencies. We plan to make the package installable via PyPI and welcome any feature requests from the community.

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