Neutrino Interactions in the GeV Regime

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By NASA/Chris Hadfield
Neutrino Interactions in the GeV Regime

Outline

• Neutrino Oscillations
  – An identity-changing game – Underlying math – Seeing is believing
• Oscillation Measurements
  – Accelerator-based neutrino experiments – #measured \( \nu \) / #produced \( \nu \)
    – Beam flux, \( \nu \) and \( \bar{\nu} \) interactions
      – \( \nu \) and \( \bar{\nu} \) interactions – Impact of \( \nu \) and \( \bar{\nu} \) interactions
• Interaction Measurements
  – MINERvA
    – Inclusive 'low-recoil' analysis – Inclusive to exclusive
• Exclusive Measurements
  – Why particle spectra won't work
• Transverse Kinematic Imbalance (TKI)
  – Principle – Analysis – Future experiments – The very idea
    – Initial-state kinematics – Neutron initial-state kinematics – Proton initial-state kinematics
• Neutrino-Hydrogen Interactions
  – Review – The very idea – Perspective
Physics Beyond Standard Model
via
Neutrino Oscillations

Neutrinos have mass
Neutrino Oscillations
– An identity-changing game

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Neutrino Oscillations
– An identity-changing game

https://www.lego.com

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Neutrino Oscillations
– An identity-changing game

oscillation between flavor states as a function of \textit{time} \sim \text{distance/energy}

Only 2 flavors, same oscillation behavior
Neutrino Oscillations
– An identity-changing game

*3-flavor paradigm

oscillation between flavor states as a function of *time* ~distance/energy

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Neutrino Oscillations
– An identity-changing game

Oscillation property difference
→ CP-Symmetry violation (CP violation)
Neutrino Oscillations
– Underlying math

Neutrino oscillations depend on mixing parameters and mass differences.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \text{Pontecorvo–Maki–Nakagawa–Sakata PMNS matrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- What is the absolute neutrino mass?
- Why is this mass so small?
- How is the different mass ordered?
- Are there more than 3 types of neutrino?
Neutrino Oscillations
– Underlying math

Neutrino oscillations depend on mixing parameters and mass differences.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\theta_{13} \neq 0 \rightarrow \delta_{\text{CP}} \text{ can be observed}\]

PMNS matrix

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Neutrino Oscillations
– Underlying math

Neutrino oscillations depend on mixing parameters and mass differences.

$$c_{ij} = \cos \theta_{ij}$$
$$s_{ij} = \sin \theta_{ij}$$

$$\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}$$

$$\theta_{13} \neq 0 \rightarrow \delta_{CP}$$ can be observed

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$
$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

With a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left( \sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

CP-odd term

* neglecting matter effects
Neutrino Oscillations
– Underlying math

Neutrino oscillations depend on mixing parameters and mass differences.

\[
\begin{pmatrix}
    c_{ij} = \cos \theta_{ij} \\
    s_{ij} = \sin \theta_{ij}
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\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

\[\theta_{13} \neq 0 \rightarrow \delta_{CP} \text{ can be observed}\]

With a \(\bar{\nu}_\mu\) beam

\[P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left( \sin^2 \theta_{23} \rightarrow \sin^2 \left( \frac{2\theta_{12}\sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right) \right)\]

\[\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}\]

\[\Delta m^2_{ij} \equiv m^2_i - m^2_j\]

\(\delta_{CP} \rightarrow \text{CP violation}\)

* neglecting matter effects
Neutrino Oscillations – Seeing is believing

Charge–Parity symmetry Violation (CPV)?

Matter

Antimatter

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Neutrino Oscillations
– Seeing is believing

Charge–Parity symmetry Violation (CPV)?

\[ \nu_\mu \rightarrow \nu_e \quad \neq \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad \text{CPV} \]
Neutrino Oscillations
– Seeing is believing

Time trajectory in probability space

No CPV

Time: 60.0 ms
Distance: 18000 km
Energy: 0.6 GeV

\[ \nu \delta_{\text{CP}}=0 \]
\[ \bar{\nu} \delta_{\text{CP}}=0 \]

CPV

Time: 60.0 ms
Distance: 18000 km
Energy: 0.6 GeV

\[ \nu \delta_{\text{CP}}=-1.740 \]
\[ \bar{\nu} \delta_{\text{CP}}=-1.740 \]
Oscillation Measurements
– Accelerator-based neutrino experiments

Nuclear β decay
MeV regime

ν beam: “β decay” of highly boosted collision products
GeV regime

* also the cross section is larger at GeV
Oscillation Measurements – Accelerator-based neutrino experiments

Super-Kamiokande (ICRR, Univ. Tokyo)

T2K

J-PARC Main Ring (KEK-JAEA, Tokai)

DUNE (from 2026)

ν and $\bar{\nu}$ beams

Sanford Underground Research Facility

Fermilab

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Oscillation Measurements
– #measured $\nu$ / #produced $\bar{\nu}$

# measured $\nu$ and $\bar{\nu}$: energy, event count
# produced $\nu$ and $\bar{\nu}$: beam flux, interaction rate

DUNE (from 2026)
Oscillation Measurements
– Beam flux, $\nu$ and $\bar{\nu}$ interactions

Near Detectors @280m

DUNE (from 2026)
**Oscillation Measurements**

– *Beam flux, \( \nu \) and \( \bar{\nu} \) interactions*

- **Now@T2K:**
  
  \[ \text{flux (9\%) + interaction (15\%)} \rightarrow 8\% \text{ after Near Detector constraint} \]
- Target CP violation sensitivity requires total sys. uncertainty < 1-2%
- Neutrino interactions, if not understood, would be **fatal**
Oscillation Measurements
– $\nu$ and $\bar{\nu}$ interactions

Intrinsic difference in $\nu$ and $\bar{\nu}$ event rates without CPV

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Oscillation Measurements

– $\nu$ and $\bar{\nu}$ interactions

Nuclear effects like “2p2h” make it worse

**Nuclear effects**: all effects due to target $A>1$
Proton and neutron have VERY different experimental signatures

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Oscillation Measurements
– $\nu$ and $\bar{\nu}$ interactions

higher event rates

more complicated interactions

- Ar
- DUNE
- T2K Far Detector ($H_2O$)
- T2K Near Detector (CH)
- Simplest interaction

- O
- C
- He
- H

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**Oscillation Measurements**

– Impact of $\nu$ and $\bar{\nu}$ interactions

Difference in mass states

Mixing between $\mu$ and $\tau$ flavors

$\sin^2 \theta_{23} = \begin{cases} 0.4 & 0.5 & 0.6 \\ \nu_e = & \text{blue} & \nu_\mu = & \text{green} & \nu_\tau = & \text{red} \end{cases}$

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Oscillation Measurements

– Impact of $\nu$ and $\bar{\nu}$ interactions

Mock measurement ignoring nuclear effects of interactions

Mixing between $\mu$ and $\tau$ flavors

$\nu_3$

$\sin^2 \theta_{23} = 0.4 \quad 0.5 \quad 0.6$

$\nu_e = \bullet \quad \nu_\mu = \circ \quad \nu_\tau = \bigcirc$


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arXiv:1801.09643
Interaction Measurements
– MINERvA

Only dedicated experiment for $\nu$ and $\bar{\nu}$ interactions currently running

Various targets: He, CH, O, Fe, Pb
Interaction Measurements – MINERvA

Scintillator tracker:
Hydrocarbon (CH) target
Homogeneous non-magnetized active tracker

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Interaction Measurements – MINERvA

Quasi-elastic

Resonant pion

Deep inelastic

QE

RES

DIS

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Quasi-elastic

Resonant pion

Deep inelastic

NuMI low energy beam $<E_v> \sim 3$ GeV

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Homogeneous non-magnetized active tracker
→ same as LAr detector
What do we do with such great detail in final states?
Interaction Measurements
– Inclusive 'low-recoil' analysis
**Interaction Measurements**

– Inclusive 'low-recoil' analysis

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Available energy as energy transfer ($q_0$) proxy

$$E_{av} = \sum T_p + \sum T_{\pi\pm} + \sum E_{K\pm} + \sum E_{e\pm} + \sum E_{\pi^0} + \sum E_\gamma$$

~ single proton kinetic energy spectrum in QE

~ $\pi(+p)$ kinetic energy spectrum in RES
Base Model  (GENIE + pion reweight + RPA + 2p2h)

Neutrino, 3.33e20 LE-beam POT, MINERvA Preliminary

Anti-Neutrino, 1.02e20 LE-beam POT, MINERvA Preliminary

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Base Model + Neutrino Tune = MnvGENIE-v1

- Neutrino tune
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  \( G: 2D \) Gaussian\((q_0, q_3)\) determined in fit to neutrino data
- Empirical modification to 2p2h

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Base Model + Neutrino Tune = MnvGENIE-v1

- Apply neutrino tune directly to anti-neutrino
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  \( G \): 2D Gaussian(q0, q3) determined in fit to neutrino data
- *Empirical* modification to 2p2h

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Interaction Measurements
– Inclusive to exclusive

ν inclusive measurements
→ 2p2h tune

ν quasi-elastic-like interactions

μ– Proton below tracking threshold


Not to cover in this talk

ν quasi-elastic-like interactions

p Proton above tracking threshold

[MINERvA, Phys.Rev.Lett. 121, 022504 (2018)]
Exclusive Measurements
– Why particle spectra won't work

Problematic “lasagna” region:

Resonance production with pion absorbed in nucleus
Proton gain & lose energy in nucleus
True quasi-elastic

Why can't we tell what is wrong?
➢ Without nuclear effects, spectra still depend on
  • flux
  • nucleon-level physics
Exclusive Measurements
– Why particle spectra won’t work

Problematic “lasagna” region:

Resonance production with pion absorbed in nucleus
Proton gain & lose energy in nucleus
True quasi-elastic

MINERvA Preliminary
- GENIE No-FSI
- GENIE Nominal
- p-FSI Non-interacting
- p-FSI Acceleration
- p-FSI Deceleration
- π-FSI Absorption
- MnvGENIE-v1
- Data

MINERvA
PRL, 121, 022504 (2018)

Nuclear effects
Flux
Nucleon-level physics

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Transverse Kinematic Imbalance (TKI) – Principle

Neutrino Shadow Play


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Transverse Kinematic Imbalance (TKI) – Principle

Neutrino Shadow Play

Xianguo Lu, Oxford

**Transverse Kinematic Imbalance (TKI)**

– **Principle**

Details can be found in:

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**Single-TKI:** Interaction diagnostics

**Double-TKI:**
Select no-nuclear-effect events
ν-H out of ν-C

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Neutrino Shadow Play


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Transverse Kinematic Imbalance (TKI) – Analysis

Experimental measurements on single-TKI:

**Transverse Kinematic Imbalance (TKI)**

– Future experiments

**Single-TKI:** Interaction diagnostics

**Double-TKI:** Select $\nu$-H events

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T2K Upgrade Technical Design Report

Current T2K & MINERvA

arXiv:1901.03750
Transverse Kinematic Imbalance (TKI) – The very idea
Transverse Kinematic Imbalance (TKI) – The very idea
Transverse Kinematic Imbalance (TKI) – The very idea
Transverse Kinematic Imbalance (TKI)
– The very idea

Stationary nucleon target
Transverse Kinematic Imbalance (TKI)
– The very idea

Still back-to-back after changing:
• Flux
• Nucleon structure (form factors)
• Feynman diagram

Stationary nucleon target
Transverse Kinematic Imbalance (TKI) – The very idea

Imbalances **NOT** due to
- Flux
- Nucleon structure (form factors)
- Feynman diagram

But
- Fermi motion
- Final-state interaction (FSI)
- 2p2h
Transverse Kinematic Imbalance (TKI) – The very idea

\[ \delta \vec{p}_T = \vec{p}_T^N - \Delta \vec{p}_T \]

- Fermi motion
- final-state interaction (FSI)
- 2p2h

Stationary nucleon target

Nuclear target (A>1)

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Transverse Kinematic Imbalance (TKI)
– The very idea

\[ \delta \vec{p}_{T} = \vec{p}_{T}^{N} - \Delta \vec{p}_{T} \]

- Fermi motion
- final-state interaction (FSI)
- 2p2h

Dijet imbalance / Jet quenching

\[ \delta \vec{p}_{T} = p_{T}^{\ell'} + p_{T}^{N'} \]

Nuclear target (A>1)
Transverse Kinematic Imbalance (TKI) – Initial-state kinematics

The initial-state kinematics of the interaction depend on:
1. Fermi motion of struck nucleon (*static*)
2. Coupling of $W^{+/−}$ to neutron/proton – Fermi-motion dependent weighting (*dynamic*)

1. → could be determined by electron scattering (target specific)
2. → needs neutrinos

→ **How to measure initial state *in situ* in neutrino scattering?**
Transverse Kinematic Imbalance (TKI) – Initial-state kinematics

\[ \delta \vec{p}_T = \vec{p}_T^N \]

\[ \delta p_T \text{ is Fermi motion transverse projection} \]
Transverse Kinematic Imbalance (TKI) – Initial-state kinematics

Initial nucleon = neutron

$\vec{p}_T^N \rightarrow \vec{p}_T^{\mu}$

$\vec{q}_T = -\vec{p}_T^{\mu}$

$\delta \phi_T$, $\delta \vec{p}_T$, $\delta \alpha_T$

$N' = \text{proton}$

$\muon$

Single-TKI

Transverse projection of Fermi motion
Transverse Kinematic Imbalance (TKI) – Initial-state kinematics

We only start to learn about Fermi motion in neutrino interactions...

Transverse projection of Fermi motion
Transverse Kinematic Imbalance (TKI) – Neutron initial-state kinematics

Still back-to-back after changing:
- Flux
- Nucleon structure (form factors)
- Feynman diagram

Stationary nucleon target

Initial nucleon = neutron only for ν scattering

N' = proton
Transverse Kinematic Imbalance (TKI) – Proton initial-state kinematics

- Flow
- Nucleon structure (form factors)
- Feynman diagram: Large uncertainty

\[ N' = p + \pi^{+/0} \]

Initial nucleon = proton for both v and \( \bar{v} \) scattering

Still back-to-back after changing:
- Flux
- Nucleon structure (form factors)
- Feynman diagram: Large uncertainty

### Transverse Kinematic Imbalance (TKI)

- **Proton initial-state kinematics**

\[
\nu 0 \pi N p : \nu A \rightarrow \ell^- p X
\]

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Quasi-elastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu(n) \rightarrow \ell^- p)</td>
<td></td>
</tr>
<tr>
<td>Resonant production</td>
<td>Resonant production</td>
</tr>
<tr>
<td>(\nu(p) \rightarrow \ell^- \Delta^{++} \rightarrow \ell^- p \pi^+)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antineutrino</th>
<th>Quasi-elastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>not applicable.</td>
<td></td>
</tr>
<tr>
<td>Resonant production</td>
<td>Resonant production</td>
</tr>
<tr>
<td>(\bar{\nu}(p) \rightarrow \ell^+ \Delta^0 \rightarrow \ell^+ p \pi^-)</td>
<td></td>
</tr>
</tbody>
</table>

**neutrino**

**antineutrino**

- Neutron Fermi motion can be probed by QE, but only in neutrino scattering.
- Proton Fermi motion in RES with both neutrino and antineutrino → *direct comparison of dynamic aspect of initial state, to remove possible confusion with CPV!*
Proton Fermi motion seen by $\nu$

GiBUU and NuWro have very different predictions for MINERvA

Also very different Fermi motion peaks in $\nu$ and $\overline{\nu}$

Measurements on-going...Stay tuned!
Neutrino Interactions in the GeV Regime

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  – An identity-changing game – Underlying math – Seeing is believing
  • Oscillation Measurements
    – Accelerator-based neutrino experiments – \#measured ν / \#produced ν
      – Beam flux, ν and \bar{ν} interactions
        – ν and \bar{ν} interactions – Impact of ν and \bar{ν} interactions

• Interaction Measurements
  – MINERvA
    – Inclusive 'low-recoil' analysis – Inclusive to exclusive
      • Exclusive Measurements
        – Why particle spectra won’t work

• Transverse Kinematic Imbalance (TKI)
  – Principle – Analysis – Future experiments – The very idea
    – Initial-state kinematics – Neutron in initial-state, \( P_{\text{He}} \) in initial-state kinematics

• Neutrino-Hydrogen Interactions
  – Review – The very idea – Perspective
Neutrino-Hydrogen Interactions
– Review

• Pure hydrogen
  – Technical requirement: bubble chamber (historical: 73, 79, 78, 82, 86)
  – Safety issue: explosive
    • Due to buoyancy, more dangerous for underground experiments
• Neutrino interactions on hydrogen:
  – In the last ~30 years there has been no new measurement
  – No nuclear effects → much desired for flux constraint and nucleon cross section input for oscillation analysis
  – Nucleon structure → new frontier of hadron physics

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Neutrino-Hydrogen Interactions
– The very idea

\[
l\ p \text{ interaction} \rightarrow 3 \text{ charged particles:}
\]
\[
l\ p \rightarrow l' \ X \ Y
\]

XL, JPS Conf. Proc. 12, 010034 (2016)]
Neutrino-Hydrogen Interactions
– The very idea

\{X, Y\}
= \{p, \pi^+\} \text{ for } \nu + p \to \ell^- + \Delta^{++}
or \{p, \pi^-\} \text{ for } \bar{\nu} + p \to \ell^+ + \Delta^0

$p\nu/\bar{\nu}$
$p_{\ell^\pm}$
$p_X$
$p_Y$

$l\ p\ interaction \to\ 3\ charged\ particles:
\begin{align*}
\nu + p & \to \ell^- + \Delta^{++} \\
\bar{\nu} + p & \to \ell^+ + \Delta^0
\end{align*}

XL, JPS Conf. Proc. 12, 010034 (2016)]
Neutrino-Hydrogen Interactions – The very idea

\{X, Y\}
= \{p, \pi^+\} for ν + p → ℓ⁻ + Δ^{++}
or \{p, \pi^-\} for ν̄ + p → ℓ^+ + Δ^0

\[ l \ p \rightarrow 3 \text{ charged particles:} \]
\[ l \ p \rightarrow ℓ' \ X \ Y \]

XL, JPS Conf. Proc. 12, 010034 (2016)]
Neutrino-Hydrogen Interactions
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\[ l \ p \ interaction \rightarrow 3 \ charged \ particles:\]
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Neutrino-Hydrogen Interactions
– The very idea

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\[ l \ p \ interaction \to 3 \ charged \ particles: \]
\[ l \ p \to l' \ X \ Y \]

XL, JPS Conf. Proc. 12, 010034 (2016)]
Double-transverse momentum imbalance $\delta p_{TT}$

- H: 0
- Heavier nuclei: irreducible symmetric broadening
  - by Fermi motion $O(200$ MeV$)$ and FSI
- CH: $\nu H$ interaction can be extracted
  - $\nu H$ $\delta p_{TT} \sim O(<10$MeV$)$ after detector smearing
  - $\nu C$ $\delta p_{TT} \sim 200$ MeV
Toy simulation of T2K performance (T2K neutrino flux on CH target)
➢ Realistic detector resolution as T2K gas TPC (∼10% at 1 GeV/c)

- When tracking resolution improves, only signal distribution gets narrower, background still wide due to Fermi motion and FSI! → Signal/background improves

Measurements on-going...Stay tuned!
Neutrino-Hydrogen Interactions – Perspective

- State-of-the-art tracking resolution in gas TPC
  ALICE TPC (~1% at 1 GeV/c)

- DUNE Near Detector
  High Pressure gas TPC can achieve 95% vH purity with
  50% He + 50% CH$_4$
  or
  50% He + 50% C$_2$H$_6$
Summary

1) Neutrino interaction allows measurements of oscillations
   ➢ profound questions of the existence of cosmos
   ➢ Nuclear effects, if not well understood, will forbid such measurements.

2) Neutrino interaction measurements: inclusive 'low-recoil' analysis and
   Transverse Kinematic Imbalances (TKI)
   ➢ $\nu$-fit 2p2h-like enhancement directly applicable to $\bar{\nu}$
   ➢ TKI cancel nucleon-level baseline physics, remove beam energy
     dependence, reveal various nature of nuclear effects

3) Neutrino interaction on hydrogen needed for flux constraint and nucleon
   cross section input for oscillation analysis.
   ➢ TKI ($\delta_{TT}$) provides safe access to $\nu$H interaction.
   ➢ DUNE Near Detector HPgTPC with $\delta_{TT}$ can achieve 95% purity with
     careful choice of gas mixture.
Summary

1) Neutrino interaction allows measurements of oscillations
   • profound questions of the existence of cosmos
   • Nuclear effects, if not well understood, will forbid such measurements.

2) Neutrino interaction measurements: inclusive 'low-recoil' analysis and Transverse Kinematic Imbalances (TKI)
   • $\nu$-fit 2p2h-like enhancement directly applicable to $\bar{\nu}$
   • TKI cancel nucleon-level baseline physics, remove beam energy dependence, reveal various nature of nuclear effects

3) Neutrino interaction on hydrogen needed for flux constraint and nucleon cross section input for oscillation analysis.
   • TKI ($\delta p_{TT}$) provides safe access to $\nu$H interaction.
   • DUNE Near Detector HPgTPC with $\delta p_{TT}$ can achieve 95% purity with careful choice of gas mixture.
BACKUP
Low-Recoil Tune / 2p2h-like enhancement

[MINERvA, manuscript in preparation]

Enhance Valencia 2p2h cross section as a function of (q0, q3)
Low-Recoil Tune / 2p2h-like enhancement

[MINERvA, manuscript in preparation]

- Weight on 2p2h:
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  G: 2D Gaussian(q0, q3)
- Variations of weighted components (pp/nn, pn, or QE) as systematic uncertainties

- Weight up by 50% overall
- 2 × in dip
GiBUU models 2p2h events with weight \((T+1)\), where \(T\) is nuclear isospin parameter.

2p2h in two model settings (\(T=0\) and 1) at two different energies (0.6 and 3 GeV) all start at \(\delta\alpha_T \rightarrow 0\) and then evolve towards \(\delta\alpha_T \rightarrow 180^\circ\) with strong energy dependence.

Gross feature of energy dependence confirmed by data; contradiction between preference on \(T\) at different energies indicates sub-leading order mis-modeling.
A more general analysis of kinematic imbalance

Transverse: \[ 0 = \vec{p}_{T} + \vec{p}_{N'} - \delta \vec{p}_{T} \]

Longitudinal: \[ E_{\nu} = p_{L} + p_{N'} - \delta p_{L} \]

New variable: \[ p_{n} = \sqrt{\delta p_{T}^{2} + \delta p_{L}^{2}} \]

[For Furmanski, Sobczyk, Phys. Rev. C95 (2017) 065501]

Neutrino energy is unknown (in the first place), equations are not closed.

Assuming exclusive $\mu$-p-A' final states

Use energy conservation to close the equations

\[ E_{\nu} + m_{A} = E_{\ell'} + E_{N'} + E_{A'} \]

\[ E_{A'} = \sqrt{m_{A'}^{2} + p_{n}^{2}} \]

\( p_{n} \): recoil momentum of the nuclear remnant

Dual Interpretation

For CCQE, A' = $^{11}$C*

No more unknowns

\( p_{n} \): neutron Fermi motion

Xianguo Lu, Oxford
Only differ by longitudinal momentum imbalance

\[ \delta p_T \rightarrow p_n \]

Single-TKI + \( p_n \) = **Final-State Correlations**


\[ \delta p_T = p_T^N - \Delta p_T \]

\[ p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2} \]

Only differ by longitudinal momentum imbalance

\( p_n \) has better physics sensitivity: 3D Fermi momentum
Global Fermi Gas with Bodek-Ritchie tail

Local Fermi Gas

Spectral Function

- Base Model depends on 1p1h and Short Range Correlation (SRC) modeling
- Critical to separate QE and RES to reduce Base-Model-dependence
END