Neutrino Flux Measurement
In the DUNE Near Detector

Hongyue Duyang
University of South Carolina

For the DUNE Collaboration
Introduction to DUNE

- DUNE is a long-baseline neutrino experiment aiming to solve mass hierarchy and CP-violation by measuring $\nu_\mu$ to $\nu_e/\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation in one single experiment.
- 40 kton LAr TPC as the far detector in Lead, SD.
- A capable near detector is crucial for DUNE to constrain systematic uncertainties, including flux uncertainty.
Near Detector Options

• Currently we have several ND options under study:
  • LAr TPC
  • Fine-Grained Tracker (FGT, CDR reference design)
  • High-Pressure Ar Gas TPC
  • Scintillating plastic tracker
Near Detector Options

- Currently we have several ND options under study:
  - LAr TPC
  - Fine-Grained Tracker (FGT, CDR reference design)
  - High-Pressure Ar Gas TPC
  - Scintillating plastic tracker
Near Detector Options

- Currently we have several ND options under study:
  - LAr TPC
  - Fine-Grained Tracker (FGT, CDR reference design)
  - High-Pressure Ar Gas TPC
  - Scintillating plastic tracker
Near Detector Options

- Currently we have several ND options under study:
  - LAr TPC
  - Fine-Grained Tracker (FGT, CDR reference design)
  - High-Pressure Ar Gas TPC
  - Scintillating plastic tracker

![Diagram of NEUTRINO EXPERIMENT (DUNE)](image)
Near Detector Options

- Currently we have several ND options under study:
  - LAr TPC
  - Fine-Grained Tracker (FGT, CDR reference design)
  - High-Pressure Ar Gas TPC
  - Scintillating plastic tracker
Neutrino Flux at DUNE

- DUNE will use the new LBNF neutrino beam.
- Flux uncertainty comes from hadron production and beam focusing.
Neutrino Flux at DUNE

- DUNE will use the new LBNF neutrino beam.
- Flux uncertainty comes from hadron production and beam focusing.
Neutrino Flux at DUNE

- DUNE will use the new LBNF neutrino beam.
- Flux uncertainty comes from hadron production and beam focusing.

See talk by Jim Hylen and Rowan Zaki
Flux Measurement for DUNE

- Flux uncertainty comes from hadron production and beam focusing.

Figure from Amit Bashyal
Flux Measurement for DUNE

- Flux uncertainty comes from hadron production and beam focusing.
- External hadron production data constraint.
  - Talk on Monday by Amit Bashyal: PPFX for DUNE.

Figure from Amit Bashyal
Flux uncertainty comes from hadron production and beam focusing.

- External hadron production data constraint.
  - Talk on Monday by Amit Bashyal: PPFX for DUNE.

- In situ measurement at ND: the focus of this talk.
  - Generally speaking neutrino interaction cross-sections have large uncertainty
  - We need some neutrino interaction channels known well enough in some aspect to measure flux:
    - Neutrino-electron scattering for absolute flux.
    - Low-$\nu$ sample for flux shape.
    - Coherent pions for $\bar{\nu}/\nu$ ratio and beam divergence.
Neutrino-Electron Scattering

- Pure electroweak process with small, but very well known cross section: Good for measurement of absolute flux.
- Very forward-going electron/muon (small $E_e \theta^2$) in final state with no other particles.
- Uncertainty will be dominated by statistics: need enough detector mass.
• $E_e \theta^2 = 2m_e (1-\eta) < 2m_e$.
• Good angular resolution is critical to reduce background.
Neutrino-Electron Scattering

- $E_e \theta^2 = 2m_e(1-y) < 2m_e$.
- Good angular resolution is critical to reduce background.
- Assuming 2 mrad angular resolution, 6% background is expected.

MINERvA $\sigma(\theta) = 7.2$ mrad

Signal region: $E\theta^2 < 0.005$

NOvA $\sigma(\theta) = 19$ mrad

J. Bian’s talk on Tuesday

DUNE Work in Progress

Plot by Chris Marshall
**Neutrino-Electron Scattering**

- $E_e\theta^2 = 2m_e(1-y) < 2m_e$.
- Good angular resolution is critical to reduce background.
- Assuming 2 mrad angular resolution, 6% background is expected.
- Background comes from $\pi^0$ and $\nu_e$-CC (QE) events:
  - $e^+$ sample to control $\pi^0$ bkg: need $e^+/e^-$ ID.
  - 2-track $\nu_e$-CC QE-like events to constrain $\nu_e$-CC QE background (50% efficiency in FGT).

**DUNE Work in Progress**

- $\sigma(\theta)$ = 19 mrad
  - J. Bian’s talk on Tuesday

**NOvA Simulation**

- Signal region: $E\theta^2 < 0.005$
- NOvA $\sigma(\theta)$ = 19 mrad
- Plot by Chris Marshall

**Plot by Chris Marshall**

<table>
<thead>
<tr>
<th>E/$\theta^2$ (GeV x rad$^2$)</th>
<th>N Events / 0.0008 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

- POT-Normalized 3.43e+20 POT
- $E\theta^2<0.0032$
- MINERvA $\sigma(\theta)$=7.2 mrad
Neutrino-Electron Scattering

• Assuming 1.2 MW beam power, 5 tons ND fiducial mass, 3 years neutrino running we expect:
  • \( \sim 7.8k \) \( \nu_\mu + e^- \rightarrow \nu_\mu + e^- : \sim 2\% \) precision in 2.5~10 GeV.
  • \( \sim 4k \) \( \nu_\mu + e^- \rightarrow \nu_e + \mu^- : \sim 2.5\% \) precision in 11~50 GeV.
• Given known neutrino direction and good detector resolution it is also possible to measure flux shape (work in progress).
Low-ν method

• At very low $\nu = E_\nu - E_1$, the cross section is independent from $E_\nu$:

$$\frac{d\sigma}{d\nu} = A(1 + \frac{B \nu}{A E} - \frac{C \nu^2}{A 2 E^2})$$

(A, B and C are parameters formed by nuclear structure functions.)

• the measurement of low $\nu$ spectrum is approximately a measurement of flux shape.

• The effect of non-zero $\nu$ cut is account for by a theoretical correction:

$$S(E) = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E)^{\nu\to 0}} = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E \to \infty)^{\nu<\nu_0}}$$

• Systematic uncertainty dominant:
  • Muon energy
  • Hadronic energy ($\nu$)
  • Theoretical correction

• See Lu Ren’s talk on Tuesday for MINERvA’s Low-ν flux measurement
Low-ν method

- Beam hadron production can be parametrized using empirical functions:

\[
E \times \frac{d^3\sigma}{d^3p} = A(1 - x_R)\alpha(1 + Bx_R)x_R^{-\beta} \times \\
(1 + a'(x_R)p_T + b'(x_R)p_T^2)e^{-a'(x_R)p_T}
\]

- Use ND low-ν neutrino and antineutrino data to constrain beam hadron productions.
- Given good muon/hadron energy resolution, expect an FD/ND ratio at 1~2% precision in 0.5~50 GeV.
• Identical topology between neutrino and antineutrino to the first order: constraint on $\bar{\nu}/\nu$.

• Final state muon and pion collinear with incident neutrino with little nuclear effect: constraint on beam divergence

• Combined with neutrino-electron scattering study it might be possible to constrain flux shape $\phi(E)$.

• Requires good momentum resolution for muon and pion.

• Work in progress.
Summary

• A capable ND is important to constrain the systematic uncertainty for oscillation analysis, including neutrino flux uncertainty.

• A lot of work going on to develop flux measurement methods.
  • Neutrino-electron scattering for absolute flux.
  • Low-$\nu$ method for relative flux.
  • Coherent pions for $\bar{\nu}/\nu$ ratio and beam divergence.

• Combined with external data we aim at a precise flux prediction for DUNE.
Back up slides
Neutrino-Electron Scattering

- Pure electroweak process with small, but very well known cross section: Good for measurement of absolute flux.
- Very forward-going electron/muon (small $E_e \theta^2$) in final state with no other particles.
- Need good angular resolution.
- Uncertainty will be dominated by statistics: need enough detector mass.
- Given known neutrino direction it is also possible to measure flux shape.

\[
\begin{align*}
\nu - e \text{ scattering} &\quad \text{IMD} \\
\nu_\mu &\rightarrow e^- \\
\nu_e &\rightarrow e^- \\
\nu_e &\rightarrow \nu_e \\
\nu_\mu &\rightarrow \nu_\mu \\
\end{align*}
\]
Neutrino Flux at DUNE

- DUNE will use the new LBNF neutrino beam.
- Flux uncertainty comes from hadron production and beam focusing.

See talk by Jim Hylen and Rowan Zaki
Neutrino-Electron Scattering


- $E_e \theta^2 = 2m_e (1-y) < 2m_e$.
- Good angular resolution is critical to reduce background.
- Assuming 2 mrad angular resolution, 6% background is expected.
- Background comes from $\pi^0$ and $\nu_e$-CC (QE) events:
  - $e^+$ sample to control $\pi^0$ background: need $e^+/e^-$ ID.
  - 2-track $\nu_e$-CC QE-like events to constrain $\nu_e$-CC QE background (50% efficiency in FGT).