T2K oscillation analysis: QE model fits and generator (NEUT) development

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Oscillation physics and interaction model

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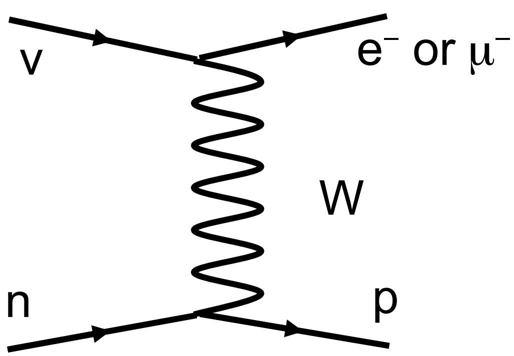
$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right) + \ldots$$

Oscillation probability depends on neutrino energy

For T2K's neutrino spectrum, dominant process is Charged Current Quasi-Elastic:

CCQE

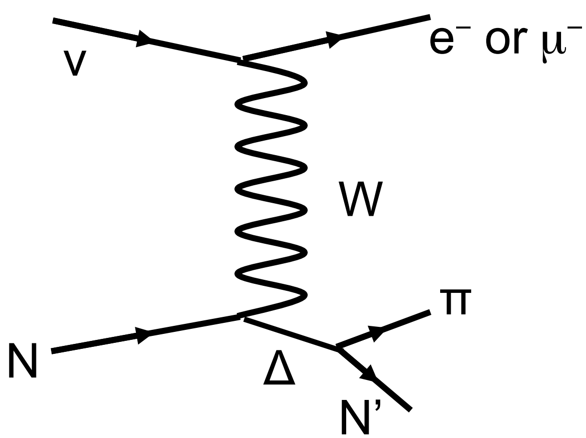


Infer neutrino properties from the lepton momentum and angle:

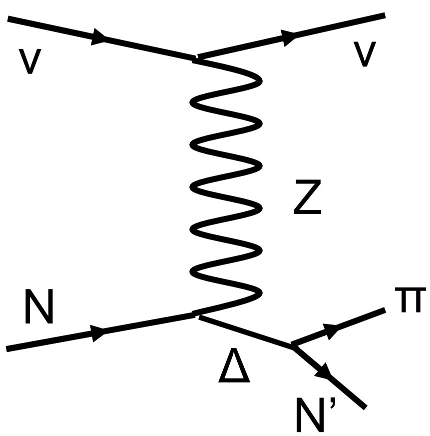
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CCπ



NCπ



Additional significant processes:

- CCQE-like multinucleon interaction
- Charged current single pion production (CCπ)
- Neutral current single pion production (NCπ)

Use of near detectors on T2K

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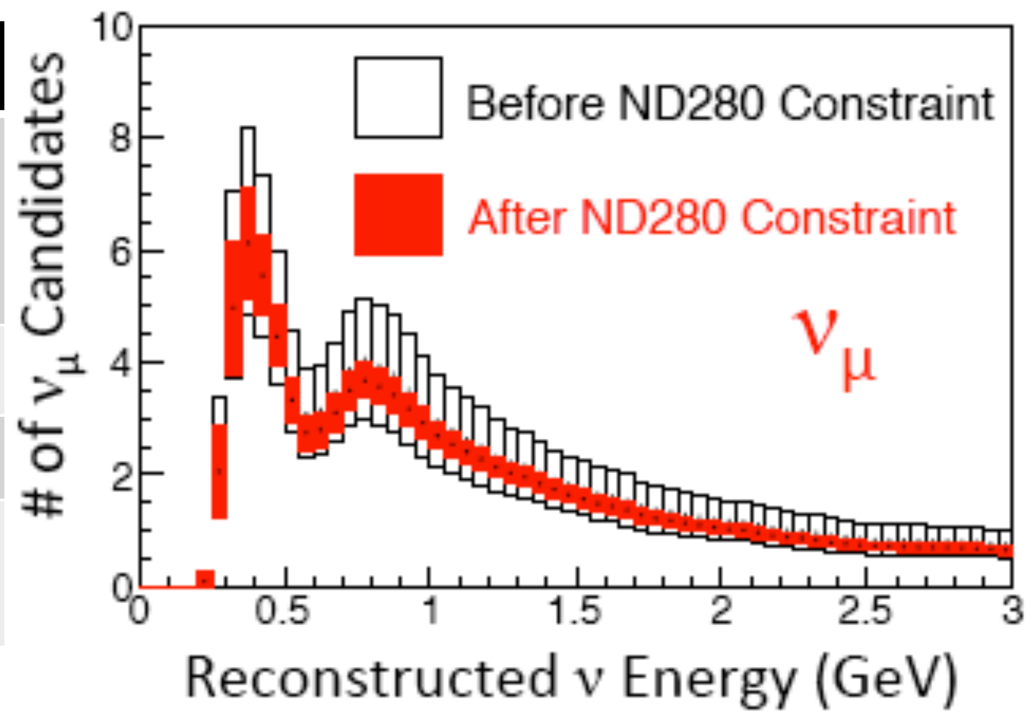
Expected number of events at the far detector is tuned based on near detector information. Near detector also provides a substantial constraint on the uncertainties of ν_e and ν_μ events:

$$FD(\nu_e) = \Phi \times \sigma \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$
$$ND(\nu_\mu) = \Phi \times \sigma \times \epsilon_{ND}$$

Uncertainties (2014)	ν_μ disap.	ν_e app
ν flux+xsec (before) after ND constraint	(21.7%) ±2.7%	(26.0%) ±3.2%
ν unconstrained xsec	±5.0%	±4.7%
Far detector	±4.0%	±2.7%
Total	(23.5%) ±7.7%	(26.8%) ±6.8%



After ND: expect 21.06 ν_e candidates (background only: 4.97)

After ND: expect 124.98 ν_μ events (no oscillation: 445.98)

Use of near detectors on T2K

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ND(ν...) = Φ × σ × ε

Cross section model parameterized with a combination of empirical and fundamental parameters

Uncertainties and correlations on those parameters determined from 1) fits to external data and 2) comparisons between appropriate alternate models to those implemented in NEUT

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ν flux+xsec (before) aft ND constrai
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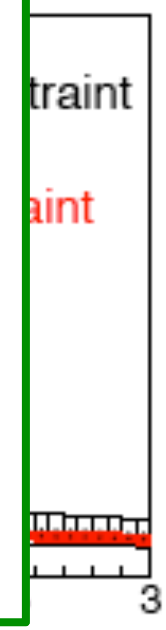
Far detecto
Total



After ND: expect 21.06 ν_e candidates (background only: 4.97)

After ND: expect 124.98 ν_μ events (no oscillation: 445.98)

Why are external data fits important?

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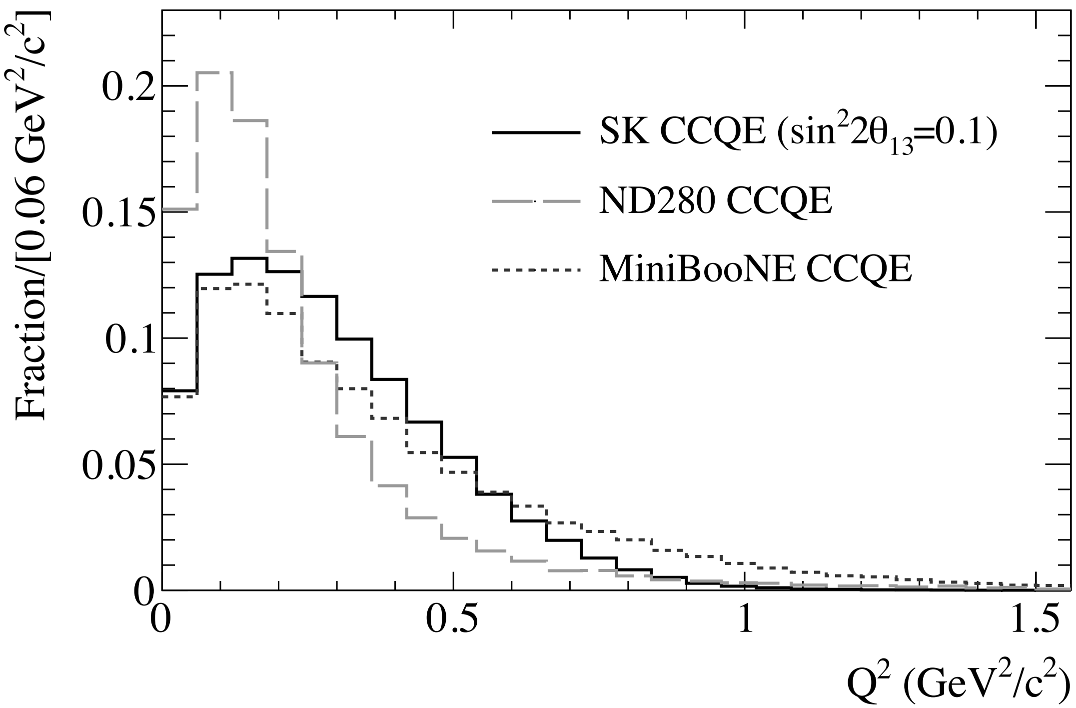
Flux at near detector and far detector are not the same, so validation of models requires multiple beam energies

Use of external data in cross section parameterization and error assignment as well as near detector



Acceptance: ND sample is forward going (small angle, low Q^2)

- External data covers larger Q^2 (MiniBooNE, 4π Cherenkov detector)

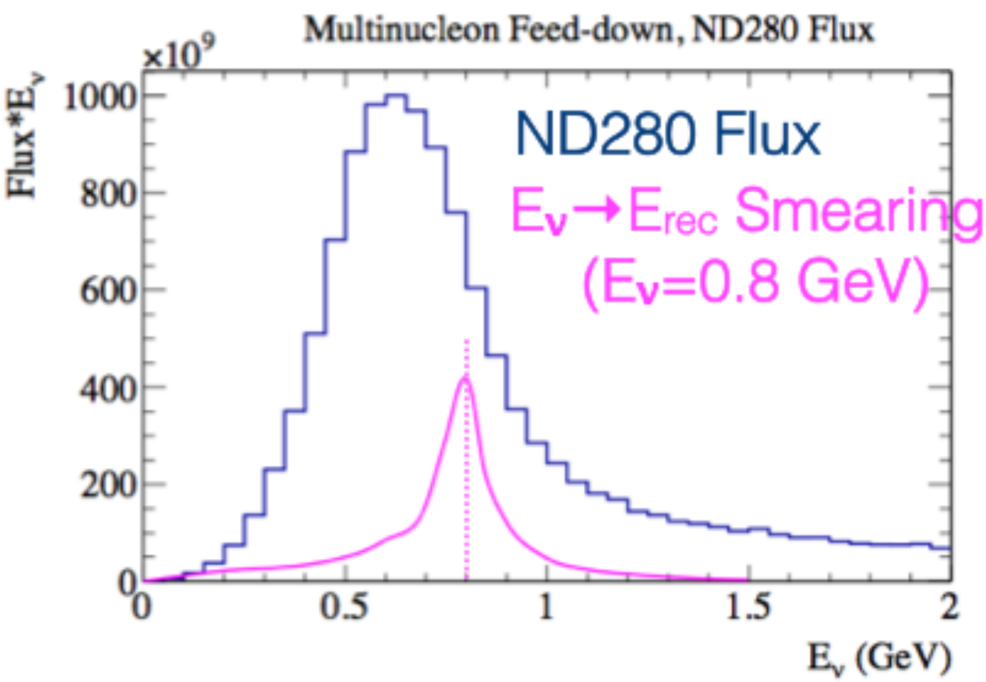
Model validation: No consistent model holds for all neutrino energies – multiple data sets needed

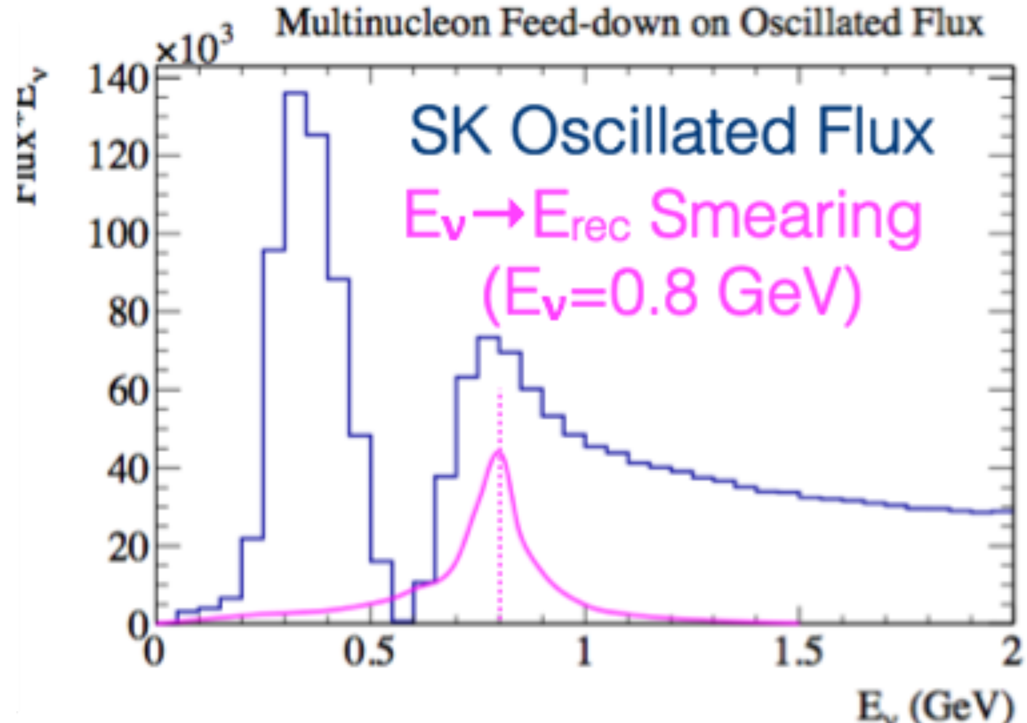
Target: ND selection is C, SK is O

- C-O model dependent uncertainties included, but new water-enhanced sample to be included

Why does the cross section model matter?

Cross section model couples through the different fluxes measured by ND and FD





$$FD(\nu_e) = \boxed{\Phi \times \sigma} \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$
$$ND(\nu_\mu) = \boxed{\Phi \times \sigma} \times \epsilon_{ND}$$

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

Overall increase to cross section cancels in extrapolation, but any shifts between true to reconstructed E feed down into oscillation dip and are ~degenerate with θ_{23} measurement

- Similar issue for CC1π+ backgrounds where pion is not tagged (absorbed in nucleus or detector)

Why does the cross section model matter?

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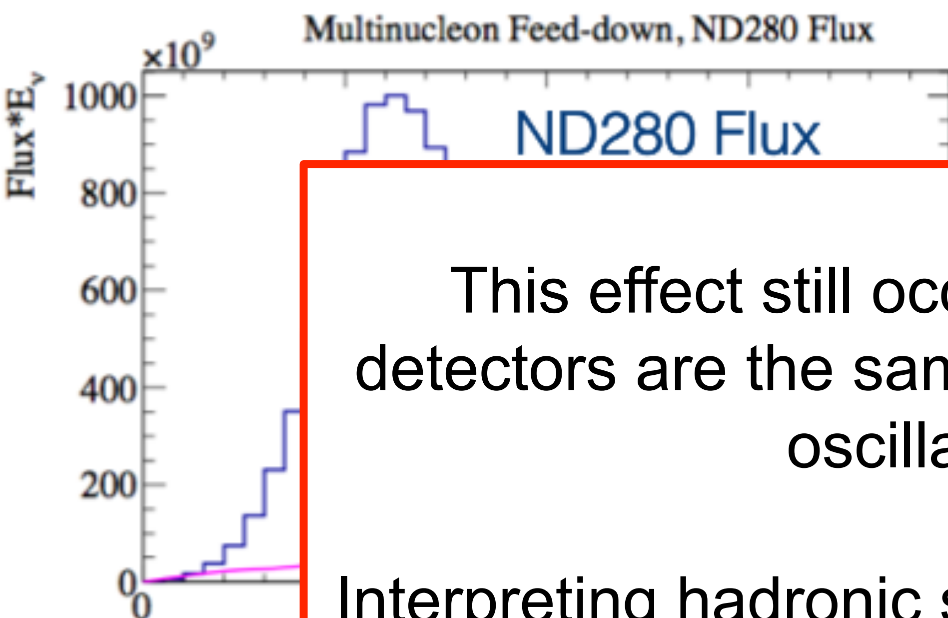
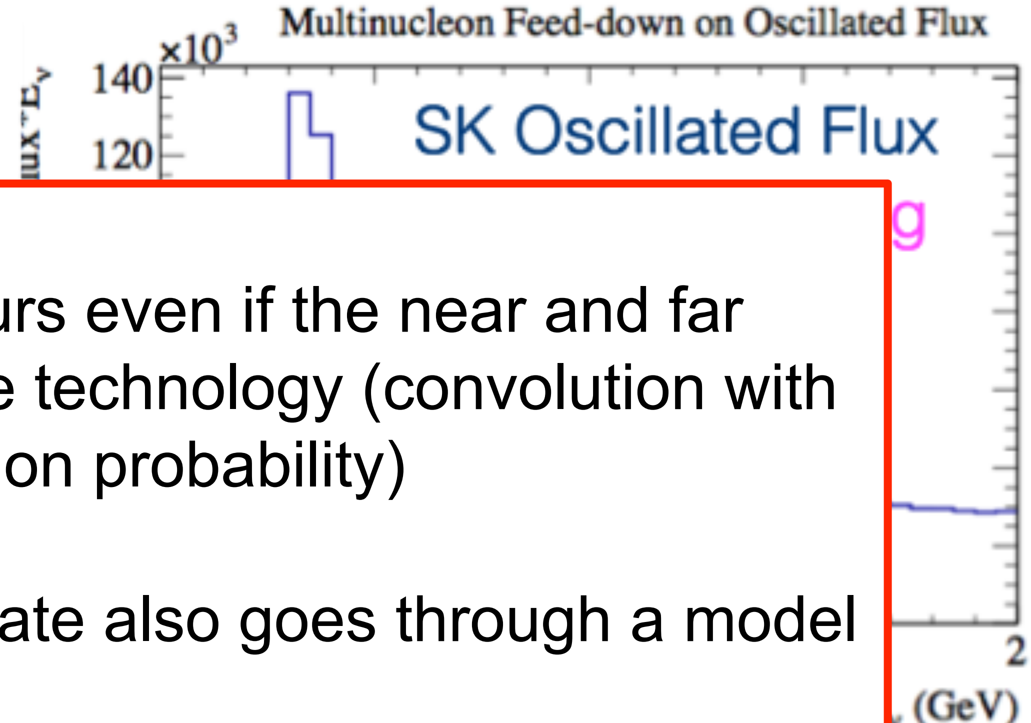
Cross section model couples through the different fluxes measured by ND and FD





This effect still occurs even if the near and far detectors are the same technology (convolution with oscillation probability)

Interpreting hadronic state also goes through a model

Include in analysis additional uncertainties on how model choice may affect extrapolation

$FD(\nu_e$ … ${}'_n E_\mu$

$ND(\nu_\mu$ … $\theta_\mu)$

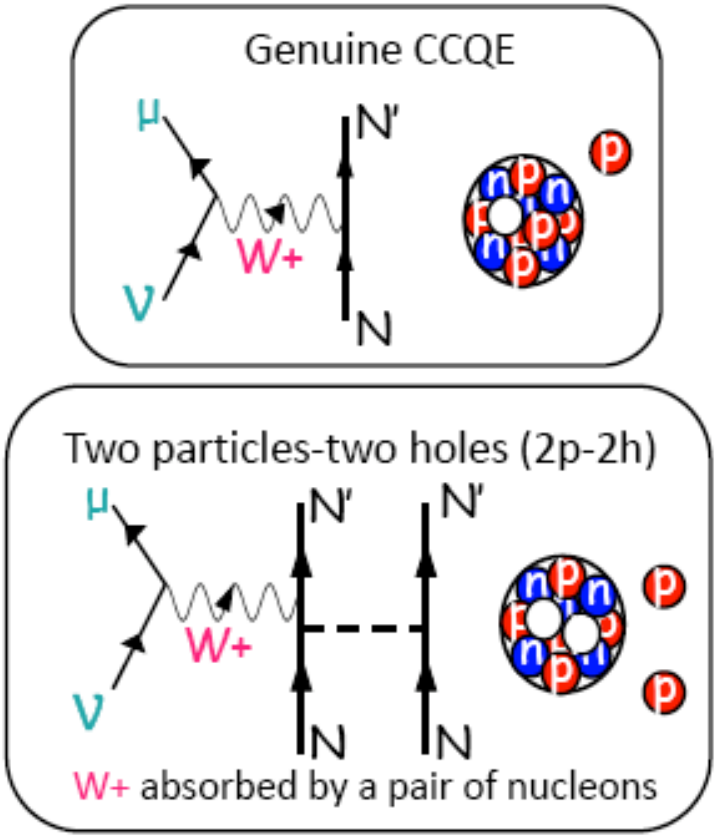
Overall inc… en true to reconstructed E feed down into oscillation dip and are ~degenerate with θ_{23} measurement

- Similar issue for CC1π+ backgrounds where pion is not tagged (absorbed in nucleus or detector)

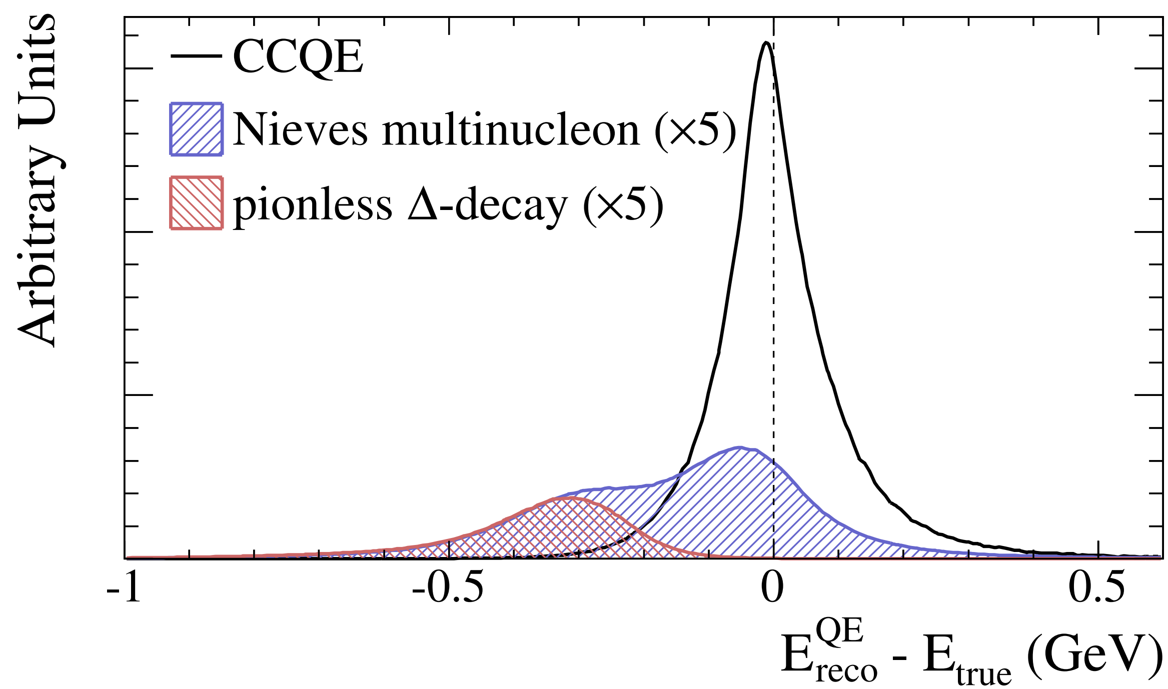
Multinucleon model example

Nuclear effects such as "multinucleon" processes may explain the enhanced CCQE cross section observed by MiniBooNE, SciBooNE, T2K experiments

- CCQE interaction simulated as interaction on a single nucleon (1p1h)
- Two models:
- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011)
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)



Picture by M. Martini



T2K collab PRL 112, 181801 (2014)

Multinucleon effect on T2K analysis

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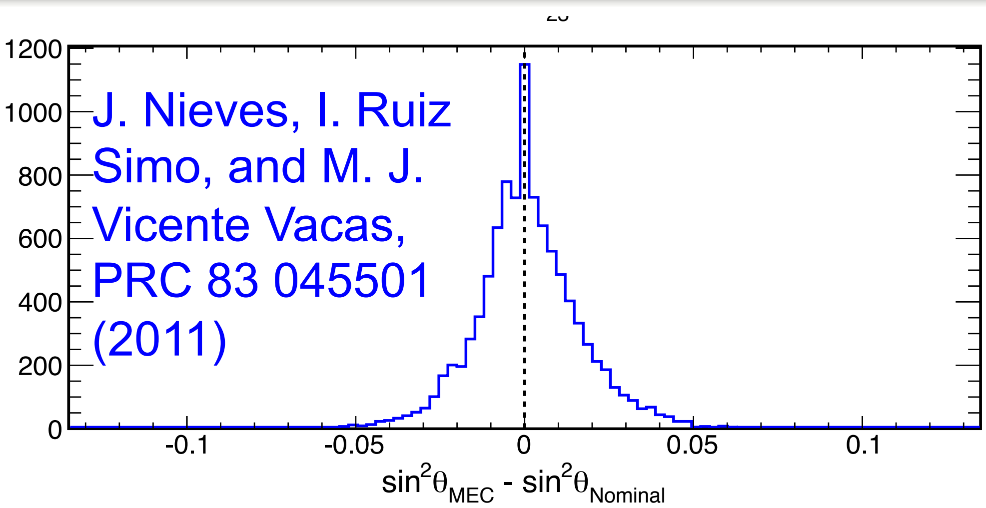

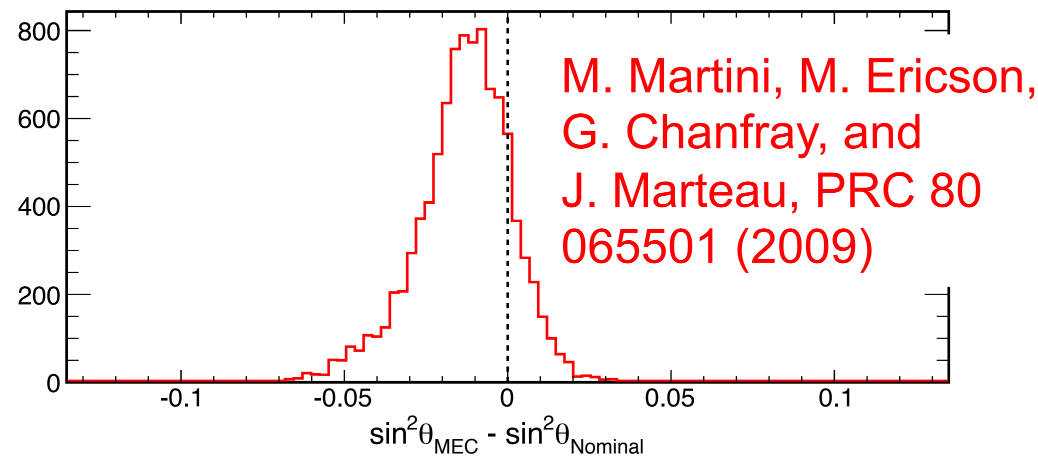

Tested possible bias on 2013/2014 T2K neutrino disappearance measurement

- Generate fake data under flux, detector, cross section variations, and perform full oscillation analysis including ND constraint
- For each fake data set, compare fitted θ_{23} with and without a 2p2h model present

Nieves et al model: 0.3% mean, 3.2% RMS
"increased Nieves" = Martini model: -2.9% mean, 3.2% RMS

Significant contribution to current systematic uncertainty on disappearance analysis (vs. 5.0% non-cancelling cross section uncertainty, 7.7% total) in extrapolation

Why acceptance, models matter

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Need to consider how phase space (both acceptance and flux differences at near and far detector) may affect alternate models not used in the analysis

- Ratio of the CCQE cross-section result from the one-track sample to that from the two-track (from 1503.07452, accepted by PRD) using on-axis near detector (INGRID)

Nuclear model in MC	Ratio of cross-section results
Relativistic Fermi gas model	$1.45 \pm 0.09(stat.)^{+0.24}_{-0.29}(syst.)$
Spectral function	$1.25 \pm 0.08(stat.)^{+0.22}_{-0.26}(syst.)$

- Different QE models have different outgoing proton kinematics, can directly affect selection
- Determination of ‘true QE’ can be different based on the model you choose

Models in NEUT, 2012-2014

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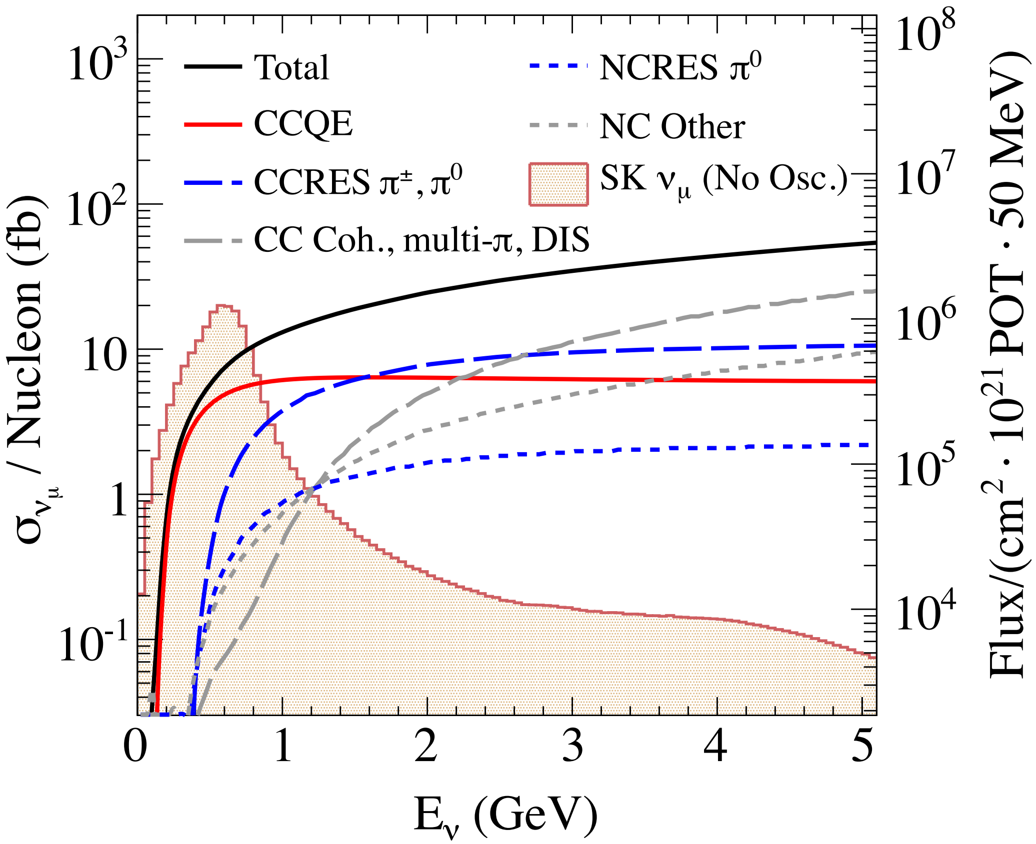

NEUT model (5.1.4.2):

- CCQE : Relativistic * Global * Fermi Gas model. Axial vector mass = 1.2GeV/c.
- No "Multinucleon" CCQE-like interaction
- 1π (NC and CC) production model: Rein-Sehgal, Simple pion-less delta decay. MARES, NCπ0 and CCπ+ normalizations tuned based on fits to external 1π samples.

Alternate models

- **GENIE:** CCQE : RFG model like NEUT. Axial vector mass = 0.99GeV/c
- **NuWro:** CCQE : Spectral function model (Benhar et al.)
    - Used to develop alternate model ('spectral function') parameter

2012-2014 QE parameterization

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MAQE (GeV)	Axial mass (QE)
QE1 $0<E_\nu<1.5$ GeV	Normalization
QE2 $1.5<E_\nu<3.5$ GeV	Normalization
QE3 $E_\nu>3.5$ GeV	Normalization
pF (MeV/c)	Fermi momentum
Spectral Function	Model comparison
CC nue/numu	Normalization

Parameter	Input Value	Uncertainty
M_A^{QE} (GeV)	1.21	0.43
x_1^{QE}	1.00	0.11
x_2^{QE}	1.00	0.30
x_3^{QE}	1.00	0.30
x_{SF}	0.0	1.0
$p_F(^{12}\mathrm{C})$ (MeV/c)	217	30
$p_F(^{16}\mathrm{O})$ (MeV/c)	225	30
x_{ν_e/ν_μ}	1.0	0.03

Details of NEUT model, parameterization, QE fits to be found here for appearance analysis:

- Phys. Rev. D 88, 032002 (2013)
- http://arxiv.org/abs/1304.0841

For disappearance analysis, added binding energy parameter in RFG model
Phys. Rev. Lett. 111, 211803 (2013)

Resonance model parameter (pionless delta decay) also important for QE

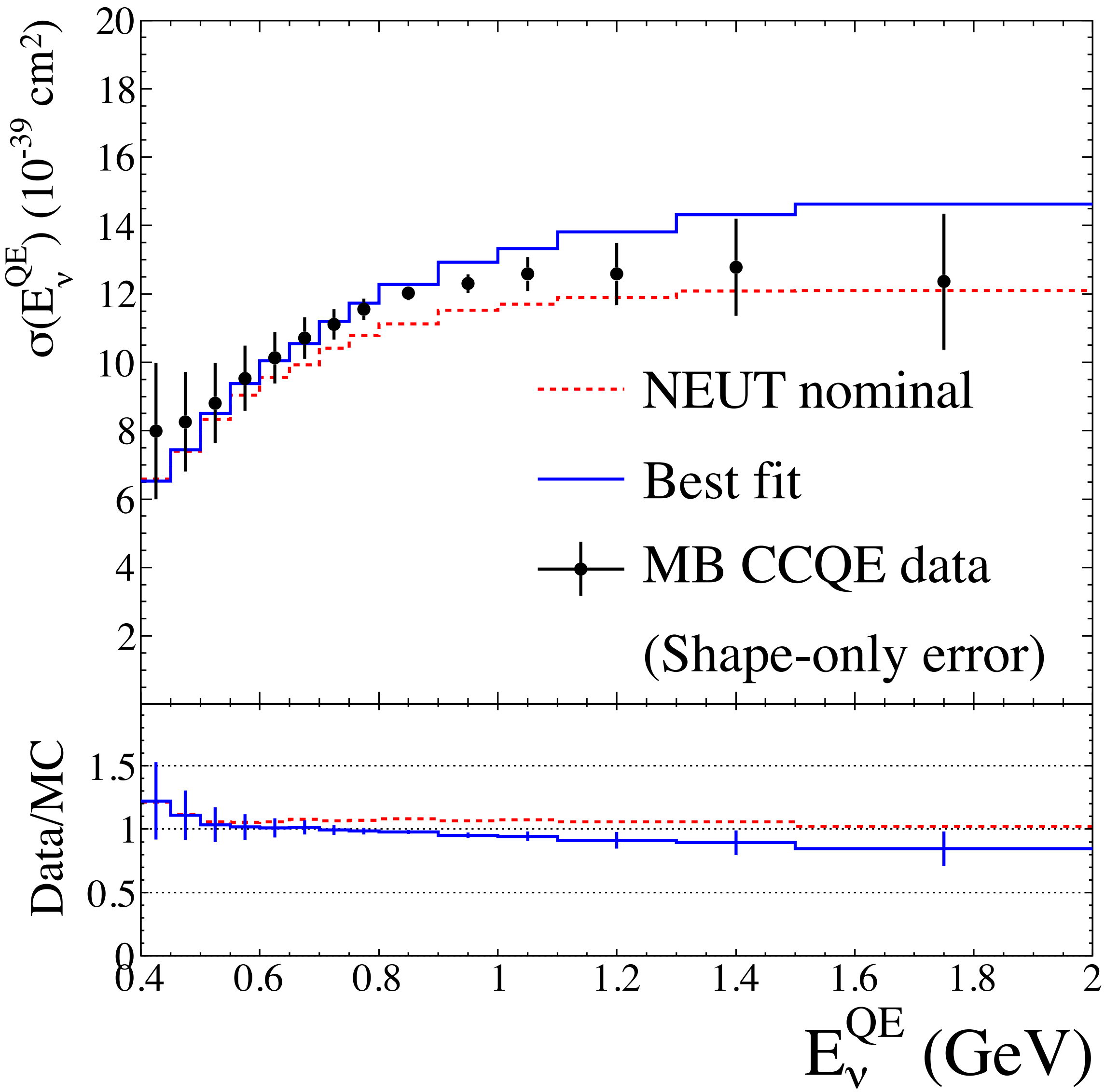
- Similar to effect of multinucleon model; Delta resonance does not produce pion out of nucleus
- 100% uncertainty assigned
- FSI effects also can absorb pions, treated separately

E_ν (GeV)

Fits to MiniBooNE neutrino scattering data

2012-2014: Attempt to fit MiniBooNE Q2_QE and muon kinematic distributions

- Poor fits, despite a wide range of parameters attempted



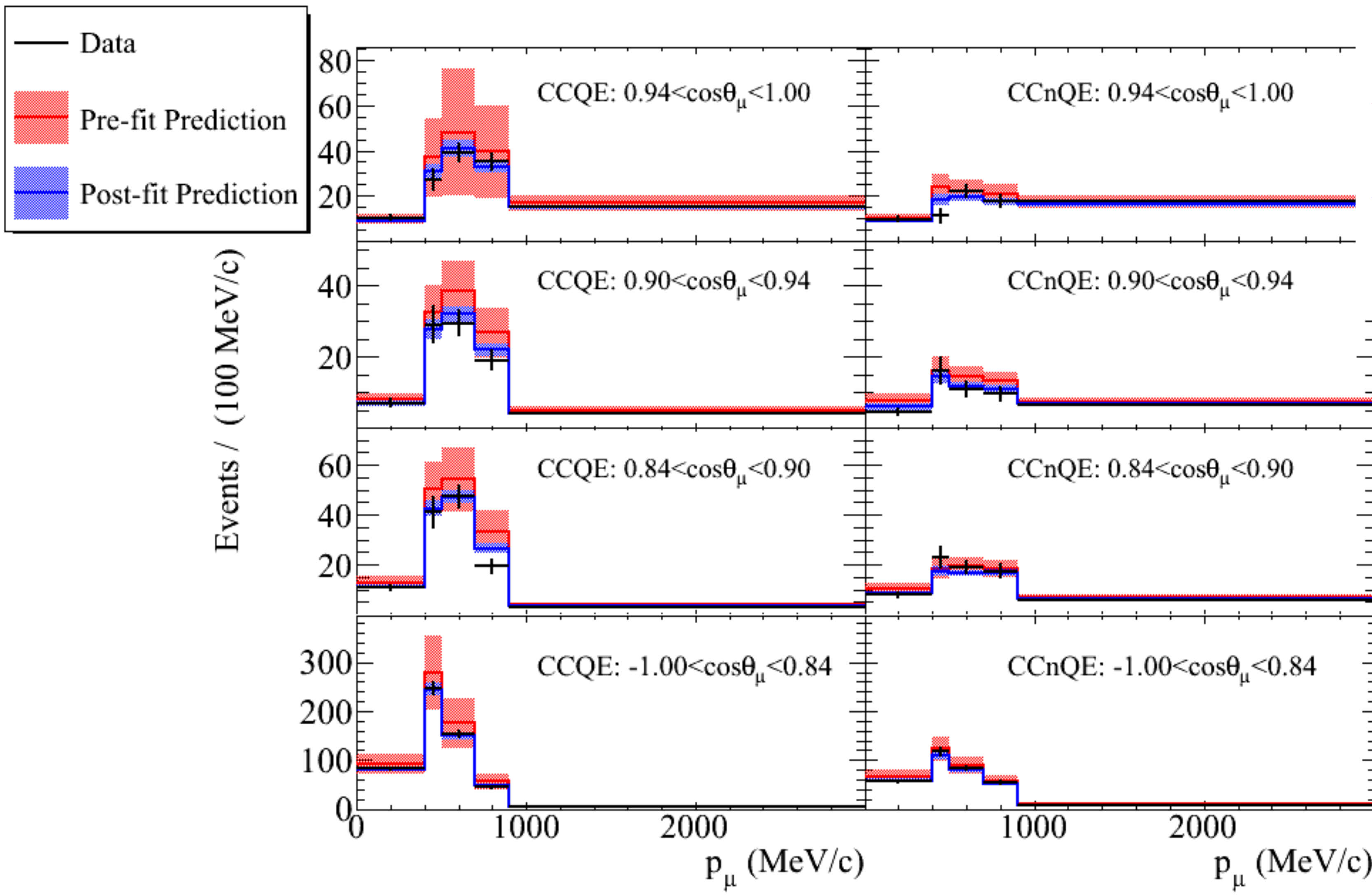
Used difference between best fit and NEUT nominal as error on MAQE

Added normalizations to recover disagreements vs. energy (e.g NOMAD)

Added nuclear uncertainties:

- Difference in shape to alternate nuclear model (xSF) model in NuWro
- Increased errors on RFG model Fermi momentum (pF) and binding energy (EB) to accommodate low Q^2 disagreement

2012 near detector fit results



Data
without ND information
with ND information

Near detector adjusts flux and cross section parameterization, agreement across CCQE-like, and CCnon-QE-like subsamples

2012 near detector cross section tuning

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M_A^{QE} (GeV)	1.21 ± 0.45	1.33 ± 0.20
M_A^{RES} (GeV)	1.16 ± 0.11	1.15 ± 0.10
x_1^{QE}	1.00 ± 0.11	0.96 ± 0.09
$x_1^{CC1\pi}$	1.63 ± 0.43	1.61 ± 0.29
$x_1^{NC1\pi^0}$	1.19 ± 0.43	1.19 ± 0.40

MAQE is increased and correlated to flux parameters for proper rate constraint at far detector

Uncorrelated cross section error (~5% in disappearance, appearance analyses):

- Alternate model (spectral function) treated separately for near and far detectors as different target materials. Affects relationship between lepton kinematics and true neutrino energy even for same target material.
- Pionless delta decay (effect similar to earlier multinucleon studies)

NEUT Model, parameterization, 2015 onward

NEUT model (5.3.2+) for 2015 (antineutrino, neutrino+antineutrino) analyses:

- CCQE : Spectral function model (Benhar et al.) Axial vector mass = 1.2GeV/c2.
  - RFG+RPA (Nieves et. al) Axial vector mass = 1.2GeV/c2.
- "Meson exchange current" (MEC, 2p2h) CCQE like scattering (Nieves et al.)
- 1π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

Parameterization:

- MAQE
- pF, EB (target material dependent)
- Removed PDD, added a 2p2h normalization (target material dependent)

Reference (antineutrino disappearance paper)

- http://arxiv.org/abs/1512.02495

E_ν (GeV)

Fits to MiniBooNE, MINERvA external data

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Fit external data (MiniBooNE, MINERvA) to suite of available models:

- Neutrino and antineutrino datasets fit to determine choice of default model (RFG +RPA, non relativistic vs. relativistic vs. SF) and uncertainties on MAQE, 2p2h normalization, and pF
- Following plots/tables are T2K preliminary

Hope was that Nieves et al model would resolve high MAQE for MiniBooNE. Instead:

- Forward scattering region for MiniBooNE neutrino model doesn't fit well
- Low Q^2 MINERvA nu/nubar disfavors Nieves RPA, suppresses 2p2h
- MINERvA data are 20% lower than MiniBooNE
- For now: uncertainties inflated to cover disagreement between datasets
- Next: improve inputs: covariance from MiniBooNE, revisit model parameterization
  - Lack of correlations affects uncertainties, may affect central conclusions of fit
  - NEUT 1p1h Global RFG is subtly different from Nieves 1p1h Local RFG
  - Still studying SF fit results and possible effect on analysis

Fit type	χ^2/N_{DOF}	M_{A} (GeV/c^2)	2p2h norm. (%)	p_{F} (MeV/c)	$\lambda_{\nu}^{\mathrm{MB}}$	$\lambda_{\bar{\nu}}^{\mathrm{MB}}$
RFG+rel.RPA+2p2h	97.8/228	1.15±0.03	27±12	223±5	0.79±0.03	0.78±0.03
RFG+non-rel.RPA+2p2h	117.9/228	1.07±0.03	34±12	225±5	0.80±0.04	0.75±0.03
SF+2p2h	97.5/228	1.33±0.02	0 (at limit)	234±4	0.81±0.02	0.86±0.02

MINERvA data comparisons

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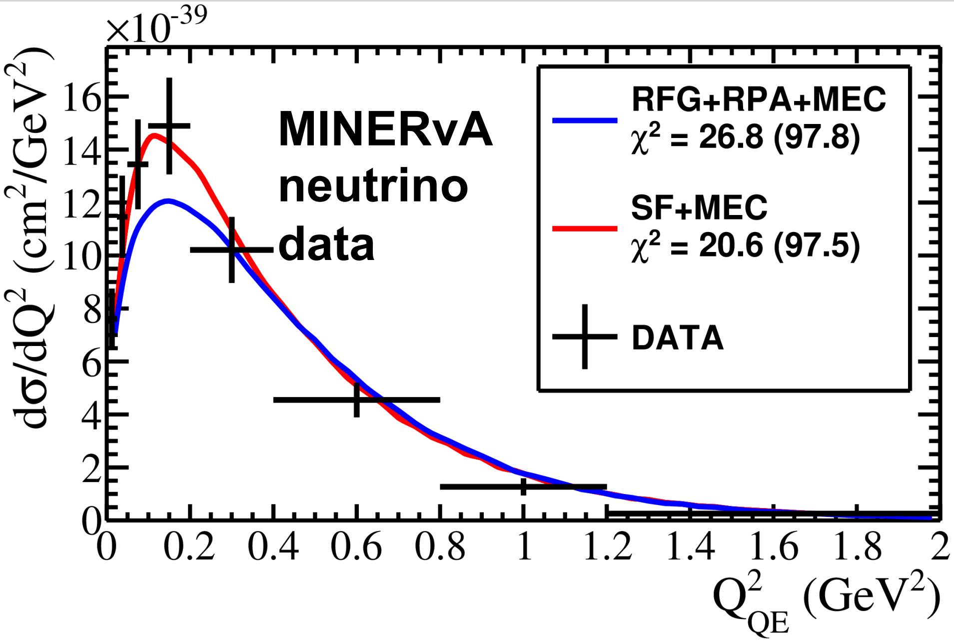
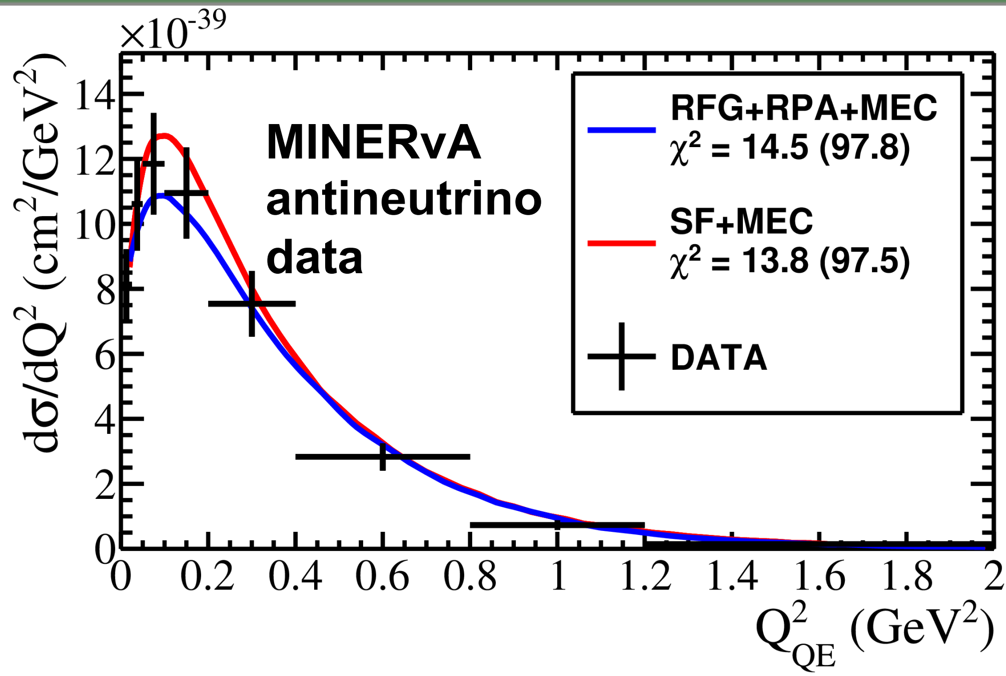
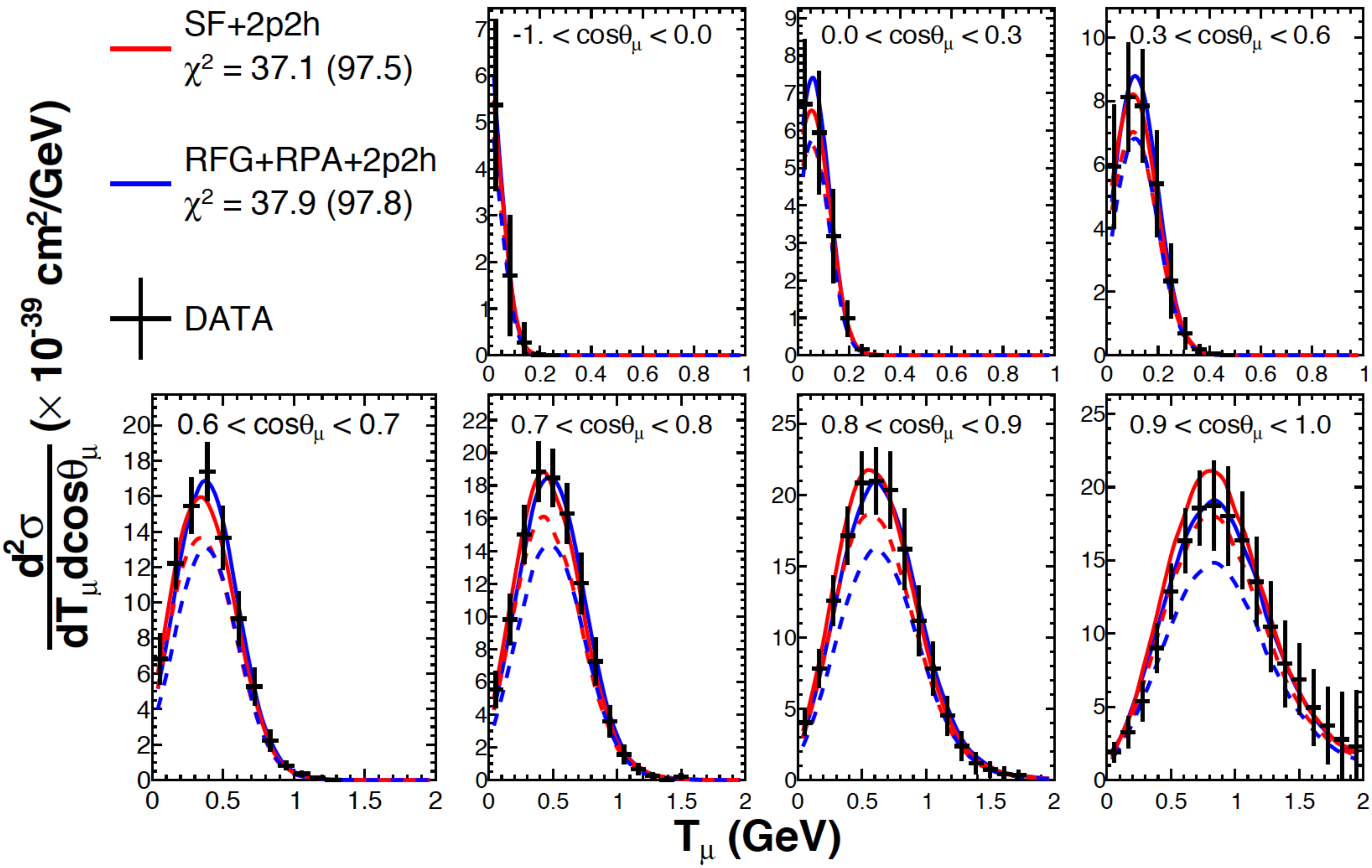




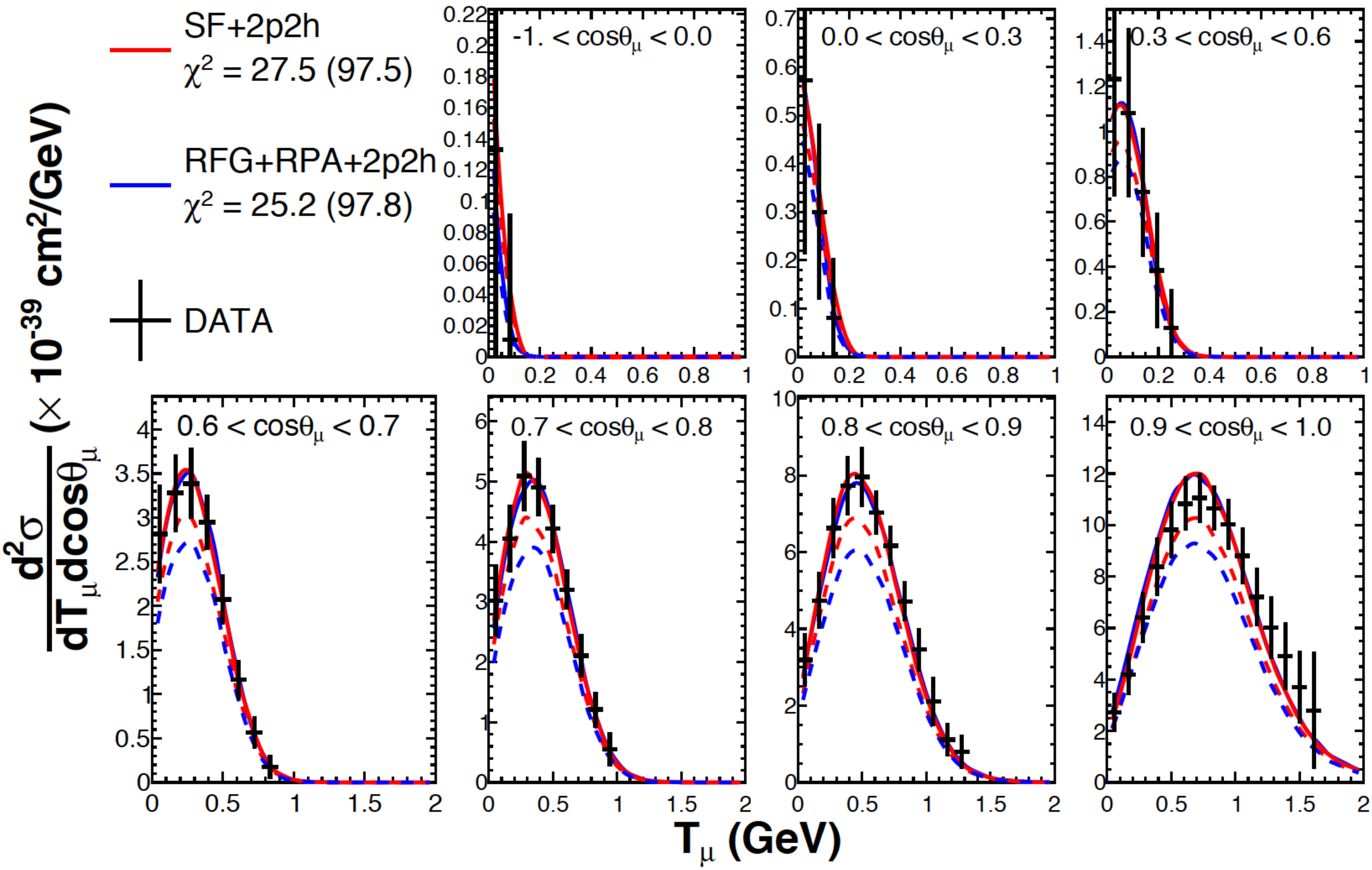
Best fit from SF+2p2h model compared to RFG+RPA+2p2h for MINERvA

MiniBooNE neutrino data comparisons



Best fit from SF+2p2h model compared to RFG+RPA+2p2h. Solid line is with normalization (floated) for MiniBooNE fits

MiniBooNE antineutrino data comparisons



Best fit from SF+2p2h model compared to RFG+RPA+2p2h. Solid line is with normalization (floated) for MiniBooNE fits

Use of near detectors on T2K

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Expected number of events at the far detector is tuned using a likelihood fit to the near detector samples

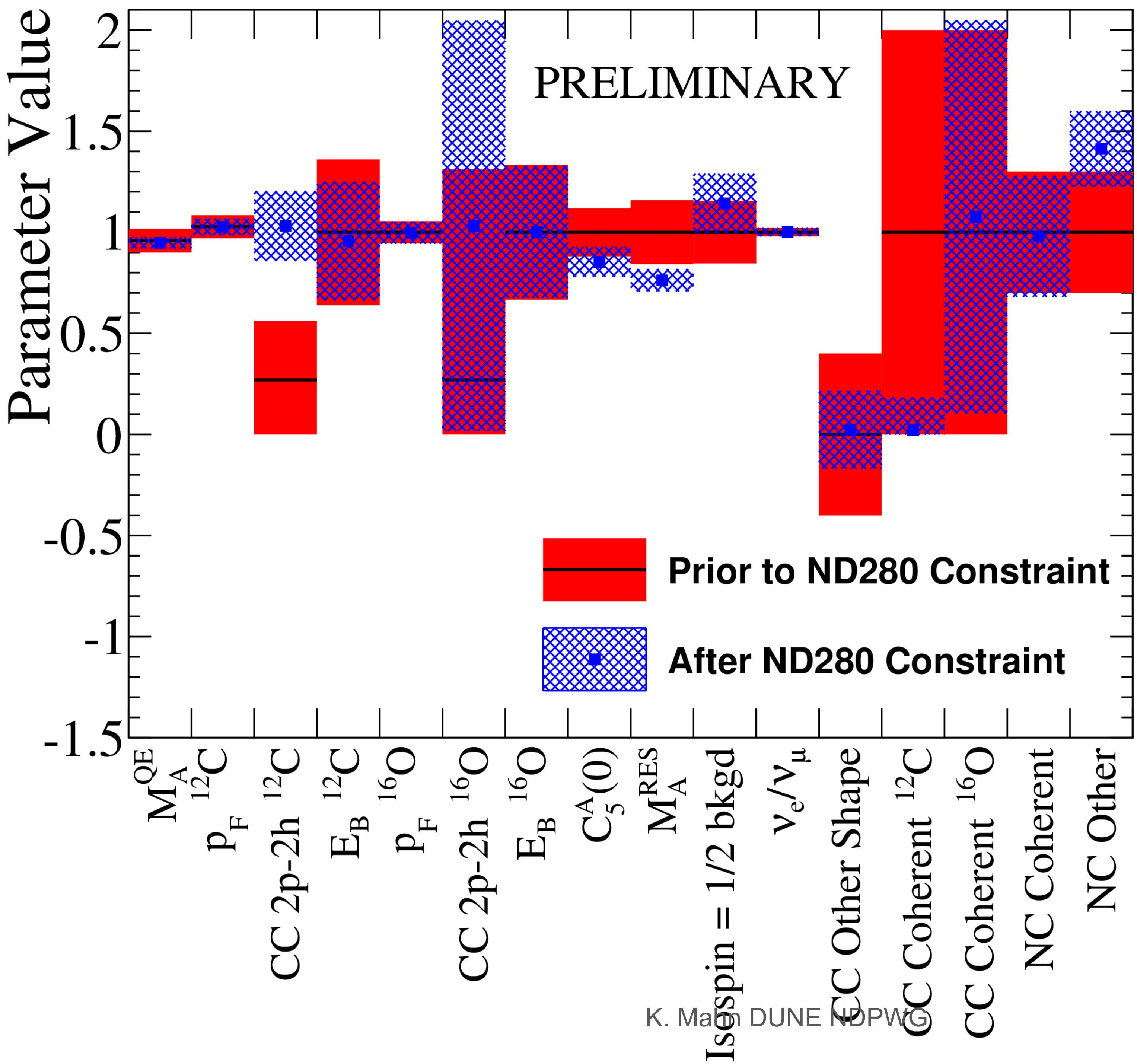
- Used near detector neutrino and antineutrino samples (see backup)
- Largest non cancelling systematic uncertainty is multinucleon (2p2h) contribution

		w/o ND measurement	w/ ND measurement
ν flux and cross section	flux	7.1%	3.5 %
	cross section cmn to ND280	5.8%	1.4 %
	(flux) × (cross section cmn to ND280)	9.2%	3.4 %
	cross section (SK only, include ↓)	10.0 %	
	multi-nucleon effect on oxygen	9.5%	
	total	13.0%	10.1%
Final or Secondary Hadronic Interaction		2.1%	
Super-K detector		3.8%	
total		14.4%	11.6%

Fractional error on number-of-event prediction

Antineutrino oscillation analysis statistics limited on T2K….

Near detector fit results



Near detector data prefers more 2p2h contribution than seen in external data fits

- Indicates model (and uncertainties) need additional work still

Thoughts for DUNE

The cross section model is an important input to the T2K oscillation analysis. Uncertainties driven by:

- Disagreements between external data sets and ND data for different beamlines
- Theoretical knowledge– what is the correct theoretical approach, given the experimental disagreements?

Comparisons to non-default models valuable

- Tested effect on oscillation analyses through fake data studies
- Identified where more effort was needed (vs. what's already covered with existing uncertainties, which may be repurposed or adjusted accordingly)

Summary

Enormous amount of new information over last ~5-10 years on QE

- T2K OA considered MINERvA, MiniBooNE, NOMAD, T2K ND data
  - Indications QE is not well represented (see ArgoNEUT “hammer” events)
- Significant theoretical developments as well now included into generators

But, challenging to find ‘one model to fit them all’

- Likely additional theoretical uncertainties needed, more experimental work to be done to resolve the current picture

Even if we don’t adopt all the current puzzles as a baseline set of systematic uncertainty for QE, important to test effect for oscillation analysis

- Can guide how ND data, external data programs, theoretical work should proceed

Backup slides

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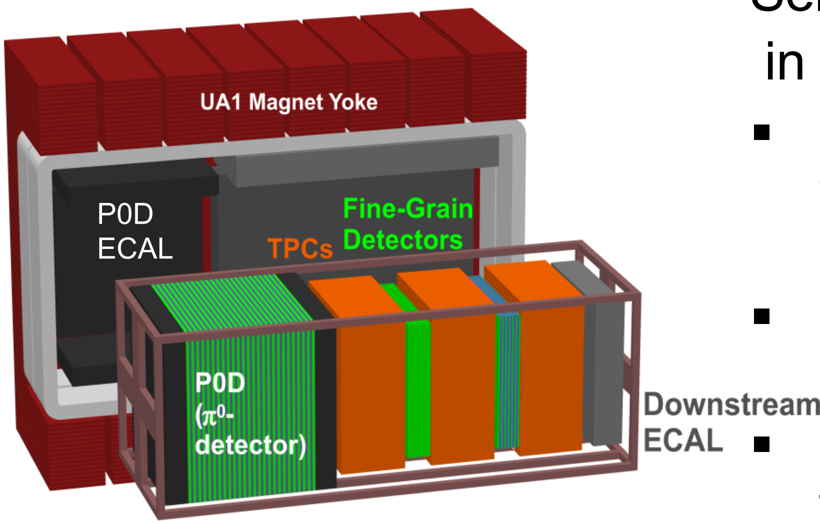
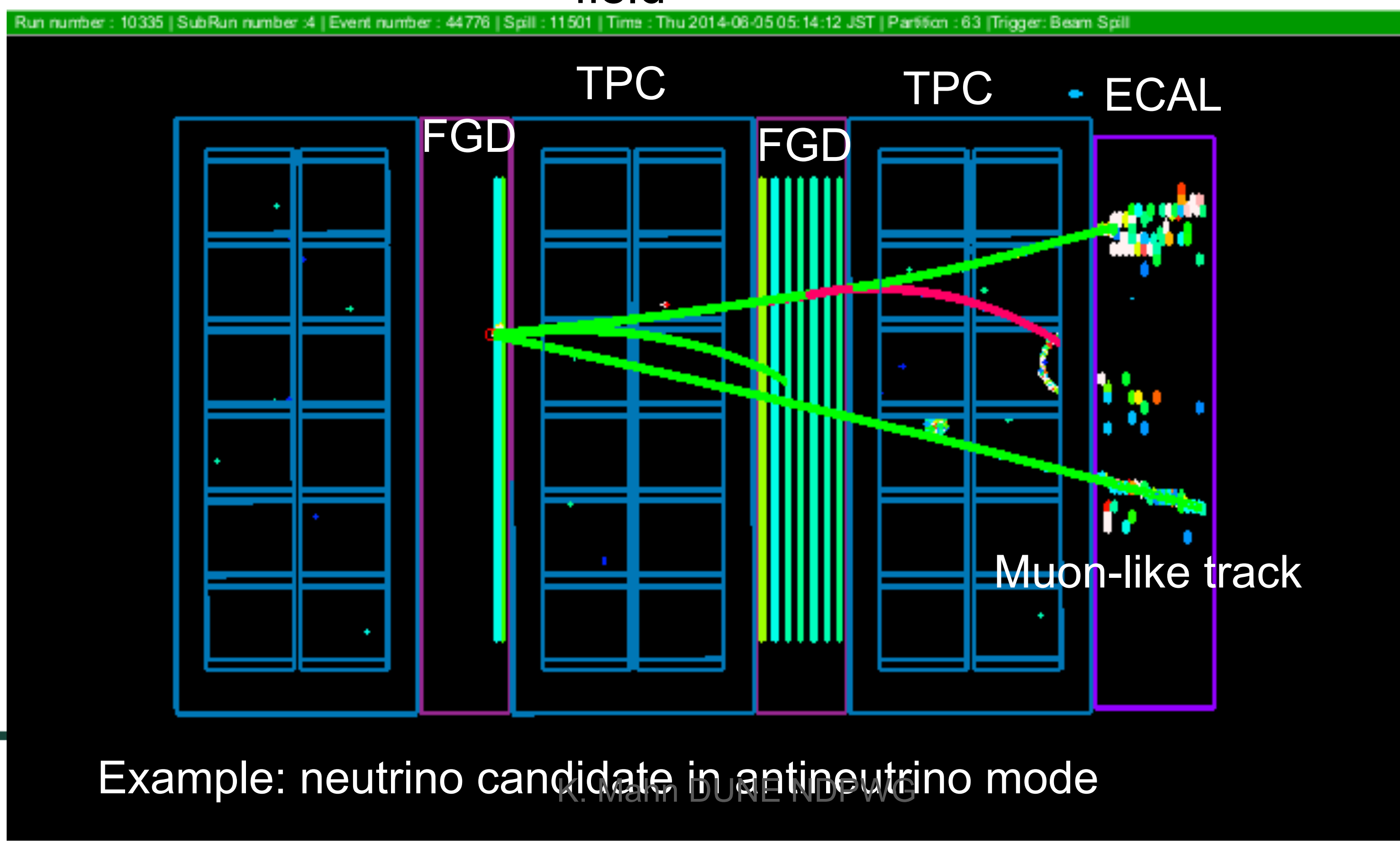
T2K off-axis near detectors: ND280



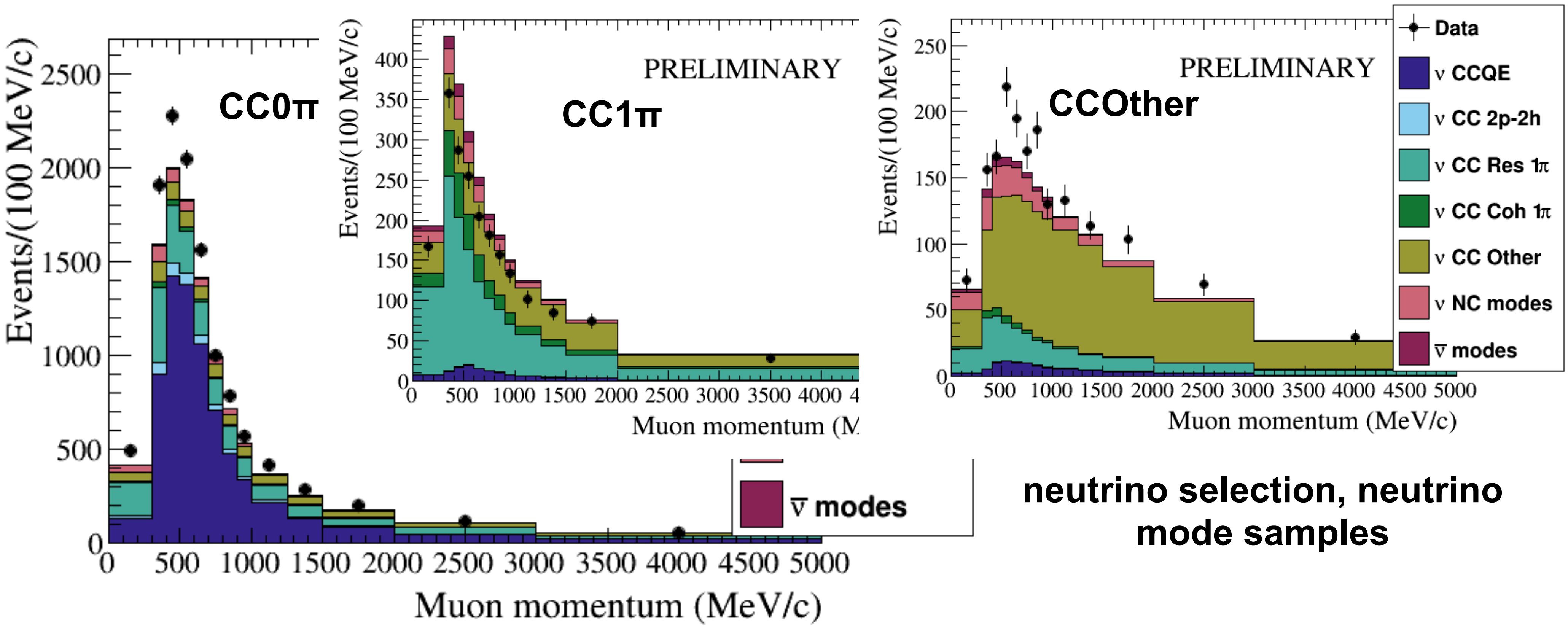
Select CC ν_μ, $\overline{\nu_\mu}$ candidates prior to oscillations in an off-axis tracking detector (ND280)

- Neutrino interacts on scintillator or water target in tracking detectors (FGDs), muon tracked through scintillator and TPCs
- Additional scintillator (P0D, SMRD) and calorimeters (ECAL)
- Muon momentum, sign from curvature in magnetic field



Example: neutrino candidate in antineutrino mode

ND280 data samples: neutrino mode



neutrino selection, neutrino mode samples

Select CC ν_μ candidates based on interactions with μ-:

- Select highest momentum track with negative charge, and PID consistent with a muon

Event samples provide information on flux, cross section model

- Separated based on presence of charged pion in final state (CC0π, CC1π, CC Other)
- Pions identified using track multiplicity, dE/dX in TPCs photons in ECALs

ND280 data samples: antineutrino mode

Select CC $\overline{\nu_\mu}$ candidates based on interactions with μ+:

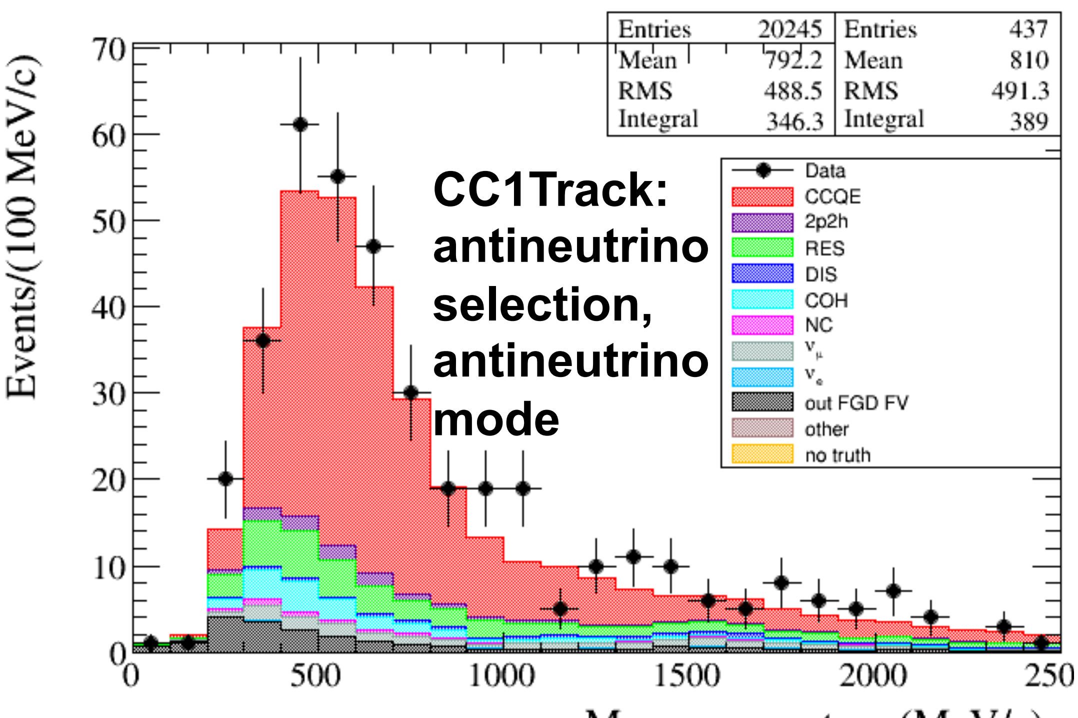
- Select highest momentum track with positive charge, and PID consistent with a muon
- Two sub-samples based on track multiplicity: CC1-Track, CC>1 Track

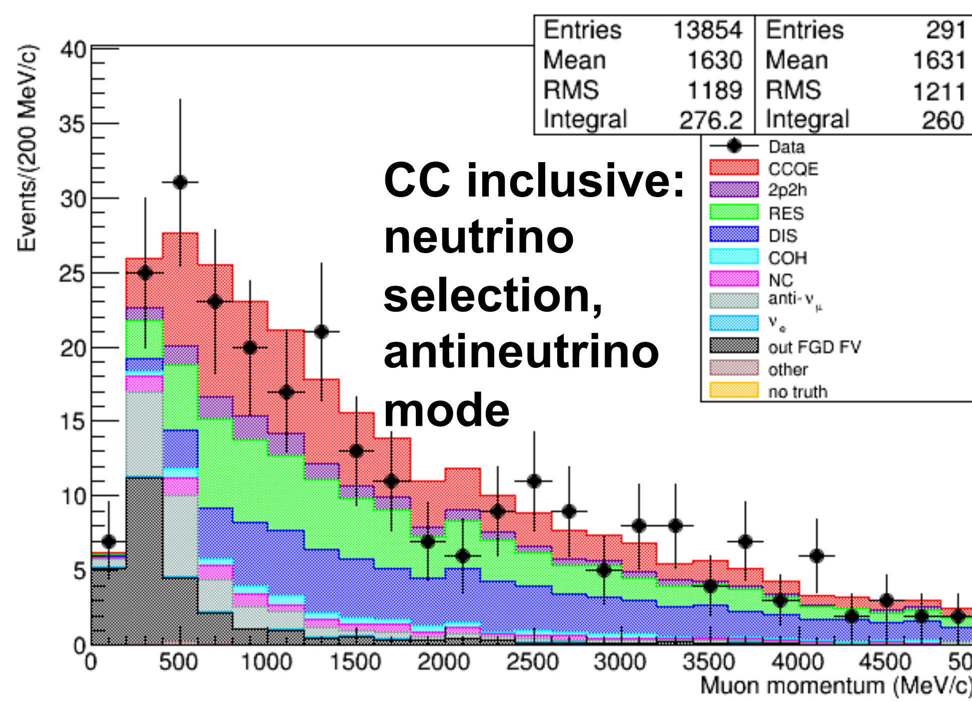
Complementary selection of neutrino candidates in antineutrino mode

Include in fit:

neutrino mode neutrino selections

antineutrino mode neutrino and antineutrino selections

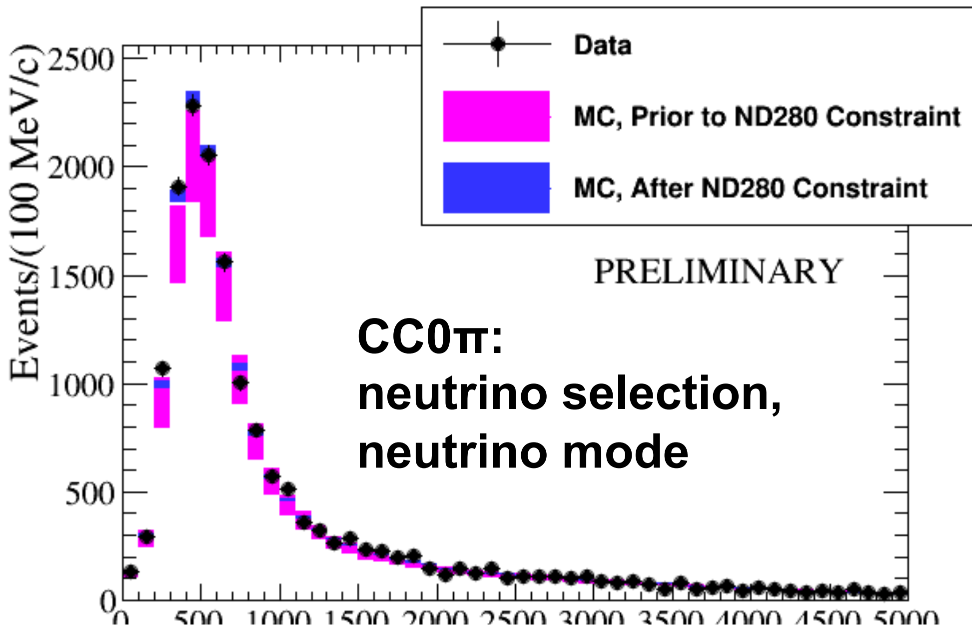


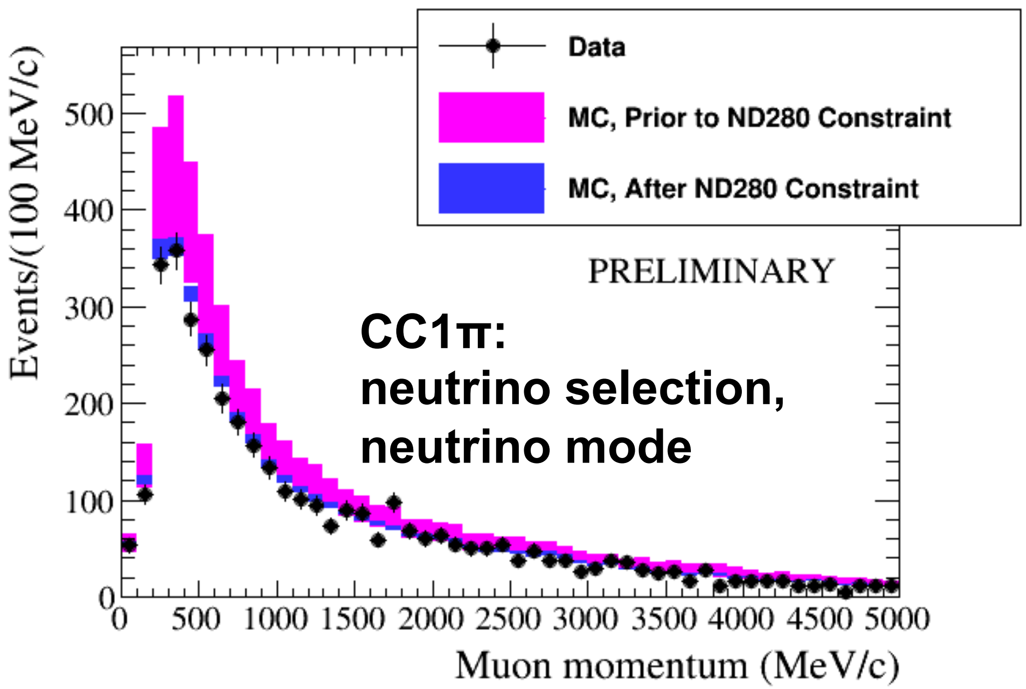


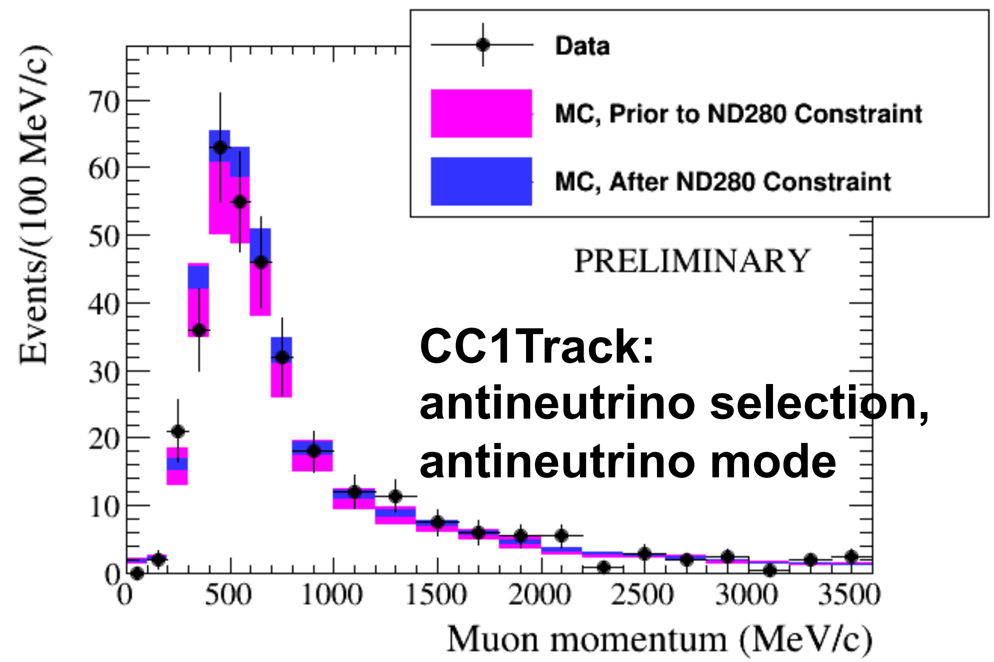
Near detector rate measurement

Expected number of events at the far detector is tuned using a likelihood fit to the near detector samples

- Neutrino, antineutrino fluxes are highly correlated between near and far detectors
- Cross sections are also correlated
- Significant reduction to overall uncertainties







Cross section tuning from near detector fit

M_A^{QE} (GeV/c^2)	1.15 ± 0.069607	1.1371 ± 0.033559
p_F ^{12}C (MeV/c)	223.0 ± 12.301	222.67 ± 8.8333
MEC ^{12}C	27.0 ± 29.053	103.11 ± 17.245
E_B ^{12}C (MeV)	25.0 ± 9.0	23.903 ± 7.3458
p_F ^{16}O (MeV/c)	225.0 ± 12.301	224.43 ± 12.152
MEC ^{16}O	27.0 ± 104.13	103.1 ± 101.49
E_B ^{16}O (MeV)	27.0 ± 9.0	27.045 ± 8.8047
$CA5^{RES}$	1.01 ± 0.12	0.86234 ± 0.074094
M_A^{RES} (GeV/c^2)	0.95 ± 0.15	0.72437 ± 0.052156
Isospin=$\frac{1}{2}$ Background	1.3 ± 0.2	1.4853 ± 0.19014
ν_e/ν_μ	1.0 ± 0.02	1.0008 ± 0.019997
CC Other Shape	0.0 ± 0.4	0.023024 ± 0.1928
CC Coh ^{12}C	1.0 ± 1.0	0.021658 ± 0.16037
CC Coh ^{16}O	1.0 ± 1.0	1.0764 ± 0.97171
NC Coh	1.0 ± 0.3	0.98 ± 0.29922
NC Other	1.0 ± 0.3	1.4128 ± 0.1858