Cross-section measurements at T2K

L. Koch for the T2K collaboration
III. Physikalisches Institut B, RWTH Aachen University
Rencontres du Vietnam, Neutrinos 2017-07-19
The T2K experiment
Tokai To Kamioka

- 300 km baseline, neutrino beam experiment
- Super-Kamiokande, 50 kt water, Cherenkov ring detector
- First to see $\nu_e$ appearance in $\nu_\mu$ beam
- Hints at Normal Mass Hierarchy, maximal CP-violation
- See talk "Recent Results from T2K" by Simon Bienstock on Tuesday
Why cross sections?

Nuclear effects

- Kinematic $\nu$ energy reconstruction
- Particle momentum under detection threshold $\Rightarrow$ invisible
- Correction using nuclear interaction models
- Source of systematic uncertainties
- Really interesting physics!
Near Detector ND280

- 280 m downstream from graphite target
- Characterises un-oscillated neutrino beam
- Cross-section measurements on different materials
- Designed for interactions in solid, scintillating detectors (e.g. Fine Grained Detectors, FGDs) and passive water targets
- Particle identification in three large Time Projection Chambers (TPCs)
- Inner detectors surrounded by Electromagnetic Calorimeters (ECALs)
Double-differential CC inclusive: $\nu_\mu + A \rightarrow \mu^- + X$, binned in $p_\mu$ and $\cos(\theta_\mu)$

Target material: FGD1, plastic (C[86%], H[7%], O[4%], Ti[2%], Si[1%])$^1$

$^1$mass fractions
**4π Charged Current inclusive measurement**

**Efficiencies and purities**

- Different acceptances of near and far detector cause systematic uncertainties
  - Super Kamiokande is symmetric, homogeneous
    - Full 4π acceptance
  - ND280 is “more complicated”
    - Used to be sensitive to forward-going muons only
- New 4π selection fixes this
  - Now can see “everything”
  - Backward efficiency lower than forward

<table>
<thead>
<tr>
<th>Purities</th>
<th>FWD</th>
<th>BWD</th>
<th>HAFWD</th>
<th>HABWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>vμ CC</td>
<td>89%</td>
<td>73%</td>
<td>82%</td>
<td>79%</td>
</tr>
<tr>
<td>¯νμ/νν/¯νν CC or NC</td>
<td>6%</td>
<td>2%</td>
<td>6%</td>
<td>3%</td>
</tr>
<tr>
<td>Out of FV</td>
<td>4%</td>
<td>22%</td>
<td>11%</td>
<td>17%</td>
</tr>
<tr>
<td>Sand μ</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

(HA = High Angle)
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Transverse variable measurement
Charged Current $0\pi + Np$ on plastic (FGD1)

\[ \nu_\mu + A \rightarrow B + \mu^- + N \times p \]

- Proton kinematics offer additional insight into neutrino interactions
- QE interaction with nucleon at rest should produce balanced transverse momentum
- All deviations from balance indicate nuclear effects
- Signal definition:
  - $p_\mu > 250 \text{ MeV}/c$
  - $\cos(\theta_\mu) > -0.6$
  - $450 \text{ MeV}/c < p_p < 1000 \text{ MeV}/c$
  - $\cos(\theta_p) > 0.4$
Transverse variable measurement

Results

Generator Comparisons

- Plenty of separation
- Result disfavours a `Fermi cliff' in $\delta p_T$
- GENIE shape in first bin of each STV related to FSI model
- Nuclear effect isolation
Gas interactions
Lowering the threshold

- CC inclusive: $\nu_\mu + A \rightarrow \mu^- + X$
- Target material: “T2K gas” (Ar[95%], CF4[3%], iC4H10[2%])
- Active, low density target
  - Low particle detection threshold
  - Low statistics
- Primary design goal of TPCs was identifying particles from FGDs
  - $A/V$ not ideal
  - Dead volumes inside TPCs
- Needed complete rewrite of reconstruction software
- Challenging but worthwhile

\(^a\)volume fractions
Gas interactions
MIP efficiencies

HMM = Highest Momentum MIP ($\mu^-$, $\pi^-$)

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Gas interactions
Proton efficiencies

- Very basic PID based on TPC dE/dx and momentum

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Low statistics and complicated efficiencies make unfolding difficult
- Efficiency depends on muon momentum, muon angle, additional particles at the vertex, ...

Will try “forward-folding” approach
- Use response matrix to bring theory to reco space
Gas interactions
Analysis approach

- Low statistics and complicated efficiencies make unfolding difficult
  - Efficiency depends on muon momentum, muon angle, additional particles at the vertex, ...
- Will try “forward-folding” approach
  - Use response matrix to bring theory to reco space
• Data not unblinded yet
• Compare Genie 2.8.0 (fake data) with Neut 5.3.2 (stacked histograms)
• Area normalised
• Efficiency and purity \(\sim 50\%\)
• Huge increase of purity when looking at identified protons w/ \(p_{\text{reco}} > 100\text{ MeV/c}\)
Conclusion and Outlook

- T2K cross-section program is progressing nicely
  - Not covered here: Water target, $\nu_e$, $\bar{\nu}_\mu$, ratios...
  - Even more: INGRID, WAGASCI, Emulsions...
- Pushing the limits of our detectors
  - Improving old measurements
  - Trying new measurements
- Proton kinematics open up a new window to nuclear effects
- Gaseous TPC will offer unprecedented look at low-momentum particles

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K. Abe et al. (T2K Collaboration) Phys. Rev. D 95, 012010 Published 26 January 2017
Thank you!
Backup
Robust cross-section measurement (same results with two models).
• Model dependence for forward going, low-momentum muons
• Higher momentum pions misidentified as muons
• Pion distribution differs between generators
• WIP
Transverse variable measurement
Discrimination power

• Distributions sensitive to multiple nuclear effects
• Bonus points: Not affected by $M_A$
  – See “MiniBooNE $M_A$ puzzle”
Gas Interaction
Muon efficiency vs momentum

True lepton momentum / [MeV/c]

$V_{\mu \text{-gas-CC}}^{\text{inc}}$

efficiency

$\mu_{\nu}$

>50 MeV/c

>100 MeV/c

>150 MeV/c

>200 MeV/c

>50 MeV/c

>100 MeV/c

>150 MeV/c

>200 MeV/c

T2K work in progress
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**Result:** Flux-integrated double-differential $\text{CC0}^\pi$ cross section on water in final state muon kinematic variables [$p_\mu$, $\cos(\theta_\mu)$]

- $0.600 \leq \text{True}-\mu \cos\theta_\mu < 0.700$
- $0.975 \leq \text{True}-\mu \cos\theta_\mu < 1.000$

5.8 x $10^{20}$ P.O.T. in Neutrino mode

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**T2K Preliminary**

**detector**
**mass**
**flux**
**cross-section**
**fsi**
**statistical (mc)**
**statistical (data)**
**NEUT (tuned)**
**data (unfolded)**
**GENIE**

**CC0$\pi$ on water** $0.975 < \cos(\theta_\mu) < 1$
**CC0$\pi$ on carbon** $0.980 < \cos(\theta_\mu) < 1$

**T2K Preliminary**
Excl. flux error
Select highest momentum positive track ($\mu^+$) from FGD-TPC:
- Quality cuts, particle ID, and veto cuts are then applied
- A control sample is used to minimize protons
  - Can be difficult to distinguish from muons at 1 – 2 GeV

4.29 x $10^{19}$ P.O.T. in Antineutrino mode
Analysis uses FGD1 data in RHC ($\bar{\nu}$) mode

- Good agreement w/ both NEUT & GENIE
- 4.29 x $10^{19}$ P.O.T. in Antineutrino mode
Splitting $\nu_e$ CC events into $\nu_e$ CC $0\pi$ and $\nu_e$ CC other sub-samples

Split $\nu_e$ CC sample according to the particles that exit the nucleus (i.e. after FSI)

* Michel/delayed electrons
* track multiplicity (+ TPC PID)

$\nu_e$ CC 0\pi (no mesons exit nucleus)

$\nu_e$ CC other (Any $\nu_e$ CC that is not CC 0\pi)

\[ \nu - \text{beam selection: T2K Run 2010 – 2013 (~6x10^{20} POT \nu - \text{beam)} } \]

NOTE: plot does not include recent run period → increased stats for measurement