The $\nu$ and $\bar{\nu}$ interaction rate measurements in the T2K near detector

16th June 2014, Anthony Hillairet for the T2K collaboration
The T2K experiment was designed to measure neutrino oscillations:

- $\nu_e$ appearance
  $\Rightarrow \sin^2(2\theta_{13})$

- $\nu_\mu$ disappearance
  $\Rightarrow \sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$

- look for CP violation in the neutrino sector
The T2K detection system is composed of multiple components:

- INGRID, near detector on-axis for neutrino beam monitoring
- Super-Kamiokande (SK) at 295km and off-axis to detect neutrinos after oscillation
- ND280, near detector off-axis measures neutrino interaction rate of the unoscillated beam going to SK
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ND280, the T2K off-axis near detector

ND280 measures the characteristics of the unoscillated neutrino beam:

- 0.2T magnetic field
- Central component is the tracker
  Composed of 3 TPCs and 2 FGDs
- $\pi^0$ dedicated detector
  $\Rightarrow$ P0D
- Electromagnetic calorimeters
  $\Rightarrow$ ECAL
- Yoke instrumented with scintillators
  $\Rightarrow$ Side Muon Range Detectors (SMRDs)
Fine-Grained Detectors (FGDs)

- 2 FGDs serving as active targets
  - FGD1: Layers of X and Y scintillator bars
  - FGD2: Layers of X and Y scintillator bars alternated with water layers
  - Provides detailed vertex information
  - Multi-Pixel Photon Counter

Made at TRIUMF
3 identical TPCs:
- filled with argon (95%), CF$_4$ (3%), isobutane (2%)
- MicroMegas detectors
- Perform momentum reconstruction and particle identification

\[ \text{Probability of identifying } \mu \text{ as electron } < 0.2\% \ (p < 10\text{GeV/c}) \]
Neutrino interactions of interest

To characterize the $\nu_\mu$ component of the beam, we start by looking for $\mu^-$ from charged-current (CC) interactions

$\nu \rightarrow CC$ inclusive selection

Due to pion absorption before it leaves the nucleus, we analyzes the CC events according to the topologies of various number of outgoing pions:

- **CC0$\pi$:** No pion observed
- **CC1$\pi^+$:** One positive pion observed
- **CC-Other:** All other CC interactions
One $\mu^-$ from FGD1 crossing TPC2 $\Rightarrow$ CC inclusive sample
2013 ND280 $\nu_\mu$ event selection

One $\mu^-$ from FGD1 crossing TPC2 $\Rightarrow$ CC inclusive sample

- No pions found $\Rightarrow$ CC0$\pi$ sample
- $1\pi^+$ found $\Rightarrow$ CC1$\pi^+$ sample
- $> 0\pi^0$ or
- $> 0\pi^-$ or
- $> 1\pi^+$ found $\Rightarrow$ CC-Other sample
2013 ND280 $\nu_\mu$ event selection

Particle identification using dE/dx in FGD1 and TPCs

Momentum and charge reconstruction in TPCs

One $\mu^-$ from FGD1 crossing TPC2 $\Rightarrow$ CC inclusive sample

- No pions found $\Rightarrow$ CC0\pi sample
- 1\pi^+ found $\Rightarrow$ CC1\pi^+ sample
- > 0\pi^0 or > 0\pi^- or > 1\pi^+ found $\Rightarrow$ CC-Other sample
2013 results, $6.30 \times 10^{20} POT$ of $\nu$ beam data

Data/MC distributions before any fit

<table>
<thead>
<tr>
<th></th>
<th>CC-0$\pi$</th>
<th>CC-1$\pi$</th>
<th>CC-Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC-0$\pi$</td>
<td>72.6%</td>
<td>6.4%</td>
<td>5.8%</td>
</tr>
<tr>
<td>CC-1$\pi$</td>
<td>8.6%</td>
<td>49.4%</td>
<td>7.8%</td>
</tr>
<tr>
<td>CC-Other</td>
<td>11.4%</td>
<td>31.0%</td>
<td>73.8%</td>
</tr>
<tr>
<td>Bkg (NC+$\bar{\nu}_\mu$)</td>
<td>2.3%</td>
<td>6.8%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Out FGD1 FV</td>
<td>5.1%</td>
<td>6.5%</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

Bkg (NC+$\bar{\nu}_\mu$) + Out FGD1 FV = 9.12% of CC inc.
From the 2013 to the 2014 ND280 analysis

The 2013 analysis had many limitations:

- Only FGD1 used as neutrino target
  \[\implies\] only the neutrino cross section on carbon is measured

- Only CC interactions producing forward-going muons were selected
  \[\implies\] phase space very different from Super-Kamiokande’s \(4\pi\) acceptance

Many improvements have been made to the calibration and the reconstruction software for the 2014 analysis.
FGD-ECal track matching improved $\rightarrow$ increased reconstruction efficiency for tracks not crossing the TPCs
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Events with $\mu^-$ at high angle can now be more efficiently reconstructed and selected in a CC inclusive sample.

Use momentum by range in ECals and SMRDs to get the $\mu^-$ momentum.

Pions are identified like for the 2013 analysis to create CC0$\pi^-$, CC1$\pi^+$ and CCOther samples as well.
Inter-detector timing calibration
⇒ track sense determination possible
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New possibility to select backward going $\mu^-$

Only $\sim 2000$ events in the available ND280 data
⇒ CC inclusive only, no sub-samples
The acceptance of the FGD1 selection will be greatly increased in 2014 thanks to software improvements.
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FGD2 contains water layers between the scintillator layers.

⇒ The FGD2 measurement will provide constraints on the neutrino cross section on oxygen.
New data: $\bar{\nu}$ beam mode started!

- T2K will now measure $\bar{\nu}_\mu$ disappearance, $\bar{\nu}_e$ appearance $\implies$ search for CP violation
- T2K taking data in anti-neutrino beam mode since 5th June
- First $\bar{\nu}_\mu$ event candidate found in FGD2:
ND280 $\bar{\nu}_\mu$ measurement crucial for T2K

- $\bar{\nu}_\mu$ cross section has never been measured at T2K $E_\nu$ range

- Expected $\sigma_{\bar{\nu}_\mu} \sim \frac{1}{3} \sigma_{\nu_\mu}$
  $\Rightarrow$ $\nu_\mu$ interaction rate not negligible compared to $\bar{\nu}_\mu$

- SK is a water Cherenkov detector
  $\Rightarrow$ No reconstruction of lepton charge

- ND280 has charge reconstruction from the TPCs
  $\Rightarrow$ ND280 can measure the interaction rate ratio $\bar{\nu}_\mu/\nu_\mu$
Summary

The ND280 measurements of the neutrino and anti-neutrino beams are crucial to the T2K neutrino oscillation measurement.

- The software and calibration improvements will provide a $4\pi$ acceptance and FGD2 measurement (with oxygen).
- We are getting ready to analyze the new anti-neutrino beam mode data.
- All these new measurements from ND280 will be used in a fit to improve constraints on flux and cross section at SK.

⇒ See Jordan’s talk next.
Thank you for your attention!
Improved matching of low momentum tracks from TPCs

\[ \nu \rightarrow \mu^- \text{ or } \pi^+ ? \]

increased reconstruction efficiency for out-of-fiducial volume background
Improved matching of low momentum tracks from TPCs
$\rightarrow$ increased reconstruction efficiency for out-of-fiducial volume background

Inter-detector timing can help identify backward going background

More than 90% of this background is rejected by track sense determination
Flux in anti-neutrino beam mode

Beam flux prediction

Flux (cm²/100MeV/10²POT)

$\bar{\nu}_\mu$

$\bar{\nu}_e$

$\nu_\mu$

$\nu_e$

E (GeV)
After the muon has been identified, the TPC particle identification (PID) is slightly modified:

- Possible types for negative particles: electron or pion
- Possible types for positive particles: positron, proton or pion

Special case:
if \( \text{PID} = \text{positrons} \) & \( p > 900 \text{ MeV/c} \) \( \Rightarrow \) reclassify as a proton
TPC PID for secondary tracks

e\(^+\) candidate

\(\pi^+\) candidate

\(\pi^-\) candidate

e\(^-\) candidate

Positive Pion Momentum candidate TPC (MeV/c)

Electron Momentum candidate TPC (MeV/c)
FGD PID for secondary tracks

Also in FGD1, the dE/dx information provides very good separation between protons and pions:

FGD secondary track selection:

1. Select FGD tracks fully contained in FGD1
2. Use measured dE/dx to select $\pi$-like tracks

Before FGD PID selection

After FGD PID selection
ND280 $\bar{\nu}_\mu$ measurement started in $\nu$ beam

- The $\bar{\nu}_\mu$ contamination in the neutrino beam mode was used to develop an $\bar{\nu}_\mu$ selection

- Start with 2013 CC inclusive selection but select positive muons instead

- The ECals particle identification is used to reduce the positive pions and protons background from the $\nu_\mu$ interactions

CC inclusive selection:
- Purity $\sim 50\%$
- Preliminary result show consistency with Monte Carlo prediction
ND280 $\bar{\nu}_\mu$ measurement started in $\bar{\nu}$ beam

- Again start with 2013 CC inclusive selection but selecting positive muons instead
- CC0$\pi$ sample purity at 74% even without using ECAl information
- CC1$\pi$ and CCOther have contamination from $\nu_\mu$ interactions
  \[\Rightarrow\text{ We may use a } \text{CC}n\pi, \ n > 0, \text{ sample instead}\]

\[\Rightarrow\text{ Ready to analyze data being collected now}\]