Impact of uncertainties in neutrino cross sections: The T2K oscillation analyses

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NuSTEC
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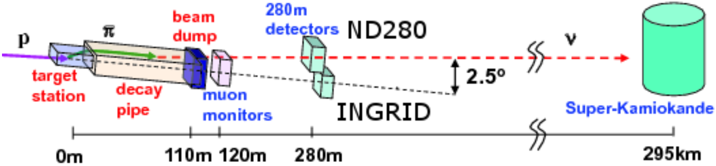
Outline

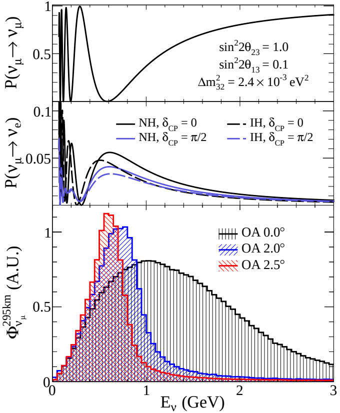
1. T2K
2. Oscillation analysis overview
3. Interaction process models and external constraints
   - CCQE
   - Resonant 1π
   - Other processes
   - Final state interactions
4. ND280 event selections & constraint
5. Oscillation analyses
   - SuperK event selections
   - Effect of systematics
   - Oscillation results
   - Effect of np-nh on ν_μ disappearance search
6. Summary & prospects

T2K

- 30 GeV proton beam running up to ∼250 kW (design 750 kW), producing ν_μ beam
- Far detector, SuperK, 2.5° off-axis
- Two near detectors at 280 m: INGRID on-axis, ND280 off-axis
- Studying neutrino oscillations & cross sections

Beam: off-axis method



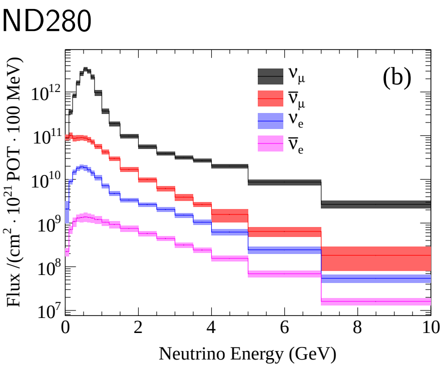


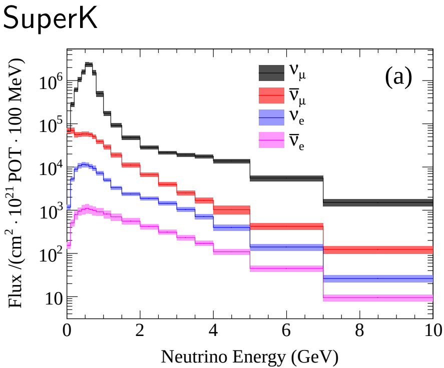
Off-axis angle 2.5° chosen to peak at the first oscillation maximum

$E_\nu \sim 0.6 GeV$

Supresses high energy backgrounds

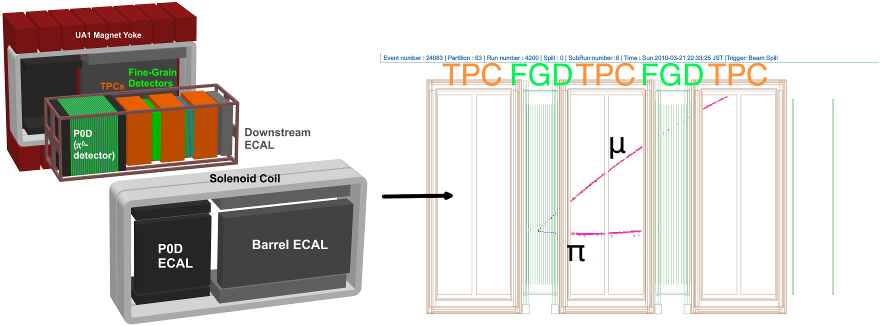
Beam flux





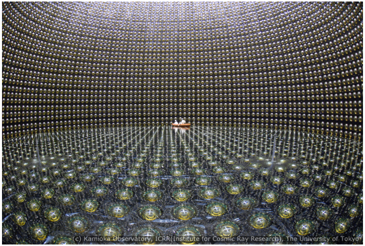
- Intrinsic $\overline{\nu}_\mu$ background $\sim$6%
  - Assuming same oscillation parameters for ν, $\bar{\nu}$
- Intrinsic ν_e background $\sim$1%
- Actual interaction rates different due to cross section differences

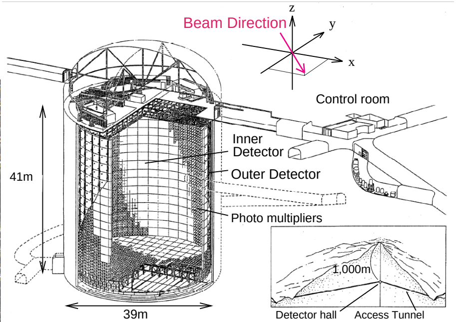
ND280



- Analysis shown in this talk uses the 'tracker' region
  - Fine-Grain Detector
    - Carbon target mass, 1 cm vertex resolution
  - Time Projection Chambers
    - Used for momentum & charge reconstruction, and particle identification

Super-Kamiokande





- 22.5 kton fiducial cylindrical water Cherenkov detector
  - 11,129 20" PMTs (40% coverage)
  - Energy threshold 4.5 MeV
  - DAQ: no dead-time
- 2700 m.w.e. overburden
- Outer detector used as veto
  - 1,885 8" PMTs

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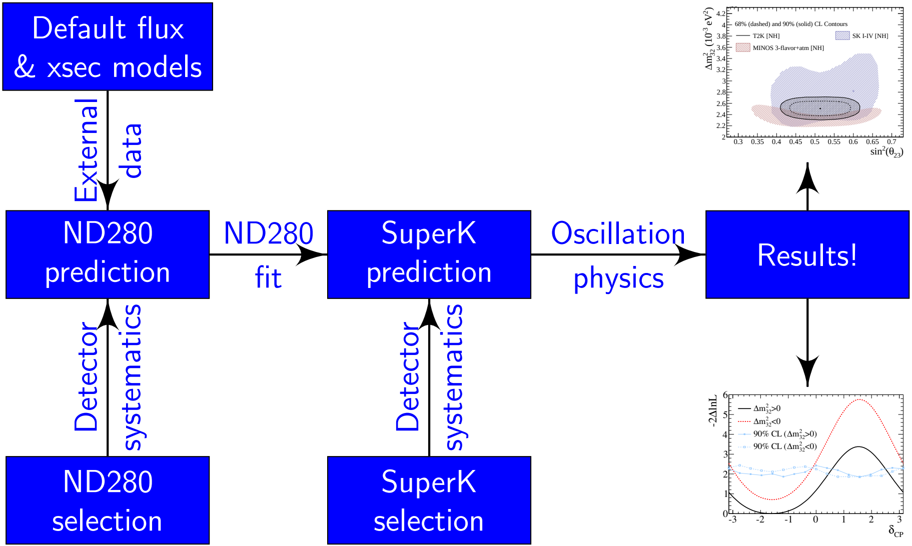
Oscillation physics

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

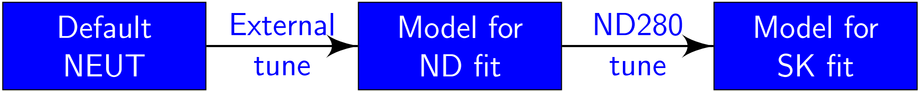
- Use the full 3-flavour formula with matter effects in the fits
- Use ν_μ disappearance to determine θ_{23} and $|\Delta m^2_{32}|$
- Use ν_e appearance to determine θ_{13}, δ_{CP}
- Perform a joint fit to fully exploit the data
  - Required to find the quadrant of θ_{23}

Oscillation analysis outline



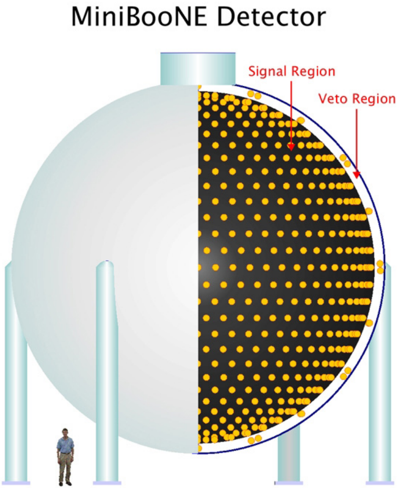
T2K cross section determination procedure

1. Take the default cross section model (NEUT)
2. Assign uncertainties & tune single pion production using external data (especially MiniBooNE)
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

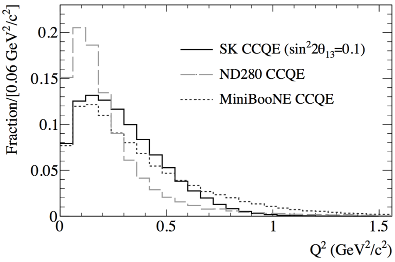
MiniBooNE

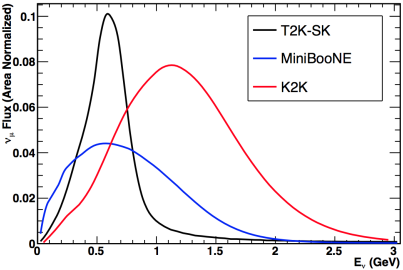


- 818 t spherical mineral oil (CH_2) Cherenkov detector
  - 610 cm inner radius
  - 1280 8" PMTs (11.3% coverage)
- Outer detector used as veto
  - 240 8" PMTs
- 540 m from the Fermilab BNB target

Detector comparisons

	ND280	SuperK	MiniBooNE
Target	C	O	C
Detector technology	fine-grained	Cherenkov	Cherenkov
Acceptance	forward-going	4π	4π





PRD 1304.0841

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CCQE in NEUT

- CCQE simulated using Llewlyn-Smith model
  - Phys.Rept.C3 261 (1972)
  - $M_A^{\mathrm{QE}} = 1.21\,\mathrm{GeV}$, $M_V^{\mathrm{QE}} = 0.84\,\mathrm{GeV}$
- Nucleus modelled using RFG (Smith & Moniz)
  - Nucl. Phys. B43, 605 (1972) & B101, 547(E) (1975)
  - $E_b = 25(27)\,\mathrm{MeV}$ and $p_f = 217(225)\,\mathrm{MeV}/c$ for $^{12}C(^{16}O)$
- NC elastic included by scaling CC cross sections
- Effect of alternate models studied using NuWro-generated events
  - Spectral function
  - np-nh

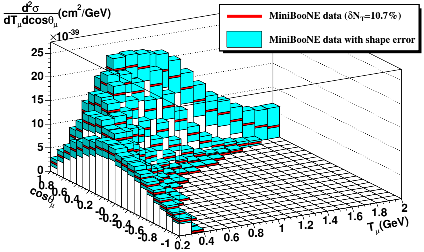
MiniBooNE CCQE cross section

- Select 1 μ-like ring events with a delayed Michel electron
  - CCQE purity 77.0%
  - $CC1\pi^+$ dominant background (18.4% of selected events)
  - Create $CC1\pi^+$ sideband as 1 μ-like ring events with 2 delayed Michel electrons

$$\sigma_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i T \Phi}$$

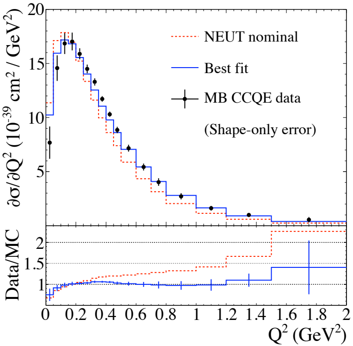
- U_{ij} unfolding matrix
  - Probability a reconstructed event in bin j lies in true bin i
- d_j data
- b_j background
  - $CC1\pi^+$ data-driven constraint & MC prediction for everything else
- ϵ_i efficiency
- T number of targets (neutrons) in fiducial volume
- Φ integrated neutrino flux

MiniBooNE CCQE fit



PRD 81:092005

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



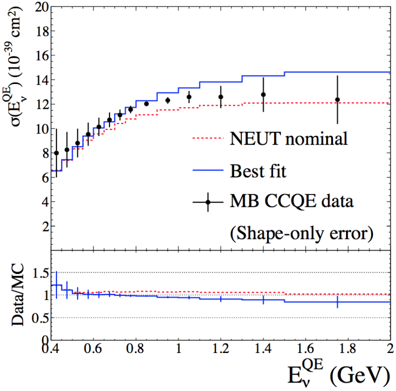
PRD 88:032002

- 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% normalisation

MiniBooNE CCQE fit

- MiniBooNE calculates $M_A^{\mathrm{QE}} = 1.35 \pm 0.17\,\mathrm{GeV}/c^2$, $\kappa = 1.07$
- T2K calculates $M_A^{\mathrm{QE}} = 1.64 \pm 0.03\,\mathrm{GeV}/c^2$
- Why so different?

- MiniBooNE empirically modified the low q^2 region (κ)
- Lack of correlations in the $\frac{\mathrm{d}\sigma}{\mathrm{d}T_\mu \mathrm{d}\cos\theta_\mu}$ errors released
- Fitting
  - $\frac{\mathrm{d}\sigma}{\mathrm{d}T_\mu \mathrm{d}\cos\theta_\mu}$ (with normalisation error)
  - $\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}$ (shape only)
- NEUT $\neq$ NUANCE



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CCQE uncertainties

M_A^{QE}

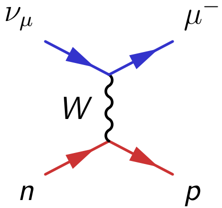
- Difference between best fit and NEUT nominal ($1.21\,\mathrm{GeV}/c^2$)

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 1π NEUT

- Resonant 1π simulated using Rein-Sehgal model
  - D. Rein, L.M. Sehgal, Ann. Phys. 133, 79 (1981)
  - D. Rein, Z. Phys. C35, 43 (1987)
- Incorporates 18 resonance states between 2 GeV, and includes interferences
- Dominated by Δ(1232)
- Resonances can also decay to Ks, ηs, γs
- Or de-excite within the nucleus
  - π-less Δ-decay

MiniBooNE single π production fit

Fit 3 samples simultaneously

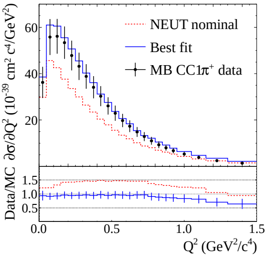
- $CC1\pi^0$ Q^2 (fully correlated errors)
- $CC1\pi^+$ Q^2 (correlated errors unavailable)
- $NC1\pi^0$ $|\mathbf{p}_{\pi^0}|$ (uncorrelated errors)

Use 9 systematic parameters

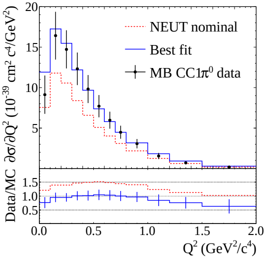
- M_A^{RES}
- W-shape: empirically modifies pion momentum distributions
- CC other shape: $\sigma_{CCother} = 0.4/E_\nu$
- 6 normalisations:
  CC coherent, $CC1\pi$,
  NC coherent, $NC1\pi^0$, $NC1\pi^\pm$, NC other

Redo fit multiple times, changing FSI parameters & π-less Δ-decay fraction

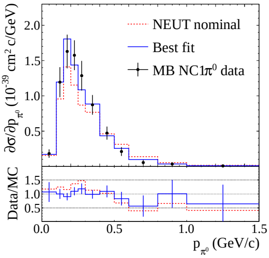
MiniBooNE single π production fit



PRD 83:052007



PRD 83:052009



PRD 81:013005

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)

Resonant π production uncertainties

M_A^{RES}, CC1π norm ($E_\nu < 2.5\,\mathrm{GeV}$), NC1$\pi^0$ norm

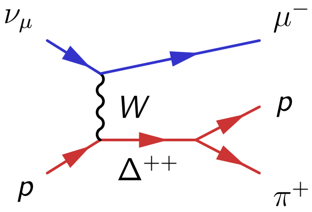
- Best-fit values from default fit & covariances built from results of alternative FSI/PDD fits

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 processes in NEUT

- Coherent 1π production simulated using Rein-Sehgal model (with lepton mass corrections)
  - D. Rein, L.M. Sehgal, Nucl. Phys. B223, 29 (1983)
  - P. Marage et al., Z. Phys. C31, 191 (1986)
  - D. Rein, L.M. Sehgal, Phys. Lett. B657, 207 (2007)
- DIS simulated using GRV98 PDFs, and low q^2 corrections by Bodek and Yang
  - M. Glück, E. Reya, A. Vogt, Eur. Phys. J. C5, 461 (1998)
  - A. Bodek, U.K. Yang, hep-ex/0308007 (2003)
- NC DIS included by scaling CC cross sections

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)

FSI in NEUT

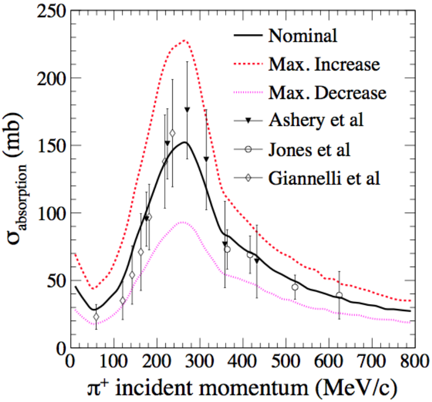
- FSI modelled using microscopic cascade
  - L. Salcedo, et.al., Nucl. Phys. A 484, 557 (1988)

1. Choose interaction point within nuclei based on Woods-Saxon nucleon density distribution
2. Step hadrons through the nucleus by unit length
3. Determine whether an interaction took place using interaction probabilities
4. Repeat steps 2-3 until interaction takes place, or particle exits nucleus

FSI uncertainties

- 6 parameters used to vary the processes
  - 3 at low energy
    - π absorption probability
    - π QE+single charge exchange probability
    - π single charge exchange branching fraction
  - 3 at high energy
    - high energy π QE+single charge exchange probability
    - high energy π single charge exchange branching fraction
    - pion production
- Span the uncertainties in π-nucleus scattering data by varying the FSI model parameters

FSI uncertainties



Generate covariance matrix in reconstructed variables r

Use the 16 parameter sets that span the data

$$V_{ij} = \frac{1}{16} \sum_{k=1}^{16} (r_i^{nom} - r_i^k)(r_j^{nom} - r_j^k)$$

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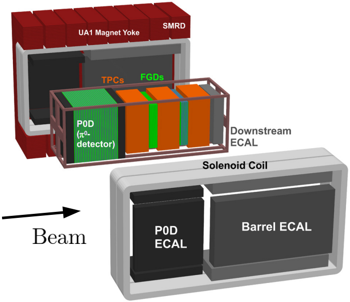
ND280 CC inclusive selection



- 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

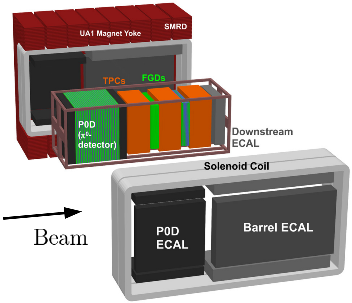
ND280 π selections

$e^{\pm}$, $\pi^{\pm}$ 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

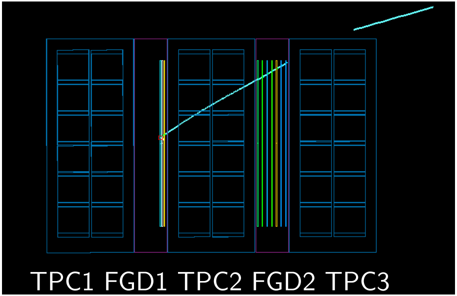
- Require a fully contained track within FGD1 & $|\cos\theta| > 0.3$
- Tag particle as $\pi^{\pm}$ using FGD1 PID based on dE/dx

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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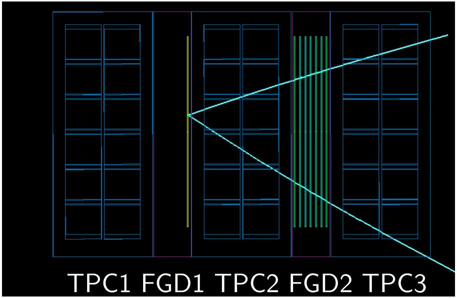

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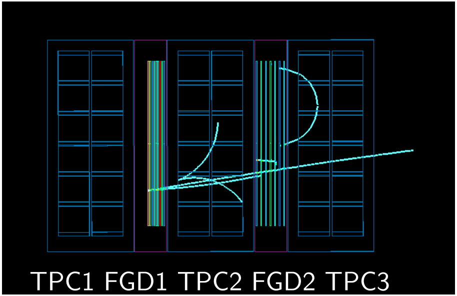
$\Longrightarrow$ beam



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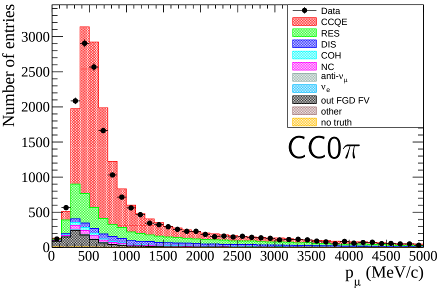
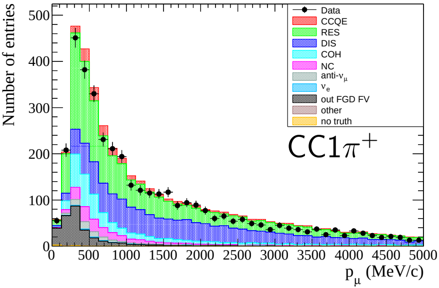
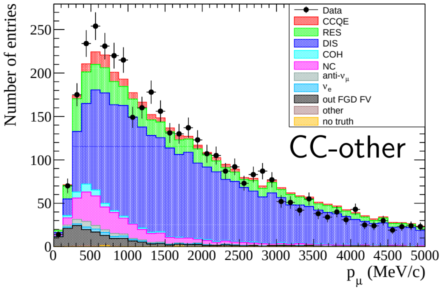
- **CC-other** All other events.

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)







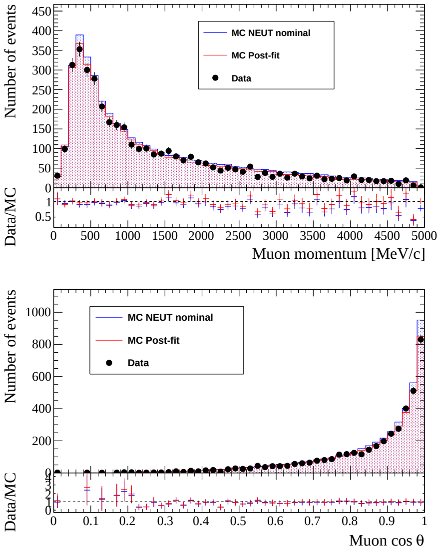
CCQE RES DIS COH

NC $\overline{\nu}_\mu$ ν_e

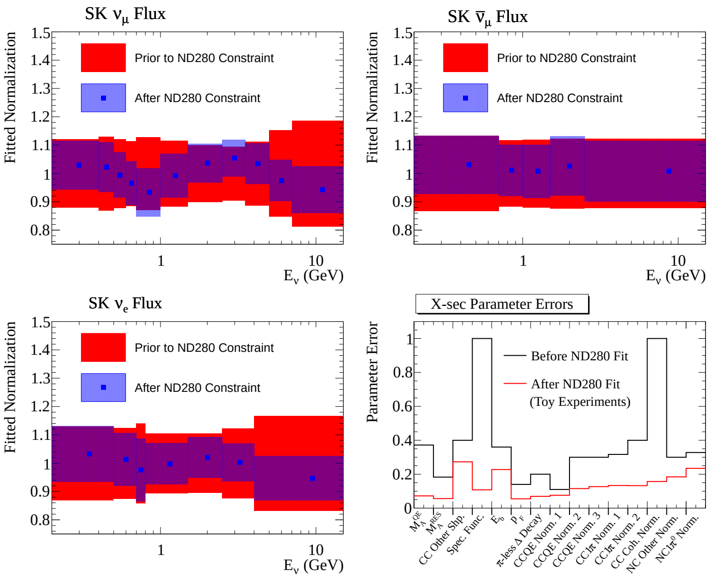
Out-of-fiducial-volume

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
- $M_A^{\rm QE}$, $M_A^{\rm RES}$, normalisations (CCQE, CC1π, NC1π^0), and flux parameters propagated to oscillation analyses
  - Including correlations



ND280 fit results



ND280 fit results

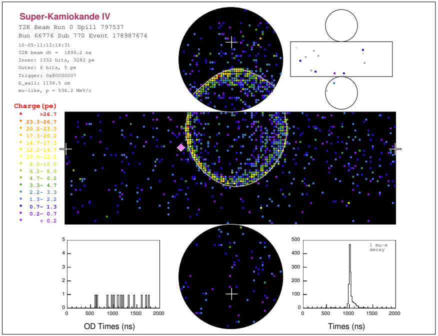
	External tune	ND280 tune
M_A^{QE} (GeV/c^2)	1.21±0.45	1.24±0.07
SF (^{12}C)	0 (RFG) → 1 (SF)	0.24±0.13
E_B (^{12}C) (MeV)	25±9	30.9±5.2
p_F (^{12}C) (MeV/c)	217±30	266.3±10.6
CCQE norm $E_\nu < 1.5$ GeV	1.00±0.11	0.97±0.08
CCQE norm $1.5 < E_\nu < 3.5$ GeV	1.00±0.30	0.93±0.10
CCQE norm $E_\nu > 3.5$ 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 norm $E_\nu < 2.5$ GeV	1.15±0.43	1.26±0.16
CC1π norm $E_\nu > 2.5$ 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

1. T2K
2. Oscillation analysis overview
3. Interaction process models and external constraints
   - CCQE
   - Resonant 1π
   - Other processes
   - Final state interactions
4. ND280 event selections & constraint
5. Oscillation analyses
   - SuperK event selections
   - Effect of systematics
   - Oscillation results
   - Effect of np-nh on ν_μ disappearance search
6. Summary & prospects

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
- $p_\mu > 200\,\mathrm{MeV}/c$

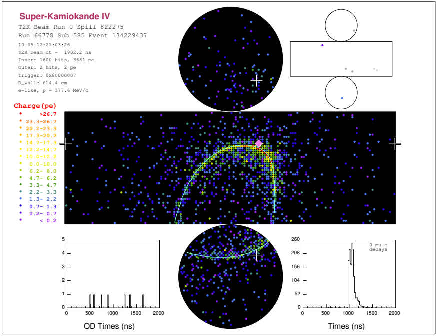
e-like

- 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

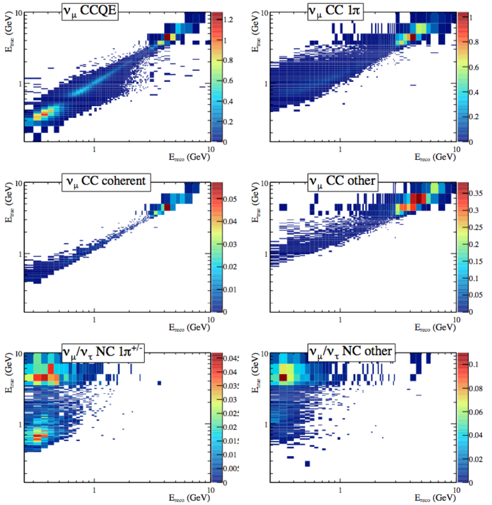
- Ring is PID'ed as μ-like
- 0 or 1 Michel electron
- $p_\mu > 200\,\mathrm{MeV}/c$

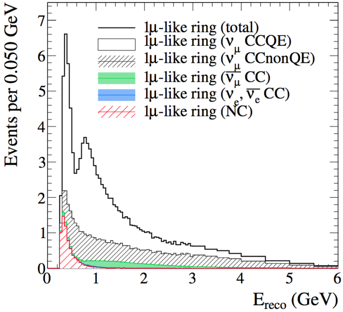
e-like

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

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

ν_μ disappearance spectrum





Unoscillated:

- 81.0% $\nu_\mu + \bar{\nu}_\mu$ CCQE
- 17.5% $\nu_\mu + \bar{\nu}_\mu$ CCnonQE
- 1.5% NC
- 0.02% $\nu_e + \bar{\nu}_e$ CC

Oscillation analyses: effect of ND280 fit

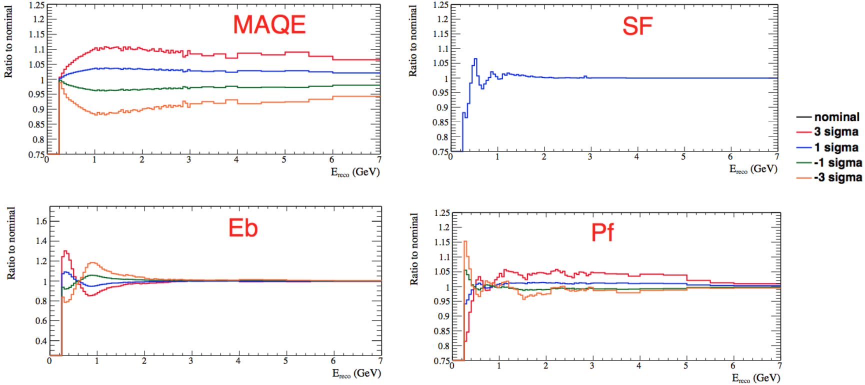
Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SK	4.0%	2.7%
FSI+SI+PN	3.0%	2.5%
ND280-independent XSec	5.0%	4.7%
ND280 prefit	21.7%	26.0%
ND280 postfit	2.7%	3.2%
Total (ND280 postfit)	7.7%	6.8%
Total (ND280 prefit)	23.5%	26.8%

- Large reduction in uncertainties for parameters constrained by ND280 fit

Oscillation analyses: effect of 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 at ND280 (ν_e, $\overline{\nu}_\mu$, CC coherent, ...)
    $\rightarrow$ can constrain more parameters
  - Need to incorporate new models into MC

Effect of CCQE systematics



Effect of systematics

Parameter	$\frac{\delta_{syst} \sin^2\theta_{23}}{\delta_{stat} \sin^2\theta_{23}}$	$\frac{\delta_{syst} \lvert\Delta m^2_{32}\rvert (eV^2/c^4)}{\delta_{stat} \lvert\Delta m^2_{32}\rvert (eV^2/c^4)}$
SK+FSI NC	1.1773	0.3993
Spectral Function	1.0255	0.3641
π-less Δ-decay	0.9775	0.2689
CCQE 0.0-1.5 GeV	0.9734	0.3171
SK+FSI $\nu_\mu/\bar{\nu_\mu}$ CCnQE	0.7611	0.1014
CC1π 0.0-2.5 GeV	0.7223	0.1277
Binding energy	0.7211	0.4678
ν_μ flux 0.7-1.0 GeV	0.6886	0.2540
M_A^{QE}	0.6812	0.2096
SK energy scale	0.6529	0.2262

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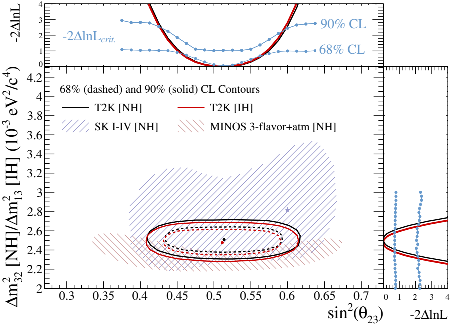
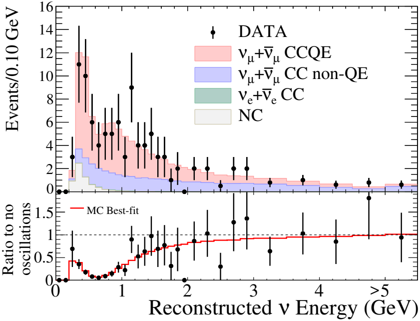
ν_μ flux 0.7-1.0 GeV	0.6886	0.2540
SK energy scale	0.6529	0.2262
M_A^{QE}	0.6812	0.2096
ν_μ flux 0.4-0.5 GeV	0.5266	0.1880
δ_{CP}	0.0383	0.1308

- Fit for only $\sin^2\theta_{23}$ and $\lvert\Delta m^2_{32}\rvert$
- For each systematic, fit at $\pm 1\sigma$ and take the largest bias
- Generate toy experiments at 12 oscillation points spanning the space
- Compare to statistical error

Oscillation results: ν_μ disappearance

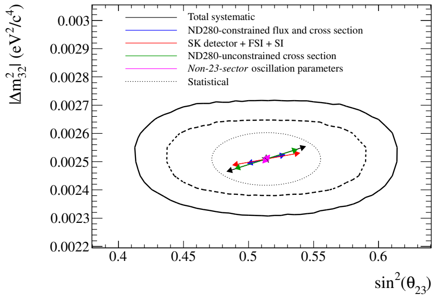


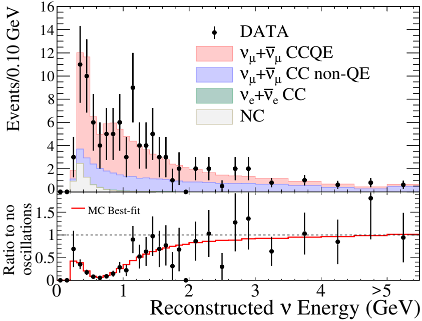


Normal (inverted) mass hierarchy:

- $\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056}$ (0.511 ± 0.055)
- $\Delta m^2_{32} = 2.51 \pm 0.10 \times 10^{-3}\,\mathrm{eV}^2/\mathrm{c}^4$
  $(\Delta m^2_{13} = 2.48 \pm 0.10 \times 10^{-3}\,\mathrm{eV}^2/\mathrm{c}^4)$

Oscillation results: ν_μ disappearance





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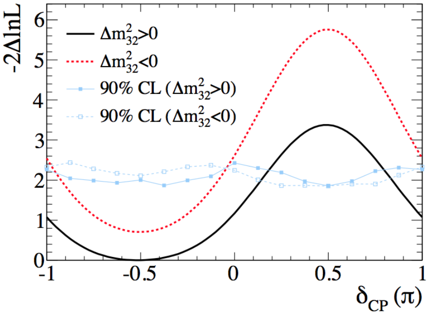
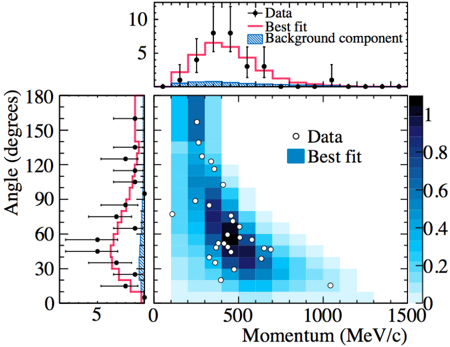
Oscillation results: ν_e appearance

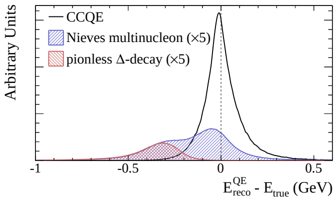




Data excludes at 90% C.L. δ_{CP} between:

- $+0.19\pi$ and $+0.80\pi$ (normal hierarchy)
- $-\pi$ and -0.97π & -0.04π and $+\pi$ (inverted hierarchy)

np-nh effect methodology



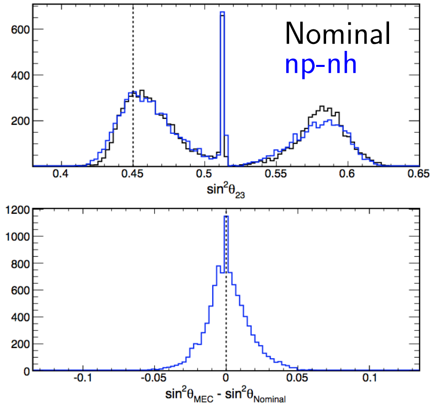
1 μ-like ring

- 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

$\sin^2\theta_{23}$

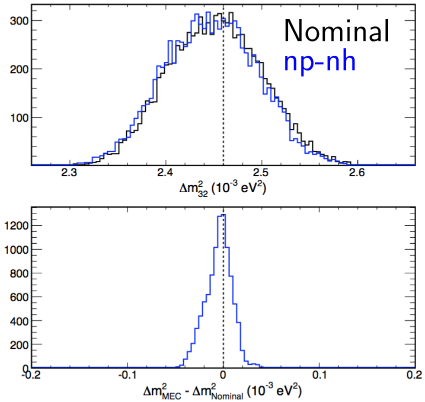


Mean: $+0.3\%$

RMS: 3.6%

Other systematics RMS: 3.8-5.6%

Δm^2_{32}



Mean: -0.2%

RMS: 0.6%

Other systematics RMS: 1.8%

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
  - 21.7% $\rightarrow$ 2.7% for 1 μ-like ring
  - 26.0% $\rightarrow$ 3.2% for 1 e-like ring
- Cross sections not constrained by ND280 are the dominant uncertainty. Can be reduced with:
  - Better models in MC
  - New data
  - Selections on water

Prospects

- Implemented new models in NEUT
  - np-nh
  - Spectral function
  - RPA (for RFG)
- Updating external data fits with the new models & new data
  - MINERνA & MiniBooNE $\overline{\nu}$
  - Fit favours RFG+RPA+MEC over SF+MEC
  - See C. Wilkinson's talk at NuFact2014
- Improving the ND280 constraint
  - Better cuts
  - Increasing phase space
  - Adding new selections
- Hope to see good improvements in next round of oscillation analyses

Backups

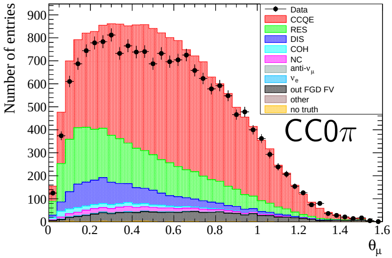
ND280 selection distributions (before ND280 fit)

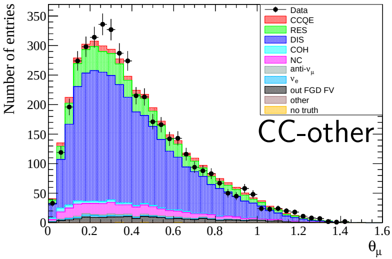
ND280 CC0π, CC1π^+, CC-other purities

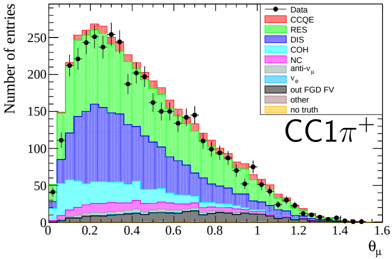
	CC0π	CC1π^+	CC-other
CC0π	**72.4**%	6.4%	5.8%
CC1π^+	8.6%	**49.2**%	7.8%
CC-other	11.5%	31.0%	**73.6**%
Background	2.3%	6.8%	8.7%
External	5.2%	6.6%	4.1%

	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)





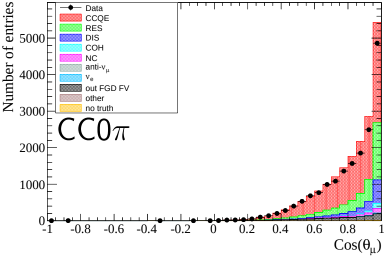


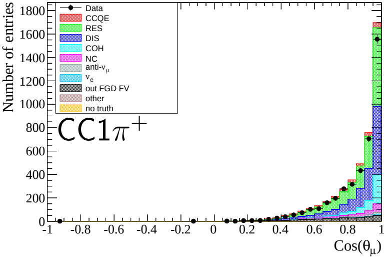
CCQE RES DIS COH

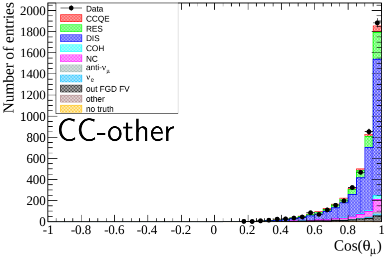
NC $\overline{\nu}_\mu$ ν_e

Out-of-fiducial-volume

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





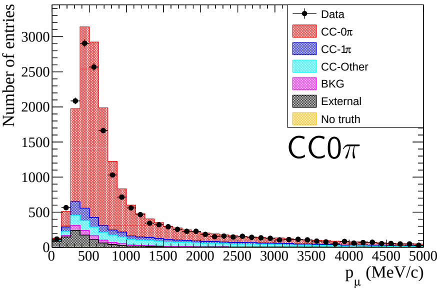


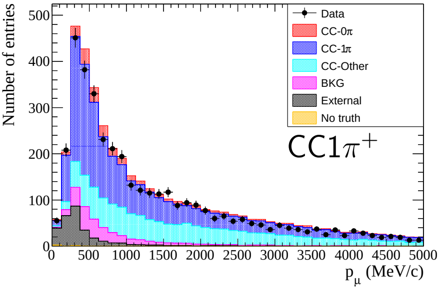
CCQE RES DIS COH

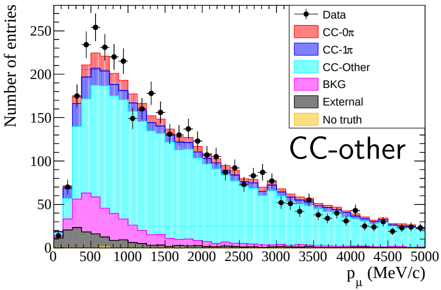
NC $\overline{\nu}_\mu$ ν_e

Out-of-fiducial-volume

ND280 p_μ (after-FSI categories)

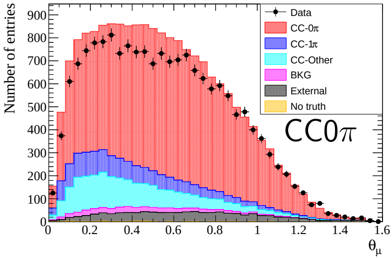


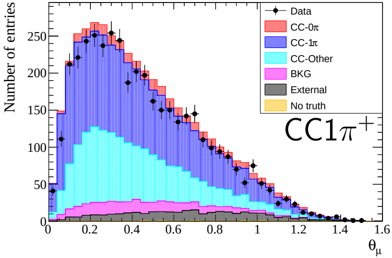


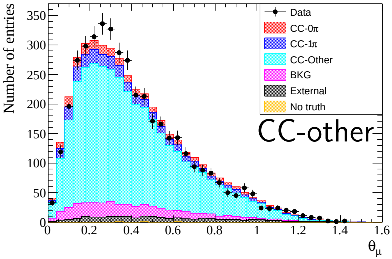


$CC0\pi$ $CC1\pi^+$ CC-other
Background External

ND280 θ_μ (after-FSI categories)

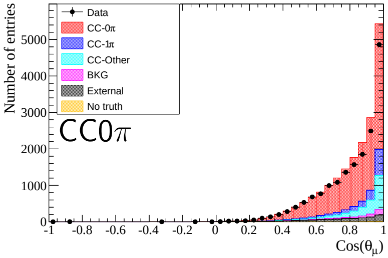


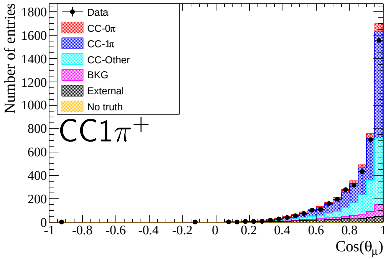


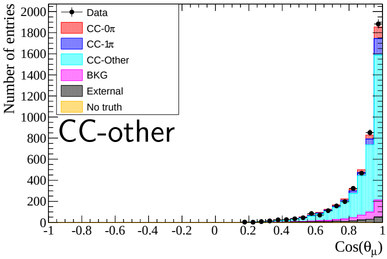


CC0π CC1π^+ CC-other
Background External

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



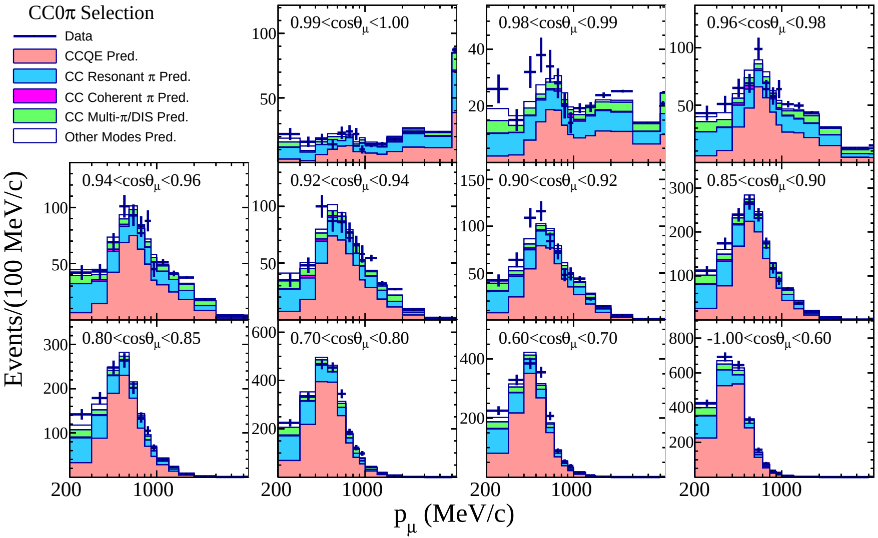




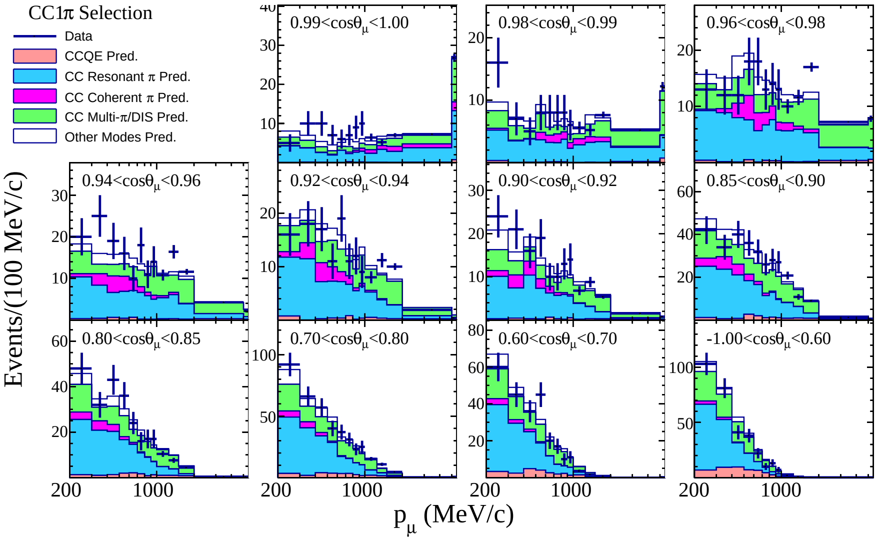
$CC0\pi$ $CC1\pi^+$ CC-other
Background External

ND280 selection distributions (after ND280 fit)

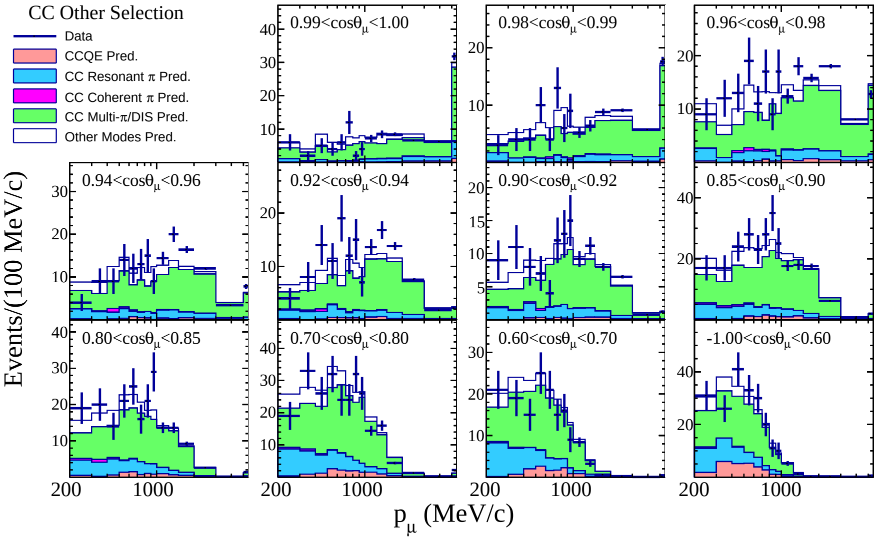
ND280 CC0π (after ND280 fit)



ND280 CC1π^+ (after ND280 fit)

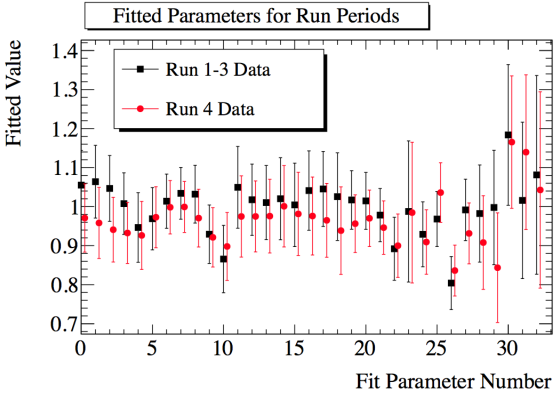


ND280 CC-other (after ND280 fit)



ND280 fit results for different run periods

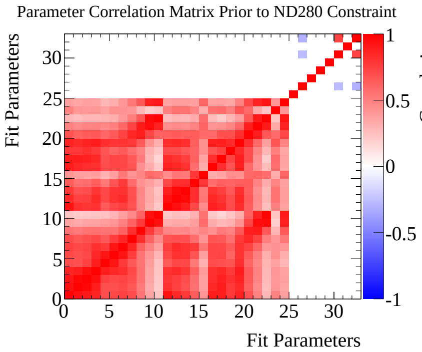
ND280 fit results for different run periods

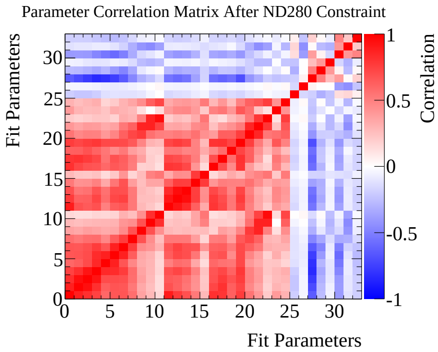


- Run 1-3 and Run 4 ($\sim$ equal statistics) fit results consistent
- Suggests fits dominated by systematics that are common to 2 statistically independent datasets

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) → 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 norm $E_\nu < 2.5\,\mathrm{GeV}$ *	1.26±0.16
CC1π 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