Recent Results from the T2K Near Detector

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on behalf of the T2K Collaboration
NuFACT 2018, Blacksburg, 15 August 2018
Neutrino – Oscillation

Neutrino oscillation between flavor states as a function of time ∼ distance/energy

Only 2 flavors, same oscillation behavior
Neutrino
– CP violation

Oscillation property difference
→ CP violation

\[ P(v_e) + P(v_\mu) + P(v_\tau) = 1 \]

*3-flavor paradigm

oscillation between flavor states as a function of time \( \sim \) distance/energy
The T2K Experiment

Charge selection on neutrino parents

→ ν or ν̄ mode
T2K far detector: Super-Kamiokande

- 50 kt water-Cherenkov
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector

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\[ \mu^\pm, e \text{ identification} \]
\[ \rightarrow \text{detect propagated } \nu \text{ from J-PARC} \]
\[ \rightarrow E_\nu \text{ rec. from } \mu/e \text{ kinematics} \]

**Charged-Current Quasi-Elastic (CC0}\pi)\text{ via }\Delta \text{ production}**

\[ \nu_\mu \sqrt{\nu}/\nu_\mu \sqrt{\nu}/e, \mu^+/e/e^+ \]

(No CC1\pi sample due to \pi absorption)
The big picture of neutrino detection in oscillation measurements

What we measure
Event counts
Final-state kinematics

What we want to know about
Number of neutrinos as a function of neutrino energy

Nuclear Effects
Unless we can use free nucleon targets safely, we have to deal with multi-dimensional problems of nuclear effects in neutrino interactions.
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The T2K Experiment

Crossed arrays of 9-ton iron-scintillator detectors
- Monitor neutrino beam stability and beam spatial profile
- estimate beam flux uncertainty
- stand-alone cross-section measurements
T2K off-axis near detector (ND280)
T2K off-axis near detector (ND280)

- **P0D**: $\pi^0$ Detector
  - Scintillator-based ECal
  - CH w/ and w/o $H_2O$

- **Tracker**:
  - FGD: Fine-Grained Detector
    - 1. CH target
    - 2. CH + $H_2O$ target
  - Time Projection Chamber (TPC)
    - constrain beam flux and cross section for oscillation analysis
    - stand-alone neutrino interaction measurements

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Cross-section measurements from T2K

<table>
<thead>
<tr>
<th></th>
<th>CC inclusive</th>
<th>CC QE(-like)</th>
<th>CC π</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>$\bar{\nu}/\nu^\mu_\mu: 1706.04257$ $\nu^e_\mu: 1503.08815$</td>
<td>$\nu^\mu_\mu: 1708.06771$</td>
<td>$\nu^\mu_\mu: 1605.07964$</td>
</tr>
<tr>
<td>CH</td>
<td>$\nu^\mu_\mu: 1801.05148$ $\bar{\nu}/\nu^\mu_\mu: 1706.04257$ $\nu^e_\mu: 1407.7389$ $\nu^\mu_\mu: 1407.4256$ $\nu^\mu_\mu: 1302.4908$</td>
<td>$\nu^\mu_\mu: 1802.05078$ $\nu^\mu_\mu: 1602.03652$ $\nu^\mu_\mu: 1503.07452$ $\nu^\mu_\mu: 1411.6264$</td>
<td>$\nu^\mu_\mu: 1604.04406$</td>
</tr>
<tr>
<td>Fe</td>
<td>$\nu^\mu_\mu: 1509.06940$ $[\nu^\mu_\mu: 1407.4256]$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NC Elastic | NC π | CC: Charged Current
H$_2$O      | $\nu^\mu_\mu: 1403.3140$ | $\nu^\mu_\mu: 1704.07467$ | NC: Neutral Current
(A) T2K measurement of $\nu_\mu$ CC inclusive cross section on CH

- Signal event: 1 $\mu^-$, 4$\pi$ phase space  [arXiv:1801.05148 to appear in PRD]

Better resemblance to SK acceptance
(A) T2K measurement of $\nu_\mu$ CC inclusive cross section on CH

- Signal event: 1 $\mu^-$, \textbf{4$\pi$ phase space} [arXiv:1801.05148 to appear in PRD]
(A) T2K measurement of $\nu_\mu$ CC inclusive cross section on CH

- Signal event: 1 $\mu^-$, **4π phase space** [arXiv:1801.05148 to appear in PRD]

- **First measurement on backward direction**
- Nominal NEUT and GENIE have consistent predictions, both describing data
(B) T2K measurement of $\nu_\mu$ CC0\pi cross section on water


Cross section on water obtained by subtraction:

$$H_2O = (CH+H_2O) - CH = WaterIn - WaterOut$$
(B) T2K measurement of $\nu_\mu$ CC0$\pi$ cross section on water


- Dominant signal channel in SK, important systematics in C/O difference.
- Model deficit at high-angle region
- C/O difference mainly at high angle

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(C) T2K measurement of $\nu_\mu$ NC1$\pi^0$ cross section on water

- Signal event: 0 $\mu^-$, 1 $\pi^0$, no other mesons, restricted ph [Phys.Rev. D97 (2018) 032002]

- P0D as target, same subtraction scheme

- One of the largest background sources for $\nu_e$ appearance in SK
- $\pi^0$ on water by subtraction $106 \pm 41$ (stat) $\pm 69$ (sys) events
- Measured/NEUT = $0.68 \pm 0.26$ (stat) $\pm 0.44$ (sys) $\pm 0.12$ (flux) $\rightarrow$ consistent within errors
Transverse kinematic imbalances

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

Convolution of Fermi motion and Intra-nuclear Momentum Transfer (IMT) due to FSI, resonance production, 2p2h etc.

Stationary nucleon target

Nuclear target

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Fermi motion 
Intra-nuclear momentum transfer (IMT) in resonance production, 2p2h and FSI

Separation of nuclear effects:

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

- Signal event: 1 $\mu^{-}$, 0 $\pi$, at least 1 p, restricted ph [arXiv:1802.05078 to appear in PRD]

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(D) T2K measurement of single-transverse kinematic imbalances ($\nu_\mu$ CCNP$0\pi$ CH)

- Signal event: 1 $\mu^-$, 0 $\pi$, at least 1 p, restricted ph [arXiv:1802.05078 to appear in PRD]

Fermi motion: Spectral Function (SF) is preferred

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IMT: 2p2h on top of SF is needed
Transverse boosting angle – non-flatness indicates strength of IMT:
Mild strength of IMT at T2K energy

*Signal event: 1 $\mu^-$, 0 $\pi$, at least 1 p, restricted ph [arXiv:1802.05078 to appear in PRD]*
Nuclear Effect Diagnostics

- Initial state
- Final state
- Non-exclusive dynamics
- Energy dependence

1) T2K measured $\delta \alpha_T$ at $\langle E_\nu \rangle = 0.6$ GeV on same target with slightly different signal phase space definitions.

2) Difference in upper quadrant indicates different IMT strength.

3) Sensitivity to isospin assignment ($T=0, 1$) in GiBUU 2p2h model.

- T2K data: arXiv:1802.05078 to appear in PRD, see also my T2K talk tomorrow

74. MINERvA Cross Section Results

- Xianguo Lu
- 14/08/2018, 14:00
- WG1+WG2
Summary

- Neutrino-nuclear cross section measurements important for oscillation analysis.
- New measurements of neutrino interactions
  - Inclusive
    (A) $1\,\mu^-,\,4\pi$ phase space, CH
  - Semi-inclusive
    (B) $1\,\mu^-,\,0\,\pi$, restricted phase space, $H_2O$
    (C) $0\,\mu^-,\,1\,\pi^0$, restricted ph, $H_2O$
    (D) $1\,\mu^-,\,0\,\pi$, at least 1 p, restricted ph., CH
  - (previous results on exclusive measurement: coherent pion production [Phys.Rev.Lett. 117 (2016) 192501])
- More cross section results:
  135. T2K Cross Section Model / Oscillation Needs
  Clarence Wret (University of Rochester)
  17/08/2018, 14:30
  WG2

- Extensive program at ND280 to improve SK measurements
  - Phase space
  - Signal/background channels
- New measurement of single-transverse kinematic imbalances
  - Surgical diagnostics of nuclear effects
  - More on final-state correlations:
    74. MINERvA Cross Section Results
    Xianguo Lu
    14/08/2018, 14:00
    WG1+WG2
- Near Detector Upgrade see next talk:
  28. T2K Near Detector Upgrades and Plans for T2HK
  Thorsten Lux
  15/08/2018, 10:20
  Plenary VI
BACKUP
(D) T2K measurement of $\nu_\mu \text{CC} \pi^+$ cross section on water

- Signal event: 1 $\mu^-$, 1 $\pi^+$, no other mesons, restricted ph [Phys.Rev. D95 (2017) 012010]

Xianguo Lu, Oxford
(D) T2K measurement of $\nu_\mu$ CC1$\pi^+$ cross section on water

- Signal event: $1\mu^-$, $1\pi^+$, no other mesons, restricted ph [Phys.Rev. D95 (2017) 012010]

- One of signal channels in oscillation analyses
- NEUT agrees with data; GENIE over data by $2\sigma$ in normalization
FIG. 17. The extracted differential cross section as a function of the single transverse variables compared to: the GENIE 2.12.4 simulation (left) and the GIBUU 2016 simulation (right). GENIE uses the Bodek and Richie RFG initial state model and this prediction also includes GENIE’s empirical 2p2h prediction (2p2h$_E$). This GENIE prediction is similar that used as a starting point for the NOνA experiment’s oscillation analyses. More details of these models can be found in Sec. IV A. The inlays on the plots show a close-up of the tail regions of $\delta p_T$ and $\delta \phi_T$. 

END