Results from ND280 Near Detectors

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On behalf of T2K collaboration
Goal of the experiment:
measurement of $\nu$ oscillations

- Appearance of $\nu_e$
  measurement of $\theta_{13}$

- Disappearance of $\nu_\mu$
  measurement of $\theta_{23}$, $\Delta m^2_{23}$

- Search for CP violation
Goals of ND280

- Flux measurement of unoscillated $\nu_\mu$ beam
- Measurement of $\nu_e$ beam contamination
- Cross sections of $\nu$ interactions
Contribution from ND280

**Neutrino flux model**
- Proton interactions with target modeled
  - With FLUKA taking into account measured
  - p, K production by NA61/SHINE @ CERN
- Verified by proton beam monitor measurements

**Neutrino cross section**
- Model with NEUT generator of n interactions
- Data driven: external neutrino, electron, pion Scattering data.

**ND280 measurement**
- Data samples enhanced with
  - Charged Current (CC) interactions with 0, 1 or multi p
- Fit to data constrains flux and cross section parameters.

Prediction of event rates at Super-Kamiokande prediction

Super-Kamiokande measurement
Near Detectors at 280m

- **Fine Grained Detectors (FGD)**
  - FGD1 scintillator detector acting as active target
  - provides vertex information
  - detects recoil protons
  - FGD2 is interlaid with water layers allows to study $\nu$ interactions on oxygen

- **Time Projection Chambers (TPC)**
  - gas argon TPC
  - momentum measurement
  - particle identification ($dE/dx$)

- **$\pi^0$ detector (P0D)**
  - Scintillator detector interlaid with water layers
  - dedicated to NC $\pi^0$ measurement

- **Electromagnetic calorimeters (Ecal)**
  - use to detect photons and reconstruct $\pi^0$ which leave FGD

- **Side Muon Range Detector (SMRD)**
  - muon tagging

- **0.2T magnetic field**

- Tracker is the central component composed of 3 TPCs and 2 FGDs
What we want to measure

- Charge Current quasi-elastic (CCQE)

- CC resonance (CCRES)

- CC Deep Inelastic Scattering (CCDIS)

To measure flux of $\nu_\mu$ beam component we are looking for interactions with $\mu^-$ produced in the tracker detector.

Divide sample into categories depending on presence of reconstructed $\pi$ tracks.
Event categories

CC 0π sample
- CC interactions without pions produced in final state, tag μ⁻
- One reconstructed π⁺ track
- π⁺ identified through dE/dx in TPC or Michel electron in FGD

CC 1π⁺ sample

CC Other sample
- Reconstructed π⁻ track or more than one charged π or π⁰ track

FGDTPCFGDTPC
FGDTPCFGDTPC
FGDTPCFGDTPC
ND280 measurement

Results from 2013 using $6.30 \times 10^{20}$ POT

**CC0π**
- 72.6% purity

**CC1π**
- 49.4% purity

**CCOther**
- 73.8% purity

Distributions of Data and MC before fit

For each category:
- $(p_\mu, \theta_\mu)$ distributions are made,
- the spectrum and cross section parameters are fitted.
ND280 fit results

Distributions of Data and MC after fit
MC was reweighted to fit results of $\nu$ spectrum and cross sections.
ND280 fit results

**νμ disappearance**

**νe appearance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior to ND280 Constraint</th>
<th>After ND280 Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$ (GeV)</td>
<td>1.21 ± 0.45</td>
<td>1.223 ± 0.072</td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV)</td>
<td>1.41 ± 0.22</td>
<td>0.963 ± 0.063</td>
</tr>
<tr>
<td>CCQE Norm.*</td>
<td>1.00 ± 0.11</td>
<td>0.961 ± 0.076</td>
</tr>
<tr>
<td>CC1π Norm.**</td>
<td>1.15 ± 0.32</td>
<td>1.22 ± 0.16</td>
</tr>
<tr>
<td>NC1π$^0$ Norm.</td>
<td>0.96 ± 0.33</td>
<td>1.10 ± 0.25</td>
</tr>
</tbody>
</table>

*For $E_\nu < 1.5$ GeV **For $E_\nu < 2.5$ GeV

Reduction of flux and cross section uncertainties with ND280 constraint.
ND280 $\nu_e$ contamination

$\nu_e$ contamination in $\nu_\mu$ beam is important for $\nu_e$ appearance analysis at SK since $\nu_e$ beam contamination is background for signal of oscillated $\nu_e$'s.

Same selection as for $\nu_\mu$ analysis, but identified track as $e^-$ instead of $\mu^-$. 

Fitted ratio on $\nu_e$ beam contamination between data and MC:

$$f(\nu_e\text{CC0}\pi) = 1.10 \pm 0.14\text{(stat.)} \pm 0.10\text{(syst.)}$$

$$f(\nu_e\text{CC1}\pi + \text{CCOther}) = 1.03 \pm 0.11\text{(stat.)} \pm 0.12\text{(syst.)}$$

Published in *Phys. Rev. D* 89, 092003 (2014)
Reduced SK prediction uncertainty

\[
\sin^2 2\theta_{13} = 0.1 \quad \text{sin}^2 2\theta_{13} = 0.0
\]

<table>
<thead>
<tr>
<th></th>
<th>(\nu_e) Prediction (Events)</th>
<th>Error from Constrained Parameters</th>
<th>(\nu_e) Prediction (Events)</th>
<th>Error from Constrained Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ND280 Constraint</td>
<td>22.6</td>
<td>26.5%</td>
<td>5.3</td>
<td>22.0%</td>
</tr>
<tr>
<td>ND280 Constraint 2012</td>
<td>21.6</td>
<td>4.7%</td>
<td>5.1</td>
<td>6.1%</td>
</tr>
<tr>
<td>ND280 Constraint 2013</td>
<td>20.4</td>
<td>3.0%</td>
<td>4.6</td>
<td>4.9%</td>
</tr>
</tbody>
</table>

Improved due to new reconstruction and selection
Effect on $\nu_e$ oscillation analysis

The predicted number of events distribution

<table>
<thead>
<tr>
<th>Event category</th>
<th>$\sin^22\theta_{13}=0.0$</th>
<th>$\sin^22\theta_{13}=0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ signal</td>
<td>0.38</td>
<td>16.42</td>
</tr>
<tr>
<td>$\nu_e$ background</td>
<td>3.17</td>
<td>2.93</td>
</tr>
<tr>
<td>$\nu_\mu$ background (mainly NC$\pi^0$)</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>$\nu_\mu + \nu_e$ background</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>Total</td>
<td>4.64</td>
<td>20.44</td>
</tr>
<tr>
<td>Total (w/ 2012 flux &amp; cross section parameters)</td>
<td>5.15</td>
<td>21.77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\sin^22\theta_{13}=0.0$</th>
<th>$\sin^22\theta_{13}=0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flux + $\nu$ int. in T2K fit</td>
<td>4.9 %</td>
<td>3.0 %</td>
</tr>
<tr>
<td>$\nu$ int. (from other exp.)</td>
<td>6.7 %</td>
<td>7.5 %</td>
</tr>
<tr>
<td>Far detector</td>
<td>7.3 %</td>
<td>3.5 %</td>
</tr>
<tr>
<td>(+FSI+SI+PN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11.1 %</td>
<td>8.8 %</td>
</tr>
<tr>
<td>Total (2012)</td>
<td>13.0 %</td>
<td>9.9 %</td>
</tr>
</tbody>
</table>
Effect on $\nu_\mu$ oscillation analysis

- To fit $\sin^2 \theta_{23}$ and $\Delta m_{23}^2$, $\chi^2$ was minimized
- Other oscillation parameters were fixed
- Systematics uncertainties on parameters were calculated for the best fitted value of $(\sin^2 \theta_{23}, \Delta m_{23}^2) = (0.5, 2.4 \times 10^{-3} \text{eV}^2)$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.50 \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{12}$</td>
<td>0.857</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.098</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>0</td>
</tr>
<tr>
<td>Mass hierarchy</td>
<td>Normal</td>
</tr>
<tr>
<td>Baseline length</td>
<td>295 km</td>
</tr>
<tr>
<td>Earth density</td>
<td>2.6 g/cm$^3$</td>
</tr>
</tbody>
</table>

Systematic uncertainties of # of events (%)

<table>
<thead>
<tr>
<th>Systematics</th>
<th>$(\sin^2 \theta_{23}, \Delta m_{32}^2) = (0.5, 2.4 \times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux/XSEC (ND280 fit)</td>
<td>2.7</td>
</tr>
<tr>
<td>Other XSEC</td>
<td>4.9</td>
</tr>
<tr>
<td>Super-K +FSI</td>
<td>5.6</td>
</tr>
<tr>
<td>Total</td>
<td>8.1</td>
</tr>
</tbody>
</table>

- It was 21.8% before ND280 fit
- Could be reduced when measurement of $\nu$ cross section on oxygen will be measured using FGD2 (same water target as Super-Kamiokande)
First $\bar{\nu}_\mu$ event at T2K!

Collected POTs of:

$\nu$ data $6.88 \times 10^{20}$

$\bar{\nu}$ data $0.51 \times 10^{20}$
$\bar{\nu}_\mu$ beam data at ND280

First $\bar{\nu}_\mu$ candidate in data taken June 2014

T2K will search for CP violation by measuring $\bar{\nu}$ oscillations in:
- $\bar{\nu}_e$ appearance and $\bar{\nu}_\mu$ disappearance analysis
- Comparing $\nu_\mu$ with $\bar{\nu}_\mu$. 
What ND280 can do with $\bar{\nu}_\mu$

- Data collected by ND280 will be used to measure cross section of $\bar{\nu}_\mu$ interactions.

- Super-Kamiokande detector has no ability to discriminate between $\mu^+$ and $\mu^-$, therefore interactions of $\nu_\mu$ can not be distinguish from $\bar{\nu}_\mu$.

- Good knowledge of $\nu_\mu$ cross section is required since the beam is mixture of $\nu_\mu$ and $\bar{\nu}_\mu$ and $\sigma_{\bar{\nu}} \sim 1/3 \sigma_{\nu}$.
Other measurements with ND280


- Measurement of $\nu_e$ CC inclusive cross section on carbon (see also talk by Mark Rayner)

- Ongoing work on measurement of multi nucleon interactions:
  - implemented in NEUT and NuWro generators
  - look at $\mu$ kinematics, information about reconstructed proton tracks and vertex activity associated with low momentum protons

- Ongoing work on measurement of $\nu_\mu$ interactions on oxygen in FGD2 module which is interlaid with water layers
T2K has taken data with ND280 since 2010 and it has already analysed $6.3\times10^{20}$ POT of data.

The ND280 measurement of $\nu_\mu$ spectrum and cross sections contributed to significant reductions in errors on the expected neutrino flux at Super-Kamiokande.

T2K measured the CC inclusive $\nu_\mu$ and $\nu_e$ cross sections using ND280.

Other interesting measurements are coming soon!
ND280 $\bar{\nu}_\mu$ measurement

- Same selection as for $\nu_\mu$ CC
- Inclusive analysis is used but positive charged $\mu$ is required to be reconstructed
- $\text{CC0}\pi$ sample has purity of 74%

MC sample of $\bar{\nu}$ beam

Tools and methods to analyze recently collected $\bar{\nu}_\mu$ data are ready to be used