Study of Neutrino Interactions at the T2K Near Detector Complex

Bruce Berger for the T2K Collaboration

• The T2K Experiment
• T2K Near Detectors
• Near Detector Results
• Future
The T2K Collaboration

12 Countries:
  Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, US

59 Institutions

~500 Collaborators
The T2K Experiment

- 295 km baseline
- ‘Quasimonochromatic’ beam
  -> first use of the off-axis technique
- Beam peak energy tuned to ~600 MeV, to give L/E at
  -> first maximum in $\nu_\mu$ oscillation probability
  -> first maximum in $\nu_e$ appearance probability
T2K Neutrino Beam

- Beam produced at J-PARC
- Continual increases in beam intensity before March 11 earthquake

-> V. Galymov's poster (#216) "Neutrino Beam Monitoring and Flux Predictions in the T2K Experiment"
ND280 - Near Detectors

- On-axis and off-axis detectors in a cylindrical 'pit' 280 m from the target
- INGRID - on axis
  - measures beam profile, position, and stability
- ND280 off-axis detector inside former UA1/NOMAD magnet
ND280 Off-Axis Detectors

SMRD (Side Muon Range Detector)
Scintillator interleaved in magnet yoke
Active veto, cosmic trigger

Magnet
UA1 magnet, B=0.2T nominal

Tracker
FGDs (Fine-Grained Detectors)
1cm square scintillator bars
Target for tracker
Fine vertex resolution
Short track detection: recoil protons
TPCs (Time Projection Chambers)
MicroMegas readout (7mmx10mm pads)
Momentum resolution <10% @ 1GeV

P0D (Pi-Zero Detector)
X-Y Scintillator planes, 40 layers
Removable water target to measure cross-sections on water
Optimized to measure π⁰ production, νₑ beam contamination

P0D ECAL

Barrel ECAL

ECALs (Electromagnetic Calorimeter)
Scintillator + lead
Measure photons, electrons from tracker, P0D

neutrino beam
ND280 Goals

Primary goals are driven by the oscillation analyses:

-> Characterize the neutrino beam:
  - $\nu_\mu$ measurement: beam flux*, muon momentum and angular distributions
    *(really the combination of flux and cross-section)
  - $\nu_e$ measurement: intrinsic beam background

-> Cross-section measurements:
  - NC$\pi^0$: important background to the $\nu_e$ appearance analysis
  - Reduce cross-section uncertainties in the oscillation analyses

ND280 will also contribute to increasing understanding of neutrino cross-sections in their own right

-> High statistics
-> Unique beam and detector features:
  - Quasimonochromatic beam at a lower energy than most previous measurements
  - Measurements on specific targets
    -> PØD water in/out
    -> water/carbon via comparison of 2 FGDs
  - photon reconstruction
  - recoil proton tracks in FGD
Terminology

Some neutrino interaction jargon:

**CCQE**: charged-current quasielastic
- charged-current: W exchange, final-state muon
- quasielastic: no mesons in the final state

**CC1π**: charged-current, single pion
- one pion in the final state
- resonance production dominates
- $CC\pi^0$, $CC\pi^+$

**NCπ0**: neutral-current, single pion
- neutral current: Z exchange, no final-state lepton
- one $\pi^0$ in the final state

**FSI**: final-state interactions
- particles from the initial nucleon interaction may not be the ones that exit the nucleus
ND280 Events

Interaction in PØD

Throughgoing 'sand' muon

2-track interaction in FGD 2

FGD 1 interaction, unrelated sand muon
ND280 Performance

PØD Reconstructed Vertices

FGD Cluster Timing

neutrino beam center
Energy loss (dE/dx) in the TPC can distinguish particle types
\implies dE/dx resolution \sim 8\%

Typical selection: select muon candidates based on 'pull' variable:
number of standard deviations from predicted energy loss
Neutrino Flux Prediction

Neutrino flux prediction based on
• Beamline measurements
• Hadron production data from NA61/SHINE at CERN
-> See poster #326, V. Galymov

$\nu_\mu$ -> primarily pion decay
  -> high-energy tail from kaon decay

$\nu_e$ -> primarily muon decay
  -> high-energy tail from kaon decay

Predicted flux at ND280

$\nu_\mu$ flux breakdown

$\nu_e$ flux breakdown
$\nu_\mu$ CC Rate at ND280

Inclusive event selection:

- TPC 1 veto (no tracks in TPC 1)
- Event vertex in FGD 1 or FGD 2
- Muon candidate: highest-momentum negative TPC track
- TPC dE/dx particle ID cut
$\nu_\mu$ CC Rate at ND280

- Reconstructed momentum and direction of muon tracks, data (points) vs. MC (NEUT)
- Ratio: $R_{\text{data/MC}} = 1.036 \pm 0.028^{+0.044}_{-0.037}\ (\text{det. sys.}) \pm 0.038\ (\text{phys. model})$
- Dominant uncertainties
  - TPC dE/dx pull: 3.0%
  - TPC-FGD matching: 2.1%
- Used in the oscillation analyses to normalize the expected flux at Super-K
  -> K. Okumura’s talk, “T2K Neutrino Oscillation Results” (IE-1)
$\nu_e$ CC Rate at ND280

Similar approach to $\nu_\mu$ analysis

- TPC $dE/dx$ used to select electrons instead of muons

- Cut to reject photon conversions in two-track events:
  -> Form invariant mass of two tracks, reject $M_{\text{inv}} < 100$ MeV

Backgrounds

- Photons from outside converting in FGD
- Photons from $\pi^0$s converting in FGD
- Misidentified muons
\( \nu_e \) CC Rate at ND280

- Reconstructed momentum and of electron tracks, data (points) vs. fit
- Mis-IDed muon template from data
- Other templates from MC, crosschecked in other samples
- Number of \( \nu_e \) events:
  \[ N_{sel}(\nu_e) = 7.8 \pm 5.5 \text{(stat.)} \pm 2.1 \text{(syst.)} \]
- Measured \( \nu_e \) content of the beam:
  \[ \frac{N(\nu_e)}{N(\nu_\mu)} = \frac{N_{sel}(\nu_e)\epsilon(\nu_e)}{N_{sel}(\nu_\mu)\epsilon(\nu_\mu)} = (1.0 \pm 0.7 \text{(stat.)} \pm 0.3 \text{(syst.)}) \% \]
- Measured \( \nu_e \) content is consistent with MC expectation
  \[ \left[ \frac{N(\nu_e)}{N(\nu_\mu)} \right]_{\text{data}} \div \left[ \frac{N(\nu_e)}{N(\nu_\mu)} \right]_{\text{MC}} = 0.6 \pm 0.4 \text{(stat.)} \pm 0.2 \text{(syst.)} \]
The neutral-current $\pi^0$ cross-section is of particular interest for T2K
-$\pi^0$ in Super-K can mimic an electron from $\nu_e$ interaction

Specific interest:
$\rightarrow$ NC$\pi^0$ cross-section on water
$\rightarrow$ Final-state $\pi^0$ - after final-state interactions

PØD analysis:
• Two reconstructed showers, fully contained in PØD
• Nothing else reconstructed in PØD
• Fit event vertex from shower parameters
• Reconstruct mass of $\pi^0$ candidate

$\rightarrow$ Stay tuned for results
A wide array of cross-section analyses are underway

**Charged-current interactions:**
- CC inclusive
- CCQE
- $CC\pi^\pm$ - $CC\pi^0$ and $CC\pi^+$
- Other CC - DIS, multi-pion modes, coherent pion production

**Neutral-current interactions:**
- $NC\pi^0$
- NC elastic scattering

**Studies of final-state interactions**

$\rightarrow$ Significant differences exist between models and recent cross-section measurements for many modes
Conclusions

ND280 neutrino interaction measurements:
  - $\nu_\mu$ rate
  - $\nu_e$ beam content

- Both measurements are important inputs to T2K oscillation analyses
- Improvements underway:
  - Differential measurements vs. momentum, angle
  - Complementary PØD analyses

NC$\pi^0$ analysis also underway, high priority

Future ND280 cross-section measurements will improve our understanding of neutrino interactions at T2K beam energies

- JPARC operation will resume in December 2011
- T2K data collection will be resumed soon afterward
- Plenary talk, “J-PARC Status after the Earthquake on March 11” by K. Tanaka, Wednesday 11:40 am (P3-6)
Backup Slides
INGRID

14 iron/scintillator modules arranged in a cross

Measures beam profile, position, and stability

Beam direction:
- Horizontal: $+0.014 \pm 0.025^{\text{(stat.)}} \pm 0.33^{\text{(syst.)}}$ mrad
- Vertical: $-0.107 \pm 0.025^{\text{(stat.)}} \pm 0.37^{\text{(syst.)}}$ mrad

Can study interactions on-axis $\rightarrow$ higher energies
MPPCs

**MPPC:** Multi-Pixel Photon Counter
- Hamamatsu solid-state photodetector
- Used by all ND280 scintillator detectors
  - 1.3 mm square array
  - 50 micron pixel size
  - 667 pixels total

**MPPC Response**
- Each pixel is an avalanche photodiode (APD)
- All pixels connected in parallel
- Signal proportional to number of pixels fired
- Clean, well-separated peaks

[Image of MPPC pixel array]
[LED illumination, mean ~2 photons]