Measurements of The Neutrino Flux Using Fine-Grained Tracker

Xinchun Tian
for the DUNE Collaboration

Department of Physics and Astronomy

DIS 2015 © Dallas, TX, 4/27-5/1, 2015
Outline

Introduction

Deep Underground Neutrino Experiment (DUNE)

A High-Resolution Fine Grained Tracker as a ND for DUNE

Measure Absolute and Relative Flux using ND
The Neutrino Fluxes

\[ U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{CP}} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

Atmospheric + Accelerator

Reactor + Accelerator

Reactor + Solar

Atmospheric (X)

Reactor (X)

Solar (X)

Accelerator (√)
Flux uncertainty dominates the cross section measurements


$Q^2_{QE}$ (GeV$^2$) | I | II | III | IV | V | VI | Total
---|---|---|---|---|---|---|---
0.0 – 0.025 | 0.06 | 0.04 | 0.02 | 0.04 | 0.09 | 0.03 | 0.13
0.025 – 0.05 | 0.06 | 0.03 | 0.02 | 0.03 | 0.09 | 0.02 | 0.12
0.05 – 0.1 | 0.06 | 0.03 | 0.02 | 0.03 | 0.09 | 0.02 | 0.12
0.1 – 0.2 | 0.06 | 0.03 | 0.03 | 0.02 | 0.09 | 0.02 | 0.11
0.2 – 0.4 | 0.05 | 0.02 | 0.03 | 0.03 | 0.09 | 0.01 | 0.11
0.4 – 0.8 | 0.05 | 0.03 | 0.04 | 0.04 | 0.09 | 0.01 | 0.13
0.8 – 1.2 | 0.08 | 0.07 | 0.07 | 0.15 | 0.09 | 0.02 | 0.22
1.2 – 2.0 | 0.12 | 0.07 | 0.07 | 0.16 | 0.09 | 0.02 | 0.24


$Q^2_{QE}$ (GeV$^2$) | I | II | III | IV | V | VI | Total
---|---|---|---|---|---|---|---
0.0 – 0.025 | 0.05 | 0.04 | 0.00 | 0.02 | 0.11 | 0.02 | 0.13
0.025 – 0.05 | 0.05 | 0.04 | 0.01 | 0.01 | 0.11 | 0.02 | 0.13
0.05 – 0.1 | 0.05 | 0.04 | 0.01 | 0.01 | 0.11 | 0.01 | 0.13
0.1 – 0.2 | 0.04 | 0.04 | 0.01 | 0.01 | 0.11 | 0.01 | 0.12
0.2 – 0.4 | 0.03 | 0.06 | 0.01 | 0.02 | 0.11 | 0.01 | 0.13
0.4 – 0.8 | 0.05 | 0.07 | 0.02 | 0.03 | 0.11 | 0.01 | 0.15
0.8 – 1.2 | 0.11 | 0.11 | 0.02 | 0.11 | 0.02 | 0.20
1.2 – 2.0 | 0.13 | 0.15 | 0.04 | 0.04 | 0.12 | 0.02 | 0.23

ANL-BNL Puzzle


• The long standing ANL-BNL pion production cross section disagree ∼25%

• Reanalysis shows that this may be due to a flux normalization problem in BNL (See also K. M. Graczyk, et al., PRD 80 093001 (2009))
How to produce and constrain the neutrino flux\textsuperscript{1}

- Hadron Cascade model comparisons (15%)
  - Geant4 vs FLUKA
  - FTFP vs QGSP vs BERT ...
- External measurements (6-10%)
  - NA49 pC @ 158 GeV, MIPP pC @ 120 GeV
- In-situ measurements
  - Secondary muon fluxes (15-30%)
  - Absolute flux: Neutrino-electron NC/CC scattering
  - Relative flux: Low-$\nu$
- Tests with modified beamline geometries
  - Moving target relative to horn (<7%)
  - Turning off the horn ...

\textsuperscript{1}Deborah Harris, CETUP 2014, South Dakota
How to produce and constrain the neutrino flux

- Hadron Cascade model comparisons (15%)
  - Geant4 vs FLUKA
  - FTFP vs QGSP vs BERT ...
- External measurements (6-10%)
  - NA49 pC @ 158 GeV, MIPP pC @ 120 GeV
- In-situ measurements
  - Secondary muon fluxes (15-30%)

  - **Absolute flux**: Neutrino-electron NC/CC scattering
  - **Relative flux**: Low-\(\nu\)

- Tests with modified beamline geometries
  - Moving target relative to horn (<7%)
  - Turning off the horn ...

Xinchun Tian  (USC, Columbia)
With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducial mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector.
Goals of the ND in DUNE

• Constrain the systematic uncertainties in the oscillation measurements/searches
  • Neutrino source: content and spectra of all 4 species, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$
  • Precise prediction of FD/ND CC spectra for all 4 species and of NC
  • Energy scale of neutrino and antineutrino
  • Background: $\pi^0, \pm$ in NC and CC; $e/\mu/proton/\pi/K$ ID

⇒ Measure the 4-momenta of particles in neutrino interactions providing an “Event-Generator Measurement” for the FD

• A generational advance in the precision neutrino physics
  • Cross sections: QE, Resonance, Coherent and DIS
  • Neutrino-nucleus interactions and nucleon structure
  • Electroweak and isospin physics

• Search for New Physics at short-baseline
  • Short-baseline oscillations, include constraining of the background for FD signal
  • Light Dark Matter, Universality, and right-handed currents, etc.
Goals of the ND in DUNE

- Constrain the systematic uncertainties in the oscillation measurements/searches
- Neutrino source: content and spectra of all 4 species, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$
- Precise prediction of FD/ND CC spectra for all 4 species and of NC
- Energy scale of neutrino and antineutrino
- Background: $\pi^0, \pm$ in NC and CC; $e/\mu$/proton/$\pi/K$ ID

⇒ Measure the 4-momenta of particles in neutrino interactions providing an “Event-Generator Measurement” for the FD

- A generational advance in the precision neutrino physics
  - Cross sections: QE, Resonance, Coherent and DIS
  - Neutrino-nucleus interactions and nucleon structure
  - Electroweak and isospin physics

- Search for New Physics at short-baseline
  - Short-baseline oscillations, include constraining of the background for FD signal
  - Light Dark Matter, Universality, and right-handed currents, etc.
A High-Resolution Fine Grained Tracker as a ND for DUNE

Quantify the Neutrino Source Using ND

- Precision measurement of all 4 neutrino species
  - $\nu_{\mu} \rightarrow \mu^{\pm}$ as a function of $E_{\nu} - \text{FD/ND} (E_{\nu})$
  - $\nu_{e} \rightarrow e^{\pm}$ as a function of $E_{\nu} - \text{FD/ND} (E_{\nu})^2$

- These considerations imply the following requirements
  - Magnetized tracker to ID positive from negative particle – $B \sim 0.4$ T
  - Low density medium to track $e^{\pm}$ – $\rho \sim 0.1$ g/cm$^3$
    - Momentum vectors of hadrons: $\pi^{\pm, 0}$, $K^{\pm, 0}$ and proton
  - Large statistics – $\sim 10^8$ neutrino interactions

The proposed FGT builds upon the NOMAD experience

$\frac{2\nu_e}{\nu_e + \bar{\nu}_e} \sim 1$ in neutrino mode .vs. $\frac{\bar{\nu}_e}{\nu_e + \bar{\nu}_e} \sim 0.5$ in antineutrino mode
High Reso. Fine-Grain Tracker \( \text{(Proposed by the Indian \& US Groups)} \)

- \( \sim 3.5 \text{m} \times 3.5 \text{m} \times 6.4 \text{m} \) STT \((\rho \approx 0.1 \text{g/cm}^3)\)
- \(4\pi\) ECAL in a dipole magnetic field \((B = 0.4 \text{T})\)
- \(4\pi\) MuID (RPC) in dipole and up/downstream
- Pressurized Ar target \(\sim \times 10\) FD statistics

- Trasition Radiation : \(e^\pm\)
- \(dE/dx : \pi^\pm, K^\pm\) and proton
- Magnet : + .vs. -
- MuID : \(\mu\)
  \(\Rightarrow\) Absolute flux measurement

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>FGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw Tube Detector Volume</td>
<td>3.5m x 3.5m x 6.4m</td>
</tr>
<tr>
<td>Straw Tube Detector Mass</td>
<td>8 tonnes</td>
</tr>
<tr>
<td>Vertex Resolution</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>2 mrad</td>
</tr>
<tr>
<td>(E_e) Resolution</td>
<td>5%</td>
</tr>
<tr>
<td>(E_\mu) Resolution</td>
<td>5%</td>
</tr>
<tr>
<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>NC(\pi^0)/CCe Rejection</td>
<td>0.1%</td>
</tr>
<tr>
<td>NC(\gamma)/CCe Rejection</td>
<td>0.2%</td>
</tr>
<tr>
<td>CC(\mu)/CCe Rejection</td>
<td>0.01%</td>
</tr>
</tbody>
</table>
Measure Absolute and Relative Flux using ND

\[ \nu e^- \rightarrow \nu e^- \] (W. Marciano and Z. Parsa, arXiV: hep-ph/0403168)

- Cross section is extremely small, but well known
  - \[ \sigma(\nu_\mu, \tau e \rightarrow \nu_\mu, \tau e) = \frac{G^2 m_e E_\nu}{2\pi} \left[ 1 - 4 \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right] \]
  - \[ \sigma(\bar{\nu}_\mu, \tau e \rightarrow \bar{\nu}_\mu, \tau e) = \frac{G^2 m_e E_\nu}{2\pi} \left[ \frac{1}{3} - \frac{4}{3} \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right] \]
  - \[ \sigma(\nu_e e \rightarrow \nu_e e) = \frac{G^2 m_e E_\nu}{2\pi} \left[ 1 + 4 \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right] \]
  - \[ \sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e) = \frac{G^2 m_e E_\nu}{2\pi} \left[ \frac{1}{3} + \frac{4}{3} \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right] \]
  - \[ \sigma(\nu_\mu, \tau e):\sigma(\bar{\nu}_\mu, \tau e):\sigma(\nu_e e):\sigma(\bar{\nu}_e e) = 1:0.854:6.077:2.547 \]
  - Assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
    - 10.5 k \( \nu e^- \rightarrow \nu e^- \) events, 7.8 k \( \nu_\mu e \), 1.7 k \( \bar{\nu}_\mu \), 1 k \( \nu_e e \)
  - A clean determination of the neutrino flux at low energy
Absolute Flux: $\nu e^- \rightarrow \nu e^-$

- **Signal**
  - Single, forward $e^-$
  - Efficiency $\sim 73\%$

- **Background**
  - $\nu_e$ CCQE & NC (charge-symmetric)
  - Benign, constrained by “$e^+$” analysis

- **Total neutrino energy**
  - High resolution tracker allows the reconstruction of $E_\nu$ from $(E_e, \theta_e)$

- **Absolute flux**: $\sim 2\%$ precision in $0.5 \leq E_\nu \leq 10$ GeV range.
Inverse Muon Decay

\[
\frac{d\sigma(\nu le \to l\nu_e)}{dy} = \frac{G^2_{\mu}}{\pi} (2m_e E_\nu - (m_l^2 - m_e^2))
\]

(1)

\[
\frac{d\sigma(\bar{\nu}_e e \to l\bar{l}_l)}{dy} = \frac{G^2_{\mu}}{\pi} (2m_e E_\nu (1 - y)^2 - (m_l^2 - m_e^2)(1 - y))
\]

(2)

\[
y = \frac{E_l - \frac{m_l^2 + m_e^2}{2m_e}}{E_\nu}
\]

(3)

\[
0 \leq y \leq y_{max} = 1 - \frac{m_l^2}{2m_e E_\nu + m_e^2}
\]

(4)

- Cross section is extremely small, but well known
  - \(\sigma(\nu_\mu e^- \to \mu^- \nu_e) \approx 3\sigma(\bar{\nu}_\mu e^- \to \mu^- \bar{\nu}_\mu) \approx \frac{2G^2_{\mu} m_e E_\nu}{\pi} \approx 1.5 \times 10^{-41} (E_\nu/\text{GeV}) \text{ cm}^2\)
- Threshold \(E_\nu \geq \frac{m_l^2 - m_e^2}{2m_e} \approx 10.9 \text{ GeV}\)
- 5.4k \(\sigma(\nu_\mu e^- \to \mu^- \nu_e)\) events assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
- A clean determination of the neutrino flux at higher energy

Absolute Flux: $\nu$-e CC Scattering (IMD)

- **Signal**
  - Single, forward $\mu^-$
  - Efficiency $\sim 91\%$

- **Background**
  - $\sim 20\%$, dominated by CCQE
  - 1-track
  - Constrained by 2-track $\nu_\mu$-CC analysis after removing the “proton”

- **Total neutrino energy**
  - High resolution tracker allows the reconstruction of $E_\nu$ from $(E_\mu, \theta_\mu)$

- **Absolute flux**: $\sim 2.5\%$ precision in $15 \leq E_\nu \leq 50$ GeV range.
Absolute Flux: $\bar{\nu}_\mu$ Proton QE Scattering

- **Signal**
  - Single $\mu^+$ obtained after subtraction: $(C_3H_6)_n$ [Radiator] - C [Graphite]
  - Collect $(1.0 \pm 0.0045) \times 10^6$ (subtracted) $\bar{\nu}$-H events ($\sim 25\%$ QE)
  - Collect $(3.3 \pm 0.0090) \times 10^6$ (subtracted) $\nu$-H events ($\sim 0\%$ QE)

- **Background**
  - Dominated by $\bar{\nu}_\mu$-CC
  - Systematic Handle (ancillary, in situ measurement of the background)
    - Conduct the analysis on multi-track $\nu_\mu$-CC to check the target location
  - Estimate a $\sim 3\%$ precision in $0.5 \leq E_\nu \leq 20$ GeV
Relative Flux: Low-$\nu$ method \( \text{(S. R. Mishra, World Sci., 84 (1990), Ed. D. Geesman.)} \)

- Low-$\nu$ \( (E_{\text{had}} = E_\nu - E_\mu) \): low energy transfer to the hadronic system
- Relative $\nu_\mu$, $\bar{\nu}_\mu$ flux vs. energy from low-$\nu$ method

\[
N(E_\nu, E_{\text{Had}} < \nu_0) = k\Phi(E_\nu)f_c\left(\frac{\nu_0}{E_\nu}\right)
\]

- The correction factor \( f_c\left(\frac{\nu_0}{E_\nu}\right) \to 1 \) for \( \nu_0 \to 0 \)

\[
f\left(\frac{\nu_0}{E_\nu}\right) = 1 + \left(\frac{\nu_0}{E_\nu}\right)\frac{B}{A} + \left(\frac{\nu_0}{E_\nu}\right)^2\frac{C}{2A} + \ldots
\]

where \( A = G_F^2M/\pi \int_0^1 F_2(x)dx \), \( B = -G_F^2M/\pi \int_0^1 (F_2(x) \mp F_3(x))dx \),
\( C = B - G_F^2M/\pi \int_0^1 F_2(x)[(1 + 2Mx/\nu)/(1 + R(x, Q^2)) - Mx/\nu - 1]dx \).

- In practice use MC to calculate the correction factor normalized at high neutrino energy \( E_\nu \)

\[
f_c(E_\nu) = \frac{\sigma(E_\nu, E_{\text{Had}} < \nu_0)}{\sigma(E_\nu \to \infty, E_{\text{Had}} < \nu_0)}
\]

where denominator is evaluated at the highest energy accessible in spectrum

- Need precise muon energy scale and good resolution at low-$\nu$ values because a larger fraction of the \( E_\nu \) per event is carried by the muon
- Reliable flux predictions for \( E \geq 2\nu_0 \)
  - DUNE spectra require \( \nu_0 = 0.25 - 0.5 \) GeV
The correction factor $f_C(E_\nu)$

MINOS, PRD 81, 072002 (2010)

Cross Sections per Nucleon for Neutrino on Carbon with $\nu$ Cut

Cross Sections per Nucleon for Antineutrino on Carbon with $\nu$ Cut

A. Bodek et al., EPJC 72, 1973 (2012)
Relative Flux: Low-$\nu$ method@DUNE with FGT

- Study relative $\nu_\mu$, $\bar{\nu}_\mu$ fluxes in DUNE with $E_{\text{Had}} < \nu_0 = 0.5$ GeV
  - Use standalone simulation with DUNE spectra and parameterized detector smearing
  - Perform empirical fits to modified $\nu_\mu$ & $\bar{\nu}_\mu$ spectra in ND (fake data)
  - Extract modified fluxes and extrapolate to FD
- Considered several systematic uncertainties
  - Cross sections QE, Res, DIS
  - Variations in $\nu_0$ correction
  - Muon and hadronic energy scales
- Overall uncertainty on FD/ND flux ratio $\sim 1$-2%
Absolute and Relative Flux in DUNE using ND

• Absolute flux
  • Leptonic channel
    • Neutrino electron NC scattering: expect a \( \sim 2\% \) precision in \( 0.5 \leq E_{\nu} \leq 10 \text{ GeV} \)
    • Neutrino electron CC scattering: expect a \( \sim 2.5\% \) precision in \( E_{\nu} \geq 11 \text{ GeV} \)
  • 2\(^{nd}\) channel
    • \( \bar{\nu}_\mu + p \rightarrow \mu^+ + n \): estimate a \( \sim 3\% \) precision in \( 0.5 \leq E_{\nu} \leq 20 \text{ GeV} \)
  • Coherent channel \( (\nu_\mu + A \rightarrow \nu_\mu + A + \rho^0) \)

• Relative flux
  • Low \( \nu_0 \) method
    • \( (\nu_\mu^+) + N \rightarrow \mu^\pm + \chi \): expect a FD/NC ratio at \( \sim 1-2\% \) precision in \( 0.5 \leq E_{\nu} \leq 50 \text{ GeV} \)
  • Coherent \( \pi/\rho \) channel
    • \( (\nu_\mu^-)A \rightarrow \mu^\pm \pi^\mp (\rho^\mp)A \): estimate a high precision in the \( \bar{\nu}_\mu/\nu_\mu \) ratio in \( 0.5 \leq E_{\nu} \leq 50 \text{ GeV} \)
Conclusion

The ND complex, with a high resolution FGT, will:

- Determination of the relative abundance and of the energy spectrum of the four neutrino species in DUNE beam: $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$
  - Extrapolation to FD and predictions of FD/ND($E_\nu$) fluxes to $\sim 1\%$
- Determination of the absolute $\nu_\mu$ and $\bar{\nu}_\mu$ fluxes to $\sim 2\%$ for oscillation measurements
MINERνA: $\nu e^- \rightarrow \nu e^-$ (Jaewon Park, FNAL W&C)

- $\nu$-e scattering events after background subtraction and efficiency correction
  - $123.8 \pm 17.0$ (stat.)$\pm 9.1$ (syst)
  - Total uncertainty: 15%
- Projected precision in Medium Energy Era, a.k.a, NOνA era
  - Statistical uncertainty $\sim 2\%$
  - Total systematic uncertainty on this measurement $\sim 7\%$
  - Total uncertainty $\sim 7.3\%$