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

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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 $\nu_e$ - appearance and $\nu_\mu$ - disappearance channels.

Far Detector

- 1300 Km baseline

- Liquid argon time projection chamber (LArTPC) technology → high resolution neutrino interaction imaging

- 4x17 kton LArTPC modules.
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

$\nu_\tau$ 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**

\[ \tau \] is heavy, \( \sim 1.777 \text{GeV} \)

Energy threshold \( \sim 3.5 \text{ GeV} \)

Life \( \sim 2.9 \times 10^{-13} \text{ sec} \)

Challenge: \( \nu_\tau \) reconstruction and the background rejection from NC.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio</th>
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<tbody>
<tr>
<td>Leptonic</td>
<td>35.2%</td>
</tr>
<tr>
<td>( e^- \bar{\nu}<em>e \nu</em>\tau )</td>
<td>17.8%</td>
</tr>
<tr>
<td>( \mu^- \bar{\nu}<em>\mu \nu</em>\tau )</td>
<td>17.4%</td>
</tr>
<tr>
<td>Hadronic</td>
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<tr>
<td>( \pi^- \pi^0 \nu_\tau )</td>
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<tr>
<td>( \pi^- \pi^+ \nu_\tau )</td>
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<tr>
<td>( \pi^- \pi^- \pi^0 \nu_\tau )</td>
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<tr>
<td>( \pi^- \pi^- \pi^+ \nu_\tau )</td>
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</tr>
<tr>
<td>( \pi^- \pi^- \pi^+ \pi^0 \nu_\tau )</td>
<td>4.5%</td>
</tr>
<tr>
<td>other</td>
<td>5.7%</td>
</tr>
</tbody>
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BR = 17.8\%

BR = 17.4\%

BR = 25.5\%

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

E\textsubscript{\text{v}} & 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.

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

Nuclear and hadronic effects are energy dependent too!
\[
\frac{d^2\sigma_A}{dx dy} = \frac{G_F^2 M_N E_\nu}{\pi (1 + \frac{Q^2}{M_W^2})^2} \left\{ \left[ y^2 x + \frac{m_i^2 y}{2E_\nu M_N} \right] F_{1A}(x, Q^2) + \left[ (1 - \frac{m_i^2}{4E_\nu^2}) - (1 + \frac{M_N x}{2E_\nu}) y \right] F_{2A}(x, Q^2) \right\} \\
\pm \left[ xy \left( 1 - \frac{y}{2} \right) - \frac{m_i^2 y}{4E_\nu M_N} \right] F_{3A}(x, Q^2) + \frac{m_i^2 (m_i^2 + Q^2)}{4E_\nu^2 M_N^2 x} F_{4A}(x, Q^2) - \frac{m_i^2}{E_\nu M_N} F_{5A}(x, Q^2) \right\}
\]

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

\[
\frac{m_i^2}{2M_N (E_\nu - m_i)} \leq x \leq 1 \quad \text{and} \quad a - b \leq y \leq a + b,
\]

where

\[
a = 1 - m_i^2 \left( \frac{1}{2M_N E_\nu x} + \frac{1}{2E_\nu^2} \right) \quad \text{and} \quad b = \frac{\sqrt{\left(1 - \frac{m_i^2}{2M_N E_\nu x}\right)^2 - \frac{m_i^2}{E_\nu^2}}}{2 \left(1 + \frac{M_N x}{2E_\nu}\right)}.
\]

→ A structure function (SF) characterize the internal structure of the nucleon.

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

→ In the limit \(m_i^2 \to 0\) only \(F_1, F_2, \text{and} F_3\) contribute, \(m_i^2 / (M_N E_\nu)\).

→ The structure functions \(F_4\) and \(F_5\) are negligible for \(\nu_\mu\) and \(\nu_e\), but become important for \(\nu_\tau\).

→ Albright-Jarlskog (AJ) relations occur only in heavy lepton (\(\tau\)) scattering, Nucl. Phys. B 84, 467 (1975)
Reasons for the deficit in the $\nu_\tau$ CC cross-section:

1) The **reduce phase space: integration limits** $(x,y) \leftarrow$ half of the suppression of $\nu_\tau$ relative to the $\nu_\mu$ 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 $\nu_\tau$ 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.
- 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


**Expected counts/year:**

- ~30 $\nu_\tau$ in CP-optimized neutrino mode
- ~130 $\nu_\tau$ in CP-optimized neutrino mode
- ~800 $\nu_\tau$ 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

\[
\frac{d^2 \sigma^{(v)}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi (1 + Q^2/M_W^2)^2} \left( (y^2 x + \frac{m_\tau^2 y}{2 E_\nu M}) F_1 + \left[ (1 - \frac{m_\tau^2}{4 E_\nu^2}) - (1 + \frac{M x}{2 E_\nu}) \right] F_2 \right)
\]

\[
\pm \left[ xy (1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4 E_\nu M} \right] F_3 + \frac{m_\tau^2 (m_\tau^2 + Q^2)}{4 E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5,
\]
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 $\rightarrow$ 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.

\[ \sigma_{CC}/E \left[ 10^{-38} \text{ cm}^2/\text{GeV} \right] \]

**GENIE 3.0.6 CC-NuTau Cross Section**

\[ \nu_\tau \]

**GENIE 3.0.6 CC- Anti NuTau Cross-Section**

\[ \bar{\nu}_\tau \]

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

SM Prediction

$F_4 = F_5 = 0$
CC - $\nu_\tau$ 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.
CC - $\nu_\tau$ 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.
The new features which appear in the case of the $\nu_\tau$–A interaction as compared to the $\nu_e$ and $\nu_\mu$ interactions and contribute to modify the cross sections are:

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

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

**Network Architecture**

- 2 independent UResNet for semantic and instance segmentation
- The instance segmentation prediction is obtained by finding the object medoids and regressing every voxel to their corresponding medoid
- The predicted semantic segmentation and class agnostic instance segmentation are combined to generate the final panoptic segmentation result

**arXiv:1801.00868**

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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

True labels

Reco labels
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
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](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 $E\nu$ and $Q^2$?

Because for fixed $x$ values of $F_1\ldots F_5$ become $\sim$ independent of $Q^2$, or $F_1,\ldots,5(x, Q^2)=F_1,\ldots,5(x)$ 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.

$\nu_\tau$ (CC) interactions give access to cross section physics not accessible otherwise!
1) DUNE
- DUNE is a long-baseline neutrino experiment currently under construction
- Will constrain the three flavor paradigm
- Measure $\delta_{CP}$ and mass ordering by studying $\nu_e \rightarrow \nu_x$ oscillations

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
- Critical that these assumptions are tested

3) Tau Neutrino Challenges
- Kinematically forbidden at typical beam energies
- Even above threshold, still suppressed
- Tau leptons have many decay modes
- Outgoing neutrinos - 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 $\nu/\nu C$ discrimination using simple kinematic cuts [2]
- Optimistic assumption: near perfect $e/\mu$ and $\mu/\nu$ discrimination in LATP
- Suggests 30% signal efficiency and 0.5% NC background efficiency possible
- Use as a first estimate of sensitivity

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 $\nu_\tau$ in neutrino mode
  - ~30 $\bar{\nu}_\tau$ in antineutrino mode
- Tau optimized configuration
- Higher energy
- Possible configuration after CP program ~400 $\nu_\tau$ per year

6) Atmospheric Oscillations
- Due to kinematic threshold, beam $\nu_\tau$ are only detected above the atmospheric oscillation maximum
- Causes a degeneracy between $\Delta m^2_{41}$ and $\sin^2 \theta_{23}$
- Due to long baseline of atmospheric neutrinos, atmospheric maximum is above kinematic threshold
- Complements beam neutrinos

References
Don’t Forget Nucleus! - Study Nuclear Effects

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

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

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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 \( \mu^2 \)

**Factorization Theorem:**

As \( \alpha_s(\mu^2) \) decreases, \( \mu^2 \) increases

Nonperturbative
\[ \mu^2 \sim 1 \text{ GeV} \]
i.e. \( \alpha_s(\mu^2) \) very large

Perturbative
\[ \alpha_s(\mu^2) << 1 \text{ if } \mu^2 \gg 1 \text{ GeV}^2 \]

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 (\( Q^2 \gg M^2 \)) Inelastic (\( W^2 \gg M^2 \)) 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.

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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.

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 $\tau$ leptons by CC($\nu$) - nucleus scattering requires neutrino energies $E_\nu \geq 3.5$ GeV. PhysRevD.100.016004
Inelastic Scattering: since the lepton and hadronic system do not interact after scattering, can factorize the cross-section into leptonic & hadronic tensors

\[ \frac{d^2 \sigma_A}{dx dy} = \left( \frac{G_F^2 y M_N E_1}{2\pi E_\nu} \right) \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \frac{|k'|}{|k|} L_{\mu\nu} W_{\mu\nu}^A \]

\[ L_{\mu\nu} = 8(k_\mu k'_\nu + k_\nu k'_\mu - k.k' g_{\mu\nu} \pm ie_{\mu\nu\rho\sigma} k^\rho k'^\sigma) \]

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

\[ W_{\mu\nu}^A = \left( \frac{q^\mu q^\nu}{q^2} - g^{\mu\nu} \right) W_{1A}(\nu_A, Q^2) + \frac{W_{2A}(\nu_A, Q^2)}{M_A^2} \left( p_A^\mu - p_A \cdot q q^\mu \right) \left( p'_A^\nu - p_A \cdot q q^\nu \right) \pm \frac{i}{2M_A^2} e^{\mu\nu\rho\sigma} p_A^\rho q_\sigma W_{3A}(\nu_A, Q^2) \]

\[ + \frac{W_{4A}(\nu_A, Q^2)}{M_A^2} q^\mu q^\nu + \frac{W_{5A}(\nu_A, Q^2)}{M_A^2} \left( p_A^\mu q^\nu + q^\mu p_A^\nu \right) + \frac{i}{M_A^2} \left( p_A^\mu q^\nu - q^\mu p_A^\nu \right) W_{6A}(\nu_A, Q^2) \]

Lorentz-invariant variables:

\[ Q^2 \equiv -q^2 = -(k - k')^2 = 4EE' \sin^2(\theta/2) \]

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

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 \( m_1^2 \to 0 \) only \( F_1, F_2 \) and \( F_3 \) contribute, \( m_1^2 / (M_N E_\nu) \).

→ Structure functions \( F_4 \) and \( F_5 \) are negligible for \( \nu_\mu \) and \( \nu_e \), but become important for \( \nu_\tau \).

For quasielastic scattering, e.g., \( \nu \to \tau p \), 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 \( W_{\min} = 1.4 \text{ GeV} \). Phys. Rept. 3, 261 (1972) Phys. Lett. B 564, 42 (2003)
A look to the CC $\nu_\tau$ and $\nu_\mu$ Cross Section

M. H. Reno - PhysRevD.74.033001

Barbara Yaeggy - University of Cincinnati

Reasons for the deficit in the $\nu_\tau$ CC cross-section:

1) The reduce phase space: integration limits $(x,y)$ ← dynamic origin, half of the suppression of $\nu_\tau$ relative to the $\nu_\mu$

2) $F_5$ minu sign & no factor of $x$:

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

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%