Controlling neutrino interaction systematics: The T2K experience

Tom Dealtry
for the T2K collaboration

University of Oxford

NuInt14
19 May, 2014

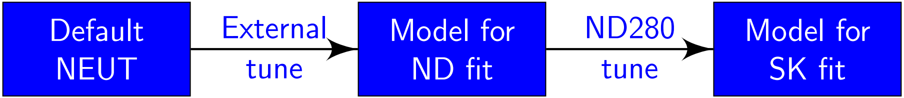
Outline

T2K

- 30 GeV proton beam running up to ∼250 kW (design 750 kW), producing ν_μ 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

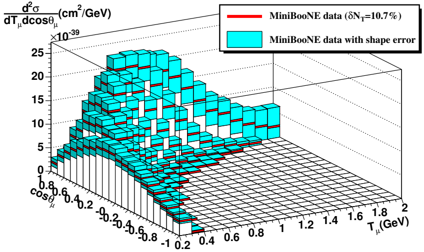
T2K cross section determination procedure

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 ν_μ 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)

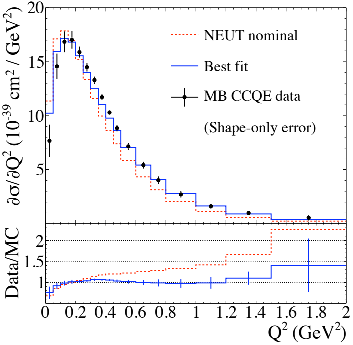
MiniBooNE CCQE fit



PRD 81:092005

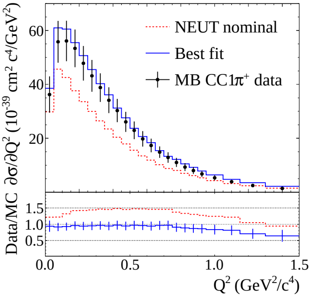
- Fit double differential cross section in lepton kinematics (T_μ & $\cos\theta_\mu$)
- No correlated bin errors available
- 2 free parameters: M_A^{QE} & 10.7% CCQE normalisation

- $M_A^{\mathrm{QE}} = 1.64 \pm 0.03\,\mathrm{GeV}/c^2$
- CCQE norm $= 0.88 \pm 0.02$



PRD 88:032002

MiniBooNE single π production fit



PRD 83:052007

Fit 3 samples

- $CC1\pi^0$ Q^2 (fully correlated errors)
- $CC1\pi^+$ Q^2 (correlated errors unavailable)
- $NC1\pi^0$ $|\mathbf{p}_{\pi^0}|$ (uncorrelated errors)

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 & π-less Δ-decay fraction

CCQE uncertainties

M_A^{QE}

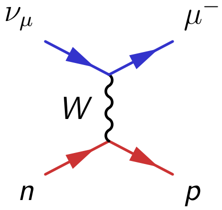
- Difference between best fit and NEUT nominal ($1.21\,\mathrm{GeV}/c^2$)

CCQE norm ($E_\nu < 1.5\,\mathrm{GeV}$)

- MiniBooNE flux error

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

- Differences between NOMAD & MiniBooNE data



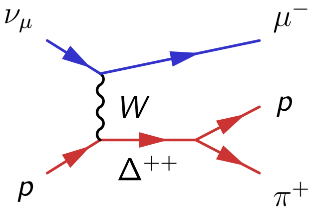
Nuclear model parameters (nucleus dependent)

- 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 π production uncertainties

M_A^{RES}, CC1π norm ($E_\nu < 2.5\,\mathrm{GeV}$), 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

CC1π norm ($E_\nu > 2.5\,\mathrm{GeV}$)

- Extrapolation of difference between NEUT nominal & MiniBooNE

π-less Δ-decay

- NEUT default is 20%. Allow to drop to 0% at 1σ

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 $4\,\mathrm{GeV}$

NC$\pi^{\pm}$, NC other

- Difference between NEUT nominal, Gargamelle & Derrick et al.

$\nu/\bar{\nu}$ norm

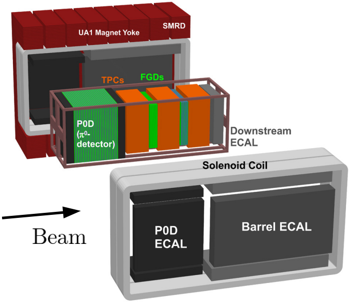
- Comparison between MiniBooNE & MINERvA

ν_e/ν_μ norm

- Uses the work of Day et al. (PRD 86:053003)

Outline

ND280 CC inclusive selection

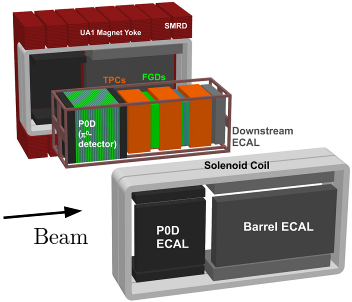


- The muon candidate is selected as the highest momentum negatively-charged TPC2 track with > 18 hits, starting in the FGD1 fiducial volume
- Veto events where the highest-momentum TPC2 track (that isn't the muon) is $> 150\,\mathrm{mm}$ upstream of muon vertex
- Veto events where the muon candidate is backwards going
- Veto events with a possible broken FGD track
- Track should be muon-like, using TPC PID based on dE/dx

ND280 π 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 π^+

π^+ track in FGD1

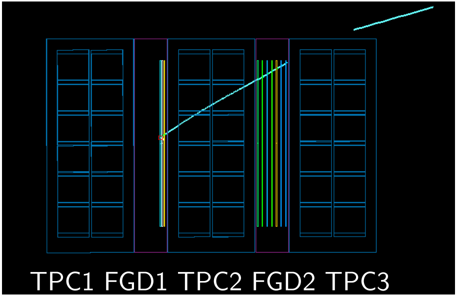
- Require a fully contained track within FGD1 & $|\cos\theta| > 0.3$
- Tag particle as $\pi^{\pm}$ using FGD1 PID based on dE/dx

ND280 CC0π, CC1π^+, CC-other selections

Split the CC inclusive sample into 3 subsamples:

- **CC0π:** 0 $e^{\pm}$ TPC2 tracks, 0 $\pi^{\pm}$ TPC2 tracks, 0 Michel electrons, 0 $\pi^{\pm}$ FGD-only tracks
- **CC1π^+:** 0 $e^{\pm}$ TPC2 tracks, 0 π^{-} TPC2 tracks, exactly one TPC2 π^+ track, Michel electron, $\pi^{\pm}$ FGD-only track
- **CC-other:** All other events.

$\Longrightarrow$ beam



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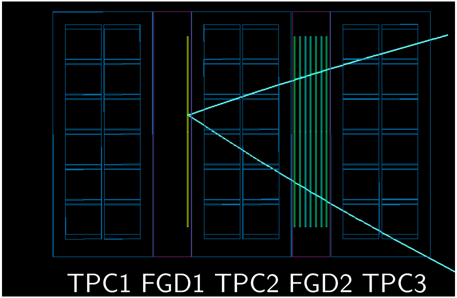
- **CC-other:** All other events.

$\Longrightarrow$ beam



ND280 CC0π, CC1π^+, CC-other selections

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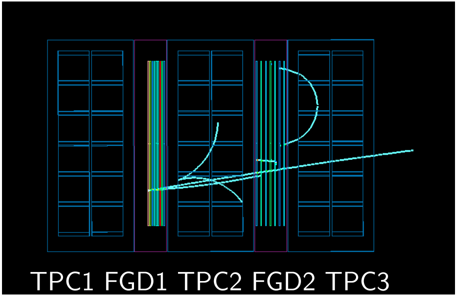
- **CC-other:** All other events.

$\Longrightarrow$
beam



ND280 CC0π, CC1π^+, CC-other selections

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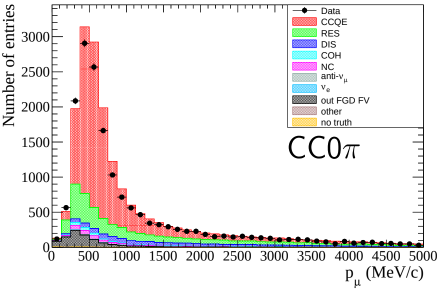
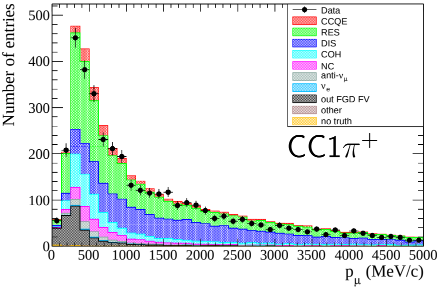
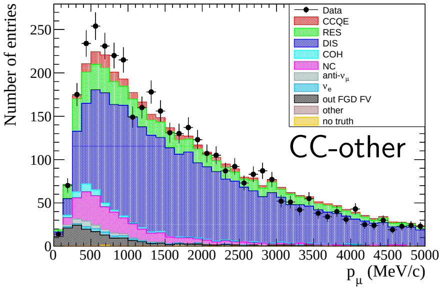
- **CC1π^+** 0 $e^\pm$ TPC2 tracks, 0 π^- TPC2 tracks, exactly one TPC2 π^+ track, Michel electrons, $\pi^\pm$ FGD-only tracks
- **CC-other** All other events.

Purity	CC0π	CC1π^+	CC-other
CC0π	**72.4**%	6.4%	5.8%
CC1π^+	8.6%	**49.2**%	7.8%
CC-other	11.5%	31.0%	**73.6**%
Background	2.3%	6.8%	8.7%
External	5.2%	6.6%	4.1%
Efficiency	47.8%	28.4%	29.7%

ND280 p_μ (before-FSI categories)







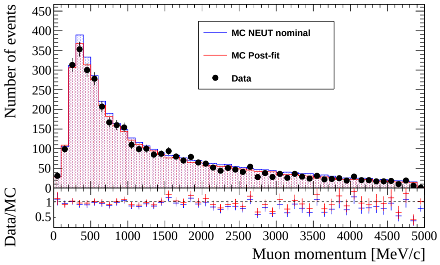
CCQE RES DIS COH

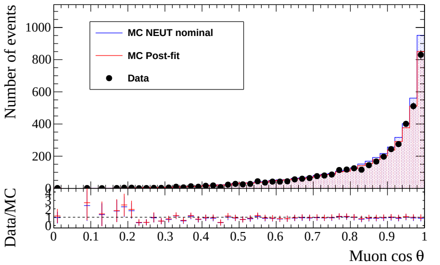
NC $\overline{\nu}_\mu$ ν_e

Out-of-fiducial-volume

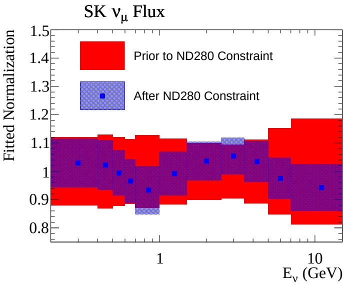
ND280 fit

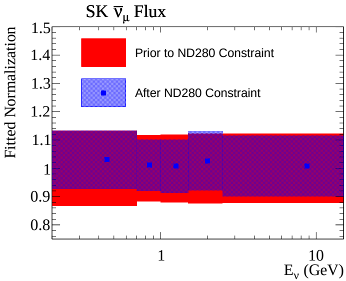
- Fit the muon kinematics (p_μ, $\cos\theta_\mu$) for each of the 3 samples simultaneously
- Include cross section, FSI, flux & detector systematics
- M_A^{QE}, M_A^{RES}, normalisations (CCQE, CC1π, NC1π^0), and flux parameters propagated to oscillation analyses
  - Including correlations

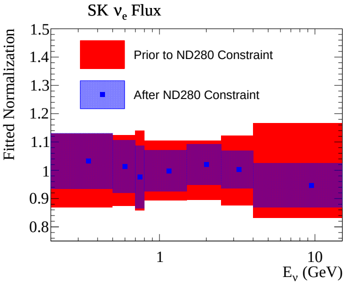


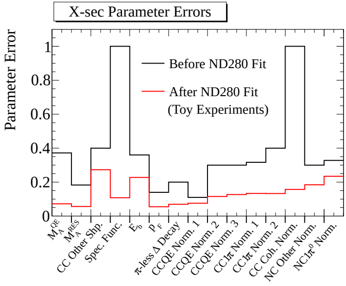


ND280 fit results









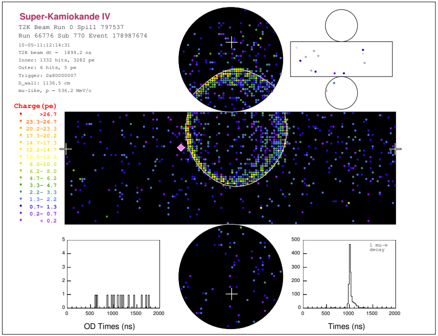
ND280 fit results

	External tune	ND280 tune
M_A^{QE} (GeV/c^2)	1.21±0.45	1.24±0.07
SF (^{12}C)	0 (RFG) → 1 (SF)	0.24±0.13
E_B (^{12}C) (MeV)	25±9	30.9±5.2
p_F (^{12}C) (MeV/c)	217±30	266.3±10.6
CCQE norm $E_\nu < 1.5\,\mathrm{GeV}$	1.00±0.11	0.97±0.08
CCQE norm $1.5 < E_\nu < 3.5\,\mathrm{GeV}$	1.00±0.30	0.93±0.10
CCQE norm $E_\nu > 3.5\,\mathrm{GeV}$	1.00±0.30	0.85±0.11
M_A^{RES} (GeV/c^2)	1.41±0.11	0.96±0.07
π-less Δ decay fraction	0.20±0.20	0.21±0.08
CC1π^0 norm $E_\nu < 2.5\,\mathrm{GeV}$	1.15±0.43	1.26±0.16
CC1π^0 norm $E_\nu > 2.5\,\mathrm{GeV}$	1.00±0.40	1.12±0.17
CC coherent norm	1.00±1.00	0.45±0.16
NCπ^0 norm	0.96±0.43	1.13±0.25
CC other shape (GeV)	0.00±0.40	0.23±0.29
NC other norm	1.00±0.30	1.41±0.22

Outline

Oscillation analyses

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



1 μ-like ring

μ-like

- Ring is PID'ed as μ-like
- 0 or 1 Michel electron
- $p_\mu > 200\,\mathrm{MeV}/c$

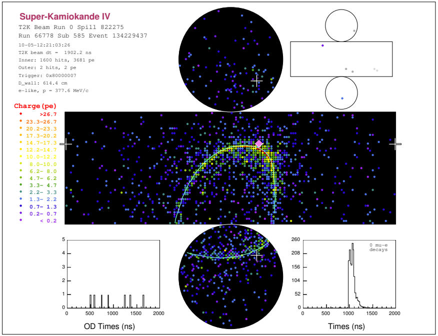
e-like

- Ring is PID'ed as e-like
- 0 Michel electrons
- $E_{\mathrm{reco}} < 1.25\,\mathrm{GeV}$
- π^0 rejection

$$E_{\mathrm{reco}} = \frac{m_p^2c^4 - (m_nc^2 - E_b)^2 - m_\mu^2c^4 + 2(m_nc^2 - E_b)E_\mu}{2(m_nc^2 - E_b - E_\mu + p_\mu c\cos\theta_\mu)}$$

Oscillation analyses

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



1 e-like ring

μ-like

- Ring is PID'ed as μ-like
- 0 or 1 Michel electron
- $p_\mu > 200\,\mathrm{MeV}/c$

e-like

- Ring is PID'ed as *e*-like
- 0 Michel electrons
- $E_{\mathrm{reco}} < 1.25\,\mathrm{GeV}$
- π^0 rejection

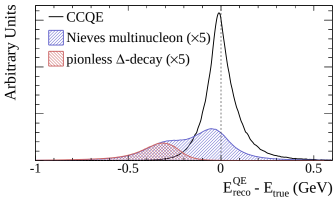
$$E_{\mathrm{reco}} = \frac{m_p^2c^4 - (m_nc^2 - E_b)^2 - m_\mu^2c^4 + 2(m_nc^2 - E_b)E_\mu}{2(m_nc^2 - E_b - E_\mu + p_\mu c\cos\theta_\mu)}$$

Oscillation analyses: effect of ND280 fit

Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SK+FSI	5.00%	3.65%
ND280-independent XSec	5.00%	4.69%
ND280 prefit	21.75%	26.04%
ND280 postfit	2.74%	3.15%
Total (ND280 postfit)	7.65%	6.75%
Total (ND280 prefit)	23.45%	26.80%

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

np-nh effect methodology



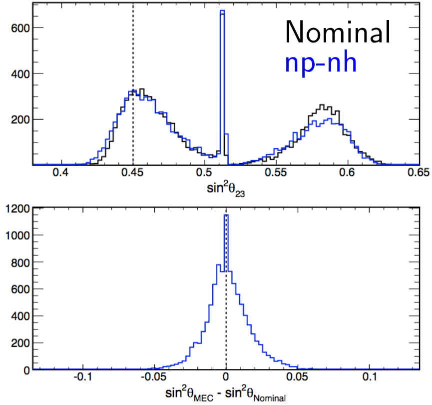
1 μ-like ring

- Model np-nh events using Nieves model (Phys.Lett.B 707:72) in NuWro
- Replace NEUT π-less Δ 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

$\sin^2\theta_{23}$

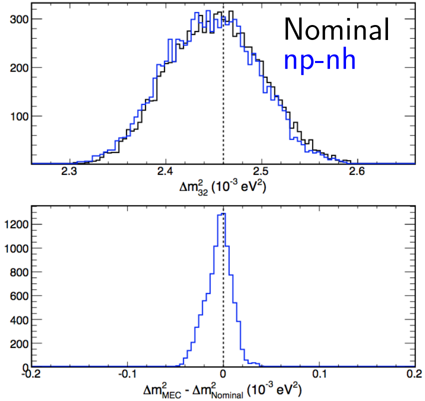


Mean: $+0.3\%$

RMS: 3.6%

Other systematics RMS: 3.8-5.6%

Δm^2_{32}



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
  - MINERνA, MiniBooNE $\overline{\nu}$, 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 CC0π, CC1π^+, CC-other selections result in greatly reduced errors
  - 21.8% $\rightarrow$ 2.7% for 1 μ-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 ν_μ 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

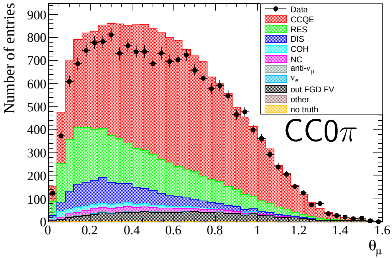
ND280 selection distributions (before ND280 fit)

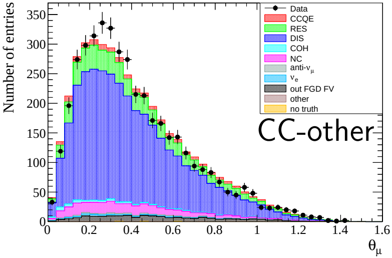
ND280 CC0π, CC1π^+, CC-other purities

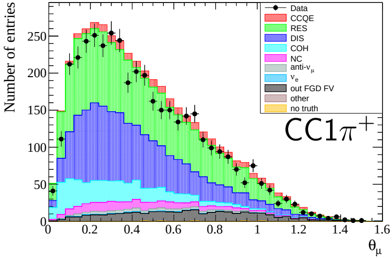
	CC0π	CC1π^+	CC-other
CC0π	**72**.4%	6.4%	5.8%
CC1π^+	8.6%	**49**.2%	7.8%
CC-other	11.5%	31.0%	**73**.6%
Background	2.3%	6.8%	8.7%
External	5.2%	6.6%	4.1%

	CC0π	CC1π^+	CC-other
CCQE	**63**.3%	5.3%	3.9%
CC resonant	20.3%	**39**.4%	14.2%
CC coherent	1.4%	**10**.6%	1.4%
CC DIS	7.5%	**31**.3%	**67**.7%
NC	1.9%	4.7%	6.8%
$\overline{\nu}_\mu$	0.19%	1.7%	0.9%
ν_e	0.17%	0.4%	0.9%
External	5.2%	6.6%	4.1%
Other	0.03%	0.04%	0.2%

ND280 θ_μ (before-FSI categories)

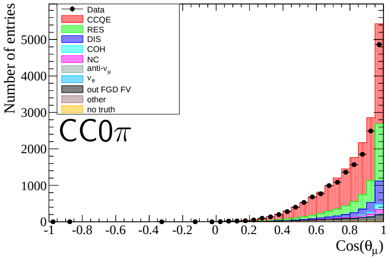


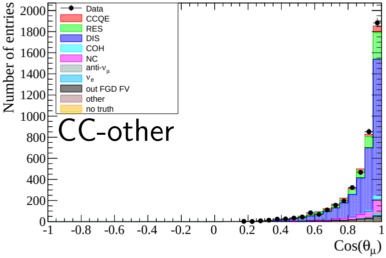


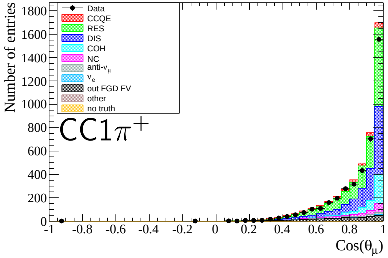


CCQE RES DIS COH
NC $\overline{\nu}_\mu$ ν_e
Out-of-fiducial-volume

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





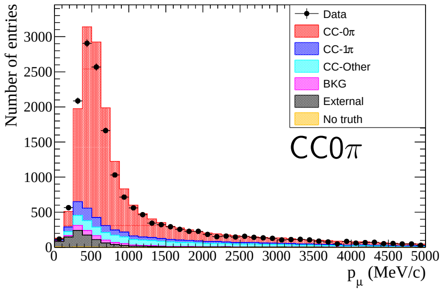


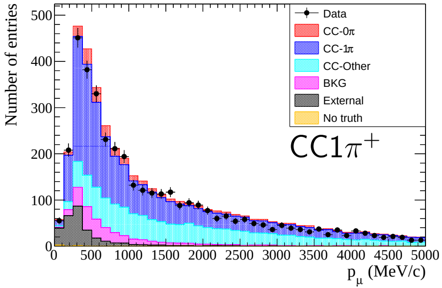
CCQE RES DIS COH

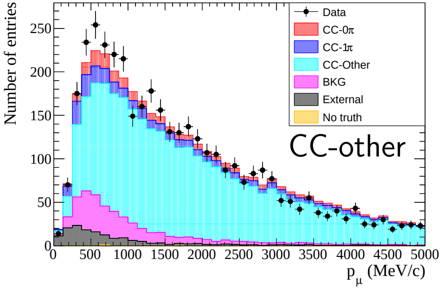
NC $\overline{\nu}_\mu$ ν_e

Out-of-fiducial-volume

ND280 p_μ (after-FSI categories)



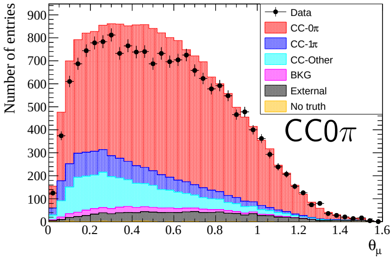


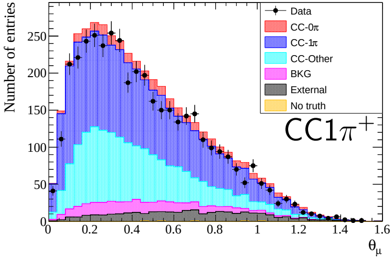


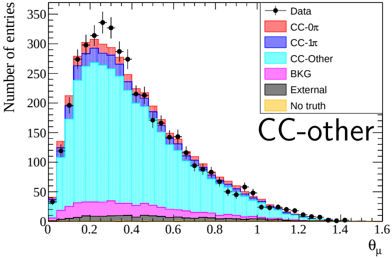
$CC0\pi$ $CC1\pi^+$ CC-other

Background External

ND280 θ_μ (after-FSI categories)

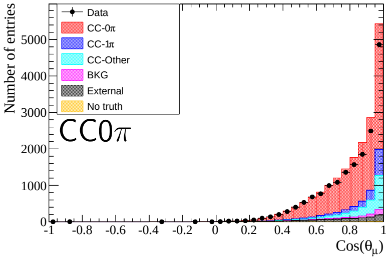


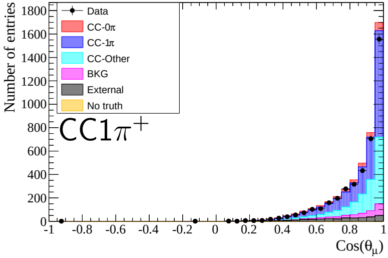


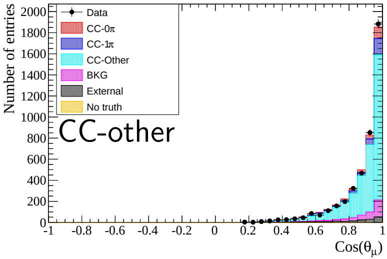


$CC0\pi$ $CC1\pi^+$ CC-other
Background External

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



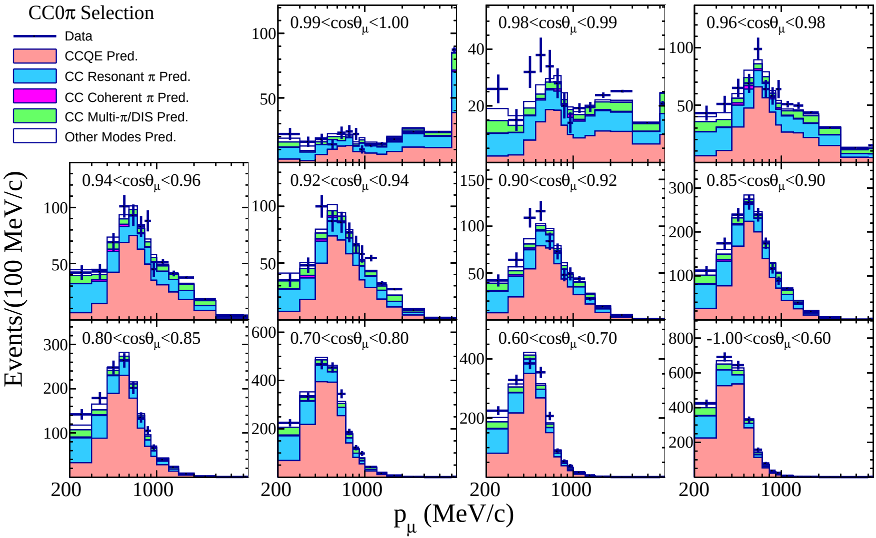




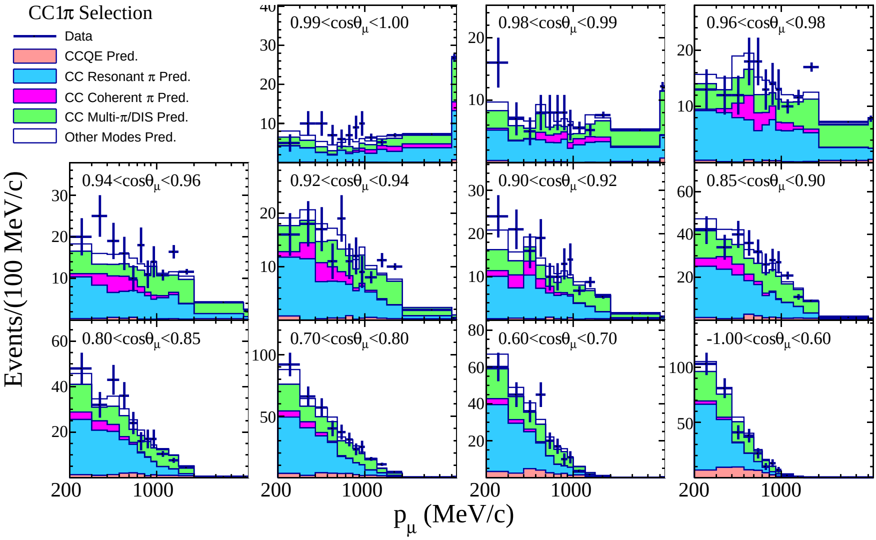
$CC0\pi$ $CC1\pi^+$ CC-other
Background External

ND280 selection distributions (after ND280 fit)

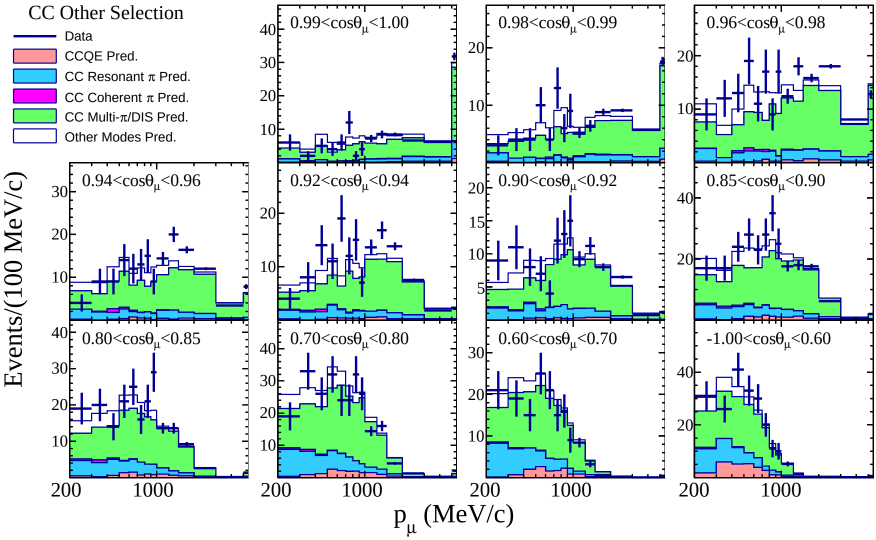
ND280 CC0π (after ND280 fit)



ND280 CC1π^+ (after ND280 fit)

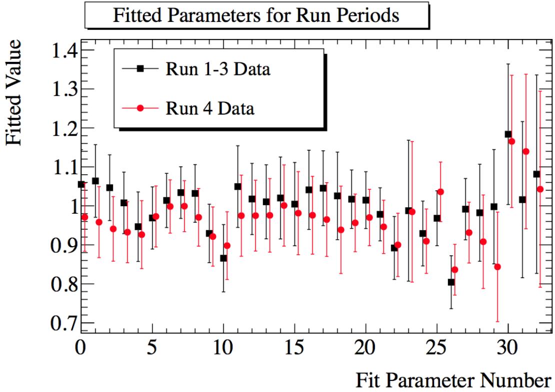


ND280 CC-other (after ND280 fit)



ND280 fit results for different run periods

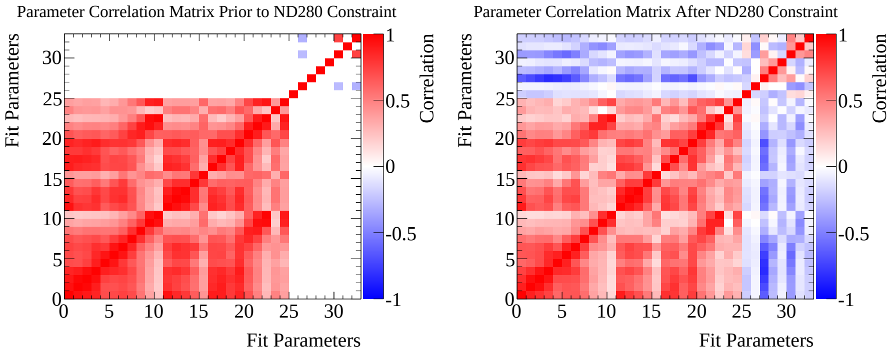
ND280 fit results for different run periods



- Run 1-3 and Run 4 ($\sim$ 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 ν_μ flux parameters, 11-15 SK $\overline{\nu}_\mu$ flux parameters, 16-22 SK ν_e flux parameters, 23-24 SK $\overline{\nu}_e$ flux parameters, 25 MAQE, 26 MARES, 27-29 CCQE normalisation, 30-31 CC1π normalisation, 32 NC1π^0 normalisation.

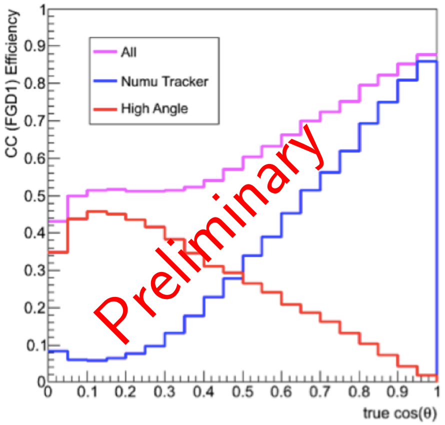
Inputs to the oscillation analyses

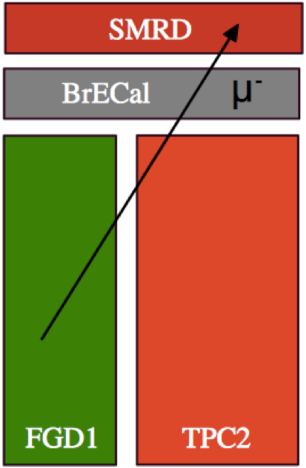
M_A^{QE} (GeV/c^2)*	1.24±0.07
p_F (^{16}O) (MeV/c)	225±30
E_B (^{16}0) (MeV)	27±9
SF (^{16}O)	0 (RFG) $\rightarrow$ 1 (SF)
CCQE norm $E_\nu < 1.5\,\mathrm{GeV}$ *	0.97±0.08
CCQE norm $1.5 < E_\nu < 3.5\,\mathrm{GeV}$ *	0.93±0.10
CCQE norm $E_\nu > 3.5\,\mathrm{GeV}$ *	0.85±0.11
M_A^{RES} (GeV/c^2)*	0.96±0.07
π-less Δ decay fraction	0.20±0.20
CC1π^0 norm $E_\nu < 2.5\,\mathrm{GeV}$ *	1.26±0.16
CC1π^0 norm $E_\nu > 2.5\,\mathrm{GeV}$ *	1.12±0.17
CC coherent norm	1.00±1.00
NCπ^0 norm*	1.13±0.25
NC$\pi^\pm$ norm	1.00±0.30
W-shape (MeV/c^2)	87.7±45.3
CC other shape (GeV)	0.00±0.40
NC other norm	1.00±0.30
ν_e to ν_μ ratio	1.00±0.03
ν to $\overline{\nu}$ ratio	1.00±0.20

*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.
   - $CC0\pi$, $CC1\pi^{+}$, CC-other. Slides 11-17, 31-40

6. Which aspects of the interaction model were tuned by the near detector data or control samples? Explain the procedure.
    - CCQE, CC1π, NC1π^0. Slides 18-20
7. 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
8. What was the systematic error improvement provided by the near detector or control samples? Provide details (uncertainty before / after constraint).
    - Slide 20
9. 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
10. 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

11. Did you consider the possible effect of Np-Nh contributions? How does it affect you analysis?
    - Small effect. Slides 25-26
12. 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
13. 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
14. How did you estimate the absolute neutrino energy? What was the impact of nuclear and hadronic simulation uncertainties?
    - Quasi-elastic formula. Slide 23
15. Based on recent knowledge, is there any systematic uncertainty which you think may have been underestimated?