Neutrino-Nucleus Interaction Cross-Section Measurements at T2K

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Overview

• Brief introduction to T2K experiment and the near detectors

• Highlights from recent cross-section measurements at the T2K near detectors: variety of measurements on different targets, fluxes, detectors, neutrino and anti-neutrino flavours – **test T2K cross-section model and uncertainties on multiple neutrino spectra**
  - CC-\(\nu_e\) and CC-\(\bar{\nu}_e\) inclusive on plastic (2.5° off-axis detectors)
  - NC single gamma production (2.5° off-axis detectors)
  - CC-\(\nu_\mu\) 0\(\pi\) on plastic and water (2.5° off-axis detectors)
  - CC-\(\nu_\mu\) charged-current inclusive on plastic, water and iron (On-axis detectors)
  - CC-\(\bar{\nu}_\mu\) 0\(\pi\) 0proton on plastic and water (1.5° off-axis detectors)

• Summary
T2K long-baseline neutrino oscillation experiment in Japan

- Off-axis narrow band $\nu_\mu$ beam to far and near detectors
  - Enhanced signal at oscillation maximum
  - Reduce high-energy tail background
- Measurements of the $\nu_e$ appearance and $\nu_\mu$ disappearance
- Currently searching for CP-violation in the neutrino sector

See Laura Kormos talk from Friday morning
T2K accumulated protons-on-target (POT)

23 Jan. 2010 – 31 May 2018

POT total: $3.16 \times 10^{21}$

$\nu$-mode $1.51 \times 10^{21} \ (47.83\%)$

$\bar{\nu}$-mode $1.65 \times 10^{21} \ (52.17\%)$
Importance of neutrino cross-sections to neutrino oscillations

- Good neutrino interaction model is essential to reduce neutrino oscillation systematic uncertainties
  - Need a variety of measurements on different targets and for all neutrino and anti-neutrino flavours
- Differences between near – far detectors
  - Target, acceptance, flux

TABLE I. Systematic uncertainty on far detector event yields.

<table>
<thead>
<tr>
<th>Source</th>
<th>(\nu_\mu)</th>
<th>(\nu_e)</th>
<th>(\nu_{\mu\pi}^+)</th>
<th>(\bar{\nu}_\mu)</th>
<th>(\bar{\nu}_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-unconstrained cross section</td>
<td>2.4</td>
<td>7.8</td>
<td>4.1</td>
<td>1.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Flux &amp; ND280-constrained cross sec.</td>
<td>3.3</td>
<td>3.2</td>
<td>4.1</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>SK detector systematics</td>
<td>2.4</td>
<td>2.9</td>
<td>13.3</td>
<td>2.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Hadronic re-interactions</td>
<td>2.2</td>
<td>3.0</td>
<td>11.5</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td>Total</td>
<td>5.1</td>
<td>8.8</td>
<td>18.4</td>
<td>4.3</td>
<td>7.1</td>
</tr>
</tbody>
</table>

11 – 14 % before near detector constraints

Neutrino charged-current quasi elastic (CCQE) – T2K far detector golden channel
Neutrino cross-section measurements at the T2K near detectors at $2.5^\circ$ off-axis
Near detector at $2.5^\circ$ off-axis (ND280)

- $2.5^\circ$ off-axis to measure neutrino interactions and estimate the background contamination
- Refurbished UA1 magnet - 0.2T field
- Front optimized to measure $\pi^0$ interactions (P0D) on water/plastic
- Rear optimized to measure charged-current interactions
  - 2 Fine-Grained Detectors (FGD)
    - First is plastic (FGD1), the other is plastic + water (FGD2)
  - 3 Time Projection Chambers (TPC) following the P0D and the FGDs
    - Tracking, dE/dx
- Surrounded by the electromagnetic calorimeter and muon detector

Electron (anti-)neutrinos at ND280

- First T2K CC-$\nu_e$ cross-section measurement on plastic published in 2014 (Phys. Rev. Lett. 113, 241803, 2014)

- New measurement with twice the neutrino mode statistics and including the anti-neutrino mode data until 2017
  - First CC-$\bar{\nu}_e$ measurement after Gargamelle in 1978

- Challenging analysis
  - $\nu_e$ is only $\sim$1.5% of the neutrino beam
  - Perfect particle identification to select electrons and remove muons, pions and protons
  - Large ($\pi^0$) backgrounds from charged-current and neutral-current $\nu_\mu$ interactions in and outside the FGDs
  - CC-$\bar{\nu}_e$ selection in neutrino mode is currently not used due to tiny statistics and low purity

- CC-$\nu_e$/CC-$\bar{\nu}_e$ is the only irreducible background at the far detector neutrino analyses for $\nu_e$ ($\bar{\nu}_e$) appearance
CC-$\nu_e$ and CC-$\bar{\nu}_e$ inclusive selections in FGD1

- Low momentum region is dominant by the gamma background
  - Data – MC discrepancy but large systematic uncertainties
  - $\sim 1/3$ of the gamma background is coming from external photons

- Gamma background in each selection is controlled by an independent control sample selecting e-e+ pairs
CC-$\nu_e$ and CC-$\bar{\nu}_e$ inclusive cross-sections on plastic

- CC-$\nu_e$ and CC-$\bar{\nu}_e$ selections and their corresponding gamma control samples are fitted simultaneously.
- Limited phase-space ($\theta < 45^\circ$ and $p > 300$ MeV/c) due to detector acceptance effects.
- Cross-section results agree within errors with the Neut and Genie neutrino generator models.

See also poster 761
NC single photon production

- Select FGD1 – TPC e-e+ pairs with low invariant mass

- Background dominant from NC $1\pi^0$ and external photons


Important background process for the far detector electron-neutrino appearance searches
$\nu_\mu$ CC-0$\pi$ cross-section measurement on plastic and water

- Combined FGD1 + FGD2 analysis
- For FGD2 split events in two samples based on the interaction vertex to get a water enriched sample
- Extract the cross-sections using a simultaneous fit including all FGD1 and FGD2 samples
$\nu_\mu$ CC-0π cross-section results on plastic

T2K Preliminary
$\nu_\mu$ CC-0π results cross-section results on water

T2K Preliminary
CC-$\nu_\mu$ 0$\pi$ water/plastic ratio

T2K Preliminary
Neutrino cross-section measurements at the T2K near detectors on-axis
Near detectors on-axis

- INGRID
  - Continuous beam monitor
  - Iron (96%)

- Proton module
  - Plastic scintillator
  - $5.89 \times 10^{20}$ POT collected in neutrino mode

- Water module
  - Water (80%) + plastic (20%)
  - $7.25 \times 10^{20}$ POT collected in neutrino mode

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CC-$\nu_\mu$ charged-current cross sections on water, hydrocarbon and iron

- Phase-space
  - $p_\mu > 0.4$ GeV/c and $\theta_\mu < 45^\circ$
- First neutrino cross-section ratios for water / CH and water / iron
- Most precise neutrino cross-section measurement on water in the low-GeV energy range
Neutrino cross-section measurements at the T2K near detectors at 1.5° off-axis
Near detectors at 1.5° off-axis

- Vertex in proton module or water module
- INGRID is used for muon tracking
- Detector system is not magnetized
  - No separation between neutrinos and anti-neutrinos
- $7.91 \times 10^{20}$ POT collected in anti-neutrino mode from October 2017 until May 2018

See also next talk by Etam Noah
CC-$\nu_{\mu}$ 0π 0proton selection

- Neutrino vertex either in WAGASCI or proton module

- Phase-space
  - $p_\mu > 0.4$ GeV/c and $\theta_\mu < 30^\circ$
  - No pions: $p_\pi > 0.2$ GeV/c and $\theta_\pi < 70^\circ$
  - No protons: $p_p > 0.6$ GeV/c and $\theta_p < 70^\circ$

- Large neutrino background with larger cross-sections
  - Measure both CC-$\nu_{\mu}$ and CC-$\bar{\nu}_{\mu}$ + CC-$\nu_{\mu}$ cross-sections
CC-\bar{\nu}_\mu 0\pi 0\text{proton cross-section measurement on plastic and water}

T2K Preliminary
CC-$\bar{\nu}_\mu$ + CC-$\nu_\mu$ 0π 0proton cross-section measurement on plastic and water
CC-$\nu_\mu$ + CC-$\bar{\nu}_\mu$ 0π 0proton cross-section water/plastic ratio

T2K Preliminary
Previous T2K cross-section measurements


- First measurement of the $\nu_\mu$ charged-current cross section without pions in the final state on a water target (Phys.Rev. D97, 012001, 2018)


- First Measurement of the Muon Neutrino Charged Current Single Pion Production Cross Section on Water with the T2K Near Detector (Phys.Rev. D95, 012010, 2017)


- Measurement of double-differential muon neutrino charged-current interactions on C8H8 without pions in the final state using the T2K off-axis beam (Phys.Rev. D93, 112012, 2016)

- Measurement of the $\nu_\mu$ inclusive charged-current cross section in the energy range of 1-3 GeV with the T2K INGRID detector (Phys.Rev. D93, 072002, 2016)

- Measurement of the $\nu_\mu$ charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam (Phys. Rev. D 91, 112002, 2015)

- Measurement of the $\nu_\mu$ CCQE cross section on carbon with the ND280 detector at T2K (Phys. Rev. D 92, 112003, 2015)

- Measurement of the inclusive $\nu_\mu$ charged current cross section on iron and hydrocarbon in the T2K on-axis neutrino beam (Phys. Rev. D 90, 052010, 2014)


- Measurement of the neutrino-oxygen neutral-current interaction cross section by observing nuclear deexcitation γ rays (Phys. Rev. D 90, 072012, 2014)

Summary

- **T2K has a rich and unique neutrino cross-section program**
  - Different neutrino fluxes (on-axis, different off-axis angles), targets, detectors, neutrino and anti-neutrino flavours
  - Vital to reduce systematic uncertainties for the neutrino oscillation measurements and CP-violation searches
  - Also important for the design of the next generation of long baseline neutrino oscillation experiments

- Highlights of the 2019 T2K cross-section measurements presented in this talk

- Many more to come...
BACK UP
**MW Proton Facility: J-PARC**

**Unique facility**

3 GeV + 30 GeV

Multi-purposes

- Materials and life sci.
- Nucl. and part. phys.
- Nucl. transmutation

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**J-PARC = Japan Proton Accelerator Research Complex**
Gamma control samples for CC-$\nu_e$ selections

- Select FGD1 – TPC e-e+ tracks with low invariant mass
- Apply same veto cuts as the CC-$\nu_e$ analysis

T2K Preliminary

T2K Preliminary

T2K Preliminary
NC single gamma processes

\[ N^* = \text{baryon resonance} \]
\[ M = \text{neutral vector meson} \]