Cross section Measurements in the T2K ND280 Detector

Steve Boyd
on behalf of the T2K Collaboration
Cross section Measurements in the T2K ND280 Detector

- T2K Introduction / Signals and Backgrounds
- The Near Detector Suite
- A brief look at prospects for...
  - Charged current Quasi-elastic
  - Inclusive Neutral Current $\pi^0$
  - Charged current coherent pion production
- Near Detector Status
Better measurement of 23-sector: $\nu_\mu \to \nu_x$

$$\delta(\sin^2(2 \theta_{23})) \approx 0.01(0.04) \quad \delta(m_{23}^2) \approx 10^{-4}(10^{-3})$$

Detection of $\nu_e$ appearance: $\nu_\mu \to \nu_e$

$$\sin^2(2 \theta_{13}) < 0.008(90\% \ CL)(0.14)$$
T2K Layout

0.75 MW, 30 GeV

Muon Monitor

ND280 Off-Axis Detector

280 m Hall

2.5°

295 km

Beam Axis

Super-Kamiokande

INGRID On-Axis Detector

A. Marino, CIPANP 09
T2K Layout

0.75 MW, 30 GeV

Muon Monitor

ND280 Off-Axis Detector

Super-Kamiokande

2.5°

≈ 0.5% $\nu_e$ contamination at the $\nu_\mu$ peak

A. Marino, CIPANP 09
Signals and Backgrounds

$\nu_\mu$ disappearance:

S : QE : $\nu_\mu + n \rightarrow \mu^- + p$
→ can reconstruct $\nu$ energy

B : non-QE
→ inelastic background

<table>
<thead>
<tr>
<th>Systematic Error Source</th>
<th>Limit</th>
<th>Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam direction</td>
<td>&lt;1 mrad</td>
<td>INGRID, ND280, MuMon</td>
</tr>
<tr>
<td>Flux shape</td>
<td>&lt;10%</td>
<td>ND280, NA61, INGRID</td>
</tr>
<tr>
<td>$\mu$ energy scale</td>
<td>&lt; 2%</td>
<td>ND280</td>
</tr>
<tr>
<td>$\mu$ momentum resolution</td>
<td>&lt;10%</td>
<td>ND280</td>
</tr>
<tr>
<td>nonQE/QE ratio</td>
<td>&lt;10%</td>
<td>ND280</td>
</tr>
</tbody>
</table>
Signals and Backgrounds

$\nu_e$ appearance:

**S**: $\nu_\mu \rightarrow \nu_e$ \hspace{1cm} $\nu_e + N \rightarrow e^- + X$

**B**: Beam \hspace{1cm} $\nu_e + N \rightarrow e^- + X$

$\nu_\mu + N \rightarrow \pi^0 + X$

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**Systematic Error Source** | **Limit** | **Detectors**
--- | --- | ---
Beam direction | <1 mrad | INGRID, ND280, MuMon
Flux shape | <10% | ND280, NA61, INGRID
$\nu_e$ component ($\approx$ 0.5%) | <10% (relative) | ND280, NA61

NC 1 $\pi^0$ cross section | <10% | ND280
Near Detectors

ND280 off-axis detector

INGRID on-axis detector
ND280 Near Detector

- UA1/NOMAD Magnet
- SMRD
- FGDs
- TPCs
- Tracker ECAL
- Magnet Coils
- $\nu$ beam
- $\pi^0$ Detector (P0D)
- P0D ECAL
Designed to study $\pi^0$ production in NC and CC on water target

- 40 XY Brass/Scint tracking planes
- Interspersed water volumes
- Fiducial mass: C/O : 1.8t / 0.9t
- Coarse 5$X_0$ thick surrounding Pb/Scint calorimeter to tag $\gamma$ leakage/mip tagging
- 5.7 $X_0$ Forward and Back $\gamma$ stops
Tracker (FGD/TPC)

**Designed to study exclusive final states (CC and NC)**

- $5\sigma$ $e/\mu$ separation
- charge/momentum measurement
- $\sigma_p / p < 10\%$
- high resolution tracking

**TPCs**

- fine grained tracker and target
- 2 x 1.3 ton active target
- 1 cm$^2$ scintillator bar + WLS fibre readout
- water cross section using subtraction

**FGDs**

**v$_\mu$ induced CCQE event**

$v_\mu + n \rightarrow \mu^- + p$
**Tracker ECAL:**

- Entire inner volume surround by lead scintillator sampling calorimeter
- Improve CCQE efficiency by tagging high angle tracks
- Improve beam $\nu_e$ measurement
- Cosmic/Magnet event veto

**P0D ECAL:**

- Coarse lead scintillator sampling calorimeter around P0D
- $\gamma/\mu$ tagger

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3.2 GeV $\pi$
Dominant interaction in T2K energy region
Quasi-2 body interaction allows neutrino energy reconstruction with only the primary lepton.
Recent data has shown this channel to be more complicated than it seems...

Cross section uncertainty dominated by axial form factor – usually modelled as a dipole (?)

\[ F_A(Q^2) = F_A(0) \left(1 + \frac{Q^2}{M_A^2}\right)^{-2} \]

Axial mass measured from \( Q^2 \) distribution

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>( M_A ) (GeV/c(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MiniBooNE</td>
<td>C</td>
<td>1.35 ± 0.17</td>
</tr>
<tr>
<td>MINOS</td>
<td>Fe</td>
<td>1.19 ± 0.15</td>
</tr>
<tr>
<td>NOMAD</td>
<td>C</td>
<td>1.07 ± 0.05</td>
</tr>
<tr>
<td>K2K</td>
<td>( H_2O )</td>
<td>1.20 ± 0.12</td>
</tr>
<tr>
<td>K2K</td>
<td>C</td>
<td>1.14 ± 0.11</td>
</tr>
<tr>
<td>Past World Av.</td>
<td>( D_2 )</td>
<td>1.02 ± 0.03</td>
</tr>
</tbody>
</table>

\( Q^2 \) shape issue common to K2K, MiniBooNE, SciBooNE, MINOS,...
## CCQE Event Rates

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>CCQE</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K</td>
<td>C/O</td>
<td>300k/150k</td>
</tr>
<tr>
<td>SciBooNE*</td>
<td>C</td>
<td>11k</td>
</tr>
<tr>
<td>MiniBooNE*</td>
<td>C</td>
<td>112k</td>
</tr>
<tr>
<td>MINERvA</td>
<td>C</td>
<td>800k</td>
</tr>
<tr>
<td>MINOS*</td>
<td>Fe</td>
<td>210k</td>
</tr>
<tr>
<td>NOMAD*</td>
<td>C</td>
<td>7k</td>
</tr>
<tr>
<td>K2K (SciBar)*</td>
<td>C</td>
<td>5k</td>
</tr>
<tr>
<td>K2K (SciFi)*</td>
<td>O</td>
<td>7k</td>
</tr>
</tbody>
</table>

Nominal 5 yr \((10^{21} \text{ POT/yr})\) in Tracker

Efficiency $\sim 70\%$ ; purity $\sim 84\%$

- Only high-statistics measurement on Oxygen.
- Statistical error $< 1\%$
- Systematic errors being evaluated.

Work continuing to optimise CCQE selection

MINOS: M. Dorman, NuInt09
MiniBooNE : T. Katori, NuInt09
SciBooNE : J.L. Alcaraz-Aunion, NuInt09
NOMAD : V. Lyubushkin, NuInt09
K2K : F. Sanchez, NuInt07

*Physics. Rev. D 74, 052002*
Beam Monitoring

Upstream proton monitoring

$$p \rightarrow \pi \rightarrow \mu$$

2.5°

280m

NA61

Hadronic cross sections

Muon monitor

INGRID

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Beam Monitoring

Upstream proton monitoring

δ(Far/Near ratio) : ~ 2-3%

δ(Absolute flux) : ~ 5%

NA61

Hadronic cross sections

Muon monitor

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Inclusive NC $\pi^0$
Inclusive NC $\pi^0$

5 year, $1 \times 10^{21}$ POT/yr  $\varepsilon_{\pi^0} \sim 55\%$; purity $\sim 60\%$

<table>
<thead>
<tr>
<th>P0D Event Rate</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Type</td>
<td>C/Pb/Brass</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>20k</td>
</tr>
<tr>
<td></td>
<td>8k</td>
</tr>
<tr>
<td>NC multi $\pi^0$</td>
<td>6k</td>
</tr>
<tr>
<td></td>
<td>6k</td>
</tr>
<tr>
<td>$\nu$-Background</td>
<td>10k</td>
</tr>
<tr>
<td></td>
<td>4k</td>
</tr>
<tr>
<td>External Background</td>
<td>0.4k</td>
</tr>
<tr>
<td></td>
<td>0.3k</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Systematic Source</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>multi-$\pi^0$ production</td>
<td>15%</td>
</tr>
<tr>
<td>Background $\sigma$</td>
<td>20%</td>
</tr>
<tr>
<td>External Background</td>
<td>50%</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>3%</td>
</tr>
<tr>
<td>Weighted Total</td>
<td>8%</td>
</tr>
</tbody>
</table>

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CC Coherent $\pi^+$

SCIBAR (K2K)

5 year, $1 \times 10^{21}$ POT/yr

Tracker / C+O | P0D / C+O
---|---
8k | 12k

SciBooNE (NUINT09)

Assumes 30% efficiency, 30% systematic error

*SciBooNE see some indication of a signal in antineutrino running.
Status of ND280 Detector

- Both FGDs shipped
- 2 of 3 TPCs complete
- DSECAL in Japan
- 40% of rest by end of the year

- Field mapping underway
- SMRD Installed

- P0D being installed now
- INGRID Complete
Summary

• T2K Near Detector suite will provide the largest measurement of sub-GeV neutrino cross sections on oxygen to date
  
  - P0D designed to look at inclusive $\pi^0$ production
  - Tracker will look at exclusive final states
  - Flux shape and absolute normalisation constrained by a system of flux monitors and new hadron production cross section measurements

• Lot's of activity to build and install subdetectors in the NOMAD magnet. Build is largely on-schedule. Subdetectors being commissioned – installation in magnet in Nov, 2009

• First beam particles have been put on the T2K target and first muons seen in muon monitor. Beamline up and running!
Backup Slides
JPARC

J-PARC-January 2008

The ND280 Pit

Neutrino Beamline

30 GeV Proton Synchrotron

Phase 1: 0.75 MW

181 MeV Linac

3 GeV RCS
First Beam

First protons on target, and decay muons detected on April 23rd 2009

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INGRID

• 16 modules in the shape of a cross.
• Each module is an iron/scintillator calorimeter

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- Large acceptance spectrometer
- Measure secondary $\pi/K$ production cross sections
- Will run 30 GeV protons on thin / thick C targets
• Estimate $\delta(F/N) < 3\%$, absolute flux < 5\%  
• Thin target $\pi^-,p$ data almost ready  
• More thin target, and thick target running this year
MPPC

- Active area \( \sim 1.0-2.0 \text{ mm}^2 \)
- Gain \( \sim 10^6 \)
- Fast (<1ns pulses possible)
- PDE \( \sim 10\%-15\% \)
- Bias voltage \( \sim 70 \text{ V} \)
- Cross-talk/Afterpulsing effects
- Strong temperature dependence

- Mechanically robust
- Better matched to WLS spectrum
- Insensitive to magnetic fields.
- Same cost (per channel) as MAPMTs

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