On beyond $\nu_\mu$ CC

Future cross section measurements and capabilities at T2K

Stephen Dolan

For the T2K Collaboration

Stephen.Dolan@llr.in2p3.fr
Overview

• T2K and ND280

• Upcoming measurements
  – Vertex activity
  – Combining measurements
  – Pion production

• Highlighting cross section challenges

• Summary
The T2K Experiment

Super-Kamiokande

Near Detectors

J-PARC

Mt. Noguchi-Goro 2,924 m

Mt. Ikeno-Tama 1,360 m

1,700 m below sea level

~0.6 GeV Muon Neutrino Beam

295 km

Far Detector (Off-Axis)

Super-Kamiokande

Use off-axis beam to give a narrow neutrino energy spread

Near Detectors

Off-Axis: ND280

On-Axis: INGRID

Electromagnetic Calorimeter (ECal)
P0D ECal

\( \pi^0 \) detector (P0D)
Neutrino Interactions at T2K

CCQE (1p1h)
(Charged-Current Quasi-Elastic)

CCRES
(Charged-Current Resonant)

2p2h
(2 particle – 2 hole)

Nuclear Effects

Diagrams by Patrick Stowell
What can we measure

Interaction Modes

CCQE

\[ \nu_\mu \rightarrow \mu^- \]

\[ n \rightarrow p \]

CCRES

\[ \nu_\mu \rightarrow \mu^- \]

\[ n \rightarrow \Delta^- \]

\[ \pi^+ \rightarrow n \]

2p2h

\[ \nu_\mu \rightarrow \mu^- \]

\[ p \rightarrow p \]

Interaction Topologies

CC0π (CCQE-like)

\[ \nu_\mu \rightarrow \mu^- \]

\[ n \rightarrow p \]

CC1π (CCRES-like)

\[ \nu_\mu \rightarrow \mu^- \]

\[ n \rightarrow \Delta^- \]

\[ \pi^+ \rightarrow n \]

CC0π+Np (N>0)

\[ \nu_\mu \rightarrow \mu^- \]

\[ n \rightarrow p \]

• Nuclear effects obfuscate interaction mode

• To minimise model dependence we measure interaction topologies

Interaction modes in CC0π topology:
(NEUT 5.3.2 w/ ND280 flux)

- CCRES 6.91%
- CCQE 80.60%
- 2p2h 12.11%
- Other 0.38%
ND280 (off axis)

Former UA1 Magnet:
- Provides 0.2 T field

$\pi^0$ detector (PØD):
- CH scintillator tracker
- Target for $\nu$
- Interwoven heavy targets + drainable water bags

On Axis ~ 1.1 GeV
Peak $E_\nu$
Off Axis ~ 0.6 GeV
ND280 (off axis)

- CH scintillator tracker
- Target for $\nu$
- FGD2 contains water

On Axis ~ 1.1 GeV

Off Axis ~ 0.6 GeV
ND280 (off axis)

Fine-Grained Detectors (FGD 1 & 2):
- CH scintillator tracker
- Target for $\nu$
- FGD2 contains water

Time Projection Chambers (TPC):
- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID

On Axis ~ 1.1 GeV
Off Axis ~ 0.6 GeV

Peak $E_\nu$
ND280 Upgrade (off axis)

- Facilitates $4\pi$ acceptance with lower reconstruction thresholds

Two new high-angle TPCs

New finely segmented Scintillator detector
(SuperFGD – arXiv1707.01785)

Ready by ~ 2021

On Axis ~ 1.1 GeV
Off Axis ~ 0.6 GeV

Proposal - CERN-SPSC-P357
INGRID (on axis)

On Axis ~ 1.1 GeV

Off Axis ~ 0.6 GeV

Peak $E_{\nu}$

INGRID (front View):

Beam center

~10m

1.5m

~10m
INGRID (on axis)

**INGRID (front view):**

- **Beam center**
- **Veto planes**
- **Iron plate**
- **Tracking planes**

**INGRID Modules:** Stacks of scintillator bars interleaved with Iron sheets.

**INGRID (top view):**

- **Proton Module** (fully active scintillator tracker) or **Water Module** (interleaved layers of water)

Fe, $H_2O$ and CH targets available
Wagasci + Baby MIND (off axis)

Wagasci detector:
- 2 modules;
  - CH tracker (47 kg FV)
  - CH tracker with interleaved H$_2$O (188 kg FV)
4π acceptance to charged particles thanks to scintillator lattice structure

Muon range detectors
- Currently being used as INGRID Water Module

Baby MIND
- Magnetised Iron Neutrino Detector
- Arrived Dec. 2017!
- Now fully installed

All ready for Jan. 2019 (after SK tank-open work)
Overview

• T2K and ND280

• Upcoming measurements
  – Vertex activity
  – Combining measurements
  – Pion production

• Highlighting cross section challenges

• Summary
On beyond muon kinematics

- Would like to disentangle the role of separate nuclear effects and the free nucleon cross-section.
- Current results provide an important piece of the puzzle but further complementary measurements are needed…
But the models don’t always work!

- Available models describe muon kinematics quite well
- But fail when describing the hadronic system ...
- Something must be wrong with the physics models
- Can’t just continue to tune our generators!!!
- Need new models and the measurements which can inspire these:
  - Transverse kinematics
  - Inferred kinematics
  - Proton multiplicity
  - Available energy
Finer binning?

- T2K correlated-kinematics measurements are already quite limited by detector resolution

- Significantly finer binning would require excessive regularisation
Vertex activity (VA) at T2K

- Energy deposited around an interaction vertex gives access to physics below the ND280 reconstruction thresholds

- FGD1 is well-suited to study this (1 cm$^2$ scintillator bars), superFGD even better (could look at asymmetric VA boxes)

- Can subtract the contribution from visible tracks
Correlations in many dimensions

- Higher statistics will allow measurements using combinations of observables which are sensitive to nuclear effects

- Combinations of the single-transverse variables, inferred kinematics and reconstructed neutron momentum are interesting candidates

- Can combine constraints on nuclear-effect sensitive observables with measurements of VA

\[
\delta \alpha_T - \text{ single transverse variable, see backups}
\]
\[
p_n - \text{ reconstructed neutron momentum}
\]
\[
\text{Box 5x5 VA w/ restrictions on } \delta \alpha_T \text{ and } p_n
\]
\[
\text{CC0\pi Np selection (N>0) } p+\mu \text{ subtracted}
\]
\[
\frac{\partial^2 \sigma}{\partial \Omega \partial k'} = \frac{G_F^2 \cos^2 \theta_c (k')^2}{2 \pi^2} \cos^2 \frac{\theta}{2} \left[ G_E^2 \frac{q^2}{q'^2} R_{NN} \right.
+ G_A^2 \frac{(M_\Delta - M_N)^2}{2 q^2} R_{\sigma \tau(L)}^\Delta
+ \left. G_A^2 \left( \frac{\omega^2}{q^2} + G_A^2 \right) \left( -\frac{q^2}{q'^2} + 2 \tan^2 \frac{\theta}{2} \right) \left( R_{\sigma \tau(T)}^N + 2 R_{\sigma \tau(T)}^\Delta + R_{\sigma \tau(T)}^\Delta \right) \right] \\
\pm 2 G_A G_M \frac{k + k'}{M_N} \tan^2 \frac{\theta}{2} \left( R_{\sigma \tau(T)}^N + 2 R_{\sigma \tau(T)}^\Delta + R_{\sigma \tau(T)}^\Delta \right)
\]

- Asymmetry between neutrinos and antineutrinos isolates term in the cross section
- Asymmetry term contains strong 2p2h contribution

- T2K has recently made joint measurements of CC0\(\pi\) \(\nu/\bar{\nu}\) (result coming soon)

\[0.98 < \cos\theta^\text{true}_{\mu} < 1.0\]

\[0.9 < \cos\theta^\text{true}_{\mu} < 0.94\]

\[
\text{Asymmetry} = \frac{d\sigma_{\nu_{\mu}} - d\sigma_{\bar{\nu}_{\mu}}}{d\sigma_{\nu_{\mu}} + d\sigma_{\bar{\nu}_{\mu}}}
\]

Expected uncertainties are \(~15\%\)

Expected uncertainties are \(~0.2\)

Ciro Ricco using model of Martini et. al.

\[\times 10^{-39}\]

Ciro Ricco using model of Martini et. al.


Combining measurements – A Scaling

- Measurements of cross section on different nuclear targets can help differentiate nucleon- and nucleus-level physics

- Recently used INGRID to measure:
  \[
  \frac{\sigma_{CC}^{H_2O}}{\sigma_{CC}^{CH}} = 1.03 \pm 0.05 \quad \frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{H_2O}} = 1.02 \pm 0.06
  \]
  (ratio of cross sections per nucleon within a restricted muon-kinematic phase space)

- More heavy target ratio analyses are in process – stay tuned!

- T2K has also made measurements of CC0π on both carbon and oxygen

- Models predict sensitivity to A-scaling in the very forward region

- Need a joint measurement to probe this – coming soon!
Different beam peaks → access to different processes

The flux uncertainties are highly correlated

Can explore how nuclear effects change with neutrino energy

Difficult to combine measurements with different acceptance

What to measure - ratio, sum, difference?
ν/\bar{\nu} CC1π⁺/⁻

- T2K energy is well suited to measuring CC1π (on- and off-axis)
- Several analyses underway on T2K
- Joint ν/\bar{\nu} in the longer term

NC1π⁺

- Measurement of NC1π⁺ is in progress
- Significant systematic for OA (background to νµ disappearance)
Neutral pion measurements

- Approaching first T2K NC\(\pi^0\) measurement using ND280’s P0D
- Important background for oscillation analysis

- Multitude of background contributions, difficult to control
- \(\pi^0\) combinatorics problem:
  - Often reconstructed photons are not both from the same \(\pi^0\)
- Challenging measurement
Overview

• T2K and ND280

• Upcoming measurements
  – Vertex activity
  – Combining measurements
  – Pion production

• Highlighting cross section challenges

• Summary
Double transverse kinematic imbalance

\(\{X, Y\}\)
\(= \{p, \pi^+\}\) for \(\nu + p \rightarrow l^- + \Delta^{++}\)
or \(\{p, \pi^-\}\) for \(\bar{\nu} + p \rightarrow l^+ + \Delta^0\)

- Describes the momentum imbalance between the proton and the pion in the plane transverse to both the incoming neutrino and the outgoing lepton.

- Potential to isolate RES pion-production interactions on hydrogen (no nuclear effects).

- Comparison to interactions on heavier targets might allow a probe of nuclear effects.
Double transverse kinematic imbalance

- Difficult to reconstruct a three track final state accurately
  - Often have to reconstruct at least one short track with a messy vertex
  - Large backgrounds, coarse resolution

- Background distribution is very sensitive to nuclear effects (Fermi motion, FSI)
  - Model dependent background subtraction

- Limited phase space for three tracks above detection threshold

- Very interesting observable, but a very challenging measurement

**Wrong sign pions**

- $\nu CC1\pi^-$ is mostly produced through FSI processes.
- Measuring this process is a direct probe of pion FSI.
- Statistics are extremely low (~1% of neutrino interactions at ND280).
- These pions tend to have low momenta → difficult to reconstruct.
- Need a magnetised detector with more statistics and a lower reconstruction threshold (ND280 upgrade superFGD, DUNE ND?)
Summary

Lots of interesting measurements in progress:
- Vertex activity
- Multi-dimensional analyses
- Combined $\nu/\bar{\nu}$, C/O, on-/off-axis
- New pion measurements of all flavours (CC/NC $\pi^+/\pi^-/\pi^0$)

Highlighted limitations / difficulties for ND280:
- $\pi^0$ kinematics
- High multiplicity track reconstruction
- Detection thresholds

New longer-term physics potential from ND280 upgrade

Beyond what I had time to mention in this talk:
- Low momentum protons
- New electron neutrino analyses
- NC elastic
- Kaons
Thank you for listening
BACKUPS
Low momentum protons

- Low momentum protons are sensitive to interesting nuclear effects (FSI, Pauli blocking), ND280 threshold ~ 450 MeV/c
Low momentum protons

- Low momentum protons are sensitive to interesting nuclear effects (FSI, Pauli blocking), ND280 threshold ~ 450 MeV/c

- Can lower proton momentum threshold by searching for interactions in the material surrounding the TPCs (low stats.)

arXiv: 1802.05078

T2K Work in Progress
Low momentum protons

- Low momentum protons are sensitive to interesting nuclear effects (FSI, Pauli blocking), ND280 threshold ~ 450 MeV/c
- Can lower proton momentum threshold by searching for interactions in the material surrounding the TPCs (low stats.)
- Can also analyse interactions in the TPC gas, permits very clean measurements on Argon! (very low stats.)

FGD1 target

arXiv: 1802.05078
Low momentum protons

- Low momentum protons are sensitive to interesting nuclear effects (FSI, Pauli blocking), ND280 threshold ~ 450 MeV/c

- Can lower proton momentum threshold by searching for interactions in the material surrounding the TPCs (low stats.)

- Can also analyse interactions in the TPC gas, permits very clean measurements on Argon! (very low stats.)

- ND280 upgrade superFGD has a lower threshold and wider acceptance

![Image of low momentum protons](image-url)
Electron neutrinos at T2K

- Beam $\nu_e$ are the largest background in $\nu_e$ appearance at SK

- Two major efforts for T2K $\nu_e$ cross-section analyses (using FGD1+FGD2):
  - First measurement to $\nu_e$ CC0$\pi$ below 1 GeV
  - First $\bar{\nu}_e$ CC since Garagamelle

- Challenging measurements:
  - Very low statistics (115 events in current $\bar{\nu}_e$ CC selection)
  - Substantial background from pair-producing photons

See: talk by S. King at NuInt 2017
The T2K Experiment

- Large increase in statistics foreseen in the coming years
- Huge potential for cross-section measurements: lower uncertainties, rarer processes, more bins and more dimensions

![Graph showing MR Beam Power and Integrated Delivered Protons]
dE/dx separation
Detector thresholds

- Graphs showing efficiency as a function of $p_{\mu}^{\text{true}}$ (MeV) and $\cos(\theta_{\mu}^{\text{true}})$ for NEUT and GENIE.
Kinematic resolution – CC0π+Np

![Graphs showing kinematic resolution for CC0π+Np](image)

- $p_{\mu^-}$
  - Mean: 0.9879
  - RMS: 0.1183

- $p_p$
  - Mean: 0.9795
  - RMS: 0.08808

- $\theta_{\mu^-}$
  - Mean: 0.9935
  - RMS: 0.09077

- $\theta_p$
  - Mean: 0.9957
  - RMS: 0.06159
Single Transverse Variables

\[ p^v \]

\[ p^l \]

\[ p^p \]

\[ \nu_{\mu} + n \rightarrow \mu + p \]

No nuclear Effects
Single Transverse Variables

\[ p^l_T = -p^p_T \]

No nuclear Effects
Single Transverse Variables

\[ p_T^l \neq -p_T^p \]

With Nuclear Effects
Single Transverse Variables

- Any deviation from $\delta p_T = 0$, $\delta \phi_T = 0$ is indicative of nuclear effects

- STVs offer an excellent probe of nuclear effects

- STV shape is mostly independent of $M_A$

Proton – Muon Coplanarity Angle

**Before Acceptance Cuts**

Andrew Cudd using NuWro 17.01

**After Acceptance Cuts**

BLACK: Total  SOLID: INGRID
BLUE: CCQE  DASHED: ND280
RED: 2p2h  VIOLET: RES

Andrew Cudd using NuWro 17.01

**Acceptance Cuts:**
Common phase space for both.

- **INGRID**
  - $P_p > 500$ MeV and $\cos(\theta_p) > 0.4$
  - $P_{\mu} > 500$ MeV and $\cos(\theta_{\mu}) > 0.26$

- **ND280**
  - $P_p > 500$ MeV and $\cos(\theta_p) > 0.4$
  - $P_{\mu} > 500$ MeV and $\cos(\theta_{\mu}) > 0.26$

This is the cosine of the angle between the muon and proton momentum vectors.
The Flux

- **Off-axis $\nu_\mu$ beam**
  - Tightly-peaked at 600 MeV $2.5^\circ$ off-axis towards SK
  - Low contamination from non-$\nu_\mu$ components
  - Flux estimation aided by hadron production measurements from NA61/SHINE at CERN

**Figure:**
- Neutrino flux vs. $E_\nu$ (GeV)
- Fractional error vs. $E_\nu$ (GeV)

**References:**
- Phys. Rev. D 87, 012001
Reconstructing the Neutrino Direction

Mean Neutrino Parent
Decay Point (PDP)

Reconstructed Neutrino
Direction

Reconstructed Interaction
Vertex

Decay Tunnel

280 m

FGD 1

T2K Work
In Progress

T2K Work
In Progress

T2K Work
In Progress

T2K Work
In Progress