Controlling neutrino interaction systematics: The T2K experience

Tom Dealtry
for the T2K collaboration

University of Oxford

NuInt14
19 May, 2014
30 GeV proton beam running up to \(\sim 250\) kW (design 750 kW), producing \(\nu_\mu\) beam
Far detector, SK, 2.5° off-axis
Two near detectors at 280 m. INGRID on-axis, ND280 off-axis
Studying neutrino oscillations & cross sections
T2K cross section determination procedure

1. Take the default cross section model (NEUT)
2. Assign uncertainties & tune single pion production using external data
3. Tune nucleus-independent cross section parameters using ND280 $\nu_\mu$ CC selections on carbon
   - Fit also constrains SK flux parameters
4. Use a combination of the ND280 & external errors in oscillation fits at SK on oxygen

Flux prediction proceeds in a similar way (see talk by M. Posiadała)
MiniBooNE CCQE fit

- Fit double differential cross section in lepton kinematics ($T_\mu$ & $\cos \theta_\mu$)
- No correlated bin errors available
- 2 free parameters: $M_A^{QE}$ & $10.7\%$ CCQE normalisation

$M_A^{QE} = 1.64 \pm 0.03 \text{ GeV}/c^2$

$\text{CCQE norm} = 0.88 \pm 0.02$

PRD 81:092005

PRD 88:032002
MiniBooNE single $\pi$ production fit

Use 9 systematic parameters

- $M_A^{RES}$
- W-shape: empirically modifies pion momentum distributions
- CC other shape: $\sigma_{CCother} = 0.4/E_\nu$
- 6 normalisations: CC coherent, CC1$\pi$, NC coherent, NC1$\pi^0$, NC1$\pi^\pm$, NC other

Redo fit multiple times, changing FSI parameters & $\pi$-less $\Delta$-decay fraction

Fit 3 samples

- CC1$\pi^0$ $Q^2$
  (fully correlated errors)
- CC1$\pi^+$ $Q^2$
  (correlated errors unavailable)
- NC1$\pi^0$ $p_{\pi^0}$
  (uncorrelated errors)
CCQE uncertainties

$M^\text{QE}_A$

- Difference between best fit and NEUT nominal (1.21 GeV/c^2)

CCQE norm ($E_\nu < 1.5$ GeV)

- MiniBooNE flux error

CCQE norm (1.5 < $E_\nu$ < 3.5, $E_\nu$ > 3.5 GeV)

- Differences between NOMAD & MiniBooNE data

Nuclear model parameters (nucleus dependent)

- Relativistic Fermi gas (RFG) parameters
  - Fermi momenta ($p_F$) and nuclear binding energy ($E_b$)
  - Uses electron scattering data

- Difference between RFG and spectral function models
  - Calculated using NuWro
Resonant $\pi$ production uncertainties

$M_{A}^{\text{RES}}$, CC1$\pi$ norm ($E_\nu < 2.5$ GeV), NC1$\pi^0$ norm

- Best-fit values from default fit & covariances built from results of alternative FSI/PDD fits

W-shape

- Difference between nominal & best-fit CC1$\pi$ norm ($E_\nu > 2.5$ GeV)
- Extrapolation of difference between NEUT nominal & MiniBooNE

$\pi$-less $\Delta$-decay

- NEUT default is 20%. Allow to drop to 0% at 1$\sigma$
Other cross section uncertainties

CC coherent norm
- 90% C.L. upper limits are below the NEUT nominal.
  Assign 100% error

NC coherent norm
- Difference between NEUT nominal & SciBooNE

CC other shape
- Extrapolate error on MINOS inclusive cross section from 4 GeV

NC $\pi^\pm$, NC other
- Difference between NEUT nominal, Gargamelle & Derrick et al.

$\nu/\bar{\nu}$ norm
- Comparison between MiniBooNE & MINERvA

$\nu_e/\nu_\mu$ norm
- Uses the work of Day et al. (PRD 86:053003)
Outline

1. T2K
2. T2K cross section determination procedure
3. Input uncertainties
4. ND280 event selections & constraint
5. Oscillation analyses
6. Effect of np-nh on $\nu_\mu$ disappearance search
7. Summary
The muon candidate is selected as the highest momentum negatively-charged TPC2 track with > 18 hits, starting in the FGD1 fiducial volume.

Veto events where the highest-momentum TPC2 track (that isn’t the muon) is > 150 mm upstream of muon vertex.

Veto events where the muon candidate is backwards going.

Veto events with a possible broken FGD track.

Track should be muon-like, using TPC PID based on $dE/dx$. 
**ND280 $\pi$ selections**

$e^\pm, \pi^\pm$ in TPC
- Require long TPC2 tracks with FGD1 vertices
- Tag particle as $p$, $e^\pm$, $\pi^\pm$ using TPC2 PID and charge ID

Michel electron in FGD1
- Require a time-delayed out-of-bunch FGD1 cluster, with a total charge of at least 200 photoelectrons
- Tagged as $\pi^+$

$\pi^+$ track in FGD1
- Require a fully contained track within FGD1
- $|\cos \theta| > 0.3$
- Tag particle as $\pi^\pm$ using FGD1 PID based on $dE/dx$
ND280 CC$0\pi$, CC$1\pi^+$, CC-other selections

Split the CC inclusive sample into 3 subsamples:

- **CC$0\pi$:** 0 $e^{\pm}$ TPC2 tracks, 0 $\pi^{\pm}$ TPC2 tracks, 0 Michel electrons, 0 $\pi^{\pm}$ FGD-only tracks
- **CC$1\pi^+$:** 0 $e^{\pm}$ TPC2 tracks, 0 $\pi^-$ TPC2 tracks, exactly one TPC2 $\pi^+$ track, Michel electron, $\pi^{\pm}$ FGD-only track
- **CC-other:** All other events.
ND280 CC$0\pi$, CC$1\pi^+$, CC-other selections

Split the CC inclusive sample into 3 subsamples:

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- **CC-other:** All other events.
ND280 CC0\(\pi\), CC1\(\pi^+\), CC-other selections

Split the CC inclusive sample into 3 subsamples:

- **CC0\(\pi\):** 0 \(e^\pm\) TPC2 tracks, 0 \(\pi^\pm\) TPC2 tracks, 0 Michel electrons, 0 \(\pi^\pm\) FGD-only tracks
- **CC1\(\pi^+\):** 0 \(e^\pm\) TPC2 tracks, 0 \(\pi^-\) TPC2 tracks, exactly one TPC2 \(\pi^+\) track, Michel electron, \(\pi^\pm\) FGD-only track
- **CC-other:** All other events.

---

**beam**

TPC1 FGD1 TPC2 FGD2 TPC3
ND280 CC$0\pi$, CC$1\pi^+$, CC-other selections

Split the CC inclusive sample into 3 subsamples:

- **CC$0\pi$** 0 $e^{\pm}$ TPC2 tracks, 0 $\pi^{\pm}$ TPC2 tracks, 0 Michel electrons, 0 $\pi^{\pm}$ FGD-only tracks
- **CC$1\pi^+$** 0 $e^{\pm}$ TPC2 tracks, 0 $\pi^-$ TPC2 tracks, exactly one TPC2 $\pi^+$ track, Michel electrons, $\pi^{\pm}$ FGD-only tracks
- **CC-other** All other events.

<table>
<thead>
<tr>
<th>Purity</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>72.4%</td>
<td>6.4%</td>
<td>5.8%</td>
</tr>
<tr>
<td>CC$1\pi^+$</td>
<td>8.6%</td>
<td>49.2%</td>
<td>7.8%</td>
</tr>
<tr>
<td>CC-other</td>
<td>11.5%</td>
<td>31.0%</td>
<td>73.6%</td>
</tr>
<tr>
<td>Background</td>
<td>2.3%</td>
<td>6.8%</td>
<td>8.7%</td>
</tr>
<tr>
<td>External</td>
<td>5.2%</td>
<td>6.6%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>47.8%</td>
<td>28.4%</td>
<td>29.7%</td>
</tr>
</tbody>
</table>
ND280 $p_\mu$ (before-FSI categories)

**CC0π**

- CCQE
- RES
- DIS
- COH
- NC
- $\nu_\mu$
- $\bar{\nu}_\mu$
- Out of FGD FV
- Other
- No truth

**CC1π^+**

- CCQE
- RES
- DIS
- COH
- NC
- $\nu_\mu$
- $\bar{\nu}_\mu$
- Out of FGD FV
- Other
- No truth

**CC-other**

- CCQE
- RES
- DIS
- COH
- NC
- $\nu_\mu$
- $\bar{\nu}_\mu$
- Out of FGD FV
- Other
- No truth

Out-of-fiducial-volume
Fit the muon kinematics \((p_\mu, \cos \theta_\mu)\) for each of the 3 samples simultaneously.

- Include cross section, FSI, flux & detector systematics
- \(M^\text{QE}_A\), \(M^\text{RES}_A\), normalisations (CCQE, CC1\(\pi\), NC1\(\pi^0\)), and flux parameters propagated to oscillation analyses
  - Including correlations
ND280 fit results

**SK $\nu_\mu$ Flux**

- Prior to ND280 Constraint
- After ND280 Constraint

**SK $\nu_e$ Flux**

- Prior to ND280 Constraint
- After ND280 Constraint

**X-sec Parameter Errors**

- Before ND280 Fit
- After ND280 Fit
  (Toy Experiments)
## ND280 fit results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>External tune</th>
<th>ND280 tune</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$ (GeV/c$^2$)</td>
<td>1.21±0.45</td>
<td>1.24±0.07</td>
</tr>
<tr>
<td>SF ($^{12}$C)</td>
<td>0 (RFG) → 1 (SF)</td>
<td>0.24±0.13</td>
</tr>
<tr>
<td>$E_B$ ($^{12}$C) (MeV)</td>
<td>25±9</td>
<td>30.9±5.2</td>
</tr>
<tr>
<td>$p_F$ ($^{12}$C) (MeV/c)</td>
<td>217±30</td>
<td>266.3±10.6</td>
</tr>
<tr>
<td>CCQE norm $E_\nu &lt; 1.5$ GeV</td>
<td>1.00±0.11</td>
<td>0.97±0.08</td>
</tr>
<tr>
<td>CCQE norm $1.5 &lt; E_\nu &lt; 3.5$ GeV</td>
<td>1.00±0.30</td>
<td>0.93±0.10</td>
</tr>
<tr>
<td>CCQE norm $E_\nu &gt; 3.5$ GeV</td>
<td>1.00±0.30</td>
<td>0.85±0.11</td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV/c$^2$)</td>
<td>1.41±0.11</td>
<td>0.96±0.07</td>
</tr>
<tr>
<td>$\pi$-less $\Delta$ decay fraction</td>
<td>0.20±0.20</td>
<td>0.21±0.08</td>
</tr>
<tr>
<td>CC1$\pi^0$ norm $E_\nu &lt; 2.5$ GeV</td>
<td>1.15±0.43</td>
<td>1.26±0.16</td>
</tr>
<tr>
<td>CC1$\pi^0$ norm $E_\nu &gt; 2.5$ GeV</td>
<td>1.00±0.40</td>
<td>1.12±0.17</td>
</tr>
<tr>
<td>CC coherent norm</td>
<td>1.00±1.00</td>
<td>0.45±0.16</td>
</tr>
<tr>
<td>NC$\pi^0$ norm</td>
<td>0.96±0.43</td>
<td>1.13±0.25</td>
</tr>
<tr>
<td>CC other shape (GeV)</td>
<td>0.00±0.40</td>
<td>0.23±0.29</td>
</tr>
<tr>
<td>NC other norm</td>
<td>1.00±0.30</td>
<td>1.41±0.22</td>
</tr>
</tbody>
</table>
Outline

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7. Summary
Select single-ring events, fully contained with a fiducial volume vertex.

**μ-like**
- Ring is PID’ed as μ-like
- 0 or 1 Michel electron
- $p_μ > 200$ MeV/c

**e-like**
- Ring is PID’ed as e-like
- 0 Michel electrons
- $E_{reco} < 1.25$ GeV
- $\pi^0$ rejection

$$E_{reco} = \frac{m_p^2 c^4 - (m_n c^2 - E_b)^2 - m_\mu^2 c^4 + 2 (m_n c^2 - E_b) E_\mu}{2 (m_n c^2 - E_b - E_\mu + p_\mu c \cos \theta_\mu)}$$
Select single-ring events, fully contained with a fiducial volume vertex.

\[ E_{\text{reco}} = \frac{m_p c^4 - \left(m_n c^2 - E_b\right)^2 - m_\mu c^4 + 2 \left(m_n c^2 - E_b\right) E_\mu}{2 \left(m_n c^2 - E_b - E_\mu + p_\mu c \cos \theta_\mu\right)} \]

**μ-like**
- Ring is PID’ed as μ-like
- 0 or 1 Michel electron
- \( p_\mu > 200 \text{ MeV/c} \)

**e-like**
- Ring is PID’ed as e-like
- 0 Michel electrons
- \( E_{\text{reco}} < 1.25 \text{ GeV} \)
- \( \pi^0 \) rejection
## Oscillation analyses: effect of ND280 fit

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$1R_\mu , \delta N_{SK}/N_{SK}$</th>
<th>$1Re , \delta N_{SK}/N_{SK}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK+FSI</td>
<td>5.00%</td>
<td>3.65%</td>
</tr>
<tr>
<td>ND280-independent XSec</td>
<td>5.00%</td>
<td>4.69%</td>
</tr>
<tr>
<td>ND280 prefit</td>
<td>21.75%</td>
<td>26.04%</td>
</tr>
<tr>
<td>ND280 postfit</td>
<td>2.74%</td>
<td>3.15%</td>
</tr>
<tr>
<td>Total (ND280 postfit)</td>
<td>7.65%</td>
<td>6.75%</td>
</tr>
<tr>
<td>Total (ND280 prefit)</td>
<td>23.45%</td>
<td>26.80%</td>
</tr>
</tbody>
</table>

- Large reduction in uncertainties for parameters constrained by ND280 fit
- ND280-independent XSec parameters have large uncertainties
  - Need cross sections on water → can constrain $E_B$, $p_F$, SF
  - Need new dedicated samples to fit ($\nu_e$, $\overline{\nu}_\mu$, CC coherent, ... → can constrain more normalisations

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Controlling neutrino interaction systematics at T2K

NuInt14, 19 May, 2014
np-nh effect methodology

1 $\mu$-like ring

- Replace NEUT $\pi$-less $\Delta$ decay events

- Create toy MC including np-nh events at ND280
  - Fit without an np-nh-controlling parameter
- Create toy MC including np-nh events at SK with same systematic tweaks as ND280
  - Fit using the updated ND280 covariance matrix
  - Fit without an np-nh-controlling parameter
- Repeat for toy with no np-nh events
- Find best-fit point differences between the 2 toys
np-nh effect results

\[ \sin^2 \theta_{23} \]

\[ \Delta m_{32}^2 \]

Mean: \(+0.3\%\)
RMS: \(3.6\%\)
Other systematics RMS: \(3.8-5.6\%\)

Mean: \(−0.2\%\)
RMS: \(0.6\%\)
Other systematics RMS: \(1.8\%\)
Improvements for future analyses

- Implemented an np-nh model in NEUT
  - See talk by P.Sinclair
- Implemented a spectral function model in NEUT
  - See talk by A.Furmanski
- Updating external data fits with the new models & new data
  - MINER\(\nu\)A, MiniBooNE \(\bar{\nu}\), bubble chamber
  - See poster by C.Wilkinson
- Improving the ND280 event selections
  - Better cuts
  - Increasing phase space
  - Adding new selections
- We are constantly looking for new ways to constrain & improve our cross section model
Summary

- Initial uncertainties determined using fits to MiniBooNE data and comparisons with other datasets
- Fits to ND280 CC0$\pi$, CC1$\pi^+$, CC-other selections result in greatly reduced errors
  - $21.8\% \rightarrow 2.7\%$ for 1 $\mu$-like ring
  - $26.0\% \rightarrow 3.2\%$ for 1 e-like ring
- Work being done to reduce the effect of the ND280-independent XSec parameters from current value of 5%
- np-nh bias evaluated in $\nu_\mu$ disappearance fits as a small effect
  - Small bias (0.2%-0.3%), much less than the RMS from other systematics (1.8%-5.6%)
Backups
ND280 selection distributions (before ND280 fit)
## ND280 CC0π, CC1π⁺, CC-other purities

<table>
<thead>
<tr>
<th></th>
<th>CC0π</th>
<th>CC1π⁺</th>
<th>CC-other</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC0π</td>
<td>72.4%</td>
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<tr>
<td>External</td>
<td>5.2%</td>
<td>6.6%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CC0π</th>
<th>CC1π⁺</th>
<th>CC-other</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>63.3%</td>
<td>5.3%</td>
<td>3.9%</td>
</tr>
<tr>
<td>CC resonant</td>
<td>20.3%</td>
<td>39.4%</td>
<td>14.2%</td>
</tr>
<tr>
<td>CC coherent</td>
<td>1.4%</td>
<td>10.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>CC DIS</td>
<td>7.5%</td>
<td>31.3%</td>
<td>67.7%</td>
</tr>
<tr>
<td>NC</td>
<td>1.9%</td>
<td>4.7%</td>
<td>6.8%</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>0.19%</td>
<td>1.7%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>0.17%</td>
<td>0.4%</td>
<td>0.9%</td>
</tr>
<tr>
<td>External</td>
<td>5.2%</td>
<td>6.6%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Other</td>
<td>0.03%</td>
<td>0.04%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
ND280 $\theta_\mu$ (before-FSI categories)

CC0$\pi$

CC1$\pi^+$

CCQE RES DIS COH
NC $\bar{\nu}_\mu$ $\nu_e$
Out-of-fiducial-volume
ND280 $\cos \theta_\mu$ (before-FSI categories)

**CC0π**

**CC1π⁺**

**CC-other**

CCQE RES DIS COH
NC $\nu_\mu$ $\nu_e$
Out-of-fiducial-volume
ND280 $p_\mu$ (after-FSI categories)

**CC0π**

**CC1π**

**CC-other**

Background

External

No truth
ND280 $\theta_\mu$ (after-FSI categories)

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ND280 $\cos \theta_\mu$ (after-FSI categories)

**CC0$\pi$**

**CC1$\pi^+$**

**CC-other**

Background External
ND280 selection distributions (after ND280 fit)
ND280 CC0π (after ND280 fit)

CC0π Selection
- Data
- CCQE Pred.
- CC Resonant π Pred.
- CC Coherent π Pred.
- CC Multi-π/DIS Pred.
- Other Modes Pred.

Events/(100 MeV/c)

0.99<cosθ_μ<1.00
0.98<cosθ_μ<0.99
0.96<cosθ_μ<0.98
0.94<cosθ_μ<0.96
0.92<cosθ_μ<0.94
0.90<cosθ_μ<0.92
0.85<cosθ_μ<0.90
0.80<cosθ_μ<0.85
0.70<cosθ_μ<0.80
0.60<cosθ_μ<0.70
-1.00<cosθ_μ<0.60

p_μ (MeV/c)
ND280 CC1\(\pi^+\) (after ND280 fit)

CC1\(\pi\) Selection
- Data
- CCQE Pred.
- CC Resonant \(\pi\) Pred.
- CC Coherent \(\pi\) Pred.
- CC Multi-\(\pi\)/DIS Pred.
- Other Modes Pred.

Events/(100 MeV/c)

\(0.99 < \cos \theta_\mu < 1.00\)

\(0.98 < \cos \theta_\mu < 0.99\)

\(0.96 < \cos \theta_\mu < 0.98\)

\(0.94 < \cos \theta_\mu < 0.96\)

\(0.92 < \cos \theta_\mu < 0.94\)

\(0.90 < \cos \theta_\mu < 0.92\)

\(0.85 < \cos \theta_\mu < 0.90\)

\(0.80 < \cos \theta_\mu < 0.85\)

\(0.70 < \cos \theta_\mu < 0.80\)

\(0.60 < \cos \theta_\mu < 0.70\)

\(-1.00 < \cos \theta_\mu < 0.60\)

\(p_\mu\) (MeV/c)
ND280 CC-other (after ND280 fit)

CC Other Selection
- Data
- CCQE Pred.
- CC Resonant π Pred.
- CC Coherent π Pred.
- CC Multi-π/DIS Pred.
- Other Modes Pred.

Events/(100 MeV/c)

0.99<cosθμ<1.00

0.98<cosθμ<0.99

0.96<cosθμ<0.98

0.94<cosθμ<0.96

0.92<cosθμ<0.94

0.90<cosθμ<0.92

0.85<cosθμ<0.90

0.80<cosθμ<0.85

0.70<cosθμ<0.80

0.60<cosθμ<0.70

-1.00<cosθμ<0.60

pμ (MeV/c)
ND280 fit results for different run periods
Run 1-3 and Run 4 (∼ equal statistics) fit results consistent
Suggest fits dominated by systematics that are common to 2 statistically independent datasets
Inputs to the oscillation analyses
Inputs to the oscillation analyses

0-10 SK $\nu_\mu$ flux parameters, 11-15 SK $\bar{\nu}_\mu$ flux parameters, 16-22 SK $\nu_e$ flux parameters, 23-24 SK $\bar{\nu}_e$ flux parameters, 25 MAQE, 26 MARES, 27-29 CCQE normalisation, 30-31 CC1$\pi$ normalisation, 32 NC1$\pi^0$ normalisation.
## Inputs to the oscillation analyses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$ (GeV/c²) *</td>
<td>1.24±0.07</td>
</tr>
<tr>
<td>$p_F (^{16}\text{O})$ (MeV/c)</td>
<td>225±30</td>
</tr>
<tr>
<td>$E_B (^{16}\text{O})$ (MeV)</td>
<td>27±9</td>
</tr>
<tr>
<td>$0 (\text{RFG}) \rightarrow 1 (\text{SF})$</td>
<td></td>
</tr>
<tr>
<td>$M_A^{\text{RES}}$ (GeV/c²) *</td>
<td>0.96±0.07</td>
</tr>
<tr>
<td>$\pi$-less $\Delta$ decay fraction</td>
<td>0.20±0.20</td>
</tr>
<tr>
<td>$CC1\pi^0$ norm $E_\nu &lt; 2.5$ GeV *</td>
<td>1.26±0.16</td>
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<td>$CC1\pi^0$ norm $E_\nu &gt; 2.5$ GeV *</td>
<td>1.12±0.17</td>
</tr>
<tr>
<td>CC coherent norm</td>
<td>1.00±1.00</td>
</tr>
<tr>
<td>$NC\pi^0$ norm*</td>
<td>1.13±0.25</td>
</tr>
<tr>
<td>$NC\pi^{\pm}$ norm</td>
<td>1.00±0.30</td>
</tr>
<tr>
<td>$W$-shape (MeV/c²)</td>
<td>87.7±45.3</td>
</tr>
<tr>
<td>$CC$ other shape (GeV)</td>
<td>0.00±0.40</td>
</tr>
<tr>
<td>$NC$ other norm</td>
<td>1.00±0.30</td>
</tr>
<tr>
<td>$\nu_e$ to $\nu_\mu$ ratio</td>
<td>1.00±0.03</td>
</tr>
<tr>
<td>$\nu$ to $\bar{\nu}$ ratio</td>
<td>1.00±0.20</td>
</tr>
</tbody>
</table>

*Constrained by ND280
Analysis improvements
High angle tracks

Complementary to current selection (no double counting) (i.e. events with tracks with \( \leq 19 \) TPC2 hits)
Questions
1. What external neutrino scattering data were used to inform the generator level uncertainties (before obtaining any constraint from own data)?
   ▶ MiniBooNE, SciBooNE, MINERvA, NOMAD, ... Slides 5-9

2. Did you also utilise any electron-nucleus and hadron-nucleus scattering data. What aspects of the interaction model were constrained?
   ▶ RFG parameters. Slide 7

3. Quote all the input generator level uncertainties.
   ▶ Slide 20

4. How were these uncertainties propagated to the physics analysis? Did you consider correlations between the generator level uncertainties and if no, why?
   ▶ Correlations & tuning only for the pion fit. Slide 8

5. Which were the samples used for constraining the interaction uncertainties? Please provide details on the selection cuts, purity and efficiency and a breakdown of event categories according to generator.
   ▶ CC0π, CC1π⁺, CC-other. Slides 11-17, 31-40
Which aspects of the interaction model were tuned by the near detector data or control samples? Explain the procedure.

- CCQE, CC$1\pi^0$, NC$1\pi^0$. Slides 18-20

Was there a significant tension between the interaction model tunes (tunes based on external vs own data, tunes obtained with data from different running periods / different running conditions)?

- MiniBooNE/ND280 tension in $M_A^{RES}$. Slide 17
- No tension in Runs 1-3 vs Run 4. Slide 42

What was the systematic error improvement provided by the near detector or control samples? Provide details (uncertainty before / after constraint).

- Slide 20

How was the effect of neutrino interaction uncertainties decoupled from the effect of flux uncertainties and detector response effects?

- Include all flux, detector, cross section parameters in a single fit. Slides 18-19, 44

What uncertainties were not constrained directly by the near detector or control sample and how were they estimated?

- Parameters not on Slide 18 are estimated using Slides 7-9
Did you consider the possible effect of Np-Nh contributions? How does it affect your analysis?

- Small effect. Slides 25-26

How were the interaction uncertainties propagated to the oscillation analysis? Which correlations between systematics did you take into account?

- Correlations between flux & cross section systematics. 
  Other cross section systematics uncorrelated. Slides 44-45

If applicable, which uncertainties were correlated between the near and far detectors? What was the level of error cancellation? Which were the dominant uncertainties?

- $\sim 20\% \rightarrow \sim 3\%$ error reduction. Slide 24

How did you estimate the absolute neutrino energy? What was the impact of nuclear and hadronic simulation uncertainties?

- Quasi-elastic formula. Slide 23

Based on recent knowledge, is there any systematic uncertainty which you think may have been underestimated?