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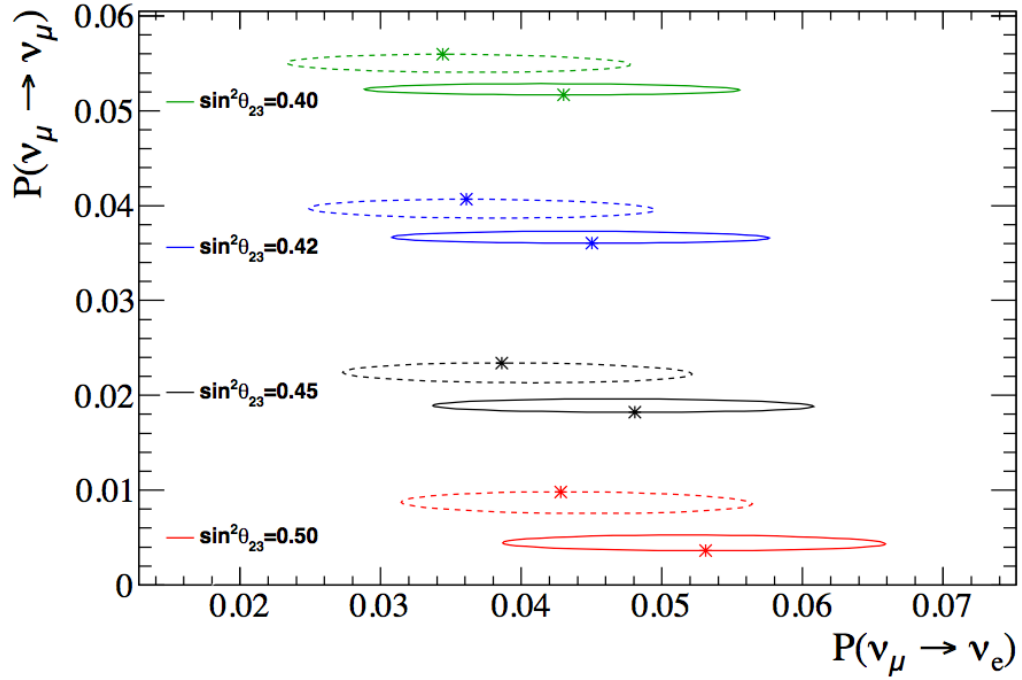
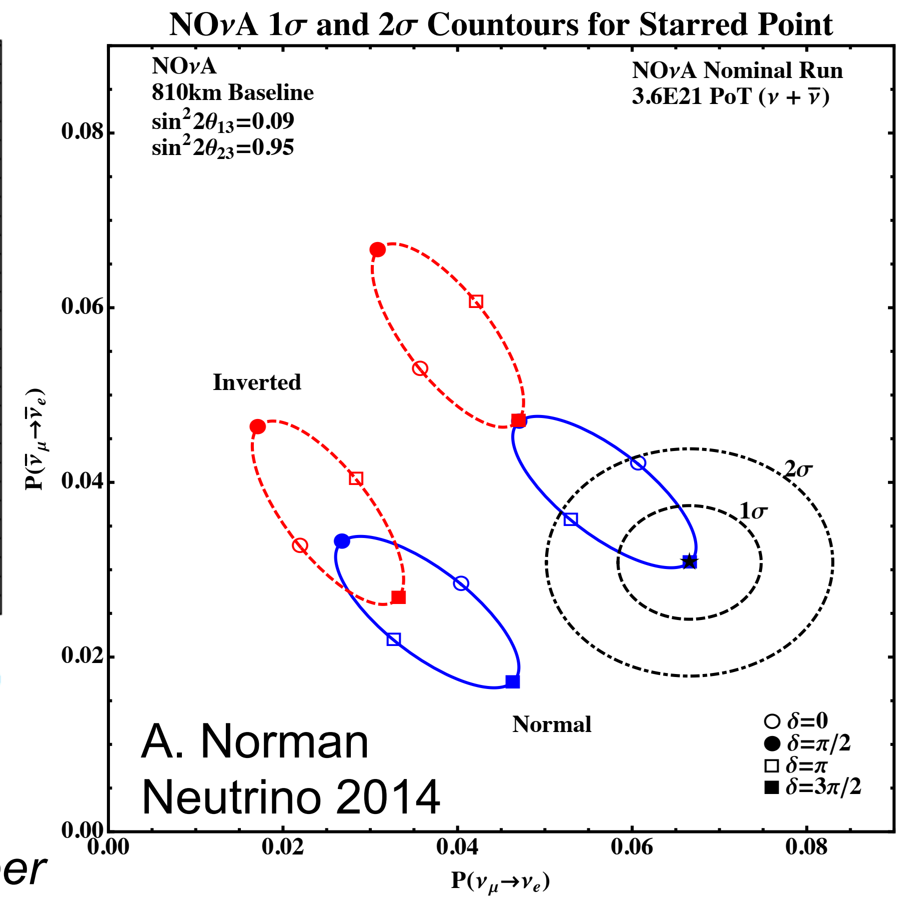
Systematic uncertainty considerations for long baseline experiments

K. Mahn
Michigan State University

Rates to oscillation probabilities…



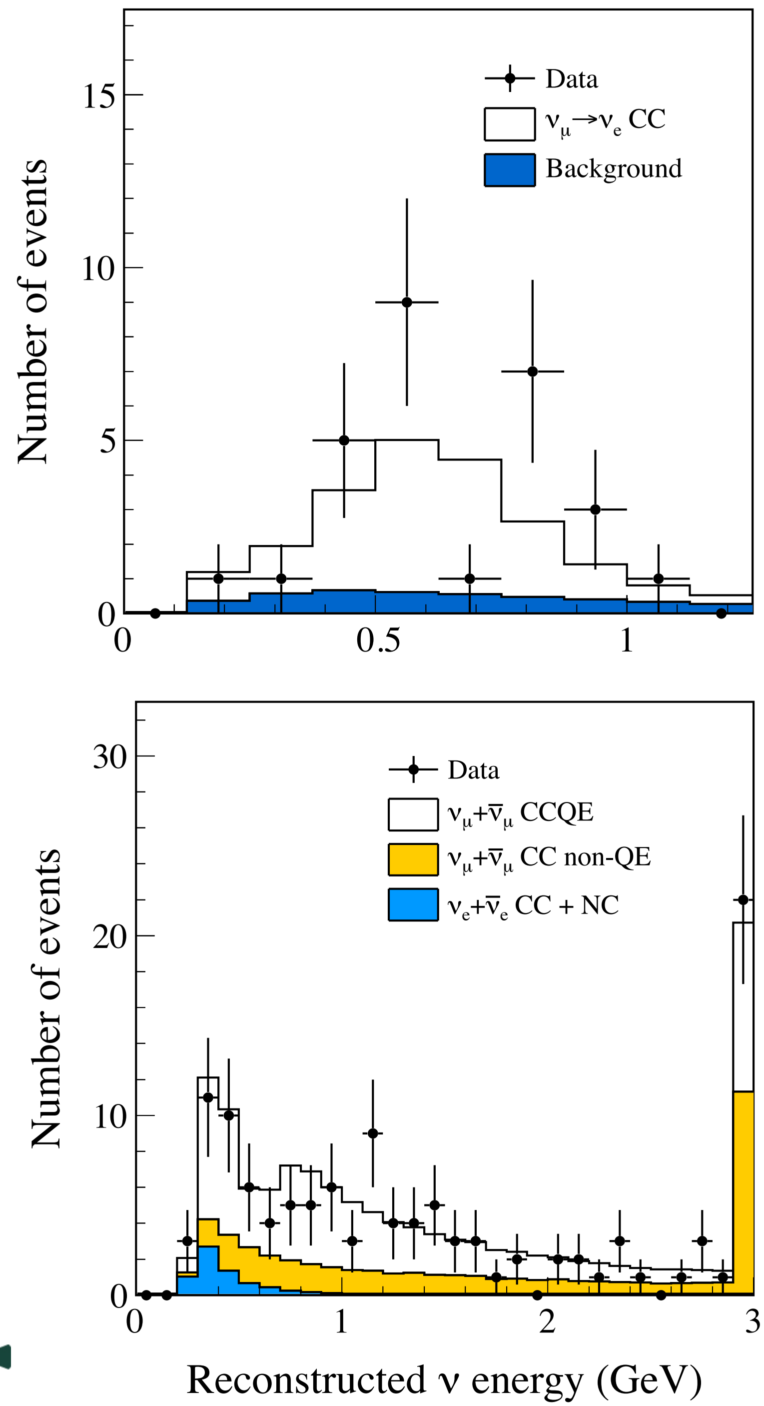
T2K collab, arxiv:1502.01550v1,
PRD 91, 072010 (2015)
Most of plots from this talk are from this long paper and PRD 88, 032002 (2013)



Event rates are used to infer the oscillation probability and mixing parameters

- Understanding δ_{CP} currently requires information about θ_{23} (and mass hierarchy)
- Comparisons between neutrino/antineutrino appearance oscillation probabilities will be used to also infer δ_{CP}, mass hierarchy and θ_{23} octant

Data from T2K:



T2K collab, arxiv:1502.01550v1, submitted to PRD

Appearance channel:

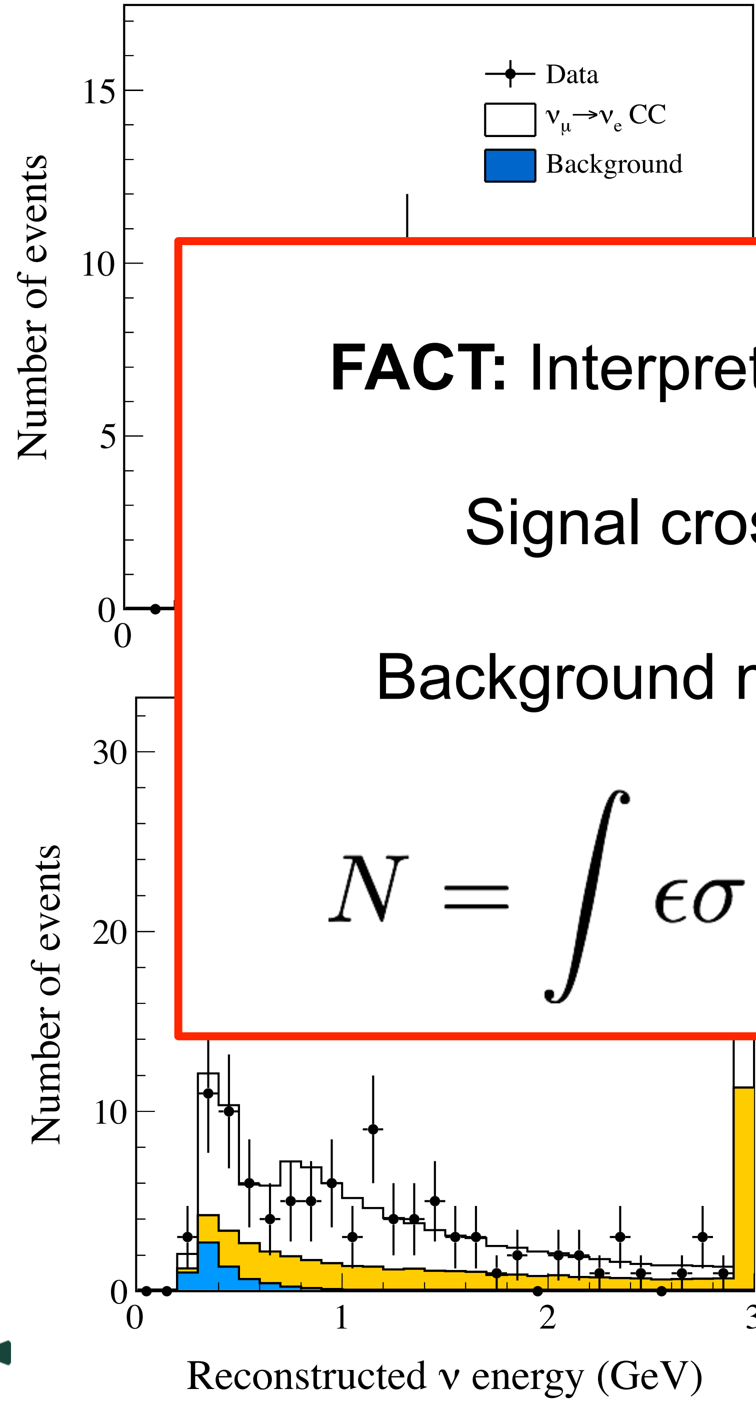
- T2K: 28 candidate ν_e events
  - Phys. Rev. Lett. 112, 061802 (2014)
- Transition depends on all mixing parameters (Δm^2_{32}, θ_{23}, θ_{13}, δ_{CP}, mass hierarchy and Δm^2_{21}, θ_{12})

Disappearance channel:

- T2K: 120 candidate ν_μ events
- Determine Δm^2_{32}, $\sin^2\theta_{23}$ from distortion to estimated neutrino energy spectrum
  - Phys. Rev. Lett. 112, 181801 (2014)

Data from T2K:

T2K collab, arxiv:1502.01550v1, submitted to PRD



Appearance channel:

- T2K: 28 candidate ν_e events
  - Phys. Rev. Lett. 112, 061802 (2014)

FACT: Interpretation of this data depends on:

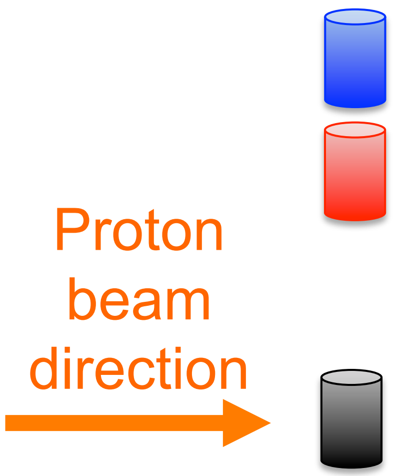
Signal cross section model (CCQE)

Background model ($CC1\pi^+$, $NC\pi^+$, $NC\pi^0$)

$$N = \int \epsilon\sigma(E_\nu)\Phi(E_\nu)P(E_\nu)dE_\nu$$

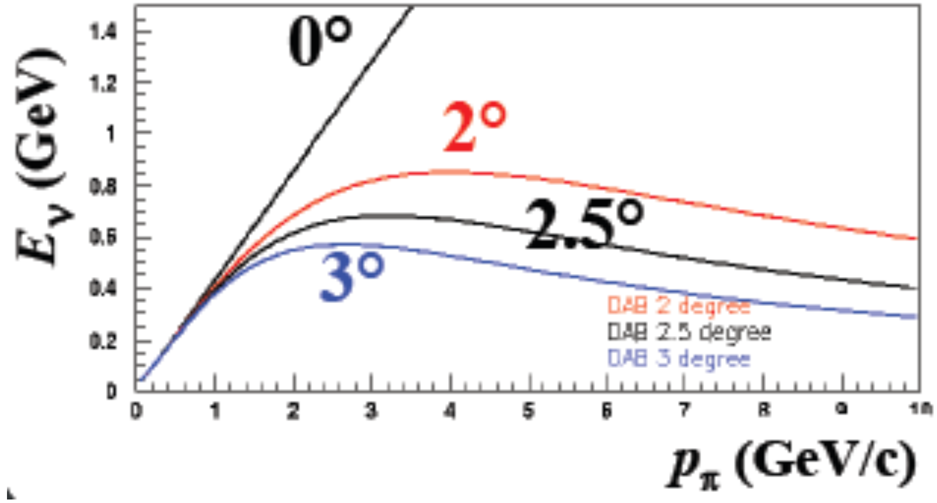
- Phys. Rev. Lett. 112, 181801 (2014)

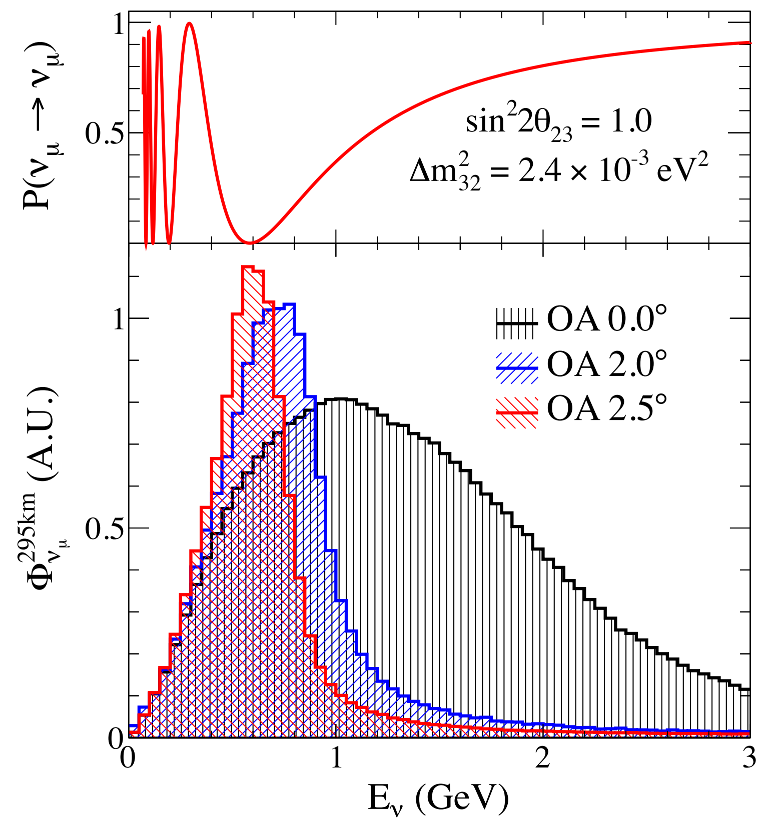
Neutrino source: accelerator-driven



Accelerator based sources also are tunable as the neutrino energy spectrum depends on:

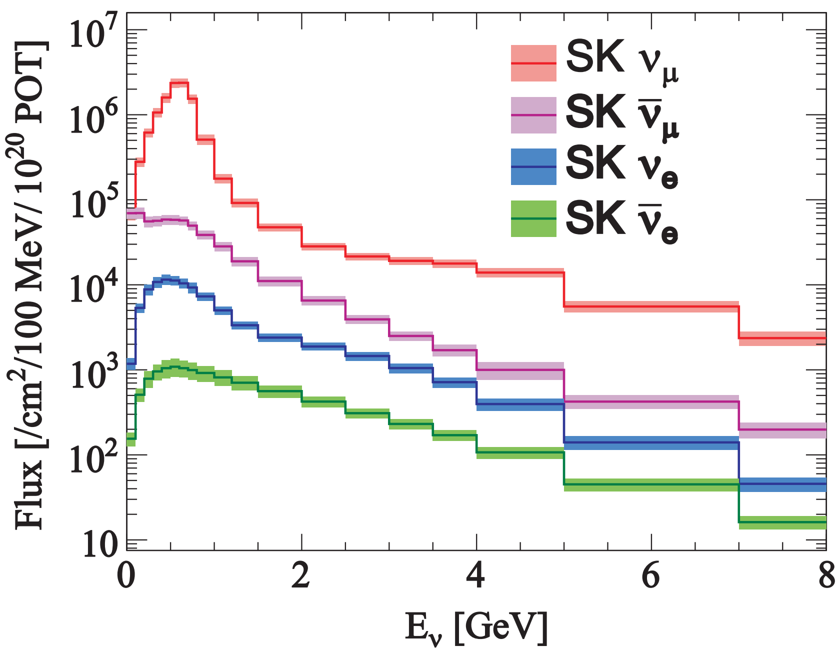
- Proton beam energy
- Position of the detector relative to the proton beam direction
- T2K uses an “off axis” (2.5°) beam, peaked at E_ν~0.6 GeV to maximize the oscillation probability





PRD 88, 032002 (2013)

Neutrino source: uncertainties



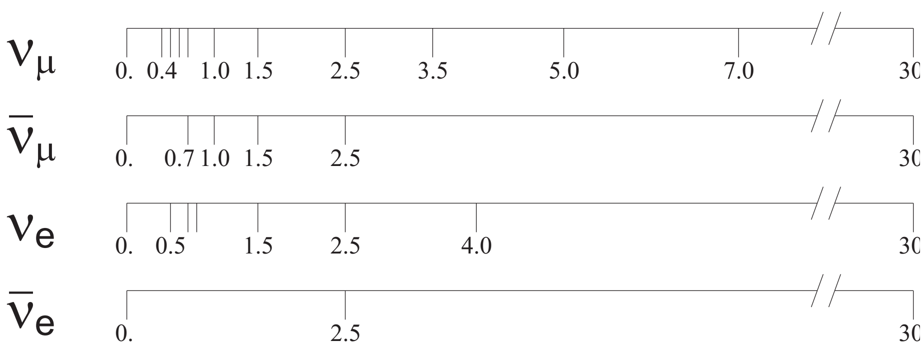


TABLE III. Contributions to the systematic uncertainties for the unoscillated ν_μ and ν_e flux prediction at SK, near the peak energy and without the use of near detector data. The values are shown for the ν_μ (ν_e) energy bin $0.6\ \text{GeV} < E_\nu < 0.7\ \text{GeV}$ ($0.5\ \text{GeV} < E_\nu < 0.7\ \text{GeV}$).

	Uncertainty in SK flux near peak (%)	
Error source	ν_μ	ν_e
Beam current normalization	2.6	2.6
Proton beam properties	0.3	0.2
Off-axis angle	1.0	0.2
Horn current	1.0	0.1
Horn field	0.2	0.8
Horn misalignment	0.4	2.5
Target misalignment	0.0	2.0
MC statistics	0.1	0.5
Hadron production		
Pion multiplicities	5.5	4.7
Kaon multiplicities	0.5	3.2
Secondary nucleon multiplicities	6.9	7.6
Hadronic interaction lengths	6.7	6.9
Total hadron production	11.1	11.7
Total	11.5	12.4

Uncertainties on the flux prediction come from in-situ or external (e.g. NA61) measurements

Neutrino interaction models on T2K

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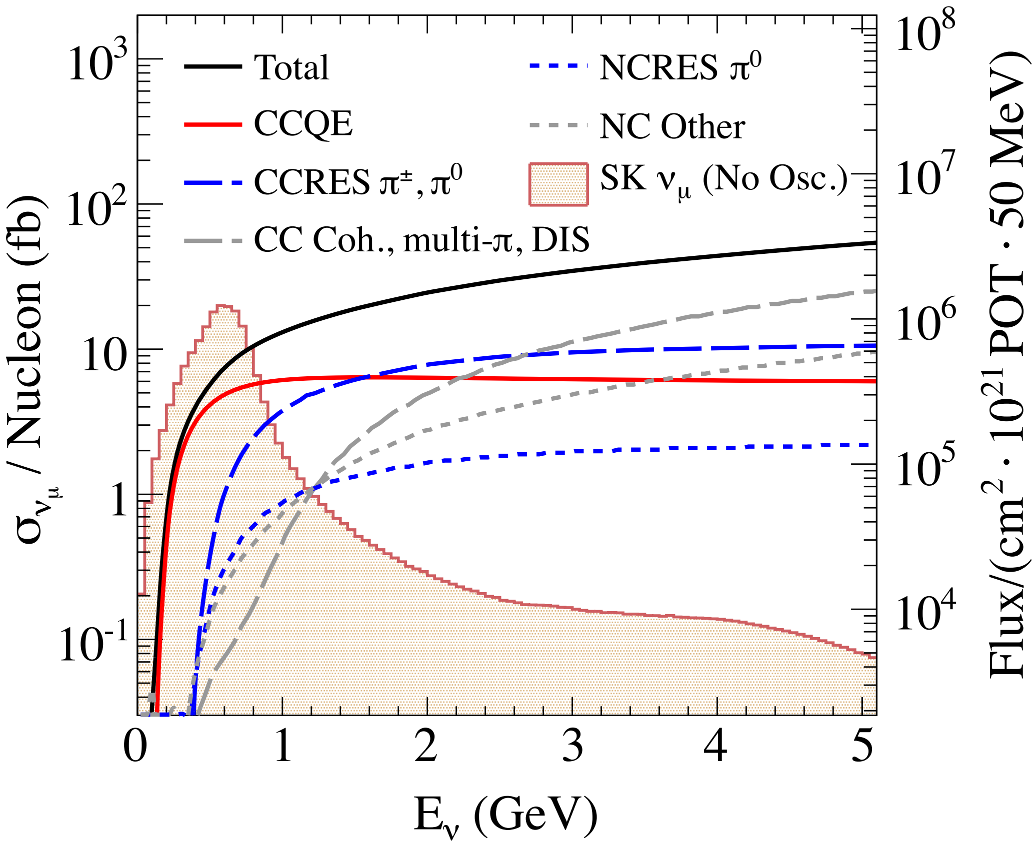

NEUT model (5.1.4.2) for 2013 earlier analyses:

- CCQE : Relativistic * Global * Fermi Gas model. Axial vector mass = 1.2GeV/c.
- No "Multinucleon" CCQE like interaction
- 1pi (NC and CC) production model: Rein-Sehgal, Simple pion-less delta decay. MARES, NCpi0 and CCpi+ normalizations tuned based on fits to external 1pi samples.

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)
- "Meson exchange current" (MEC) CCQE like scattering (Nieves et al.)
- 1pi (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

Neutrino interaction models on T2K

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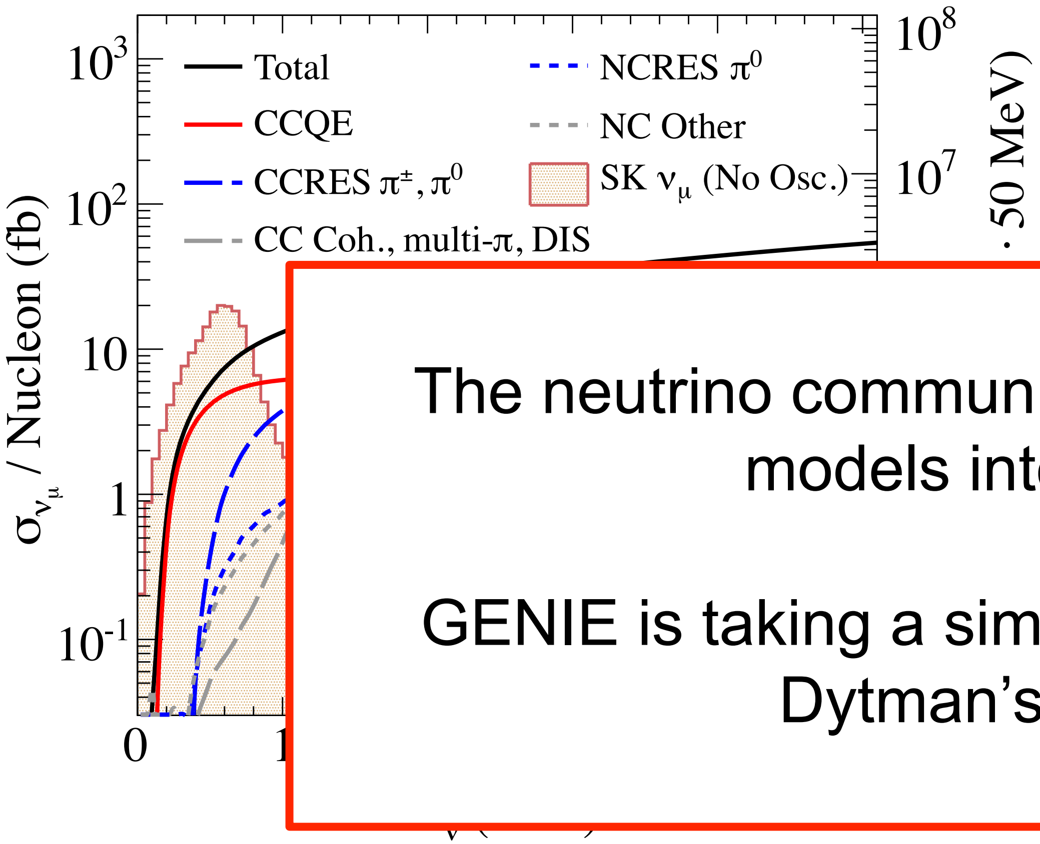

NEUT model (5.1.4.2) for 2013 earlier analyses:

- CCQE : Relativistic * Global * Fermi Gas model. Axial vector mass = 1.2GeV/c.

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The neutrino community is now adding modern models into generators.

GENIE is taking a similar approach (see Steve Dytman's talk earlier)

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

- CCQE : Spectral function model (Benhar et al.) Axial vector mass = 1.2GeV/c2.
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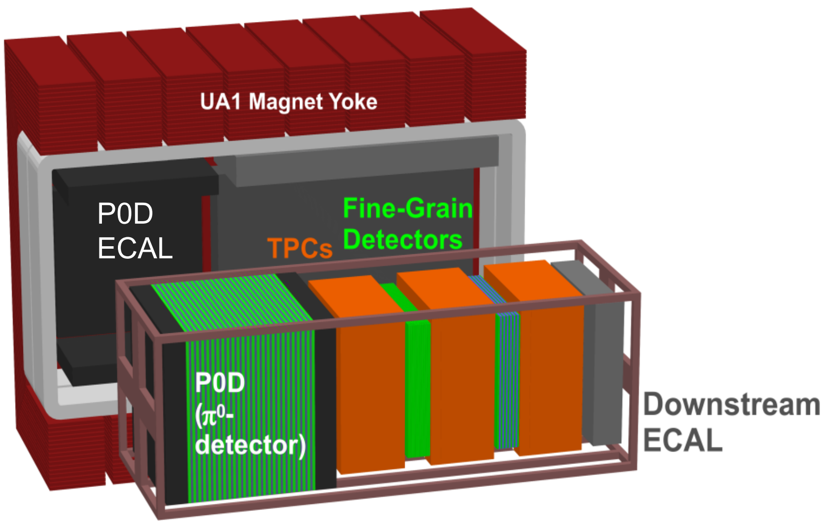
- 1pi (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

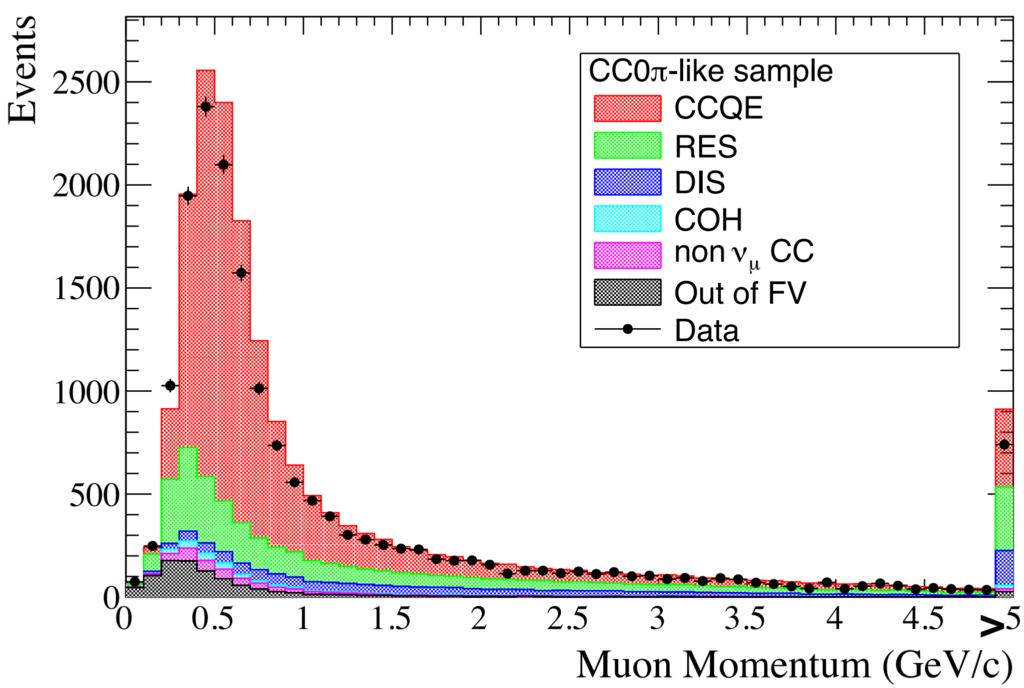
E_ν (GeV)

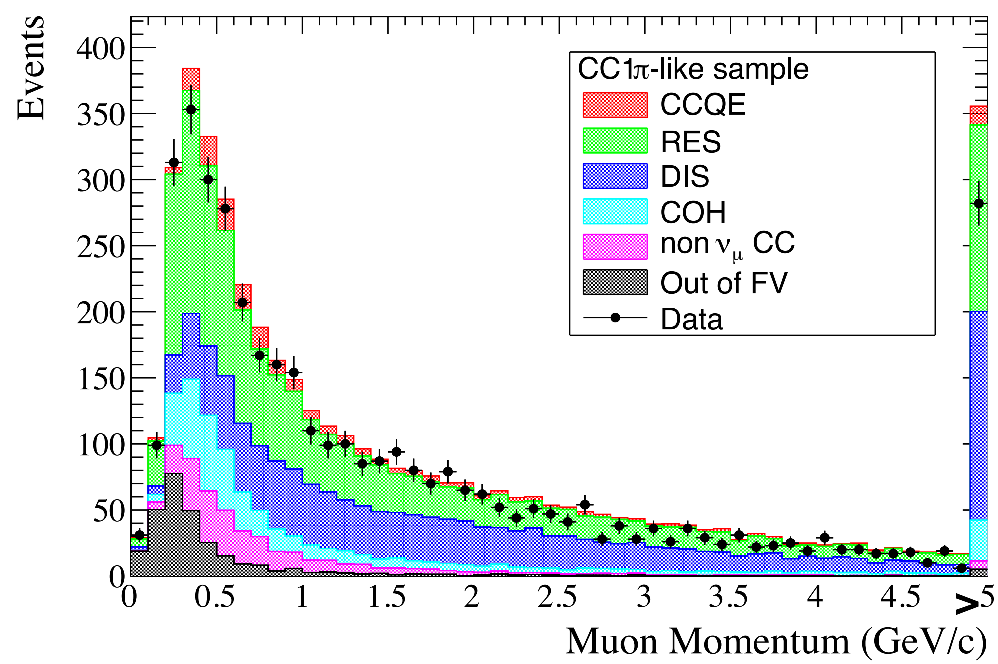
T2K near detectors



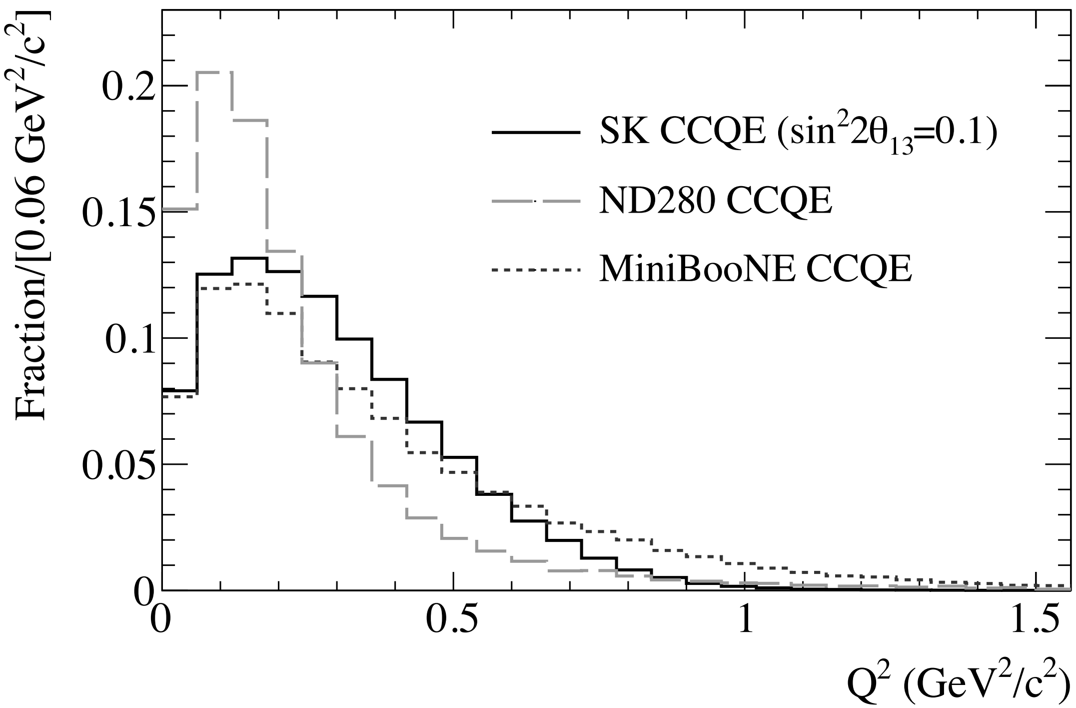
Select CC ν_μ candidates prior to oscillations in an off-axis tracking detector (ND280)

- Neutrino interacts on scintillator tracking detector, muon tracked through scintillator and TPCs
- Muon momentum from curvature in magnetic field
- Events separated based on presence of charged pion in final state





Challenges of use of ND data



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

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

Target: ND selection is C, SK is O

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

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

Use of external data in fits as well as near detector

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

Incomplete data: MiniBooNE

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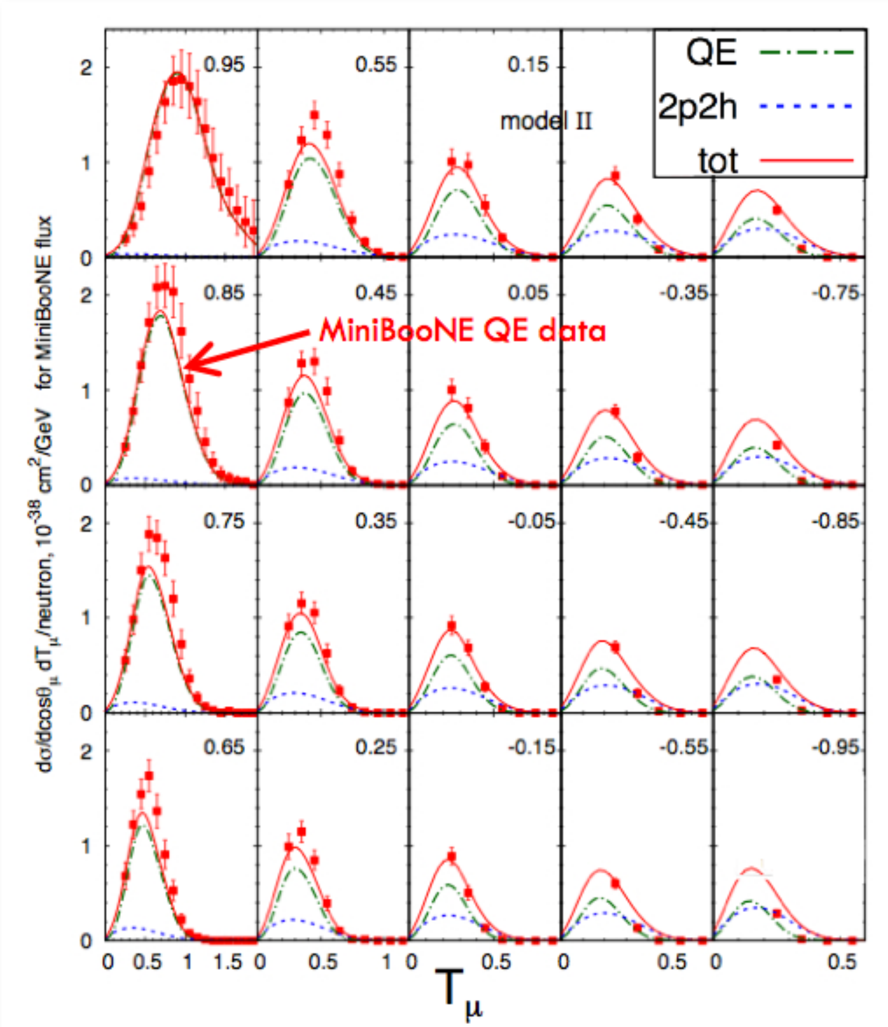
MiniBooNE data is critical due to 4π acceptance… but…



one example: Lalakulich, Gallmeister, Mosel
PRC 86, 014614 (2012)

S. Zeller, JLAB Workshop, May 2015

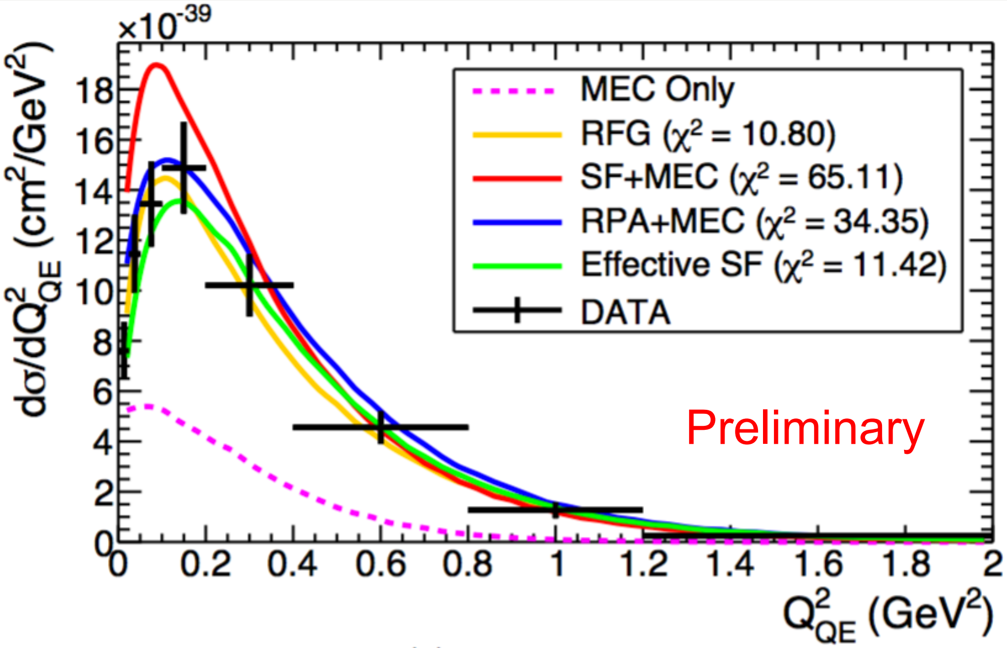
No offdiagonal correlations for MiniBooNE data releases

- First round of fits got an "extra crazy" value of MAQE, not alleviated by masking low Q^2 bins
- Internal studies indicate this gives a flawed statistic for estimating uncertainty
  - Working now with MiniBooNE to secure needed information
  - Useful to understand background subtraction

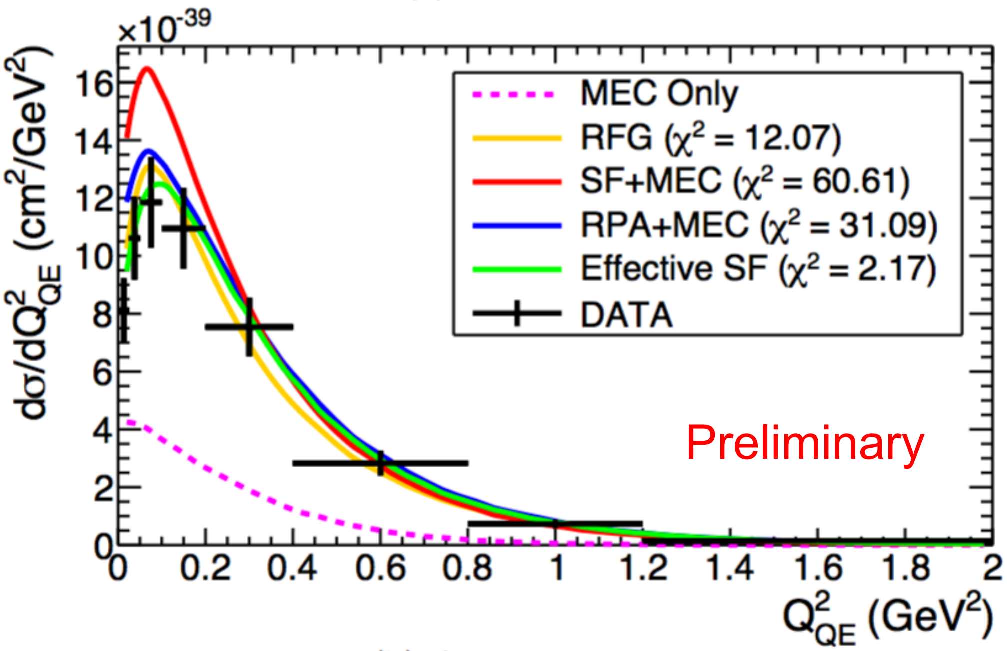
No correlations between samples

- Comparing CC to NC in single model
- Neutrino to antineutrino

QE model comparisons



(a) Neutrino



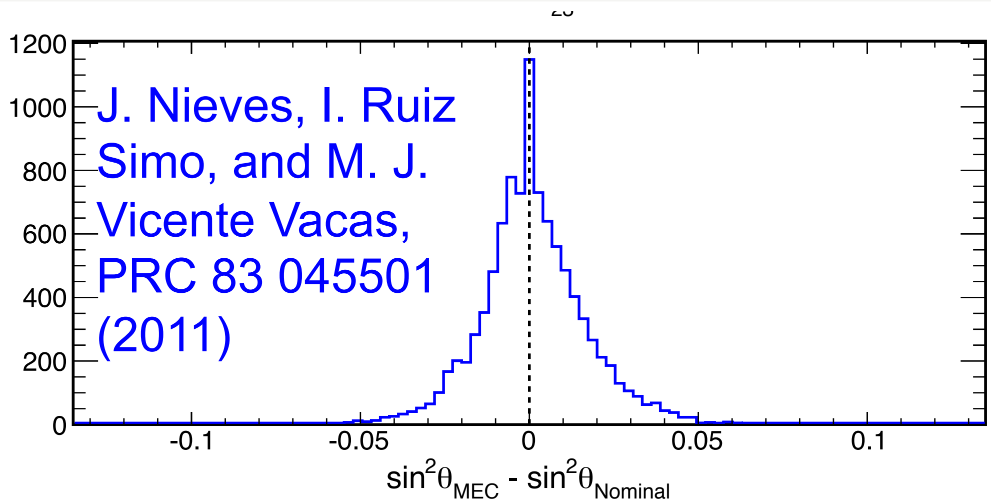
(b) Antineutrino

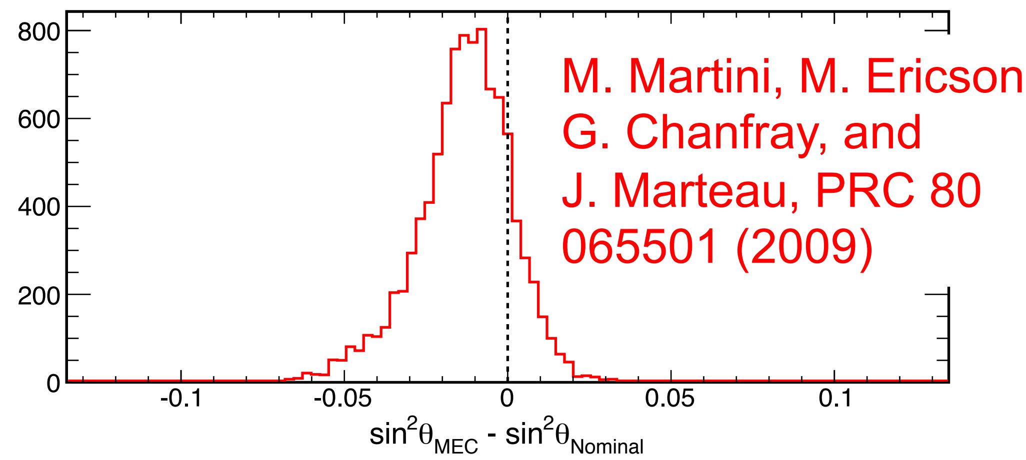
MINERvA provides neutrino and antineutrino datasets and correlations

Compare T2K ND, MINERvA and MiniBooNE fit results with a Parameter Goodness of Fit (PGoF) statistic

- Tensions in data mean inflating associated uncertainties to cover these differences
- Is disagreement 2p2h, nuclear effects? Different effect in osc analysis
- Parameterization probably still incomplete, revisit theoretical errors
- Which experiment is sensitive to which effects and where in the phase space?

Multinucleon effect on T2K analysis





Tested possible bias on 2013/2014 T2K 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 relative to current systematic uncertainty on disappearance analysis (vs. 5.0% non-cancelling cross section uncertainty, 7.7% total)

Also a part of non-cancelling cross section uncertainty– effect of alternate model on 1p1h kinematics

Multinucleon effect on T2K analysis

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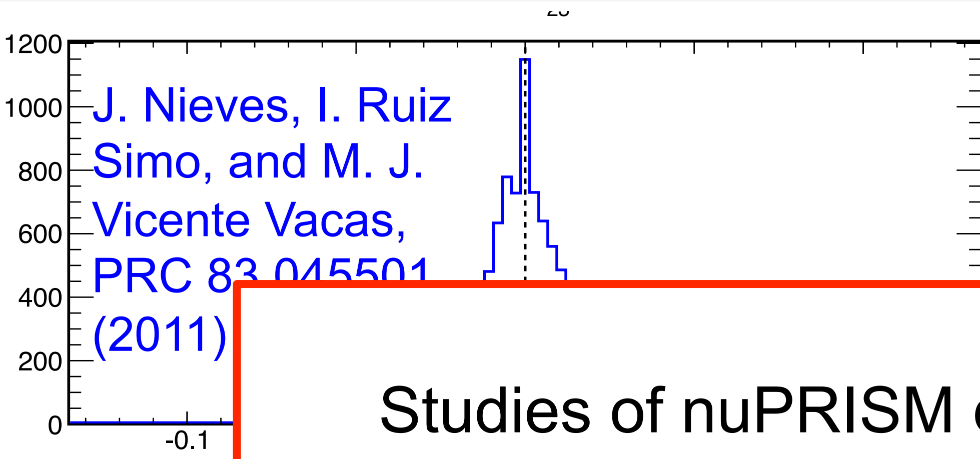

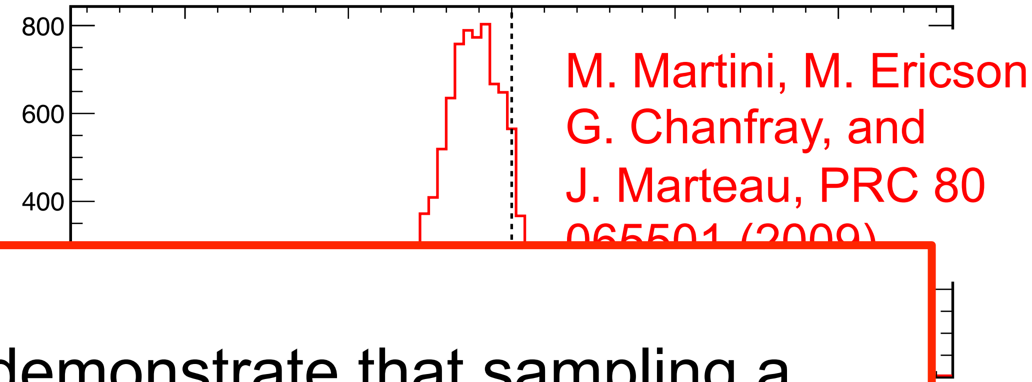

Studies of nuPRISM demonstrate that sampling a different fluxes in the same detector circumvent this bias in much the same way as a mono-energetic neutrino beam would (LOI: arxiv:1412.3086)

Provides a novel, unique probe of the axial current with comparable uncertainties to the current neutrino scattering program

Tested pos

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- For eacl ... nt

Nieves et a
"increased

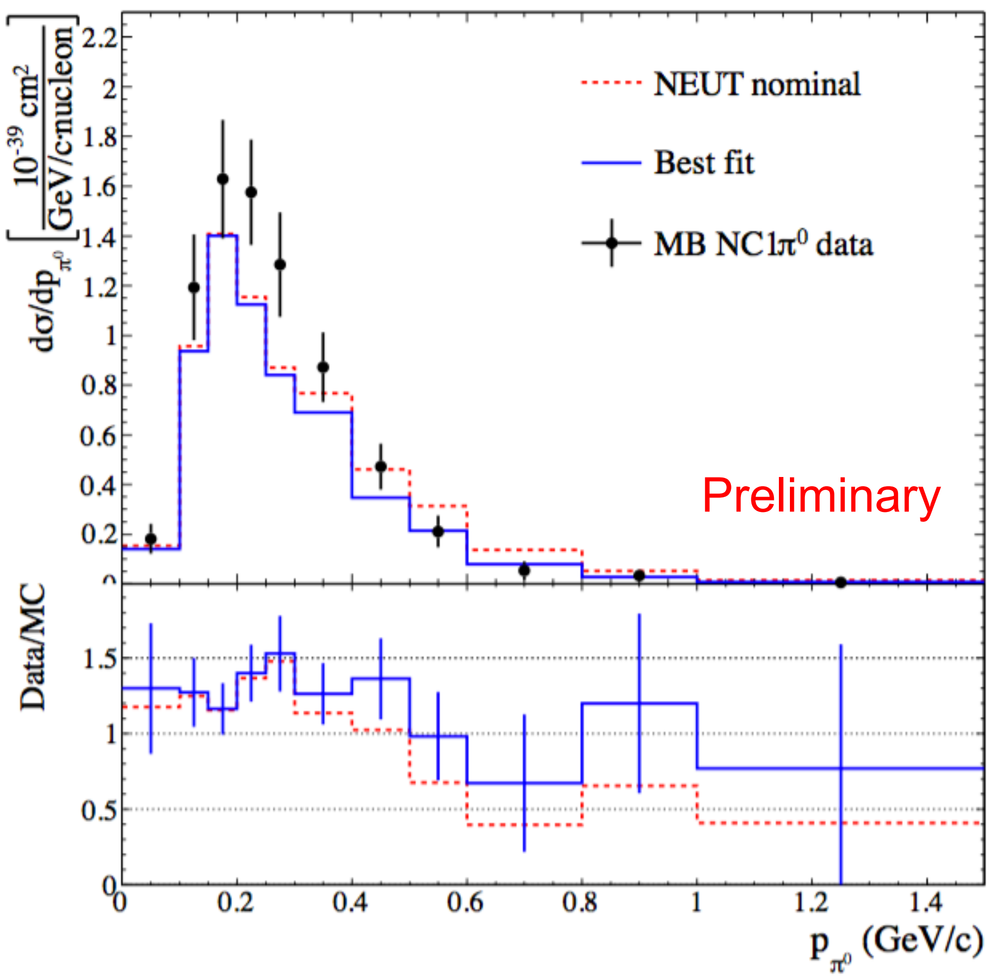
Significant relative to current systematic uncertainty on disappearance analysis (vs. 5.0% non-cancelling cross section uncertainty, 7.7% total)

Also a part of non-cancelling cross section uncertainty– effect of alternate model on 1p1h kinematics

Single pion production

Incomplete parameterization, difficult to reproduce rate, shape of pions

- π^0 spectrum for MiniBooNE NCπ^0 is harder than NEUT, NUANCE
- Added empirical parameter to alter relative contribution of high W to low W contributions. Disagreement could also be due to in-medium treatment



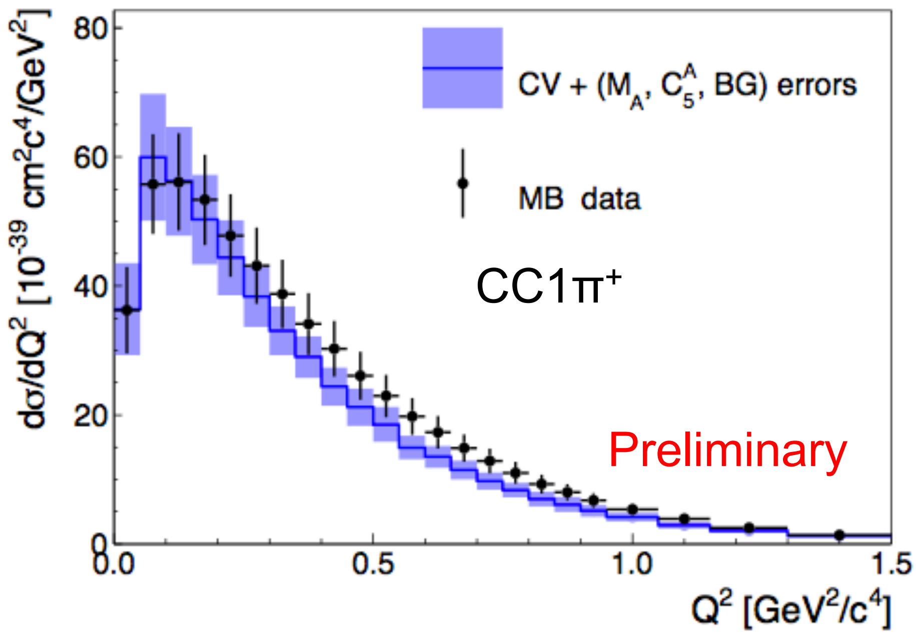
2015: Updated RS form factors from K. M. Graczyk and J. T. Sobczyk. Phys. Rev. D, 77:053001 (2008)

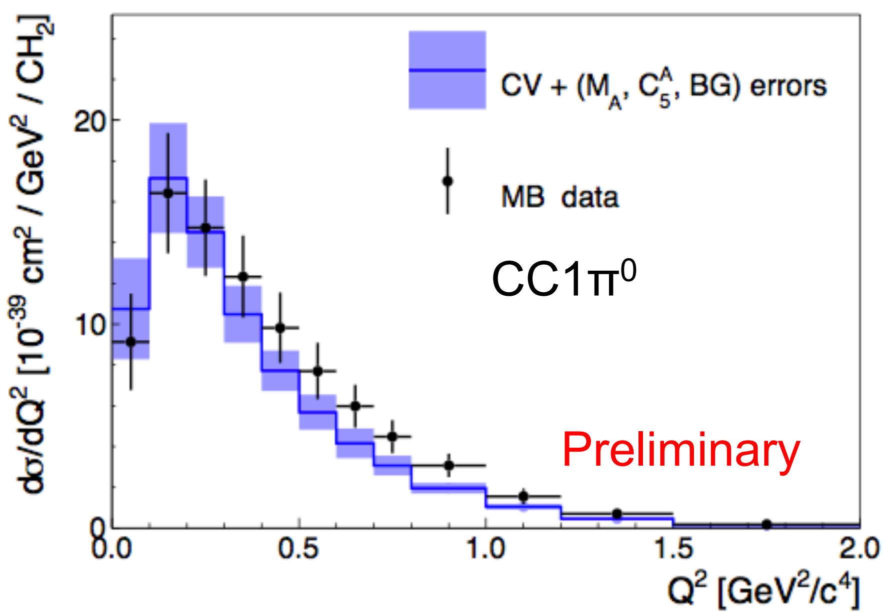
Fit neutrino deuterium channels:

- C^A_5 (0) driven by ANL/BNL disagreement
- MARES (axial form factor mass)
- Non-resonant background scale factor

Results of resonance model retune

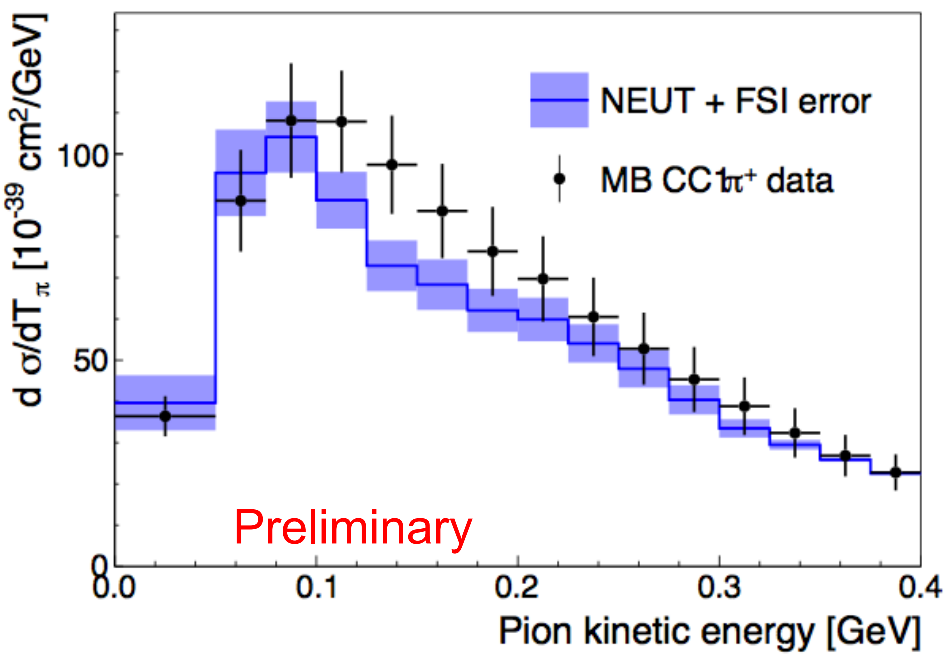
- Reasonable agreement Q^2 (and reco. E assuming pion)
- Fixing remaining difference in Q^2 doesn't resolve other kinematic variable differences, such as pion momentum (pion angle OK)

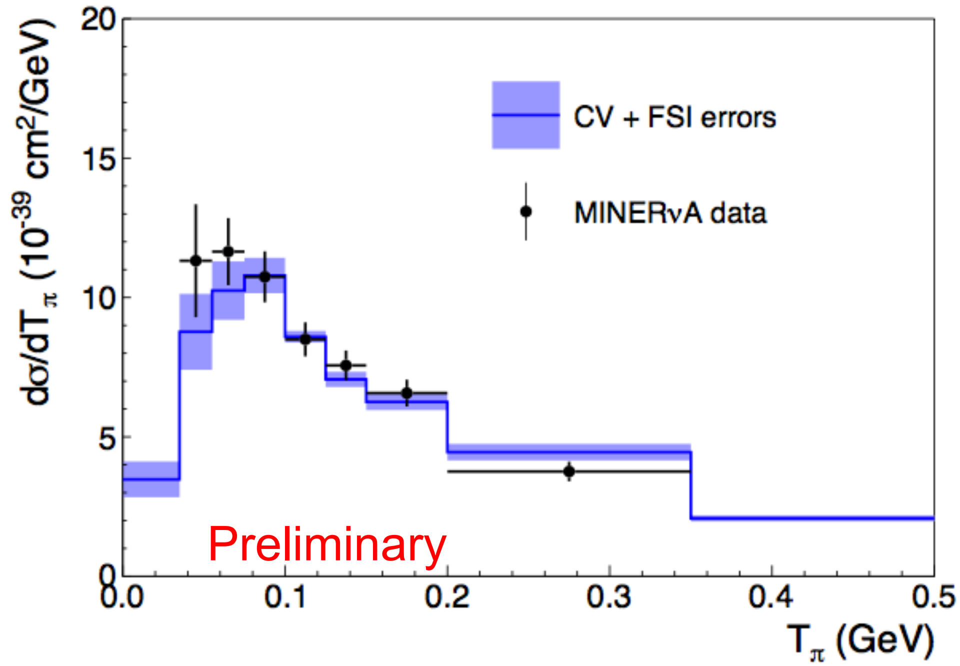




Results of resonance model retune

- Fitting MiniBooNE data is possible, but requires significant suppression of absorption
- Need to revisit FSI + in medium treatment



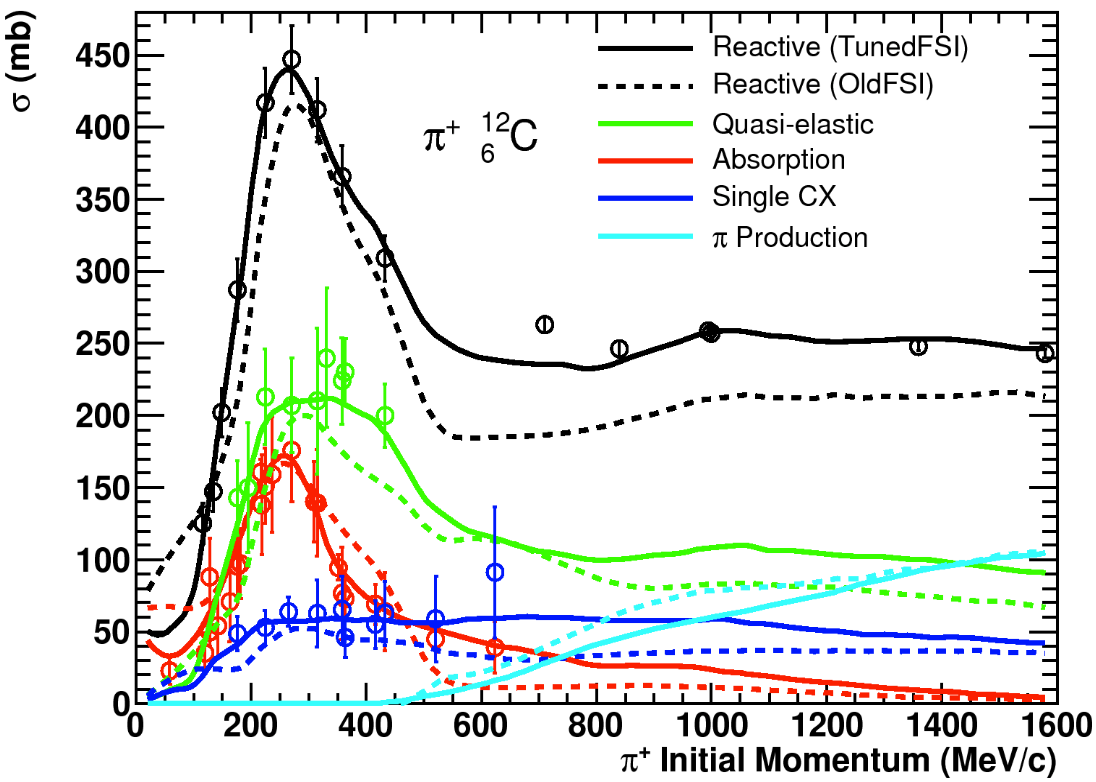


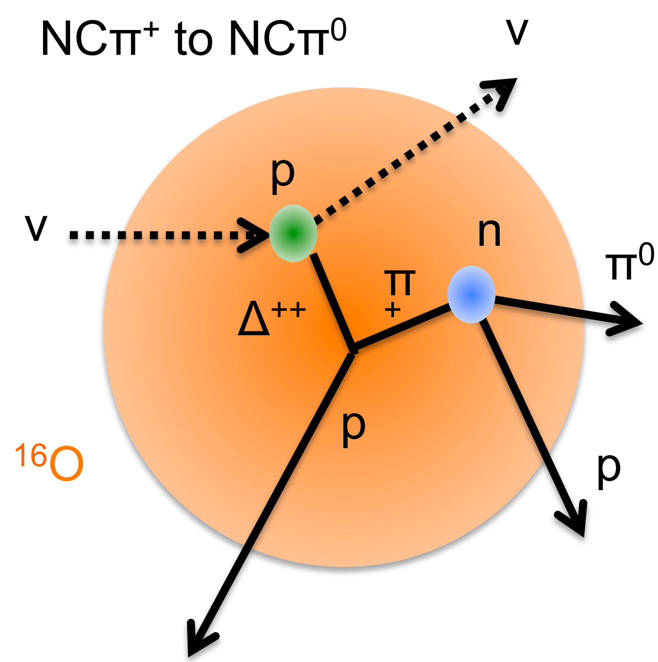
New T2K near detector measurements of pion production coming soon

Final state interaction model

NEUT FSI model is a cascade model tuned on ``free-range'' π+N data

- ~3% error in disappearance analysis at far detector
- New data (DUET) and consideration of correlations between points
- Do we represent angular distributions of scattered pions?
- Model uncertainty: Would GiBUU (transport model) give a different answer?
- Relationship to Enu: Are models representative of Δ -> π in medium?
  - Data Mining collaboration for comparable Q^2 as neutrino probe





Related: pion interactions in detector

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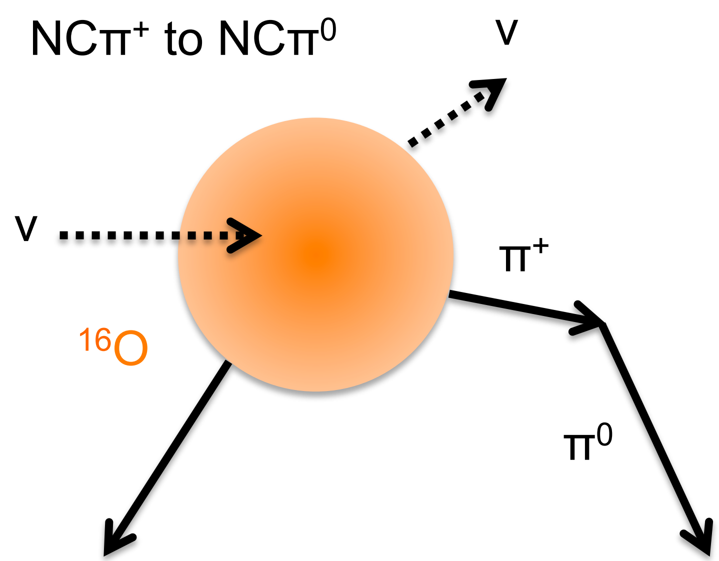
Pion scattering in the detector is a background to cross section understanding of what comes out of the nucleus (``secondary interactions'')

- Consistent treatment within same model at far detector
- Significant detector uncertainty for near detectors

TABLE XI: Minimum and maximum fractional errors among all the (p_μ,$\cos\theta_\mu$) bins, including the largest error sources. The last column shows the fractional error on the total number of events, taking into account the correlations between the (p_μ,$\cos\theta_\mu$) bins.

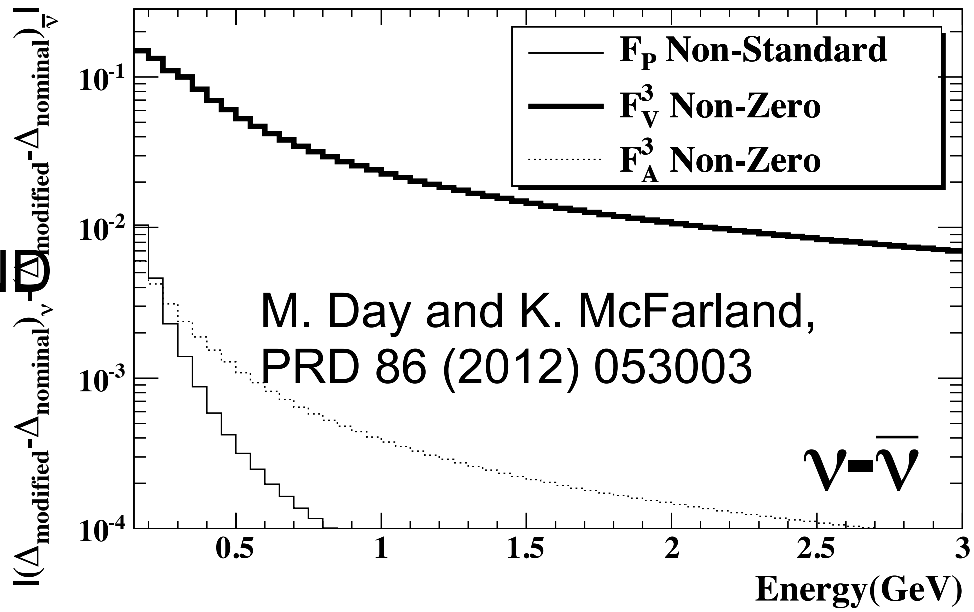
Systematic error	Error Size (%)	
	Minimum and maximum fractional error	Total fractional error
B-Field Distortions	0.3 - 6.9	0.3
Momentum Scale	0.1 - 2.1	0.1
Out of FV	0 - 8.9	1.6
Pion Interactions	0.5 - 4.7	0.5
All Others	1.2 - 3.4	0.4
Total	2.1 - 9.7	2.5



ν_e/ν_μ cross section, NC1γ

Differences between ν_e and ν_μ cross sections difficult to probe experimentally, but significant for for future program

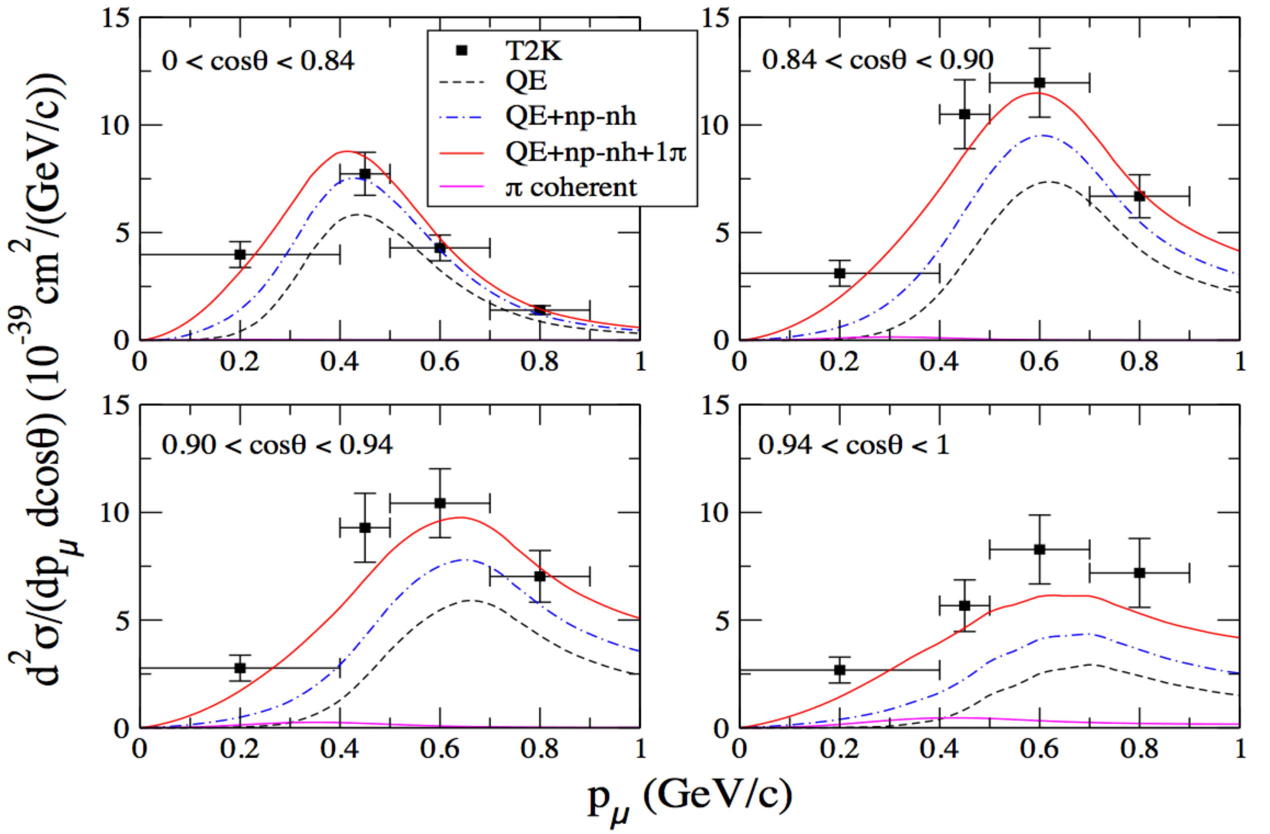
- ν_μ cross section used to infer ν_e from ND
- T2K uncertainty on ν_e/ν_μ xsec is 3%
- Difficult to measure due to limited statistics



NC single photon production is difficult to isolate due to statistics, intrinsic ν_e events and photon backgrounds, may also be significant for future.

- Mimics ν_e appearance, recent improvements further reject NCπ^0
- How can we use information from CC, NC resonance production to constrain this background?

T2K: indirect 2p2h probes



Martini and Ericson, Phys.Rev. C90 (2014) 2, 025501
T2K inclusive data: Phys.Rev. D87 (2013) 9, 092003

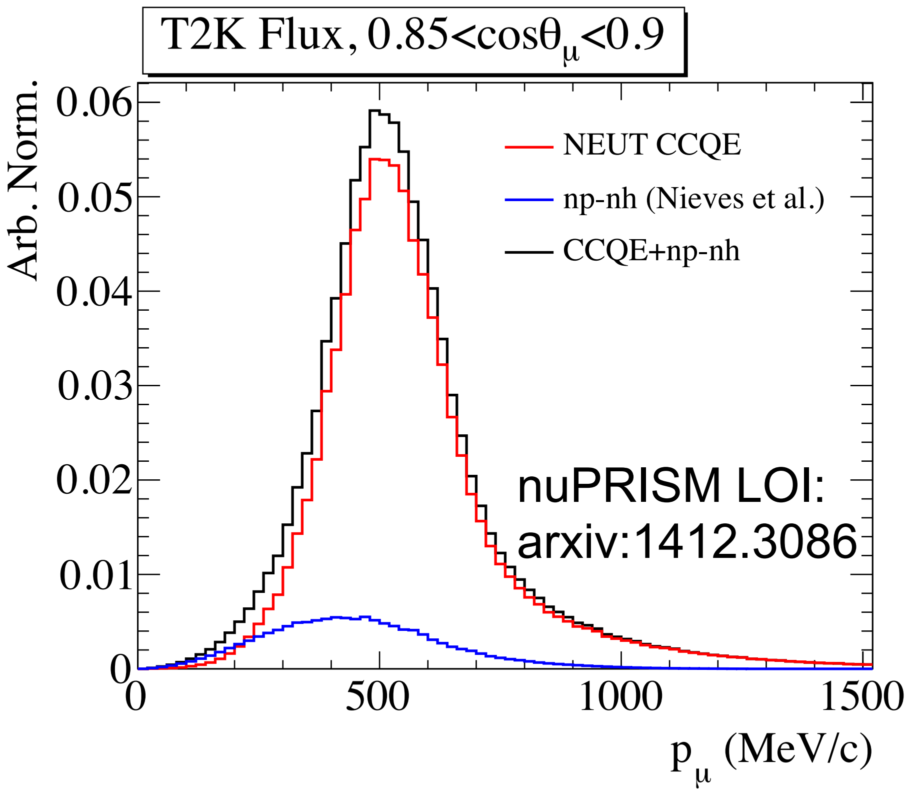
Indirect probe of multinucleon interactions through muon kinematics

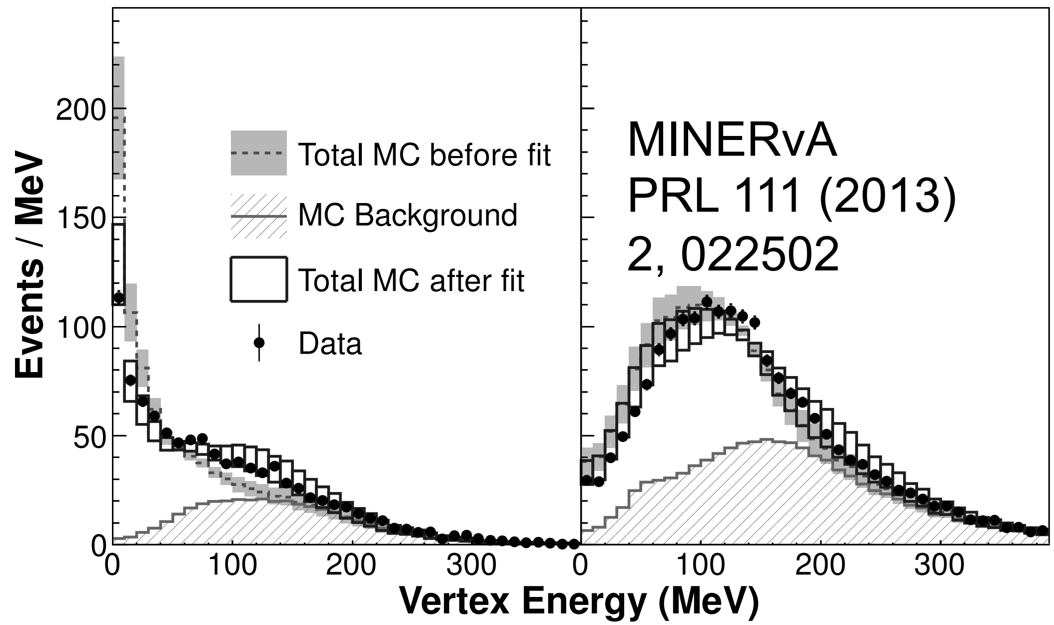
- Peak at 0.6 GeV, off-axis detectors are as close to monochromatic as we currently make. On-axis (and detectors, INGRID) at ~1-2 GeV energy.
- Upcoming analyses looking at muon, muon+proton, both with no pion and no kinematic cuts for comparison to new QE, MEC models
- Taking data with predominantly antineutrino beam

T2K direct 2p2h probes?

Challenges to ``direct'' measurement of multinucleon (2p2h) interactions:

- Minimal theoretical insight to final state kinematics, multiplicity of protons
- Models are also limited to certain ranges of validity
- 2p2h "hides" under the flux peak, where nuclear effects also modify CCQE

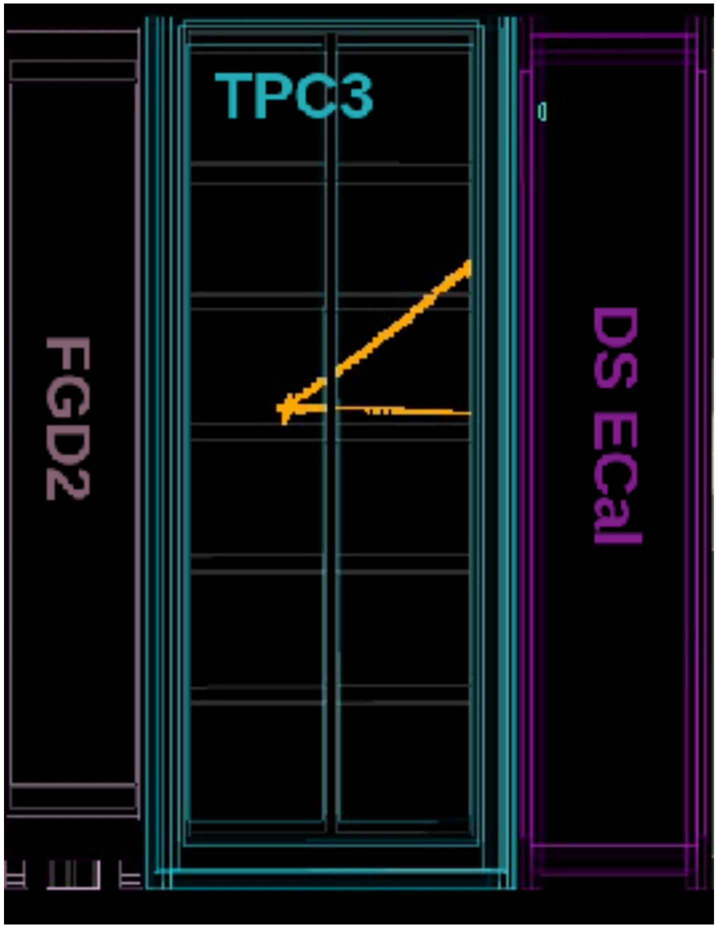


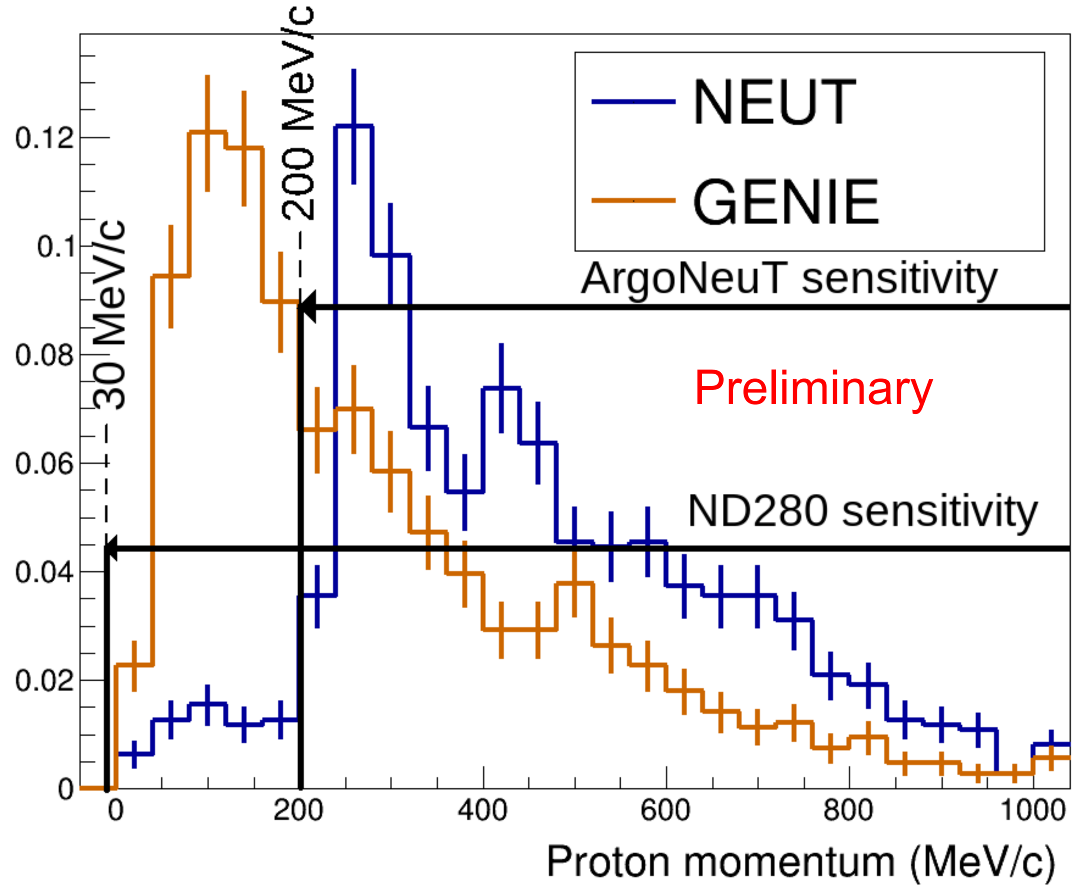


Approach:

- Follow ArgoNEUT, MINERvA, report proton multiplicity, proton and proton-muon kinematics
- Iterate with CC1π measurements and model development for backgrounds

T2K as a cross section experiment





Gaseous TPCs (3 in total) are predominantly Ar gas:

- Proton threshold is lower than LAr
- New reconstruction, search underway for such events

Summary

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Future long baseline programs require tight control of systematics (~1%) on few GeV neutrino beams

- T2K currently has <10% uncertainties, thanks to a enormous work of the flux prediction, near detector data, and updates to cross section model
- Near detectors are enormously helpful, however, near detector measures unoscillated flux. Predicting oscillated flux relies on the cross section model

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

- Data sets with multiple beam energies (T2K, MINERvA, NOvA, MiniBooNE on C, ArgoNEUT, CAPTAIN-MINERvA, MicroBooNE on Ar) are important to break the degeneracies of 1p1h, 2p2h and resonance contributions
- An alternate approach is the nuPRISM ``mono-energetic'' beam.

Personal thoughts on next steps

Electron scattering data (Data Mining collaboration) can help:

- Alternate probe to validate in-medium and final state effects in generators, like GENIE

Theory can help:

- Where is there consensus on a particular theoretical approach? What are the differences? (Marco Martini, INT 2013)
- What are uncertainties in each model? (theory or data driven) M. Valverde, J.E. Amaro, J. Nieves, PLB638 (2006) 325-332
- What about harder to measure sources of uncertainty like ν_e/ν_μ and NC1γ?

Experiment can help:

- Steve Dytman: apply similar selections on MINERvA to mimic MiniBooNE 1π, and vice versa

Thank you for your attention. Thank you for the invitation!

Backup slides