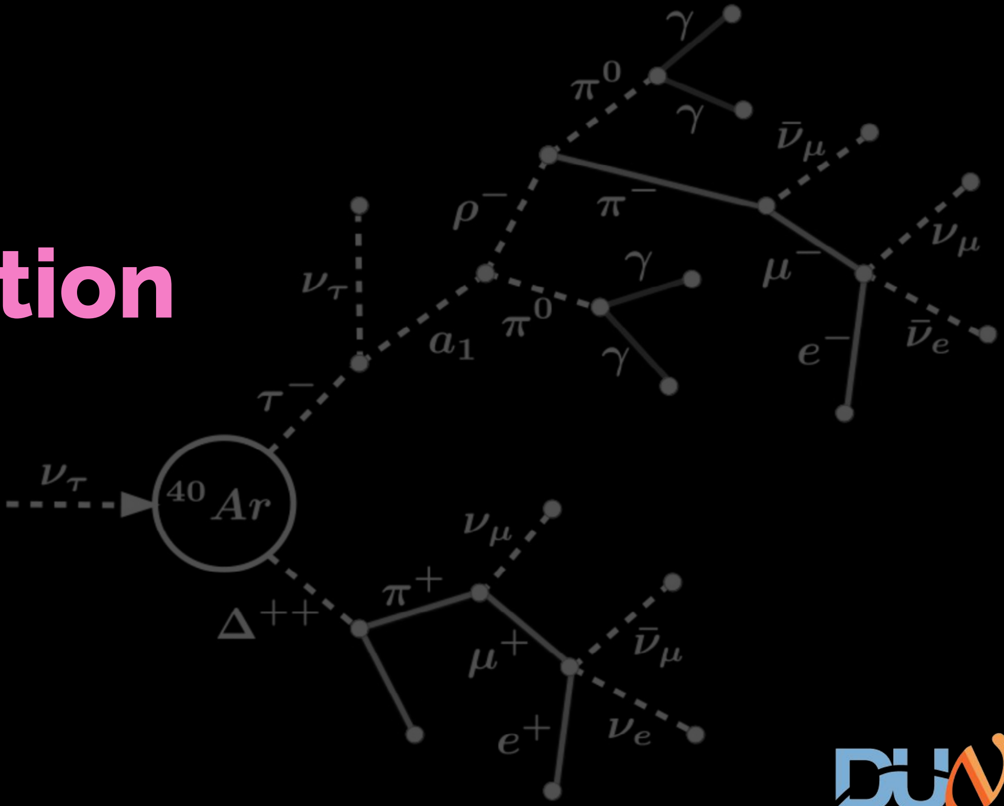
**17th International Workshop on Tau Lepton Physics (TAU2023)**
University of Louisville
Kentucky, USA

UNIVERSITY OF Cincinnati

# 3D-Reconstruction of $\nu_\tau$ in LArTPC Detectors



**Barbara Yaeggy**
*On behalf of the DUNE Collaboration*

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

# Outline

1. The DUNE Experiment
2. $\nu_\tau$ at DUNE
3. Graph Neural Networks
4. NuGraph
5. $\nu_\tau$ Reconstruction via NuGraph

# The Deep Underground Neutrino Experiment (DUNE)

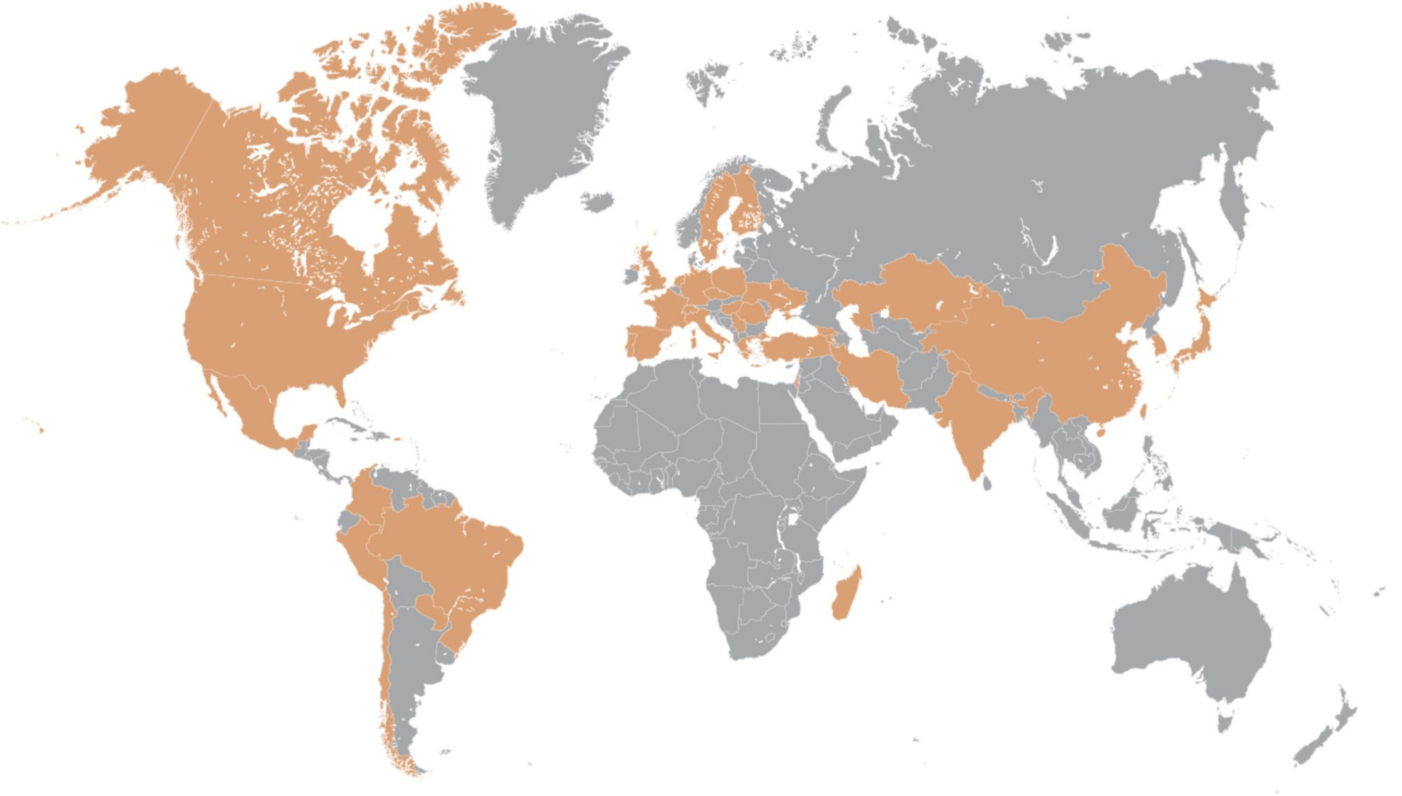
Currently under construction

~1450 collaborators

200 institutions

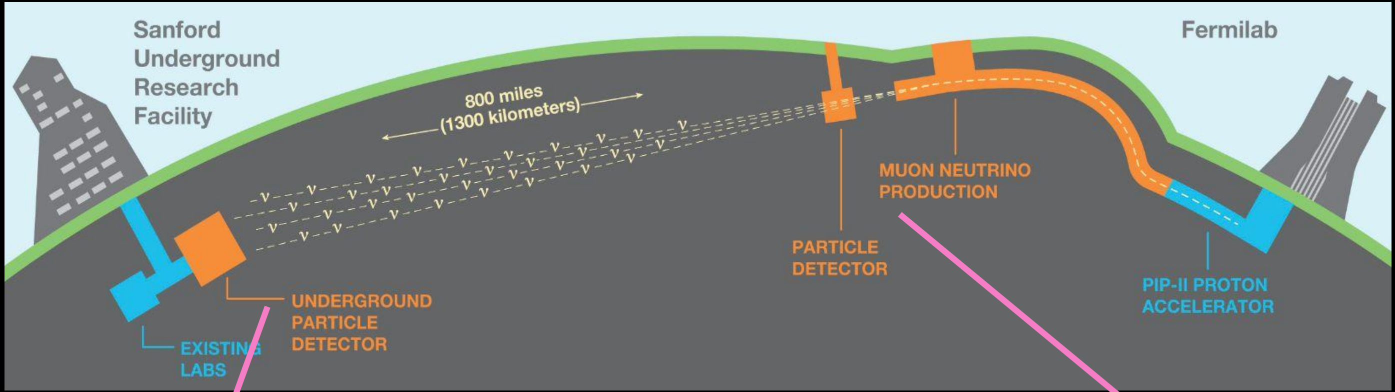
35 countries

DUNE will be able to constrain the three-massive-neutrinos paradigm by providing complementary measurements to those from the $\nu_e$ - appearance and the $\nu_\mu$ - disappearance channels.



Detailed overview about DUNE in Martin Tzanov talk (morning session)

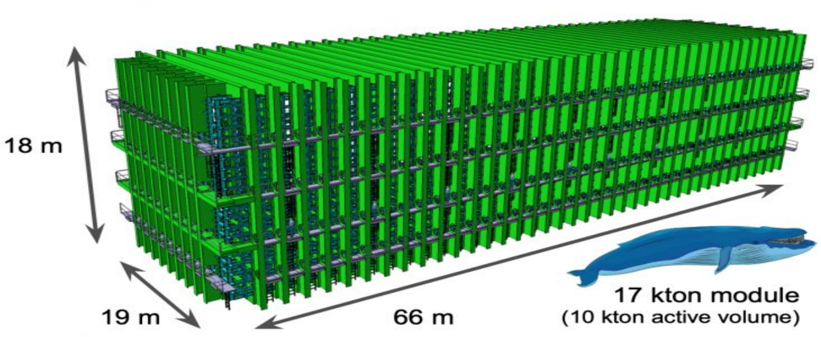
# The Deep Underground Neutrino Experiment (DUNE)



## Far Detector (FD)

- 1300 Km baseline, 1.5 Km deep
- 80% excavation done
- Detector commissioning expected in 2029
- Liquid argon time projection chamber (LArTPC) technology →high resolution neutrino interaction imaging
- 4x17 kton LArTPC modules.

Wideband neutrino beam, (~100 MeV – 10 GeV)



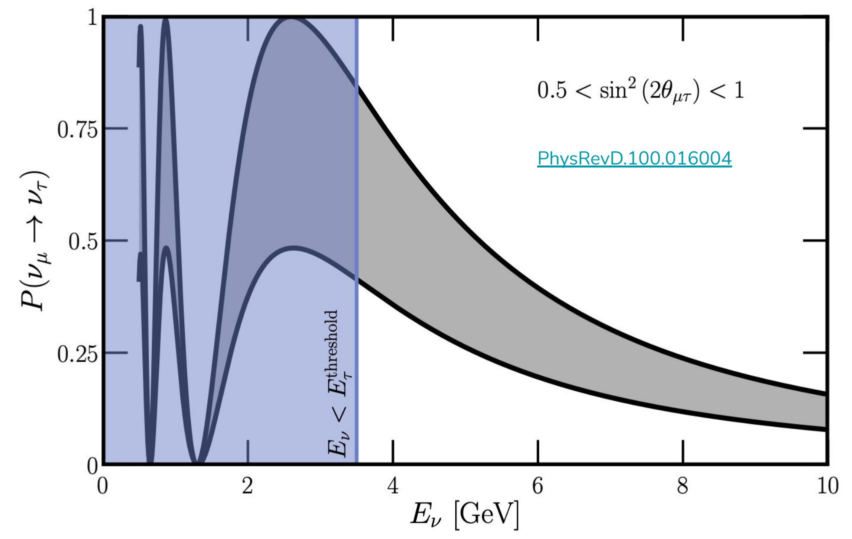
FD facility ~ 8 football fields

## Near Detector (ND)

- 62 m deep
- One LArTPC with pixelated readout
- Temporary Muon Spectrometer
- On-axis, magnet and calorimeter for flux monitoring

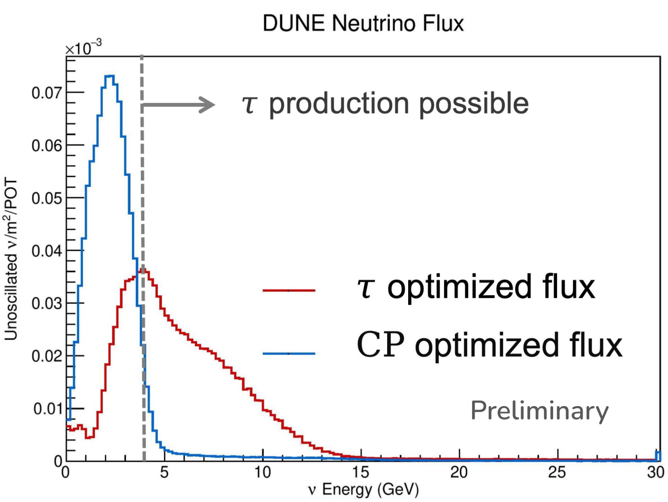
# DUNE Beam Flux

- DUNE's flux peaks between 2-3 GeV being the max.oscillation at 2.5 GeV, which is not ideal for $\nu_\tau$
- The far detector (FD) is at a fixed distance from the neutrino production point, the first oscillation maximum is below the $\nu_\tau$-CC kinematic thresholds, creating ambiguities between $\Delta m^2_{31}$ and $\sin^2\theta_{23}$
- Still, we will have quite a few oscillated tau neutrinos in the high energy tail.



PhysRevD.100.016004

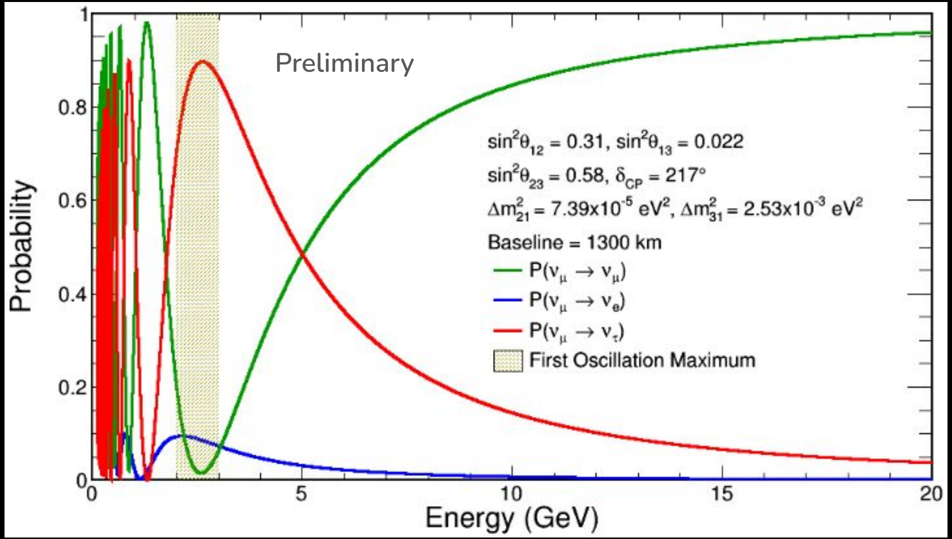
- CP-optimized beam (3 horns configuration)
  - Low energy
  - Default starting configuration
- Tau-optimized beam (2 horns configuration)
  - High energy beam
  - Possible configuration after CP programs has completed

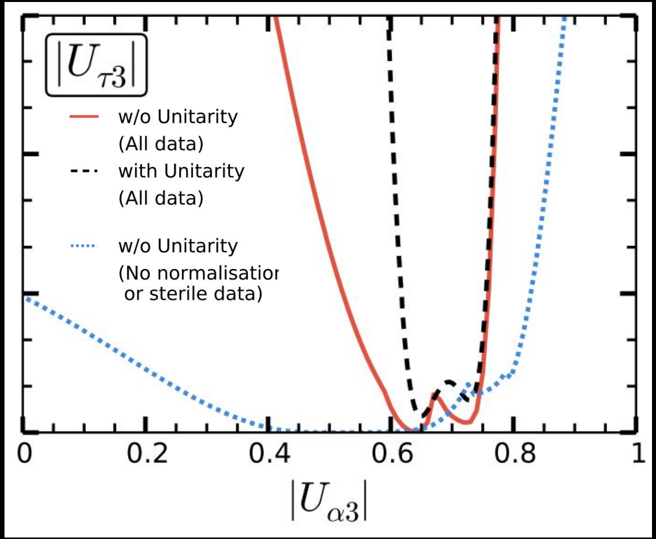


Expected counts/year:

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

# **Why Tau Neutrinos?** We have the chance to check if our assumption of unitarity (three flavor paradigm) its right or not





S. Parke and M. Ross-Lonergan, PRD 93, 1103009 (2016)

At oscillation maximum (atmospherics) the majority of $\nu_\mu$ oscillate to $\nu_\tau$

Almost all the knowledge of $\nu_\tau$ sector comes from the assumptions:

- Lepton universality for cross-sections
- PMNS unitarity for oscillations

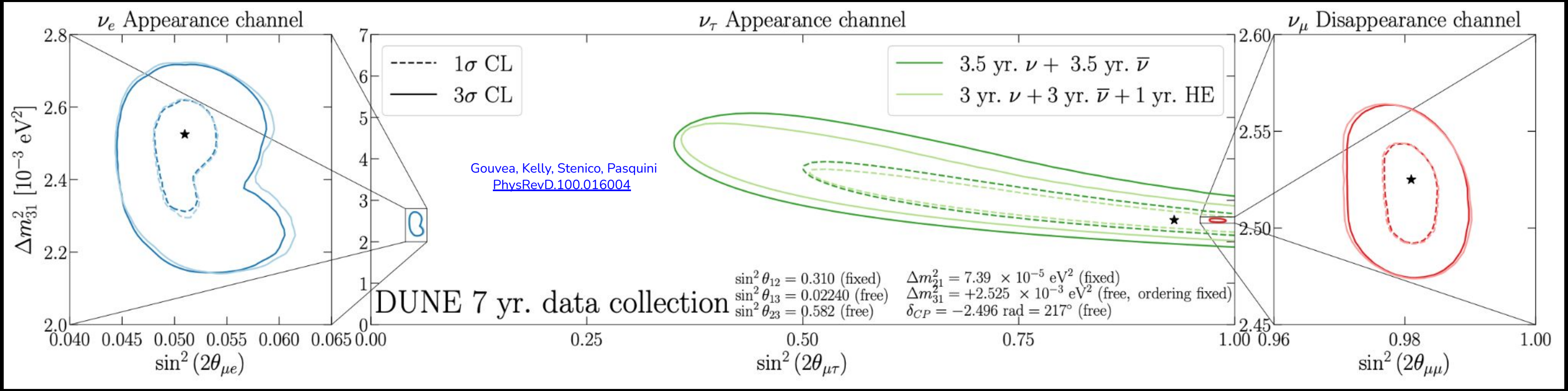
DUNE will be the only experiment able to directly observe tau neutrinos appearing

– High statistics samples both from beam and atmospherics

# Why Tau Neutrinos? Model-independent Non-Unitarity

Within the three-neutrino picture, effective mixing angles are related, but we can determine the measurement capability of each of the three channels at DUNE. Consistency check: do the mixing angles sum properly?

$$\sin^2(2\theta_{\mu e}) + \sin^2(2\theta_{\mu\tau}) = \sin^2(2\theta_{\mu\mu})$$



Gouvea, Kelly, Stenico, Pasquini
PhysRevD.100.016004

- DUNE data alone are expected to constrain the normalization of the 3rd PMNS column to ~ 5%

  Gouvea, Kelly, Stenico, Pasquini PhysRevD.100.016004

- All other neutrino data constrain normalization to ~ 7.5 %

  S. Parke and M. Ross-Lonergan, PRD 93, 1103009 (2016)

# Why Tau Neutrinos?

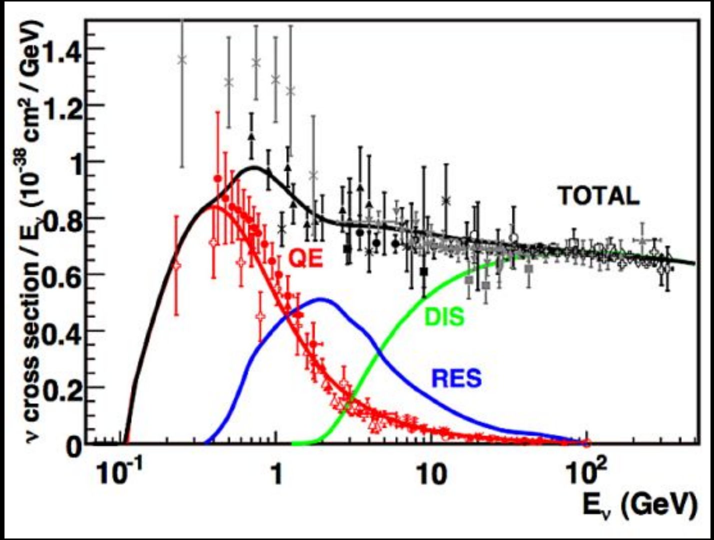
$\nu\tau$ (CC) interactions (heavy lepton) give access to cross section physics not accessible otherwise, adding two structure functions ($F_4$ and $F_5$) to the **cross section**. Nucl. Phys. B 84, 467 (1975)

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right] F_2 \right.$$
$$\left. \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\right),$$

Physical Sciences, Vol 8, issue 1.

- Neutrino interactions (cross section) are the major contributor of systematic uncertainties in oscillation measurements (T2k, NOvA).
- $E_\nu$ & ν-nucleus interactions relies on reconstruction techniques either based on kinematics (T2K/HK) or calorimetric methods (DUNE/NOvA/SBN) and both requires reliable predictions from interaction models.
- Extraction of oscillation parameter is biased by the interaction model.

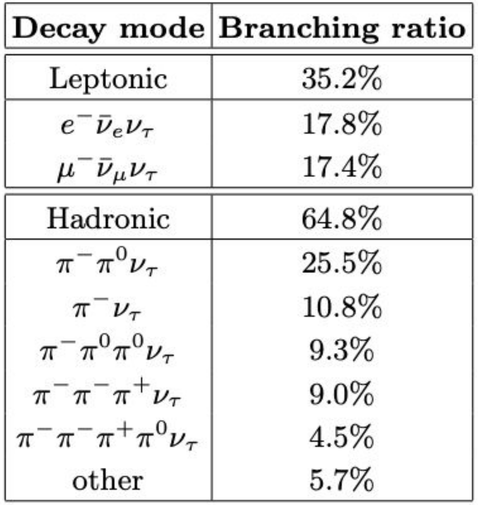
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij}\ \sin^2\left(\frac{\Delta m_{ij}^2}{4}\frac{L}{E_\nu}\right)$$



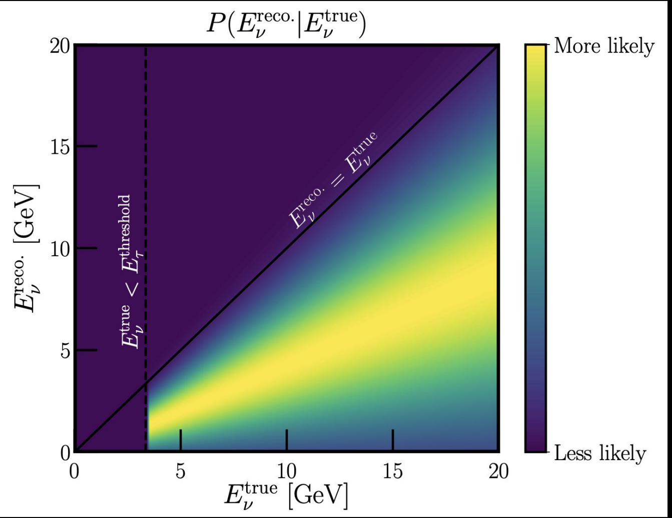
Kinematical changes in $Q^2$ and $E_l$ due to the presence of $m_\tau$

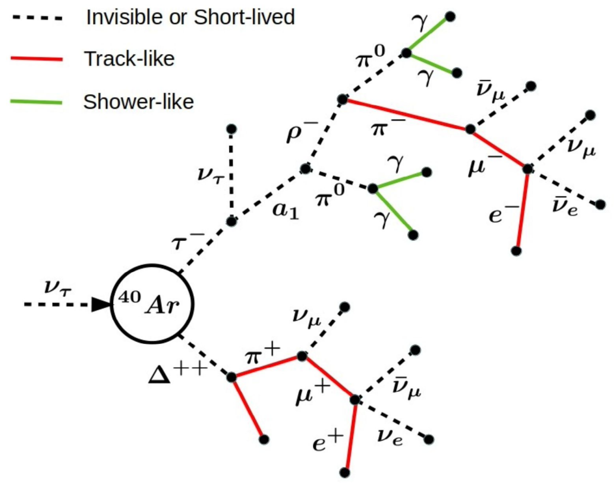
# Challenges

- Tau leptons have many decay modes
- CC-($\nu_e$, $\nu_\mu$) or NC events have same particle content
  -Angular correlations due to missing neutrino(s) from $\tau$ decay is the key signature
- Hadronic modes can be complicated
- Difficult to separate hadronic systems
- from $\tau$ decay and nucleus



| 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 decay length ~ 87 μm
$^{40}$Ar nuclear radius, ~ 3.4 fm

Tau decay products aren't subject to the $^{40}$Ar nuclear potential

Tau lifetime (2.903±0.005) ×$10^{-13}$ s
Mass: 1.7 GeV/$c^2$

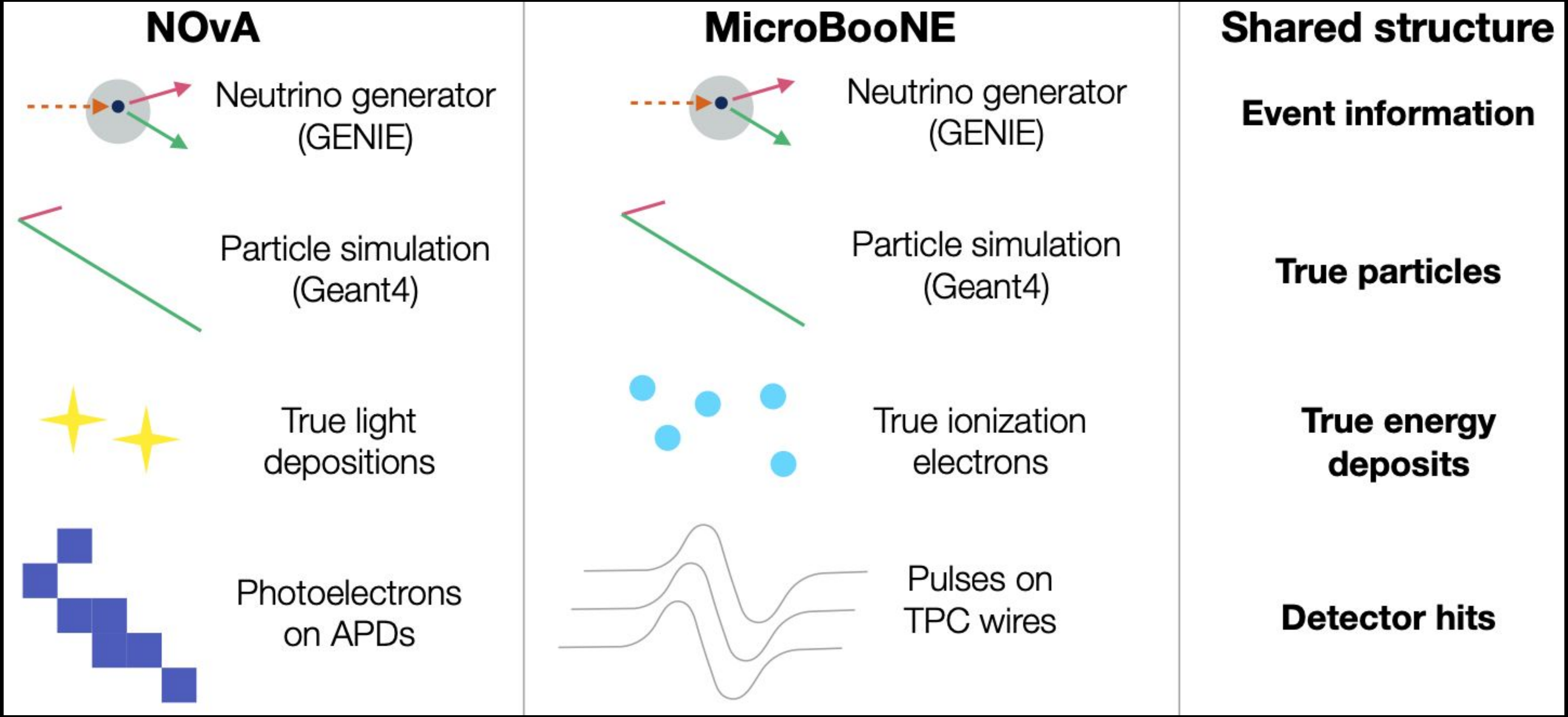
Tau doesn't lead to observables displaced vertices

DUNE granularity is limited by a wire spacing of 3mm

**Observation of Tau tracks is unlikely!**

# Graph
# Neural
# Networks

# The idea of using a GNN started with finding a solution to a common paradigm at a high level

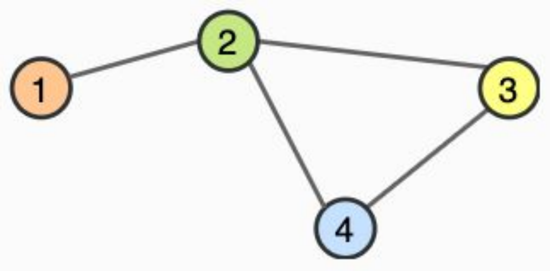


| NOvA | MicroBooNE | Shared structure |
|---|---|---|
| Neutrino generator (GENIE) | Neutrino generator (GENIE) | **Event information** |
| Particle simulation (Geant4) | Particle simulation (Geant4) | **True particles** |
| True light depositions | True ionization electrons | **True energy deposits** |
| Photoelectrons on APDs | Pulses on TPC wires | **Detector hits** |

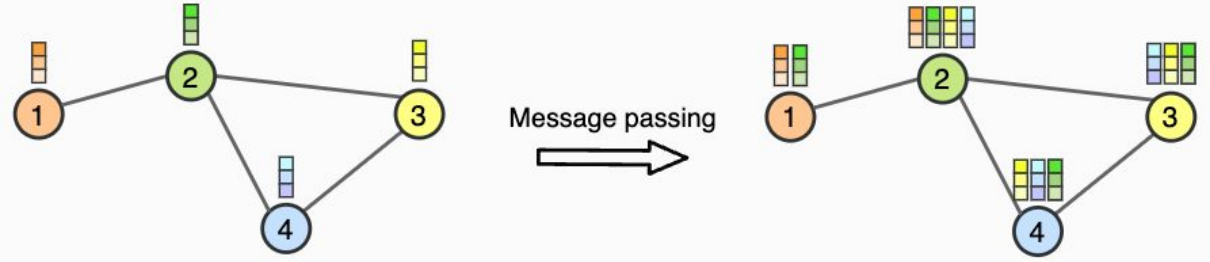
# What is a graph?

1) A graph is defined as a tuple of set of nodes/vertices and a set of edges/links

2) Each edge is a pair of two vertices & represents a connection between them



Graphs are excellent in dealing with complex problems with relationships and interactions. They are used in pattern recognition, social networks analysis, recommendation systems, and semantic analysis



- Each node creates a feature vector that represents the message to be send to all its neighbors.
- The node receives one message per adjacent node

**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

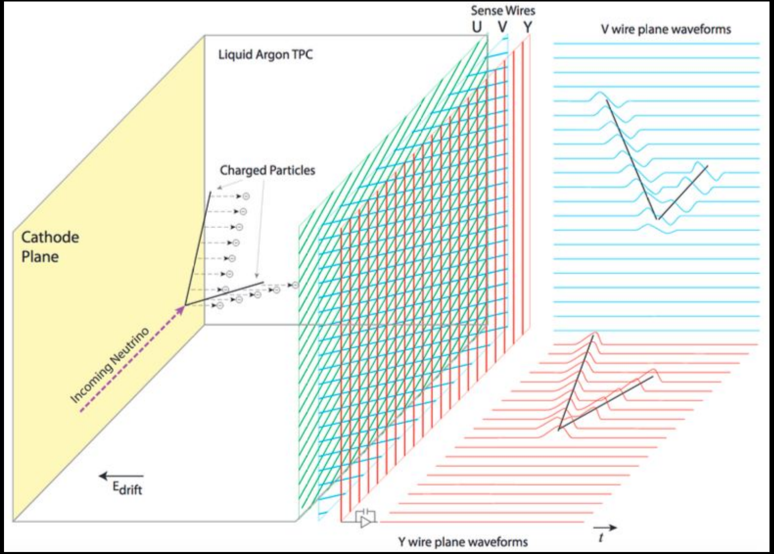
# Liquid Argon Time Projection Chambers (LArTPC)

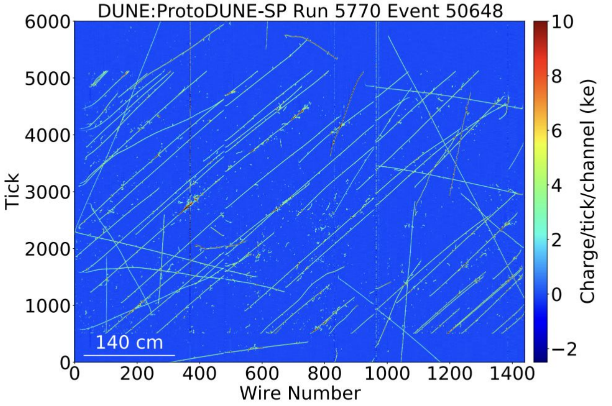
- LArTPC are currently heavily used in neutrino physics
  -Today: ICARUS, MicroBooNE, SBND, ProtoDune
  -Future: DUNE (70 kT far detector deep underground)

- Charged particles ionize liquid argon as they travel
- Ionization electrons drift due high potential between cathode and anode planes
- Closely spaced wires (~3mm) at anode provide high-resolution image of neutrino interaction
- Multiple wire planes provide 3D information

**We would like to:**

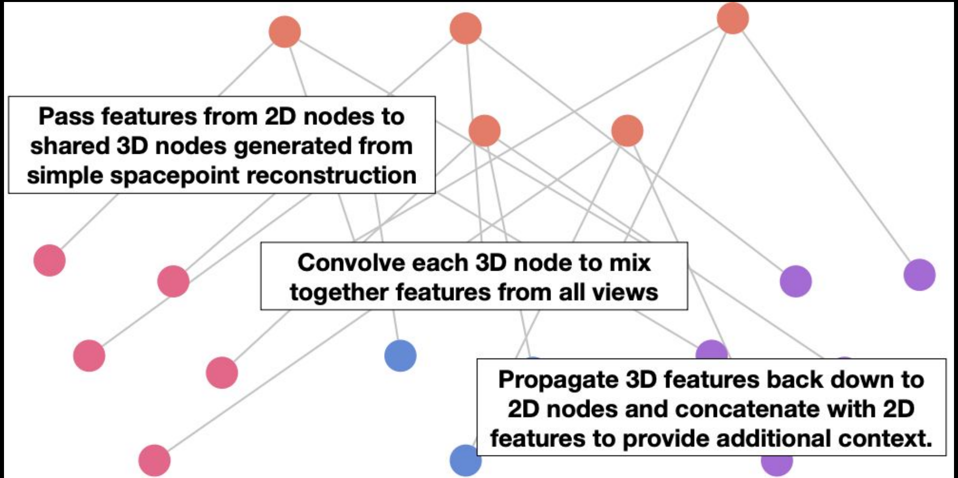
- Cluster hits into objects
- Classify objects according to the particle that created it
-Assemble the objects into an event
-Determine type and kinematic properties of the event





ProtoDUNE-SP cosmic shower event. JINST 15 P12004

# **NuGraph:** originally designed for identifying jets in hadron interactions (Exa.TrkX is a collaboration - U.Cincinnati ). **Primary goal is to classify each detector hit according to particle type.**

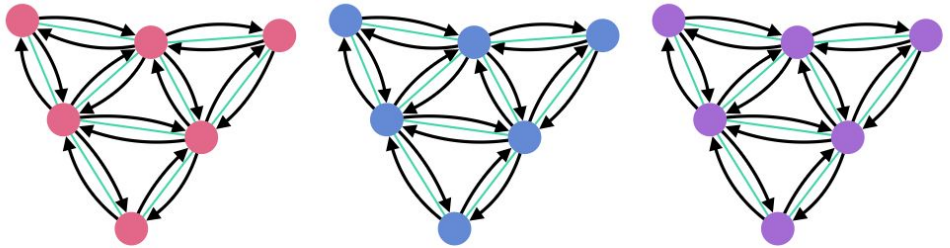


Pass features from 2D nodes to shared 3D nodes generated from simple spacepoint reconstruction

Convolve each 3D node to mix together features from all views

Propagate 3D features back down to 2D nodes and concatenate with 2D features to provide additional context.

**3D graph nodes/convolutions: perform message-passing independently in each detector view.**

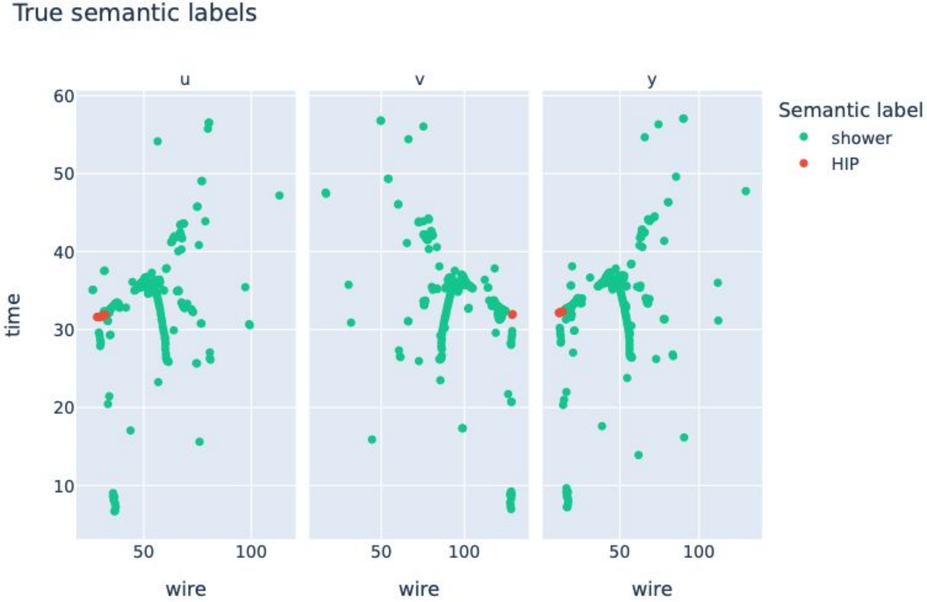


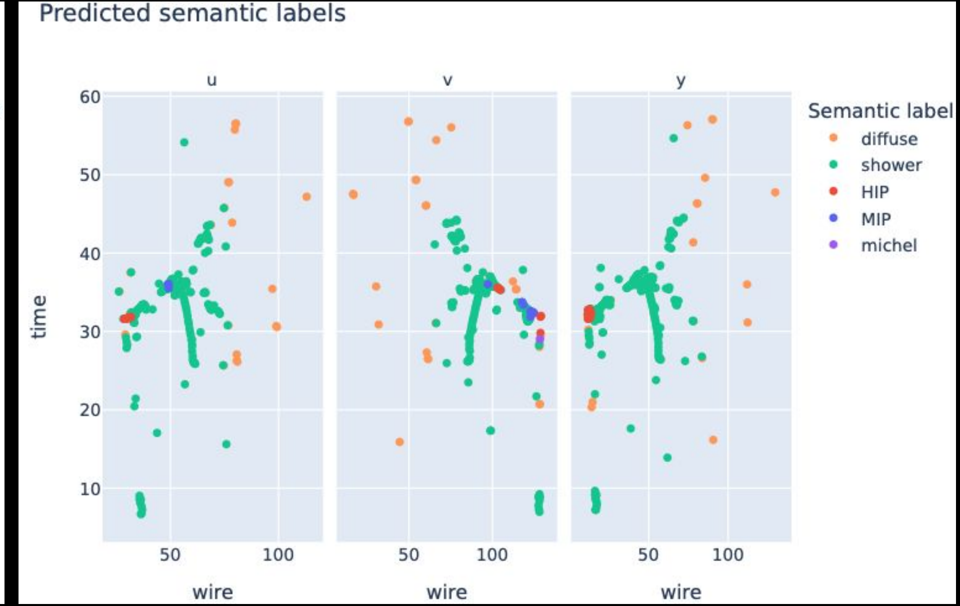
- All of this is repeated through many iterations, allowing key information to propagate through the graph and use these key features for training (energy depositions, 3D position, etc)
- There are two phases for the network: a planer encoder and then a nexus block
- This allows messages to be passed through the nexus block and context to be shared via the planar encoder

Originally tested with MicroBoone open data set with an excellent performance at semantic segmentation:

Overall efficiency and purity ~ 95%
Consistency between planes ~98%

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





**We have five semantic types:**

Shower

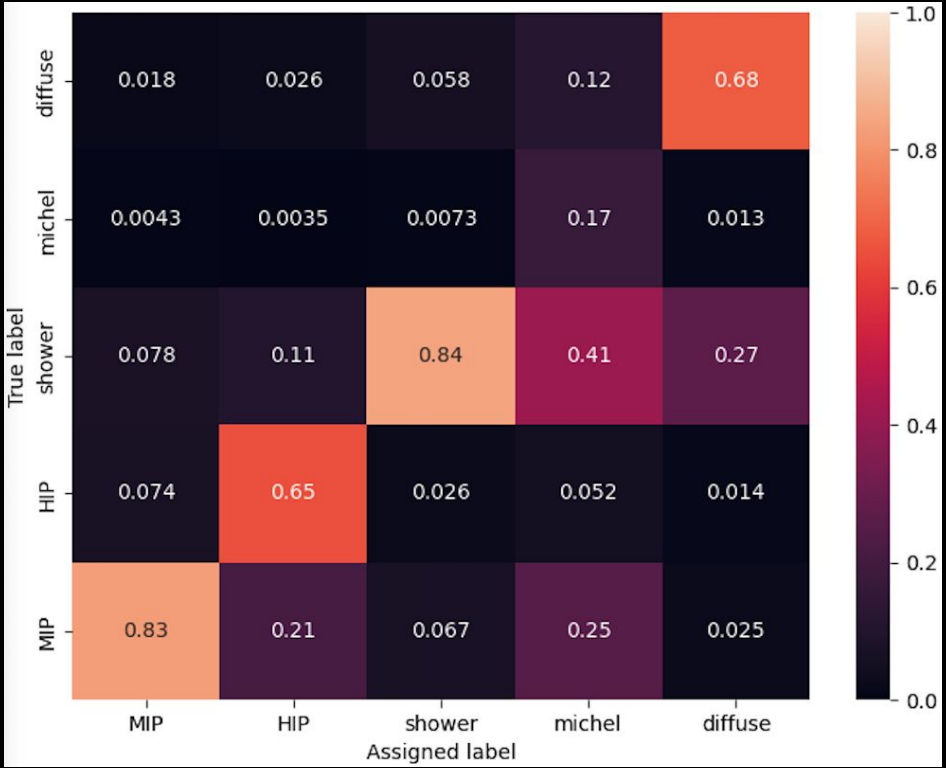
HIP: highly ionizing particle

MIP: minimum ionizing particle

Michele

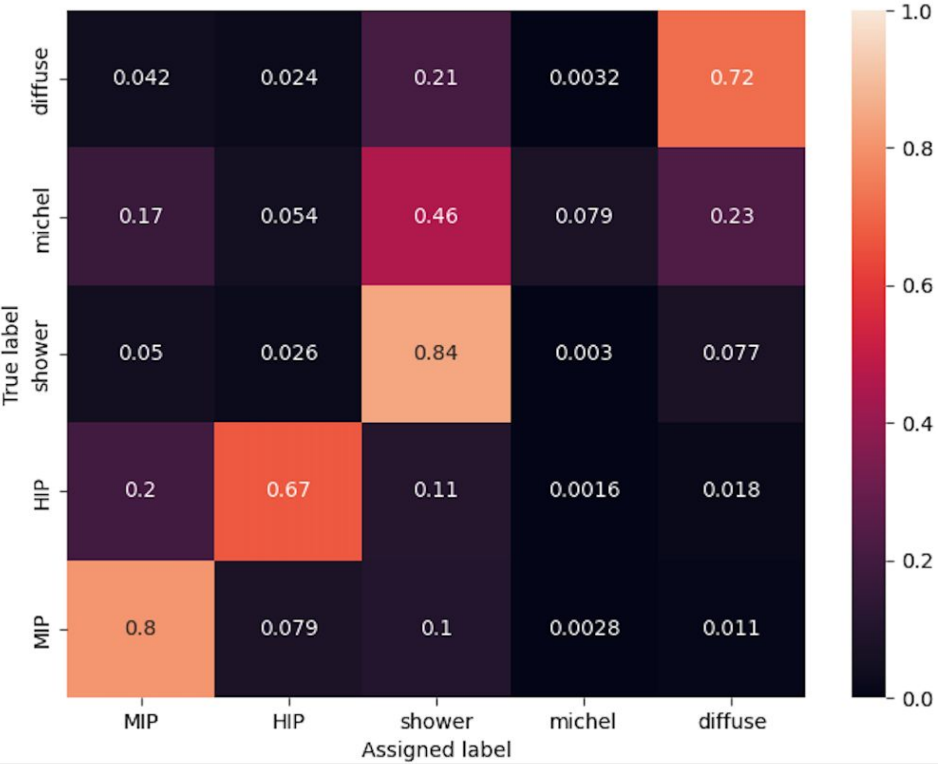
Diffuse: any small EM activity (compton scatters, etc) + anything that creates small blips (neutrons)

## Confusion matrix - **predicted semantic label** to show purity (precision/prediction)



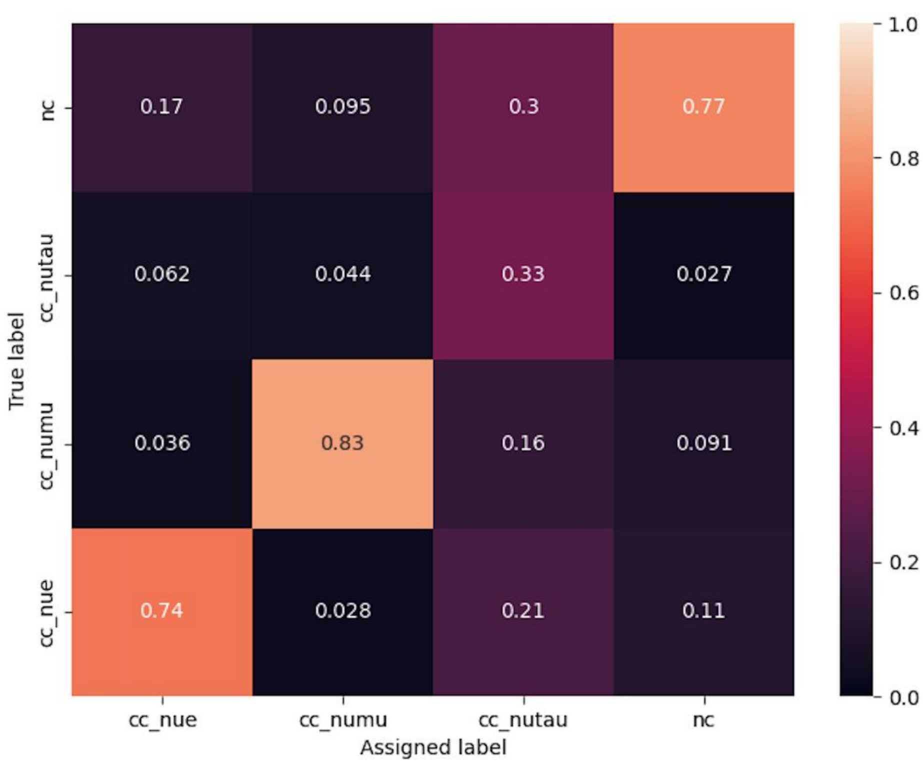
| True label \ Assigned label | MIP | HIP | shower | michel | diffuse |
|---|---|---|---|---|---|
| diffuse | 0.018 | 0.026 | 0.058 | 0.12 | 0.68 |
| michel | 0.0043 | 0.0035 | 0.0073 | 0.17 | 0.013 |
| shower | 0.078 | 0.11 | 0.84 | 0.41 | 0.27 |
| HIP | 0.074 | 0.65 | 0.026 | 0.052 | 0.014 |
| MIP | 0.83 | 0.21 | 0.067 | 0.25 | 0.025 |

## Confusion matrix - **true semantic label** to show efficiency (recall/sensitivity)



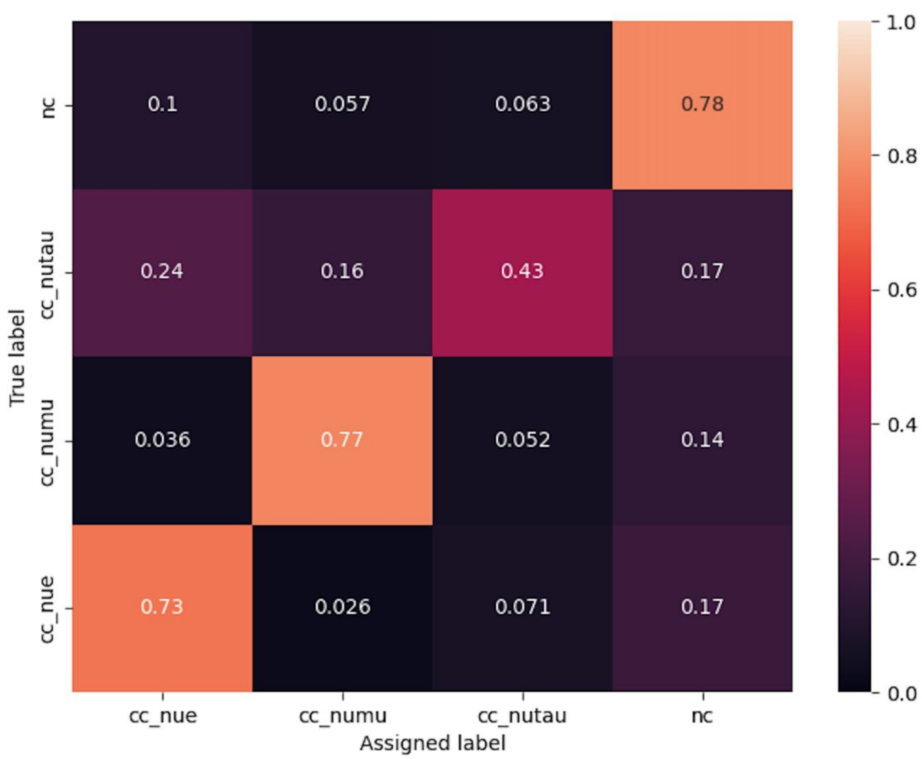
| True label \ Assigned label | MIP | HIP | shower | michel | diffuse |
|---|---|---|---|---|---|
| diffuse | 0.042 | 0.024 | 0.21 | 0.0032 | 0.72 |
| michel | 0.17 | 0.054 | 0.46 | 0.079 | 0.23 |
| shower | 0.05 | 0.026 | 0.84 | 0.003 | 0.077 |
| HIP | 0.2 | 0.67 | 0.11 | 0.0016 | 0.018 |
| MIP | 0.8 | 0.079 | 0.1 | 0.0028 | 0.011 |

## Confusion matrix - **predicted event label** to show purity (precision/prediction)



| True label \ Assigned label | cc_nue | cc_numu | cc_nutau | nc |
|---|---|---|---|---|
| nc | 0.17 | 0.095 | 0.3 | 0.77 |
| cc_nutau | 0.062 | 0.044 | 0.33 | 0.027 |
| cc_numu | 0.036 | 0.83 | 0.16 | 0.091 |
| cc_nue | 0.74 | 0.028 | 0.21 | 0.11 |

## Confusion matrix - **true event label** to show efficiency (recall/sensitivity)



| True label \ Assigned label | cc_nue | cc_numu | cc_nutau | nc |
|---|---|---|---|---|
| nc | 0.1 | 0.057 | 0.063 | 0.78 |
| cc_nutau | 0.24 | 0.16 | 0.43 | 0.17 |
| cc_numu | 0.036 | 0.77 | 0.052 | 0.14 |
| cc_nue | 0.73 | 0.026 | 0.071 | 0.17 |

**NuGraph it's not doing a great job distinguishing cc_nutau and nc and even gets a decent number of cc_nutau confused with cc_nue**

## Next steps

- **We need to change the codebase for our training and adapt it to DUNE geometry, get the center of each TPC module & drift directions of each module + decoder** (done this week!)

- NuGraph was originally made for MicroBoone (single TPC module) and DUNE has multiple modules.

- **Add decay channels information**

# Conclusions

- DUNE is uniquely capable of providing a high-purity & high-statistics sample of beam and atmospheric $\nu_\tau$
- $\nu_\tau$ are challenging to select and reconstruct, but they provide a needed independent check of the three-flavor model
- Atmospheric $\nu_\tau$ provide a high-purity window into 1st atmospheric oscillation maximum
- **NuGraph** efficiently reject background detector hits & classify those by particle type. **Currently working on vertexing and event classification.**
- Looking forward for a next generation of **NuGraph** able to reconstruct complex interactions like high energy **tau neutrino interactions**.

**NuGraph public repo**

THANK YOU!

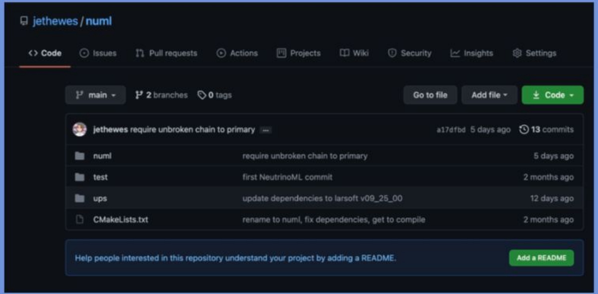
# Backup

# **NuGraph:** is a state-of-the-art graph neural network for semantically labelling detector hits in neutrino physics experiments.

**NuML:** toolkit for writing physics event records to an HDF5 file format.

**PyNuML:** Provide a generic, accessible, efficient and flexible solution for many of the necessary tasks in leveraging ML for particle physics

https://github.com/vhewes/numl



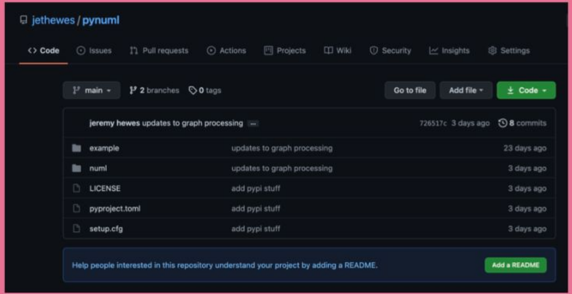
jethewes require unbroken chain to primary … a17dfbd 5 days ago 13 commits

| | | |
|---|---|---|
| numl | require unbroken chain to primary | 5 days ago |
| test | first NeutrinoML commit | 2 months ago |
| ups | update dependencies to larsoft v09_25_00 | 12 days ago |
| CMakeLists.txt | rename to numl, fix dependencies, get to compile | 2 months ago |

Help people interested in this repository understand your project by adding a README.

- Hold low-level information such as simulated particles, hits, true energy depositions etc.
- Generic data structure can be shared across experiments

https://github.com/vhewes/pynuml

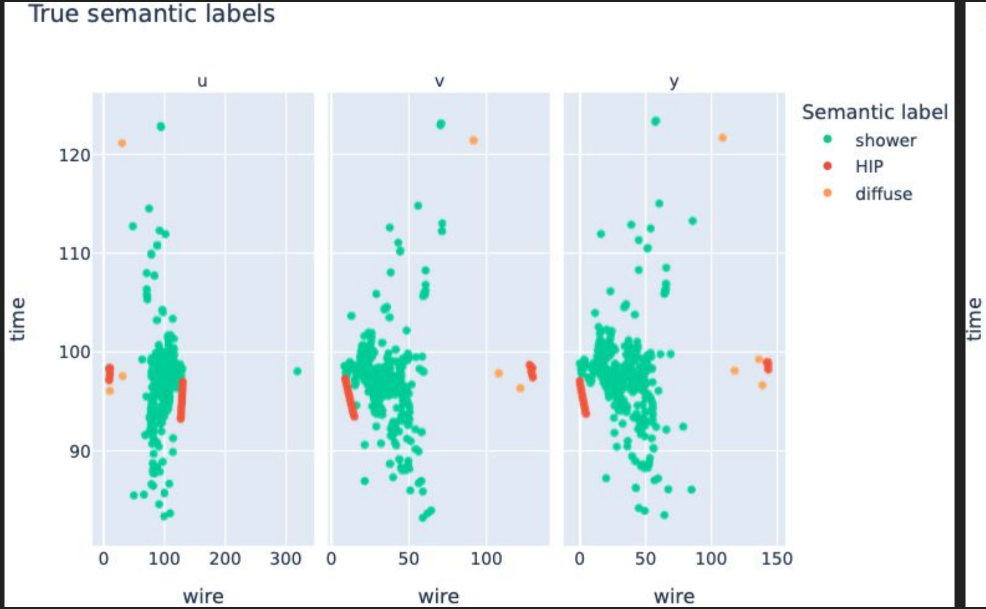


jeremy hewes updates to graph processing … 726517c 3 days ago 8 commits

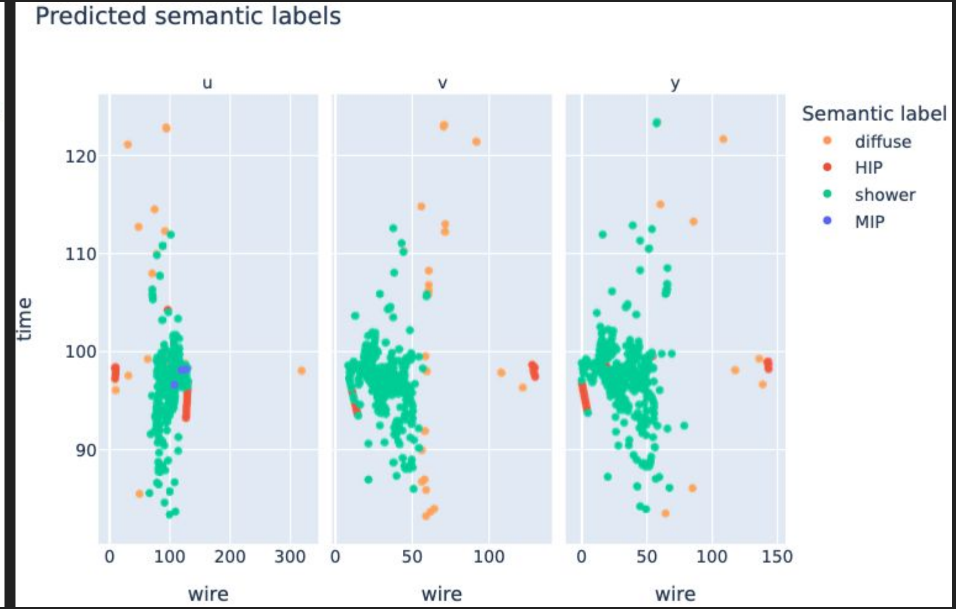
| | | |
|---|---|---|
| example | updates to graph processing | 23 days ago |
| numl | updates to graph processing | 3 days ago |
| LICENSE | add pypi stuff | 3 days ago |
| pyproject.toml | add pypi stuff | 3 days ago |
| setup.cfg | add pypi stuff | 3 days ago |

Help people interested in this repository understand your project by adding a README.

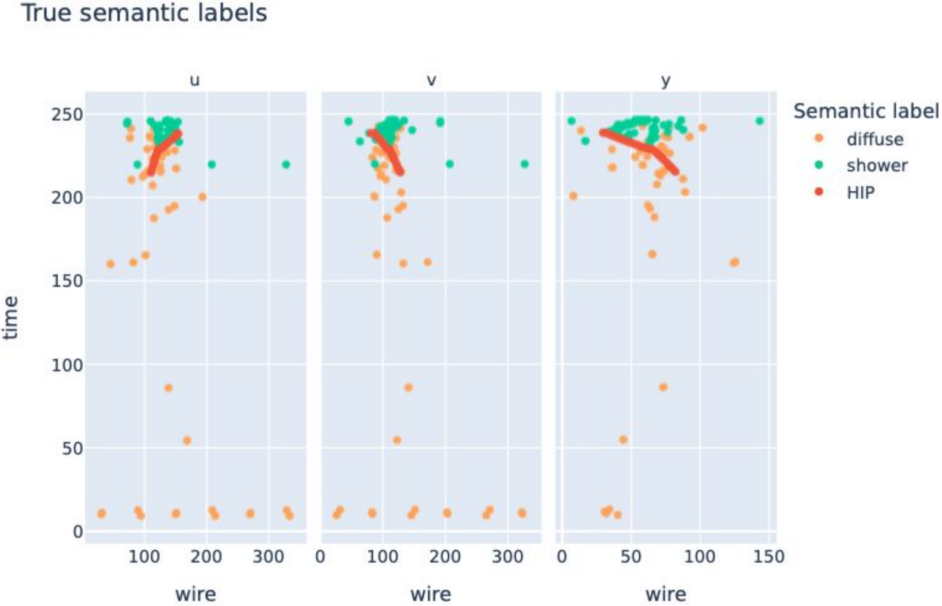
- Define particle ground truth labels for Geant4-simulated particles
- Arrange detector hits into ML objects, ie. graphs, CNN pixel maps, etc



True semantic labels



Predicted semantic labels


True semantic labels
u
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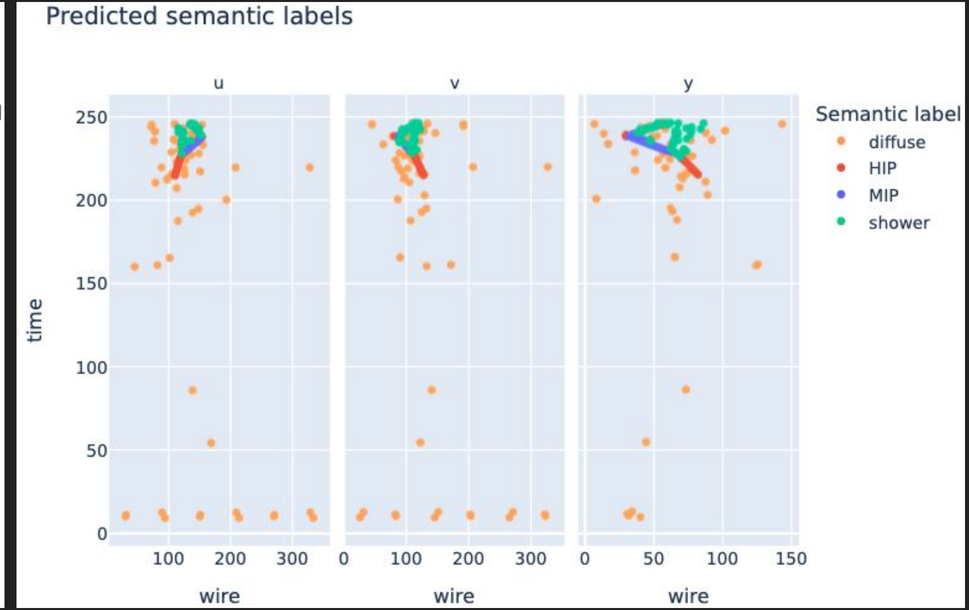
wire
wire
wire
Semantic label
diffuse
shower
HIP


Predicted semantic labels
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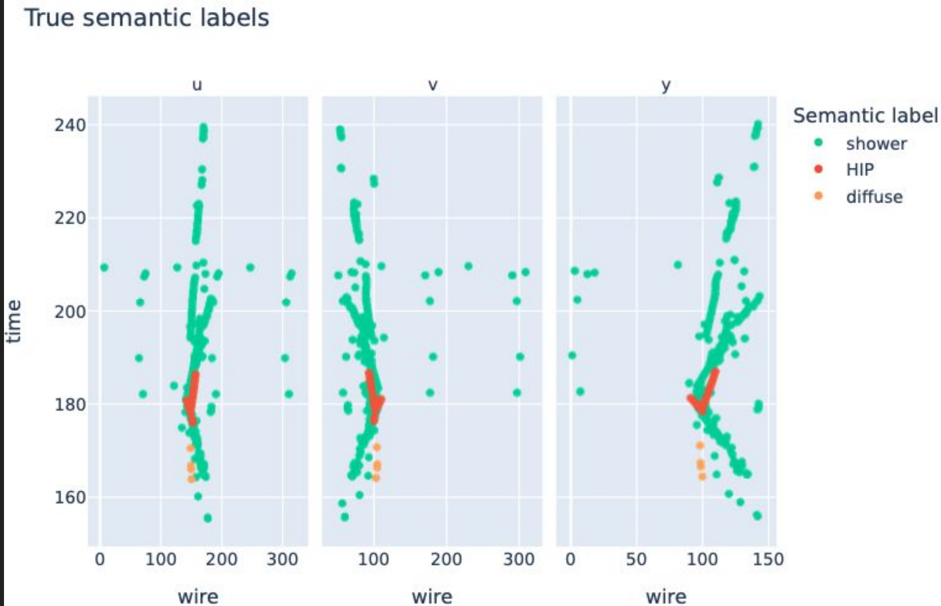
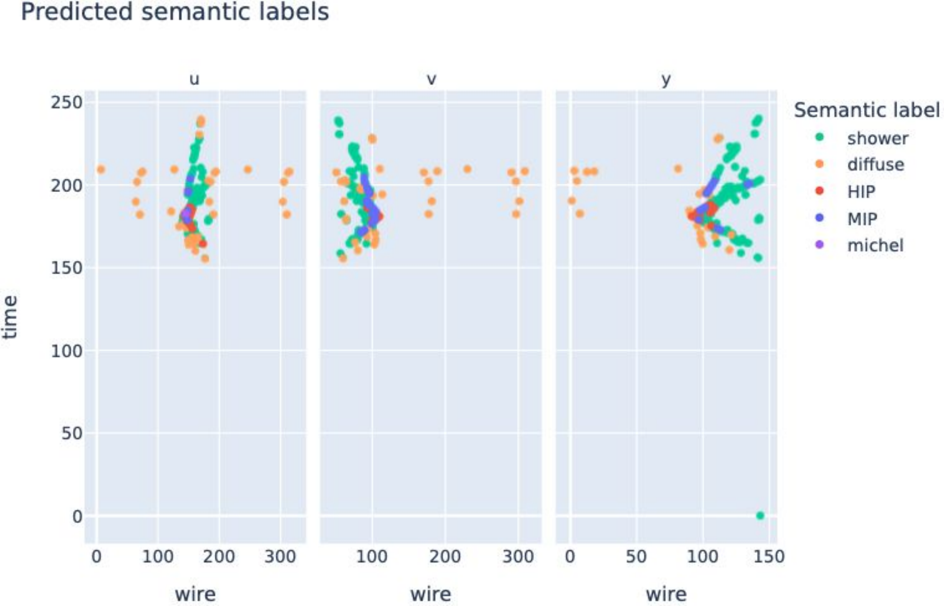
wire
Semantic label
diffuse
HIP
MIP
shower



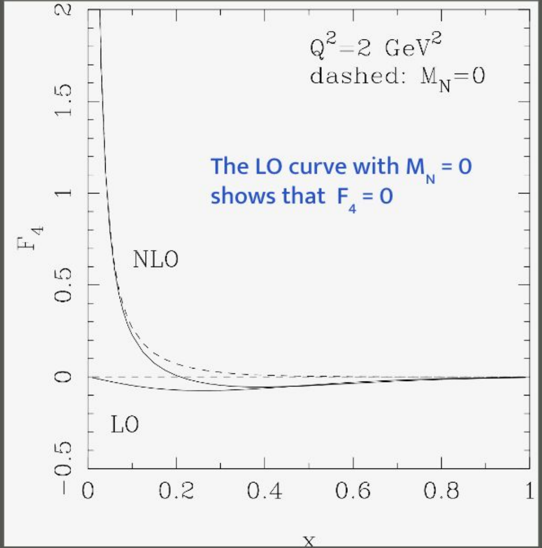
True semantic labels



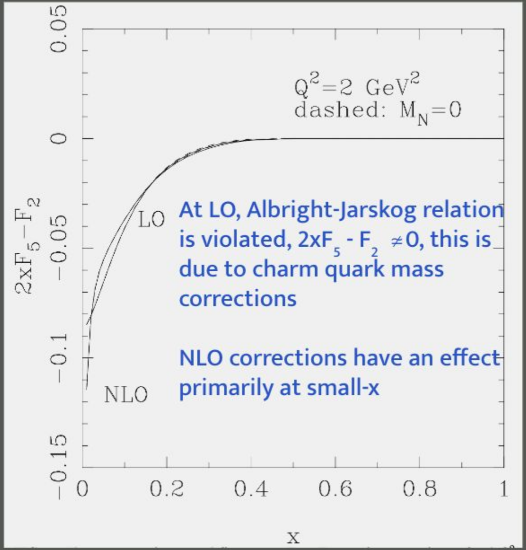
Predicted semantic labels

# A look to $F_4$ and $F_5$ Structure Functions

M. H. Reno - PhysRevD.74.033001
arXiv:1007.1966v1



The LO curve with $M_N = 0$ shows that $F_4 = 0$



At LO, Albright-Jarskog relation is violated, $2xF_5 - F_2 \neq 0$, this is due to charm quark mass corrections

NLO corrections have an effect primarily at small-x

## Structure functions

The Callan-Gross relations:

$$2xF_1 = F_2$$
$$-xF_3 = F_2$$

At LO, in the limit of massless quarks & target hadrons, Albright-Jarlskog pointed:

$$2xF_5 - F_2 = 0$$

$F_4 = 0$, also holds when the nucleon target is replaced by a lepton target.

$$F_{1N}(x) = W_{1N}(\nu, Q^2)$$
$$F_{2N}(x) = \frac{Q^2}{2xM_N^2} W_{2N}(\nu, Q^2)$$

$$F_{3N}(x) = \frac{Q^2}{xM_N^2} W_{3N}(\nu, Q^2)$$
$$F_{4N}(x) = \frac{Q^2}{2M_N^2} W_{4N}(\nu, Q^2)$$

$$F_{5N}(x) = \frac{Q^2}{2xM_N^2} W_{5N}(\nu, Q^2).$$

- At NLO, *$F_4$ ~ 1% of $F_5$* , AJ relations are good approximations to the NLO result, arXiv:hep-ph/0605295.
- Both of the figures show that in evaluations of the total charged current cross section, the naive AJ relations are good approximations to the NLO results. This is true at low energies, where $\nu_\tau$ cross-section does not probe small-x and at high energies where $F_4$, $F_5$ are suppressed, anyway.