Chasing cosmic tau neutrinos in the abyss

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SIMULATION

> We don't want to conquer the cosmos, we simply want to extend the boundaries of Earth to the frontiers of the cosmos
>
> Stanislaw Lem, Solaris

In order to determine the detection efficiency of the signal of interest and the backgrounds, a complete simulation of the envisaged measurement is made. In this chapter, a brief summary of the various simulation steps is presented. It is adapted from the KM3NeT letter of intent [67]. Due to the complexity of the problem, the Monte Carlo technique is used. A comparison of the simulation with data from the first string prototype (PPM-DU) is discussed in Chap. 4.

3.1 EVENT GENERATION

In the event generation, the interaction of a neutrino or the passage of a particle through the detector is simulated. To save computing time, a region containing the instrumented volume at its center is defined (the so-called "can"). The can typically extends three times the absorption length of light in water around the instrumented volume.

The first step of the simulation chain is the generation of particle fluxes in the can. Since some particles can travel distances larger than the can, events are generated in a volume significantly larger than the can (called the generation volume). For each generated event, the produced particles are propagated and if at least one reaches the can, the event is recorded.

Each neutrino interaction is simulated using the GENHEN code [89]. In this, an energy spectrum according to a power law with a given index is assumed. The events can then be reweighted according to a specific neutrino flux to, for instance, represent the IceCube flux or an atmospheric neutrino flux. The simulation includes propagation through Earth, deep-inelastic scattering, quasi-elastic scattering and resonant interactions. For the propagation of the produced muons and taus, the MUSIC code [90] and TAUOLA code [91] are used, respectively.

The atmospheric muons are simulated using the MUPAGE code [92]. MUPAGE uses a parameterization of the atmospheric muon flux at different energies and zenith angles. As a result, events can be generated with sufficient statistics, to match the actual detection rate of atmospheric muons. In addition to single atmospheric muons, atmospheric muon bundles are simulated. Muon bundles are especially important at high energies. The results of MUPAGE have been compared to results from a full air-shower simulation using CORSIKA [93] and are found to be in good agreement. Since the energy spectrum of atmospheric muons is steep, MUPAGE simulations have been performed for different muon threshold energies. This allows to simulate adequate statistics at energy regions of interest for cosmic neutrino detection.

3.1.1 *Tau neutrino simulations*

The tau neutrino CC interaction has some distinct features compared to the other neutrino flavors. Currently, the MC simulations lack an implementation for two of them: Regeneration of the tau neutrino when propagating through Earth and the light production during the propagation of the tau lepton through the can.

The Earth becomes opaque for neutrinos with energies in excess of 100 TeV (see Sec. 1.2.2). When a neutrino interacts via the CC, it is transformed into a charged lepton. Since electrons and muons are stopped in the Earth's matter, the neutrinos are effectively absorbed. This is not the case for tau leptons, because the tau leptons will decay into a tau neutrino before being stopped. The so produced tau neutrino will carry a substantial amount of the initial neutrino energy. This process is called "tau regeneration". It is energy dependent, as the tau neutrino interaction probability increases with the neutrino energy and energy is lost each interaction. Hence, the energy lost by a tau neutrino as it travels through Earth increases with its initial energy as shown in Fig. 21. For example, a tau neutrino of 1 PeV initial energy traversing Earth's full diameter will on average loose 90 % of its energy, while a a tau neutrino of 10 PeV initial energy will on average loose 98 % of its energy [94]. This energy dependent effect causes tau neutrinos from below the horizon to reach the can, even if their energy is above 100 TeV. However, the rate of tau neutrinos from below the horizon is significantly lower than that from above the horizon. A rough estimate expects a 20 % increase in expected event rates due to this effect.

The light produced by the tau lepton during propagation is currently not simulated. This is a reasonable approximation, since the tau lepton acts as a minimal ionizing particle at the energies under consideration. Considering its typically short flight path [94], it will only produce a relative small amount of Cherenkov photons.

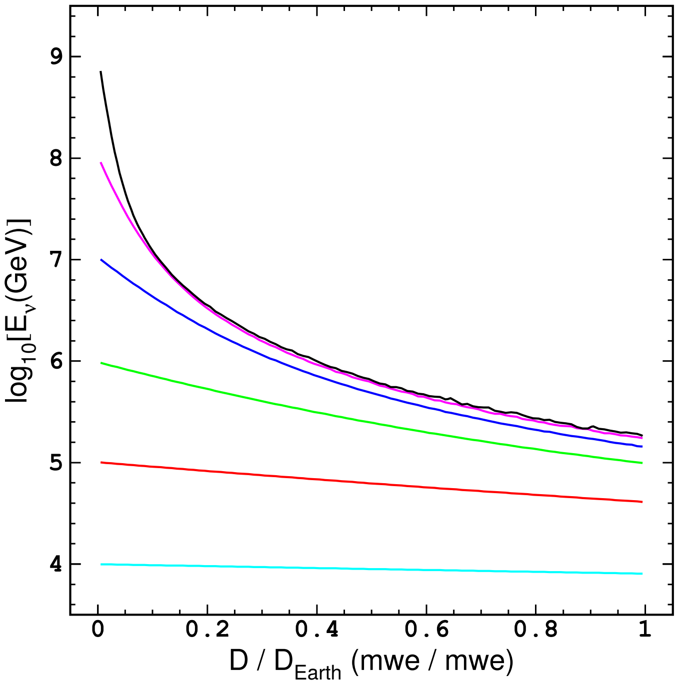

Figure 21: Mean remaining energy of ν_τ as a function of traversed fraction of Earth diameter for starting energies of 10^4, 10^5, 10^6 to 10^9 GeV (bottom to top) [94].

3.2 LIGHT SIMULATION AND DETECTOR RESPONSE

The light production of particles in the can is simulated using tabulated results from a GEANT 3.21 simulation. This approach is used as tracking of single photons is too time consuming. The code used for this is called KM3 and for this work KM3 v5r3 is used [95].

The light production for showers is simulated using a so-called "multi-particle" approximation. Except for muons and taus, the light production of particles is simulated by treating them like an electron shower with a scaled equivalent energy and distance to the vertex. This simulation technique results in shower maxima positions in agreement with calculated values as shown in Fig. 22. The light production of hadronic shower is scaled to be one third of that of an electron shower.

For the light produced, KM3 projects it to the PMTs in the detector taking into account the scattering and absorption of the light in the sea water. In the next step the light detection is modeled including absorption in the glass sphere and the gel, as well as the PMT efficiency and PMT angular acceptance.

Light from ^{40}K decays and dark rates from the PMTs are simulated by adding 5 kHz of random noise to the PMTs. Light from bioluminescence bursts is not simulated. The PMT response is simulated using the Jpp software package [96]. It includes the transition time and the amplification of the PMT as well as the effects of the readout electronics. After the PMT response is simulated, the events are then triggered with the algorithms described in Sec. 2.5.1.

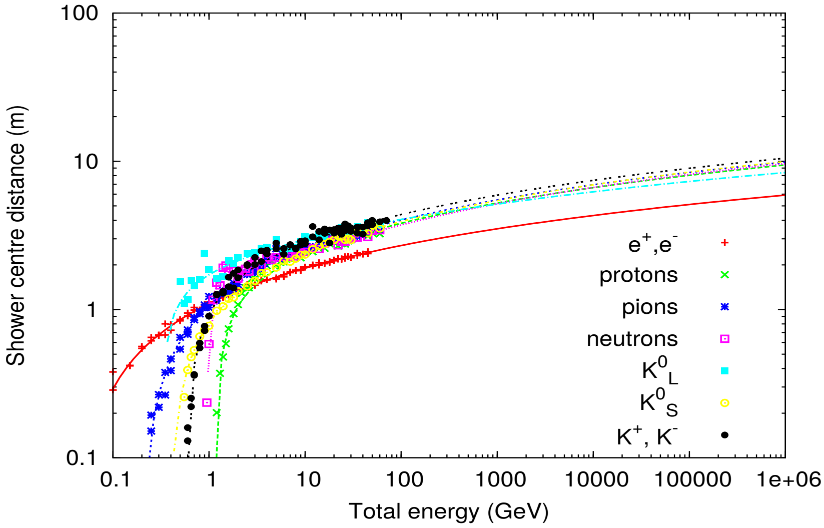

Figure 22: Shower maxima (points) compared to calculations (lines) for a given initial energy for different particles; pions denote charged pions (neutral pions are treated as electrons).

3.3 TAU TOY MONTE CARLO

The tau toy Monte Carlo (MC) simulation is a simplified approach to emulating the signature of tau events. Within the tau toy MC each parameter can be tuned independently, therefore allowing controlled studies of the influence of quantities such as Bjorken Y and tau travel distance on the reconstructions. In addition, the toy MC allows for the simulation of a large amount of contained events at interesting energies and flight length in a short time compared to a normal MC production. In the following all results produced using the toy MC are named as such.

The increase in speed to a normal MC simulation is achieved by approximating each shower with a single particle and using arbitrary positions and directions for the neutrino. The tau flight direction is aligned with the neutrino direction. The energy of the neutrino is set to a desired value and the tau energy fraction can also be freely chosen. The tau flight length is then calculated according to Eq. 22, fixing the lifetime for a given energy to the corresponding mean lifetime.

Events are only written if the tau decay position and the neutrino position are contained in the detector. At both positions a particle is placed which will cause the shower signature: At the neutrino position a π^+ with energy equal to the difference between neutrino and tau energy; at the tau decay position a π^+ or electron with energy equal to 75 % of the tau energy. The choice of particle type for the tau shower allows to simulate the hadronic or e.m. decay modes of the tau. The reduction is approximately the average energy loss caused by the neutrinos created in a real tau decay. Consequently, each event contains the following particles:

- Neutrino of chosen energy
- Tau
    - Energy is a fraction of neutrino energy
    - Direction is neutrino direction
- Neutrino hadronic shower
    - Approximated with a π^+
    - Position: neutrino position
    - Direction: neutrino direction
    - Energy: neutrino energy with tau energy subtracted
- Tau decay shower
    - Approximated with a π^+ or electron
    - Position: offset a distance as given by Eq. 22 in tau direction from neutrino position
    - Direction: is neutrino direction
    - Energy: 75 % of tau energy

The files are then processed using KM3 for the light simulation. Afterwards they are triggered using standard trigger software. During the trigger process random background hits simulating the potassium decays are added for an assumed potassium singles rate of 5 kHz.