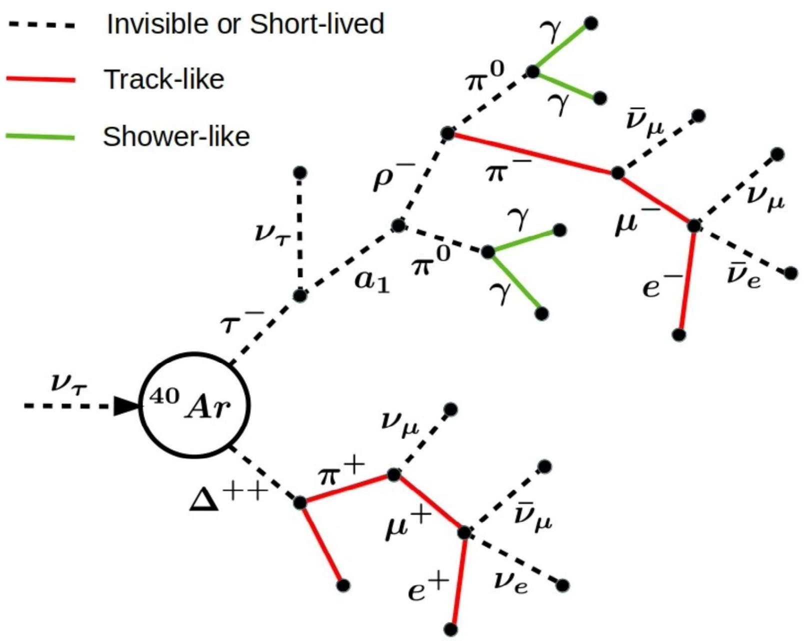
Lepton-Photon 2025
August 25th, 2025
Madison, WI

Reconstruction of ν_τ in LArTPC Detectors



Barbara Yaeggy
On behalf of the DUNE Collaboration

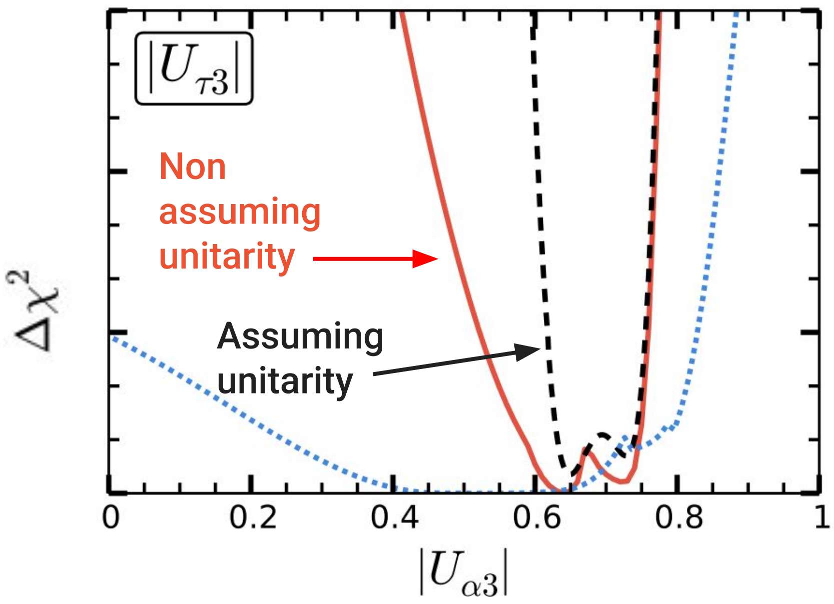
University of CINCINNATI
U.S. DEPARTMENT of ENERGY
DUNE

The hardest of the hard, why study ν_τ ?

Current generation of **neutrino experiments** provides **nearly complete description** of **three flavor paradigm**

Almost all knowledge of ν_τ sector is taken from:

- ***Lepton universality for cross sections,*** *ν_τ - CC cross section @ SK determined at the 21% precision*
- ***PMNS unitarity for oscillations,*** *unitarity of τ row in PMNS at 30% level (@95% CL)*

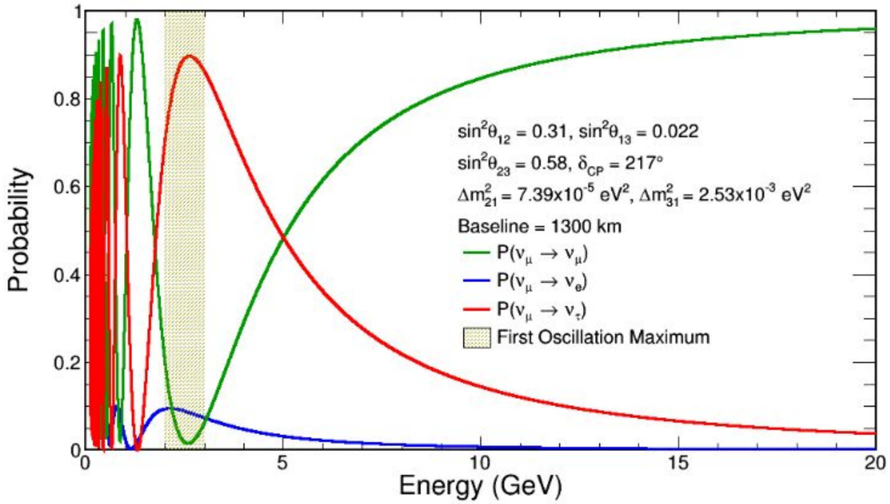


arXiv:1508.05095

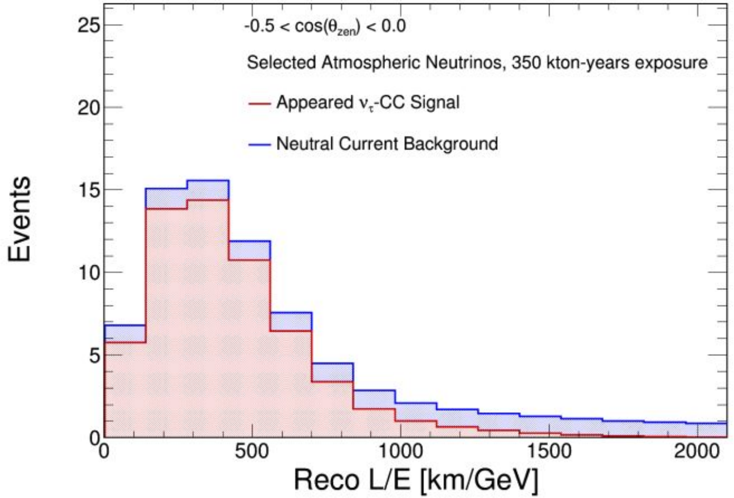
It's critical that these assumptions are tested !

The hardest of the hard, why study ν_τ ?

Phys. Rev. D 100, 016004



arXiv:2203.05591



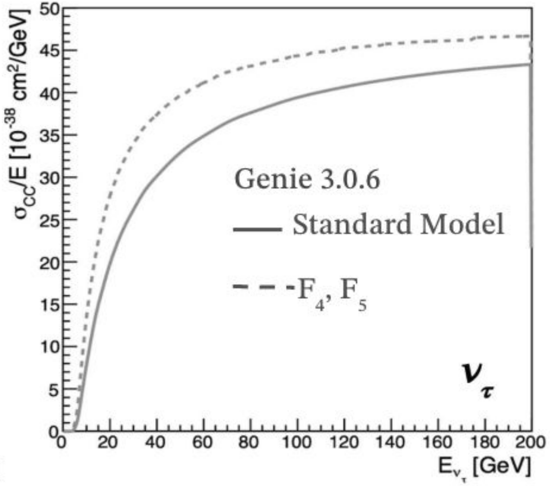
At **atmospheric oscillation maximum all ν_μ oscillate to ν_τ** $\rightarrow$ causes a degeneracy between Δm^2_{31} and $\sin^2\theta_{23}$

Atmospherics have a favorable L/E: better coverage of first oscillation maximum, large matter effect$\rightarrow$ **we can get the three oscillations modes**.

The hardest of the hard, why study ν_τ ?

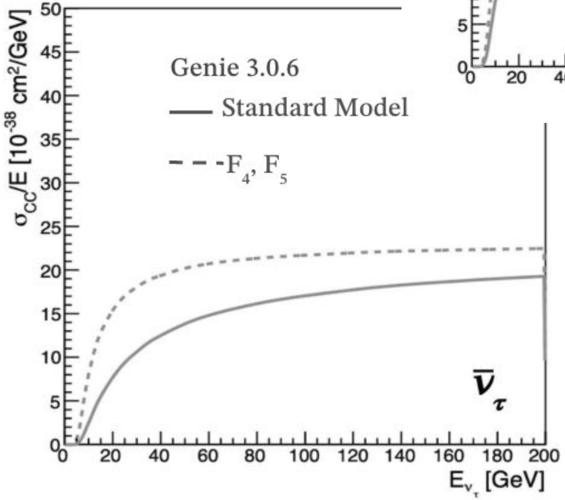
ν_τ - CC cross section: extra structure functions appear!
Suppressed in ν_e and ν_μ interactions

Nucl. Phys. B 84, 467
PhysRevD.74.033001



$$N_{FD}^{\alpha\rightarrow\beta}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma_\beta^i(E_\nu)\times P(\nu_\alpha\rightarrow\nu_\beta)\times\epsilon_\beta(E_\nu, E_{\nu,rec})$$

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



F_4, F_5 are sensitive in values for X_{Bj} and Q^2 that wrap different interactions models.

Extraction of **oscillation parameter** is **biased by** the **interaction model**

We can improve our interaction models & systematics uncertainties

NuFact 2022 Proceedings

What can we learn from ν_τ ?

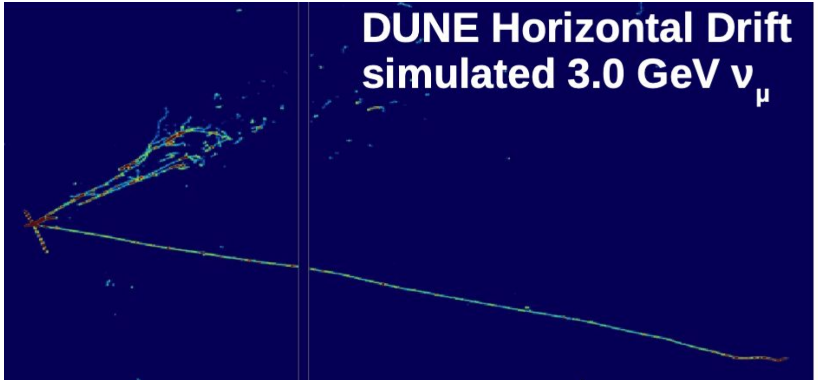
- Non-unitarity constraints
- Consistency of three-neutrino oscillation
- Non-standard interactions
- Energy dependent neutrino mixing parameters

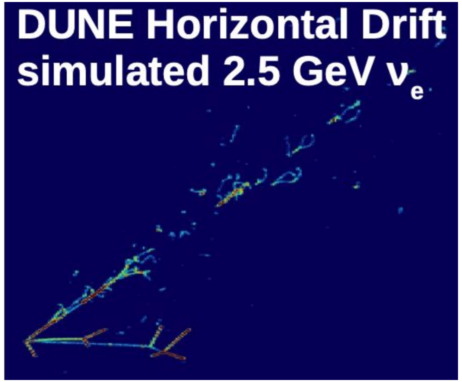
Phys. Rev. D 100, 016004 (2019)

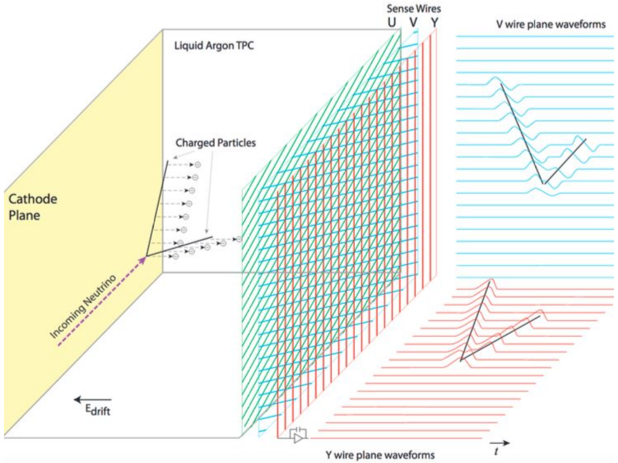
J. Phys. G: Nucl. Part. Phys. 49, 11 (2022)

Why ν_τ in LArTPC Detectors ? 3D tracking and calorimetry (wire spacing ~5mm) → high resolution images

B. Abi et al 2020 JINST 15 P12004





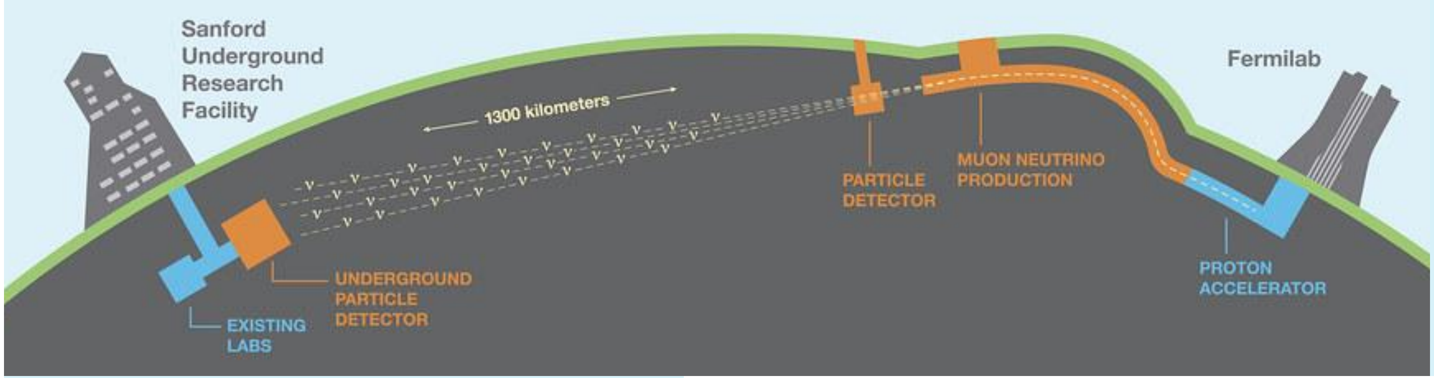


Current: ICARUS, MicroBooNE, SBND, ProtoDune

Future: DUNE

- Charged particles ionize liquid argon as they travel
- Ionization electrons drift due high potential between cathode and anode planes
- **Excellent spatial and calorimetric resolution**
- **3D reconstruction** by combining 2D views (wire planes)

Deep Underground Neutrino Experiment (MeV - 10 GeV)



Near Detector (ND)

- 574 m baseline
- 147 ton LArTPC component + muon spectrometer
- On-axis

Far Detector (FD)

- 1300 Km baseline
- 1.5 Km deep
- LArTPC technology
- 4x17 kton LArTPC modules
- Excavation completed in 2024

DUNE will be able to constrain the three-massive-neutrinos paradigm by providing complementary measurements to those from the ν_e - appearance and the ν_μ - disappearance channels.

Atmospherics data take expected in 2028

Physics data with full ND + FD +Beam ~ 2032

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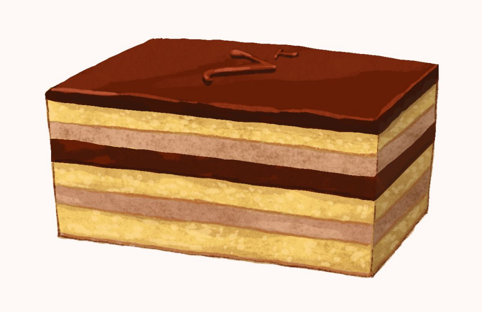
Okay, so, how hard is to detect ν_τ ?

DUNE is expected to be able to **collect an unprecedented high-statistics & purity** sample of oscillated **ν_τ** events from a beam than all existing experiments so far: **~30 ν_τ events so far!**

DONUT - 9 ν_τ events
0711.0728

July 21, 2000, the DONUT (Fermilab) announced the detection of ν_τ for the first time



OPERA - 5 ν_τ events
1804.04912

IceCube - 15 ν_τ events
arXiv:2403.02516

Illustrations from Symmetry Magazine - July 2025

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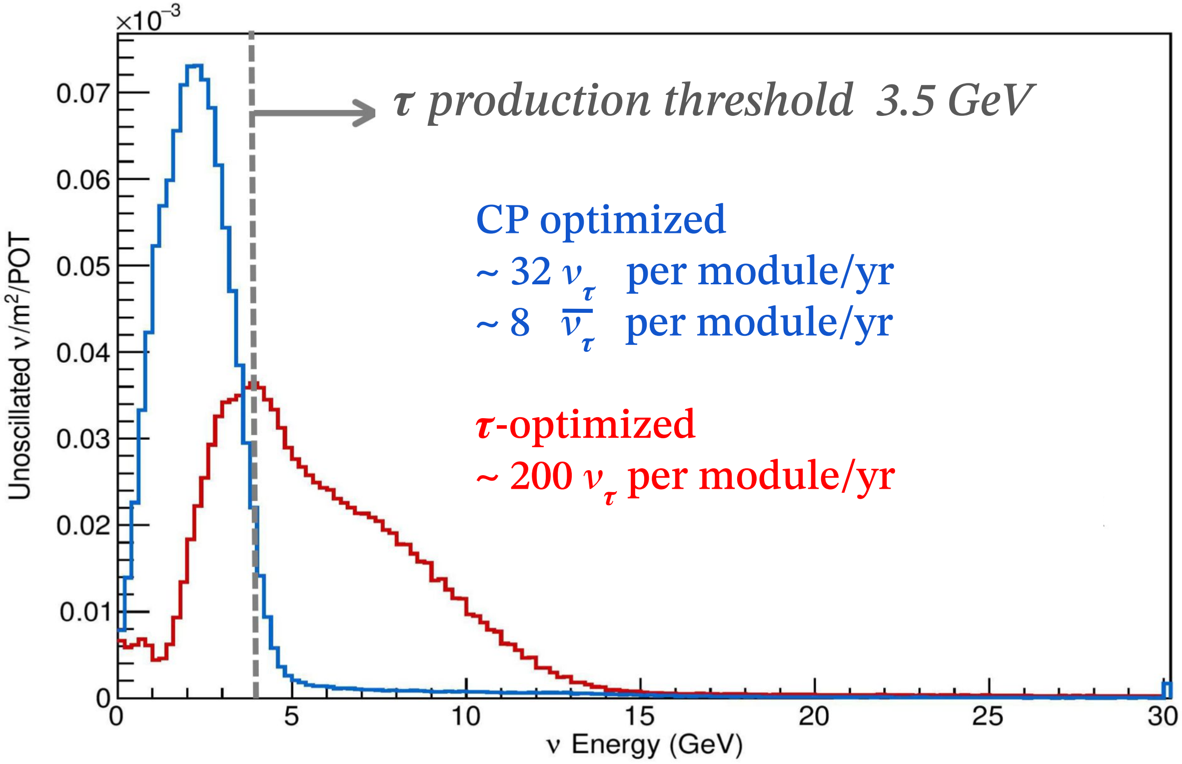
DUNE's Beam Flux: what can be achieved?

arXiv:2203.05591



CP-Optimized beam (3 horns configuration)

- Default starting configuration
- **Low energy, peak ~2.5 GeV**
- FHC/RHC mode 7yrs

τ-Optimized beam (2 horns configuration)

- Proposal for after the CP program, 1yr FHC mode
- **Higher energy, peak ~3.5 GeV**

ν_τ Identification Challenges

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

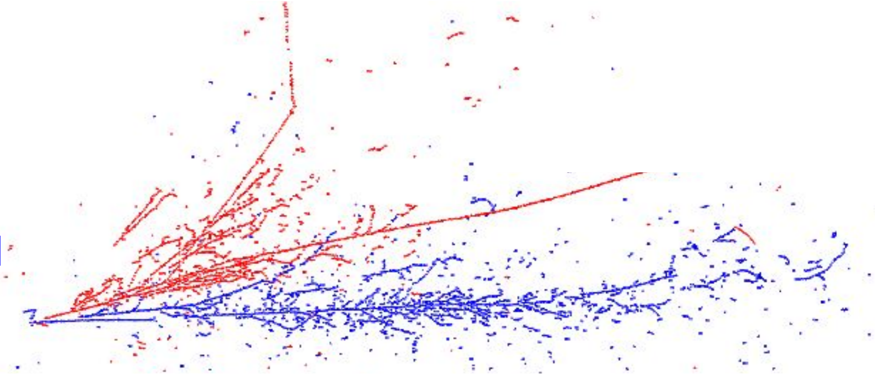
Difficult to separate hadronic systems from τ-decay and nucleus

A **key element** in the study of ν_τ physics are the (many) **decay modes of the τ-lepton**

τ decay length, 87 μm vrs **wire spacing,** 5mm

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%

arXiv:2007.00015



CC - ν_τ interaction - DUNE far detector. The hadronic systems produced by the τ decay and nuclear recoil

We could look for ν_τ-CC events with τ-leptons decaying into e, μ, and ρ-mesons in the high-energy beam

$\rho^+ \to \pi^+\pi^0$

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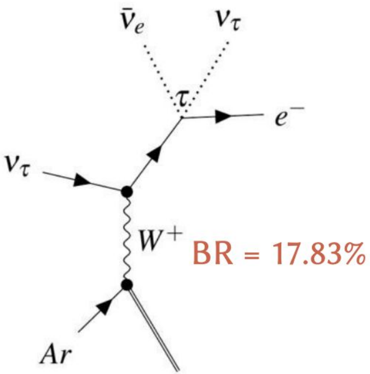
ν_τ Identification Challenges

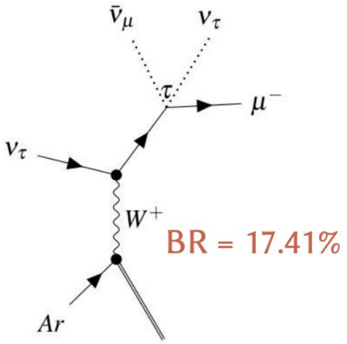
Angular correlations are distinguishing feature

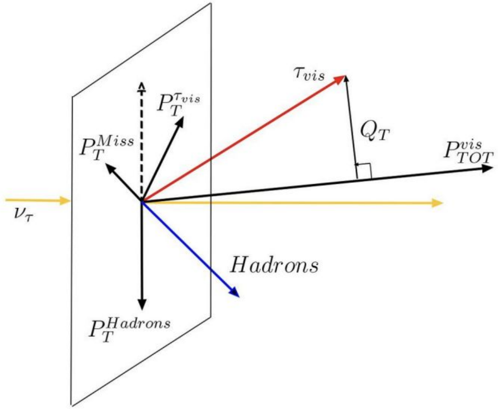
More realistic reconstruction relies on the transverse plane kinematic approach

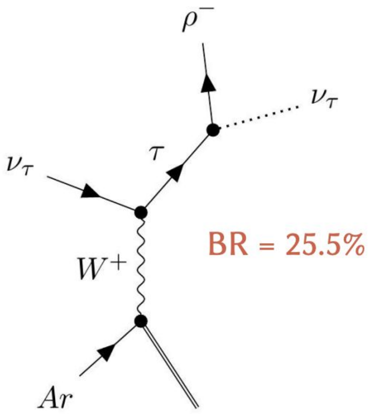
Can be applied to hadronic decays if the τ-lepton products can be identified

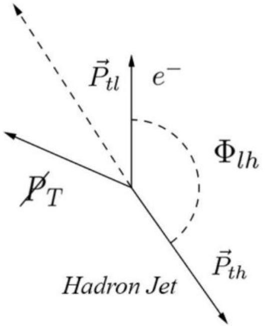
Use machine learning approaches for improved particle ID and reconstruction



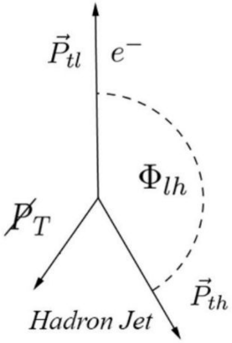






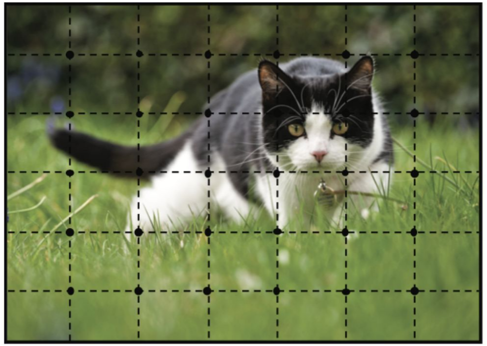


Signal interaction products



Background interaction products

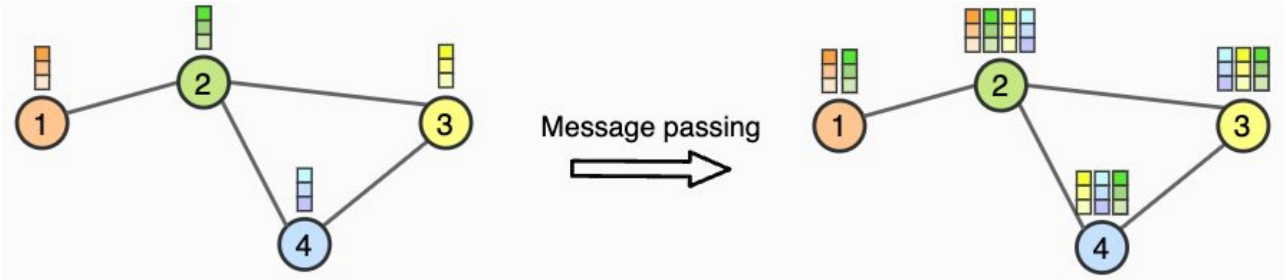
How we reconstruct ν_τ then? Tricky road that brought us to use a Graph Neural Network [Phys.Rev.D 110 (2024) 3, 032008]



GNNs are generalizations of CNNs

CNN : can only operate on regular Euclidean space (grid)
GNN : ~ non-Euclidean

A graph is a tuple of **set of nodes**/vertices and a **set of edges**/links



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

GNNs are an ideal structure for understanding physics data!

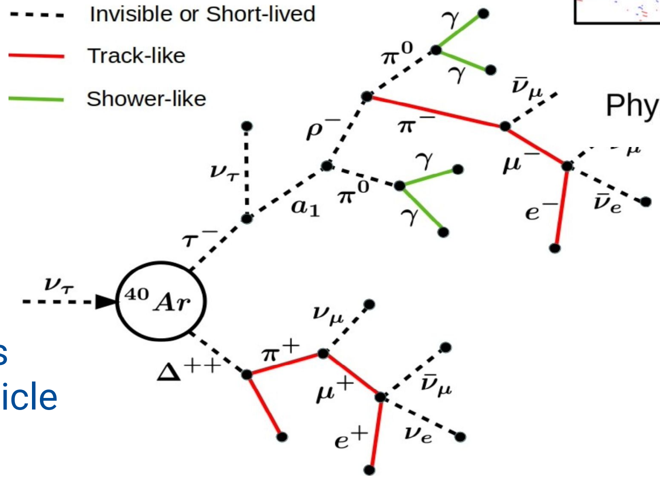
Hits (causal structure) can easily be modeled by edges

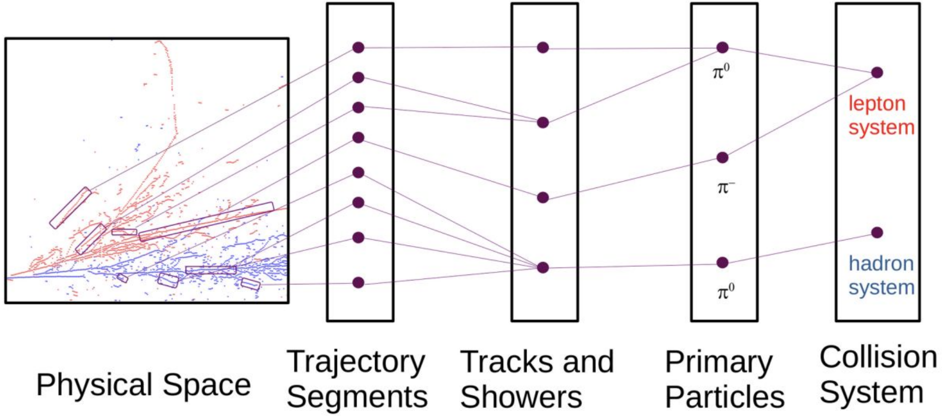
A $\boldsymbol{\nu_\tau}$ **interaction with ^{40}Ar** can be represented as a graph in several different ways:

Like tracking

Nodes = hits

Edges = adjacent hits caused by same particle





A.Aurisano, NPML 2024

Or as a particle tree

Nodes = particles

Edges = parentage relationship

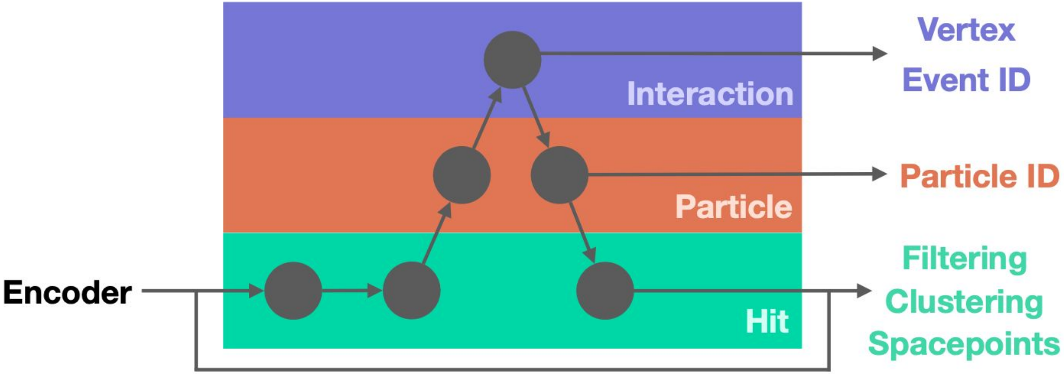
NuGraph: a generalizable GNN reconstruction toolkit for ν physics interactions

NuGraph3 arXiv:2403.11872
NuGraph2 arXiv:2403.11872v1
NuGraph Public Repo

Architecture with a **hierarchical graph network** approach (NuGraph3)

Construct a **heterogeneous graph** with **nodes representing** different levels of information such as **hits, particles and interactions.**

LArSoft support: MicroBooNE, ICARUS, DUNE FD and ND



Each stage connects elements from stage before to produce higher level objects

Beam ν_τ Identification via NuGraph

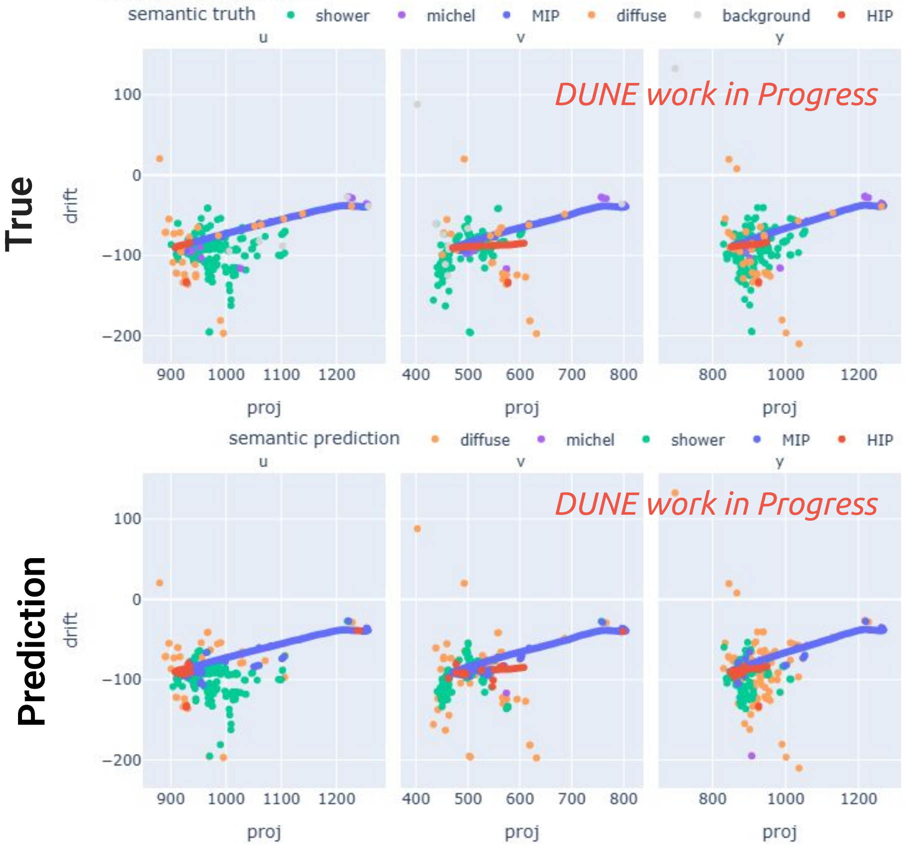
Predict event-level quantities:

- Classify entire event with semantic label.
- CVN-style neutrino flavor ID.
- Reconstruct 3D vertex position.
- Perform 2D → 3D coordinate transformation, identify vertex inside event.

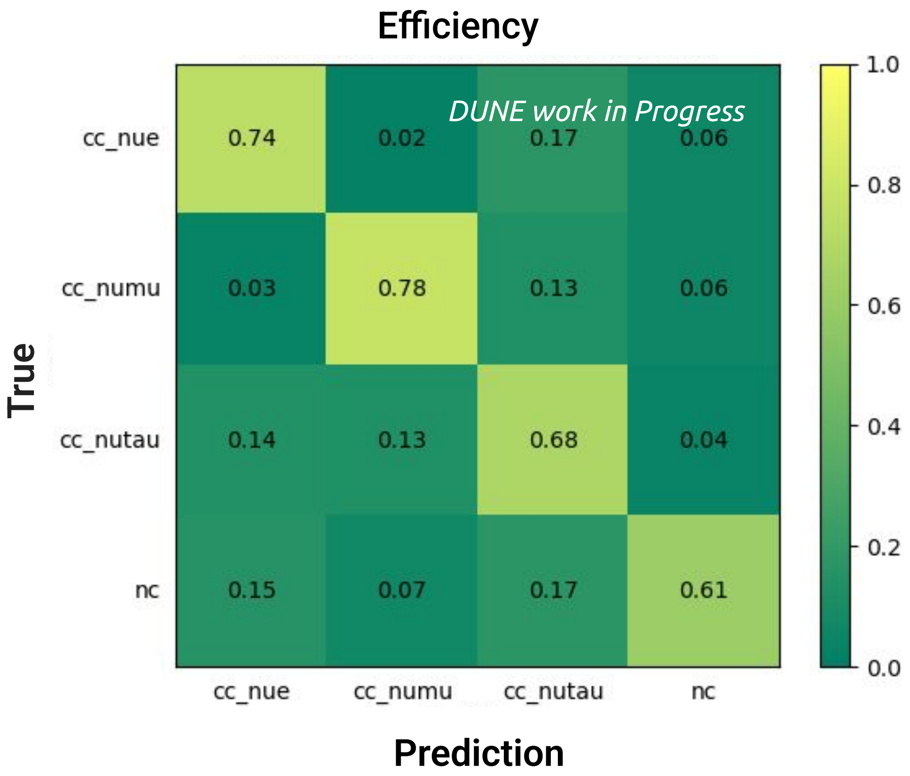
No discrimination between polarities.

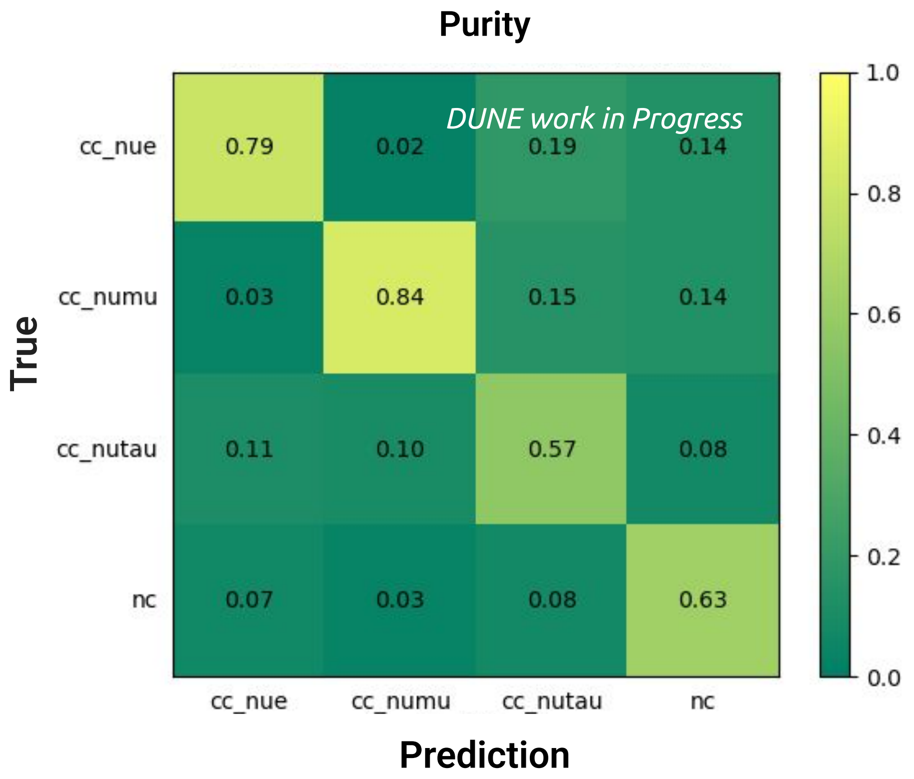
Accounts for:

- TPC module coordinates and drift direction (DUNE FD)
- True 3D position energy deposits on the detector hits when processing the graph



Beam ν_τ Identification via NuGraph: a proof of concept, we will do better!





Comments

- DUNE is uniquely capable of providing a high-purity & high-statistics sample of beam ν_τ
  We can have access to the three oscillations modes!

- **ν_τ are challenging to select and reconstruct,** BUT, they provide a needed independent check of unitarity & cross section SM model assumptions

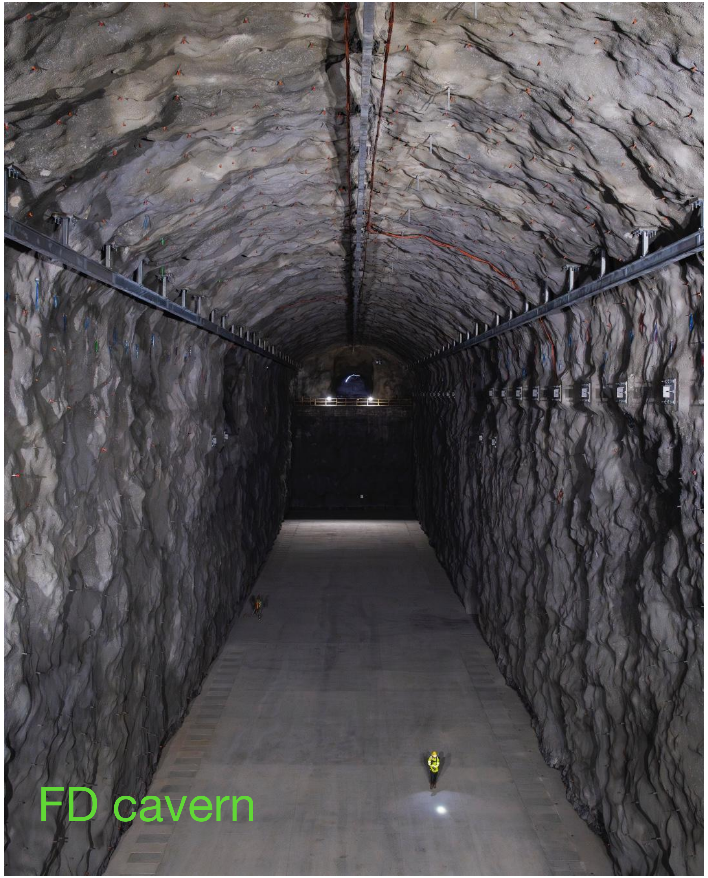
- Performance of **ν_τ selection using GNNs is promising** & with room for improvement!

- Based on the selection on ν_τ via NuGraph, **multiple studies are underway:** sensitivities, cross sections, decay channels, etc

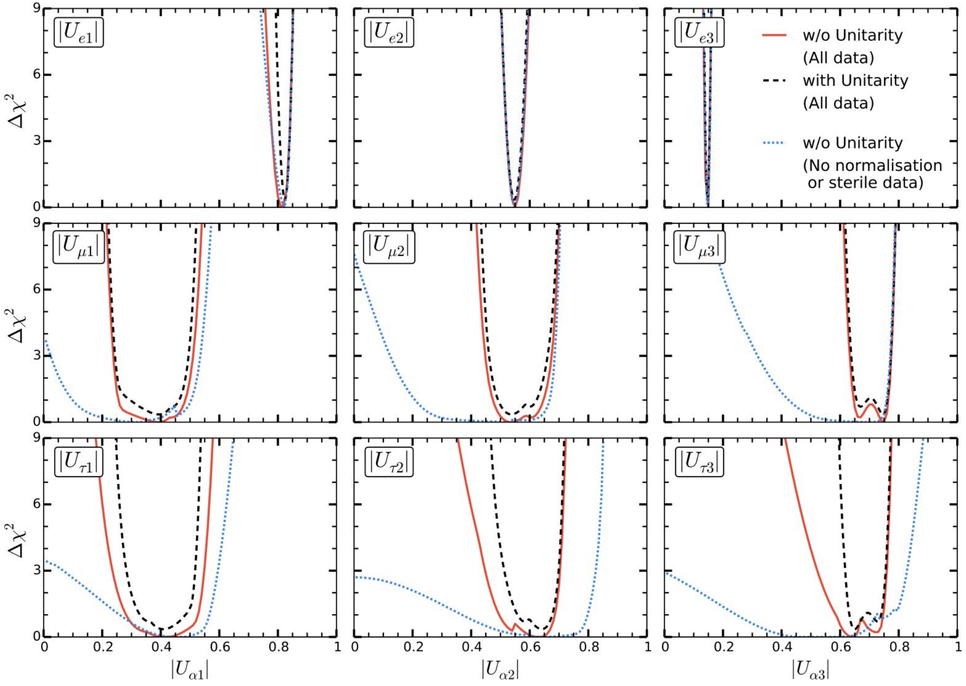
- **Coming soon: ν_τ atmospherics and ν_τ flux optimized trainings**

THANK YOU!

PIP-II



BACKUP



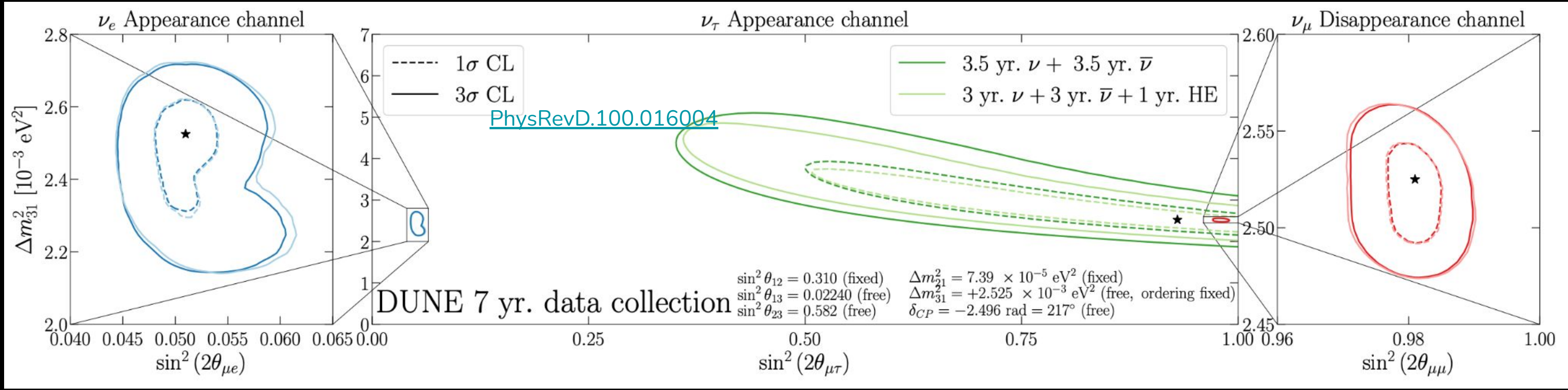
arXiv:1508.05095

FIG. 1: Marginalised 1-D $\Delta\chi^2$ for each of the magnitudes of the 3x3 neutrino mixing matrix elements, without (red solid) and with (black dashed) the assumption of unitarity, using all data. The x-axis is the magnitude of each individual matrix element, and the y-axis is the associated $\Delta\chi^2$ after marginalisation over all parameters other than the one in question. Also shown is the fit in which no normalisation or sterile search data is used (blue dotted), to highlight their importance to the fit. The blue and red curves coincide closely with the unitary case in $|U_{e2}|$ and $|U_{e3}|$. This analysis was preformed for the normal hierarchy, the inverse hierarchy providing the same qualitative result.

Why Tau Neutrinos? Model-independent constraints on non-unitary neutrino mixing

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

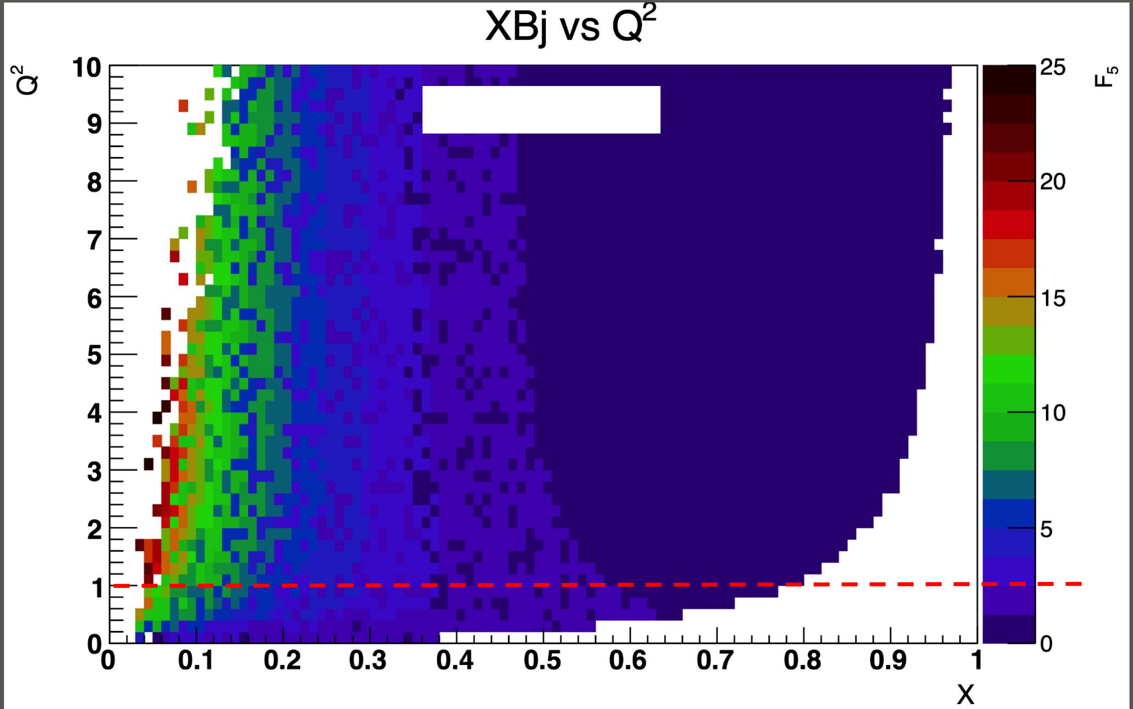
$$\sin^2(2\theta_{\mu e}) + \sin^2(2\theta_{\mu\tau}) = \sin^2(2\theta_{\mu\mu})$$



PhysRevD.100.016004

- DUNE data alone are expected to constrain the normalization of the 3rd PMNS column to ~ 5% 100.016004
- All other neutrino data constrain normalization to ~ 7.5 % 1103009

Nature of $F_5\ (x, Q^2)$



- This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.
- At lower X , F_5 values are high.
- Below $Q^2=1$, non-perturbative
- Above $Q^2=1$, perturbative

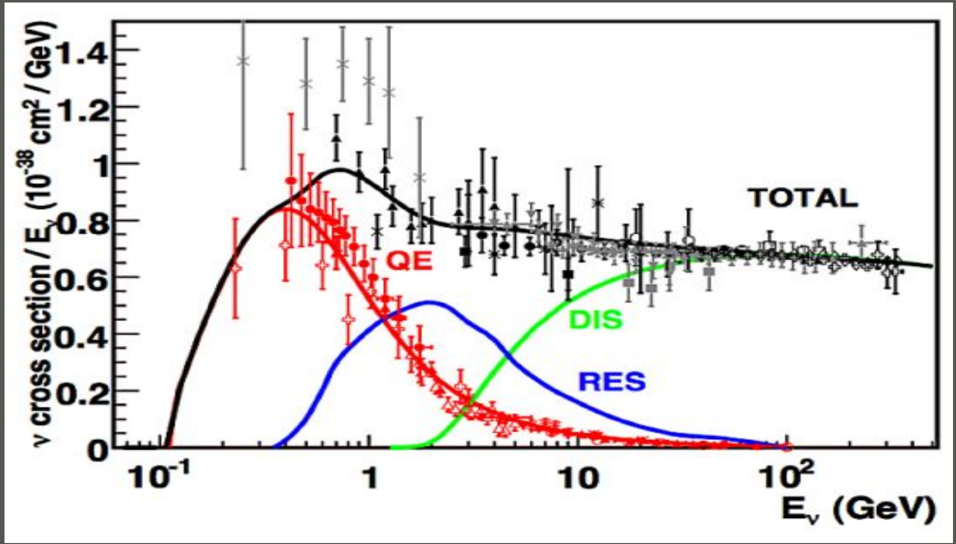
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x+\frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2})-(1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2})-\frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2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

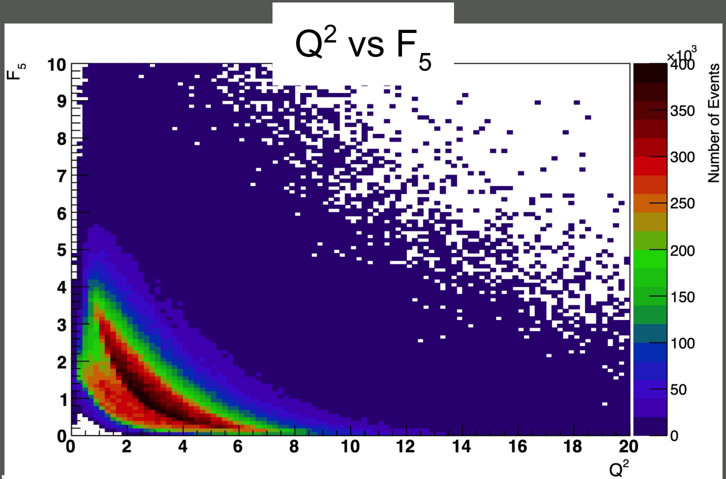
Nature of $F_5(x, Q^2)$

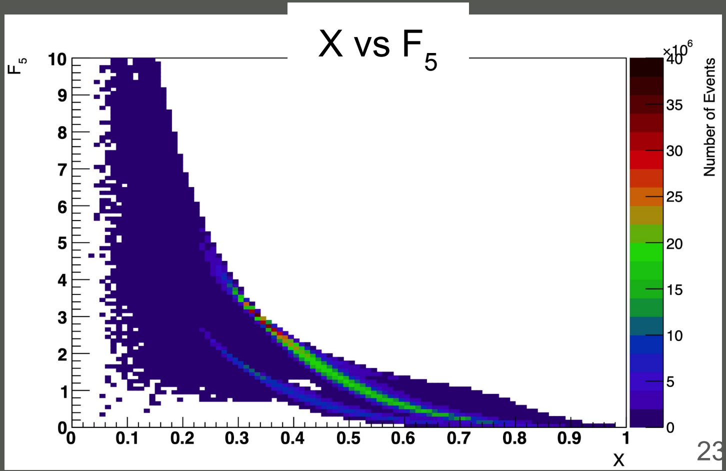
This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.

Nuclear models rely → approximations, which are valid in specific kinematics and for specific process.

For F_5 is sensitive in values for x and Q^2 that wrap different interactions models.





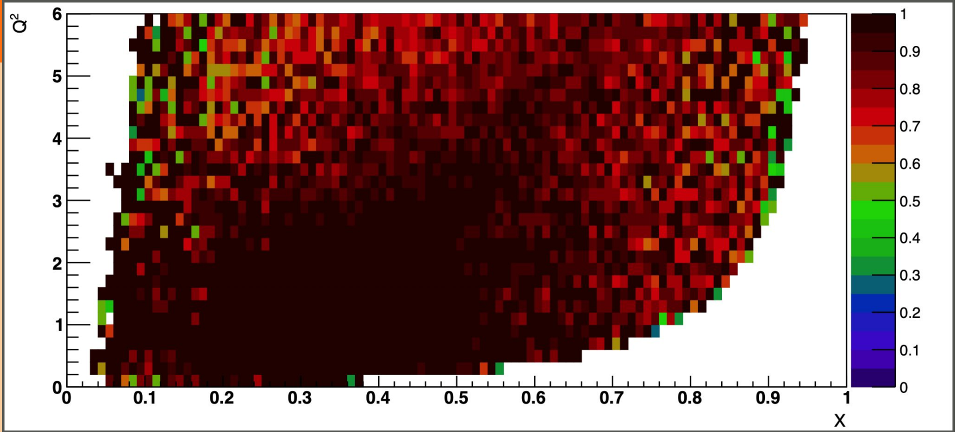


Effect of F_5 in the total number of events.

The ratio is greater than 1:

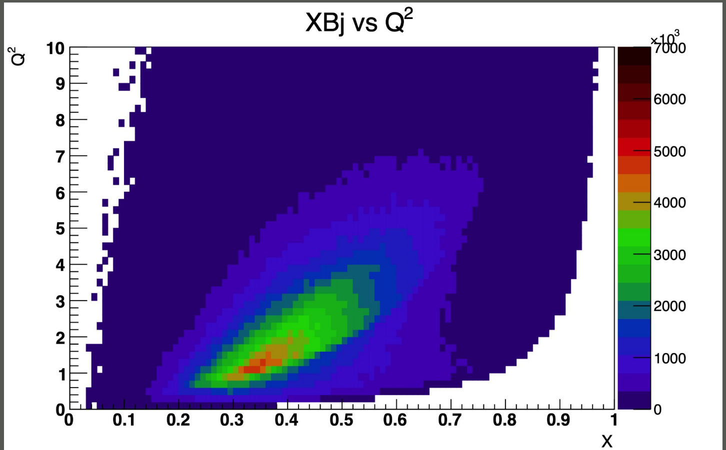
- Which is expected since F_5 is a subtracted component of the total XSec.
- Also, it means that there is a chance to disentangle an overall normalization change from a scaling of F_5

F_5 value covers all the phase space

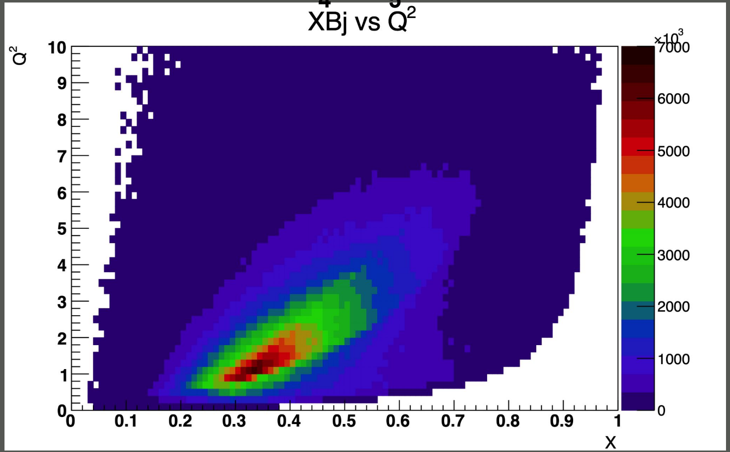


Ratio of F5 Disable / F5 Enable

SM Prediction



$F_4 = F_5 = 0$



Number of Events