Measurement of neutrino interactions in the T2K near detector

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Overview

- The T2K Experiment
- Cross sections at T2K
- ND280 cross-section measurements and results
  - Focus on $\nu_\mu$ CCQE-like analyses
- Ongoing analyses and future work
- Summary
The T2K Experiment

Beam power continuously improving!

\[ \sim 500 \text{ kW} \text{ in 2018 is double the 2014 value of } \sim 225 \text{ kW} \]

POT = Protons On Target

23 Jan. 2010 – 31 May 2018

POT total: \(3.16 \times 10^{21}\)

- \(\nu\)-mode: \(1.51 \times 10^{21} \text{ (47.83\%)}\)
- \(\bar{\nu}\)-mode: \(1.65 \times 10^{21} \text{ (52.17\%)}\)
T2K latest oscillation results

Presented at NEUTRINO 2018:

$2\sigma$ confidence intervals

→ The significance to exclude CP conservation is greater than $2\sigma$!

Run 1-9c preliminary, measured oscillation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reactor</th>
<th>Best-fit (NH)</th>
<th>±1σ (NH)</th>
<th>Best-fit (IH)</th>
<th>±1σ (IH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{CP}$</td>
<td>Yes</td>
<td>-1.822</td>
<td>[-2.412,-1.169]</td>
<td>-1.382</td>
<td>[-1.925,-0.898]</td>
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<tr>
<td>$\delta_{CP}$</td>
<td>No</td>
<td>-2.011</td>
<td>[-2.738,-1.192]</td>
<td>-1.257</td>
<td>[-1.949,-0.635]</td>
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<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>No</td>
<td>0.0268</td>
<td>[0.0222,0.0319]</td>
<td>0.0305</td>
<td>[0.0253,0.0369]</td>
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<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>Yes</td>
<td>0.536</td>
<td>[0.490,0.567]</td>
<td>0.536</td>
<td>[0.495,0.567]</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$ or $\Delta m^2_{13}$ $(10^{-3} \text{ eV}^2/\text{c}^4)$</td>
<td>Yes</td>
<td>2.434</td>
<td>[2.370,2.498]</td>
<td>2.410</td>
<td>[2.347,2.472]</td>
</tr>
</tbody>
</table>
The ND280 off-axis detector

Characterise the unoscillated neutrino beam and measure neutrino cross sections

- Scintillator-based $\pi^0$ detector (P0D), water target (+ brass and lead targets)
- Trackers:
  - Time Projection Chambers (TPC) : momentum reconstruction and particle identification
  - Fine-Grained Detectors (FGD) : CH scintillator, FGD2 also contains water, carbon and water targets
- Electromagnetic Calorimeter (ECAL), Side Muon Range Detector (SMRD) and 0.2 T magnet

anti-neutrino event in FGD2 on the ND280 event
Why are cross sections important for the oscillation analysis?

1. To reduce the cross-section uncertainties on the event rate at Super-K.
2. To control the bias on the reconstructed energy.

NB: Oscillation fit now done in the lepton kinematics variables \((p, \theta)\), energy extracted from models.

- Oscillation analysis requires neutrino energy spectrum
- \(E_\nu\) reconstructed using observed lepton \(\ell\) kinematics, assuming stationary target (a nucleon) and elastic scattering:
  \[
  E_{\nu}^{\text{reco}} = \frac{m_p^2 - m_n^2 - m_\ell^2 + 2m_nE_\ell}{2 \left(m_n - E_\ell + p_\ell \cos \theta_\ell \right)}
  \]

Bias due to Fermi motion, and non-elastic components:
- Meson exchange current (2p2h)
- Final State Interactions (FSI)
- Nucleon correlations

→ biased or unrealistic sensitivity to the oscillation parameters
Neutrino Charged-Current (CC) interactions at T2K

→ Charged-Current Quasi-Elastic (CCQE) interactions are dominant at T2K.

Nuclear effects

Free Nucleon + Fermi Motion + 2p2h + Final State Interaction (FSI)
What can we measure?

→ Nuclear effects can hide the interaction mode.
→ To minimise the model dependence: measurements based on interaction topologies.

Interaction modes in CC0π topology:

- CCQE
- CCRES
- 2p2h

CC0π + Np (N>0)

(NEUT MC)

LCQE 80.60%
CCRES 6.91%
2p2h 12.11%
Other 0.38%

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**Neutrino MC Generators**

Results are compared to some/all of the NEUT, GENIE, NuWro and GiBUU interaction simulations.

- All contain plausible and widely used models
- GENIE (in the versions shown) does not include a multi-nucleon correlation model
- GiBUU is more theory driven whilst NEUT, GENIE and NuWro tune models to previous data

- **GENIE** - http://www.genie-mc.org
- **NuWro** - http://nu.ift.uni.wroc.pl/nuwro/
- **GiBUU** - https://gibuu.hepforge.org/trac/wiki
**νμ CC0π interactions on carbon with FGD1**


- Flux-integrated double-differential cross section in final-state **muon kinematic** variables \( p_\mu, \cos \theta_\mu \)

![Graphs showing analysis II](image)

- Two analyses performed, I **Binned likelihood fit** and II **D’Agostini iterative unfolding**

  Unfolding: deconvolution of physics and detector effects


Comparison to 2p2h Nieves and 2p2h Martini models, not including CCRRes + pion absorption FSI, with and w/o 2p2h

\[ \text{Data / MC discrepancies indicates missing contributions, from nuclear interactions (?)} \]
$\nu_\mu$ CC0\pi interactions on water with P0D

Phys. Rev. D 97, 012001 (January 2018)

- Measure flux-integrated double-differential cross section in $p_\mu, \cos \theta_\mu$
- D’Agostini iterative unfolding

- P0D water layers can be filled or drained: "water-in" or "water-out" modes → subtraction to get cross section on water

→ Comparison of P0D result on water (black) to FGD1 result on carbon (red)
Difference: Important to reduce systematic uncertainty in the oscillation analysis
$\nu_\mu$ CC0π + Np interactions on carbon with FGD1

arXiv:1802.05078

- Muon kinematics → only information about $\nu + N$ scattering assuming a stationary target and an elastic scattering
- Proton kinematics → new handle on **nuclear effects**

- Measure **flux-integrated** cross section in bins of $\cos \theta_\mu$, $\cos \theta_p$, $p_p$
- Binned **likelihood fit**
- Phase space : $p_p > 500$ MeV/c
- Allows simultaneous extraction of number of protons

![Graphs showing cross sections and likelihood fits](image-url)

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Latest T2K Cross-Section Results
$\nu_\mu$ CC0\pi + Np interactions on carbon with FGD1

arXiv:1802.05078

Proton kinematics using \textbf{transverse kinematic imbalance}

- Measure \textbf{flux-integrated} cross section in bins of \textbf{Single Transverse Variables} (STV) with a likelihood fit
- If no nuclear effect: $p_T^l = -p_T^p$
- Deviation from $\delta p_T = 0$, $\delta \phi_T = 0$ → nuclear effects

STVs offer an interesting probe of \textbf{nuclear effects} (Phys. Rev. C 94, 015503)

- Results strongly disfavour a simple Fermi-gas nuclear model, favour a 2p2h-like contribution

\begin{align*}
\nu_\mu + A &\rightarrow B + \mu^- + N \times p
\end{align*}
$\nu_\mu$ CC incl. on carbon with FGD1, 4\pi angular coverage

- ND280 used to be sensitive to forward-going $\mu$ only but Super-K has a full 4\pi acceptance $\rightarrow$ systematic uncertainty
- More nuclear effects in backward tracks
- 4\pi selection including **high-angle and backward** tracks in ND280 $\rightarrow$ fixes this issue
CC0π $\bar{\nu}_\mu$ interactions on water with P0D

- Measure flux-integrated $\bar{\nu}_\mu$ cross section in bins of $p_\mu$, $\cos \theta_\mu$
- Binned likelihood fit

CC0π $\nu_\mu + \bar{\nu}_\mu$ joint analysis, interactions on carbon with FGD1

- Measure flux-integrated $\nu_\mu$ and $\bar{\nu}_\mu$ cross section in bins of $p_\mu$, $\cos \theta_\mu$
- Binned likelihood fit with samples of neutrino and anti-neutrino
- Nuclear effects are affecting differently $\nu$ and $\bar{\nu}$
What I am working on for my thesis!

- Measure flux-integrated cross section on water, carbon, and their ratio, in bins of $p_\mu, \cos \theta_\mu$
- Binned likelihood fit with samples from FGD1 and FGD2:
  - FGD2 contains alternate layers of water and carbon.
  - Adding FGD1 (only carbon) improves the precision on carbon interaction measurement and the anticorrelation between events in water and carbon.

Ongoing:
- Fit validation
- Different improvements on the control samples, vertex backward migration,...
Summary

• Understanding neutrino-nucleon interactions is essential to interpret the results in oscillation analyses, T2K is very involved in development of new models.

• T2K detectors allow for a large variety of cross-section measurements
  → Many recent interesting results have been published.

• New techniques are developed to improve previous results and try new measurements:
  - first measurements using proton kinematics
  - extension to $4\pi$ angular coverage
  - anti-neutrino mode measurements

• Recent preliminary results are getting prepared to be published, stay tuned!
Thank you!

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BACKUPS
$\nu_\mu$ CC0\pi selection in FGD1 and FGD2

- **Signal region:**
  4 samples depending on the topology:

- **Background:**
  2 control regions, to constrain the backgrounds CC1\pi and CC-other (DIS, Res)

$\rightarrow$ **Fit** the number of selected events of the 4 + 2 samples to MC predicted number of events in each ($p_\mu$, $\theta_\mu$) bin.

$p_\mu$, $\theta_\mu$ distributions in FGD1
\(\nu_\mu\) CC-inclusive interactions on carbon with FGD1

\(\nu_e\) CC-inclusive interactions on carbon with FGD1

\(\nu_\mu\) CC coherent pion production on carbon with FGD1

\(\nu_\mu\) CC1\(\pi\) interactions on water with FGD2

\(\nu_\mu\) and anti-\(\nu_\mu\) CC-inclusive interactions on water with P0D

\(\nu_\mu\) CC1\(\pi\) interactions on carbon with FGD1
Paper in preparation
\( \nu_\mu \) and \( \bar{\nu}_\mu \) CC-inclusive interactions on water with P0D


- Measure the \( \nu_\mu \) and \( \bar{\nu}_\mu \) cross sections and their ratio.

Open squares: MC model predictions (1) NEUT with a default spectral function [37], (2) RFG model, (3) RFG model with RPA corrections and (4) RFG with RPA corrections and 2p2h interactions

Solid circle: Data results with error bars
The INGRID on-axis detector

Monitor beam direction and track beam rate

- Proton module: CH target
- INGRID modules: scintillator and iron
  → Carbon and iron targets
$\nu_\mu$ CCQE interactions on carbon with INGRID Proton Module


$\nu_\mu$ CC-inclusive interactions on iron and carbon with INGRID

T2K Neutrino flux

Neutrino Mode Flux at ND280

Antineutrino Mode Flux at ND280

Neutrino Mode Flux at SK

Antineutrino Mode Flux at SK
$\nu_\mu$ CC$0\pi$ interactions on carbon with FGD1


- Comparison of the two analysis results (likelihood fit VS D’Agostini iterative unfolding)