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The Performance of Shower Reconstruction in TRIDENT

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TRopIcal DEep-sea Neutrino Telescope (TRIDENT) is a next-generation neutrino observatory to be located in the South China Sea. With its large instrumented volume, unique position near the equator and use of advanced hybrid digital optical modules (hDOMs), TRIDENT aims to discover multiple astrophysical neutrino sources and probe all-flavor neutrino physics. In contrast to track-like events, shower-like neutrino events have a low rate of background atmospheric muon events. Neutrino telescopes with degree-level angular resolution for shower-type neutrino events would boost source-searching sensitivity and probe neutrino oscillation across astronomical baselines. In this contribution, we present TRIDENT's angular resolution in the reconstruction of shower-like neutrino events from 10 TeV to 1 PeV.

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1. Introduction

The measurement of astrophysical neutrinos, produced in the interactions of cosmic rays with surrounding matter and electromagnetic fields, can provide the smoking-gun evidence to the origins of high-energy cosmic rays. Neutrino production involving the decay of charged pions followed by muon decay results in a flavor ratio of $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$. Neutrinos traveling over astronomical distances undergo oscillation, leading to a flavor ratio approximately $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 1 : 1)$ at Earth. In other scenarios, such as muon damped and neutron decay, astrophysical neutrinos are expected to be produced in the flavor ratios of $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 1 : 0)$ and $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 0 : 0)$, respectively. It is predicted that these production scenarios are distinguishable through the precise measurement of the flavor composition of neutrinos arriving at Earth [1]. These measurements would give deeper insight into the sources of high-energy neutrinos and cosmic rays [2], and potentially probe hidden physics processes that may occur over their propagation [3].

High energy neutrinos may undergo deep inelastic scattering (DIS) with nucleons in ice or water through the neutral current (NC) or charged current (CC) channels, resulting in the production of secondary particles. By detecting the Cherenkov photons emitted by these secondary charged particles, the direction and energy of primary neutrinos can be reconstructed. Neutrino flavors can be distinguished based on their characteristic energy deposition signatures in ice and water. Track-like events primarily arise from ν_μ CC interactions. These events can produce km-long energy depositions, and can be measured with sub-degree angular precision [4], making them the preferred channel used in searches for neutrino sources. The detection of neutrinos from TXS 0506 [5], NGC 1068 [6] by IceCube rely on these track-like events. In contrast, shower-like events, originating from ν_e-CC interactions and NC interactions of all flavor neutrinos, have angular resolution of a few degrees in IceCube. Due to reduced light scattering in water compared to ice [7], the angular resolution for cascade events is substantially better in Baikal-GVD [8] and KM3NeT [9]. These shower events, benefiting from low atmospheric backgrounds, are particularly suitable for measuring diffuse flux and searching for extended sources [10], such as the recent reported observation from our galaxy [11]. Moreover, shower events exhibit superior energy resolution due to having complete energy deposition within the detector volume, which is crucial to determine the Glashow Resonance event in IceCube [12]. The identification of astrophysical ν_τ can be characterized by the double bang signature, which arises from the hadronic shower produced by the primary neutrino interaction vertex and the subsequent shower resulting from the decay of the τ lepton. These double bang events can be identified as a double pulse in the readout waveform [13] or reconstructed as a double cascade [14], where accurate reconstruction of cascades can therefore be used to identify tau events.

TRopIcal DEep-sea Neutrino Telescope (TRIDENT) expects to have exceptional precision in pinpointing neutrino sources with its size and use of hybrid digital optical modules (hDOMs), which contain multiple small photomultiplier tubes (PMTs) and silicon photomultipliers (SiPMs) [15]. TRIDENT also seeks to explore fundamental physics as well as physics beyond the Standard Model (BSM) by measuring all flavor neutrinos. In September 2021, the TRIDENT pathfinder experiment was successfully completed at a selected site in the South China Sea [16]. This study mainly focuses on the simulation of cascade events in the TRIDENT detector, implementing optical measurements from the pathfinder experiment. The direction reconstruction of shower events in the TRIDENT detector is also shown for eletron neutrinos ranging from 10 TeV to 1 PeV.

2. Simulation of TRIDENT

The event generator in the TRIDENT simulation framework is built based on CORSIKA8 [17]. The TRIDENT detector is represented as a cylinder with a radius of 2500 m and a height of 1000 m, situated at a depth of 2900 m under the sea. Primary neutrino DIS interactions are simulated via Pythia8, which is integrated into CORSIKA8. In this study, the position of ν_e-CC and NC interaction vertices are fully contained within the detector. The daughter particles generated from DIS interactions are saved and subsequently transferred to Geant4 for further simulation.

A parameterized simulation is employed to handle the electrons produced in the primary DIS interactions. The energy and direction of secondary particles produced in electromagnetic (EM) showers are parameterized, instead of a detailed simulation in Geant4, where all secondary particles are tracked. This parameterized simulation significantly reduces simulation time, achieving a speed-up to $\mathcal{O}(1000)$. Each defined Cherenkov step, which includes the time, position, momentum, and number of Cherenkov photons is transferred to OptiX [18], a GPU based ray-tracing software, for the simulation of photon propagation in sea water. To this end, the detector response is simulated in Geant4, in which the TRIDENT detector is constructed, composed of 1200 strings, with each string containing 20 hDOMs separated vertically by 30 m [16]. Figure 1 illustrates the simulated detector response produced by a 1 PeV ν_e-CC interaction, where the color represents the arrival time of photons and the size indicates the number of photons hit on each hDOM. The following section introduces the methods used to reconstruct cascade direction using photon hits measured on hDOMs.

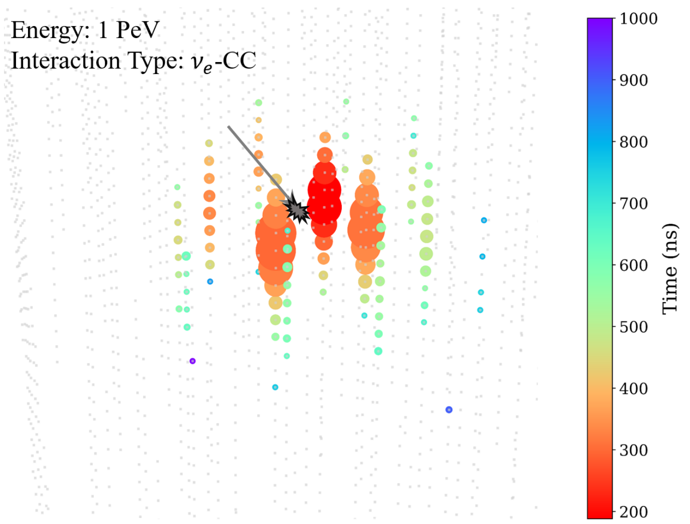

Figure 1: The detector response of 1 PeV ν_e-CC interaction induced shower event in TRIDENT. The color indicate the arrival time of photons and the size shows the number of photons hit on each hDOM.

3. Reconstruction Method

First, a simple fit of the interaction vertex and direction is made by assuming it is a point source and the photons are emitted according to Cherenkov angle. These two first guess results are further improved by the M-Estimator fitting, a robust regression method which can significantly reduce the impact of outliers.

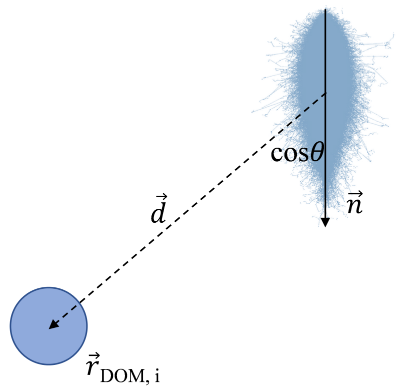

Figure 2: Schematic view of a shower event and the hit DOM. $\vec{r}_{\text{DOM,i}}$ indicates the position of hit hDOM and $\vec{n}$ is the direction along shower axis. The PDF built for maximum likelihood estimatoe is based on $|\vec{d}|$ and $\cos\theta$.

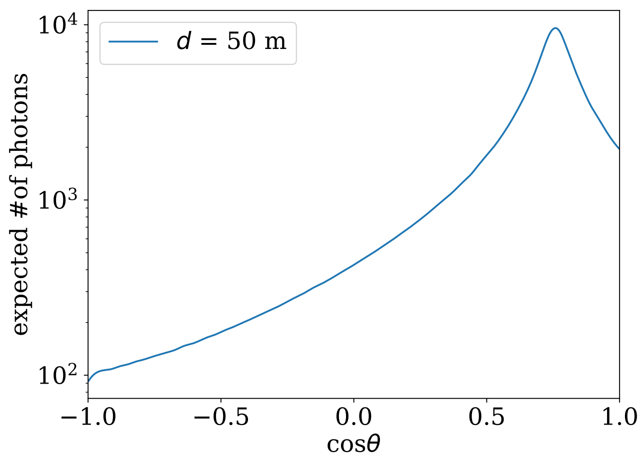

Figure 3: A slice of PDF versus $\cos\theta$ for 100 TeV ν_e-CC events.

A two dimensional PDF is built based on the expected number of hits at given distance d and angle $\cos\theta$, as indicated in Figure 2, where all detected hits are assumed to be positioned at the centre of the hit hDOM. d is the distance between the hDOM position and the shower, while $\cos\theta$ is the open angle between the shower axis and the vector pointing from the shower to the hDOM $\cos\theta = \vec{n} \cdot \vec{d}/|\vec{d}|$. A slice of the 2d PDF versus $\cos\theta$ at distance $d = 50$ m is shown in Figure 3. The Cherenkov angle peak can be seen at $\cos\theta \sim 0.74$. The reconstructed results are shown in Figure

4 at energies of 10 TeV, 100 TeV and 1 PeV. It can be seen that, the median angular error is ~ 2° at 100 TeV and ~ 1.8° at 1 PeV.

It is expected that improved performance may be achieved by including information such as measured photon arrival times, the direction and position of individual photon sensor on hDOMs. The inclusion of timing information would allow for a better constraint on the direction by comparing the measured hit time and predicted arrival time. Photon sensors on the hDOMs that face the shower have a higher probability of receiving light than those on the opposite side of the hDOMs. The current reconstruction method's angular resolution is also limited by assuming the cascade as a point source. Considering the reduced scattering in water, it is essential to take into account the extended energy deposition of cascade events along the shower axis to improve the angular resolution.

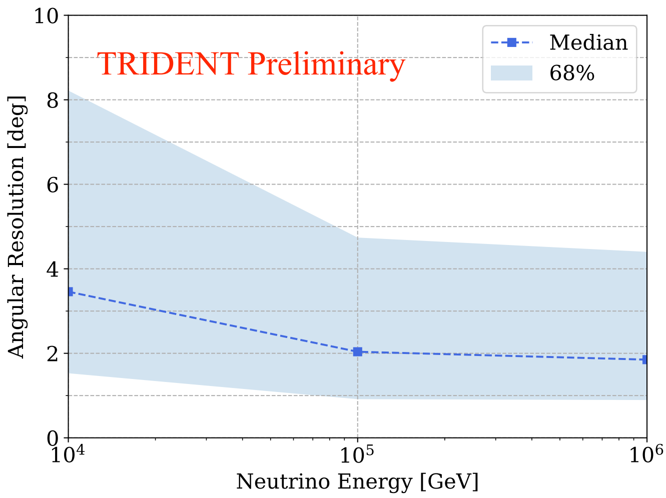

Figure 4: The angular resolution of shower events as a function of energies based on the maximum likelihood reconstruction. The dashed line indicate the median angular error and the shaded band is the 68% region. The median angular error at 100 TeV and 1 PeV is ~ 2° and ~ 1.8°, respectively.

4. GNN Reconstruction

In addition traditional reconstruction method, we also developed a method for direction reconstruction based on Graph Neural Network (GNN). Each neutrino event is represented as a point cloud. For more details about the network architecture used in this work, please refer to [19]. The cascade reconstruction is trained to predict the direction of the primary electron neutrino.

Each DOM is treated as a node in the point cloud. The position of the i-th node is represented as the position of i-th DOM. Input for i-th node includes the timing information of the i-th node is represented as the time of first hit t_i on the i-th DOM, and the number of hits within 1000 ns on each DOM is divided into 100 time bins. Feature vectors of each node are the collection of position, time, and number of recorded hits in each 10 ns time bin, as summarized in Table 1.

The dataset used for the reconstruction for GNN are the same as the maximum likelihood reconstruction. The median angular errors of reconstructed events at 10 TeV, 100 TeV and 1 PeV are shown in Figure 5. At energies of 100 TeV and 1 PeV, the median angular error can be seen to reach 1.5°.

Table 1: Features at each node.

Features	Description
(x_i, y_i, z_i)	position of DOM
t_i	timing of the first hit
$N_{i,j}$	number of hits in each 10 ns time bin j

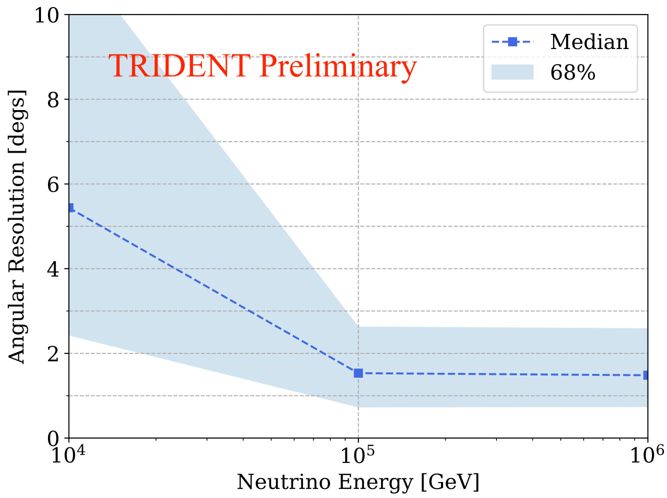

Figure 5: The angular resolution of shower events as a function of energy based on GNN reconstruction. The dashed line indicate the median angular error and the shaded band is the 68% region. The median angular error at 100 TeV and 1 PeV is ~ 1.5°.

5. Discussion and Outlook

In this proceeding, two methods are developed to reconstruct the direction of ν_e-CC produced shower events in the TRIDENT detector. The median angular error with traditional maximum likelihood reconstruction method is ~ 1.8° for 1 PeV primary electron neutrinos, whereas GNN-based reconstruction method can reach ~ 1.5°. Even though the GNN-based method shows a better performance, the maximum likelihood reconstruction method is expected to benefit in the inclusion of photon arrival times, directional information of PMTs and SiPMs on a single hDOM, and replacing the point-source assumption with a multi-point energy deposition event. Furthermore, we are also investigating the robustness of the GNN method against various uncertainties, such as optical properties of water, detection efficiency of photon sensors. Looking ahead, our future work aims to implement both reconstruction methods in TRIDENT for cross-validation.

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