Measurement of Neutrino-Hydrogen Interactions in a Straw Tube Tracker for the DUNE ND

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PONDD, Fermilab Dec 03 2018
Why Hydrogen?

\[ N(E_{rec}) = \int_{E_{\nu}} dE_{\nu} \Phi(E_{\nu}) \Omega(E_{\nu}) \sigma(E_{\nu}) R_{det}(E_{\nu}, E_{rec}) \]

Number of events observed in the detector

Neutrino flux

Oscillation probability

Detector response

Cross section
Why Hydrogen?

\[ N(E_{rec}) = \int_{E_{\nu}} dE_{\nu} \Phi(E_{\nu}) P_{osc}(E_{\nu}) \sigma(E_{\nu}) R_{det}(E_{\nu}, E_{rec}) \]

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Modern neutrino experiments use heavy nuclear targets for statistics. For example, Ar in DUNE.
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\[ N(E_{rec}) = \int_{E_{\nu}} dE_{\nu} \Phi(E_{\nu}) P_{osc}(E_{\nu}) \sigma(E_{\nu}) R_{det}(E_{vis}, E_{rec}) \]

- Modern neutrino experiments use heavy nuclear targets for statistics. For example, Ar in DUNE.
Why Hydrogen?

\[
N(E_{rec}) = \int_{E_{v}} dE_{v} \Phi(E_{v}) P_{osc}(E_{v}) \sigma(E_{v}) R_{det}(E_{rec}, E_{v})
\]

- Modern neutrino experiments use heavy nuclear targets for statistics. For example, Ar in DUNE.
- Nuclear effects (Fermi motion, nucleon-nucleon correlations, final state interactions etc.) are important:
  - Energy reconstruction
  - Flux and other measurements

\[
\sigma_{\nu-N} \times R_{NuclearEffects}(E_{\nu}, E_{vis})
\]
Neutrino Energy Reconstruction

- Nuclear smearing of neutrino energy in Ar is large.
- Rely upon MC to do the correction is model-dependent.
Why Hydrogen?

\[
N(E_{\text{rec}}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) P_{\text{osc}}(E_\nu) \sigma(E_\nu) R_{\text{det}}(E_{\text{rec}}, E_\nu)
\]

- Number of events observed in the detector
- Neutrino flux
- Oscillation probability
- Detector response

\[
\sigma_{\nu-N} \times R_{\text{NuclearEffects}}(E_\nu, E_{\text{rec}})
\]

- Neutrino-Hydrogen measurements will provide:
  - Measurements free from nuclear effects:
    - Neutrino energy scale.
    - Neutrino flux.
  - Disentangle nuclear effects from others.
  - Measurement of neutrino-hydrogen interactions is also important to cross-section physics.
A “Hydrogen Detector” at DUNE ND?

\[ N(E_{\text{rec}}) = \int_{E_{\nu}} dE_{\nu} \Phi(E_{\nu}) P_{\text{osc}}(E_{\nu}) \sigma(E_{\nu}) R_{\text{det}}(E_{\text{rec}}, E_{\nu}) \]

- Number of events observed in the detector
- Neutrino flux
- Oscillation probability
- Detector response

\[ \sigma_{\nu-N} \times R_{\text{NuclearEffects}}(E_{\nu}, E_{\text{rec}}) \]

- We don’t have many neutrino-hydrogen datas:
  - Early bubble chamber datas suffer from low-statistics.
  - No such experiments for ~30 years.
- Neutrino-hydrogen measurements for DUNE should:
  - Be exposed to same flux
  - Have as similar as possible detector response with nuclear targets (Ar).
- A pure hydrogen detector (liquid or gas) with large mass causes safety concerns.
  - Can also be expensive.
Measurement of Neutrino-Hydrogen in STT

Possible external target

Ar (gas)
C
(C₃H₆)ₙ

Roberto Petti
USC 09
Multiple nuclear targets in FGT: (C\textsubscript{3}H\textsubscript{6})\textsubscript{n} radiators, C, Ar gas, Ca, Fe, etc.

Separation from excellent vertex (\sim 100 \mu m) and angular (< 2 mrad) resolutions

Subtraction of C TARGET from polypropylene (C\textsubscript{3}H\textsubscript{6})\textsubscript{n} RADIATORS provides neutrino AND anti-neutrino interactions on free proton target

Absolute $\bar{\nu}_\mu$ flux from QE

Model-independent measurement of nuclear effects and FSI from RATIOS A/H

Pressurized Ar GAS target (\sim 140 atm) inside C tubes and solid Ca TARGET (more compact & effective) provide detailed understanding of the FD A=40 target

Collect more than $\times 10^6$ unoscillated FD statistics on Ar target

Study of flavor dependence & isospin physics

Measurement of Neutrino-Hydrogen in STT

Radiator (CH\textsubscript{2}) provides most of the detector mass with abundant hydrogen
Multiple nuclear targets in FGT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, etc.

Separation from excellent vertex (∼100 µm) and angular (<2 mrad) resolutions

Subtraction of C target from polypropylene $(C_3H_6)_n$ radiators provides neutrino and anti-neutrino interactions on free proton target

Absolute $\bar{\nu}$ flux from QE

Model-independent measurement of nuclear effects and FSI from ratios A/H

Pressurized Ar gas target (∼140 atm) inside C tubes and solid Ca target (more compact & effective) provide detailed understanding of the FD $A=40$ target

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Roberto Petti

Measurement of Neutrino-Hydrogen in STT

Dedicated carbon (graphite) target to measure carbon background

Radiator (CH2) provides most of the detector mass with abundant hydrogen
Possible external target

Radiation targets in FGT:

- (C\textsubscript{3}H\textsubscript{6})\textsubscript{n} radiators, C, Ar gas, Ca, Fe, etc.

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Measurement of Neutrino-Hydrogen in STT

Dedicated carbon (graphite) target to measure carbon background

Subtraction of C from CH\textsubscript{2} provides hydrogen (free proton) target

Radiator (CH\textsubscript{2}) provides most of the detector mass with abundant hydrogen
Measurement of Neutrino-Hydrogen in STT

Possible external target

Ar (gas) C (C₃H₆)ₙ

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Dedicated carbon (graphite) target to measure carbon background

Ar and other nuclear targets provide understanding of the nuclear effects

Subtraction of C from CH₂ provides hydrogen (free proton) target
Possible external target

Ar (gas) → C → (C₃H₆)n

**Radiator (CH2)** provides most of the detector mass with abundant hydrogen

Dedicated carbon (graphite) target to measure carbon background

**Ar** and other nuclear targets provide understanding of the nuclear effects

Subtraction of C from CH2 provides hydrogen (free proton) target

Statistics

- Assuming 5-ton radiator (CH2) mass

<table>
<thead>
<tr>
<th>Process</th>
<th>CP optimized beam</th>
<th>ντ optimized beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FHC 1.2MW, 5y</td>
<td>RHC 1.2MW, 5y</td>
</tr>
<tr>
<td>νμ CC on CH₂</td>
<td>34,300,000</td>
<td>5,500,000</td>
</tr>
<tr>
<td>¯νμ CC on CH₂</td>
<td>1,680,000</td>
<td>13,100,000</td>
</tr>
<tr>
<td>νe CC on CH₂</td>
<td>508,000</td>
<td>242,000</td>
</tr>
<tr>
<td>¯νe CC on CH₂</td>
<td>85,700</td>
<td>187,000</td>
</tr>
<tr>
<td>νμ CC on H</td>
<td>3,360,000</td>
<td>542,000</td>
</tr>
<tr>
<td>¯νμ CC on H</td>
<td>308,000</td>
<td>2,490,000</td>
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<tr>
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<td>49,700</td>
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</tr>
<tr>
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<td>15,400</td>
<td>34,400</td>
</tr>
<tr>
<td>ντ CC on CH₂</td>
<td>65,570,000</td>
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<td>ντ CC on H</td>
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<td>ντ CC on H</td>
<td>3,810,000</td>
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<tr>
<td>ντ CC on H</td>
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<td>190,000</td>
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Assuming 5-ton radiator (CH2) mass

- Do we need to subtract carbon events from CH2 in full phase space?

### Statistics

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<tr>
<th>Process</th>
<th>CP optimized beam FHC 1.2MW, 5y</th>
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<th>$\nu_\tau$ optimized beam FHC 2.4MW, 2y</th>
<th>RHC 2.4MW, 2y</th>
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<tr>
<td>$\nu_\mu$ CC on CH$_2$</td>
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<td>1,152,000</td>
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<tr>
<td>$\bar{\nu}_\mu$ CC on H</td>
<td>308,000</td>
<td>2,490,000</td>
<td>210,000</td>
<td>4,330,000</td>
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<tr>
<td>$\nu_\tau$ CC on H</td>
<td>49,700</td>
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<td>65,800</td>
<td>17,800</td>
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<tr>
<td>$\bar{\nu}_\tau$ CC on H</td>
<td>15,400</td>
<td>34,400</td>
<td>12,600</td>
<td>33,900</td>
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Excellent hydrogen statistics!
Statistics

- Assuming 5-ton radiator (CH2) mass

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<td>Large number of carbon background!</td>
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Excellent hydrogen statistics!

- Do we need to subtract carbon events from CH2 in full phase space?
Hydrogen: Momentums of final-state particles are balanced in the direction transverse to the beam direction without nuclear effects. The only smearing is detector effects.

Carbon: Nuclear effects causes imbalance on the transverse plane.

Key detector features: low-threshold, high resolution measurement of all final-state particles as much as possible.
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**$\nu$-H Selection: Transvers Kinematics**

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**ν-H Selection: Resonance (3-Track Events)**

- Resonance pion production $\nu p \rightarrow \mu^- p \pi^+$
- Two simple transverse variables:
  - $p_{T\perp}^H$: momentum imbalance in the “double transverse” direction.

\(\nu\)-H Selection: Resonance (3-Track Events)

- Resonance pion production \(\nu p \rightarrow \mu^- p \pi^+\)
- Two simple transverse variables:
  - \(p_{T\perp}^H\): momentum imbalance in the “double transverse” direction.
  - \(R_{MH} = (P_T^M - P_T^H)/(P_T^M + P_T^H)\), where \(P_T^M\) and \(P_T^H\) are the missing \(p_T\) and total \(p_T\) of hadrons.
- \(\sim 90\%\) purity of hydrogen events (neutrino energy independent).
- The remaining carbon background is measured by the graphite target.
• Build log likelihood function using more variables \( (R_{MH}, p_T^M, p_{TT}, \phi_{ LH}, \theta_{\mu T}) \) can achieve even better purity while maintaining efficiency.
The subtraction of carbon background by the graphite target is totally data-driven, model-independent.

\[ N_H(\vec{x}) \equiv N_{CH_2}(\vec{x}) - N_C(\vec{x}) \times \frac{M_{C/CH_2}}{M_C} \]

Optimizing graphite mass to minimize statistical uncertainty.
$\nu$-$H$ Selection: More Channels

<table>
<thead>
<tr>
<th>Process</th>
<th>$R_{mH}$ and $p_{T\perp}^H$ cuts</th>
<th>$\ln \lambda^H$ cut</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency</td>
<td>Purity</td>
</tr>
<tr>
<td>$\nu_\mu p \rightarrow \mu^- p\pi^+$</td>
<td>93%</td>
<td>86%</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu p \rightarrow \mu^+ p\pi^-$</td>
<td>89%</td>
<td>84%</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu p \rightarrow \mu^+ n$</td>
<td>95%</td>
<td>80%</td>
</tr>
<tr>
<td>$\nu_\mu p$ CC inclusive</td>
<td>83%</td>
<td>73%</td>
</tr>
</tbody>
</table>

- Various channels studied with simple cuts and LH.
- Working on improvements.
\( \nu \)-H Selection: \( \bar{\nu}_\mu \) CCQE

- Anti-neutrino QE: \( \bar{\nu}_\mu p \rightarrow \mu^+ n \)
- About 25\% of the neutrons interact within STT producing charged secondary particles. Can be greatly improved if considering ECAL.
- Interaction vertex position is obtained from the muon.
- Get the neutron direction from the vertex to interaction point.
- Get the neutron energy from the muon kinematics with QE assumption.
Hydrogen shape is free from nuclear effects (detector smearing only).

The shapes of nuclear targets are model-dependent.
• Hydrogen shape is free from nuclear effects (detector smearing only).
• The shapes of nuclear targets are model-dependent.
Flux Measurements: Low-$\nu$ Method

$$N(E_{\text{rec}}) = \int_{E_{\nu}} dE_{\nu} \Phi(E_{\nu}) P_{\text{osc}}(E_{\nu}) \sigma(E_{\nu}) R_{\text{det}}(E_{\text{rec}}, E_{\nu})$$
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Need a process with small cross-section uncertainty
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- Cross section is flat at low $\nu = E_\nu - E_\mu$ with smaller uncertainty: flux shape measurement (used by NOMAD, MINOS, MINERvA).
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Need a process with small cross-section uncertainty: Nuclear effects!

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Nuclear effects!

- Cross section is flat at low $\nu = E_{\nu} - E_{\mu}$ with smaller uncertainty: flux shape measurement (used by NOMAD, MINOS, MINERvA).

- The cross-sections of $\nu$-H are better understood than heavy nucleus and free from uncertainties from nuclear effects.
Flux Measurements: Low-$\nu$ Method

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\[ \nu < 0.5 \text{ GeV}: \sim 25\% \text{ efficiency} \]

Cross-section uncertainty < 1%
Flux Measurements: Low-$\nu$ Method

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Cross-section uncertainty < 1%

Uncertainties further constrained by differential measurements in inclusive sample.
Flux Measurements: $\bar{\nu}_\mu$-CCQE

\[
\frac{d\sigma}{dQ^2} \bigg|_{Q^2=0} = \frac{G_F^2 \cos^2 \theta_c}{2\pi} \left[ F_1^2(0) + G_A^2(0) \right]
\]

- Measuring neutrons at a distance from vertex allows measurement of very low $Q^2$.
- At $Q^2 \to 0$, the QE cross section of free proton is known to < 1% from measurements of neutron decay.
- Good for absolute/relative $\bar{\nu}_\mu$ flux measurements.
Can we measure $\nu$-H in an alternative way?

- A pure-hydrogen detector with comparable statistics causes safety concerns, and can be potentially expensive.
  - Fill Argon-Gas TPC with hydrogen would also reduce $\nu$-Ar statistics.
- 3DST (CH target) has smaller (1/2) number of hydrogen and poorer resolution.
  - Larger statistical uncertainty.
  - Lower efficiency.
  - Higher background level makes subtraction difficult.
  - No dedicated carbon targets (with same detector response as CH) to constrain background systematics.
Summary

• We propose to measure $\nu$-H in the STT detector by statistically subtracting C from CH2.
  • Large statistics.
  • Subtraction is data-driven.
  • Safe, and cheap.
• Lots of benefits to DUNE
  • Neutrino energy scale free from nuclear effects.
  • Measure/constrain nuclear effects.
  • Flux measurement.
  • Cross-section physics.
• Complementary to other ND measurements.
Back up slides
Straw Tube Tracker (STT)

- Approximately 3.5m x 3.5m x 6.5m, $\rho \approx 0.1$ g/cm$^3$, $X_0 \approx 6$ m.
- Magnetic field for charge and momentum measurement.
- $4\pi$ ECAL coverage.
- $4\pi$ MuID (RPC) in dipole and up/downstream.
- Multiple nuclear targets:
  - Pressurized $^{40}$Ar target ($\approx \times 69$ FD-stat), & $^{40}$Ca, C ($\approx \times 220$ FD-stat).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
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<tbody>
<tr>
<td>Radiator (Target) Mass</td>
<td>7 tons</td>
</tr>
<tr>
<td>Other Nuclear Target Mass</td>
<td>1–2 tons</td>
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<tr>
<td>Vertex Resolution</td>
<td>0.1 mm</td>
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<tr>
<td>Angular Resolution</td>
<td>2 mrad</td>
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<tr>
<td>$E_e$ Resolution</td>
<td>$6% / \sqrt{E}$ (4% at 3 GeV)</td>
</tr>
<tr>
<td>$E_\mu$ Resolution</td>
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<td>$\nu_\mu / \bar{\nu}_\mu$ ID</td>
<td>Yes</td>
</tr>
<tr>
<td>$\nu_e / \bar{\nu}_e$ ID</td>
<td>Yes</td>
</tr>
<tr>
<td>$\pi^- .vs. \pi^+$ ID</td>
<td>Yes</td>
</tr>
<tr>
<td>$\pi^+ .vs. proton .vs. K^+$ ID</td>
<td>Yes</td>
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<tr>
<td>NC $\pi^0$/CCe Rejection</td>
<td>0.1%</td>
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<td>NC $\gamma$/CCe Rejection</td>
<td>0.2%</td>
</tr>
<tr>
<td>CC $\mu$/CCe Rejection</td>
<td>0.01%</td>
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**Nu-H Selection: Transvers Kinematics**

- **Hydrogen**: Momentums of final-state particles are balanced in the direction transverse to the beam direction without nuclear effects. The only smearing is detector effects.
- **Carbon**: Nuclear effects causes imbalance on the transverse plane.
- **Key detector features**: low-threshold, high resolution measurement of all final-state particles as much as possible.
Anti-Neutrino Mode: 3trk

Define a new variable $R_{MH} = p_{MT} - p_{HT}$ (where $p_{MT}$ is total missing $p_T$, and $p_{HT}$ is the hadron $p_T$). It shows additional separation power.

As simple $R_{MH}$ cut significantly improves the purity from 59% to 84% while maintaining high efficiency.

A multivariate analysis using complete set of kinematic variables can further improve the separation power (ongoing work).
TABLE III. Comparison of the efficiency and purity for the kinematic selection of H interactions from the CH$_2$ plastic target using simple cuts on $R_{mH}$ and $p_{T\perp}^H$ with the NuWro [21], GiBUU [22], and GENIE [23] event generators. The same selection cuts as in Tab. I are used in all cases.

<table>
<thead>
<tr>
<th>Process</th>
<th>NuWro</th>
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<th>GiBUU</th>
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<th>GENIE</th>
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<td>84%</td>
<td>89%</td>
<td>87%</td>
<td>89%</td>
<td>89%</td>
</tr>
</tbody>
</table>

This is to show that the number of efficiencies and purities we estimate is realistic. The difference between generators here will not be systematics because we will have carbon data to measure them.
Background Shape

Prediction by different models for C12

Models differ in prediction of background shape:
We must have carbon data to measure it!
• The selection efficiency is flat for most of the energy region: the selection is independent from incoming neutrino energy.
Hydrogen Event Selection ($\nu_\mu$ QE)

- Get the vertex position from the muon (with $z \pm 1 \text{cm}$ smearing).
- About 25% neutron interact in STT producing charged particles according to GEANT4 simulation.
- Get the neutron direction from the vertex to interaction point.
- Get the neutron energy from the muon kinematics with QE assumption.
A Geant4 study of neutrons in STT has been conducted. Hand-scanned 200 neutrons in STT event display:

- 12% make good tracks in STT.
- 22% make a few hits in STT, but not enough for track.
- 48% have ECAL hits but no STT hit.
- 4% is totally invisible.

Measuring neutrons also greatly helps in constraining nuclear effects.
Neutrons in STT

Neutron Kinetic Energy (GeV)

Fraction of Visible Neutrons

- STT Hit Only
- Ecal Hit Only
- Ecal or STT Hit
Flux Measurements: Low-$\nu$ Method

$$N(E_{rec}) = \int dE_\nu \Phi(E_\nu) P_{osc}(E_\nu) \sigma(E_\nu) R_{det}(E_{rec}, E_\nu)$$

Need a process with small cross-section uncertainty

- Cross section is flat at low $\nu = E_\nu - E_\mu$ with smaller uncertainty: flux shape measurement (used by NOMAD, MINOS, MINERvA).
- The cross-sections of $\nu$-H are better understood than heavy nucleus and free from uncertainties from nuclear effects.
- Two channels: $\nu p \rightarrow \mu^- p \pi^+$, $\bar{\nu}_\mu p \rightarrow \mu^+ n$

Uncertainties further constrained by differential measurements in inclusive sample.
Low-$\nu$ Neutrino Flux Measurement

- Uncertainty from muon energy scale
The cross-sections of $\nu$-H are better understood than $\nu$-nucleus.

Low-$\nu$ (energy transfer to hadronic system) cut significantly reduces remaining uncertainties from hadronic modeling.

Expect 0.4M events: a precise measurement of relative flux.

Use of $\nu$-(\bar{$\nu$})-Hydrogen interactions dramatically reduces hadronic uncertainties:
- Select exclusive $\mu p \pi^3$-track topology on Hydrogen;
- Cut $\nu < 0.5 \text{ GeV}$ flattens cross-sections reducing uncertainties on $E_\nu$ dependence;
- Flux uncertainties dominated by muon energy scale ($\Delta E_{\mu} \sim 0.2\%$ in low density tracker).

$\Rightarrow$ Potentially achieve unprecedented precision on fluxes $\sim 1-2\%$ $\nu < 0.5 \text{ GeV}$ NO CUT
\(\nu\)-H Selection

- Similar technique is applicable to the inclusive sample sample
- Working on improving efficiency and purity.
Measure absolute $\bar{\nu}$ fluxes from QE on Hydrogen $\bar{\nu}p \rightarrow \mu^+ n$:

$$\frac{d\sigma}{dQ^2} \bigg|_{Q^2=0} = \frac{G_F^2 \cos^2 \theta_c}{2\pi} \left[ F_1^2(0) + G_A^2(0) \right]$$

where terms in $(m_l/M)^2$ are neglected.

- Cross-section independent of neutrino energy for $\sqrt{2E_\nu M} > m_l$;
- At $Q^2 = 0$ QE cross-section determined by neutron $\beta$-decay to a precision better than 1%;

⇒ Additional theoretical $E_\nu$ uncertainties to consider?