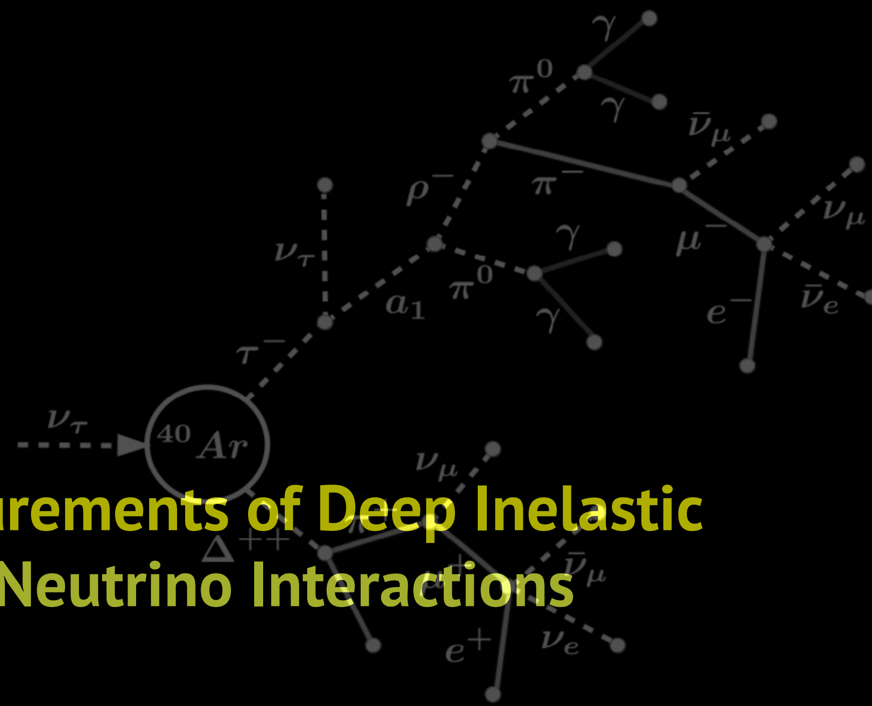
SNOWMASS - Seattle, WA 2022
Neutrino Physics Frontier



Prospects for DUNE Measurements of Deep Inelastic Charged-Current Tau Neutrino Interactions

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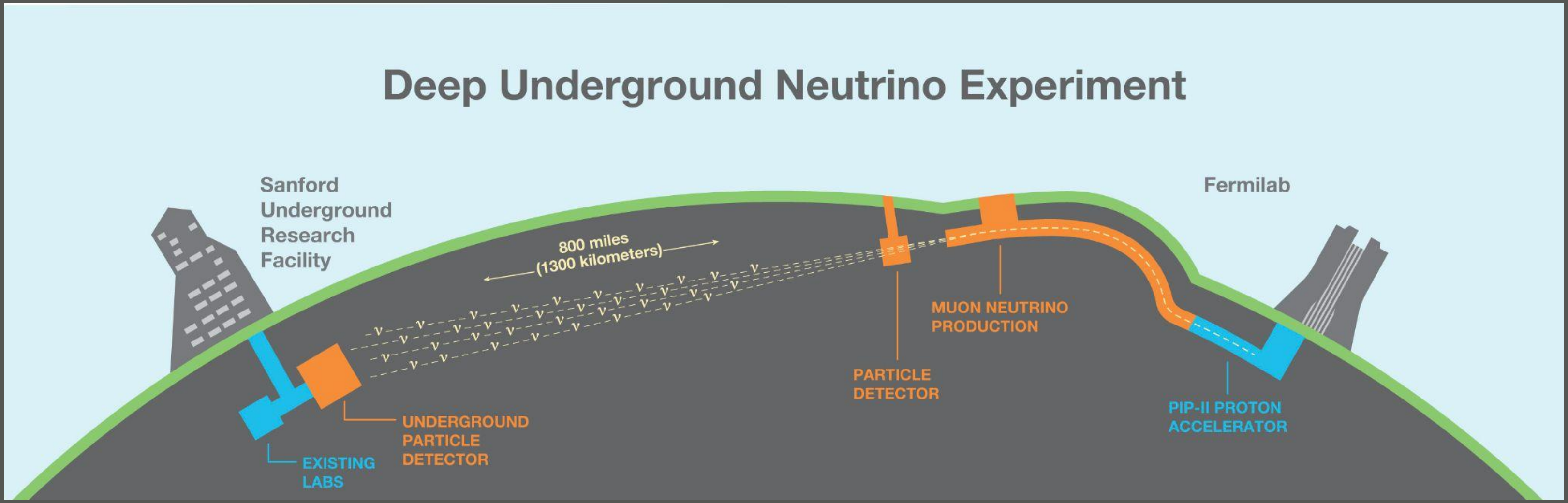
of the DUNE Collaboration
byaeggy@fnal.gov

UNIVERSITY OF Cincinnati

DEEP UNDERGROUND NEUTRINO EXPERIMENT

The Deep Underground Neutrino Experiment (DUNE)

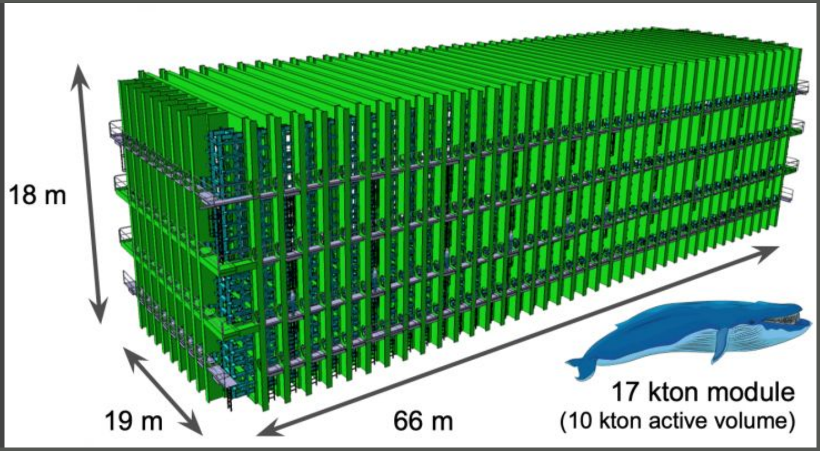


- Currently under construction.

- A broad set of topics to being pinned down at DUNE, it will be able to constrain the three-massive-neutrinos paradigm by providing complementary measurements to those from the ν_e - appearance and ν_μ - disappearance channels.

Far Detector

- 1300 Km baseline
- Liquid argon time projection chamber (LArTPC) technology →high resolution neutrino interaction imaging
- 4x17 kton LArTPC modules.



NuTau at DUNE - What we can learn from ν_τ ?

- **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.

Currently there is a broad of topics being pin- down at DUNE, summarized in the Snowmass Whitepaper arXiv:2203.05591

- Detection and studies of atmospherics
- Transverse-plane kinematics approach in the far detector (FD)
- Anomalous appearance in the near detector (ND)
- Interactions and Cross-sections in the FD

ν_τ data can help to understand non trivial questions:

Current generation of neutrino experiments provides nearly complete description of three flavor paradigm, but:

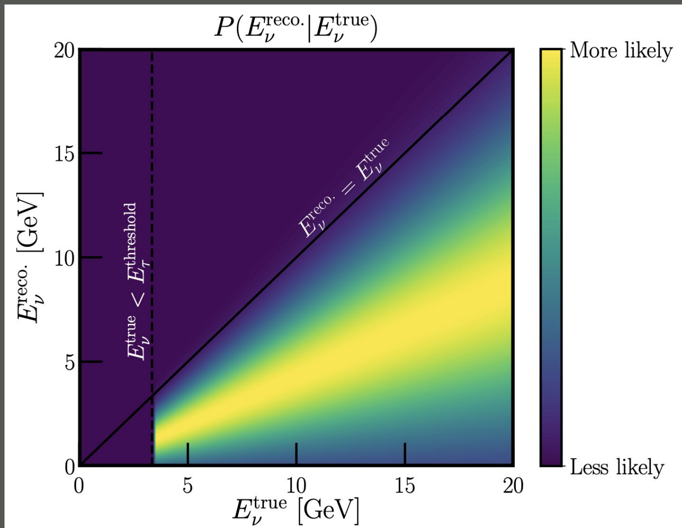
• Almost all knowledge of tau neutrino sector is taken from:

→ Lepton universality for cross sections

→ PMNS unitarity for oscillations

• Critical that these assumptions are tested

Tau Neutrino Interactions



A.Gouvea, K. Kelly, G.Stenico, P.Pasquini
PhysRevD.100.016004

. P.Machado, J.Turner. H. r Schulz
arXiv:2007.00015

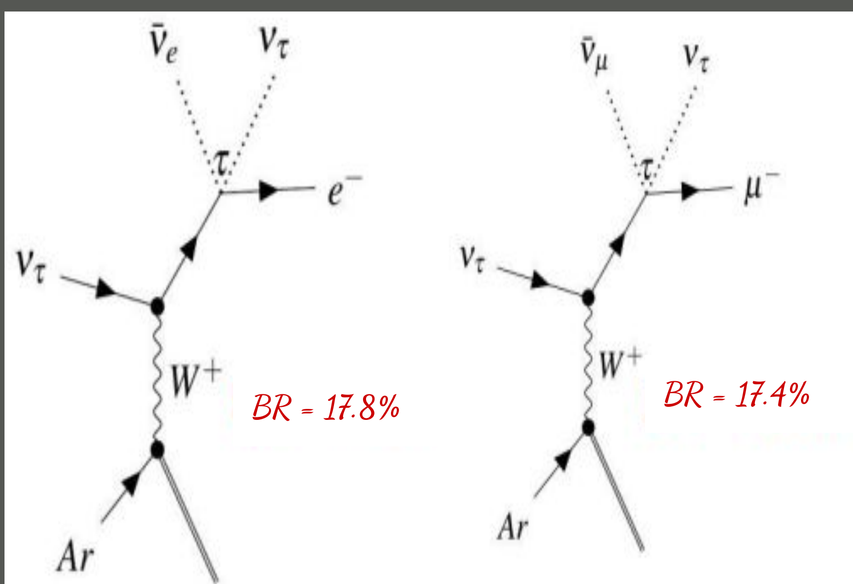
Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%

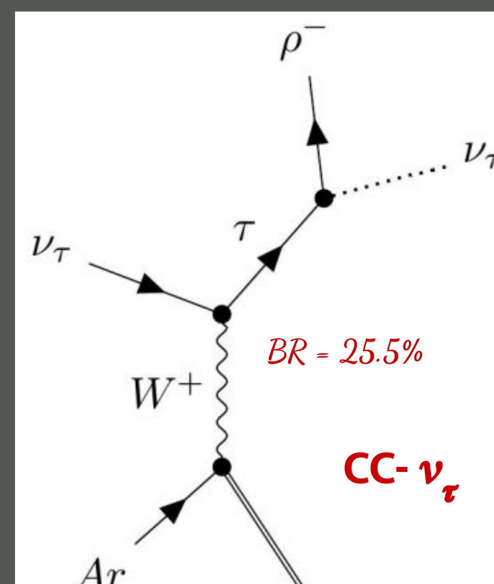
τ is heavy, ~ 1.777GeV

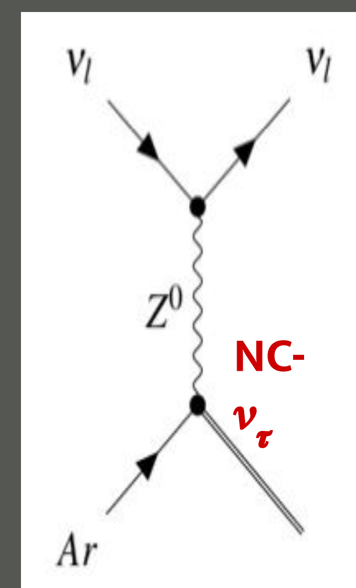
$\tau_{\text{energy threshold}}$ ~ 3.5 GeV

$\tau_{\text{life}} \sim 2.9 \times 10^{-13}$ sec

Challenge: ν_τ reconstruction and the background rejection from NC.







Why cross sections are important?

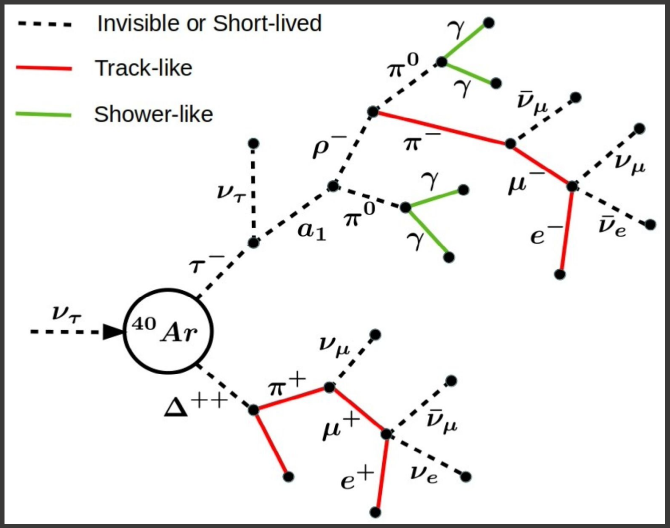
- **Neutrino interactions** (cross section) are the major contributor of systematic uncertainties in oscillation measurements (T2k, NOvA).

- E_ν & **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.

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

$$N^{\alpha\to\beta}_{FD}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma^i_\beta(E_\nu)\times P(\nu_\alpha\to\nu_\beta)\times\epsilon_\beta(E_\nu, E_{\nu,rec})$$



Nuclear and hadronic effects are energy dependent too!

DIS CC-ν_τ Cross-section arxiv.1007.1966v1

Albright, Jarlskog '75 Paschos, Yu '98 Kretzer, Reno '02

$$\frac{d^2\sigma_A}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\Big\{\Big[y^2 x + \frac{m_l^2 y}{2E_\nu M_N}\Big] F_{1A}(x,Q^2) + \Big[\Big(1-\frac{m_l^2}{4E_\nu^2}\Big) - \Big(1+\frac{M_N x}{2E_\nu}\Big) y\Big] F_{2A}(x,Q^2)$$

$$\pm \Big[xy\Big(1-\frac{y}{2}\Big) - \frac{m_l^2 y}{4E_\nu M_N}\Big] F_{3A}(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x} F_{4A}(x,Q^2) - \frac{m_l^2}{E_\nu M_N} F_{5A}(x,Q^2)\Big\}$$

The scaling variables $x(=\frac{Q^2}{2p\cdot q})$ and $y(=\frac{\nu}{E_\nu}=\frac{q_0}{E_\nu})$ lie in the range:

A lepton mass correction appear $\rightarrow$ limits x,y

$$\frac{m_l^2}{2M_N(E_\nu - m_l)} \le x \le 1 \qquad \text{and} \qquad a-b \le y \le a+b,$$

where

$$a = \frac{1 - m_l^2\left(\frac{1}{2M_N E_\nu x} + \frac{1}{2E_\nu^2}\right)}{2\left(1+\frac{M_N x}{2E_\nu}\right)} \qquad \text{and} \qquad b = \frac{\sqrt{\left(1-\frac{m_l^2}{2M_N E_\nu x}\right)^2 - \frac{m_l^2}{E_\nu^2}}}{2\left(1+\frac{M_N x}{2E_\nu}\right)}.$$

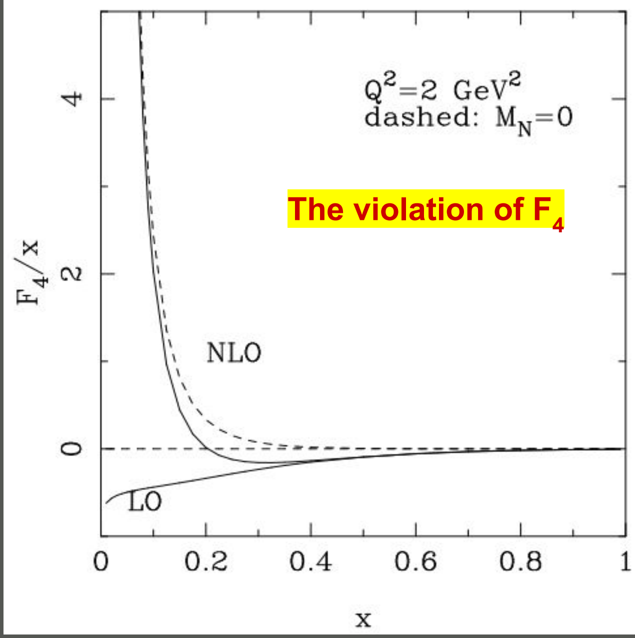
$\rightarrow$ A **structure function (SF)** characterize the internal structure of the nucleon

$\rightarrow$ The **contributions of the SF to the cross-section** are functions of charged lepton mass.

$\rightarrow$ In the limit $m_l^2 \rightarrow 0$ only F_1, F_2 and F_3 contribute, $m_l^2/(M_N E_\nu)$.

$\rightarrow$ The structure functions F_4 and F_5 are negligible for ν_μ and ν_e, but become important for ν_τ

$\rightarrow$ **Albright-Jarlskog (AJ) relations** occur only in heavy lepton (τ) scattering, Nucl. Phys. B 84, 467 (1975)



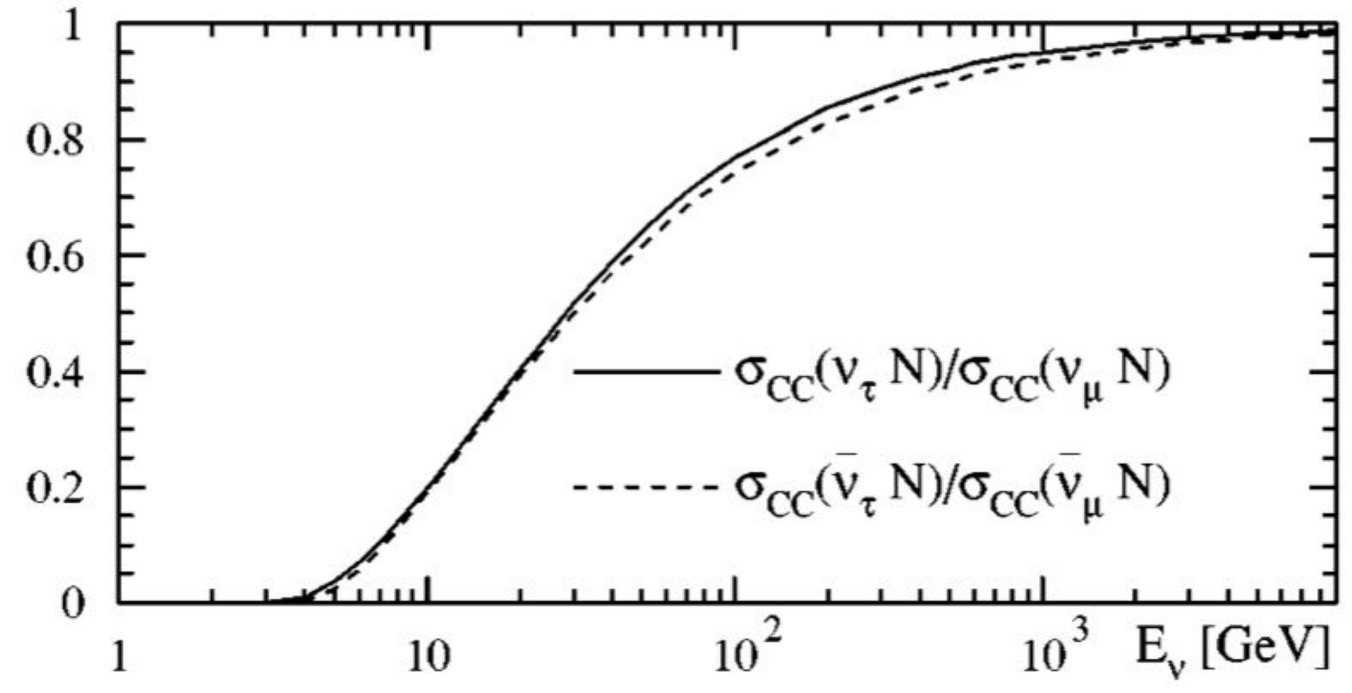
A look to the CC ν_τ and ν_μ Cross Section

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

Reasons for the deficit in the ν_τ CC cross-section:

1) The **reduce phase space: integration limits (x,y)** ← half of the suppression of ν_τ relative to the ν_μ it is from a dynamic origin.

2) F_5 minus sign & no factor of x: $-\frac{m_\tau^2}{E_\nu M_N} F_5^{W^\pm}$



AJ pointed out that there are two additional structure functions, F_4 and F_5 that contribute to the ν_τ XSec.

Structure Functions:

$2xF_1 = F_2$
$-xF_3 = F_2$
$xF_5 = F_2$
$F_4 = 0$ also holds when the nucleon target is replaced by a lepton target.

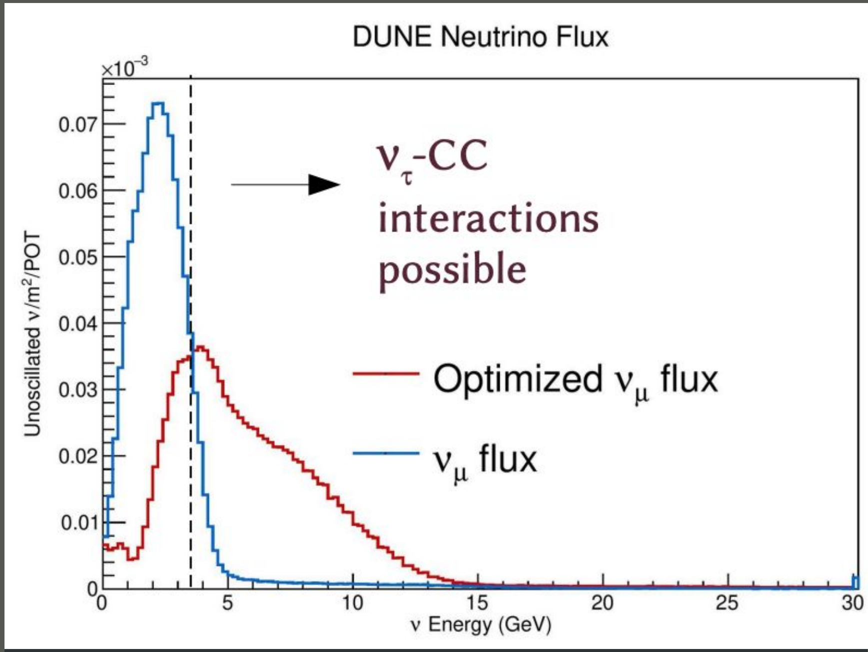
Exploring The Nature of F_5

- GENIE 3.0.6 truth Information
- Using DUNE far detector geometry (Argon 40)
- Tau optimized flux

- **CP optimized (3 horns)**
- **Low energy**
- **Default starting configuration**

- **Tau-optimized (2 horns) - future upgrade, under investigation**
- **high energy spectrum**
- **Possible configuration after CP program has completed**
-

More details Snowmass Whitepaper: Tau Neutrinos in the Next Decade: from GeV to EeV arXiv:2203.05591

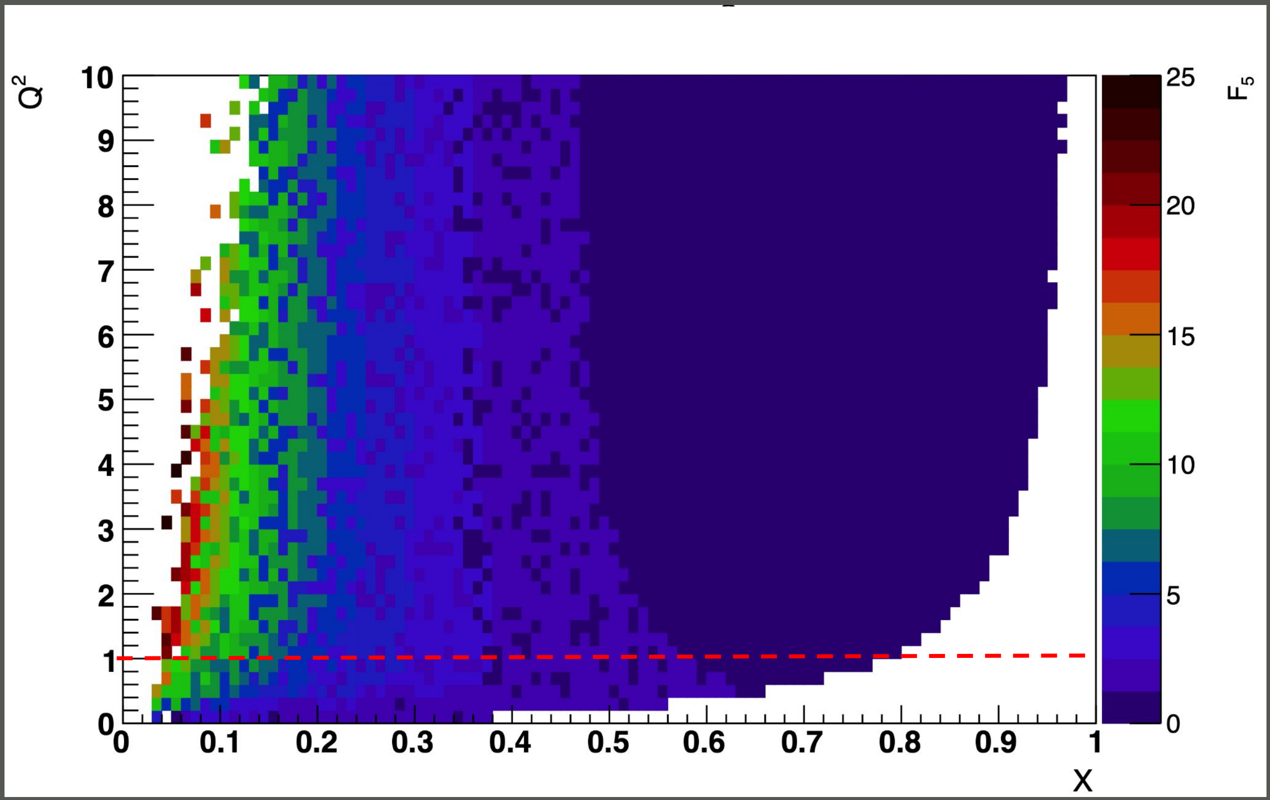


Expected counts/year:

~ 30 ν_τ in CP-optimized neutrino mode
~ 130 ν_τ in CP-optimized neutrino mode
~ 800 ν_τ in Tau-optimized neutrino mode

Nature of F_5 (x, Q^2)

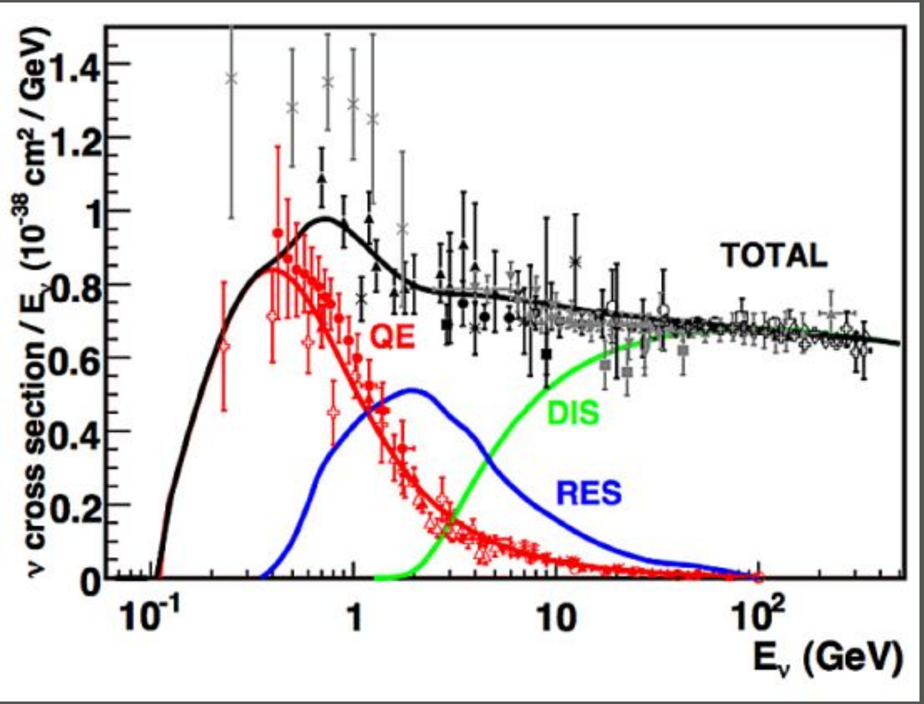
- This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.
- At lower X , F_5 values are high.
- Below Q^2 =1 , non-perturbative
- Above Q^2 =1 , perturbative



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

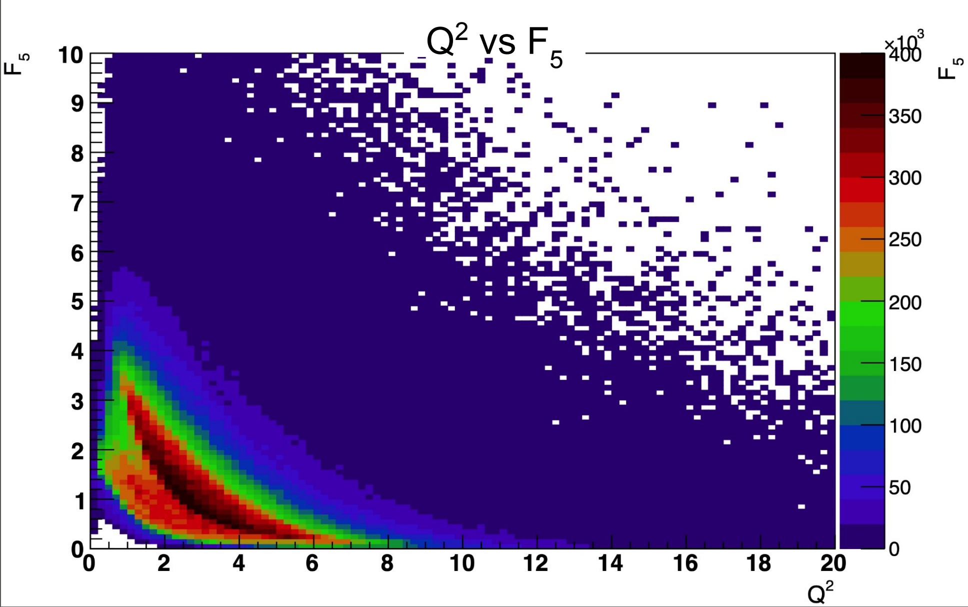
Nature of F_5 (x, Q^2)

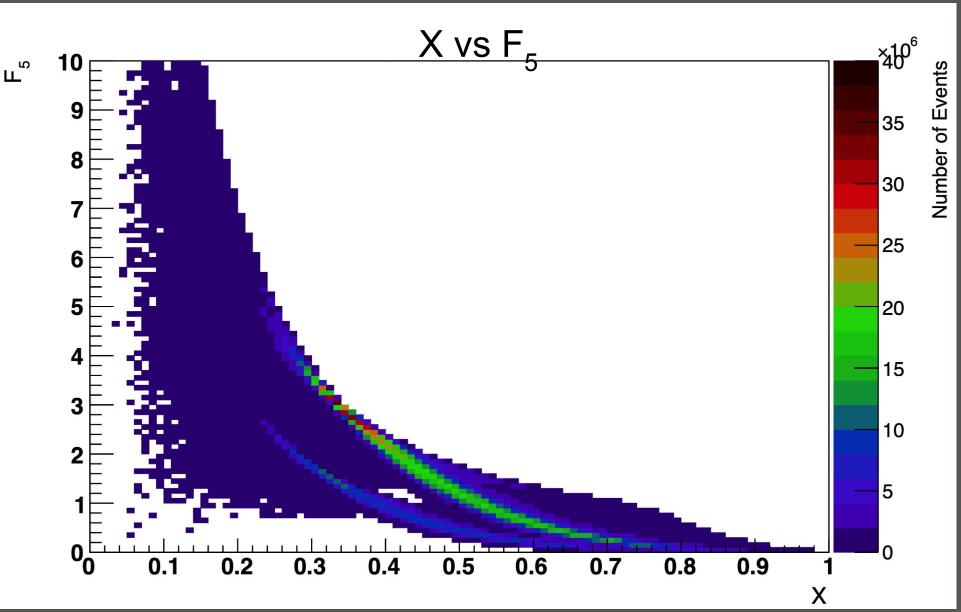
This is F_5 in terms of x and Q^2, its effect is in all [x,Q^2] phase space.



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

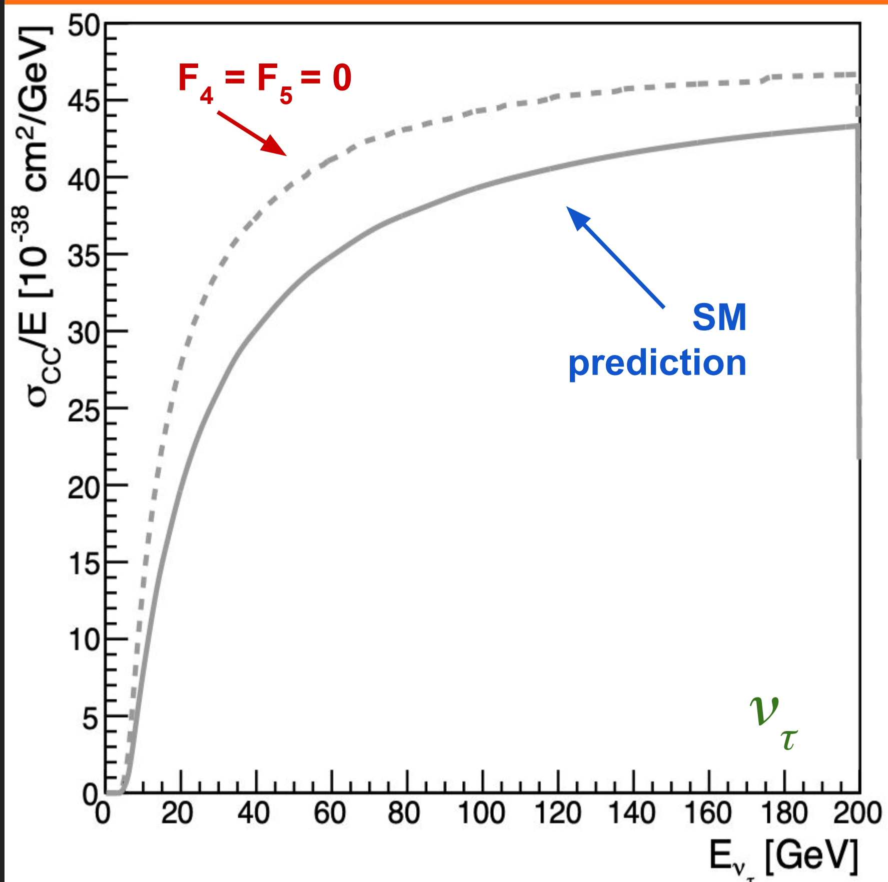
For F_5 is sensitive in values for x and Q^2 that wrap different interactions models.



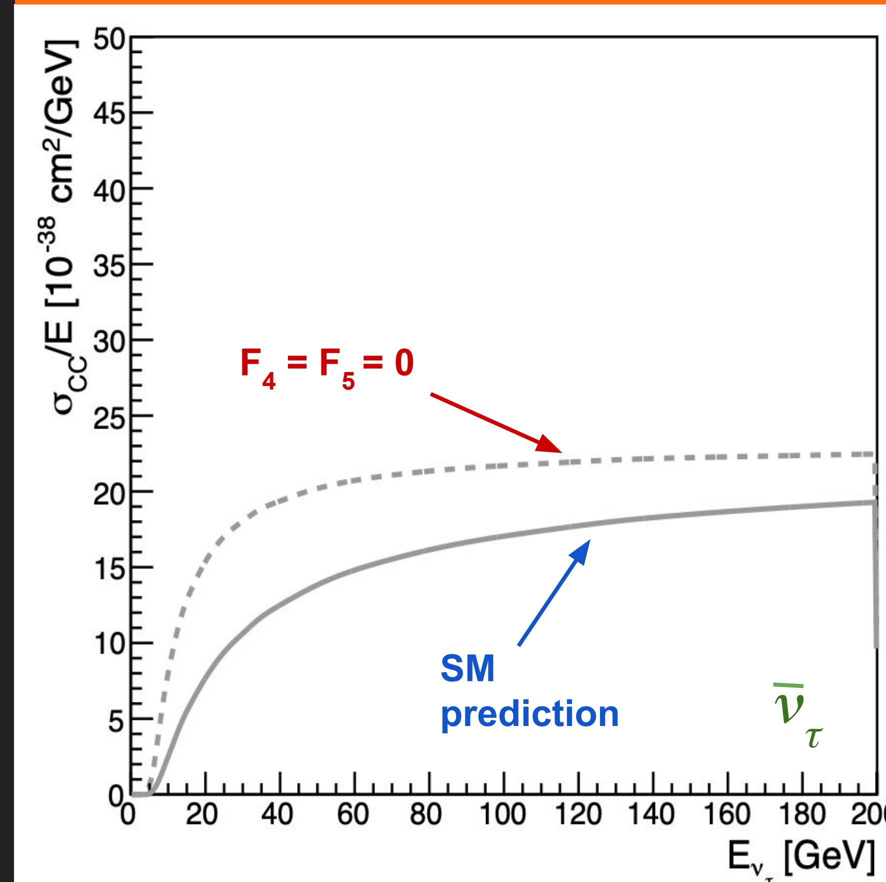


Notice the difference between the cross-sections in the $F_4 = F_5 = 0$ hypothesis and the SM prediction **is larger for lower neutrino energies.**

GENIE 3.0.6 CC-NuTau Cross Section



GENIE 3.0.6 CC- Anti NuTau Cross-Section



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

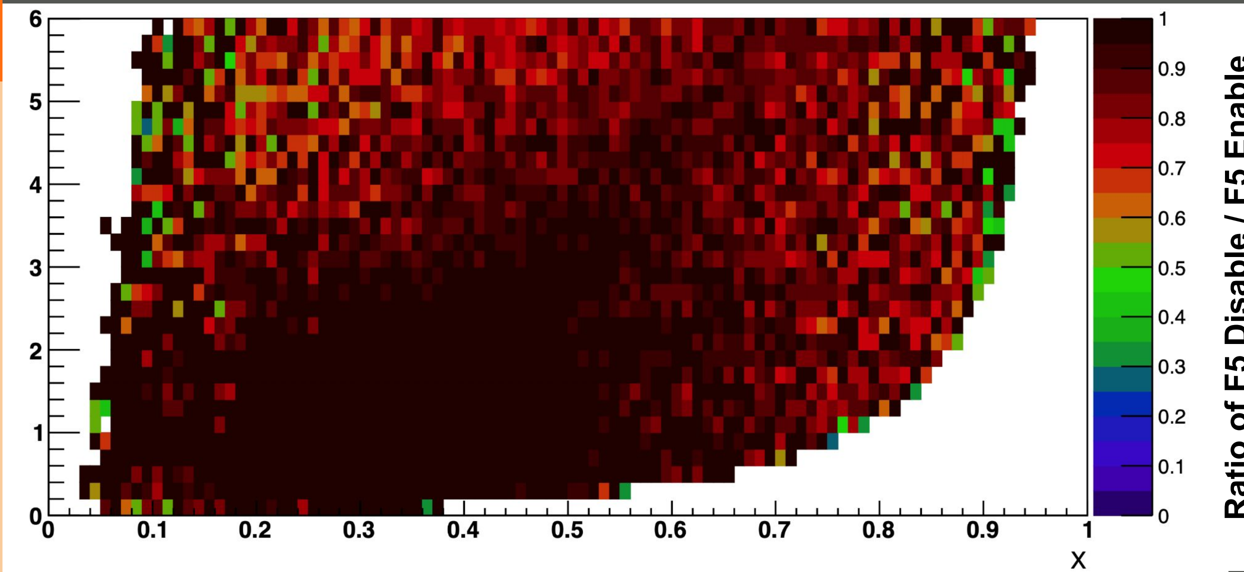
Effect of F_5 in the total number of events.

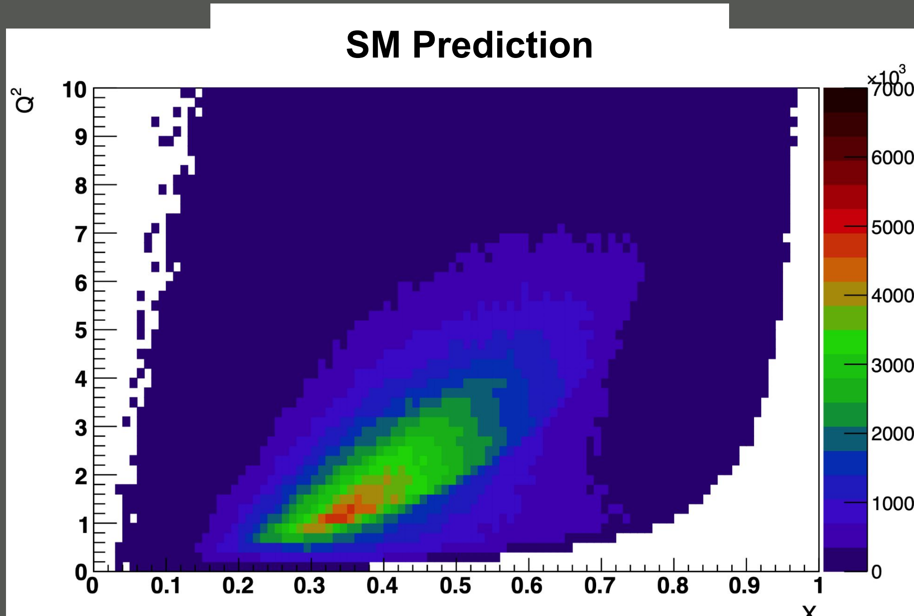
The ratio is greater than 1:

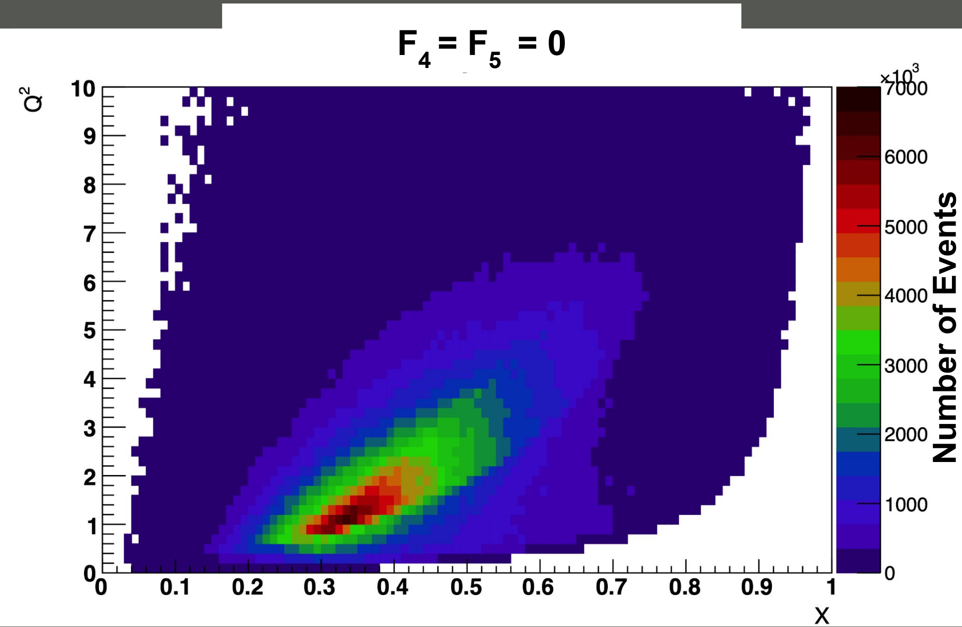
- Which is expected since F_5 is a subtracted component of the total XSec.

- 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



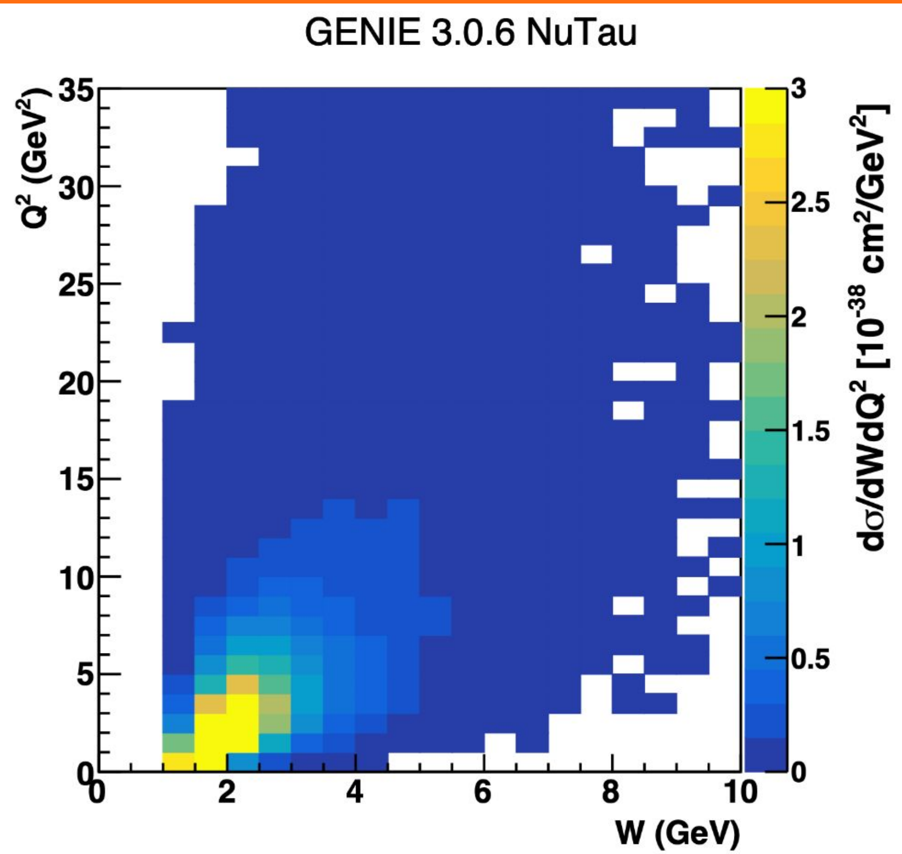




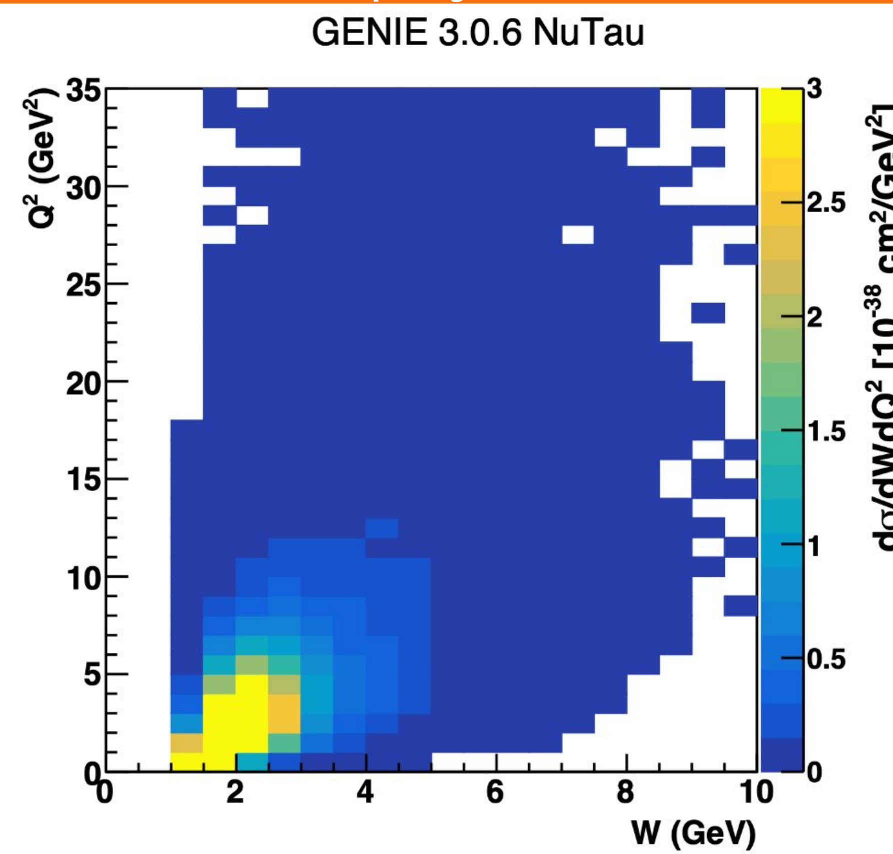
CC - ν_τ TRUTH Level studies show that indeed, when DIS cuts are applied and $F_5 = 0$ we can extract new information from the lepton cross section.

ν_τ

SM Prediction



$F_4 = F_5 = 0$



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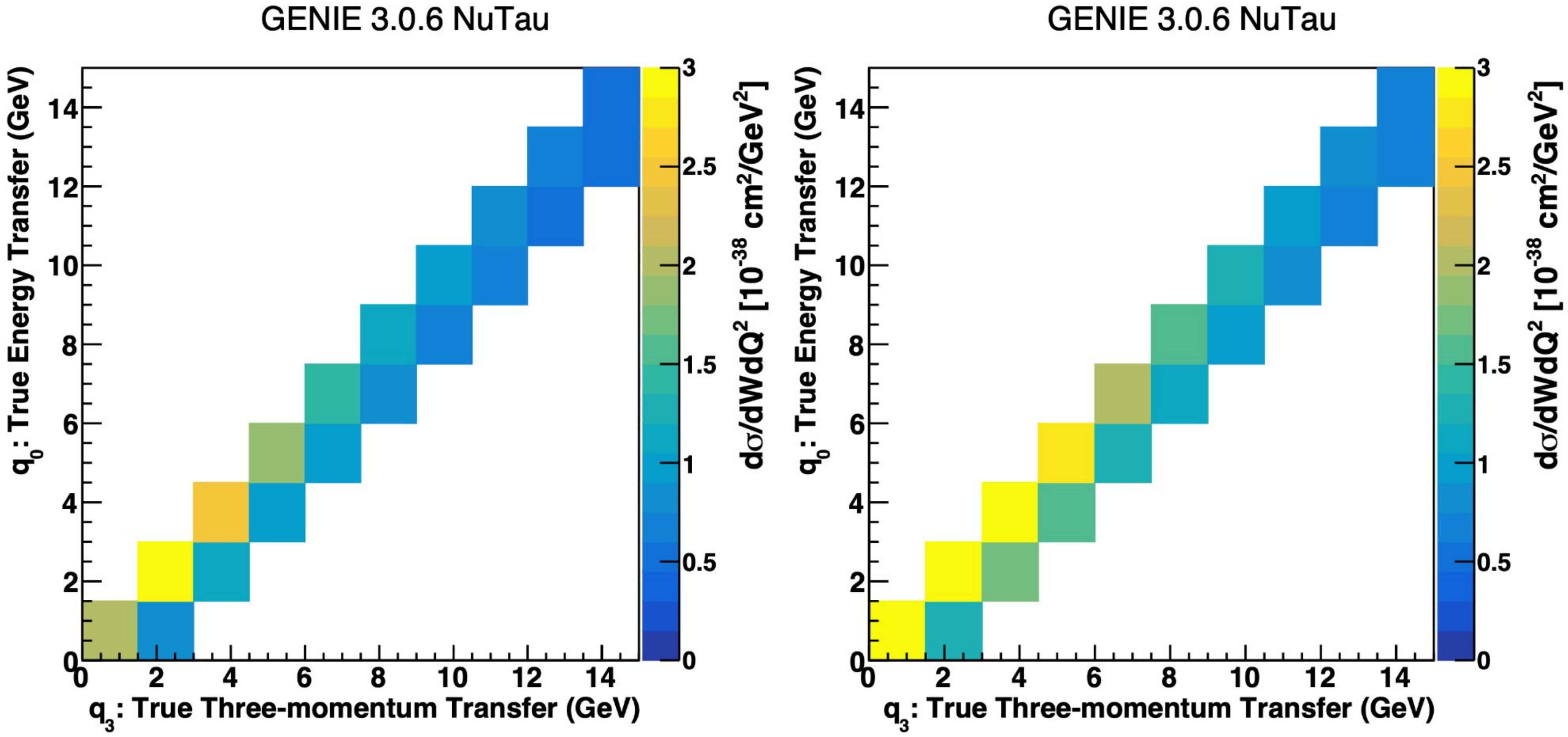
ν_τ

SM Prediction | **$F_4 = F_5 = 0$**



Barbara Yaeggy - University of Cincinnati

So Far

The new features which appear in the case of the ν_τ–A interaction as compared to the ν_e and ν_μ interactions and contribute to modify the cross sections are:

- Kinematical changes in Q^2 and E_ℓ due to the presence of m_τ
- The contributions due to the additional nucleon structure functions $F_4(x,Q^2)$ and $F_5(x,Q^2)$ in the presence of $m_\tau \neq 0$.
- As a function of Q^2, there is an enhancement doesn't come just from a normalization but due the changes on the shape the presence of m_τ

Some of the above effects are modified in the nuclear medium → we need reliable nuclear model to describe DIS of leptons from nuclear targets.

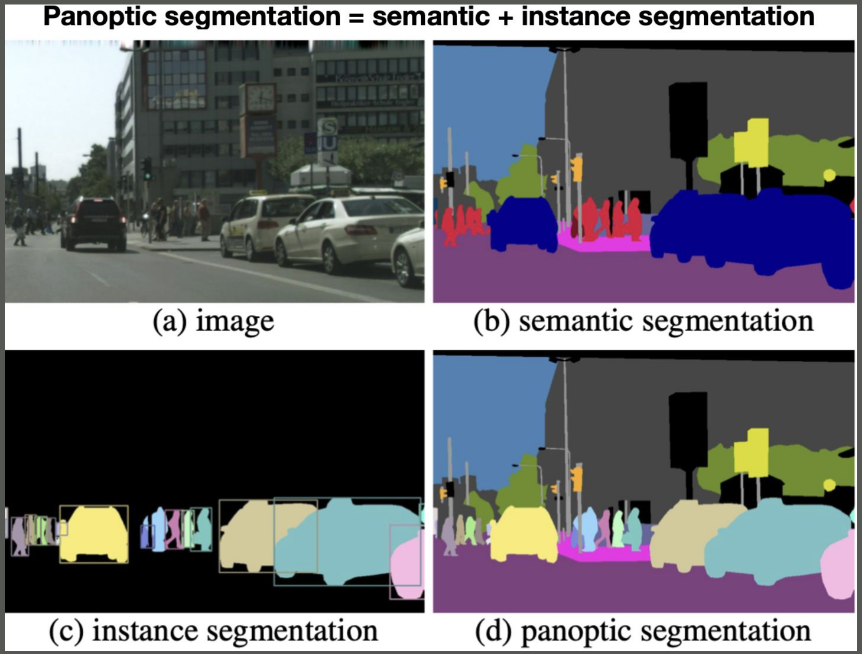
Get a reliable kinematic reconstruction it's a must!

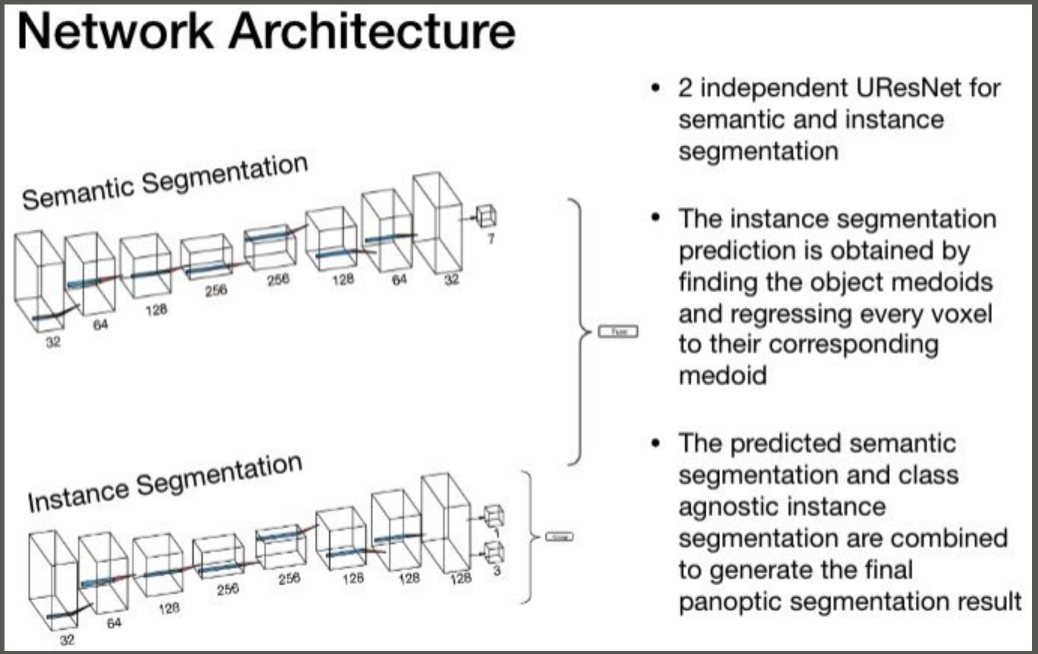
We are checking on machine learning techniques...

Panoptic Segmentation: Semantic + Instance Segmentation

by Carlos Sarasty sarastce@mail.uc.edu "Panoptic Segmentation for Particle ID in ProtoDUNE"

- Semantic segmentation is the process of assigning a class label to each pixel
- Instance segmentation is the task of detecting objects in the image





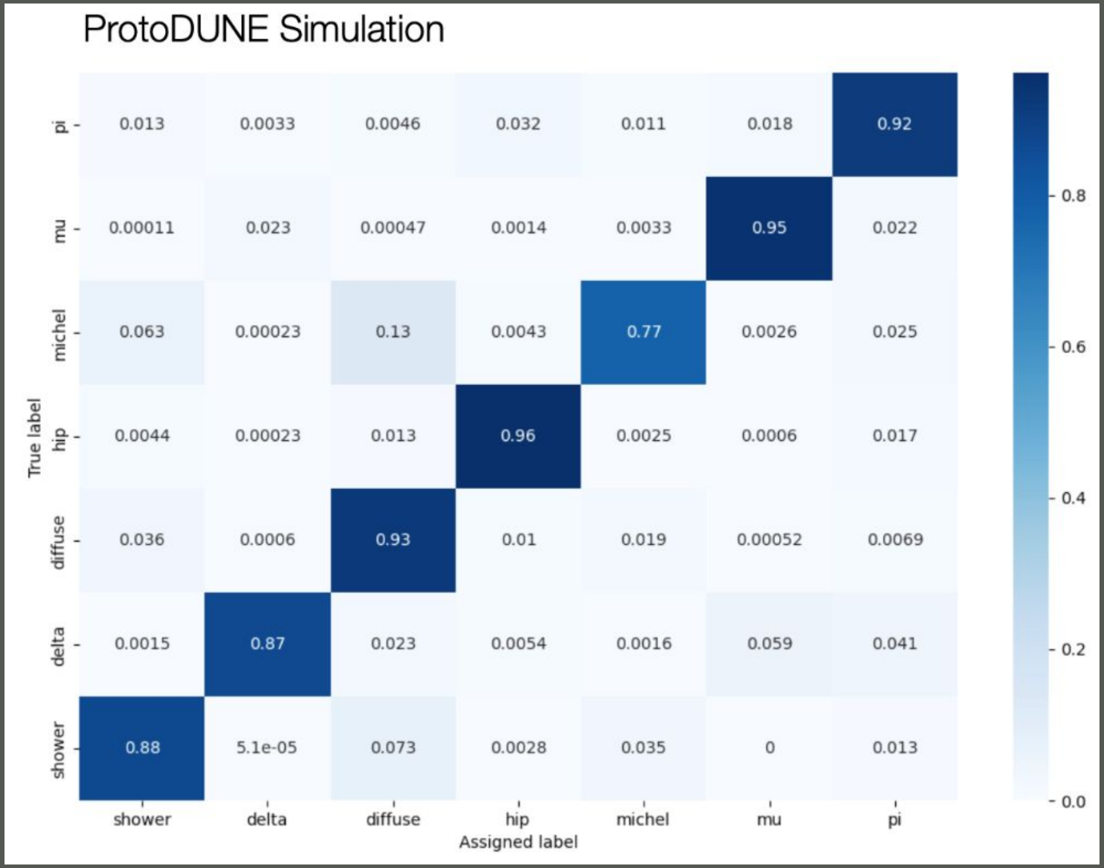
arXiv:1801.00868

Results/Metrics: Semantic Segmentation

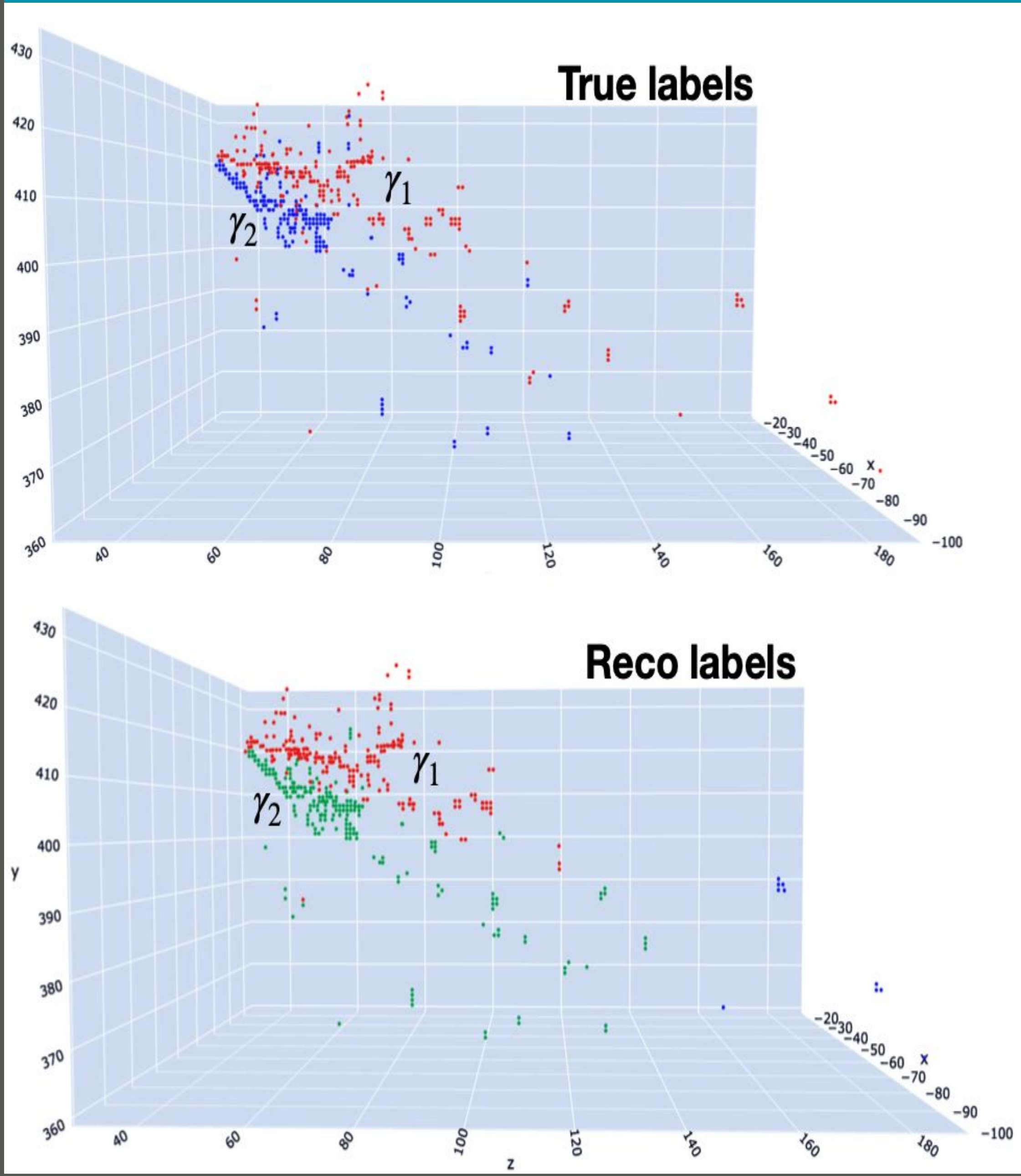
ProtoDUNE by Carlos Sarasty sarastce@mail.uc.edu

- **The network is capable to identify shower like and track like separation with high accuracy**

- **The confusion matrix shows the overlap between classes**



Event Display: two showers from neutral pion decay



Outlook

- **DUNE** will provide a **unique opportunity** to study the connections among neutrinos.

- **Tau neutrinos will help us understand whether or not the PMNS matrix is unitary.**

- **Improve our nuclear models:**

  There are models in which they single out the tau neutrino to satisfy other constraints, and in other cases, the model does not depend on the flavor of the neutrino, but tau neutrinos may be the only means of probing the model.

- **Tau neutrinos** play a central role in **testing the lepton flavor universality** violating hints uncovered in flavor physics experiments.

Thank you!

Backup

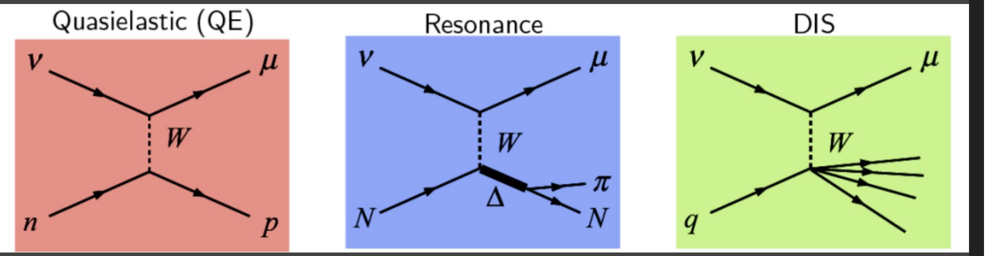
Some Remarks About Our Scenario

A Cross-section analysis leads to different kinds of interesting but complex studies, one of them: the nuclear structure.

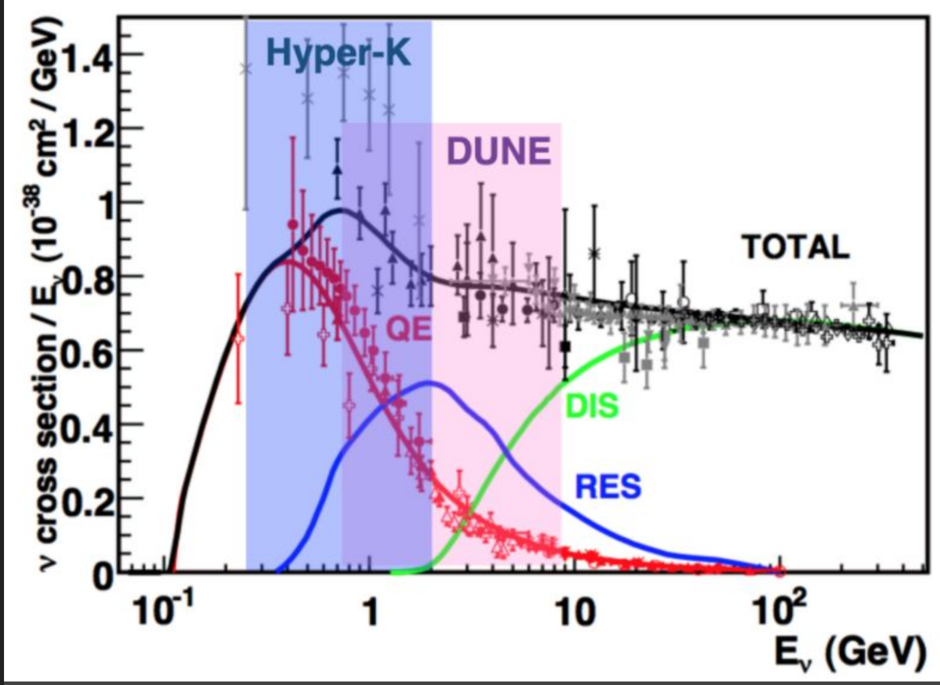
In order to obtain very high energies more easily, many particle colliders and accelerators have hadrons, in particular protons and antiprotons, in the initial state.

Hadrons are however composite particles → quarks and gluons → the fundamental constituents that are involved in the collisions.

- Recent interest in neutrino interactions in few GeV energy region comes from the need of accelerator based neutrino oscillation experiments to reduce systematic errors.
- These interactions channels are signal and the majority of backgrounds in oscillation experiments.



Bodek-Yang model arXiv:hep-ex/0308007 aims for describing DIS cross section in all Q^2 regions. Structure functions are important in the study of DIS



The name DIS here is used loosely for inelastic processes with W > 1.8 GeV (in the continuum at all Q^2, including $Q^2 = 0$).

Why Structure functions are written in terms of the scaling variable x and Q^2, rather than the energy transfer Eν and Q^2?

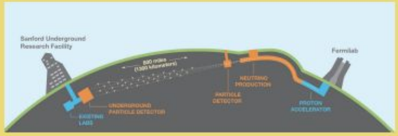
Because for fixed x values of $F_1 ... F_5$ become ~ independent of Q^2 , or $F_{1,...,5}(x, Q^2)=F_{1,...,5}(x)$ is a good approximation for a large Q^2.

This behavior is called Bjorken scaling, or scale invariance: the structure functions are left unchanged by a scale transformation.

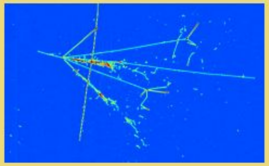
ν_τ (CC) interactions give access to cross section physics not accessible otherwise!

By Adam Aurisano (University of Cincinnati)

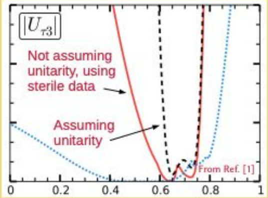
1) DUNE



- DUNE is a long-baseline neutrino experiment currently under construction
- Will constrain the three flavor paradigm
  - Measure δ_{CP} and mass ordering by studying $\nu_\mu \rightarrow \nu_e$ oscillations
- Far Detector
  - 1300 km baseline
  - Liquid argon time projection chamber (LArTPC) technology for high resolution neutrino interaction imaging
  - 4x17 kton LArTPC modules
- Near Detector
  - 574 m baseline
  - Multiple detector systems
  - 147 ton LArTPC component

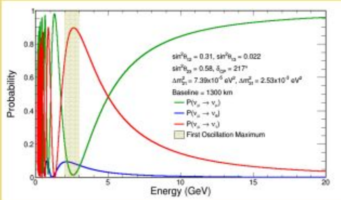


2) Why Tau Neutrinos?



- Current generation of neutrino experiments provides nearly complete description of three flavor paradigm
- Almost all knowledge of tau neutrino sector is taken from
  - Lepton universality for cross sections
  - PMNS unitarity for oscillations
- Critital that these assumptions are tested

- At atmospheric maximum, almost all muon neutrinos oscillate to tau neutrinos
- Excellent opportunity to probe:
  - Unitarity by measuring all three oscillation modes
  - Standard model cross section assumptions

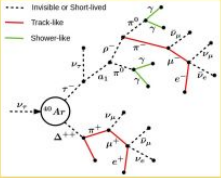


3) Tau Neutrino Challenges

τ^- Decay Mode	Branching Ratio
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-2\pi^0\nu_\tau$	9.3%
$2\pi^-\pi^+\nu_\tau$	9.3%
$2\pi^-\pi^+\pi^0\nu_\tau$	4.6%

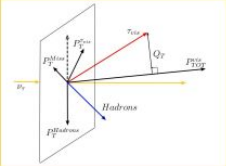
- Kinematically forbidden at typical beam energies
  - Even above threshold, still suppressed
- Tau leptons have many decay modes
  - Mimic ν_e CC, ν_μ CC, or NC events depending on decay

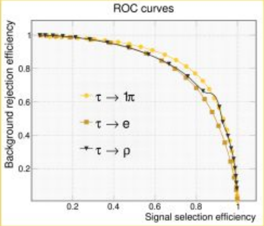
- Outgoing neutrino → missing energy
  - Worse for leptonic decay modes
- Hadronic decay modes can be complicated
  - Difficult to separate hadronic systems from tau decay and nucleus



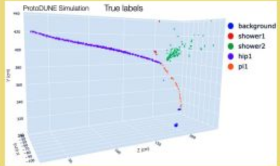
4) Selection

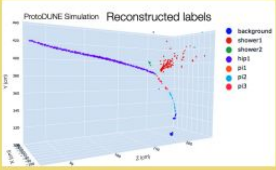
- Truth-level study of atmospheric tau neutrinos suggested excellent hadronic ν_τ/NC discrimination using simple kinematic cuts [2]
  - Optimistic assumption: near perfect e/γ and μ/π discrimination in LArTPC
  - Suggests 30% signal efficiency and 0.5% NC background efficiency possible
  - Use as a first estimate of sensitivity



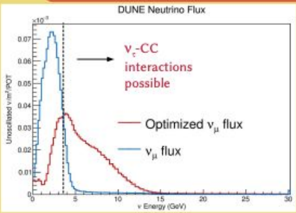


- More realistic reconstruction relies on the transverse plane kinematic approach suggested in Ref. [3]
- Can be applied to hadronic decays if the tau-lepton products can be identified
  - First attempt in Ref. [4] applied approach to $\tau \rightarrow \rho$ decays
- Investigating machine learning approaches for improved particle ID and reconstruction

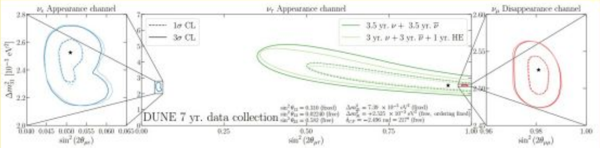




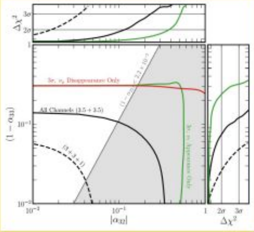
5) Long-Baseline Oscillations



- Default beam configuration peaks ~2 GeV to maximize sensitivity to CP violation
  - High energy tail is above kinematic threshold
  - Expected counts/year (1.2 MW beam)
    - ~130 ν_τ in neutrino mode
    - ~30 $\bar{\nu}_\tau$ in antineutrino mode
- Tau optimized configuration
  - Higher energy
  - Possible configuration after CP program
  - ~800 ν_τ per year

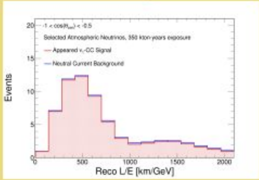


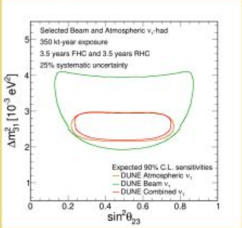
- Ref. [6] showed that DUNE can constrain normalization of 3rd PMNS column to ~5% in model independent way
  - If we assume non-unitarity is due to kinematically inaccessible sterile neutrinos, can set strong limits on α_{33}
- Tau optimized configuration is particularly useful for this



6) Atmospheric Oscillations

- Due to kinematic threshold, beam ν_τ are only detected above the atmospheric oscillation maximum
- Causes a degeneracy between Δm^2_{31} and $\sin^2\theta_{23}$
- Due to long baseline of atmospheric neutrinos, atmospheric maximum is above kinematic threshold
  - Complements beam neutrinos





- Expect ~1 ν_τ / kton-year
- Lower statistics, but clear signal at atmospheric maximum
  - Breaks degeneracy
- Interplay between atmospherics and beam important
  - Atmospherics have favorable L/E
  - Beam has defined direction and Near Detector for systematic uncertainty reduction

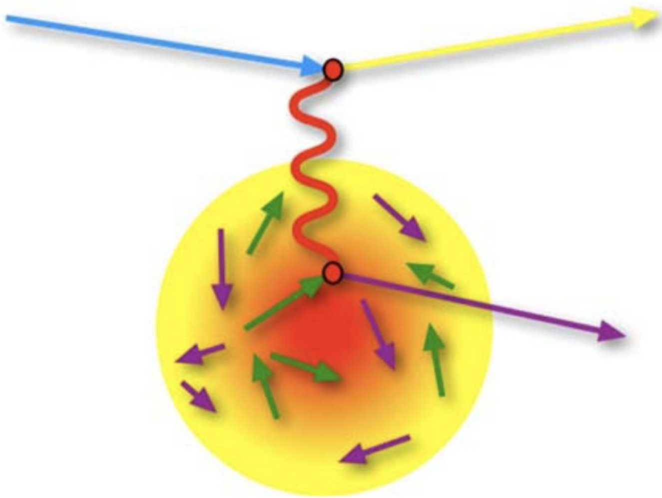
See posters:
#199 Studies of tau neutrinos appearing at the DUNE Near Detector Complex
#418 Tau Neutrino Cross Section at DUNE
for details about the tau neutrino program at DUNE

References

[1] S. Parke and M. Ross-Lonergan, Phys. Rev. D 93, 1103009 (2016)
[2] J. Conrad, A. de Gouvea, S. Shalgar, J. Spitz, Phys. Rev. D 82, 093012 (2010)
[3] C. Albright and R. Shrock, Phys. Lett. B 84, 123 (1979)
[4] T. Kosc, PhD thesis, Université de Lyon (2021)
[5] R. Mammen Abraham et al, arXiv:2202.05591
[6] A. de Gouvea, K. Kelly, G. Stenico, P. Pasquini, Phys. Rev. D 100, 016004 (2019)

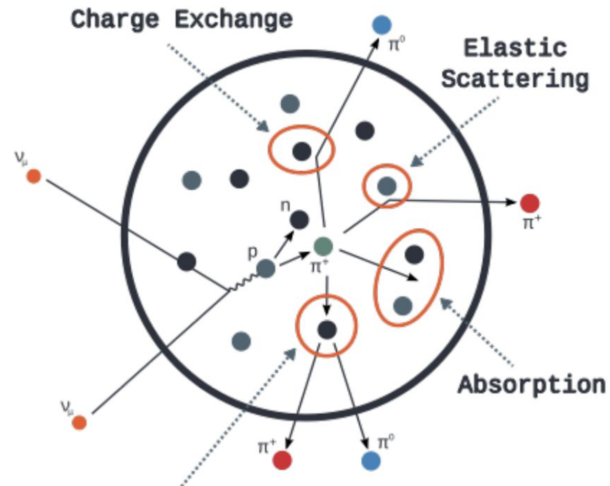
Don't Forget Nucleus! - Study Nuclear Effects

Initial State Nuclear Effect



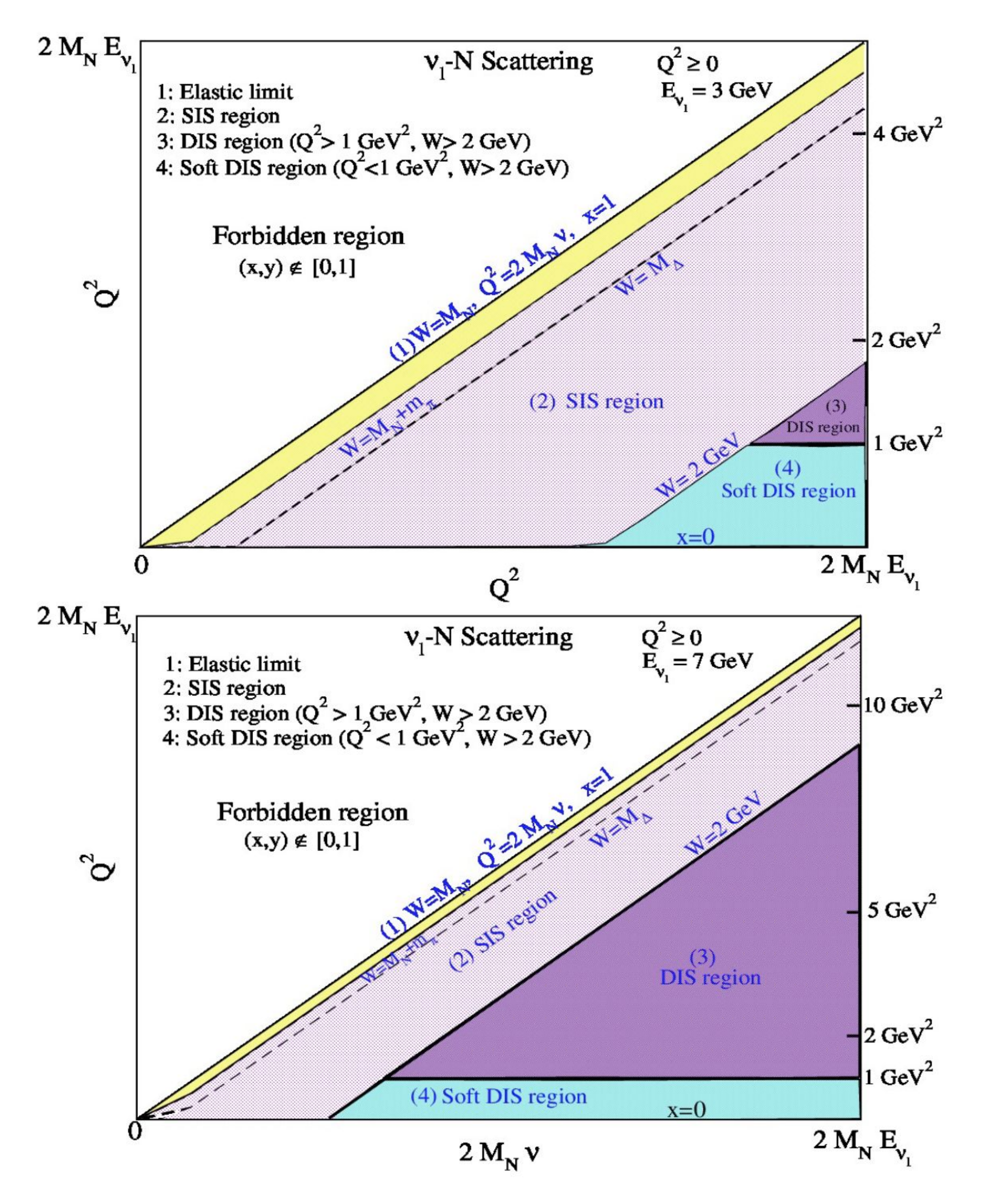
- Short, medium, and long range nucleon-nucleon correlations on the initial condition, e.g. "2p2h" effect , "RPA" effect

Final State Nuclear Effect



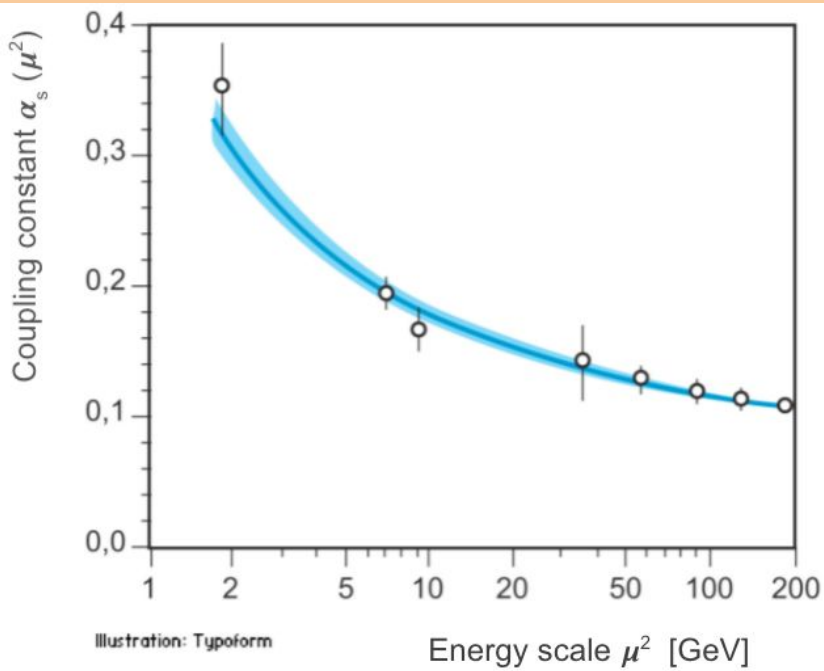
- Particles created have to work their way out of the nucleus, e.g. absorption

Signal ↔ Background Migration



ν_l-N Scattering
$Q^2 \geq 0$
$E_{\nu_l} = 3$ GeV
1: Elastic limit
2: SIS region
3: DIS region ($Q^2 > 1$ GeV^2, W > 2 GeV)
4: Soft DIS region ($Q^2 < 1$ GeV^2, W > 2 GeV)
Forbidden region
$(x,y) \notin [0,1]$
(1) $W=M_N$, $Q^2=2M_N\nu$, x=1
$W=M_\Delta$
$W=M_N+m_\pi$
(2) SIS region
(3) DIS region
W= 2 GeV
(4) Soft DIS region
x=0
4 GeV^2
2 GeV^2
1 GeV^2
$2M_N E_{\nu_l}$
0
Q^2
ν_l-N Scattering
$Q^2 \geq 0$
$E_{\nu_l} = 7$ GeV
1: Elastic limit
2: SIS region
3: DIS region ($Q^2 > 1$ GeV^2, W > 2 GeV)
4: Soft DIS region ($Q^2 < 1$ GeV^2, W > 2 GeV)
Forbidden region
$(x,y) \notin [0,1]$
(1) $W=M_N$, $Q^2=2M_N\nu$, x=1
$W=M_\Delta$
$W=M_N+m_\pi$
(2) SIS region
W=2 GeV
(3) DIS region
(4) Soft DIS region
x=0
10 GeV^2
5 GeV^2
2 GeV^2
1 GeV^2
$2M_N \nu$
$2M_N E_{\nu_l}$

Asymptotic freedom makes it possible to calculate the small distance interaction for quarks and gluons, assuming that they are free particles.



$\alpha_s\ (\mu^2)$ runs with μ^2	Factorization Theorem:	
As $\alpha_s\ (\mu^2)$ decreases, μ^2 increases	**Nonperturbative** $\mu^2 \sim 1$ GeV i.e. $\alpha_s\ (\mu^2)$ very large	**Perturbative** $\alpha_s\ (\mu^2) << 1$ if $\mu^2 >> 1\ \mathrm{GeV}^2$

How the incoming hadron is made up from the constituent quarks and gluons?

The production of any particle can be determined by the cross section.

We can use Deep (Q^2 >>M^2) Inelastic (W^2 >> M^2) Scattering to probe the structure of hadrons.

DIS experiments extract information from the lepton scattering cross sections to measure Structure Functions of the target, which are directly related to the nonperturbative Parton Distribution Functions, PDFs.

A. De Roeck, R.S. Thorne / Progress in Particle and Nuclear Physics 66 (2011) 727–781

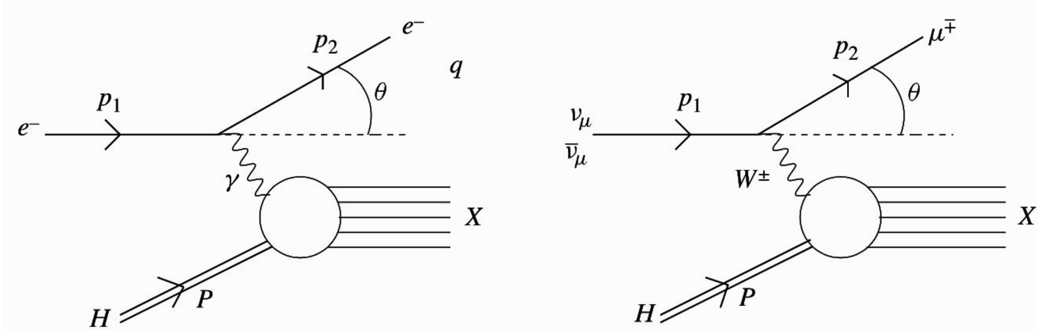


Fig. 1. The kinematics for deep inelastic scattering.

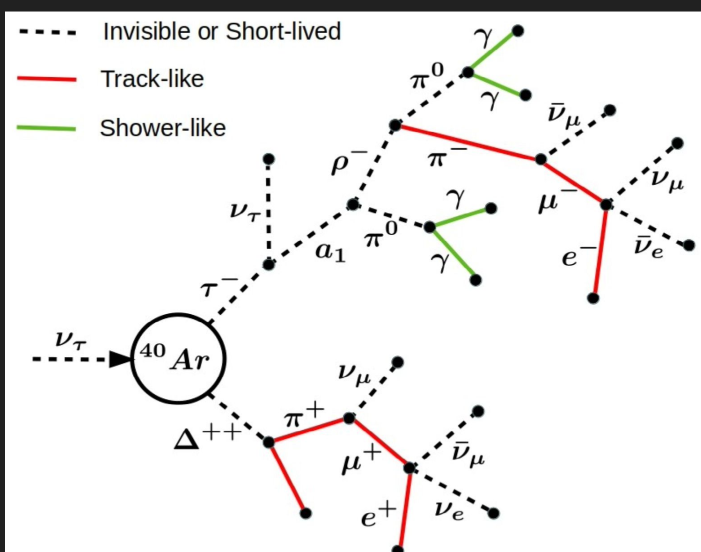
A key element in the study of tau neutrino physics is the decay modes of the tau lepton

NOTICE:

The information on the dynamics of this nuclear process should be extracted from the analysis of the energy and angular distributions of the tau decay visible products.

Therefore it is important to consider the spin polarization of taus in addition to their production cross sections. [Hernández, Nieves, Sánchez, Sobczyk]

The production of τ leptons by CC(ν_τ) - nucleus scattering requires neutrino energies $E_\nu \gtrsim 3.5$ GeV.
[PhysRevD.100.016004]



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 wire spacing of a few millimeters

↓

Observation of Tau tracks is unlikely

↓

Background for τ_μ signal mainly comes from CC-ν_μ being ν_μ flux very large.

Background for τ_e signal are CC-ν_e events, being ν_e flux a small fraction of the total neutrino flux.

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]

Inelastic Scattering: since the lepton and hadronic system do not interact after scattering, can factorize the cross-section into leptonic & hadronic tensors

$$\frac{d^2\sigma_A}{dxdy} = \left(\frac{G_F^2 y M_N E_l}{2\pi E_\nu}\right)\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{|\mathbf{k}'|}{|\mathbf{k}|} L_{\mu\nu} W_A^{\mu\nu}$$

$$L_{\mu\nu} = 8(k_\mu k'_\nu + k_\nu k'_\mu - k.k' g_{\mu\nu} \pm i\epsilon_{\mu\nu\rho\sigma} k^\rho k'^\sigma)$$

Summing over spins, and assuming parity conservation, we can write the most generic form of the hadronic tensor:

$$W_A^{\mu\nu} = \left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu}\right) W_{1A}(\nu_A, Q^2) + \frac{W_{2A}(\nu_A, Q^2)}{M_A^2}\left(p_A^\mu - \frac{p_A.q}{q^2} q^\mu\right)\left(p_A^\nu - \frac{p_A.q}{q^2} q^\nu\right) \pm \frac{i}{2M_A^2} \epsilon^{\mu\nu\rho\sigma} p_{A\rho} q_\sigma W_{3A}(\nu_A, Q^2)$$
$$+ \frac{W_{4A}(\nu_A, Q^2)}{M_A^2} q^\mu q^\nu + \frac{W_{5A}(\nu_A, Q^2)}{M_A^2}(p_A^\mu q^\nu + q^\mu p_A^\nu) + \frac{i}{M_A^2}(p_A^\mu q^\nu - q^\mu p_A^\nu) W_{6A}(\nu_A, Q^2),$$

Lorentz-invariant variables:

$$Q^2 \equiv -q^2 = -(k-k')^2 = 4EE'\sin^2(\theta/2)$$
$$\nu \equiv \frac{p\cdot q}{M} = E - E'$$

$$W^2 \equiv (p+q)^2 = M^2 + 2M\nu - Q^2$$

Structure Functions

→ A Structure function characterize the internal structure of the nucleon

→ The contributions of the structure functions to the cross-section are functions of charged lepton mass.

→ In the limit $m^2_l \to 0$ only F_1, F_2 and F_3 contribute, $m^2_l/(M_N E_\nu)$.

→ Structure functions F_4 and F_5 are negligible for ν_μ and ν_e, but become important for ν_τ

$$\frac{d^2\sigma_A}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\Big\{\Big[y^2 x + \frac{m_l^2 y}{2E_\nu M_N}\Big] F_{1A}(x,Q^2) + \Big[\Big(1-\frac{m_l^2}{4E_\nu^2}\Big) - \Big(1+\frac{M_N x}{2E_\nu}\Big) y\Big] F_{2A}(x,Q^2)$$
$$\pm \Big[xy\Big(1-\frac{y}{2}\Big) - \frac{m_l^2 y}{4E_\nu M_N}\Big] F_{3A}(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x} F_{4A}(x,Q^2) - \frac{m_l^2}{E_\nu M_N} F_{5A}(x,Q^2)\Big\}$$

The scaling variables $x(=\frac{Q^2}{2p\cdot q})$ and $y(=\frac{\nu}{E_\nu}=\frac{q_0}{E_\nu})$ lie in the range:

$$\frac{m_l^2}{2M_N(E_\nu - m_l)} \le x \le 1 \qquad \text{and} \qquad a - b \le y \le a + b,$$

where

$$a = \frac{1 - m_l^2\Big(\frac{1}{2M_N E_\nu x} + \frac{1}{2E_\nu^2}\Big)}{2\Big(1+\frac{M_N x}{2E_\nu}\Big)} \qquad \text{and} \qquad b = \frac{\sqrt{\Big(1-\frac{m_l^2}{2M_N E_\nu x}\Big)^2 - \frac{m_l^2}{E_\nu^2}}}{2\Big(1+\frac{M_N x}{2E_\nu}\Big)}.$$

For quasielastic scattering, **e.g., $\nu_\tau \to \tau p$,** the structure functions are proportional to the delta function **$\delta(W^2 - M^2)$** where W^2 is the invariant mass of the hadronic final state. These multiply the nucleon form factors ← **Avoid double counting we impose W_{min} = 1.4 GeV.** Phys. Rept. 3, 261 (1972) Phys. Lett. B 564, 42 (2003)

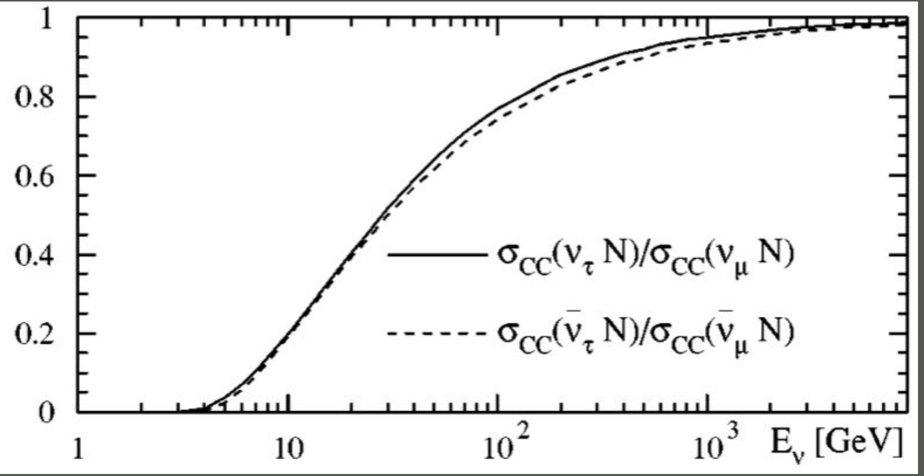
A look to the CC ν_τ and ν_μ Cross Section [M. H. Reno - PhysRevD.74.033001]

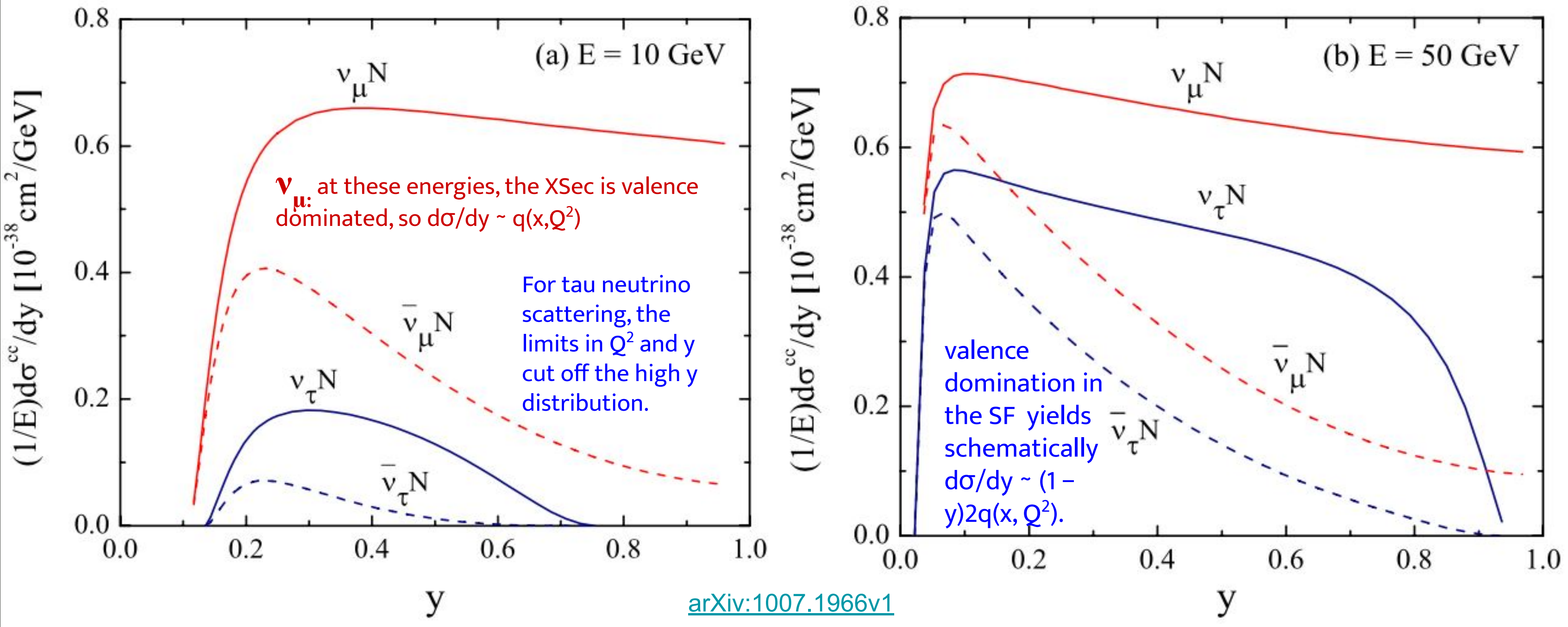
Reasons for the deficit in the ν_τ CC cross-section:

1) The **reduce phase space: integration limits (x,y)** ← dynamic origin, half of the suppression of ν_τ relative to the ν_μ

2) F_5 minu sign & no factor of x: $-\frac{m_\tau^2}{E_\nu M_N} F_5^{W^\pm}$

Since F_5 ~ F_1 ~ $q(x, Q^2)$ there is a small-x enhancement of its contribution to the cross section at high energies.





arXiv:1007.1966v1

The kinematic effects of producing a tau lepton are less noticeable.

Results/Metrics: Instance Segmentation

ProtoDUNE by Carlos Sarasty sarastce@mail.uc.edu

- **Purity:** Is the fraction of reconstructed medoids that are no more than 7 cm from the true medoid. ~ 81.3%
- **Efficiency:** Is the fraction of true particles with at least one reconstructed particle ~84.2%

Results/Metrics: Panoptic Segmentation

ProtoDUNE by Carlos Sarasty sarastce@mail.uc.edu

- **Purity:** Is the fraction of voxels in the reconstructed particles shared with the true particle. ~ 60.1%
- **Completeness:** Is the fraction of true voxels that are shared with the reconstructed particle. ~ 70.2%