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Searching for astrophysical tau neutrinos with hDOM waveforms in TRIDENT

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The first detection of astrophysical neutrinos and subsequent investigations into their origins by IceCube have unveiled a new window into the extreme universe. As we look to the next generation of neutrino telescopes, such as TRIDENT, the ability to detect all three flavors of neutrinos will shed light on the mechanisms responsible for their production within these astrophysical sources. Moreover, this comprehensive detection capability will serve as a valuable tool for exploring new physics phenomena. Notably, IceCube's observation of tau neutrino candidate events has already showcased the significant potential of PMT waveforms in event identification. In TRIDENT, we aim to record multi-channel waveforms from PMTs within the Hybrid Digital Optical Modules (hDOM), providing powerful tools for tau neutrino identification. In this study, we present the current simulation pipelines implemented in TRIDENT and share preliminary results on the classification efficiency of tau neutrinos using Graph Neural Networks.

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1. Introduction

Neutrino astronomy has ushered in a new era in astrophysics, with high-energy astrophysical neutrinos serving as extraordinary messengers These elusive particles originate from hadronic processes in extreme astrophysical environments such as Active Galactic Nuclei (AGN) and Gamma-ray Burst[1, 2]. Due to their weak interactions, neutrinos can escape from the original dense environments and traverse vast distances through space unaffected by interstellar magnetic fields. This unique property enables the possibility of detecting neutrinos on Earth with neutrino telescopes and retracing them back to their sources.

IceCube, the largest neutrino telescope to date, has made significant contributions to the field. It has detected extragalactic diffuse astrophysical neutrinos [3] and yielded promising observational results on transient or steady neutrino sources[4, 5], providing strong evidence supporting the hadronic origin of high-energy cosmic rays.

In the search for astrophysical neutrino sources, track-like events induced by ν_μ have received significant attention due to their superior angular resolution among the three flavors. However, recent observations in IceCube have also demonstrated the potential of shower-like events induced by ν_e and ν_τ [6, 7]. Although these flavors have inferior angular resolution, they are less affected by background events. Furthermore, precise measurement of the neutrino flavor ratio offers a powerful tool for studying the acceleration mechanisms of cosmic rays in neutrino sources [8] and exploring potential new physics phenomena, such as quantum gravity [9].

Further investigation into cascade-like events requires accurate classification and reconstruction of ν_τ and ν_e events. IceCube has reported the discovery of two astrophysical ν_τ candidates from 7.5 years of High Energy Starting Events (HESE) data [10], with a significance of 2.8 sigma. The current observations are limited by challenges posed by the detector volume and the diffusive glacial ice, where the scattering effect can lead to signal identification degeneracy with ν_e, especially at the energy range of 100 TeV.

As the next generation of water-based neutrino telescopes, the proposed TRopIcal DEep-sea Neutrino Telescope (TRIDENT) aims to advance neutrino source research and enable detection of all-flavor neutrinos [11]. TRIDENT is planned to be constructed in the West Pacific Ocean at a depth of approximately 3,500 meters. The project involves installing approximately 1200 detection strings, each equipped with 20 hybrid Digital Optical Modules (hDOMs), creating a detection volume of approximately 7.5 cubic kilometers. The hDOM design incorporates multi-channel 3-inch Photon Multiplier Tubes (PMTs) and Silicon Photomultipliers (SiPMs), providing pixelized 4π photon coverage and timing resolution on the order of 100 ps [12]. TRIDENT strings will be arranged in a Penrose-tilling geometry, with typical inter-string distance ranges from 70 to 110 meters, and a vertical inter-hDOM distance of 30 meters. Positioned near the equator, TRIDENT will complement the neutrino sky observed by IceCube.

To explore the ν_τ detection potential in TRIDENT and optimize the detector geometry, in this study, we have established simulation pipelines for neutrino interaction and detector response. Based on simulated hDOM waveforms, we employ a Graph Neural Network (GNN) model to differentiate ν_τ from the backgrounds of ν_e and ν_μ. The results demonstrate great performance, achieving an accuracy of approximately 88% within the energy range of 100 TeV to 1 PeV.

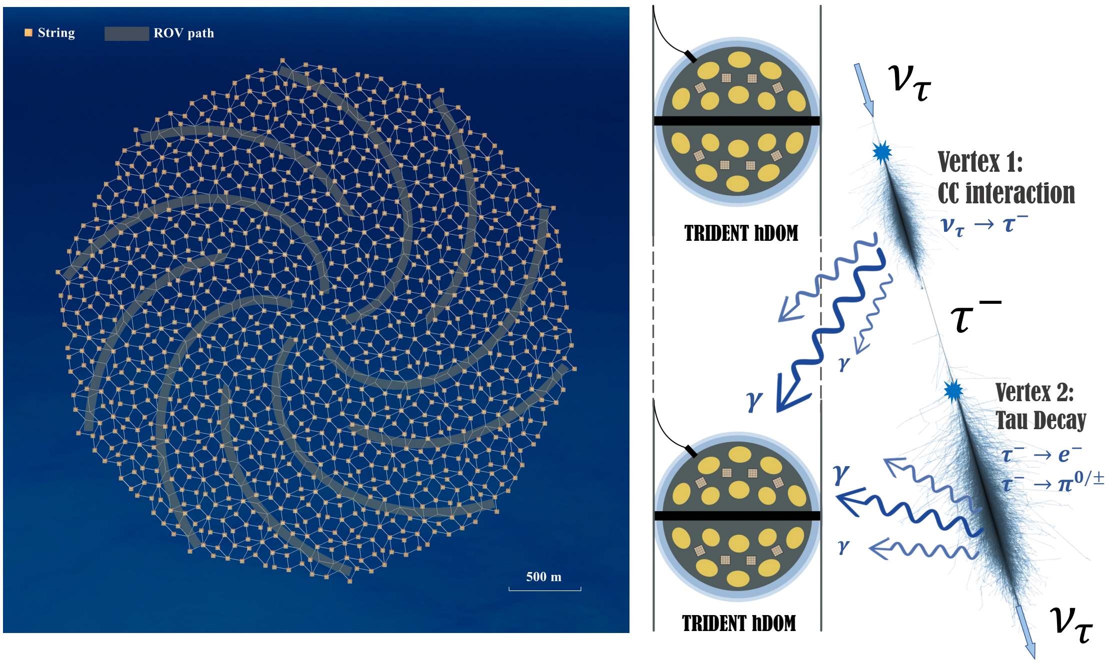

Figure 1: The TRIDENT Penrose geometry and the tau neutrino interaction process in the detector

2. Tau neutrino simulation pipeline

Figure 1 illustrates the TRIDENT detector geometry and a possible topology of tau neutrino signals. When a tau neutrino enters the detector, it can undergo charge current (CC) interaction with the nucleus in the medium, consequently genererating of a tau lepton at the first vertex. This interaction typically takes the form of Deep Inelastic Scattering (DIS) for high-energy astrophysical neutrinos. The DIS process disrupts the atom and initiates the first hadronic shower with secondary particles. As the tau lepton propagates further, it undergoes random decay at the second vertex, with the mean decay length proportional to its energy, approximately $L \sim 50$ m/PeV. The decay of the tau lepton can produce either an electron or pions, leading to the second detectable signal in the form of either an electromagnetic shower or a hadronic shower. As a result, combing the two signals originating from these two vertices, as represented by the characteristic double-pulse waveforms recorded by hDOMs, we can identify tau neutrino.

To accurately simulate the tau neutrino interaction process and the detector response, the TRIDENT simulation pipeline includes two key components. The neutrino generator integrates CORSIKA 8 [13] with the PYTHIA 8 [14] module to generate the secondary particles resulting from the DIS vertex and subsequent tau decay vertex. In the detector simulation, Geant4 [15] is utilized to construct the detector geometry, including the layout of the hDOMs, and to propagate secondary particles. The propagation of Cherenkov photons is handled separately using the OptiX module, which employs GPU acceleration [16]. Additionally, the electromagnetic shower evolution process is parameterized to optimize computational efficiency.

For tau neutrino simulation, an additional step is employed to process the Cherenkov photons from the two vertices separately and then combine them in the subsequent analysis. This step

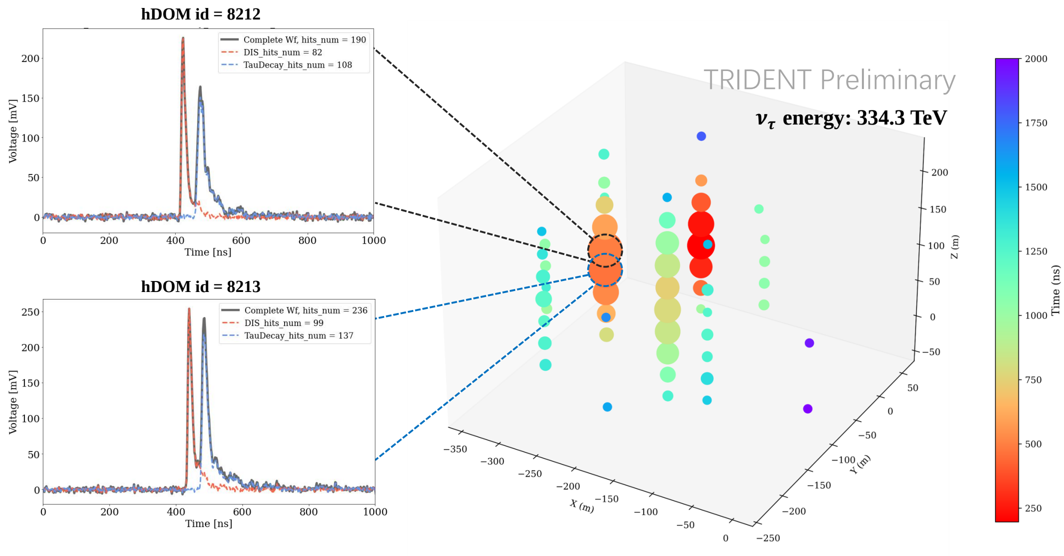

Figure 2: An example of simulated tau neutrino event in TRIDENT

provides detailed Monte Carlo truth for distinguishing the photons from the two vertices in the waveform simulation, as depicted in Figure 2. In the current simulation setup, we only consider the Cherenkov photons emitted during the two shower processes, while the photons emitted during the tau lepton propagation are neglected. These additional photons generally have a minor contribution to the signals when compared to the cascade. However, they may have a slight impact on the waveforms. This aspect will be addressed in our future work.

The Table 1 concludes the simulated neutrino events in this work. We also ensure that all the simulated vertices are located in the detector volume.

Table 1: Simulated neutrino events in this work

Neutrino Type	Energy Range	Event number
ν_τ	[100TeV, 1PeV]	5000
ν_e	[100TeV, 1PeV]	3000
ν_μ	[1TeV, 1PeV]	2000

3. PMT waveform simulation

The hDOM is designed to independently capture waveforms from each PMT channel. In our current waveform simulation, we characterize the 3-inch PMTs, which involves determining the typical waveform template of the single photoelectron signal and considering parameters such as Quantum Efficiency (QE), Transient Time Spread (TTS), Afterpulsing, Non-linear Response, and Dark Count Rate (DCR). To obtain the waveform template, we perform laboratory measurements of the PMTs and average over more than 50,000 single photon waveforms. As the PMT readout electronics module is still under development, we make assumptions regarding the time window, ADC digitization frequency, ADC saturation voltage, and the white noise of the baseline. All these simulation inputs are summarized in Table 2.

For subsequent analysis, we stack all individual PMT waveforms, aligning them in time bins to obtain hDOM-level waveforms. Figure 3 illustrates the waveform template for a single photon signal and a typical double pulse waveform generated from ν_τ simulation.

Table 2: Characterizion of PMT waveform simulation

Parameters	Input number
QE	28%
TTS	FWHM = 1.8 ns
Afterpulsing	< 1% in 1000 ns
DCR at 2°C	300Hz
Time window	2000 ns
Sampling rate	500 MHz
ADC saturation	2.16 V
White noise	σ = 0.31 mV

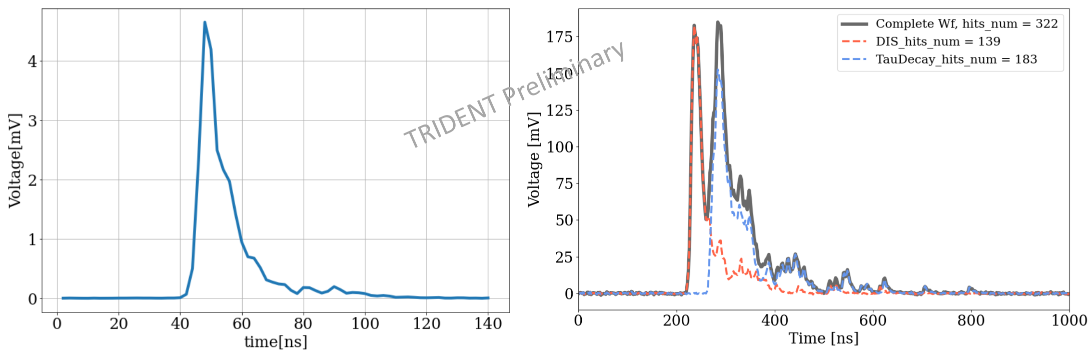

Figure 3: The left figure shows the PMT waveform template obtained from laboratory measurements. The right figure is a typical double pulse waveform, where the red and blue colors represent the photons originating from the DIS vertex and the tau decay vertex, respectively.

4. Tau neutrino identification by Graph Neural Network

GNN is a powerful machine-learning tool that shows great promise for event classification in particle physics. Its ability to handle graph-like structures makes it suitable for analyzing complex interactions in particle detectors.

In this study, we apply GNNs for ν_τ identification in the TRIDENT detector. Our established GNN model, TridentNet [17], treats each hDOM as an independent node in the graph. Each node carries input features, including the coordinate $[x_i, y_i, z_i]$ and the output waveform $[bin_1, bin_2, ..., bin_{1000}]$. By connecting these nodes, TridentNet can gather deeper joint information, enhancing the event classification process.

To analyze the simulated data, we split the dataset into three subsets: the Training set, Testing set, and Application set. We apply an initial cut to ensure a minimal of 500 photons are detected in the hDOMs for waveform output. We then select the 10 brightest hDOMs that have received the most photons, and create a 10×1000 graphical representation of their output waveforms. Although in some cases, Cherenkov photons from a single event may only concentrate on fewer than 10 hDOMs, the flexibility of GNNs allows us to handle varying node numbers without sacrificing performance.

Currently, we have focused on the Tau or Non-tau events classification, labeling ν_τ events as 1 and other two flavors as 0 during training. The preliminary results, as shown in Figure 4, indicate an accuracy for the Application set of approximately 88% for identifying "Tau-like" events with a score higher than 0.5. The Receiver Operating Characteristic (ROC) curve provides insights into the effectiveness of our GNN in distinguishing ν_τ events.

The current results represent an initial exploration of the GNN's potential for ν_τ identification in TRIDENT. However, due to the limitation of the simulation data set, there is a risk of over-training. Additionally, there are still many aspects that require optimization in the simulation pipelines. Ongoing efforts are dedicated to refining and improving our approach to achieve more robust and accurate results.

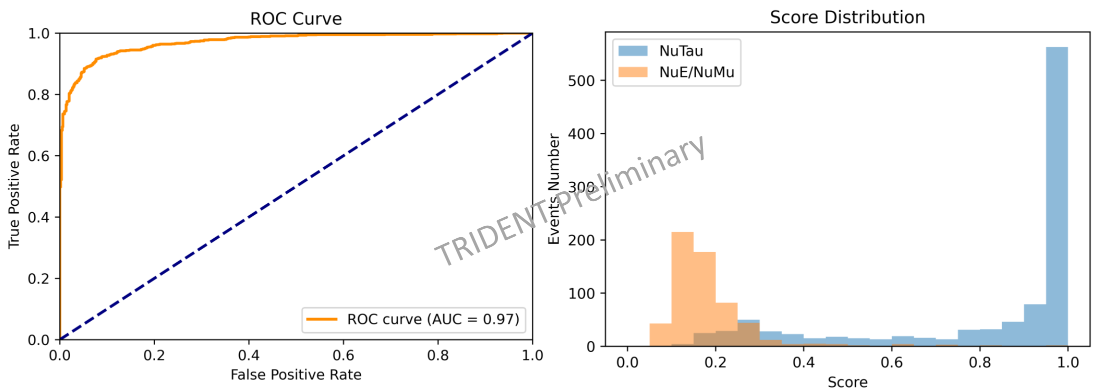

Figure 4: Left: the Receiver Operating Characteristic (ROC) curve of our GNN performance. Right: the score distribution for tau/non-tau events

5. Summary and future work

In summary, this study explores the potential of using Graph Neural Network (GNN) for ν_τ identification in the proposed TRIDENT detector. The analysis of simulated hDOM waveforms demonstrates the promising performance of the GNN model in event classification.

Moving forward, our future work aims to compare the performance of traditional algorithms with the GNN model and understand the identification criteria and estimation uncertainties, as the GNN operates like a black box. Additionally, we intend to investigate the impact of the optical

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properties of the medium in the neutrino telescope and optimize the identification strategy to further enhance the accuracy and robustness of ν_τ identification in TRIDENT.

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