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# Very high energy electromagnetic cascades in the LPM regime with IceCube

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**Abstract:** With a volume of $\sim$1 km$^3$, IceCube will be able to detect very high energy neutrinos above $\sim$100 PeV. At these energies, bremsstrahlung and pair production are suppressed by the Landau-Pomeranchuk-Migdal (LPM) effect. Therefore, $\nu_e$ and $\nu_\tau$ interactions in the ice can produce several hundred meter long cascades. We present an analysis of IceCube sensitivity to $\nu_e$ events. It includes cascade simulation in the LPM regime and makes use of preliminary algorithms for incident angle reconstruction. We give the obtained effective area for the 22 string configuration and discuss IceCube angular reconstruction precision.

## Introduction

Different models predict a significant flux of high energy neutrinos above $\sim$100 PeV. Topological defects, superheavy relics of the Big-Bang, the GZK mechanism or gamma ray bursts could produce such high energy neutrinos (see [1] for a review).

The IceCube neutrino detector is under construction at the South Pole [2]. Currently, it is made of 22 strings each holding 60 optical detectors, instrumenting a volume of $\sim$0.3 km$^3$. Strings are separated by 125 m and modules on a string are separated by 17 m. By its completion in 2011, there will be up to 80 strings and the corresponding volume will be $\sim$1 km$^3$.

At low energies, $e^\pm$ produced by charged current interactions produce small cascades compared to the spacing between two optical modules. The produced light is emitted in the direction of the Cherenkov cone but it is scattered in the ice so that when observed from a distance, it can be considered to be emitted almost isotropically from the centre of the cascade. Therefore, the angular resolution for cascades is poor.

However, for a 100 PeV neutrino, the secondary particle energy is high enough for bremsstrahlung and pair-production to be supressed by the Landau-Pomeranchuck-Migdal (LPM) [3, 4] effect. This leads to an elongation of the cascades, which in turn could result in better angular resolution for cascade events in IceCube.

Here, we focus on electromagnetic cascade analysis for $\nu_e$ events at energies above $\sim$100 PeV where the LPM effect has to be taken into acount. The LPM effect also affects hadronic cascades but as the input energy is distributed over a large number of secondary particles, their length does not increase as dramatically. Hadronic cascades will not be discussed in this paper.

In the next section, we describe two simulation tools for high energy cascades in the LPM regime. The longitudinal profiles obtained are used to estimate the Cherenkov light output in the ice. Following that, effective area is computed for the 22 string detector. Finally, the precision of incident angle reconstruction is evaluated.

The results shown are preliminary.

## Simulation of high-energy cascades

To study high-energy cascades in ice, two simulation packages have been developed. One allows the rapid simulation of cascade profiles and uses a parameterisation of bremsstrahlung and pair-production cross sections in the LPM regime, and a parameterisation of energy deposition for the low

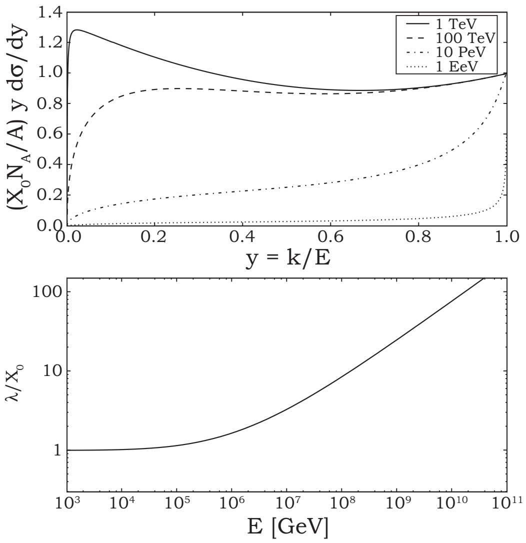


Figure 1: Top panel: differential energy cross section for bremsstrahlung as a function of $y = k/E$ where $k$ is the energy of the photon and $E$ the energy of the electron. Bottom panel: mean free path for bremsstrahlung as a function of energy.

energy products of the cascade. The other package is a full Monte Carlo simulation of cascades based on `CORSIKA`. It is devoted to fine studies of the development of cascades.

## Hybrid approach

Following Niess and Bertin [5], a simulation of the cascade development has been implemented. This simulation takes into account bremsstrahlung and pair production interactions and works only in one dimension. The suppression of both processes by the LPM effect is included. Parameterisations of bremsstrahlung and pair production cross sections are taken from [6]. Fig. 1 shows the differential cross section and radiation length parameterisation for bremsstrahlung. The increase of the mean free path above 1 PeV is due to the LPM effect.

In the simulation, high energy particles are propagated until their energy falls below a cut-off energy on the order of 1 TeV and the energy loss profile of these particles is computed using a parameterisation. The individual energy loss profiles of these low energy particles are summed to obtain the total energy deposit profile of the full shower.

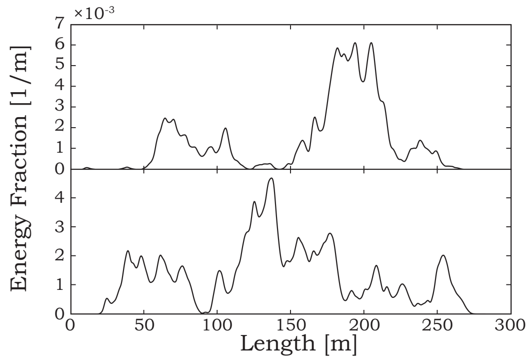


Figure 2: Longitudinal energy profiles of two 10 EeV electromagnetic cascades.

The fractional energy of the secondary particles is generated randomly from the differential cross section using a Metropolis-Hastings Algorithm [7]. This allows the quick generation of random samples. For instance, when the cut-off energy is on the order of 1 TeV, a single cascade with energies in the PeV range can be simulated in a few milliseconds. A 10 EeV cascade is simulated within less than 3 minutes when the cut-off is set to 50 TeV.

Fig. 2 shows longitudinal energy profiles of two 10 EeV cascades. Their length is about 200 m. Many different sub-cascades contribute to this profile. The figure also shows that the shape and length of the longitudinal profile can vary significantly from one cascade to another.

## Monte Carlo approach

In addition to the simple hybrid approach presented in the previous section, we have also developed a more realistic simulation tool, able to provide more precise information on cascade development. This tool is based on the well-known atmospheric cascade simulation tool `CORSIKA` [8].

As `CORSIKA` is devoted to cascade simulations in the atmosphere, several modifications had to be made in order to adapt the code to a uniform density medium. This work was initially done by T. Sloan for the ACoRNE collaboration with

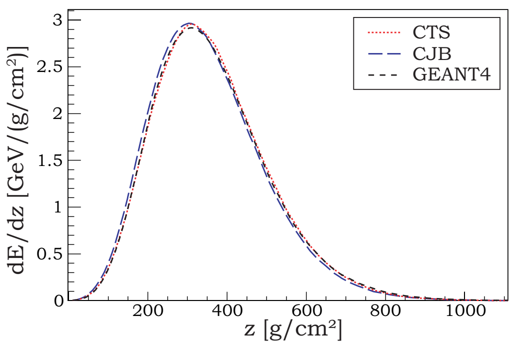


Figure 3: Average longitudinal profile of one hundred 1 TeV cascades. Comparison between `CTS`, `CJB` and `GEANT4`.

`CORSIKA 6204` [9]. Hereafter, this version will be denoted `CTS`.

We have used these modifications and taken them a step further to get more functionality and more flexibility. The new modifications allow us to:

- switch the medium from air to ice during the configuration step,
- use the different simulation packages (`VENUS`, `QGSJET` and others) available with `CORSIKA`,
- use all the other options available in `CORSIKA`, whenever they are relevant to a simulation in water/ice.

The changes were made starting from the most recent version of `CORSIKA` (`CORSIKA 6502`).

To check the validity of this software (denoted `CJB`), we simulated 1 TeV electrons using both versions `CJB` and `CTS` with the same input parameters and the same random generator seeds. The results were also compared with `GEANT4` [10].

Fig. 3 shows the energy deposition profiles for the two versions of `CORSIKA` and `GEANT4`. The profiles are very similar. The small difference between `CJB` and `CTS` comes mainly from minor revisions in the `EGS4` code [11] between `CORSIKA` releases `6204` and `6502`.

A 10 EeV cascade can be simulated in less than 2 minutes for default values of cut-off energies, provided the thinning option is enabled.

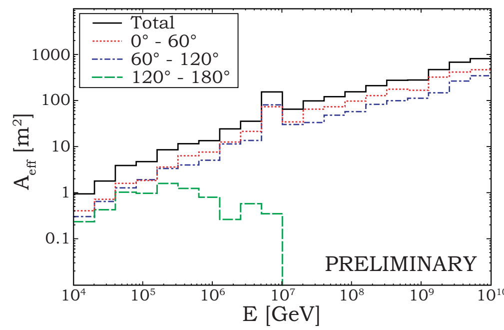


Figure 4: Effective area for different incident angles and for the 22 string configuration.

## Reconstruction and effective areas

Electron neutrinos with energies between 10 TeV and 10 EeV were generated, propagated through the Earth and forced to interact in the vicinity of the instrumented detector volume using a software package based on the `ANIS` [12] neutrino generator. The development of the cascades in the ice has been done with the hybrid simulation tool described previously. The detector response includes the simulation of light propagation through the ice, optical module responses and a trigger simulation requiring 8 modules hit within a time window of 4 $\mu$s.

A basic analysis method typically used to reject muon background was applied to the pure $\nu_e$ sample in order to calculate the effective area, taking into account the reconstruction efficiency. The selection is done by computing the ratio between the longitudinal and lateral size of the light distribution, using the fact that cascades are more spherical than muon tracks.

The number of passing events was used to calculate the neutrino effective area for three different zenith angle ($\theta$) bands for the 22 string configuration (Fig. 4). The effective area generally increases with energy due to the rising cross section of neutrino interactions. However, for neutrinos with energies above ~1 PeV the earth becomes opaque and the effective area for neutrinos coming from below the horizon ($120^o < \theta < 180^o$) falls off. The peak between 5 PeV and 10 PeV is caused by resonant $\overline{\nu_e} + e^-$ scattering at energies around 6.3 PeV (the Glashow resonance).

## Precision of incident angle reconstruction

Cascade-like events passing the trigger conditions are reconstructed using a simple *line-fit* algorithm [13] usually used for muon track reconstruction. It uses the hit times to produce a track defined by a vertex point and a direction.

The difference $\phi$ between generated and reconstructed directions is computed. Fig. 5 shows the cumulative fraction of events reconstructed with an arbitrary precision $\phi$. At 1 EeV, the proportion of cascades reconstructed with a precision better than 20$^o$ is $\sim$5%. At 10 EeV, when the LPM effect is taken into account, this proportion is $\sim$20%.

## Conclusions

At very high energies, the LPM effect can increase the length of cascades to several hundred meters. This could lead to better angular resolution for high energy cascades. We have developed two new tools in order to study these events.

A very simple *line-fit* method seems to indicate a significant improvement of angular reconstruction precision at high energies. However, this improvement, due to cascade lengthening, still leads to insufficient resolution for possible high energy neutrino source identification.

Achieving this goal will require dedicated algorithms to fully exploit the cascade lengthening and to obtain improved angular resolution. Such methods are under development.

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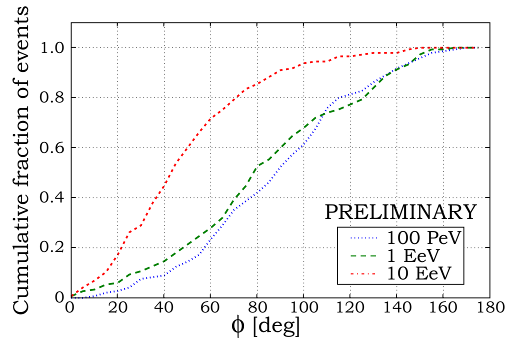


Figure 5: Cumulative fraction of events reconstructed with an arbitrary precision $\phi$, for the 2007 22 string configuration.

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