Snowmass2021 - Letter of Interest

ν_τ Reconstruction in the Deep Underground Neutrino Experiment

NF Topical Groups: (check all that apply ☐/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
■ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (RF4) Rare Processes and Precision Frontier: Baryon and Lepton Number Violating Processes
■ (RF5) Rare Processes and Precision Frontier: Charged Lepton Flavor Violation

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Abstract: Despite a wealth of experimental data in recent years concerning ν_μ and ν_e oscillation, experimental results concerned with ν_τ oscillations are still relatively scarce. The upcoming DUNE experiment provides a unique opportunity to experimentally measure charged current ν_τ interactions from both beam and atmospheric sources, in order to probe the unitarity of the PMNS matrix that describes standard three-flavour neutrino oscillations. In order for these searches to be fruitful, techniques must be developed for efficiently identifying and reconstructing charged current ν_τ interactions. This letter discusses the specific challenges faced in reconstructing ν_τ interactions, and the development of machine learning and jet reconstruction-based techniques designed to overcome those challenges.

1 Introduction

Standard oscillations between the three active neutrino flavours are described by the PMNS matrix, a rotation matrix that is assumed to be unitary. Since our knowledge of the mixing angles in this matrix is derived primarily from ν_μ and ν_e interactions, we cannot be confident that the three-flavour model is correct. Explicitly testing this unitarity requires direct measurement of ν_τ oscillation – for instance, for beam neutrino interactions, we must measure the ν_τ appearance from ν_μs in our beam, to confirm it is consistent with existing ν_μ disappearance measurements.

2 Reconstructing ν_τ events

Identifying ν_τ interactions is challenging for several reasons. Firstly, due to the mass of the τ, charged current (CC) interactions are kinematically unavailable for ν_τ energies less than 3.5 GeV. This both limits the available statistics, as any ν_τ flux below this threshold is effectively lost, and means CC ν_τ events are primarily deep inelastic scattering (DIS) events, which contain a substantial amount of hadronic activity from nuclear recoil and are therefore challenging to reconstruct.

Secondly, the τ lepton produced in a CC ν_τ interaction decays at short enough distance scales that it will not be resolved in a LArTPC. As a consequence, the various modes through which the τ decays can be difficult to disambiguate from other modes of neutrino interaction – CC ν_τ interactions where the τ decays hadronically are hard to distinguish from neutral current (NC) neutrino interactions, while interactions where the τ decays into a μ or e are hard to distinguish from CC ν_μ and ν_e interactions, respectively.

In all cases, separating true ν_τ events from various backgrounds is possible. Although topologies are usually very similar, differences in event kinematics mean enriched CC ν_τ samples can be selected using the angular distribution of outgoing particles. However, such selections rely on reconstruction techniques that are able to take full advantage of the resolution provided by a LArTPC detector to efficiently reconstruct and cluster individual particles in high-multiplicity events. In the context of hadronic CC ν_τ interactions, this requires the separation of the hadronic system into its leptonic and nuclear components, while for muonic CC ν_τ interactions this requires efficient reconstruction of the hadronic system and μ angle.

3 Graph Neural Networks

Image-based machine learning techniques have proven very effective as tools for event identification and particle reconstruction in neutrino physics, and are seeing increasingly widespread use in neutrino physics[2–4]. However, since these techniques operate on dense tensors, they scale very inefficiently to large, high-resolution inputs, and are sub-optimal when the structure of the input is not natively arranged in a grid structure.

HEP collaborations are starting to investigate Graph Neural Networks (GNNs) as an alternative to standard convolutional neural networks (CNNs). Such networks structure the input as a graph, which learns in the space of quantised nodes and the edges that describe the relationships between those nodes. The HEP.TrkX collaboration considers detector hits as graph nodes, and classifies the edges between those nodes in order to draw particle tracks[5]; the IceCube collaboration considers detector optical modules as graph nodes, and classifies the entire graph simultaneously in order to accept or reject signal candidates[6].

For atmospheric ν_τ events, which are commonly high in energy and have a large spatial extent, dense

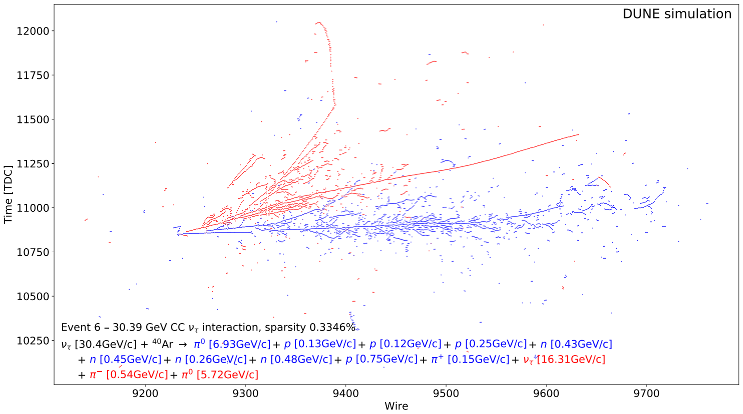

Figure 1: Event display of a simulated atmospheric CC ν_τ interaction in the DUNE far detector, in which the τ decays hadronically. The hadronic systems produced by the tau decay and nuclear recoil are labelled in red and blue, respectively.

CNN approaches for reconstruction are impractical. Fig. 1 shows a simulated high-energy hadronic CC ν_τ event in the DUNE far detector; only 0.33% of the pixels in this image contain physically meaningful information, and so over 99% of the convolution operations performed by a dense CNN approach are wasted computations. Efficiently reconstructing the substructure of high-energy atmospheric interactions using machine learning requires natively sparse applications such as GNNs.

4 ν_τ reconstruction in LArTPCs

Natively sparse machine learning-based methods for reconstructing events in LArTPCs are currently in development. A GNN-based technique has been developed that operates on 2D hit graphs, and is currently 80% efficient at connecting hits produced by the same true particle for a sample of charged current quasielastic ν_e and ν_μ beam events. Development is currently underway to improve and expand on these preliminary results, in addition to techniques that move beyond simple hit-to-hit edge classification in favour of approaches that form clusters of hits explicitly, and ultimately to construct a hierarchical graph-based representation of the entire event.

In addition, a sparse convolutional neural network that operates on voxelised 3D spacepoints from ProtoDUNE simulation is in development, which is 70-90% efficient at classifying individual voxels into various particle categories. Work is currently ongoing to apply this network to simulated atmospheric ν_τ events and assess its performance.

On a more fundamental level, if enough topological information is reconstructed in LArTPCs, one may envision implementing LHC techniques to improve signal-to-background ratios in tau neutrino searches. Jet clustering algorithms and machine learning techniques are promising candidates for such improvements[7].

The DUNE experiment offers great promise for measuring ν_τ oscillations, and experimentally testing fundamental assumptions about the nature of neutrino oscillations. The ability to reconstruct complex ν_τ topologies is critical for enabling such searches, and continued development of advanced techniques such as those machine learning and jet clustering techniques described in this letter is vital in order for this potential to be realised.

References

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