3D-Reconstruction of Tau Neutrinos in LArTPC Detectors

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FERMILAB-POSTER-24-0078-LBNF-V

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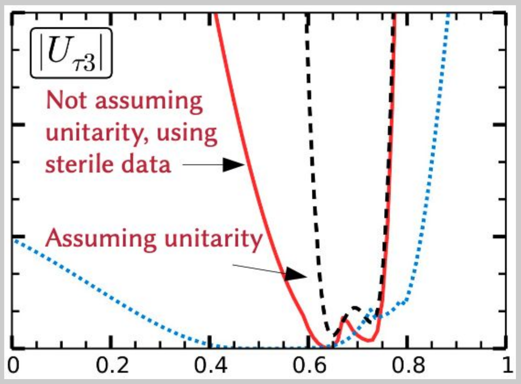
Motivations [1,2,5] (1)

- DUNE is the only upcoming neutrino experiment expected to be able to collect a larger sample of oscillated ν_τ events



from a beam than all existing experiments, (DONUT + OPERA ~ 18 NuTau events).

- ν_τ data can help to understand non trivial questions and enhance searches for BSM physics

Almost all knowledge of tau neutrino sector is taken from:

→ *Lepton universality for cross sections*
→ *PMNS unitarity for oscillations*

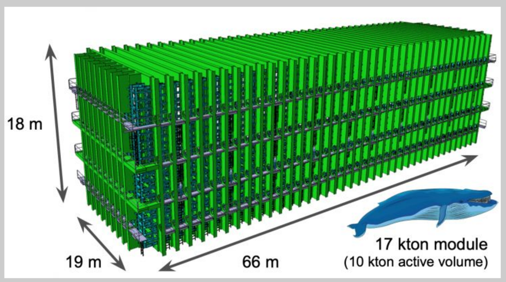
Critical that these assumptions are tested!

Liquid Argon Time Projection Chambers (LArTPC) [2] (2)

- Timing information from scintillation light collected by light detection systems.
- Ionization electrons→ drifted towards segmented wire planes
- Excellent resolution (wire spacing ~3mm)
- 3D reconstruction by combining 2D views

DUNE' Far detector (FD) [2] (3)

- 1300 Km baseline, 1.5 Km deep
- Commissioning expected in 2029
- LArTPC technology

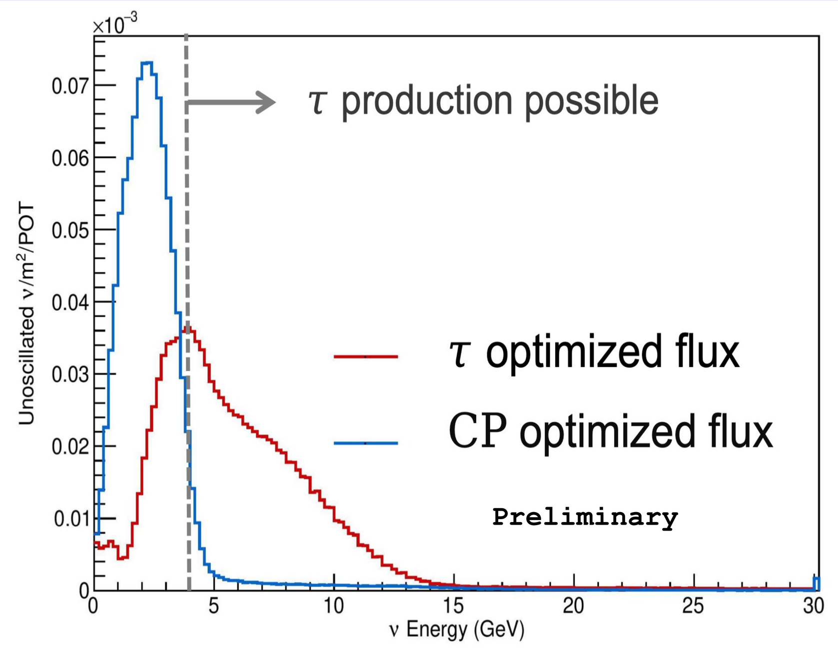


- 4x17 kton LArTPC modules
- 1.1×10^{21} protons on target (POT) per year

DUNE' Flux [2] (4)

DUNE will be the only experiment able to directly observe ν_τ appearing with high statistics

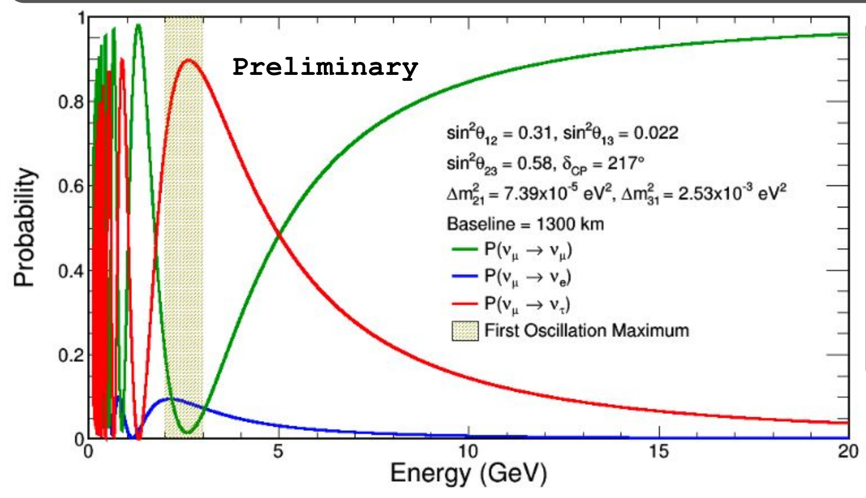
- CP-optimized beam (3 horns configuration)
  - Low energy
  - Default starting configuration
- Tau-optimized beam (2 horns configuration)
  - High energy beam
  - Proposal for after the CP program has completed



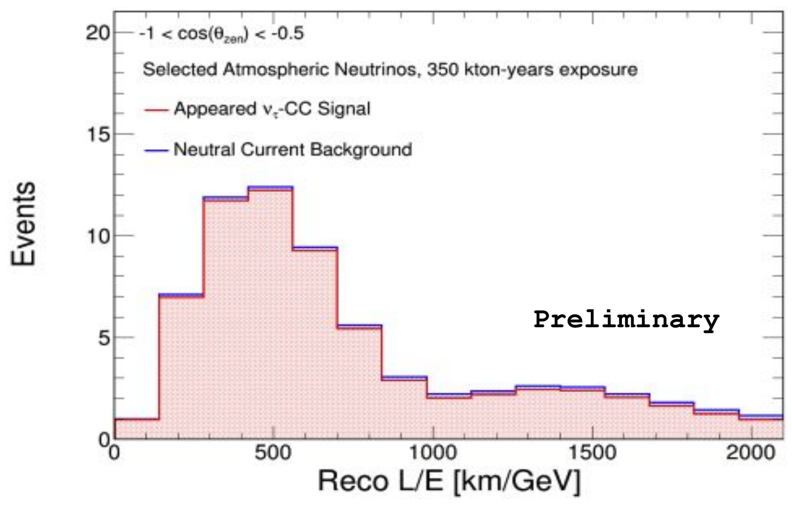
Expected counts/year

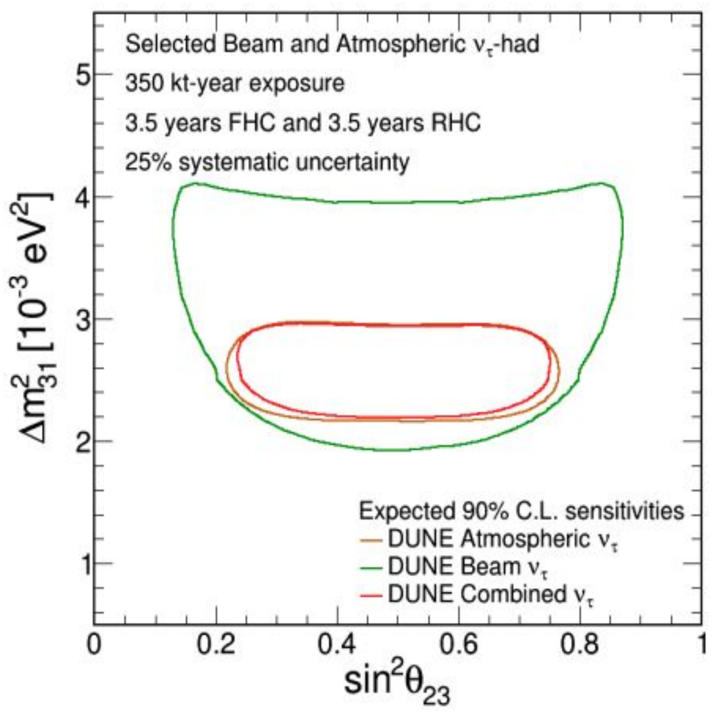
~ 30 $\bar{\nu}_\tau$ in CP-optimized anti-neutrino mode
~ 130 ν_τ in CP-optimized neutrino mode
~ 800 ν_τ in Tau-optimized neutrino mode

What about ν_τ atmospherics? [1,4,5] (6)



Due to kinematic threshold, beam ν_τ are only detected above the atmospheric oscillation maximum → causes a degeneracy between Δm^2_{31} and $\sin^2\theta_{23}$





- Atmospherics have a favorable L/E: better coverage of first oscillation maximum, large matter effect→ we can get the three oscillations modes. Great opportunity to check Unitarity & cross section SM model assumptions
- Beam has defined direction and a near detector for systematic uncertainty reduction
- DUNE data alone expected to constrain normalization of 3rd PMNS column to ~5%
- All other neutrino data constraints normalization to ~7.5%

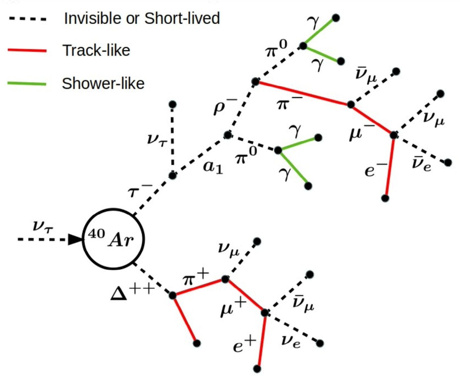
Why is challenging to reconstruct ν_τ? [1,2,4] (5)

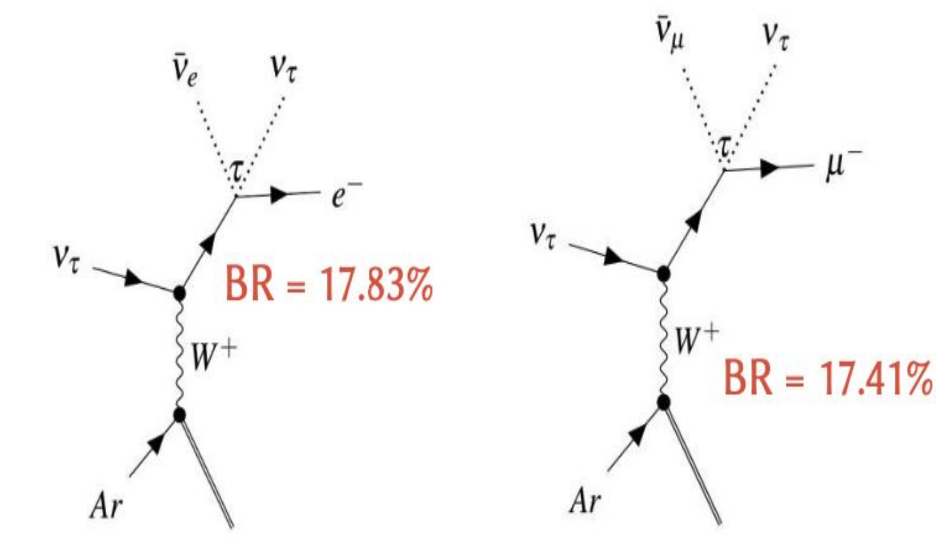
- Hadronic modes can be complicated
- Difficult to separate hadronic systems from τ decay and nucleus

Tau decay length ~ 87 μm
Wire spacing ~ 3mm
Tau lifetime (2.903±0.005) ×10-13 s

Impossible to observe Tau tracks!

Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

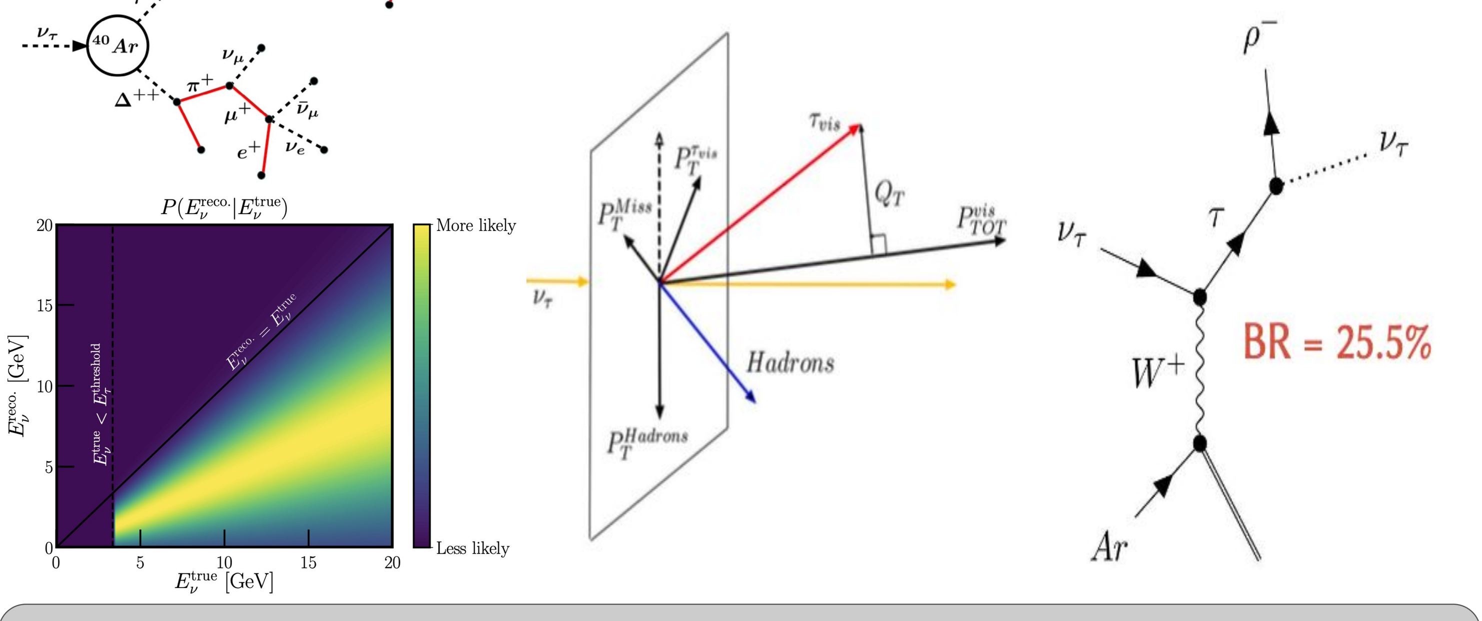




Tau leptons have many decay modes

CC- (ν_e, ν_μ) and NC events have same particle content

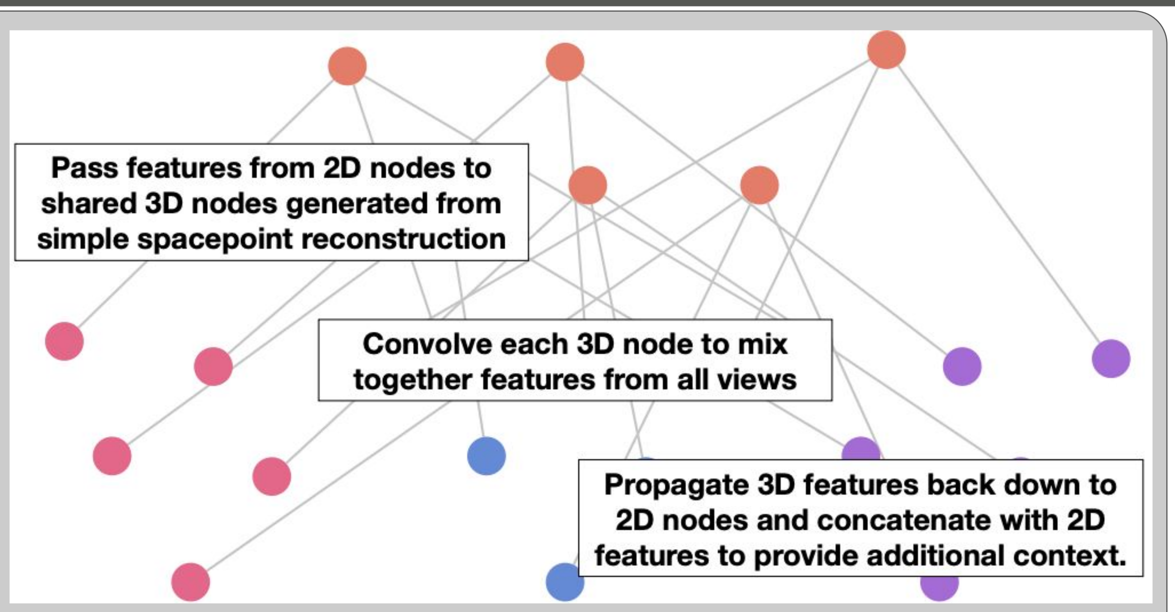
Angular correlations due to missing neutrino(s) from τ decay is the key signature



Intricate: distinguish signal from background → look for a transverse kinematic approach: **CC-ν_τ with τ-leptos decaying into e, μ and ρ-leptons**

NuGraph: originally test with MicroBooNE data, showing efficiency and purity ~ 95% and consistency between planes ~98% [6,7] (7)

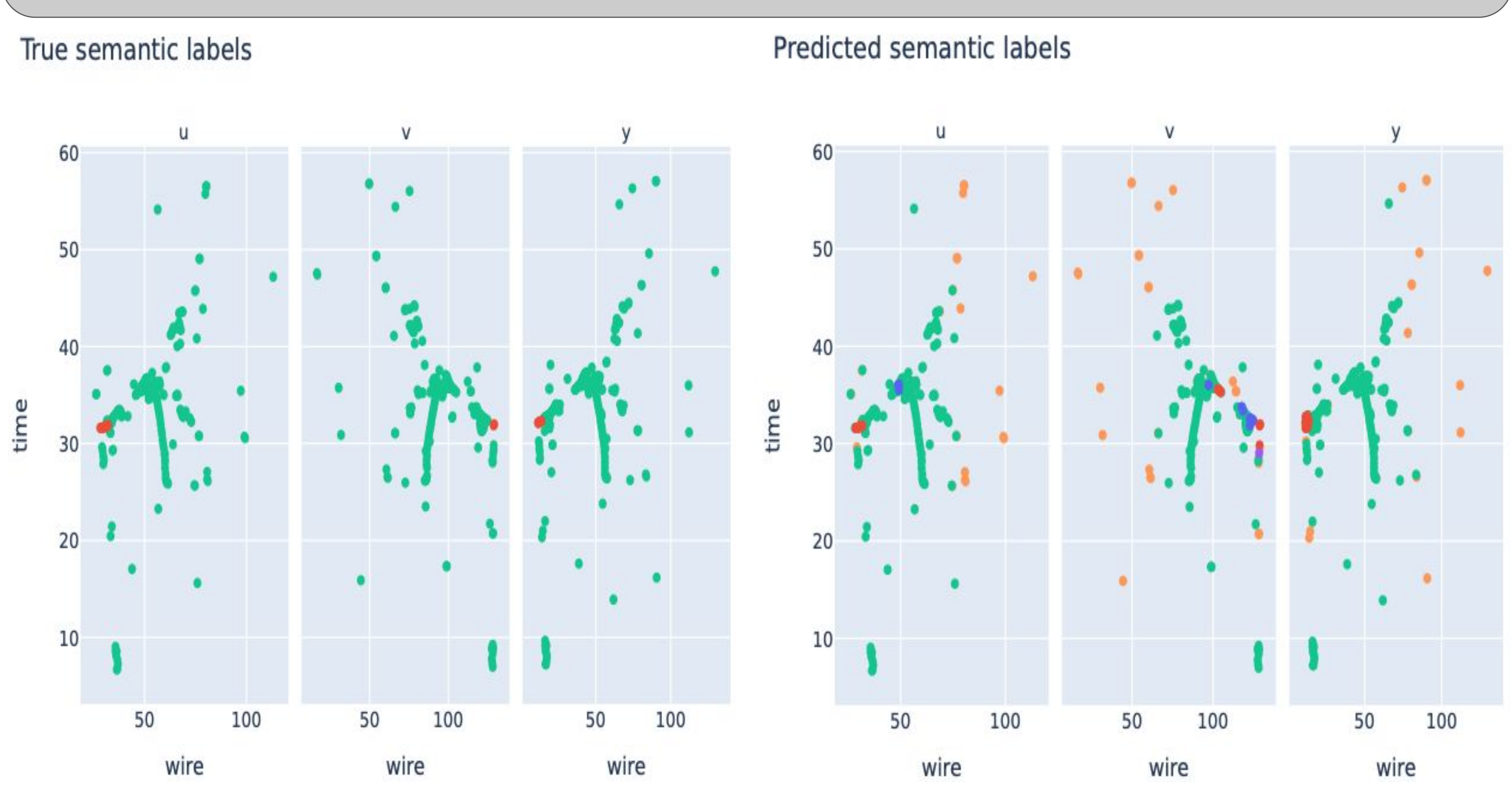
NuGraph Output: each of the particle category has a separate set of embedded features which are convolved independently



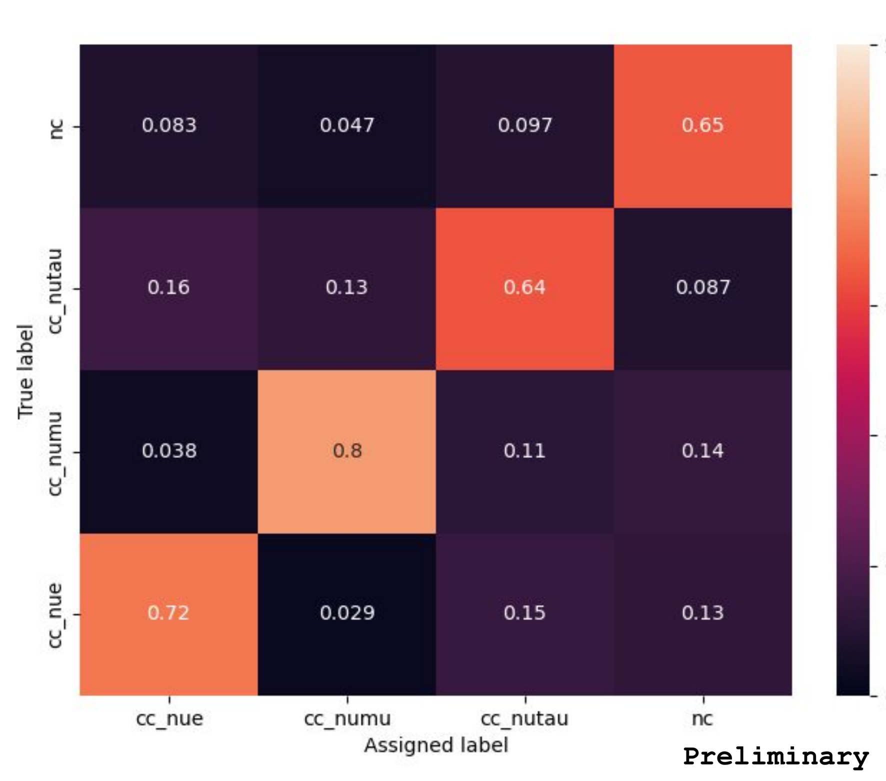
Graphs are an ideal structure for understanding physics data

- Naturally sparse
- Hits have a causal structure that can easily be modeled by edges
- Accommodates relationships beyond nearest neighbor

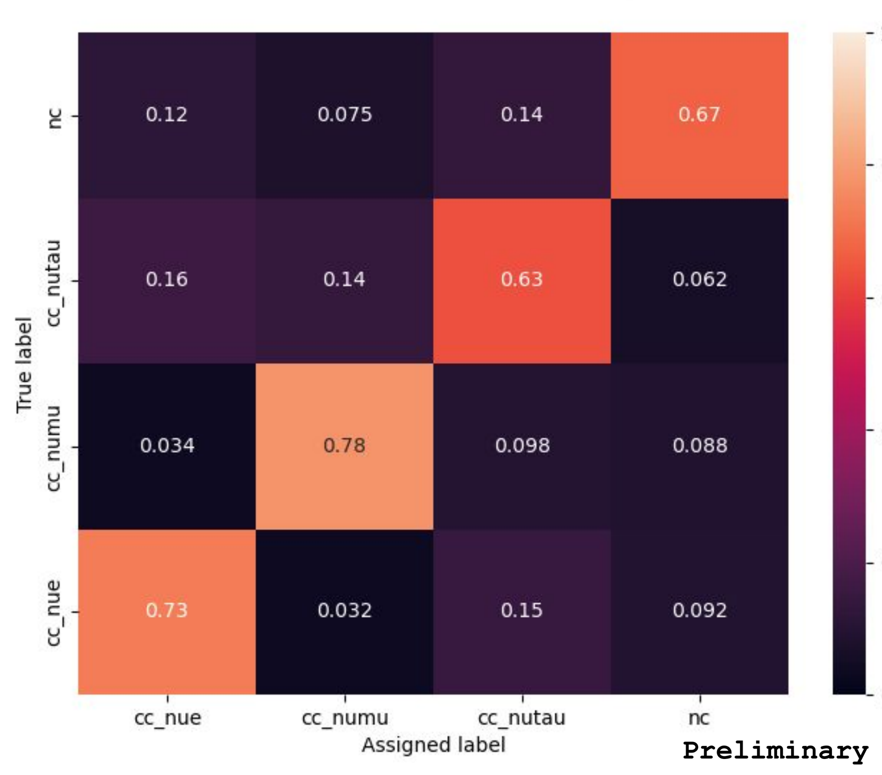
We have five semantic labels:
Shower, HIP: highly ionizing particle, MIP: minimum ionizing particle, michel and diffuse: any small EM activity



Precision/Purity



Recall/Efficiency



For more details about NuTau & NuGraph, check
#150 - NuGraph3: Towards Full LArTPC Reconstruction using GNNs
#162 - NuGraph2: A Graph Neural Network for Neutrino Event Reconstruction
#389 - DUNE's Tau Neutrino Event Reconstruction and Selection Strategies Using Graph Neural Networks

Comments

- **With DUNE we have access to the three oscillations modes!**, high-purity & high-statistics sample of beam and atmospheric ν_τ
- ν_τ are challenging to select and reconstruct, but they provide a needed independent check of unitarity & cross section SM model assumptions
- DUNE will potentially have leading sensitivity to anomalous short-baseline ν_τ appearance.
- A realistic tau flux beam optimization would maximize number of ν_τ-CC interactions
  -Looking to optimize horn shape for tau physics & update target design
- NuGraph: doing great at hadronic modes
  - *Next step: account for vertexing and event classification.*

References

[1]A. de Gouvea, et al, Phys. Rev. D 100, 016004
[2]Roshan Mammen Abraham et al 2022 J. Phys. G: Nucl. Part. Phys. 49 110501
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This document was prepared by DUNE Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.