Improving the directional reconstruction of PeV hadronic cascades in IceCube

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Abstract. Many neutrino interactions measured by the IceCube Neutrino Observatory produce only hadronic showers, which appear as almost point-like light emission due to the large detector spacing (125 m). At PeV energies these showers often saturate the PMTs closest to the interaction vertex - thus the reconstruction has to rely on more diffused photons which requires precise understanding of the optical properties of the Antarctic ice. Muons produced in the hadronic showers carry information about the neutrino direction, and their Cherenkov light arrives earlier than the photons emitted by the electromagnetic component. A new reconstruction method has been developed which explicitly takes into account the muonic component of hadronic showers and is shown to be robust against systematic ice uncertainties. By applying the new reconstruction, the angular resolution of multi-PeV cascade events can be significantly improved. This will potentially enable follow-up studies of the highest-energy cascade events measured by IceCube.

1 Introduction

High energy neutrino observatories in the TeV to PeV range detect neutrinos via Cherenkov light emitted by secondary particles created by the neutrino interactions. For this purpose, large natural media such as the Antarctic ice (for the *IceCube Neutrino Observatory* [1]), the Mediterranean Sea (*ANTARES* [2], *KM3NeT*) [3], or Lake Baikal (*Baikal GVD* [4]) have been instrumented with photomultipliers (PMTs). In these detectors, most neutrino interactions can be classified by their event signature as either *track* or *shower*. Tracks are produced when muons are created, e.g. by ν_μ charged-current interactions. Due to the long lever arm, these events can usually be reconstructed with angular uncertainties well below 1°. If no high-energy muon is produced, the entire observable energy is contained in a particle shower, with shower lengths well below the typical sensor spacing. Thus, the directional reconstruction of these events is much more challenging with reconstruction uncertainties of a few degrees [5]. For multi-PeV shower events in IceCube, the PMTs closest to the event vertex are often saturated, so that event reconstructions have to rely on more distant PMTs, where the photons

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have undergone multiple scattering processes. This increases the influence of uncertainties of the optical ice model. However, muons created in neutrino-induced hadronic particle showers carry additional information about the neutrino direction. The average range of a 10 GeV muon is already larger than 40 m, thus a muon of such energy could outrange the shower, increasing the lever arm for the reconstruction.

2 Muonic Component of Hadronic Showers

Neutrino deep inelastic scattering (DIS) results in the formation of a hadronic particle shower, where the shower energy is given by the inelasticity distribution. Muons are predominantly produced by the decay of mesons in the shower. In the case of resonant W^--production in $\bar{\nu}_e - e$ scattering (often known as Glashow resonance [6]) and subsequent hadronic decay of the W^-, the entire neutrino energy is available for the formation of the hadronic shower. This results in higher shower energies than in the DIS case.

Following [7], the muon energy distribution from pion and kaon decays in ice can be parameterized by a power law:

$$\frac{dN_\mu}{dE} = A\left(\frac{E_0}{\mathrm{GeV}}\right)^{\kappa} \cdot \left(\frac{E_\mu}{\mathrm{GeV}}\right)^{-2-\kappa}, \tag{1}$$

where E_0 is the energy of the primary particle, E_μ is the muon energy, $\kappa \approx 1$, and $A \approx 3.5 \times 10^{-3}\,\mathrm{GeV}^{-1}$. Therefore, a hadronic shower with initial energy $E_0 = 1\,\mathrm{PeV}$ produces more than 10 muons with energies larger than 10 GeV.

The leading-muon energy is of particular interest, as this determines the lever arm for directional reconstruction. As the energy available for the hadronic shower is on average higher for the Glashow resonance (GR), the muon multiplicity in these showers is larger and thus also the leading-muon energy. An accurate description of the muon flux (and leading muon energy) can be derived by simulating the neutrino interaction with `PYTHIA8` [8] and handing the products of the hadronization to `CORSIKA` [9] for propagation. Initial simulation studies show that the median leading muon energy for charged current and GR interactions at 6.3 PeV is ≈ 10 GeV and ≈ 40 GeV respectively.

3 Combining Muon and Shower Reconstruction

Muons created in the hadronic shower propagate faster than the Cherenkov light produced by the hadronic shower itself and thus can create characteristic early signals; see fig. 1. Figure 2 shows a typical PMT waveform of a multi-PeV neutrino interaction in IceCube. The PMT is close to the interaction vertex, thus it saturates immediately after the arrival of the Cherenkov front of the hadronic shower and cannot be used for reconstruction. However, prior to the shower front a small signal is induced by the muonic component. These early hits can be identified by a causality criterion, i.e. searching for hits before the expected arrival time calculated from the reconstructed event vertex. Using the early hit times, a track hypothesis for the muon position $\vec{x}$ at time t can be fitted:

$$\vec{x}(t|\vec{d}, t_0, \vec{x}_0) = \vec{x}_0 + (t - t_0) \cdot \vec{d},$$

where $\vec{x}_0$ is the position at time t_0 and $\vec{d}$ the direction of the track. The likelihood model is based on the time arrival distributions of photons emitted from the track at every PMT:

$$\mathcal{L} = \prod_{i}^{N_{\mathrm{PMTs}}} \prod_{j}^{N^i_{\mathrm{Photons}}} p_i(t_j|H), \tag{2}$$

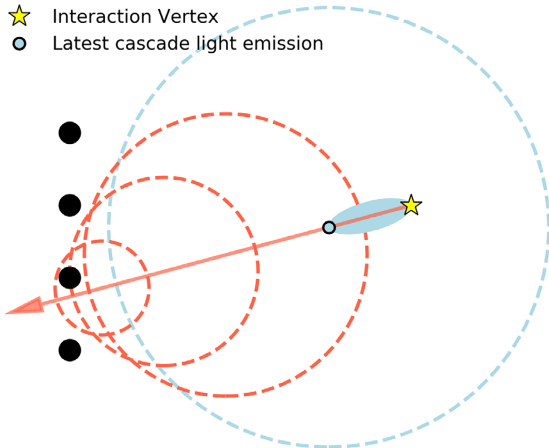
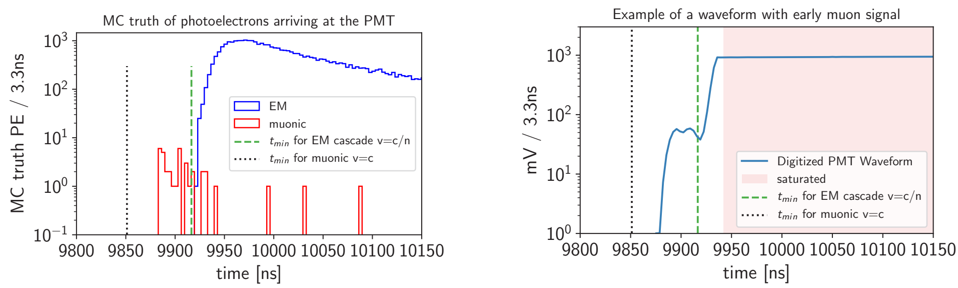


Figure 1. Sketch of the event signature of muons produced in hadronic showers. Here, the Cherenkov light emitted by the muons arrives earlier at the sensors than the Cherenkov light emitted by particles at the end of the particle shower.



(a) Photon arrival time at the PMT

(b) Simulated PMT waveform

Figure 2. Early muon signal in a PMT close to the event vertex. Black and green dashed lines indicate the muon and shower light fronts respectively.

where p_i is the photon arrival time distribution for PMT i for a given track hypothesis H. p_i can either be parametrized analytically [10] or obtained from splined lookup-tables. Due to their relatively low energies, the muons from hadronic showers will often create hits only on a single detector string, causing large degeneracies in the likelihood space of the track parameters. This can be mitigated by including the event vertex and its uncertainty obtained from a shower reconstruction as a prior into the track reconstruction. The event vertex is usually reconstructed very precisely, even in the presence of systematic uncertainties. As a proof of concept, in fig. 3 we show the result of the reconstruction in terms of angular resolution for a simulated hadronic cascade resulting from a GR neutrino interaction. The simulated event is particularly difficult to reconstruct, because the interaction vertex lies outside the instrumented volume. The median resolution for this event using the current best shower reconstruction in IceCube is $\approx 110\,\text{deg}^2$. The track reconstruction of the early muon signal improves the resolution by a factor 6 to roughly $\approx 18\,\text{deg}^2$. As the track reconstruction uses independent information from the shower reconstruction, it can be used to validate the shower reconstruction result.

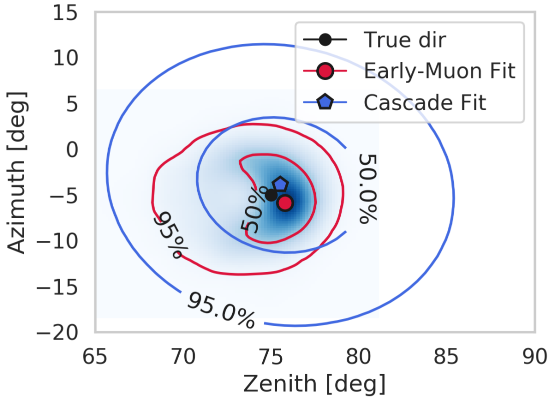


Figure 3. Angular reconstruction performance of the early muon reconstruction in comparison to the shower (cascade) only reconstruction for a multi-PeV hadronic shower. The blue-shaded region indicates the posterior PDF. The lines indicate 50% and 90% credible regions.

4 Conclusions & Outlook

The angular reconstruction of multi-PeV neutrino interactions resulting in hadronic showers can be significantly improved by explicitly reconstructing the muonic component of the shower. Simulations with `PYTHIA8` and `CORSIKA` have been performed to verify that the leading muons produced in PeV hadronic showers have enough energy to escape the shower. These muons cause early hits in the PMTs prior to the main wavefront of the hadronic shower and can be selected by causality constraints. Fitting a track hypothesis to these early hits, while using vertex information from a standard shower reconstruction, gives an independent reconstruction of the event direction. In the future this reconstruction technique can be used to improve the angular resolution of multi-PeV shower events and verify shower reconstructions in the presence of systematic uncertainties.

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