Muon Production in Hadronic Particle Showers

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Neutrino-nucleon interactions in media produce hadronic cascades. During the development of the cascade muons are produced from the decay of hadrons, mainly pion and kaon decay. If the muons have sufficient energy they can travel a significant distance through the detecting medium and alter the observed topology of the cascade event. We simulated the production of high energy muons within hadronic cascades using the simulation programs Pythia and GEANT and parameterised the muon flux. We fitted the slope from our simulations with a power law and calculated the rate of muon production to be $\gamma = 2.50 \pm 0.03\,\mathrm{GeV}^{-1}$. This rate of production of high energy muons within hadronic cascade events is lower than previously calculated and currently used in simulations of neutrino-nucleon interactions for neutrino detectors such as IceCube.

INTRODUCTION

A hadronic cascade arises in a detection medium when a neutrino interacts with a nucleon. In this interaction the energy of the collision splits the nucleus, producing quark singlets. These interact via hadronic processes to produce hadrons by subsequent jet fragmentation[15]. This is in contrast to an electromagnetic cascade whose particles only interact via electromagnetic interactions. The energy transferred to the hadronic cascade is typically approximately 20% of the incoming neutrinos energy[6]. However, there are large fluctuations in the neutrino-nucleon interaction and in some cases almost all of the neutrino's energy can be transferred into the hadronic cascade[6].

Cherenkov photons are produced from charged particles within a cascade. Neutrino detectors are constructed in large, transparent media such as water or ice in order to detect Cherenkov radiation. One such neutrino telescope is IceCube[2] which has a cubic kilometre of the Antarctic ice sheet instrumented with detecting units called *Digital Optical Modules* (DOMs)[1]. The Cherenkov photons produced in hadronic and electromagnetic cascades scatter while propagating through the ice so that the detected light distribution appears spherical. The Cherenkov light from a hadronic cascade, although similar in topology to an electromagnetic cascade, is somewhat dimmer because of the presence of neutral particles within the hadronic cascade[17]. Another unique occurrence in hadronic cascades is the production of long range particles such as muons. A muon, if produced with high enough energy, propagates through the detecting medium. If the distance travelled is significant then the track-like properties from the muon can change the appearance of the spherical light distribution of the event.

Figure 1 shows a representation of a long range muon produced in a hadronic cascade. The topology of the event can be dramatically altered due to the Cherenkov light from the muon.

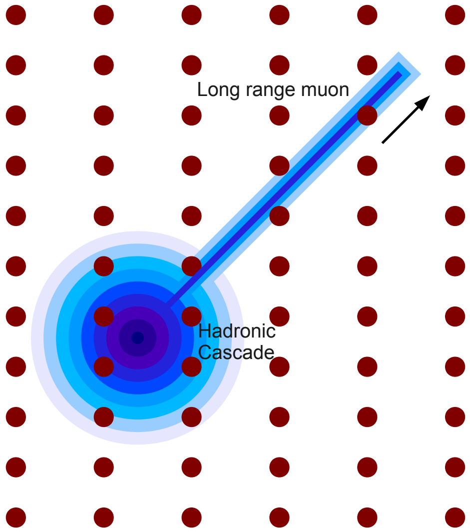


FIG. 1: A high energy muon produced in a hadronic cascade. DOMs in the IceCube detector are depicted by the red circles, the muon's travel significantly alters the topology of the light produced in the detector from the cascade event.

An electromagnetic cascade contains photons, electrons, and positrons. Photons create electron-positron pairs via pair production. The electrons and positrons then radiate photons via bremsstrahlung. The development of electromagnetic cascades can be modeled by the Heitler model[8]. In this model interactions occur after each interaction length and the primary energy is distributed evenly to the particles so that throughout the progression of an electromagnetic cascade the energies of the particles is reduced. The total charged track length of the electromagnetic cascade is calculated from the total amount of Cherenkov light detected[9] which is proportional to the energy of the electromagnetic cascade.

The development of hadronic cascades is more complex than that of an electromagnetic cascade because of the variety of particles produced which can undergo further interactions. The extended Heitler model[10] is used to describe the development of hadronic cascades. This model assumes that ten hadrons are produced in each interaction. One third of the hadrons produced will be neutral particles such as π^0 which will subsequently decay to two gamma particles producing an electromagnetic sub-cascade. Two thirds of the hadrons produced are charged particles such as pions and kaons. Muons are mainly produced from the decay of these particles and so the production of pions and kaons are important to parameterise the muon flux within hadronic cascades.

The pions and kaons produced in a hadronic cascade will lose energy, through processes such as ionization, until undergoing decay. The charged pion has a branching ratio of 99.99% for decay to a muon, so it can be assumed that every charged pion in the hadronic cascade will produce a muon. Kaon decay often results in a charged pion which will subsequently decay, producing a muon. The pions and kaons in the hadronic cascade may either decay in flight, or slow down to a stop. Of those that slow to a stop, the negatively charged particles may get captured by the Coulomb field of a nearby atom in the surrounding medium. This occurs because of the central positive charge of the atom and is called a pionic or kaonic atom[3]. This particle is analogous to a nucleon in an excited state and loses energy by evaporation of low energetic particles leaving the nucleus. Peaks are expected in the muon flux at 110 MeV and 258 MeV corresponding to positive pion and kaon decay at rest respectively. These are low energetic muons that will not travel a significant distance through the medium. Pions and kaons that decay in flight will produce high energy muons that do travel a significant distance through the medium.

SIMULATION

Simulations were performed to parameterise the muon flux in hadronic cascades. These types of simulations have been performed previously[12, 13] using a modified version of CORSIKA[7]. This work uses the programs Pythia[16] and *GEometry ANd Tracking* (GEANT)[4, 5]. These simulation programs provide a more accurate model of the detection medium, such as the Antarctic ice used by the IceCube detector, and of the observed events.

The previous simulations forced the event to take place in a medium of salt water. In these simulations an incoming proton interacted with a proton in a salt water medium. The muons produced in the cascade were recorded as they passed through an observation level, 9 m from the interaction point in the forward direction.

The simulations presented in this work use Pythia 6.2 as the event generator[16]. Simulation of an interaction is divided into components, each handled separately with a high level of accuracy. The simulation uses Monte Carlo techniques to ensure the output is non-deterministic and contains fluctuations. The Pythia event generator includes simulation of initial and final state radiation, multiple interactions among beam jets, and fragmentation. The code includes a *High Energy Physics* (HEP) subroutine that produces the event record in a Monte Carlo independent format.

The program GEANT 4.8 was used to simulate the passage of particles through matter[4, 5]. GEANT simulates the interactions of particles with matter over a large energy range. Hadronic processes are modeled using the QGSP model, which is an educated guess physics list of hadronic interactions contained within GEANT. The production of optical photons via Cherenkov radiation was enabled using the additional physics constructor and includes absorption, Rayleigh scattering, and boundary processes undergone by optical photons. GEANT provides code for generating specific detector constructions. For this work the properties of the Antarctic ice which the IceCube detector was constructed in were simulated for the detector construction. The cubic kilometre block of ice was defined by creating a three dimensional volume of H_20 with the properties of refractive index and absorption for each wavelength of light that propagates through the ice in a neutrino interaction. Values for the refractive index depend only on the phase velocity of the medium[11], and are taken from the tables in PHOTONICS[14].

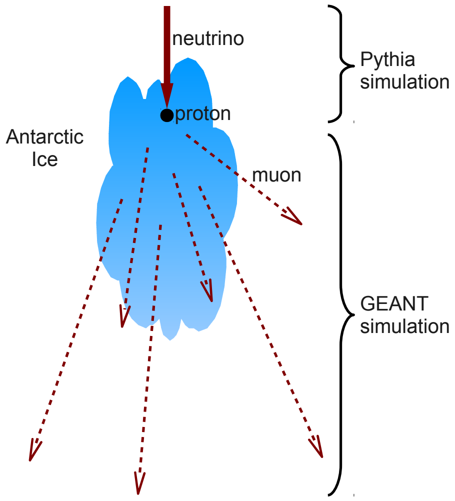


FIG. 2: Pythia and GEANT simulation. An incoming neutrino interacts with a proton in the Antarctic ice to produce hadrons. Particles are recorded as they propagate through the medium.

The simulation set up of Pythia and GEANT is shown in Figure 2, where an incoming neutrino interacts with a proton in the Antarctic ice medium. The particles and all their interactions are recorded as they propagate through the ice.

The simulation of high energy muon production in hadronic cascades using Pythia and GEANT has three major advantages over the previous simulation performed using CORSIKA[12, 13]. These advantages are:

Interaction particles
The CORSIKA simulation uses a proton+proton interaction to approximate the neutrino+nucleon interaction. The Pythia event generator simulates a neutrino+proton interaction. It is expected that the CORSIKA simulation will over-estimate the number of hadrons produced by more than an order of magnitude because of the increased number of quarks in the proton+proton interaction compared to the neutrino+nucleon interaction.

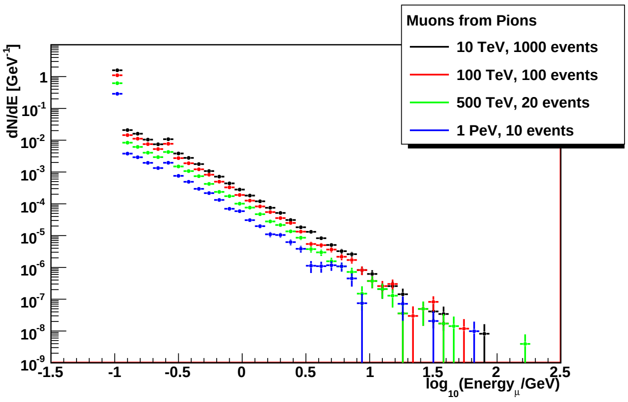
Detector medium
The CORSIKA simulation uses salt water as the interaction medium. This is because the CORSIKA was initially developed for use in the Earth's atmosphere and was later modified for neutrino detectors located in oceans. GEANT allows specific detector construction, which includes the Antarctic ice properties that IceCube was constructed in. It is expected that the ice properties will contribute an uncertainty of approximately 10% to the simulation.

Observation of muons
The CORSIKA simulation records muons at the observation level, defined as being 9 m in the forward direction from the interaction point. GEANT tracks muons, as well as all other particles, throughout their entire track length in all directions.

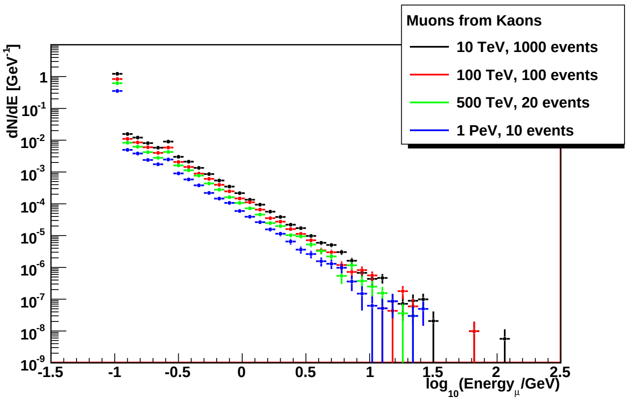
MUON FLUX

The Pythia and GEANT simulation was performed for incoming neutrino energies of 10 TeV, 100 TeV, 500 TeV, and 1 PeV. These simulations were performed with 1000, 100, 20, and 10 events respectively.

Figure 3 shows the number of muons produced from 3(a) pion decay and 3(b) kaon decay, as a function of muon energy for each simulation. The y-axis shows the number of muons produced in the simulation scaled by the neutrino energy and the number of simulated events. The peaks from pion and kaon decay at rest are seen at approximately $\log(\mathrm{E}) = 0.96$ (110 MeV) and $\log(\mathrm{E}) = 0.59$ (258 MeV) as discussed previously.



(a) Muons from pion decay.



(b) Muons from kaon decay.

FIG. 3: Number of muons produced in a hadronic cascade as a function of the muon energy.

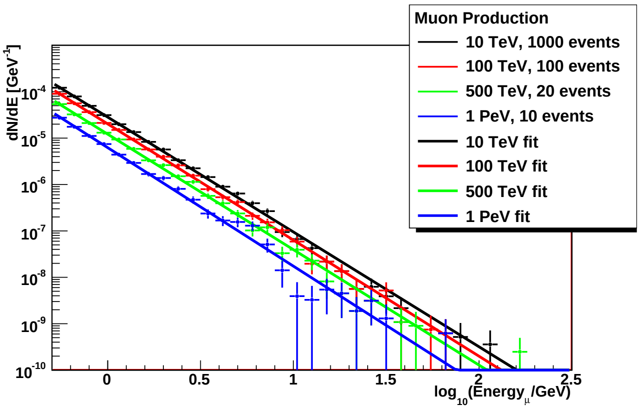


FIG. 4: Number of muons produced in a hadronic cascade as a function of the muon energy. The straight lines show the power law fits.

Figure 4 is Figures 3(a) and 3(b) combined and enlarged to the higher energy region of muon production showing the number of muons produced from pion and kaon decay, as a function of muon energy for each simulation. The fits to the muon flux at each energy are shown by the straight lines. The fits use a power law

$$\frac{dN}{dE} = A(E/\mathrm{GeV})^{\gamma}, \tag{1}$$

where A and γ are the power law parameters. The fit is calculated between the limits of $0.3 <$

$\log_{10}(\text{Energy}_\mu/\text{GeV}) < 0.7$ and numerical values for the parameters in the power law fits are shown in Table I.

Neutrino energy	A	γ (GeV^{-1})
10 TeV	2.84×10^{-5}	-2.48 ± 0.02
100 TeV	2.03×10^{-5}	-2.50 ± 0.02
500 TeV	1.22×10^{-5}	-2.49 ± 0.03
1 PeV	0.62×10^{-5}	-2.55 ± 0.04
Average		-2.50 ± 0.03

TABLE I: Values of the parameters A and γ from the power law fits to the GEANT simulations of muon production in hadronic cascades.

The value found for the rate of muon production is

$$\gamma = -2.50 \pm 0.03\,\text{GeV}^{-1}. \tag{2}$$

Previous work[12, 13] has obtained this value from simulations to be $\gamma = -2.74 \pm 0.48\,\text{GeV}^{-1}$. Our result is lower but within the uncertainty range of the fits. The production of muons above approximately 5–10 GeV is detectable in neutrino telescopes such as IceCube because they travel further than the DOM spacing on a string. Using the fits from Table I we would expect 5.99×10^{-3}, 4.28×10^{-2}, 1.29×10^{-1}, and 1.31×10^{-1} muons to be produced above 10 TeV for an incoming neutrino energy of 10 TeV, 100 TeV, 500 TeV, and 1 PeV respectively.

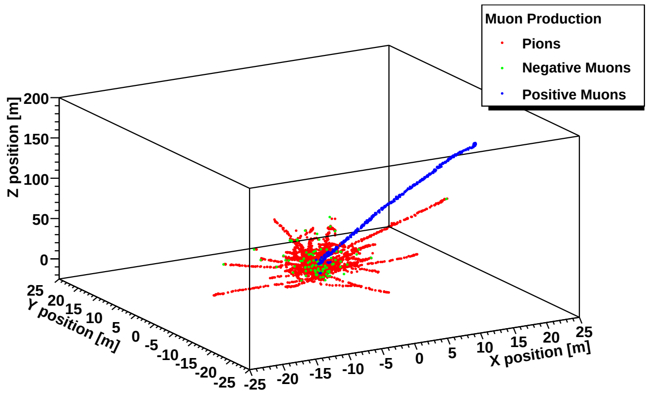


FIG. 5: Simulation of a 10 TeV neutrino. The points show the position of each pion and muon particle in the cascade as the simulation steps through in time.

Figure 5 is an illustration of the effect of a high energy muon in a hadronic cascade from the lowest energy simulation we performed. The position of each particle is plotted in metres as the simulation steps through time. Pions are indicated by the red points, negative muons by the green points, and positive muons by the blue points. As the simulation progresses the particle's trajectories can be observed by the developing path of the particles. The pions make up the majority of the cascade, largely situated close to the centre forming a roughly spherical topology. The negative muons generally form at the end of a pion track in the detector because the pion has decayed to create a muon at the end of its lifetime. In this simulation one pion decays to a high energy positive muon which subsequently traverses a much greater distance than the cascade size. This is seen by the blue points which form the muon track through the medium. This muon travels approximately 200 m through the detector, originating from a 10 TeV electron neutrino interaction.

SUMMARY

The production of high energy muons within hadronic cascades is a complication that arises in the simulations of events in neutrino telescopes. Muons are produced from the decay of hadrons, mainly pion and kaon decay. If the muons produced are energetic enough they traverse a significant distance through the medium and change the observed topology of the cascade event. We performed simulations to parameterise the muon flux in hadronic cascades. We found the average rate of muon production in hadronic cascades from our simulations to be

$$\gamma = -2.50 \pm 0.03\,\text{GeV}^{-1}. \tag{3}$$

This value is lower than previous values obtained because of the more realistic simulation parameters that we used.

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