T2K: oscillations, cross section physics and you

Kendall Mahn
Michigan State University

I’m a former Fermilab-based student on SciBooNE, MiniBooNE and now a proud member of T2K

I used to be like (I hope) many of the people listening today. Let’s talk about some physics and how it connects to what you work on now!

Open questions about neutrino mixing

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Flavor eigenstates (coupling to the W)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates (definite mass)

Unitary PMNS mixing matrix

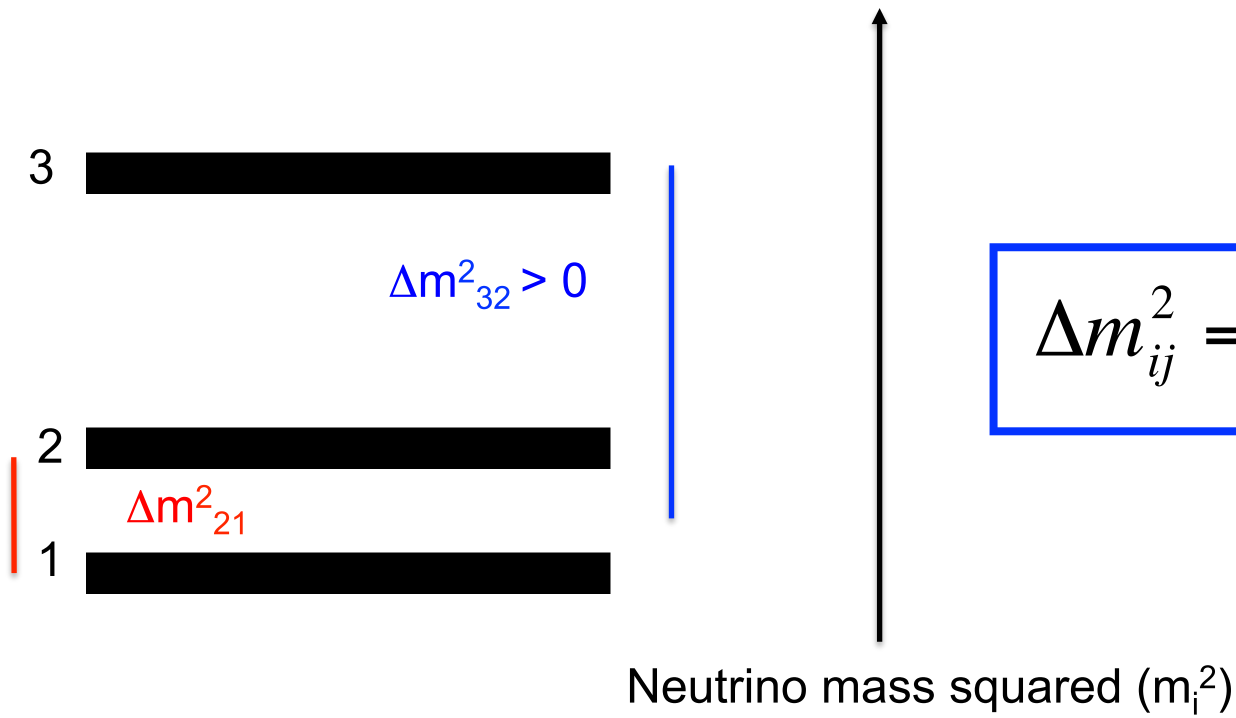
Three observed flavors of neutrinos (ν_e, ν_μ , ν_τ) means U is represented by three independent mixing angles (θ_{12}, θ_{23}, θ_{13}) and a CP violating phase δ

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\|\Delta m^2\|$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ ($2.19 - 2.56$)
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ ($1.31^{+0.29}_{-0.33}$)	$(0.00 - 0.16) \oplus (0.86 - 2.00)$ $((0.00 - 0.02) \oplus (0.70 - 2.00))$

Is θ_{23} mixing maximal (45°?)

Is there CP violation (non-zero δ?)

Open questions about neutrino mixing



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

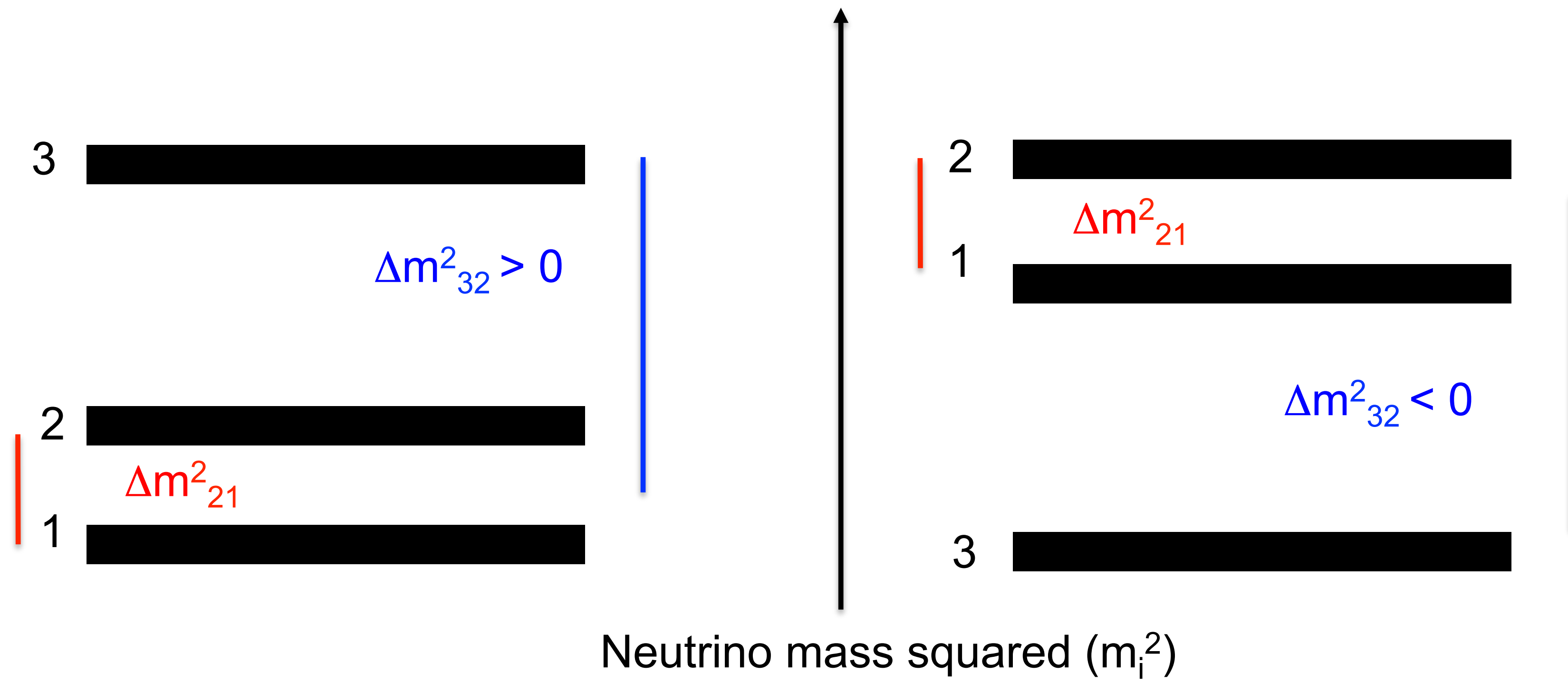
Three neutrino mass eigenstates mean two independent mass differences

Is our understanding of neutrinos complete with three flavors?

Two observed mass “splittings”, determined from atmospheric/accelerator and solar/reactor neutrino experiments, respectively

- Δm^2(atmospheric) = $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2
- Δm^2(solar) = $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2

Open questions about neutrino mixing



The sign of Δm^2_{32}, or the "mass hierarchy" is still unknown

- Normal "hierarchy" is like quarks (m_1 is lightest, $\Delta m^2_{32} > 0$)
- Inverted hierarchy has m_3 lightest ($\Delta m^2_{32} < 0$)

What is the mass hierarchy?

Oscillation probabilities

$\Delta m^2_{32} >> \Delta m^2_{21}$, producing high frequency and low frequency oscillation terms

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin^2\left(\frac{1.27\Delta m^2_{ij} L}{E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin\left(\frac{2.54\Delta m^2_{ij} L}{E}\right)$$

If choose L, E, such that $\sin^2(\Delta m^2_{32} L/E)$ is of order 1, then Δm^2_{21} terms will be small. Then...

ν_μ "disappear" into ν_e, ν_τ

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

A small amount of ν_e will "appear"

$\Delta m^2_{31} \sim \Delta m^2_{32}$

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right)$$

Only leading order terms shown

Oscillation probabilities

$\Delta m^2_{32} >> \Delta m^2_{21}$, producing high frequency and low frequency oscillation terms

$P_{\alpha\beta} =$ … $\left(\frac{1.27\Delta m^2 L}{}\right)$ … $\left(\frac{2.54\Delta m^2 L}{}\right)$

If ch…

will b…

ν_μ '…

Subleading terms of ν_μ disappearance allow for a determination of $\sin^2\theta_{23}$

Subleading terms of ν_μ to ν_e appearance depend on δ_{CP}, mass hierarchy, but interpretation requires precision measurements of:
Δm^2_{32}, θ_{23} , Δm^2_{21}, θ_{12} and θ_{13}

Measurements of ν_μ to ν_e appearance are sensitive to new or exotic physics

A small amount of ν_e will "appear"

$\Delta m^2_{31} \sim \Delta m^2_{32}$

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right)$$

Only leading order terms shown

Long-baseline experiments

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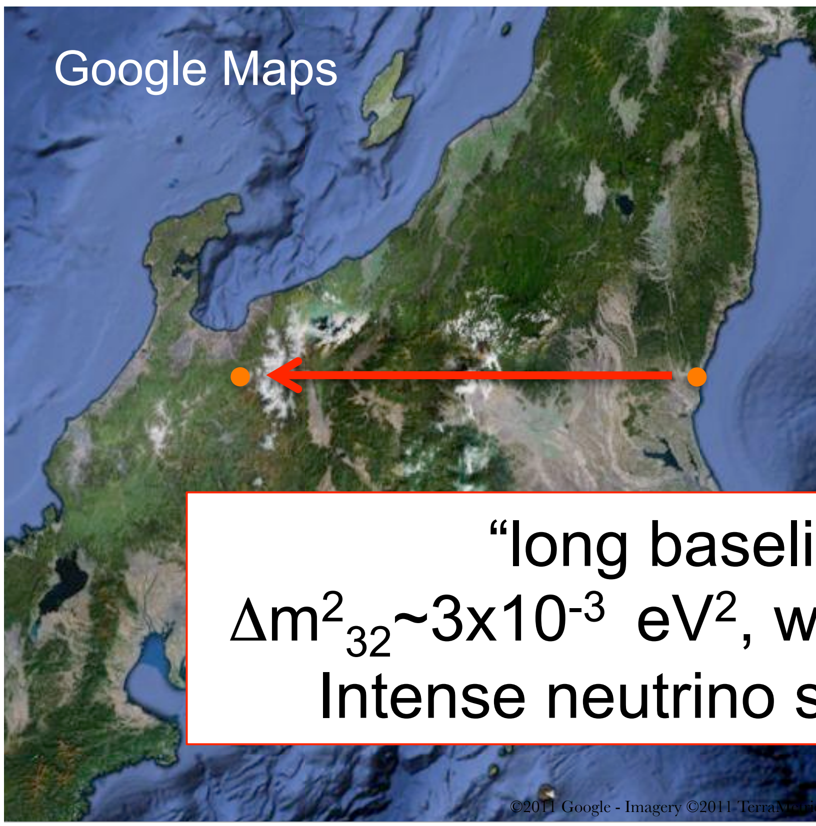
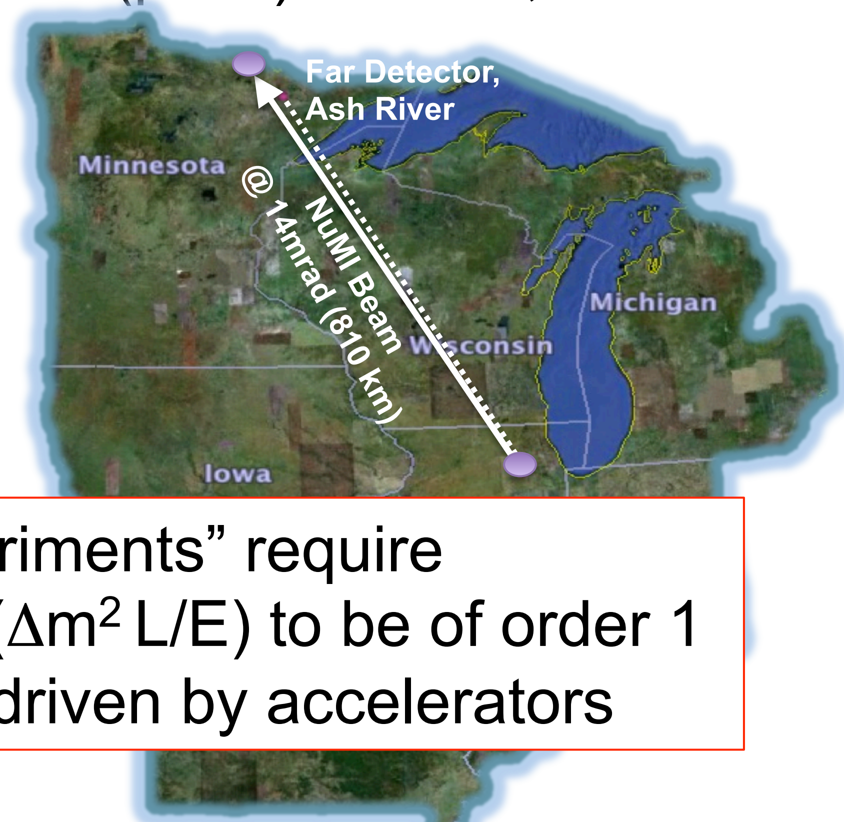
The oscillation probability, P, for ν_μ to oscillate is sinusoidal and depends on the distance L (km) the neutrinos travel and their energy E (GeV):

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

Tokai To Kamioka (T2K) experiment:
$E\nu$(peak) ~0.6GeV, L=295km

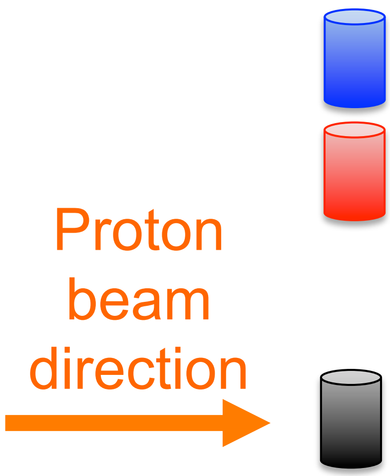


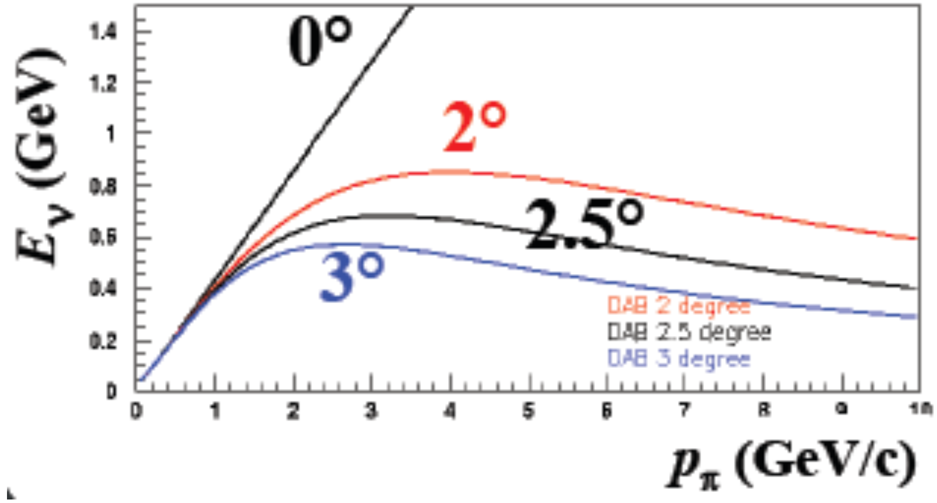
NOvA experiment:
$E\nu$(peak) ~2 GeV, L=810km

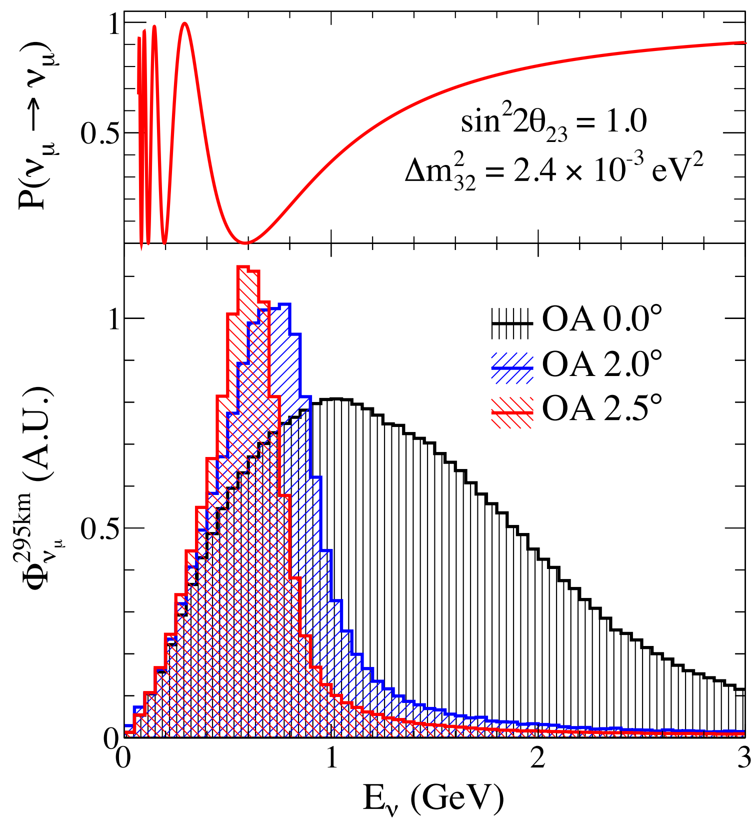


"long baseline experiments" require
Δm^2_{32}~3x10^{-3} eV^2, want $\sin^2(\Delta m^2 L/E)$ to be of order 1
Intense neutrino sources driven by accelerators

Accelerator-based neutrino sources







PRD 88, 032002 (2013)

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

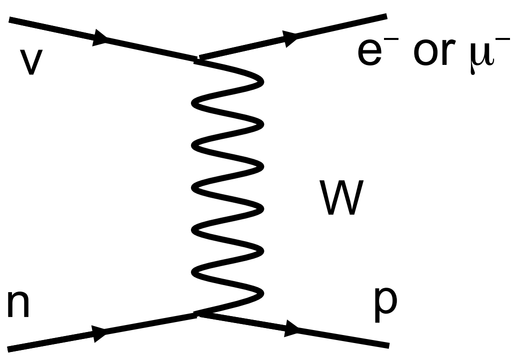
T2K oscillation analyses

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)\left[\sin^2 2\theta_{23} + \ldots\right]$$

Oscillation probability depends on neutrino energy

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

CCQE

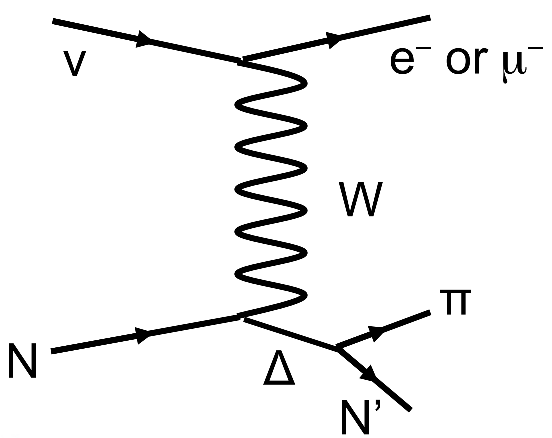


Infer neutrino properties from the lepton momentum and angle:

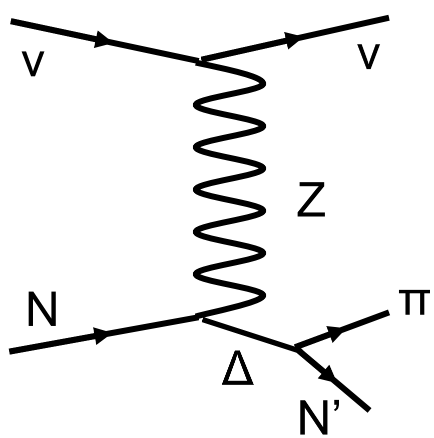
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CCπ



NCπ



Background processes are:

- Charged current single pion production (CCπ)
- Neutral current single pion production (NCπ)

T2K oscillation analyses

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

Oscillation probability depends on neutrino energy

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

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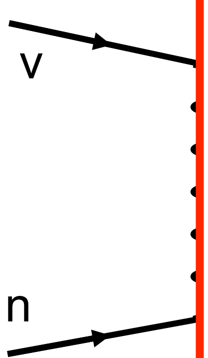


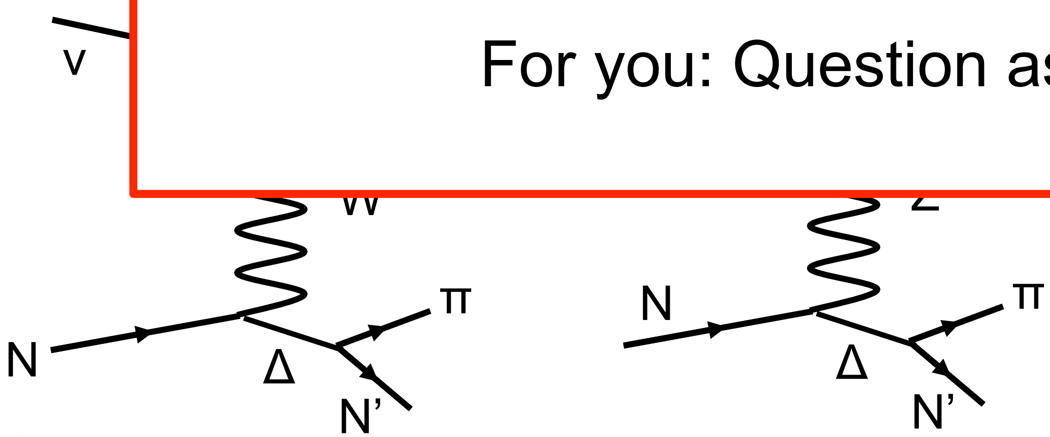
This (and our MC, and probably your MC) assumes we know the relationship between the lepton kinematics and the neutrino energy.

More on that later…

For you: Question assumptions

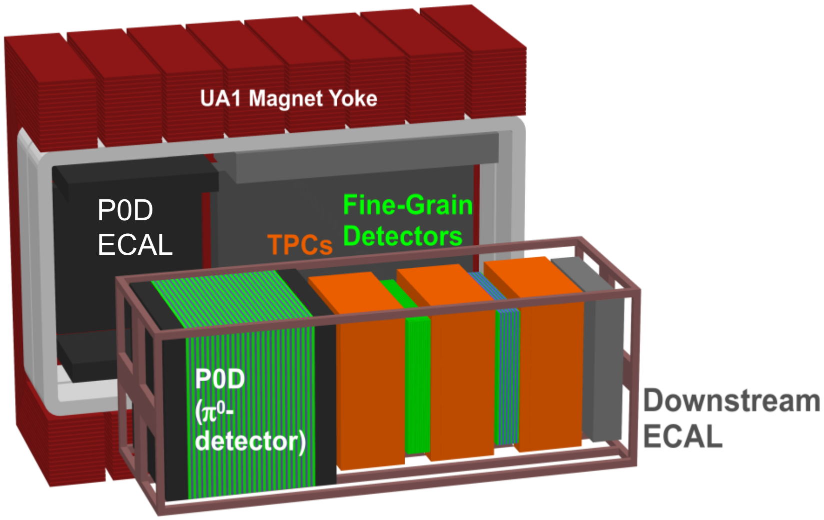
are:

e pion



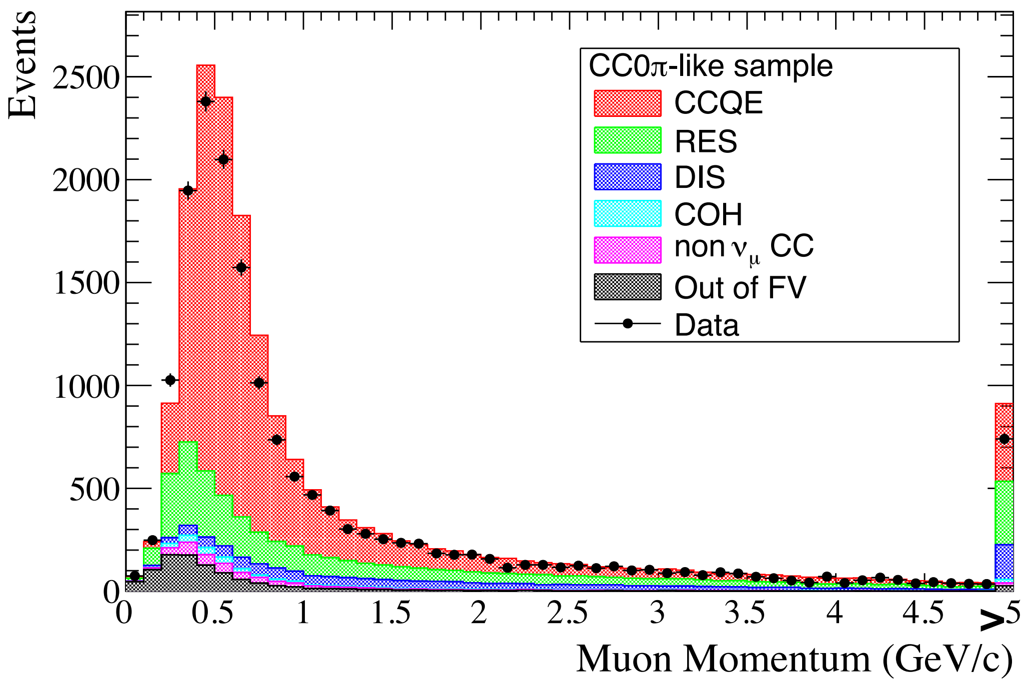
- Neutral current single pion production (NCπ)

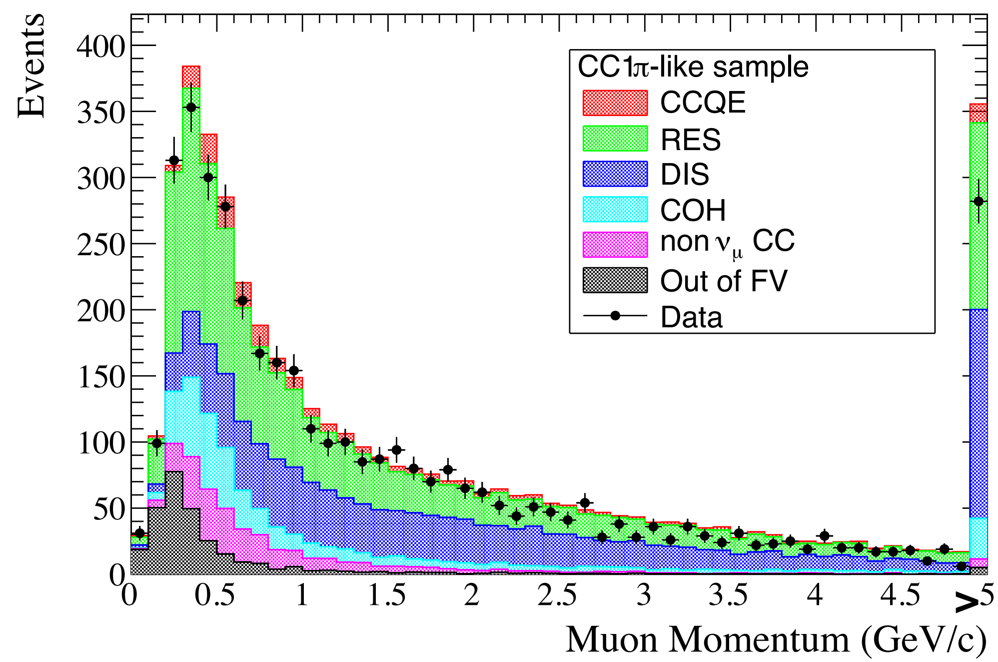
T2K near detectors



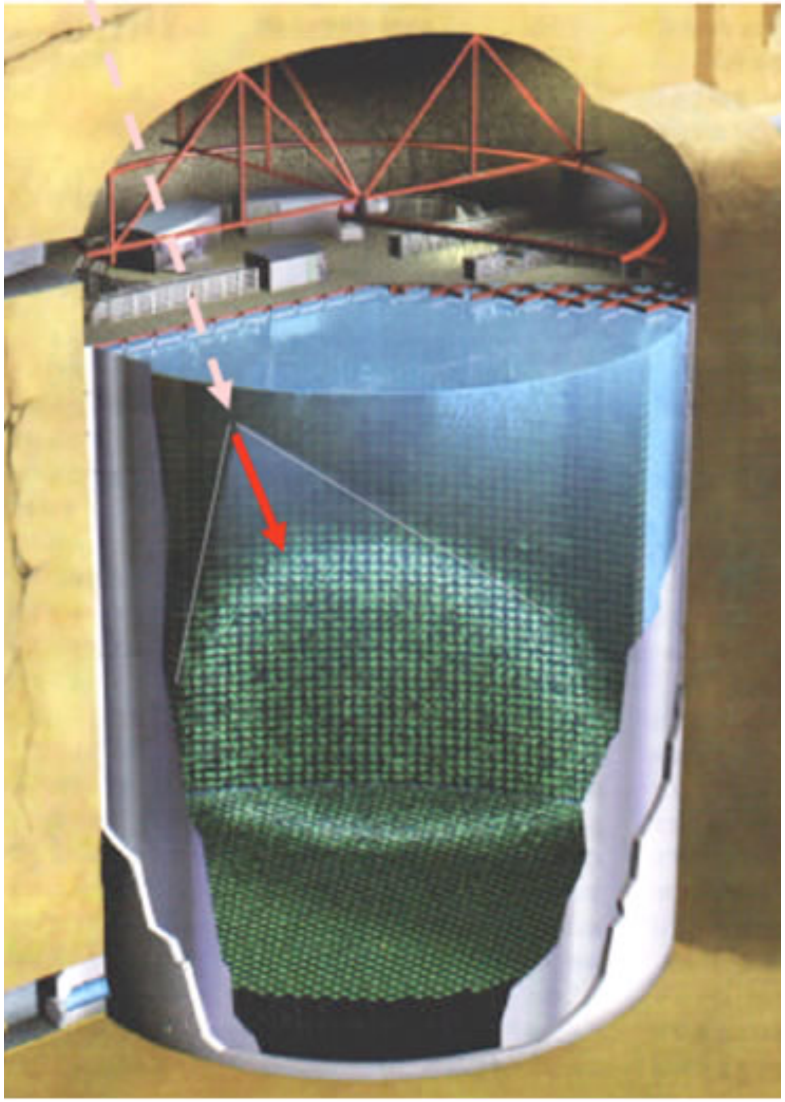
Select CC ν_μ candidates prior to oscillations in an off-axis tracking detector (ND280)

- 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





T2K far detector



Select CC ν_e and ν_μ candidates after oscillations, in a 50kton water Cherenkov detector (Super-Kamiokande)

- Select single ring; determine lepton flavor from ring shape and topology
- Reject CC nonQE interactions using ring multiplicity and decay electron tagging
- For the ν_e selection, NC events with π^0 removed based on invariant mass

After ND280 tuning (next slide), expect 21.6 events with expected ν_μ to ν_e oscillation

- Rate, p-θ kinematics of events distinguishes signal from background
- Background 4.92 events (predominantly intrinsic beam ν_e

T2K far detector

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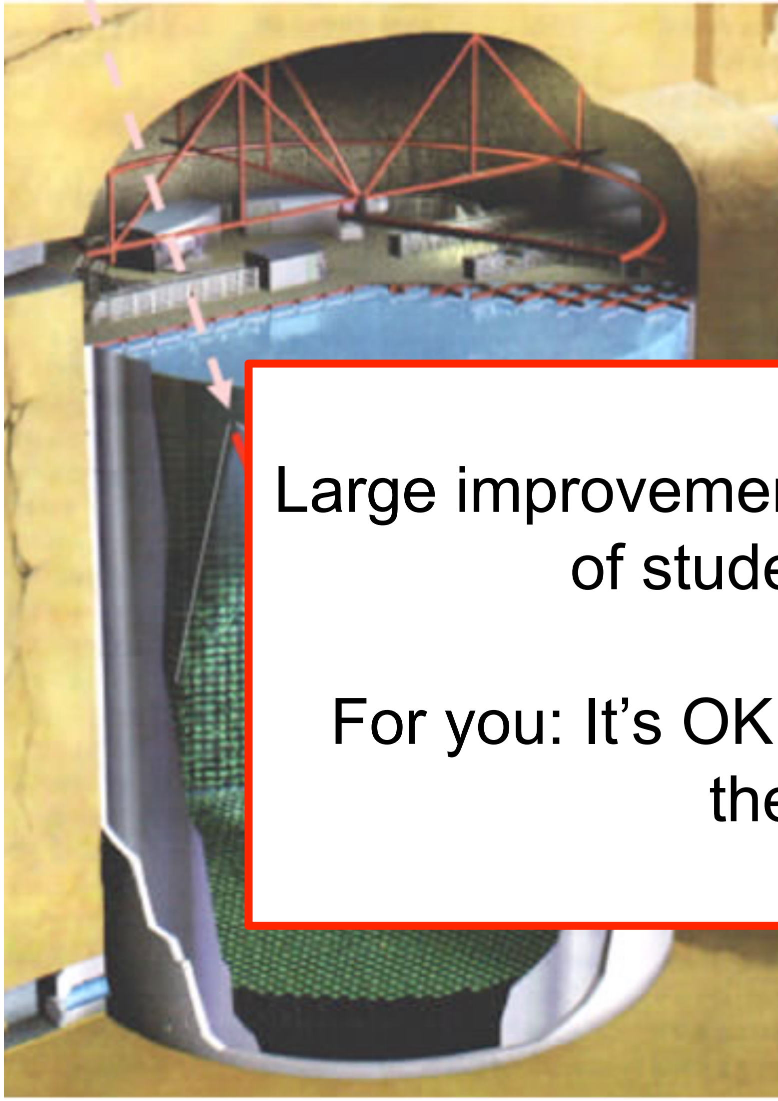

Select CC ν_e and ν_μ candidates after oscillations, in a 50kton water Cherenkov detector (Super-Kamiokande)

- Select single ring; determine lepton flavor from ring shape and topology
- Reject CC nonQE interactions using ring

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Large improvement in π^0 rejection from the hard work of students and postdocs on T2K

For you: It's OK to try something new, especially if there are large payoffs!

distinguishes signal from background

- Background 4.92 events (predominantly intrinsic beam ν_e

Use of near detectors on T2K

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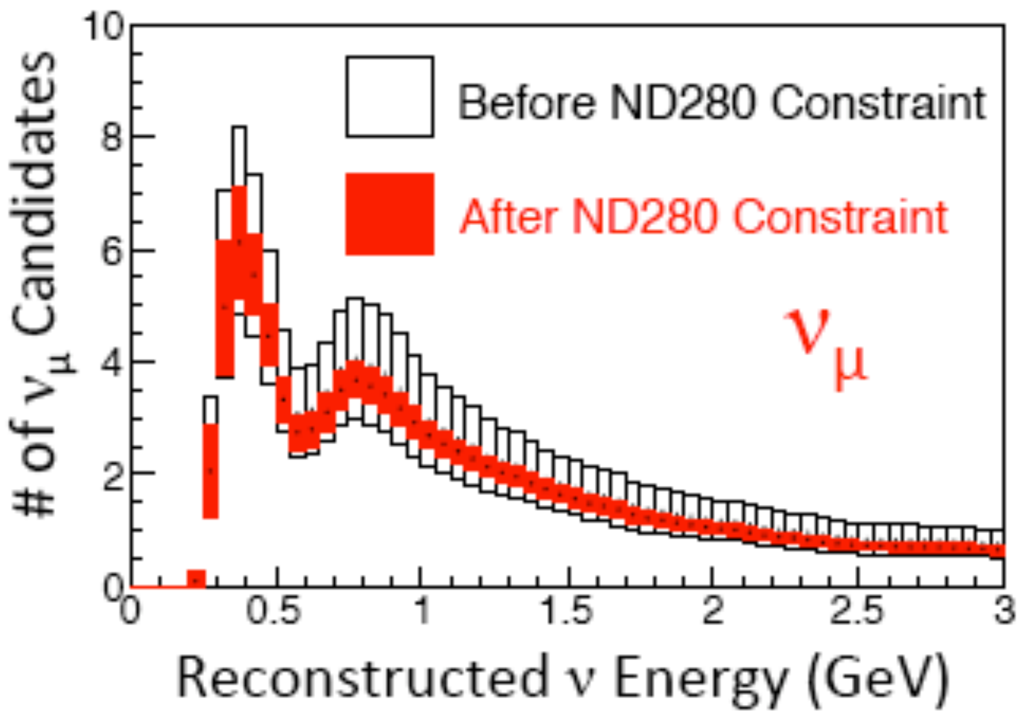
Expected number of events at the far detector is tuned based on near detector information. Near detector also provides a substantial constraint on the uncertainties of ν_e and ν_μ events:

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

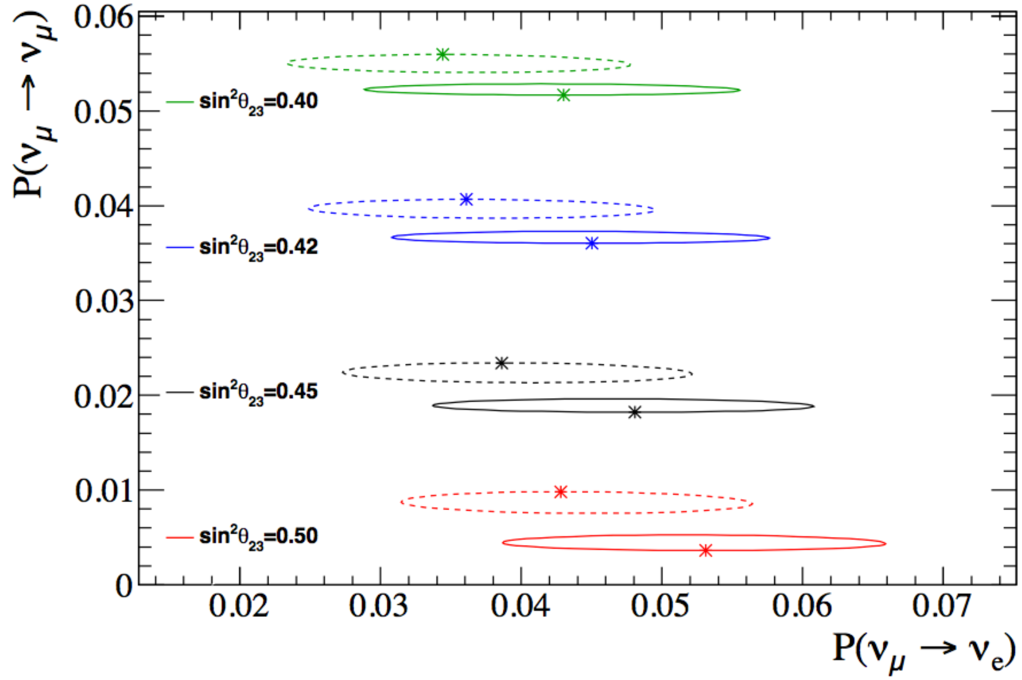
uncertainties	ν_μ disap.	ν_e app
ν flux+xsec (before) after ND constraint	(21.7%) ±2.7%	(26.0%) ±3.2%
ν unconstrained xsec	±5.0%	±4.7%
Far detector	±4.0%	±2.7%
Total	(23.5%) ±7.7%	(26.8%) ±6.8%

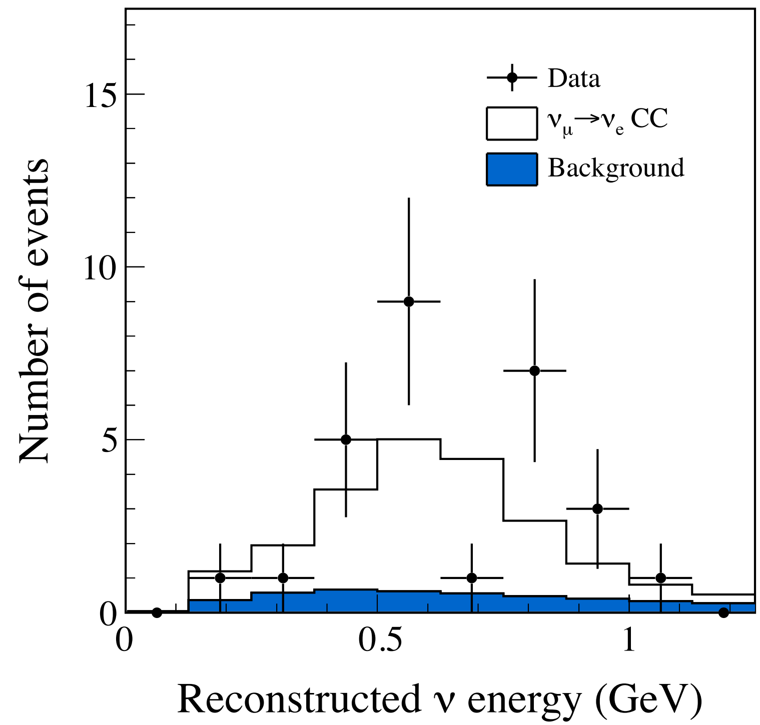


After ND: expect 21.06 ν_e candidates (background only: 4.97)

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

T2K results: appearance





T2K collab, arxiv:1502.01550v1,
PRD 91, 072010 (2015)

First observation of CC ν_e appearance with 28 candidate 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})

T2K results: disappearance

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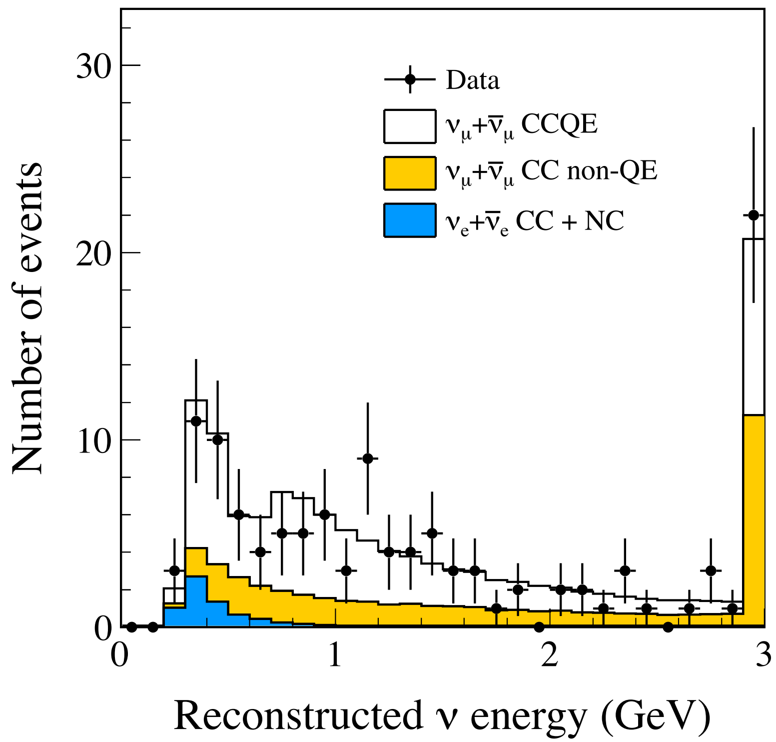
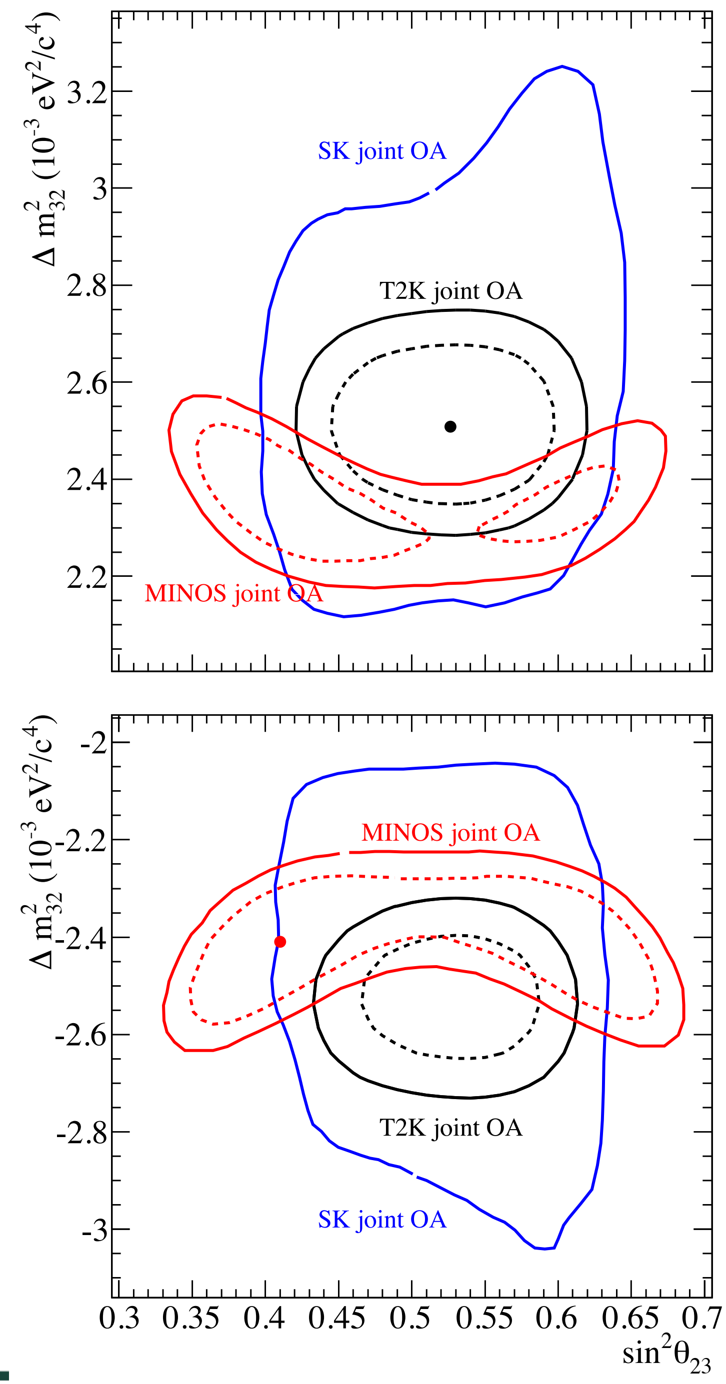


120 candidate ν_μ events observed

- Determine Δm^2_{32}, $\sin^2\theta_{23}$ from distortion to neutrino energy spectrum (PRL 112, 181801 (2014))

T2K data favors maximal disappearance

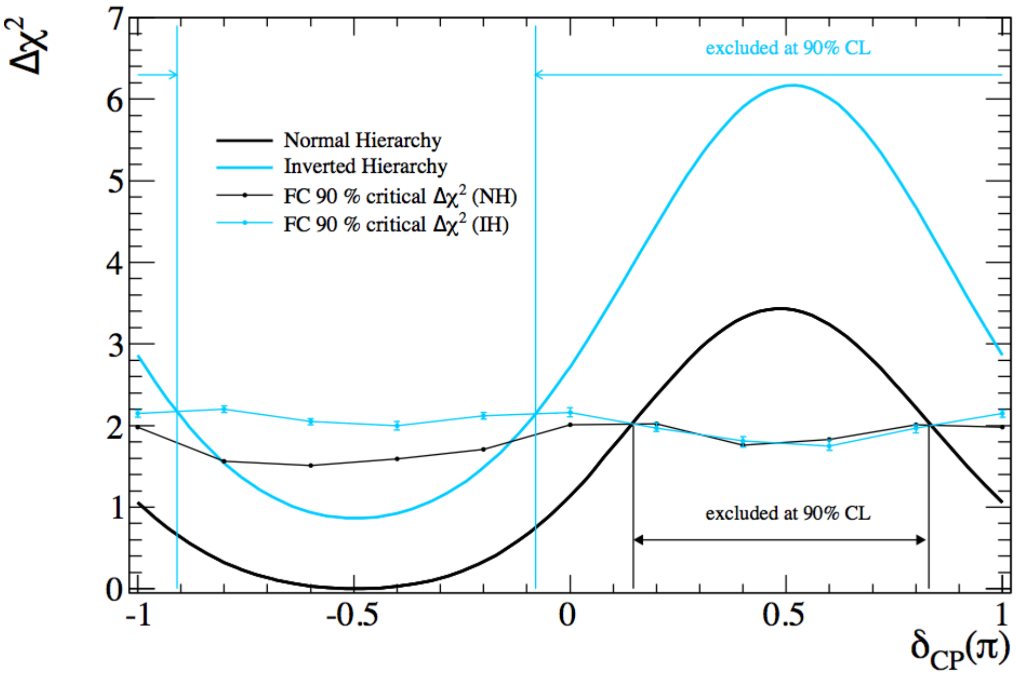
- Provides best constraint on θ_{23} to date, consistent with maximal (45°) mixing

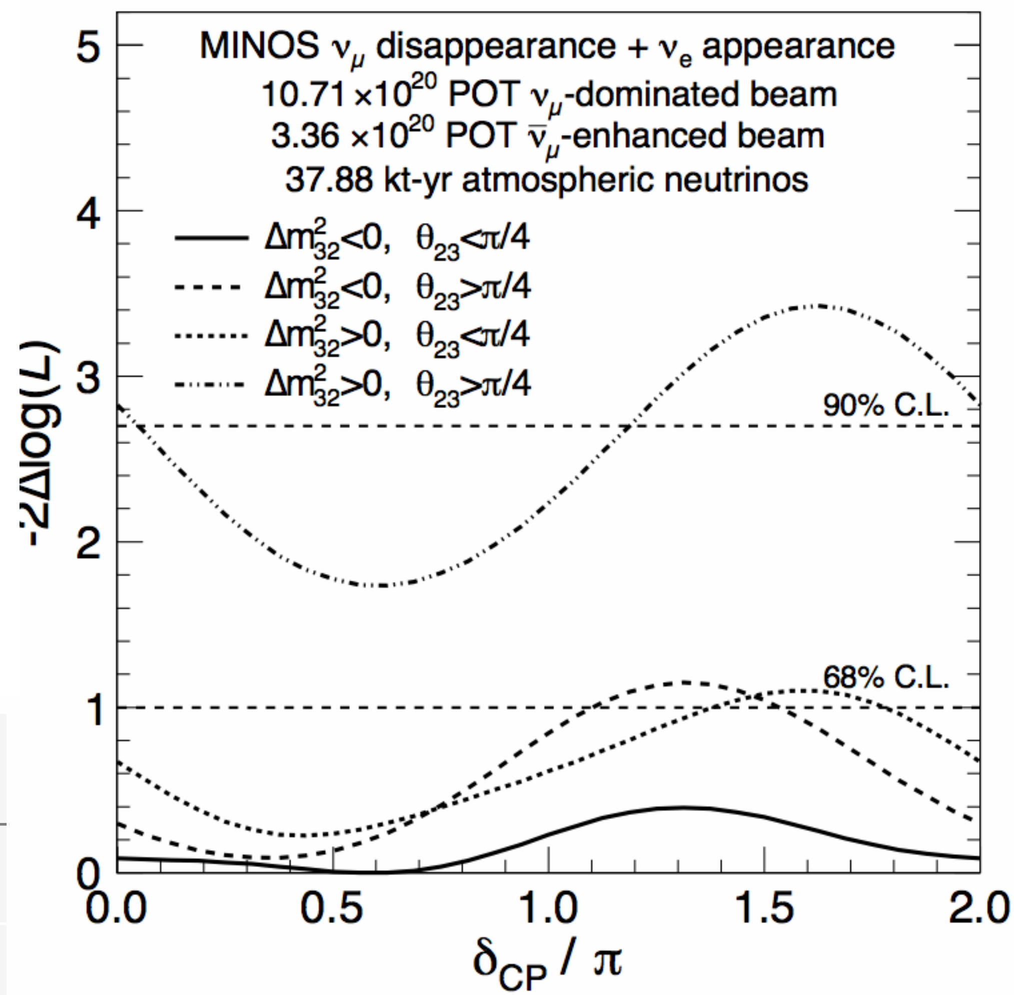


T2K collab, arxiv:1502.01550v1, submitted to PRD

What do we know about dCP?

- T2K favors δ_{CP} around –π/2 at 90%CL, disfavored by MINOS?
- But hierarchy is not determined due to entanglement with δ_{CP} and octant





Probability	$\Delta m^2_{32}>0$	$\Delta m^2_{32}<0$	Sum
$\sin^2\theta_{23} \leq 0.5$	16.5%	20.0%	36.5%
$\sin^2\theta_{23} > 0.5$	2.88%	34.7%	63.5%
Sum	45.3%	54.7%	

T2K: arxiv:1502.01550v1, submitted to PRD

MINOS: PRL 112, 191801 (2014)

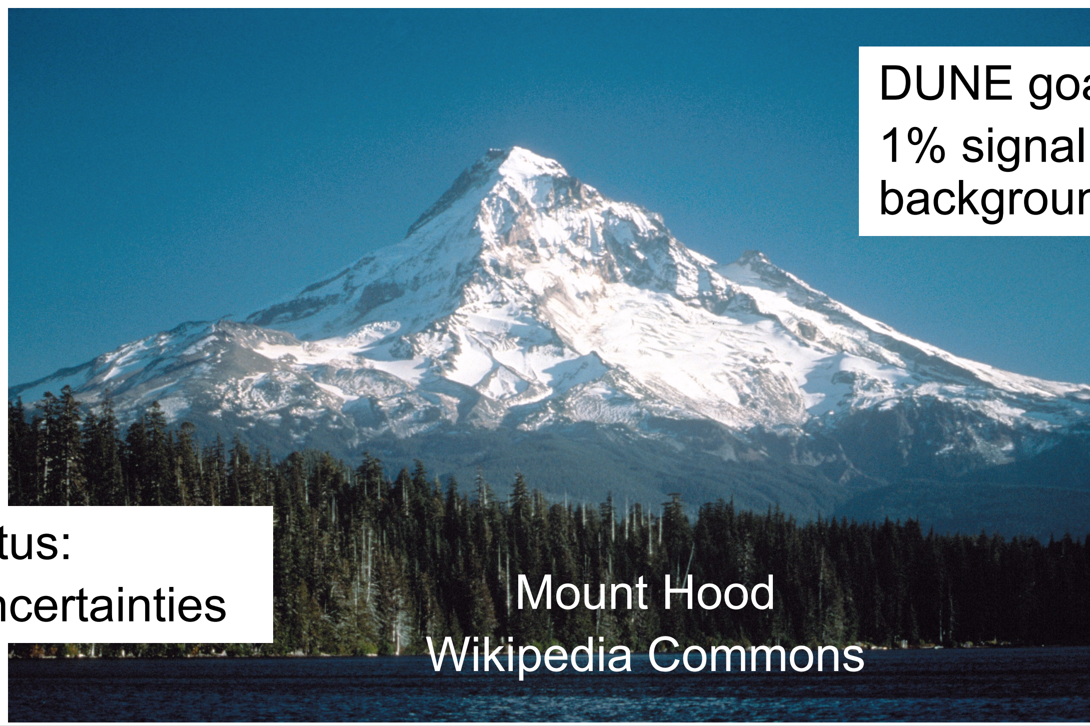
What do we need to measure dCP?

Compare ν_e appearance to $\overline{\nu}_e$ appearance to determine an asymmetry:

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

With θ_{13} "large", then A_{CP} is small (~20-30%), so a measurement of δ_{CP} will need systematic uncertainties of <5% or better

DUNE goal:
1% signal uncertainties / 5% background uncertainties



Mount Hood
Wikipedia Commons

T2K status:
6-8% uncertainties

What do we need to measure dCP?

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Compare ν_e appearance to $\bar{\nu}_e$ appearance to determine an asymmetry:

A_{CP} … $\sin\delta$

With (… ent
of δ_{CP}

Time to start climbing…

For you: DUNE is our experiment. What do we need to do to be prepared?

The rest of the talk is supporting material for the T2K antineutrino analysis (presented at KEK mid-May, t2k-experiment.org for more details)

Nice summaries of open questions:
G.T. Garvey et al., arXiv:1412.4294
L. Alvarez-Ruso et al., arXiv:1403.2673

T2K
6-8% uncertainties

Neutrino source: uncertainties

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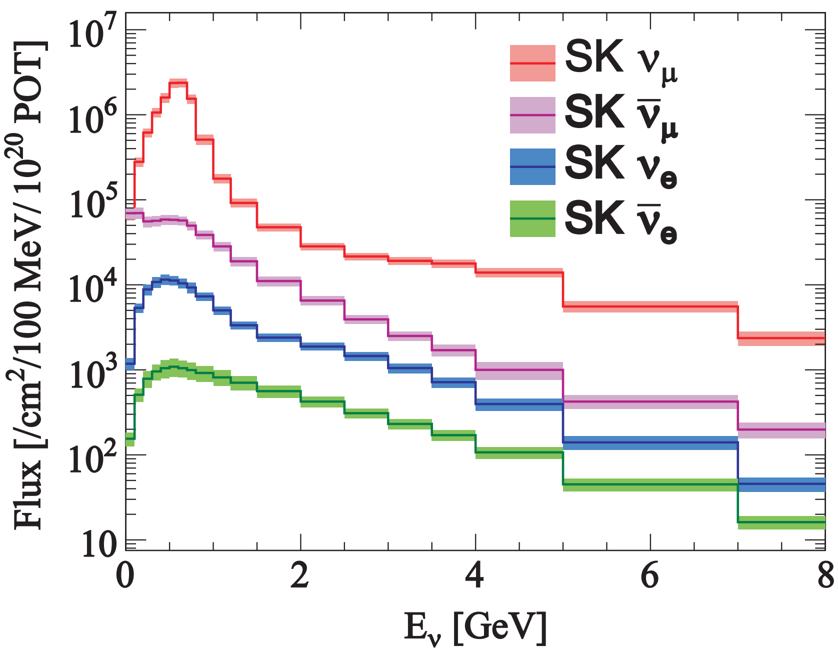
PRD 91, 072010 (2015)



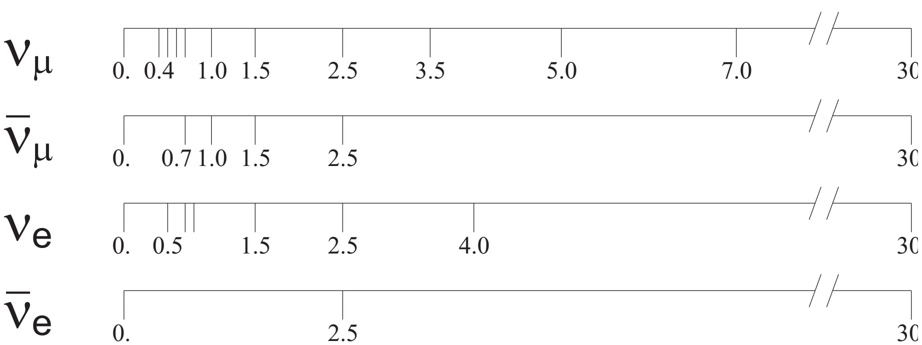


TABLE III. Contributions to the systematic uncertainties for the unoscillated ν_μ and ν_e flux prediction at SK, near the peak energy and without the use of near detector data. The values are shown for the ν_μ (ν_e) energy bin $0.6\ \text{GeV} < E_\nu < 0.7\ \text{GeV}$ ($0.5\ \text{GeV} < E_\nu < 0.7\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

Error source	Uncertainty in SK flux near peak (%) 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

FLUKA/Geant3 based simulation (PRD 87, 012001 (2013))

Uncertainties on the flux prediction are constrained by data:

- in-situ (beam monitors, on-axis detectors) or external (e.g. NA61)

Neutrino source: uncertainties

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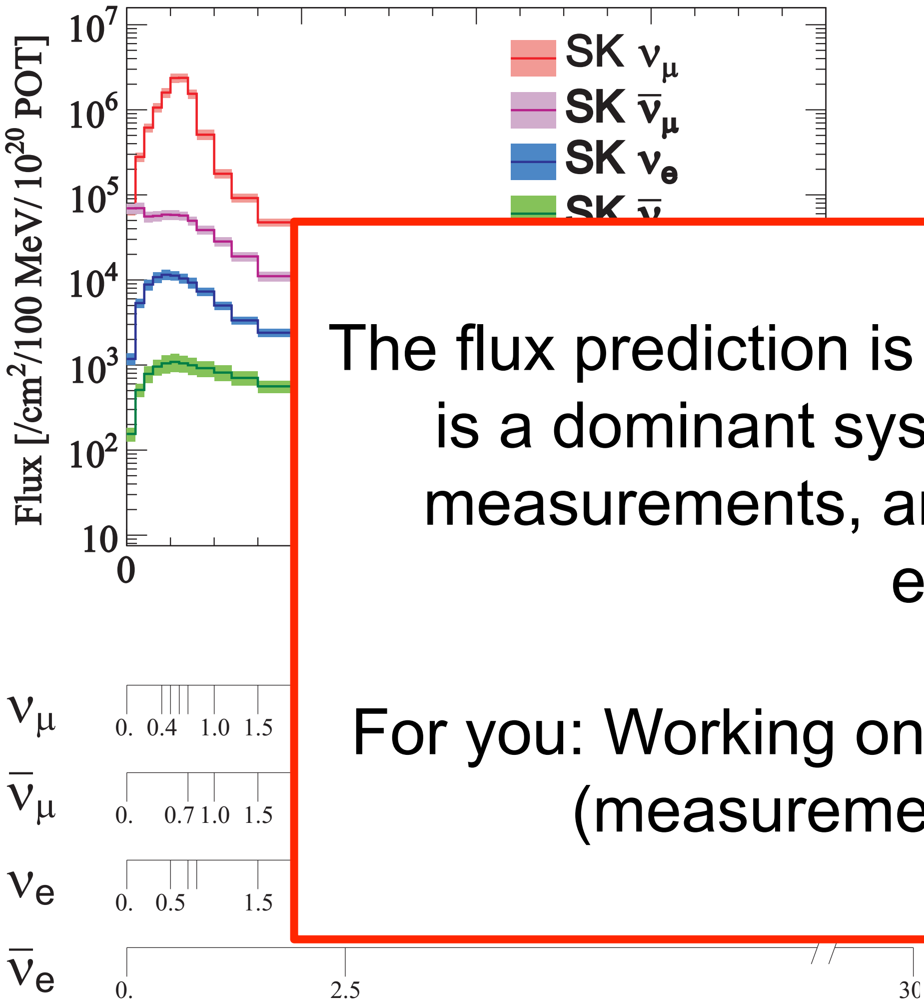
PRD 91, 072010 (2015)



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Hadronic interaction lengths	6.7	6.9
Total hadron production	11.1	11.7
Total	11.5	12.4

The flux prediction is the backbone of T2K physics– it is a dominant systematic of T2K cross section measurements, and essential in the near to far extrapolation.

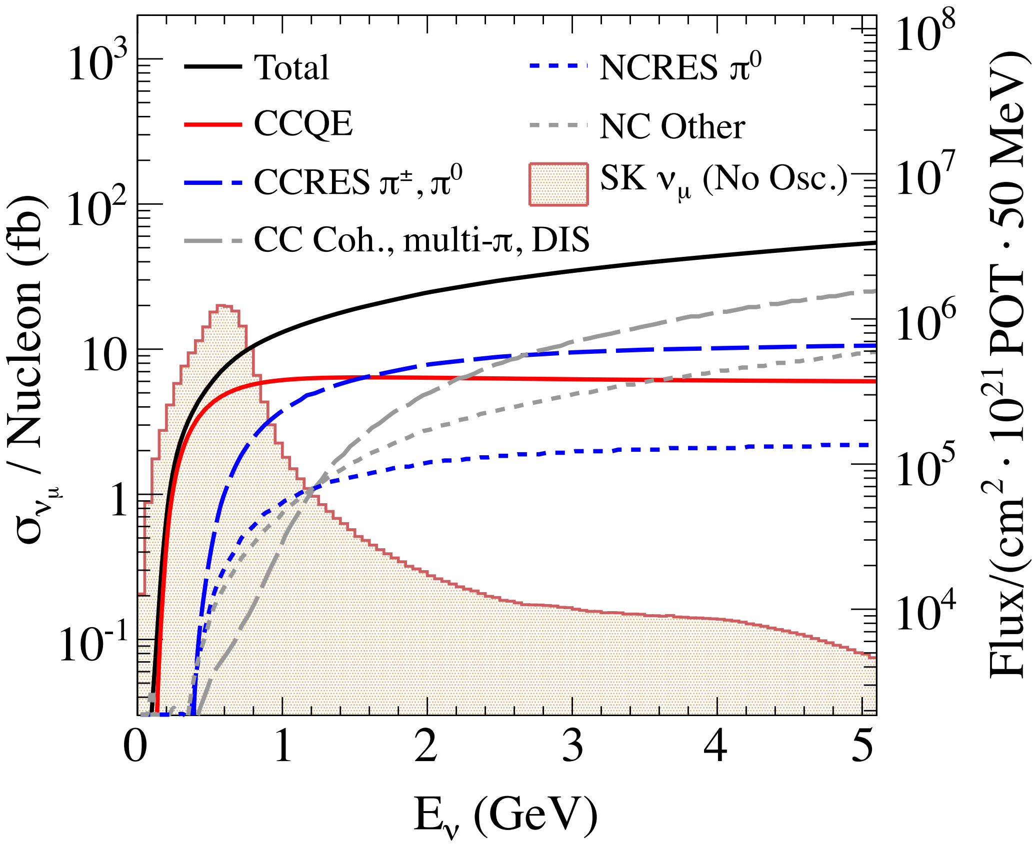
For you: Working on improving the flux prediction or (measurements for the flux) pays off

FLUKA/Geant3 based simulation (PRD 87, 012001 (2013))

Uncertainties on the flux prediction are constrained by data:

- in-situ (beam monitors, on-axis detectors) or external (e.g. NA61)

Neutrino interaction models on T2K



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
- 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.

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.)
- 1π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

E_ν (GeV)

Neutrino interaction models on T2K

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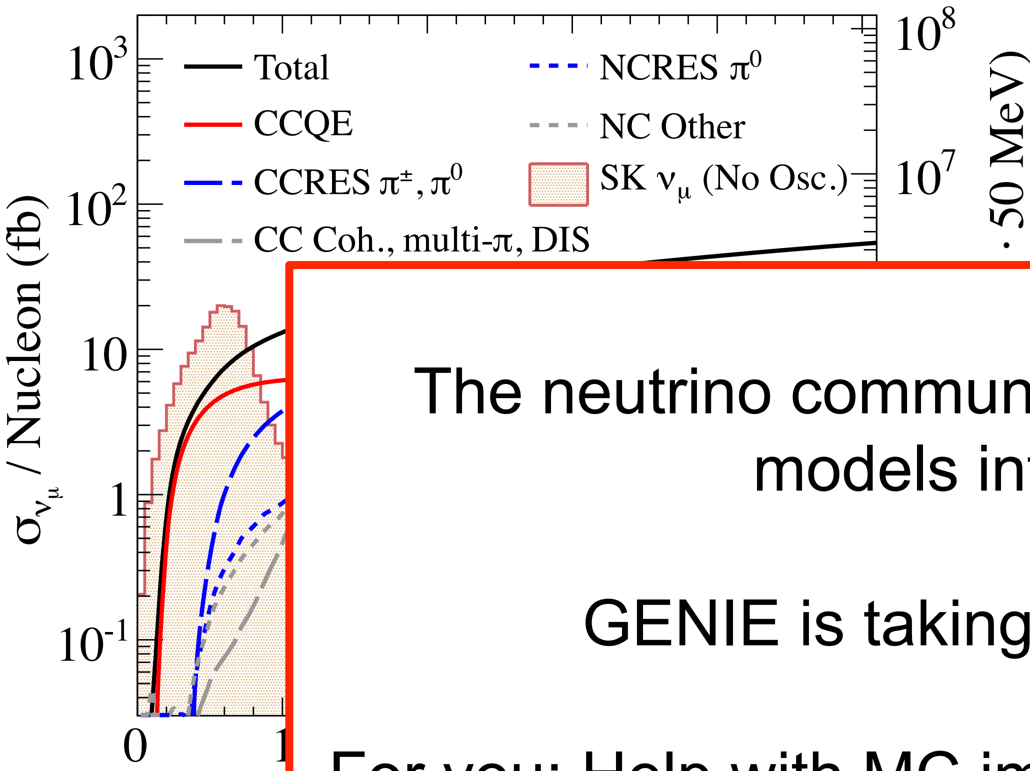

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The neutrino community is now adding modern models into generators

GENIE is taking a similar approach

For you: Help with MC improvements effort is crucial, to ensure that modern comparisons can be done to cross section measurements (MINERvA, MicroBooNE), and the effect studied for current oscillation experiments (T2K, NOvA)

NEUT m ... **lyses:**

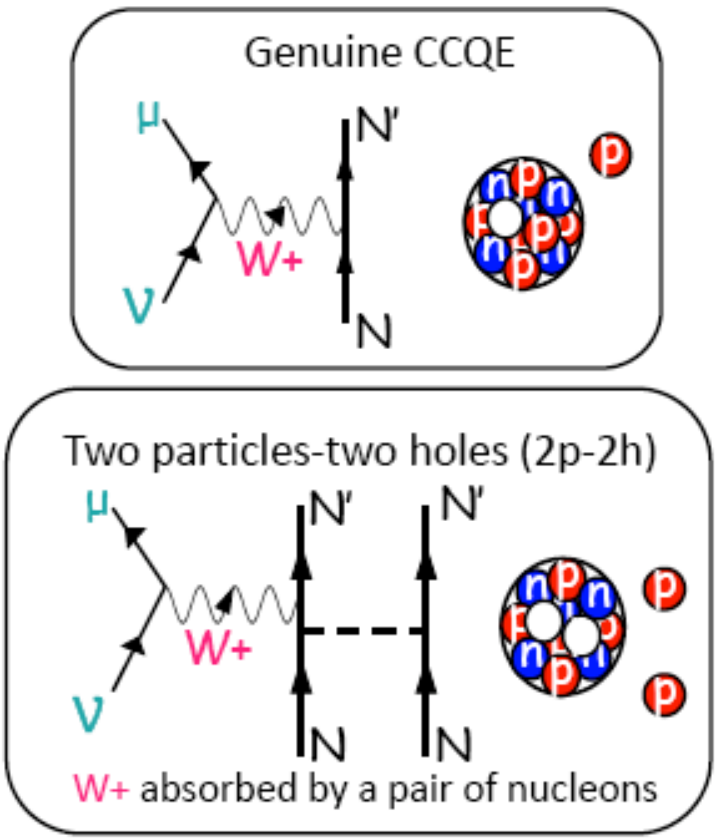
- CCQE ... GeV/c2.
  - R
- "Meso
- 1pi (N ... or for Delta. No pion-less delta decay.

E_ν (GeV)

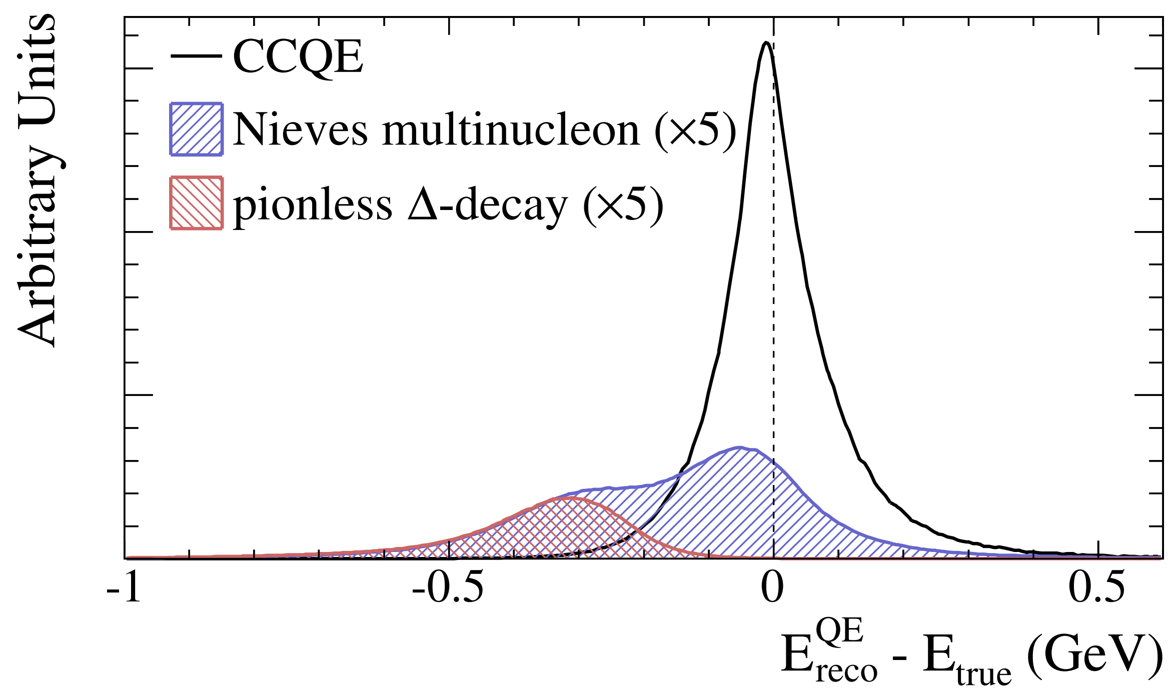
Why are new models important?

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)

Why does the cross section model matter?

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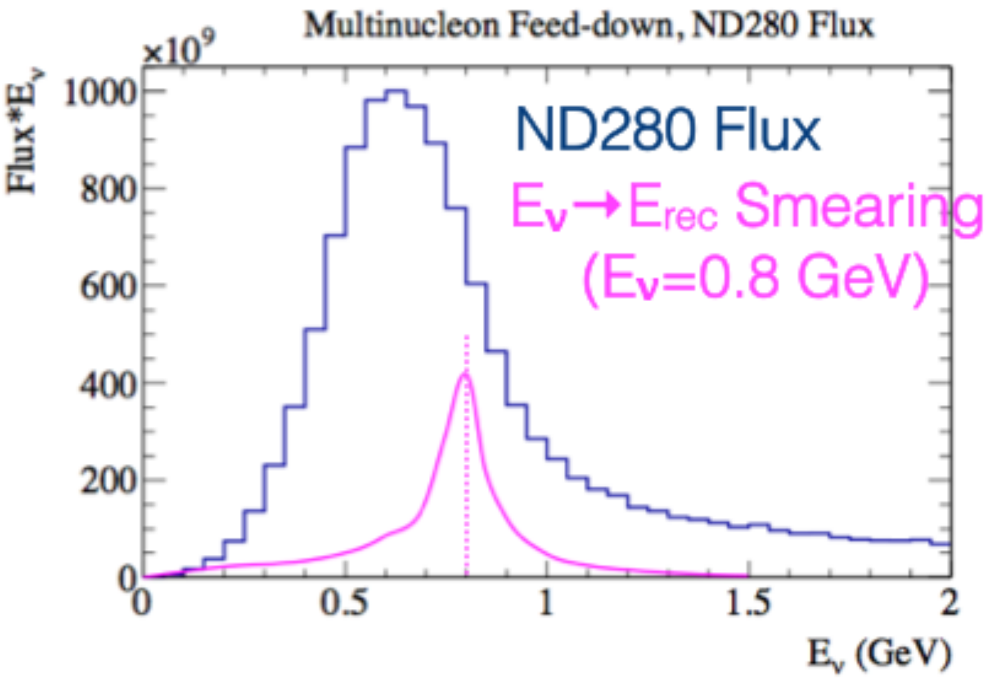
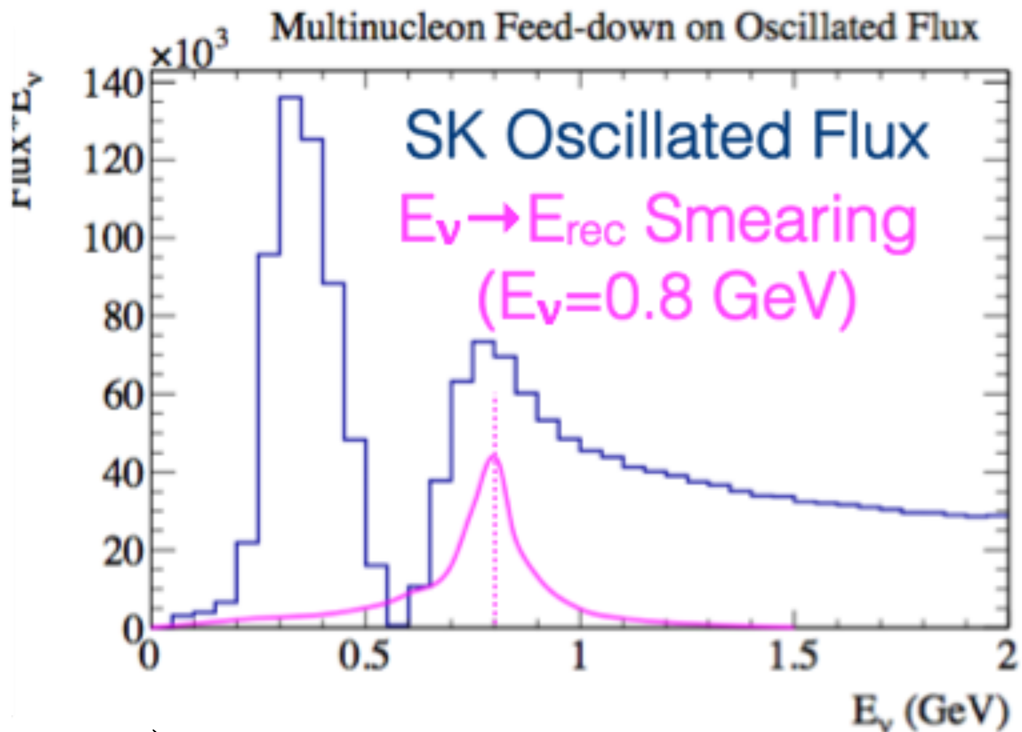
Cross section model couples through the different fluxes measured by ND and FD





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

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

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)

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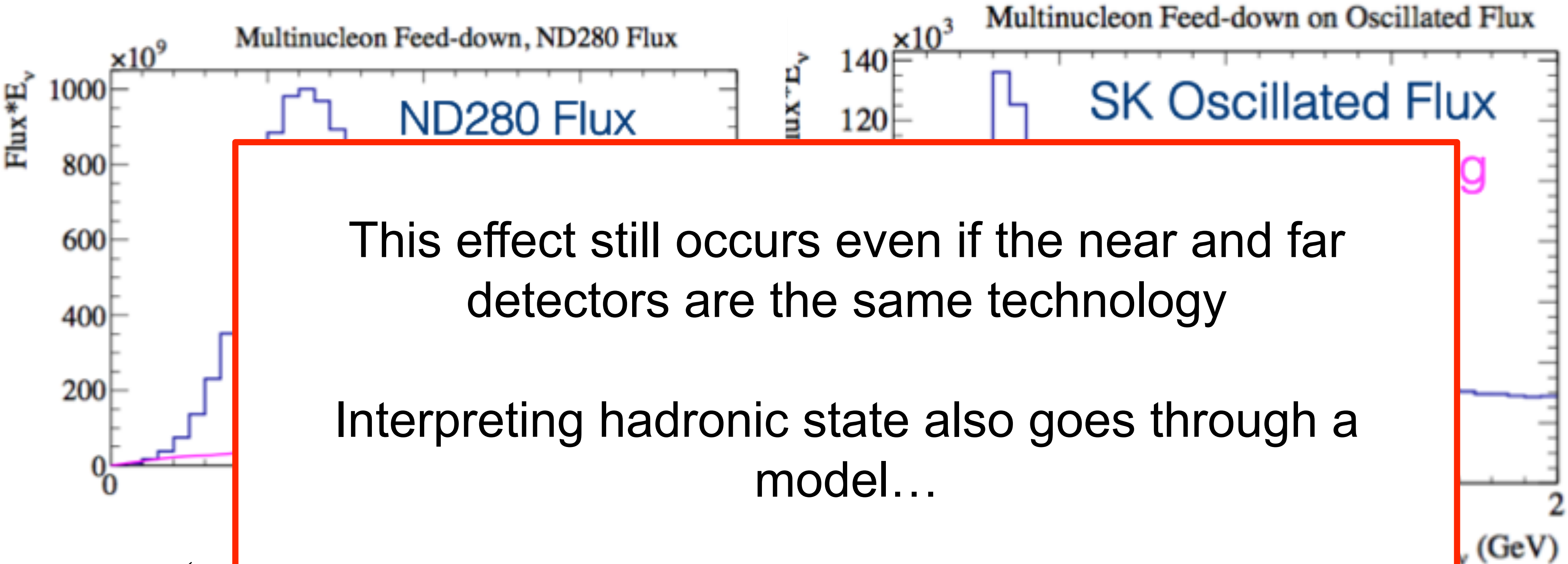

This effect still occurs even if the near and far detectors are the same technology

Interpreting hadronic state also goes through a model…

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

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

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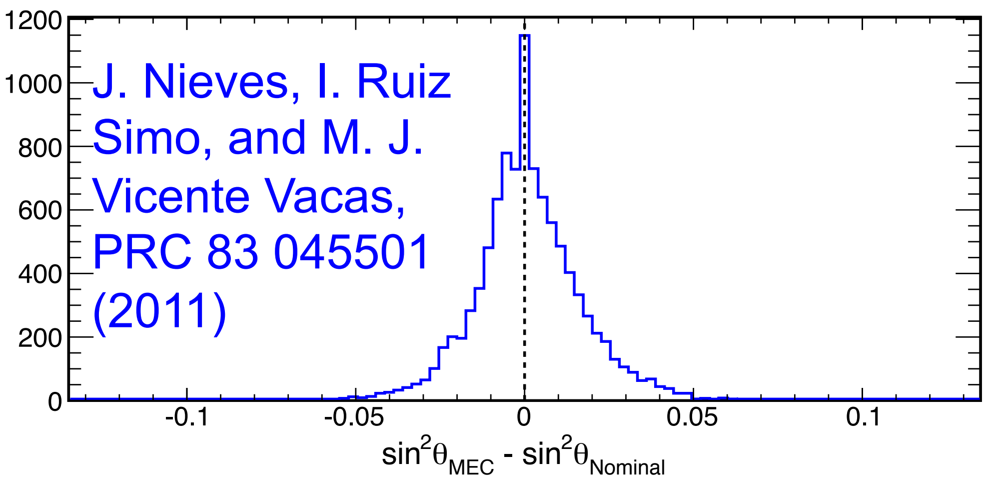
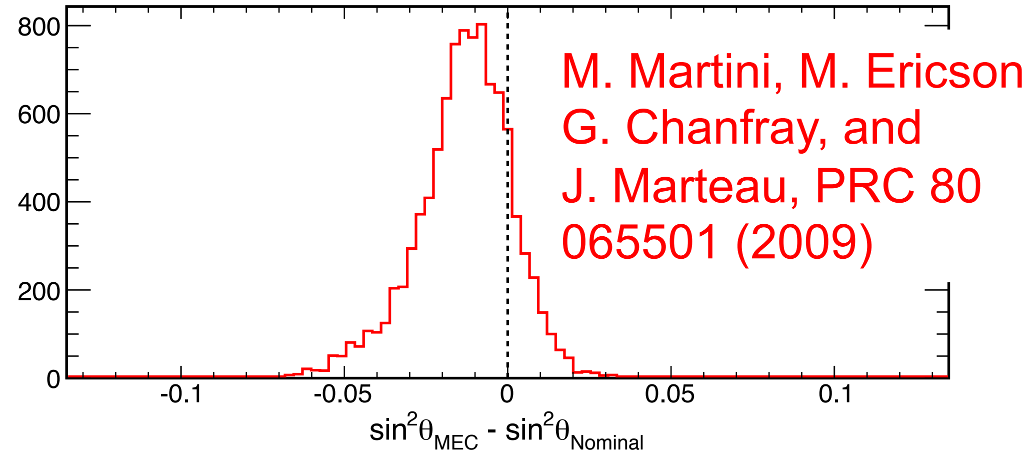
Multinucleon effect on T2K analysis





Tested possible bias on 2013/2014 T2K disappearance measurement

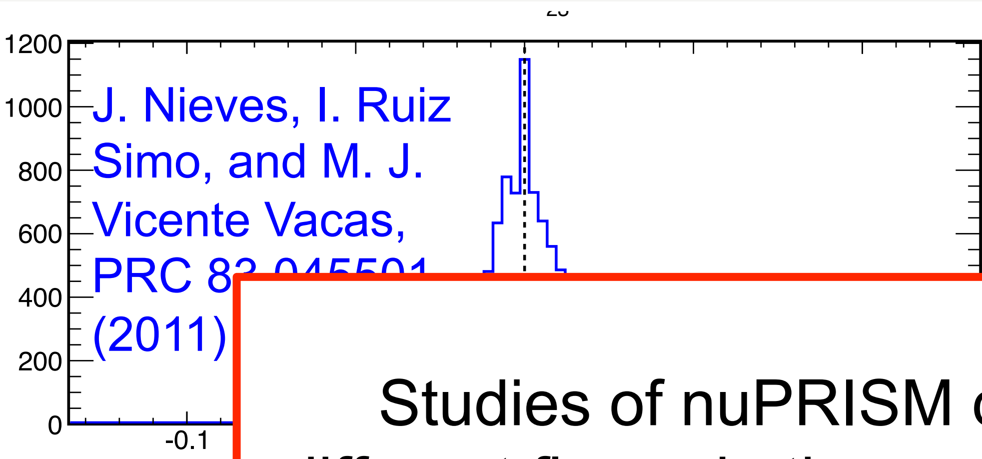
- Generate fake data under flux, detector, cross section variations, and perform full oscillation analysis including ND constraint
- For each fake data set, compare fitted θ_{23} with and without a 2p2h model present

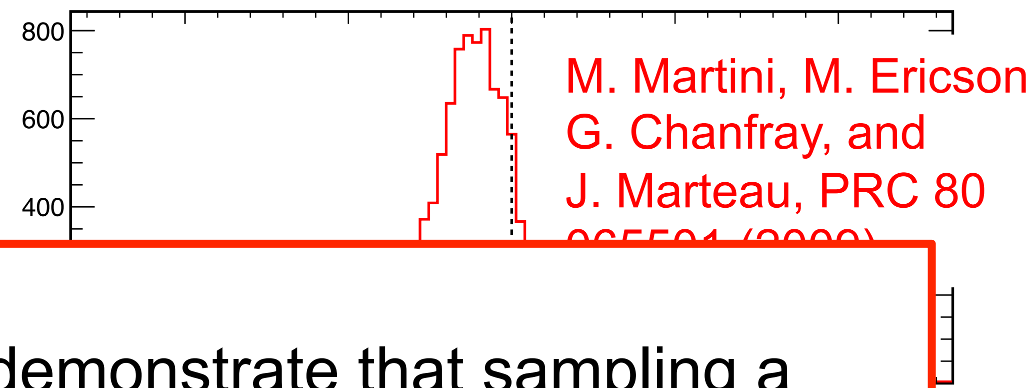
Nieves et al model: 0.3% mean, 3.2% RMS

“increased Nieves” = Martini model: -2.9% mean, 3.2% RMS

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

Multinucleon effect on T2K analysis





Tested pos

- Generat … ll
  oscillatic
- For eacl … nt

Nieves et a
“increased

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)

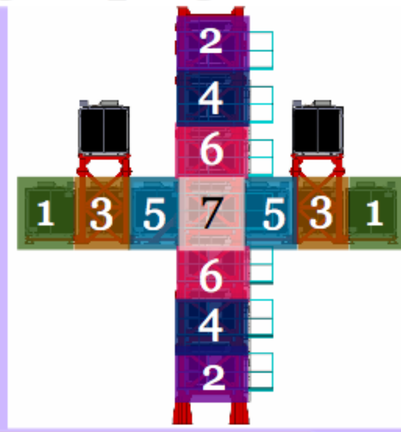
Provides a novel, unique probe of the axial current with comparable uncertainties to the current neutrino scattering program

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

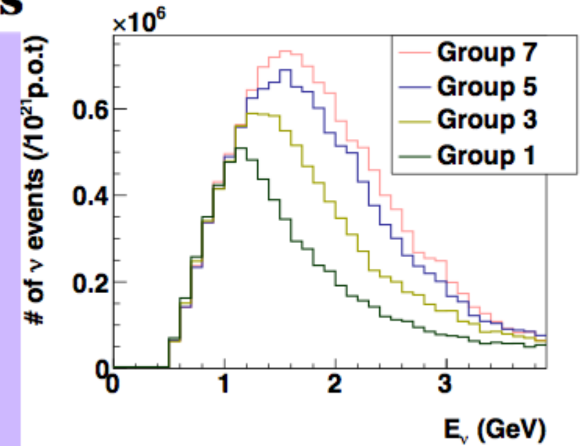
T2K flux-based cross section measurement

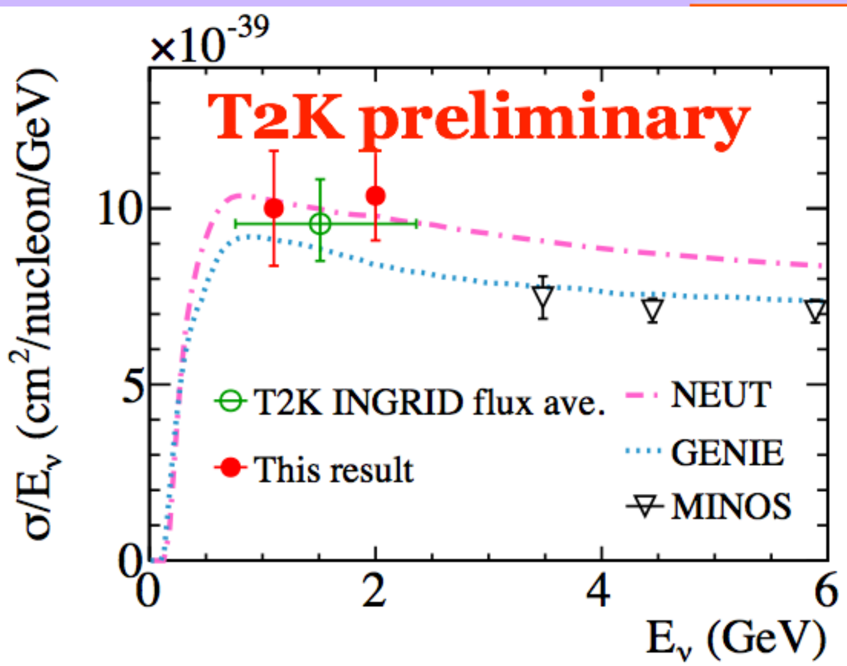
1. Utilize # of event at different modules
   - Different energy spectra at different modules because of different off-axis angles (θ_{OA}=0-0.9°)
2. Group two modules to minimize effects from the variation of the neutrino beam direction
   - 14 modules → 7 groups

Definition of grouping modules



Energy spectra predicted by MC





Compare nearby CC inclusive event rate across the on-axis (INGRID) detector:

- Flux varies across detector due to off-axis effect
- Infer energy dependence from variation
- Additional details at NuFact2014 talk by K. Suzuki, which these plots are from

Additional model considerations

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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	$1.25 \pm 0.08(stat.)^{+0.22}_{-0.26}(syst.)$

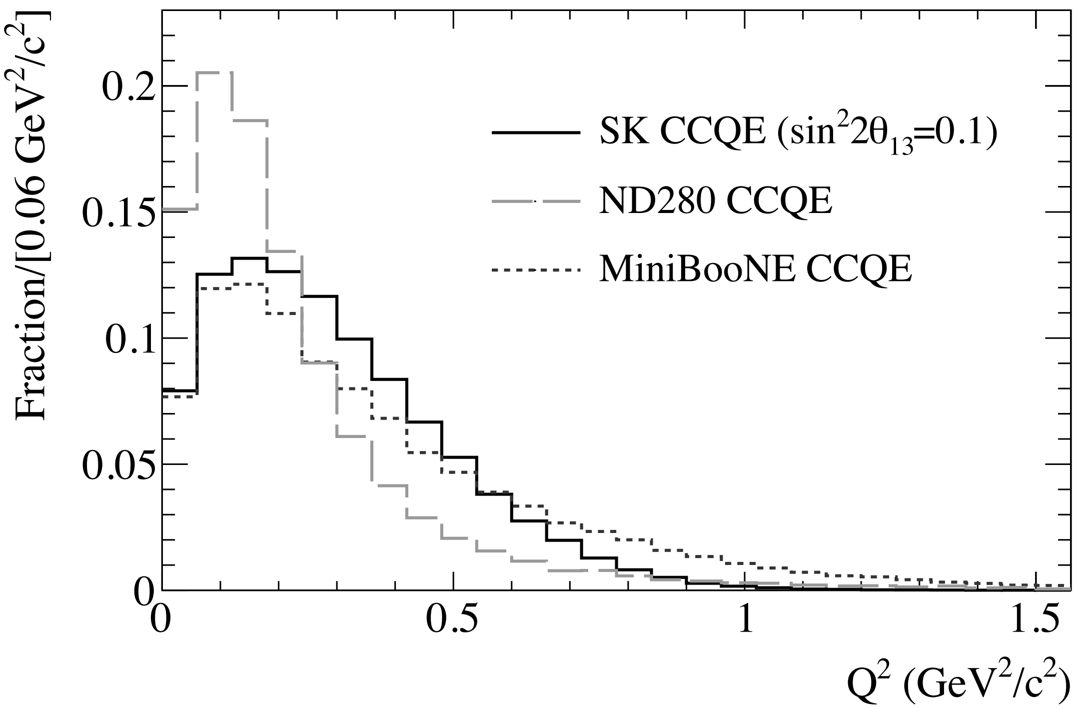
- Uncertainties in oscillation analysis include effect, where possible, of alternate models

For you: What you measure as a particular cross section may depend on selection and model used to interpret it

Challenges of use of ND data

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)

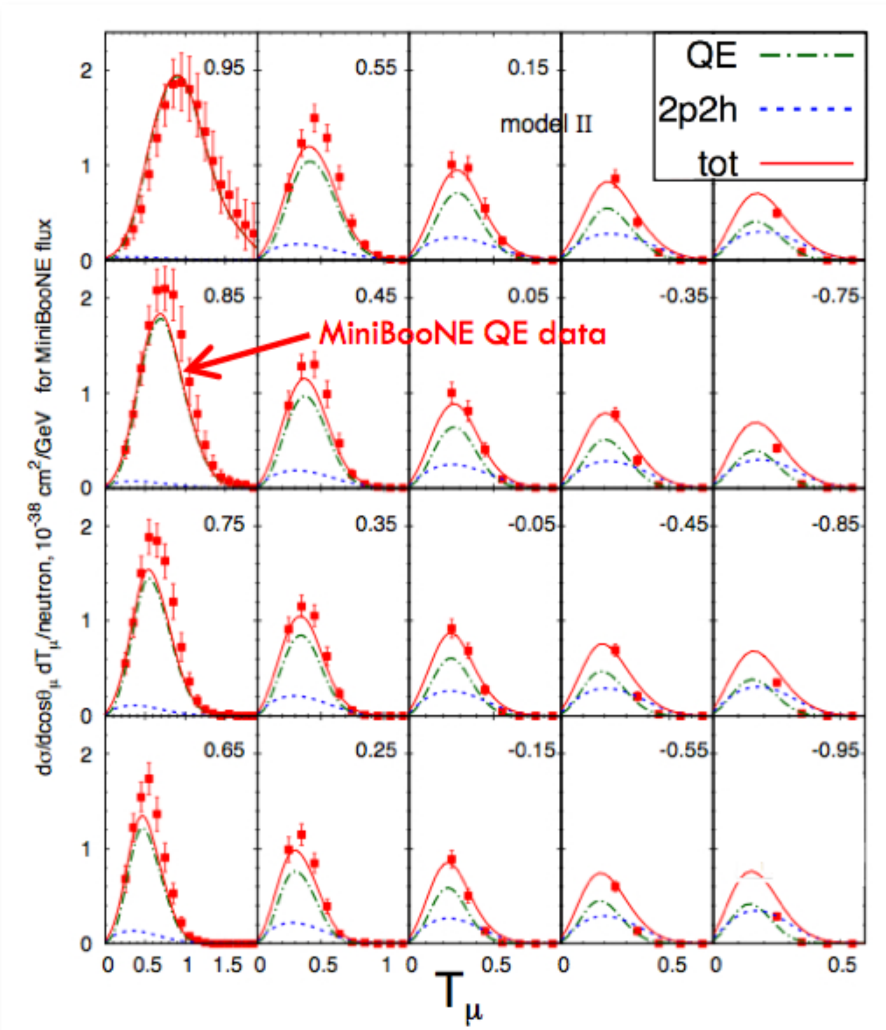
- External data covers larger Q^2 (MiniBooNE, 4π Cherenkov detector)

Target: ND selection is C, SK is O

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

Incomplete data: MiniBooNE

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 off-diagonal 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

Incomplete data: MiniBooNE

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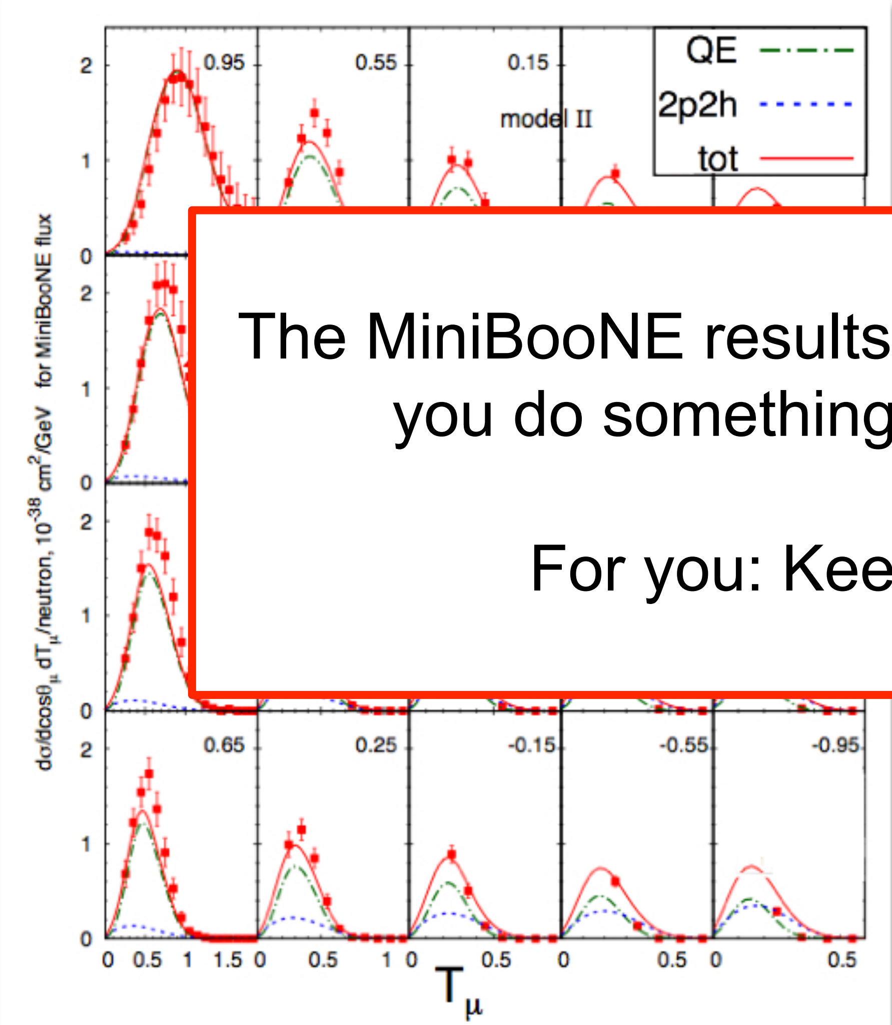

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No off-diagonal correlations for MiniBooNE data releases

- First round of fits got an "extra crazy"

a

to

The MiniBooNE results were revolutionary… but anytime you do something new, you risk and you learn

For you: Keep risking, keep learning

- Useful to understand background subtraction

No correlations between samples

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

QE model comparisons

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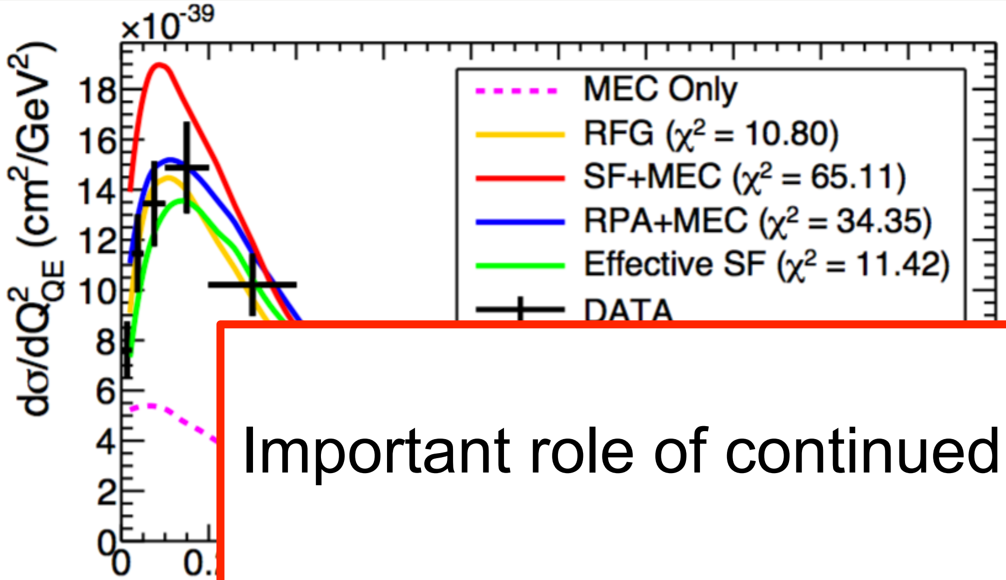
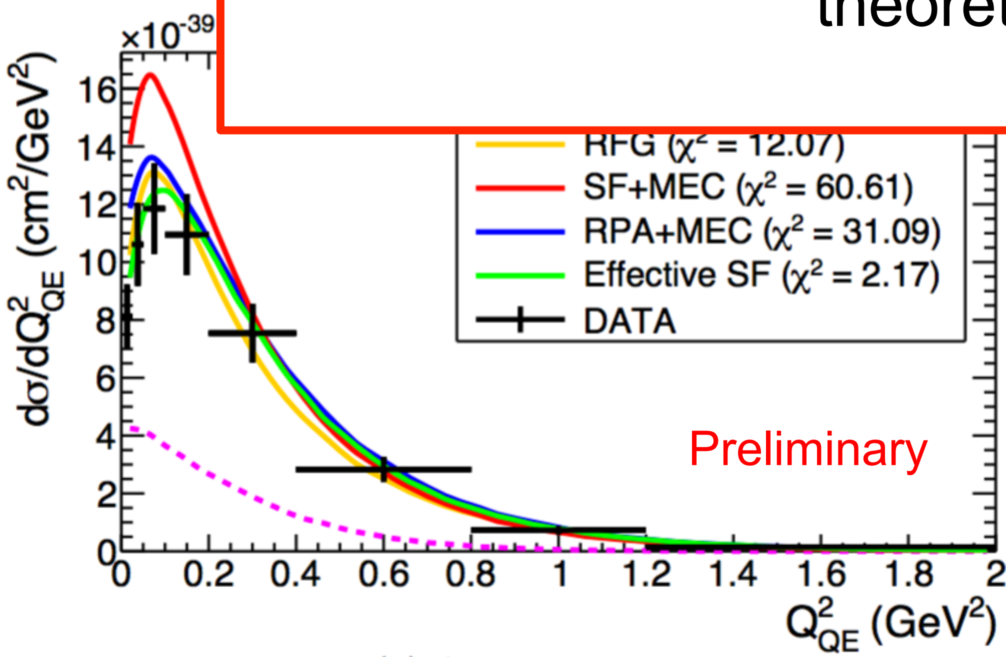




(b) Antineutrino

MINERvA provides neutrino and antineutrino datasets and correlations

Important role of continued theoretical input in this process

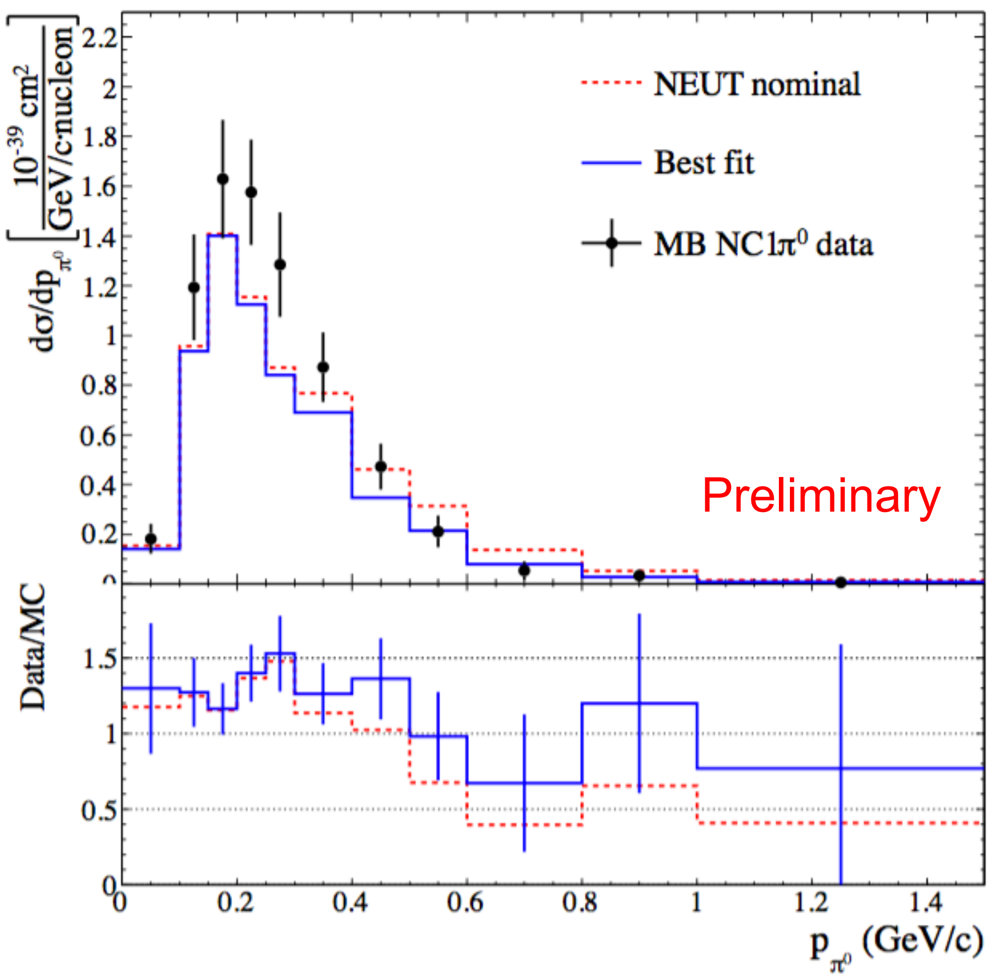
For you: develop collaborations with theorists, and read theoretical papers

- Is disagreement 2p2h, nuclear effects? Different effect in osc analysis
- Continue to investigate the CCQE model parameterization and theoretical uncertainties

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



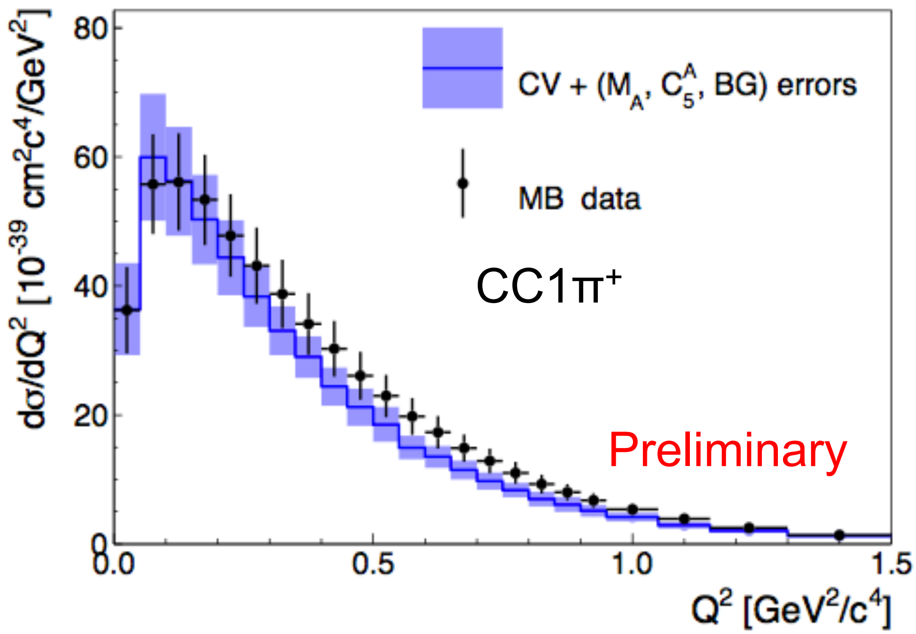
2015: Updated RS form factors from K. M. Graczyk and J. T. Sobczyk. Phys. Rev. D, 77:053001 (2008)

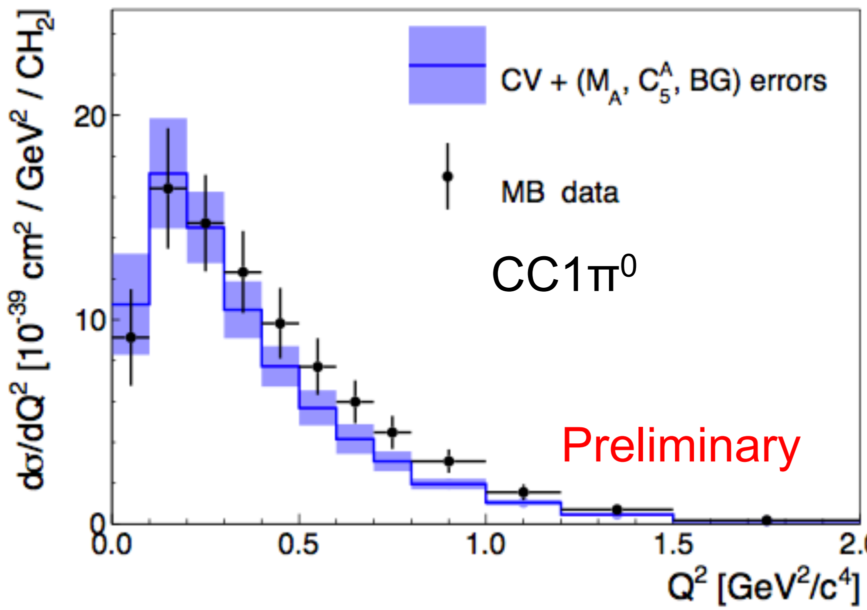
Fit neutrino deuterium channels:

- 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)

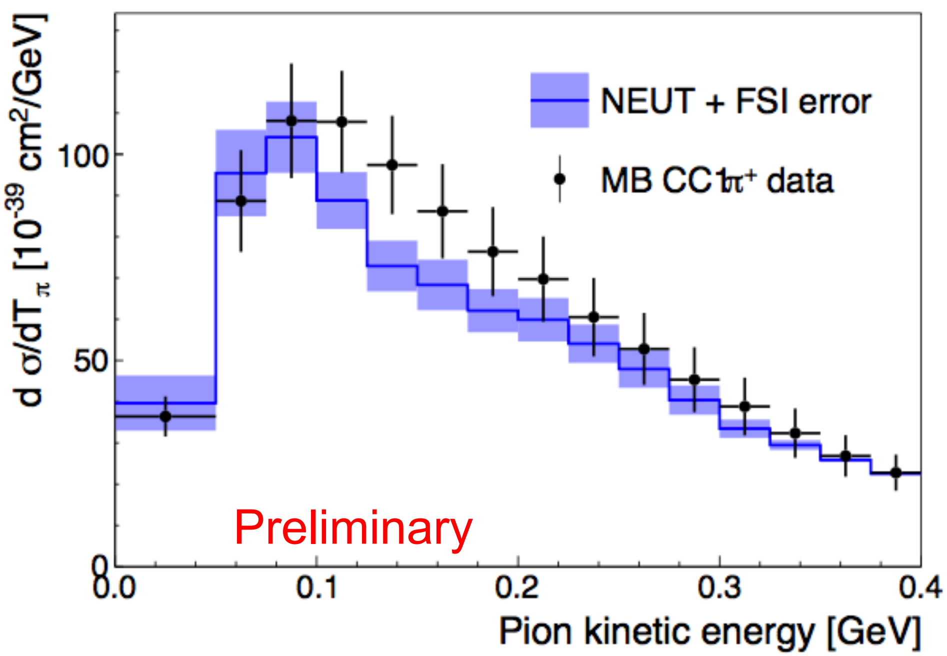


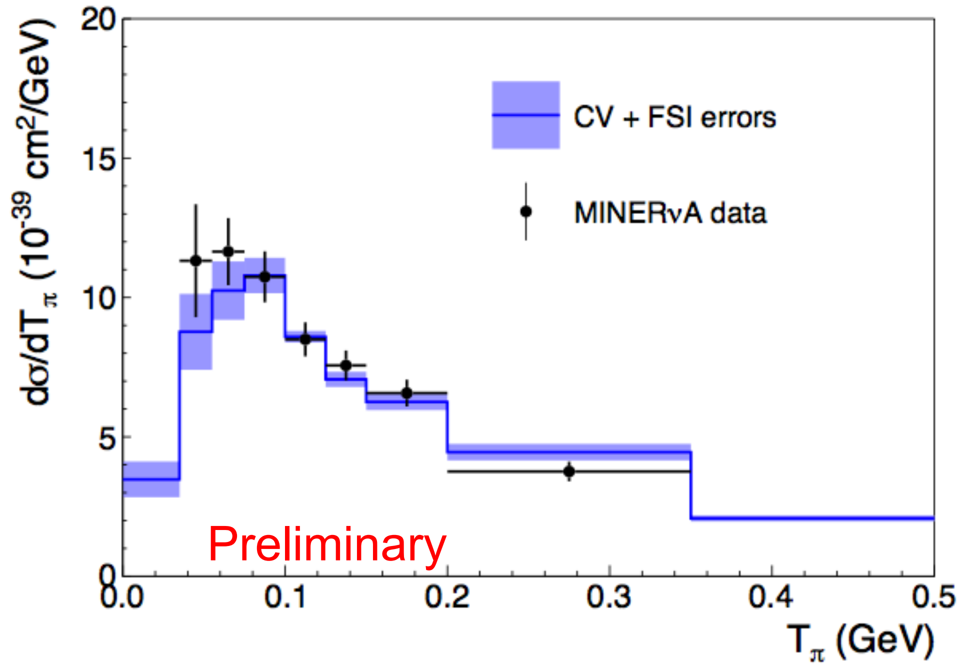


Results of resonance model retune

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

Shape-only plots, also overall rate difference between the two experiments





New T2K near detector measurements of pion production coming soon

Final state interaction model

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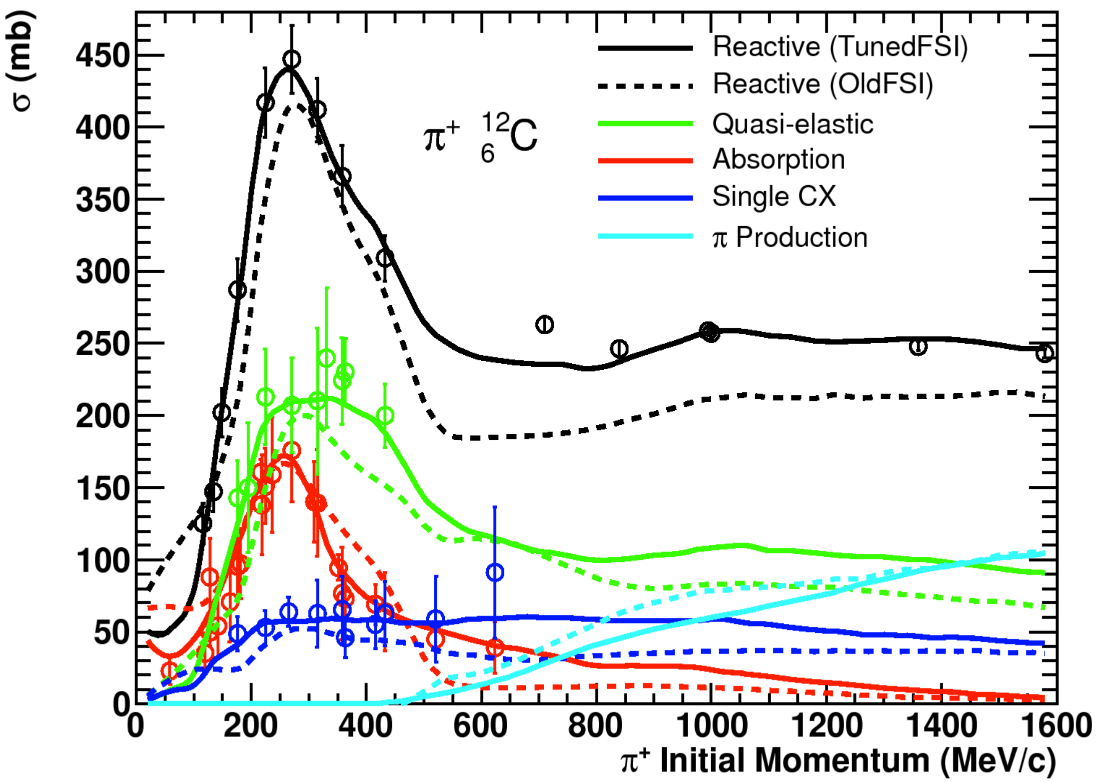
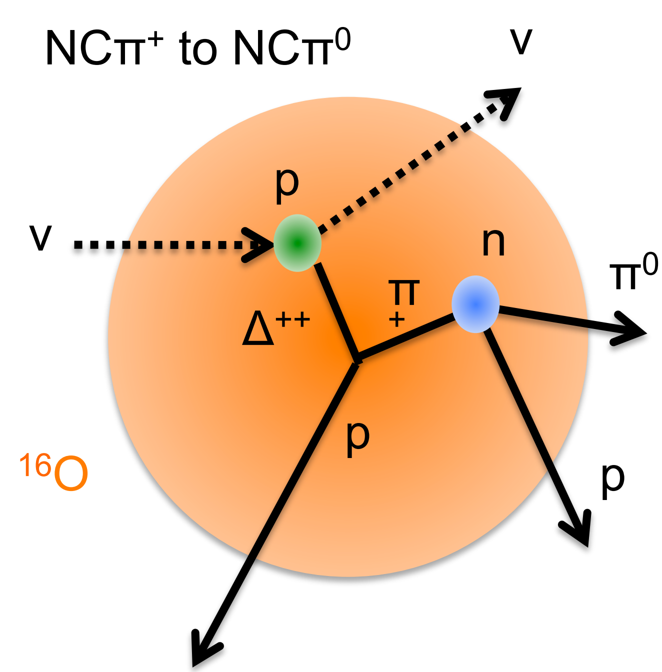
NEUT FSI model is a cascade model tuned on ``free-range'' π+N data

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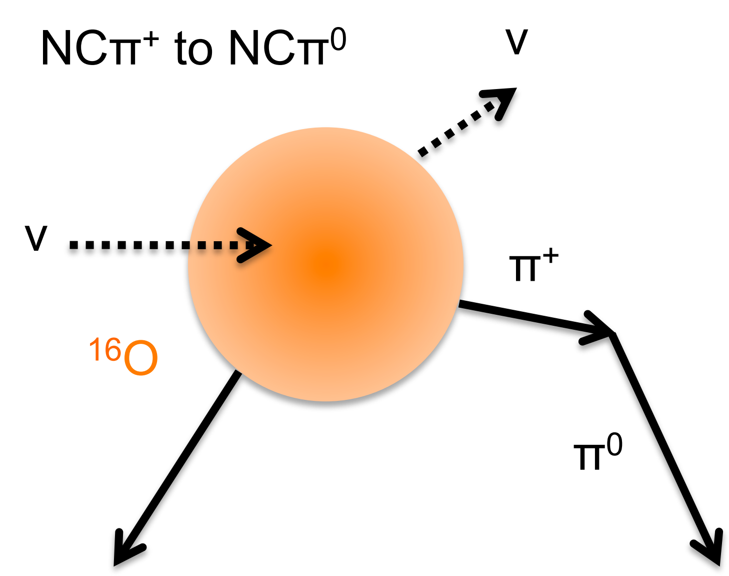
Pion scattering in the detector is a background to cross section understanding of what comes out of the nucleus (``secondary interactions'')

- Consistent treatment within same model at far detector
- Significant detector uncertainty for near detectors; LArIAT important for DUNE

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

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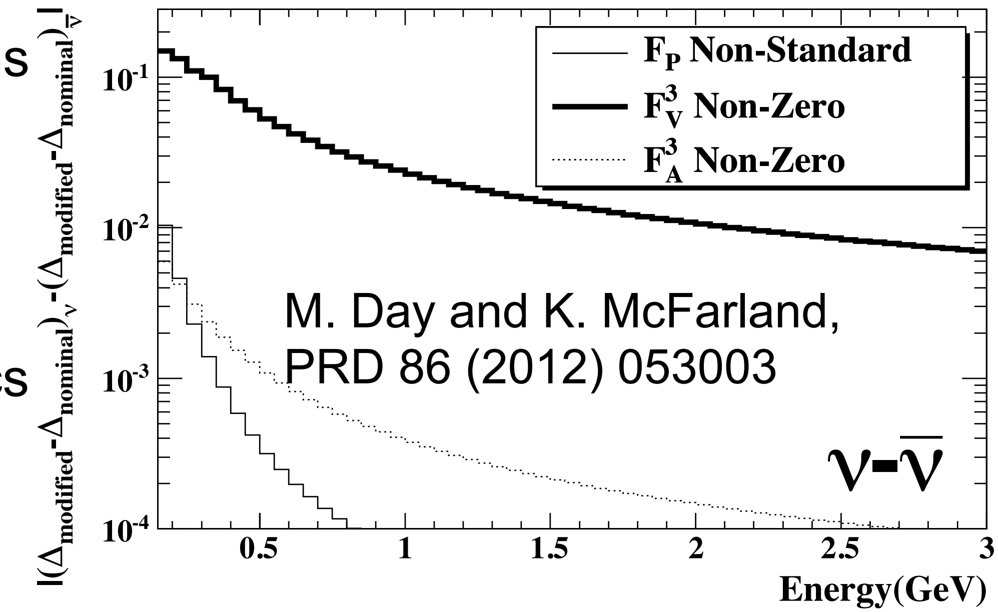
Differences between ν_e and ν_μ cross sections difficult to probe experimentally,
but significant for for future program

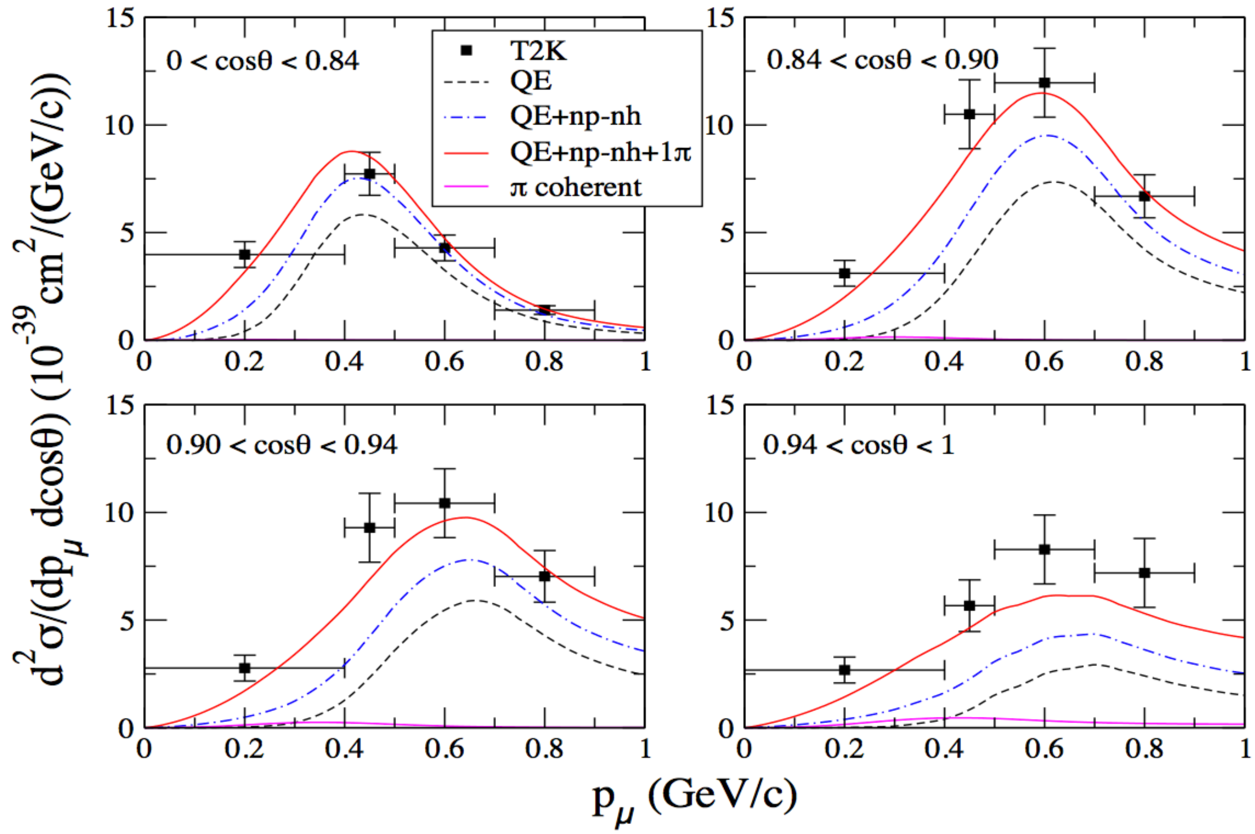
- ν_μ cross section used to infer ν_e from ND
- T2K uncertainty on ν_e/ν_μ xsec is 3%
- Difficult to measure due to limited statistics
- First CC ν_e cross section measurement:
- PRL 113, 241803 (2014)



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 $NC\pi^0$
- 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 now with predominantly antineutrino beam

T2K direct 2p2h probes?

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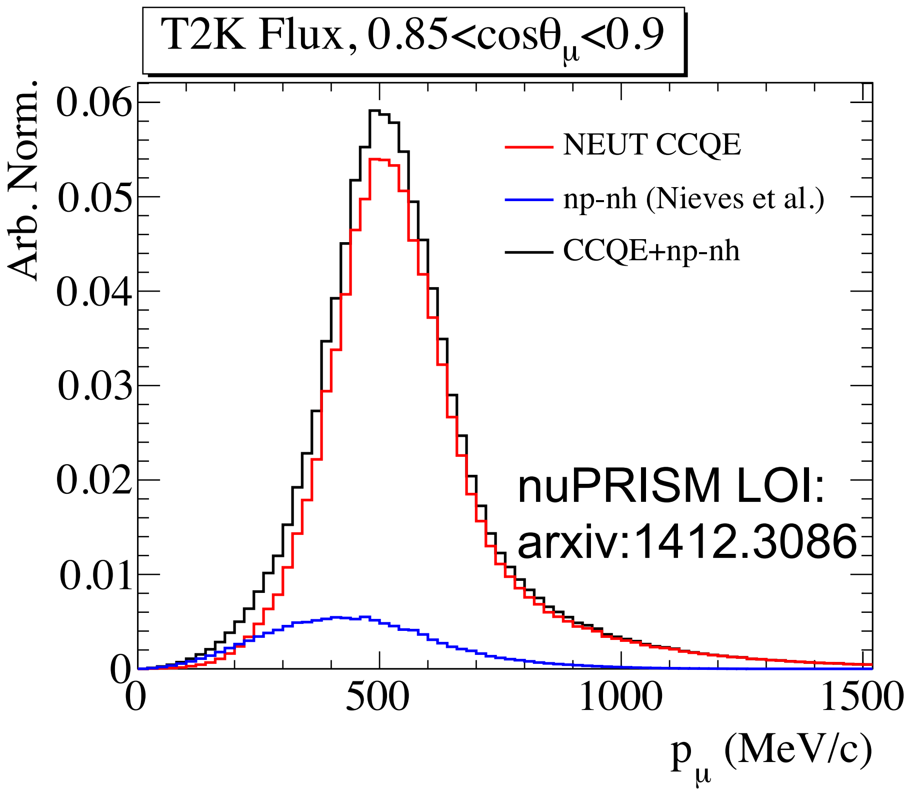
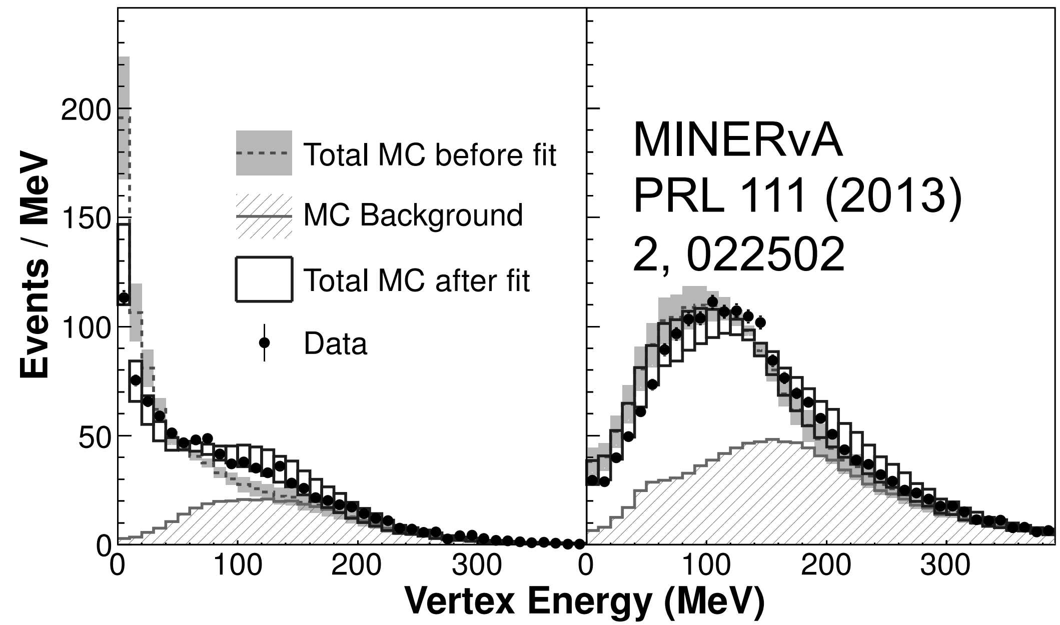
Challenges to ``direct'' measurement of multinucleon (2p2h) interactions:

- 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

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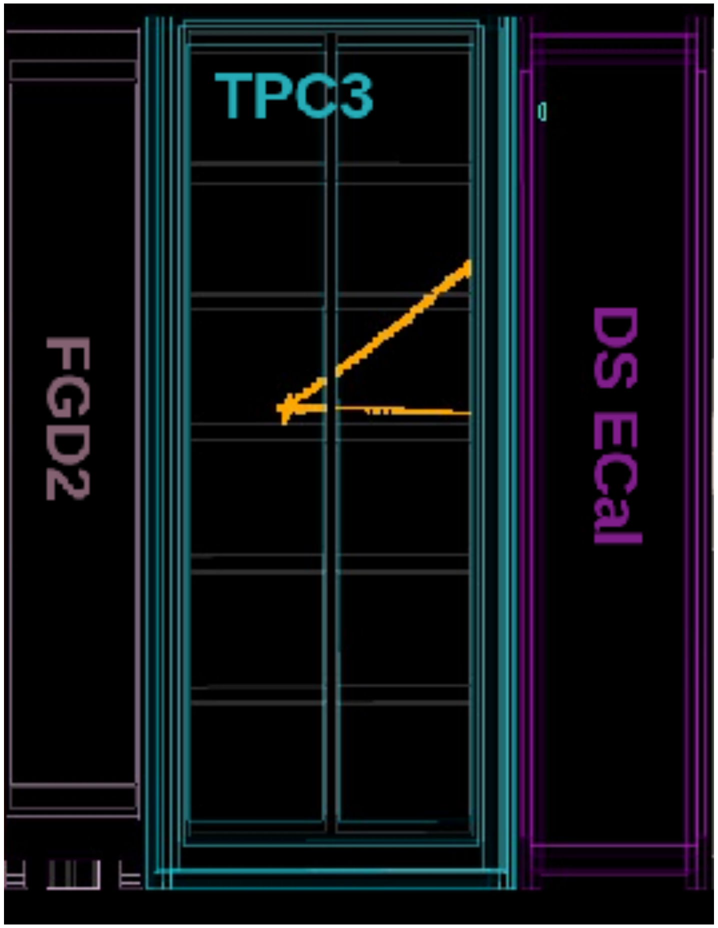
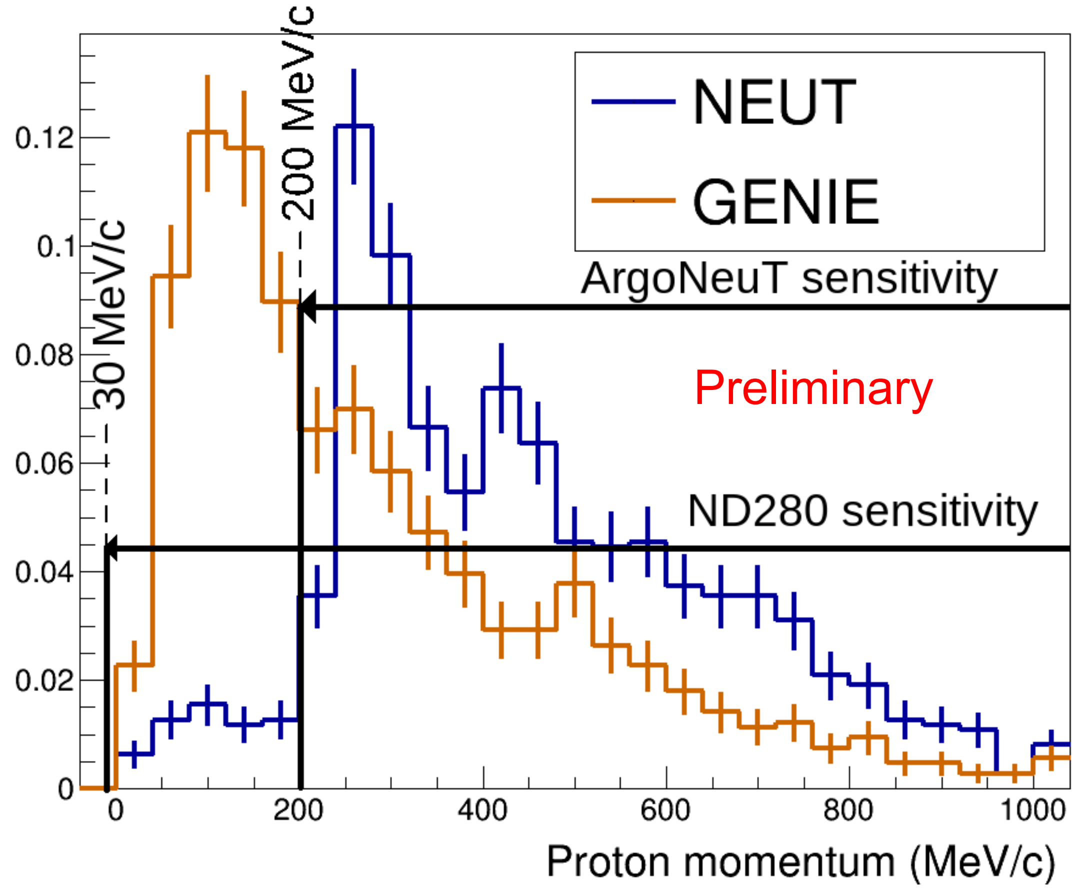




Gaseous TPCs (3 in total) are predominantly Ar gas:

- Proton threshold is lower than LAr
- New reconstruction, search underway for such events… again, spearheaded by students and postdocs

Summary

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 **even if the detectors were identical**

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%

T. Katori's artistic interpretation of our cross section group mascot

Summary

Even with these challenges, neutrino physics is in a very exciting time:

- Data sets with multiple beam energies will start to confront the degeneracies of 1p1h, 2p2h and resonance contributions:
  - T2K, MINERvA, NOvA, MiniBooNE on C, ArgoNEUT, CAPTAIN-MINERvA, MicroBooNE on Ar
- Renewed understanding of pion re-interactions
  - LArIAT on Ar, DUET on CH

The students, postdocs working on today's experiment's will come up with creative solutions to the problems we face:

- nuPRISM ``mono-energetic'' beam circumvents the core issue of associating neutrino energy to reconstructed observables

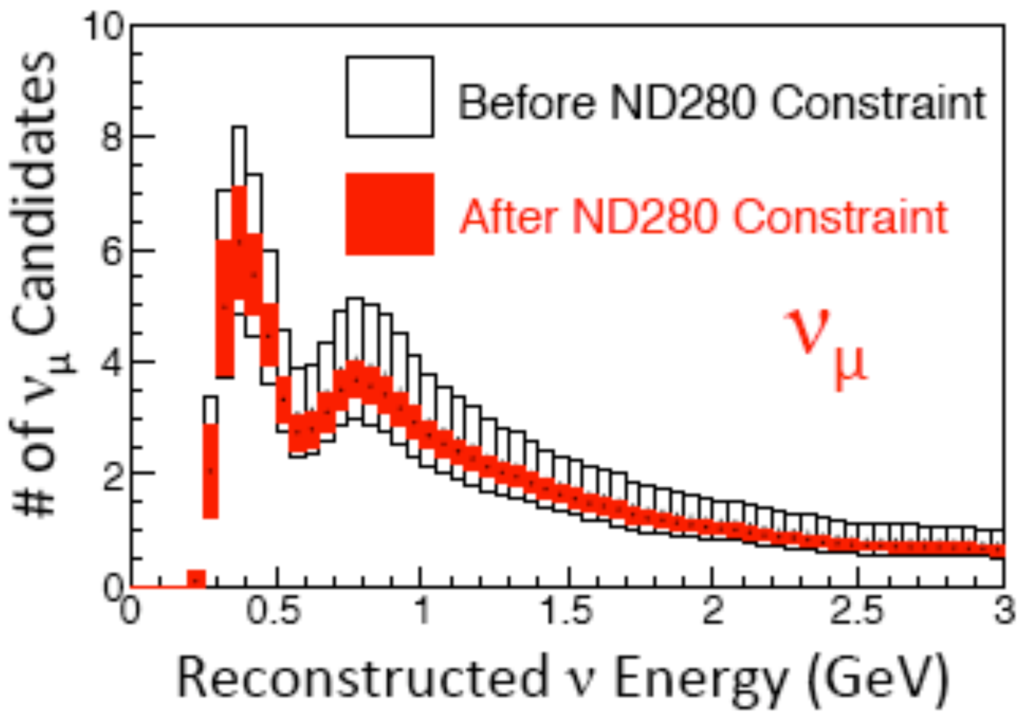
Backup slides

Use of near detectors on T2K

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:

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

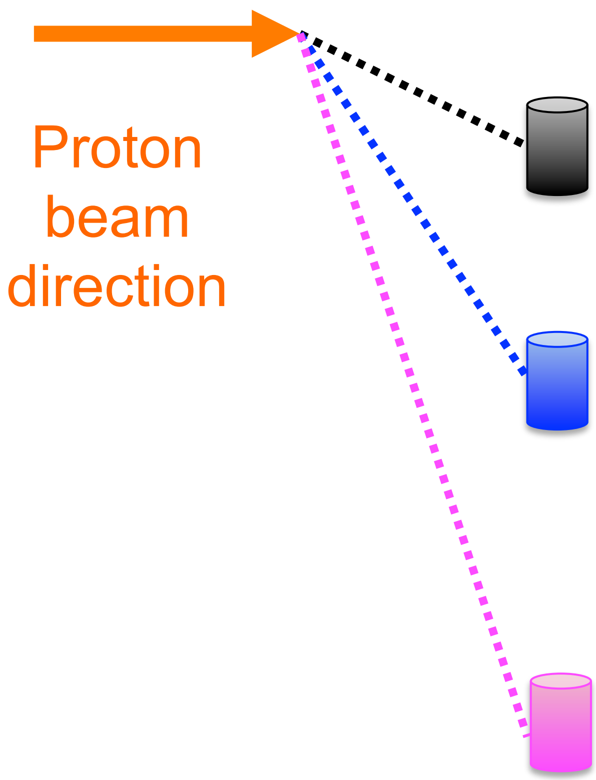
uncertainties	ν_μ disap.	ν_e app
ν flux+xsec (before) after ND constraint	(21.7%) ±2.7%	(26.0%) ±3.2%
ν unconstrained xsec	±5.0%	±4.7%
Far detector	±4.0%	±2.7%
Total	(23.5%) ±7.7%	(26.8%) ±6.8%

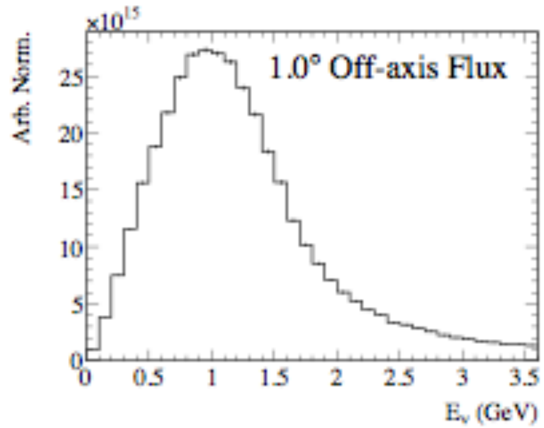


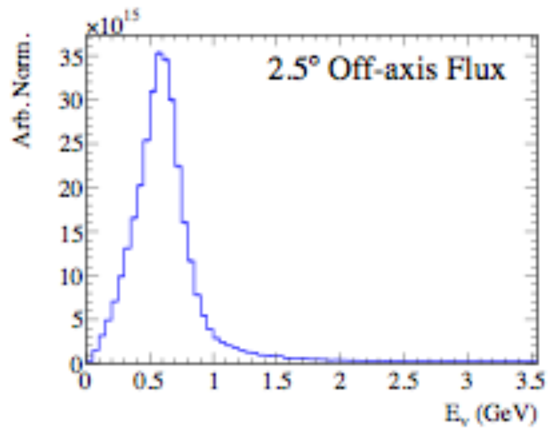
After ND: expect 21.06 ν_e candidates (background only: 4.97)

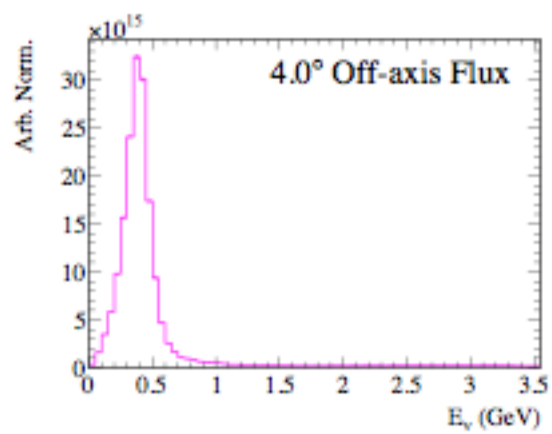
After ND: expect 124.98 ν_μ events (no oscillation: 445.98)

Revisiting off-axis beams



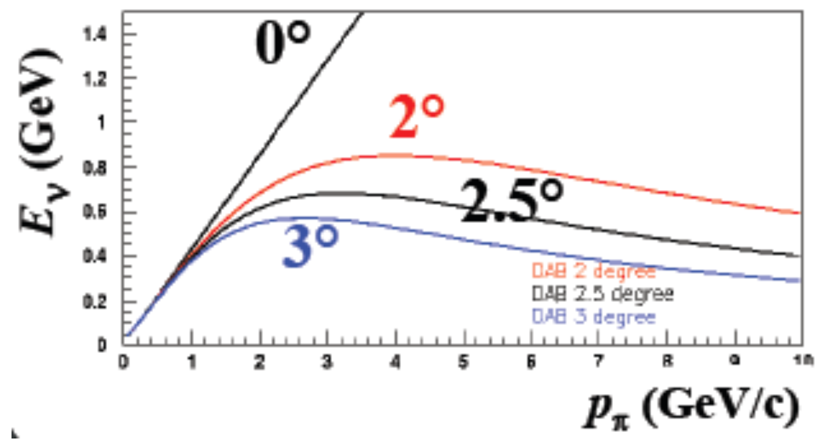




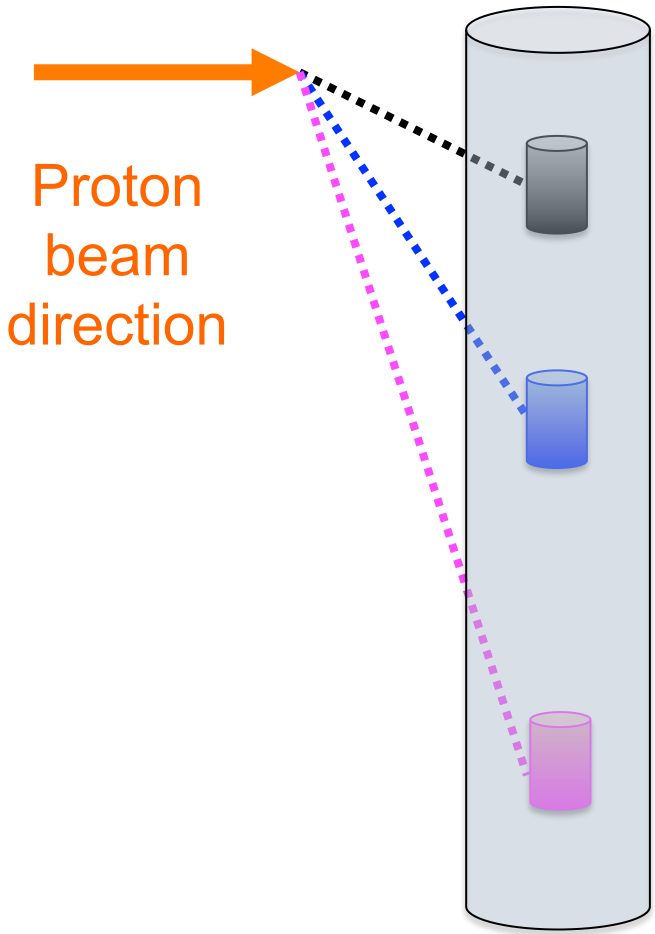


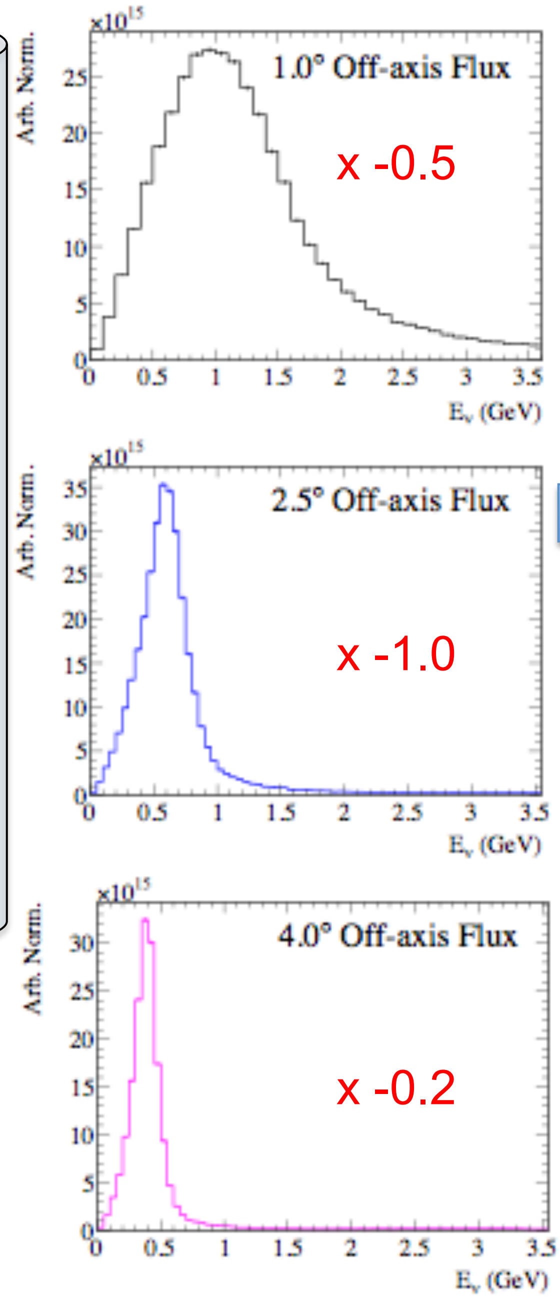
Example using T2K beamline

As off-axis angle increases, flux spectrum narrows and peak shifts down, due to the kinematics of pion decay

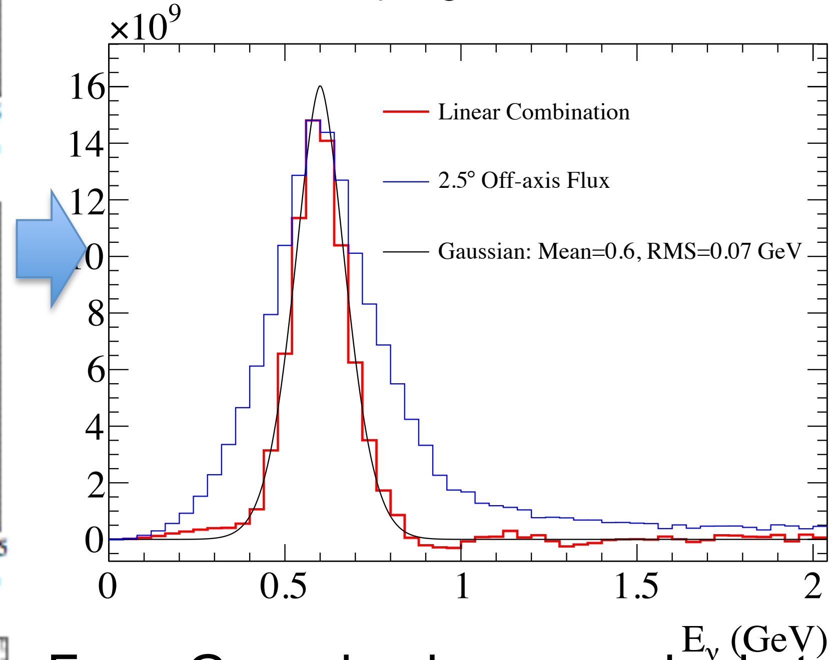


Combining different off-axis angles





$$\Phi(E_\nu) = \sum_{i=0^\circ}^{\theta_{max}} C_i \; \phi_i(E_\nu)$$



For a Gaussian beam peaked at 600 MeV, use linear combination of 30 offaxis angles:

- 0°– 6° corresponds to 1.2 GeV -0.25 GeV
- Cancels HE tail

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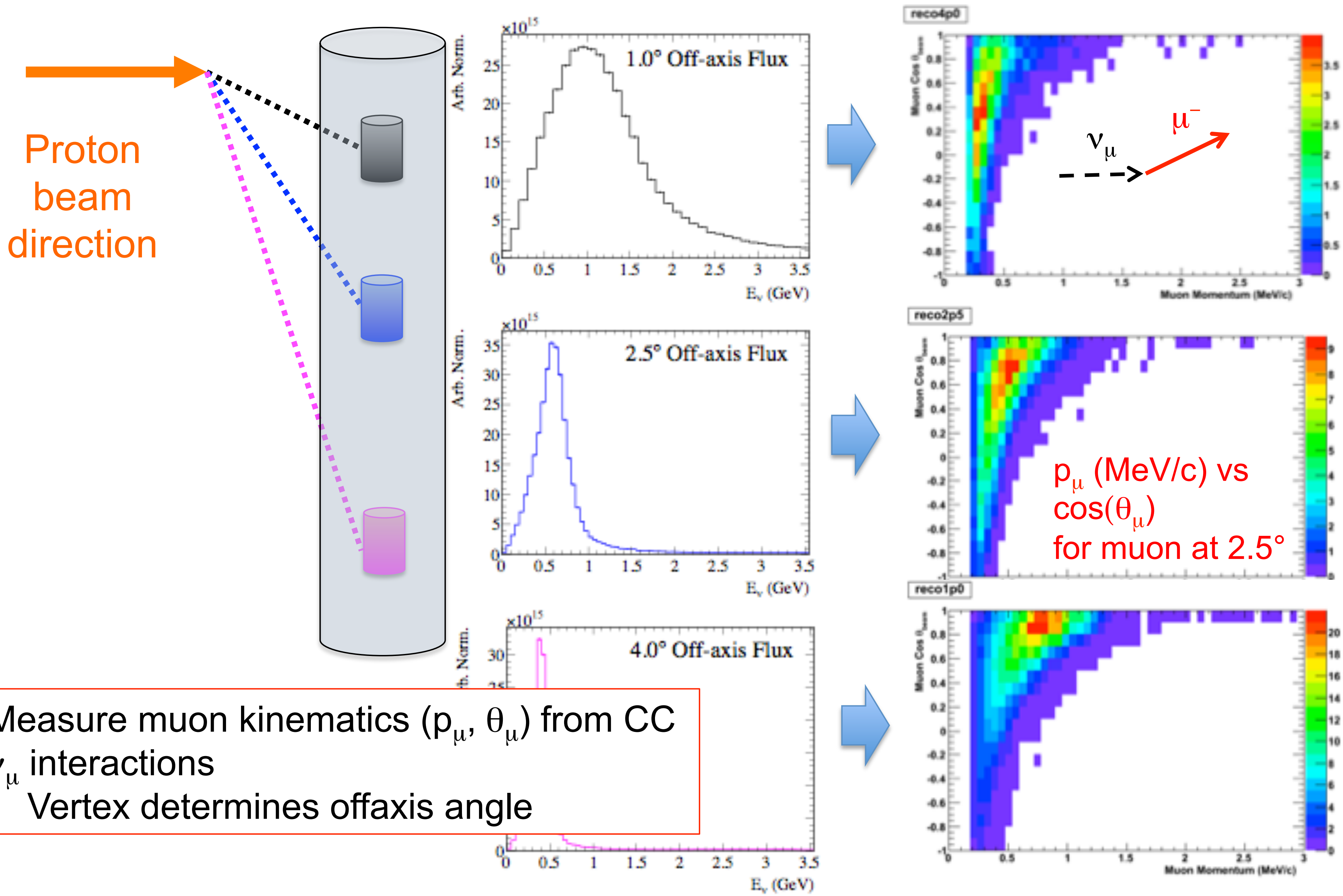
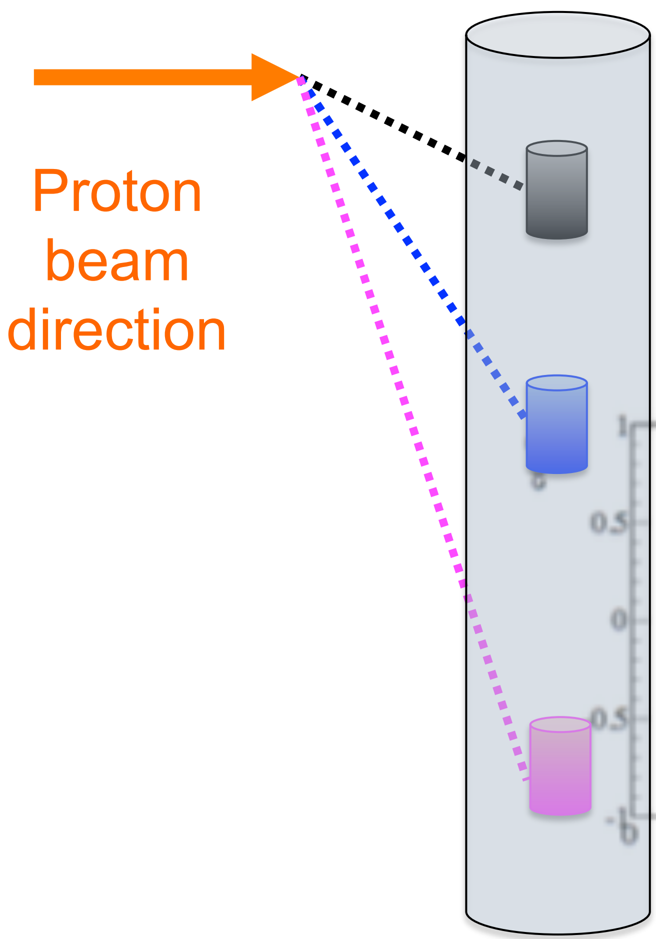


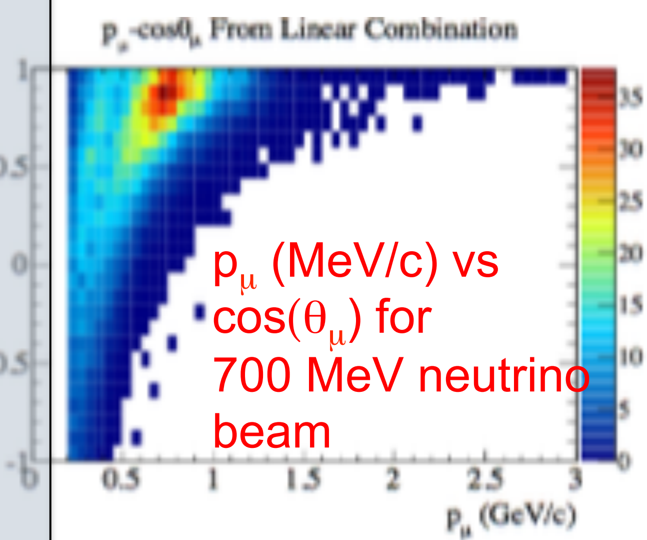
Measure muon kinematics (p_μ, θ_μ) from CC ν_μ interactions

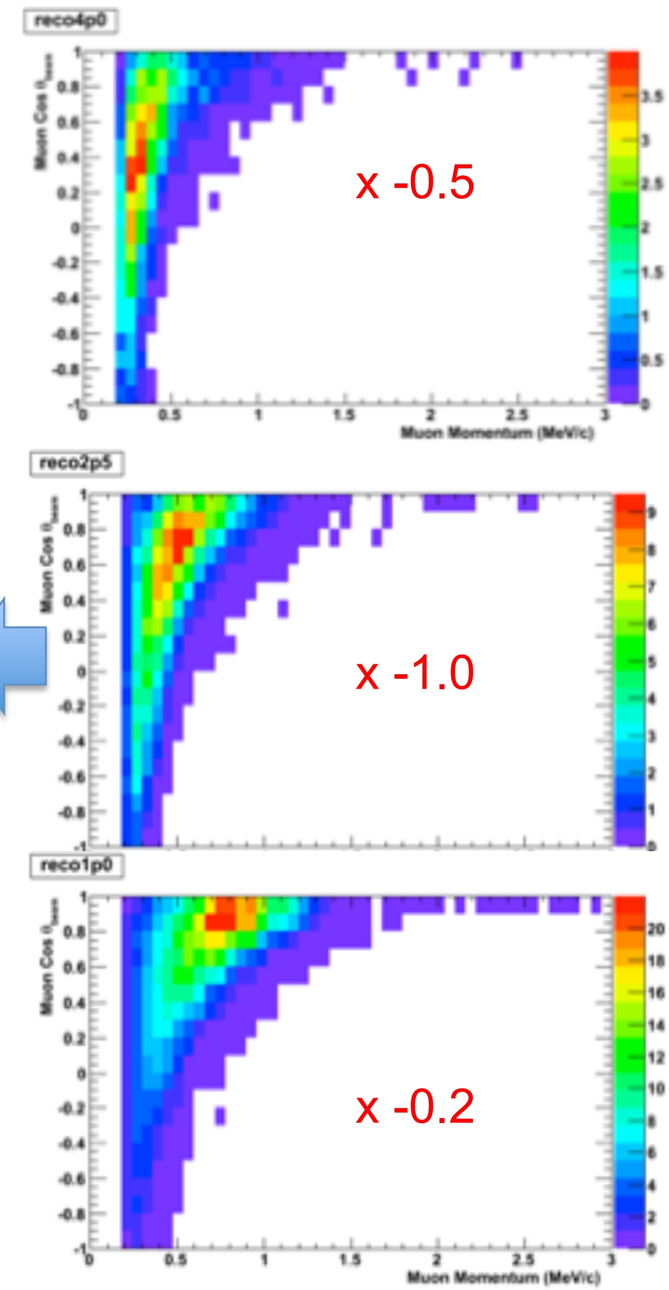
- Vertex determines offaxis angle

Relating observables to true E_ν



$$\Phi(E_\nu) = \sum_{i=0^\circ}^{\theta_{max}} C_i \; \phi_i(E_\nu)$$

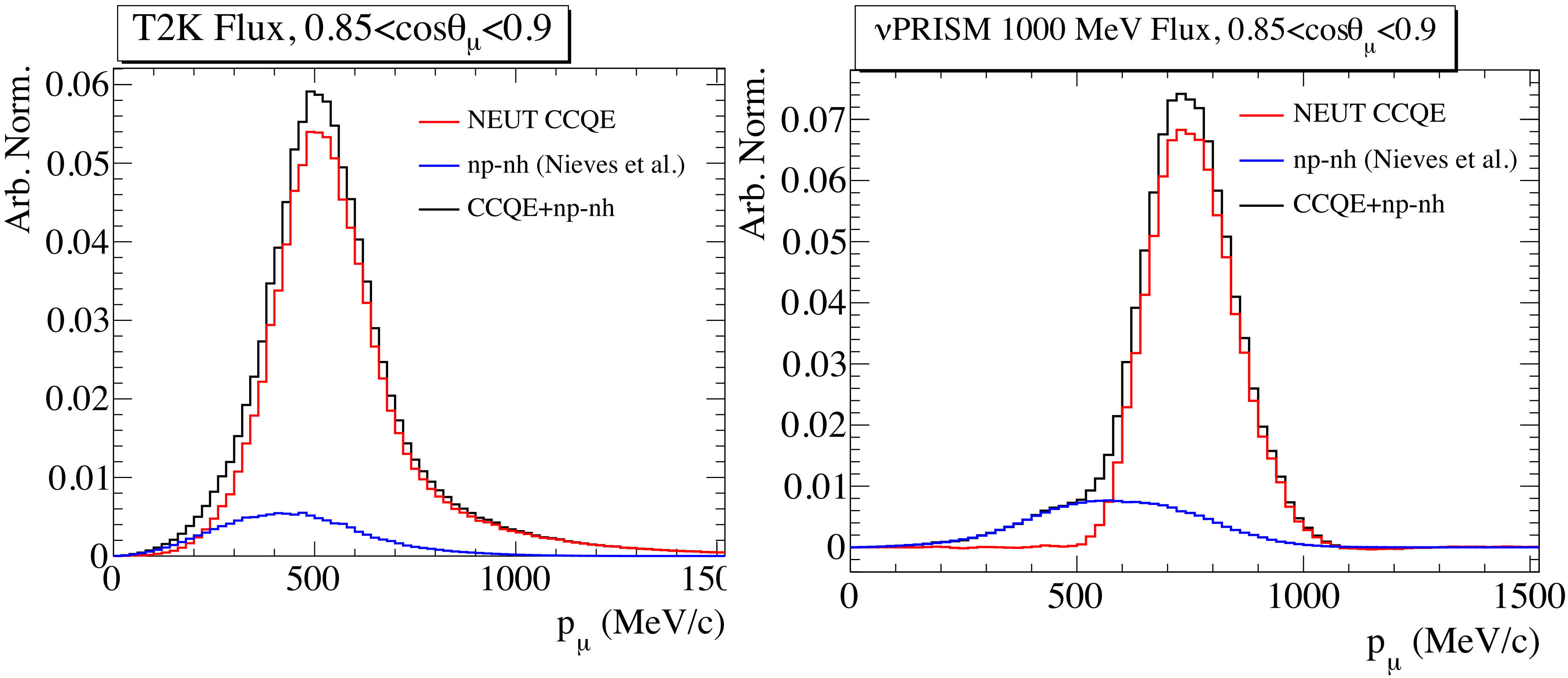




Measure muon kinematics (p_μ, θ_μ) from CC ν_μ interactions

- Vertex determines offaxis angle
- Linear combinations of (p_μ, θ_μ) provide observable for monoenergetic E_ν beam

Resolving nuclear effects with only lepton info

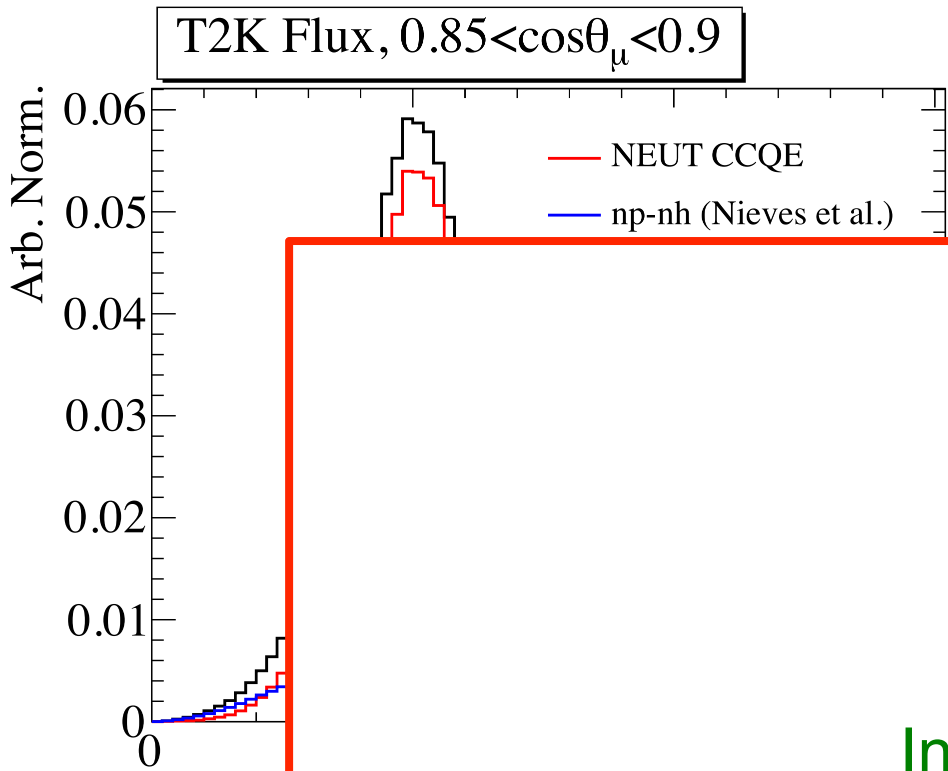


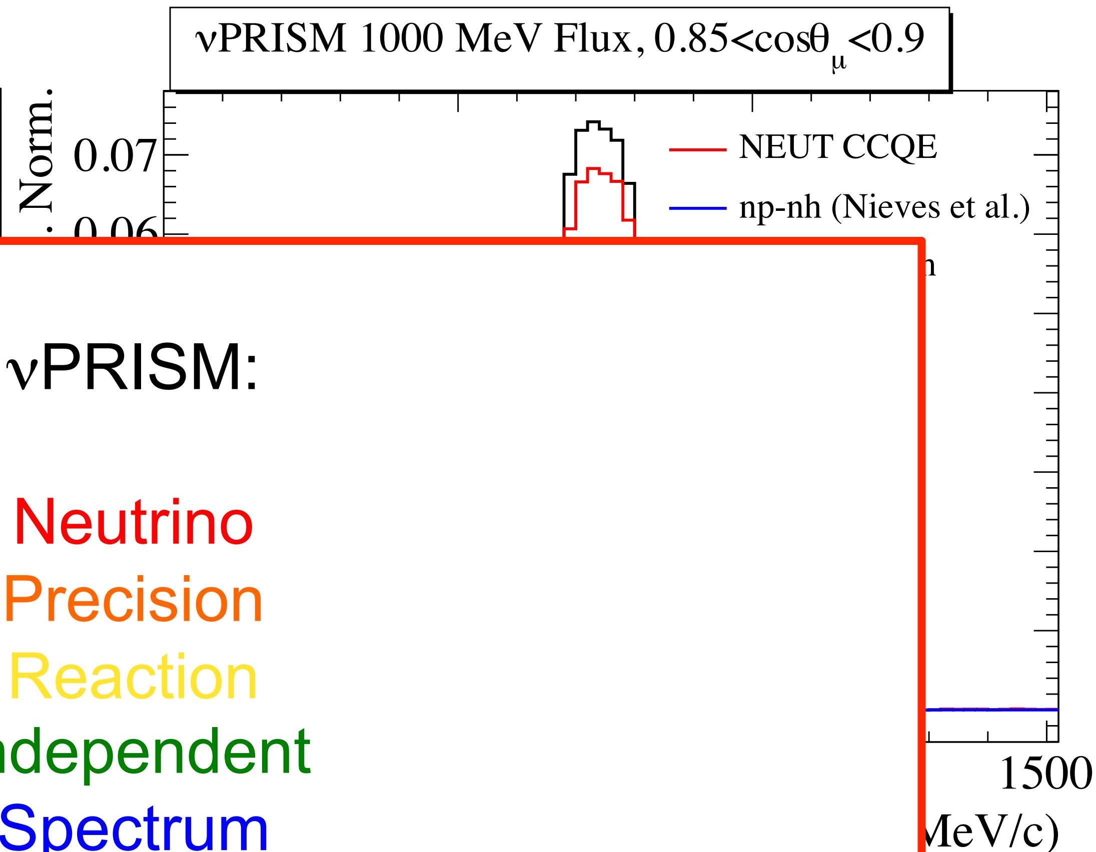
With the T2K flux, multinucleon (npnh) interactions from higher E_ν feed down into same momentum region as CCQE.

With a νPRISM generated 1 GeV "monoenergetic" flux, processes can be separated in observable muon kinematic variables

- Combinations of nearby monoenergetic fluxes provide energy dependence of cross section

Resolving nuclear effects with only lepton info





νPRISM:

Neutrino
Precision
Reaction
Independent
Spectrum
Measurement

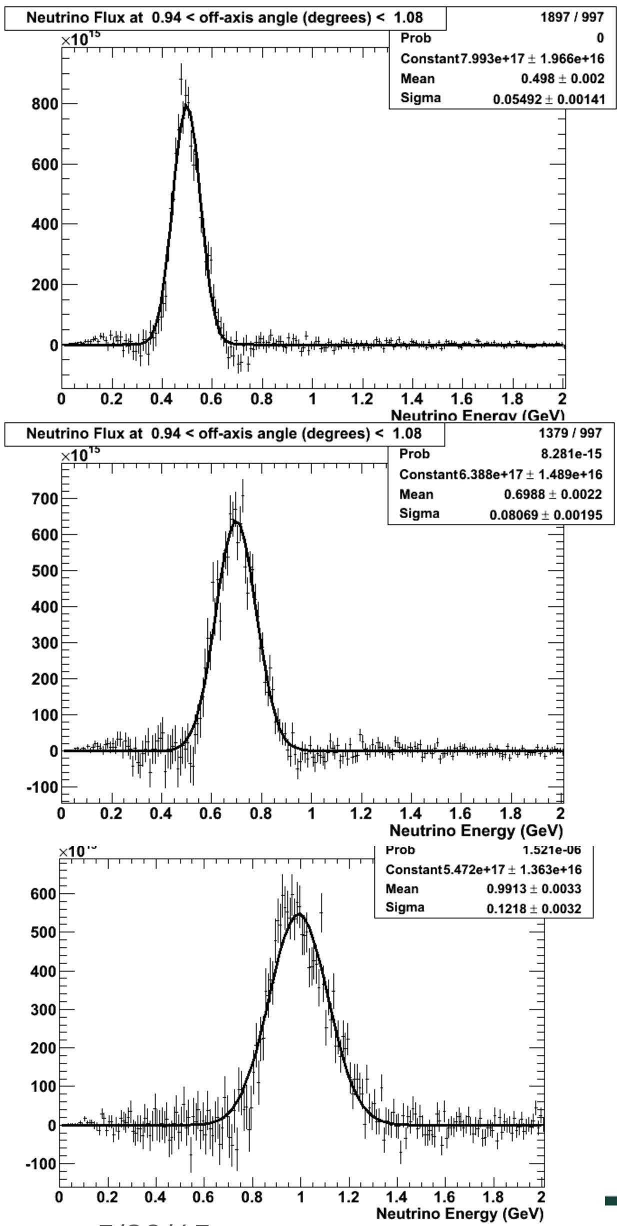
With the … into
same mo…

With a νPRISM generated 1 GeV “monoenergetic” flux, processes can be separated in observable muon kinematic variables

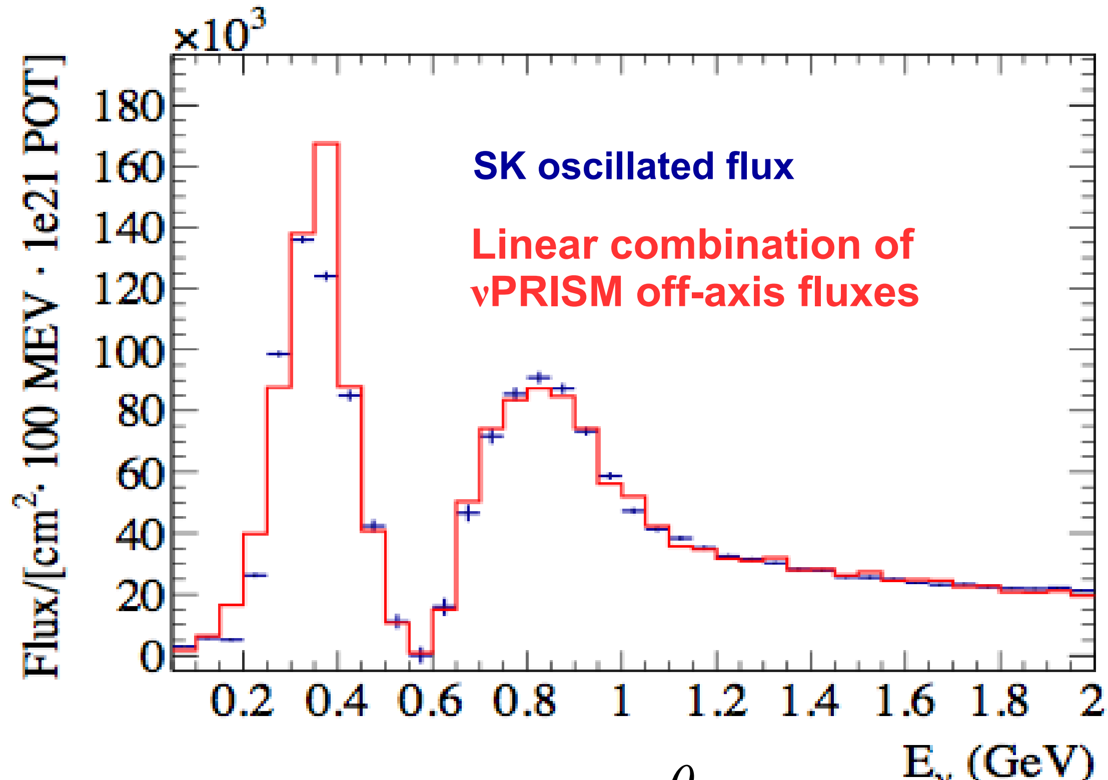
- Combinations of nearby monoenergetic fluxes provide energy dependence of cross section

Effect on oscillation analysis

Cross section model dependence enters through correction of different fluxes measured by ND and FD



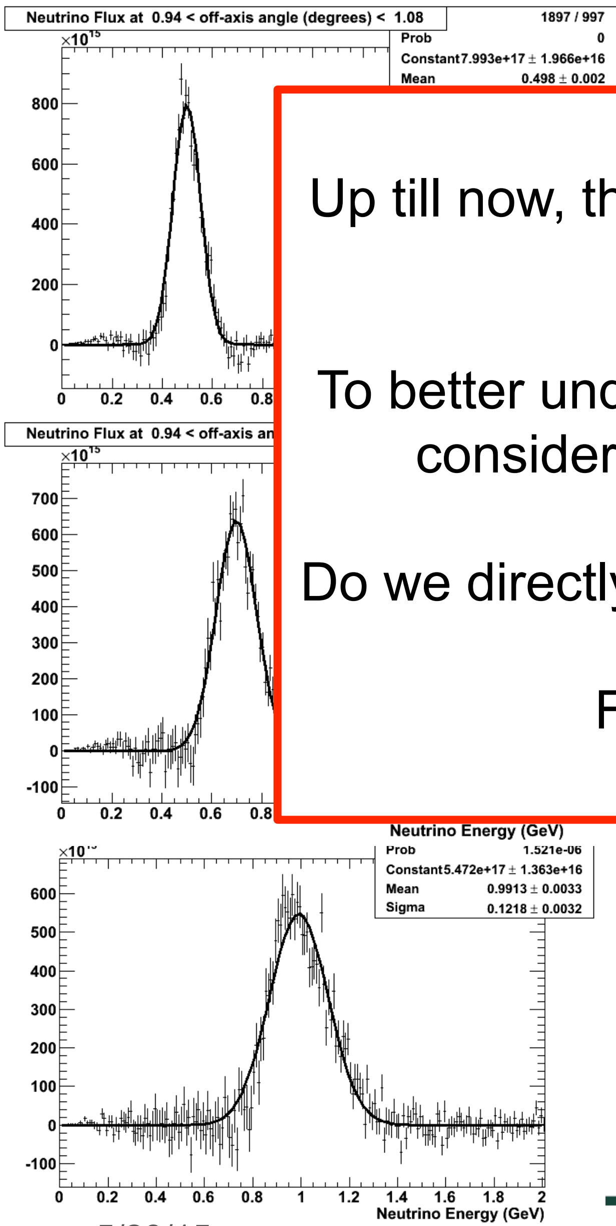
Use linear combination technique to generate oscillated spectrum from different offaxis angles



$$\Phi(\Delta m^2_{32}, \theta_{23}) = \sum_{i=0^\circ}^{\theta_{max}} k_i \ \phi_i(E_\nu)$$

Effect on oscillation analysis

Cross section model dependence enters through correction of different fluxes measured by ND and FD



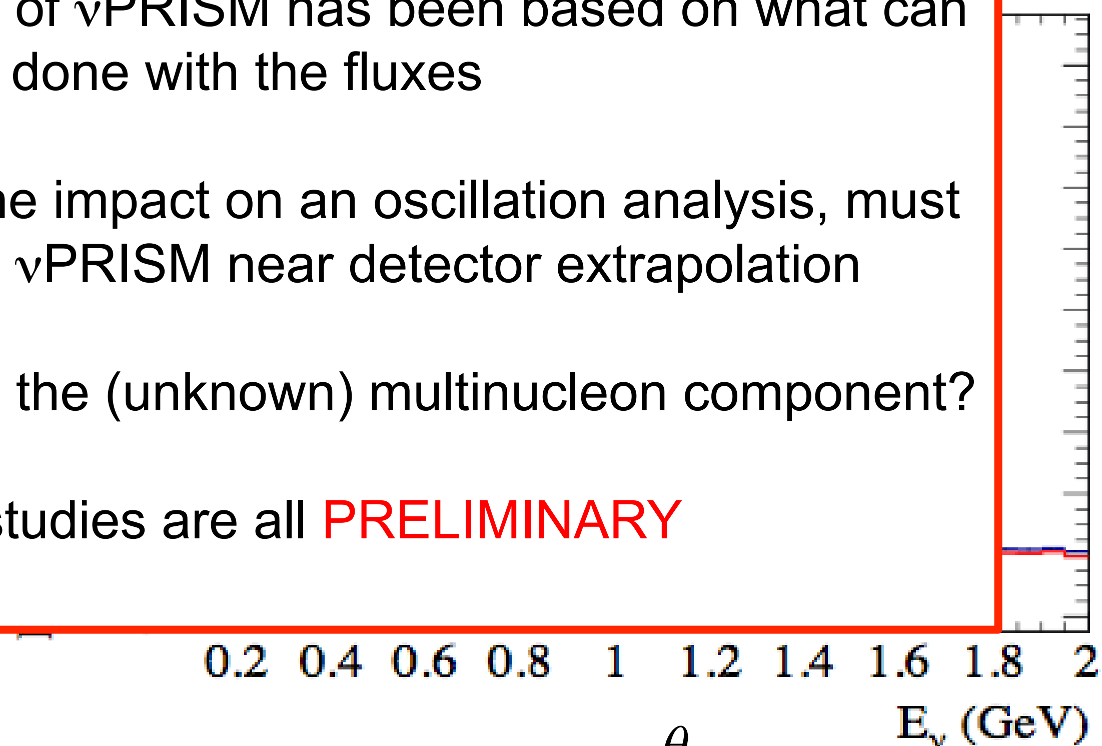
Use linear combination technique to generate ... angles

Up till now, the concept of νPRISM has been based on what can be done with the fluxes

To better understand the impact on an oscillation analysis, must consider a realistic νPRISM near detector extrapolation

Do we directly measure the (unknown) multinucleon component?

Following studies are all PRELIMINARY



$$\Phi(\Delta m^2_{32}, \theta_{23}) = \sum_{i=0^\circ}^{\theta_{max}} k_i \; \phi_i(E_\nu)$$

Considerations for the detector

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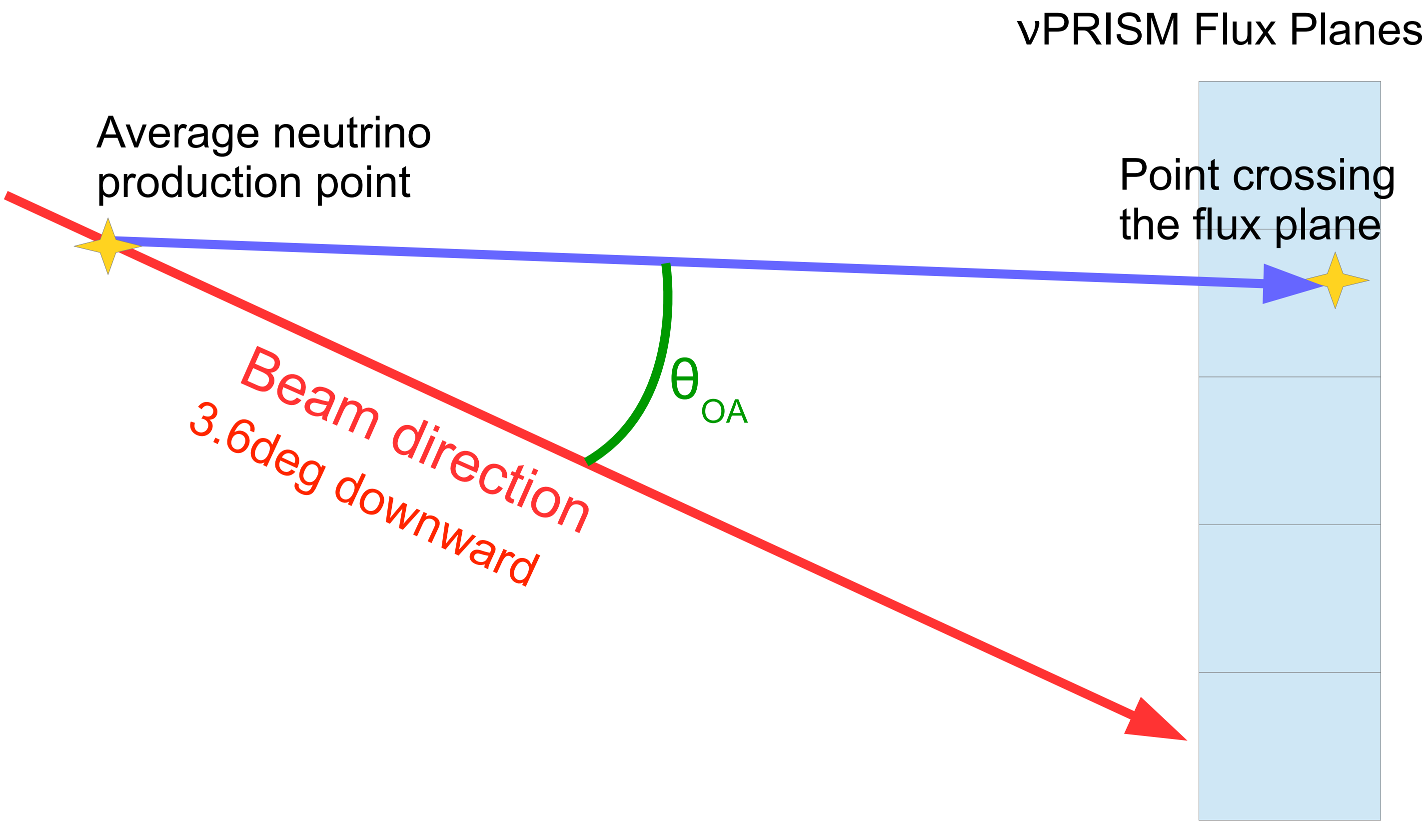


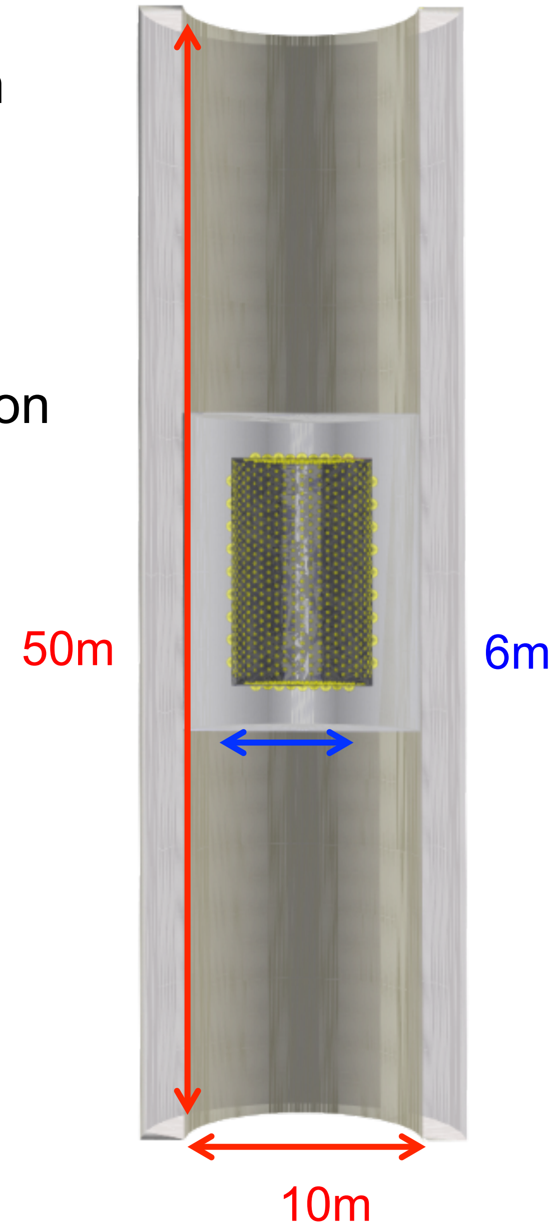
Detector needs to be placed ~1km away from T2K neutrino target

- Decay volume (95m) << 1km so that the off-axis angle is well approximated at each position in the detector
- Manageable pile up rate of interactions inside and outside the detector

Considerations for the detector

At 1km, to cover 0° – 6° would require a vertical depth of ~70m

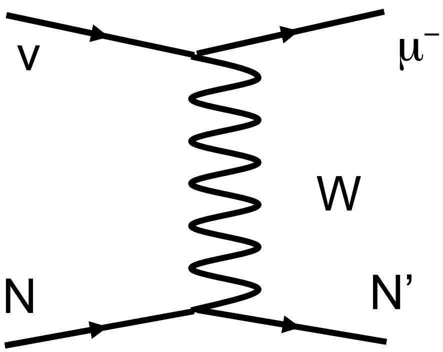
- Analysis considers a 50m high volume from 1-4° off-axis as the necessary E_ν region for the T2K oscillation analysis
  - 4° peaks at 380MeV
- Water Cherenkov detector with ~40% PMT coverage
  - Further cost reduction by instrumenting a movable portion of the detector
- Detector assumes containment of up to p_μ=1 GeV/c muons
  - 6m inner diameter, 10m including outer detector



νPRISM selection

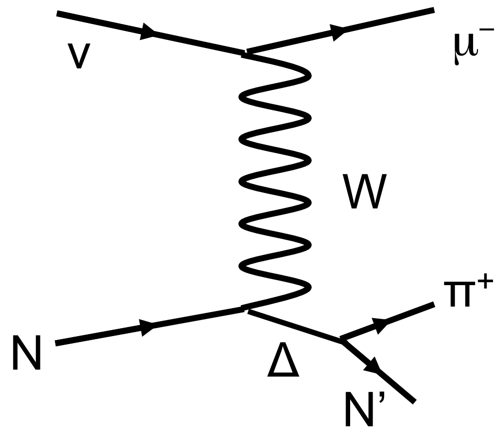
Signal: measure outgoing μ kinematics

CCQE



1p1h or 2p2h

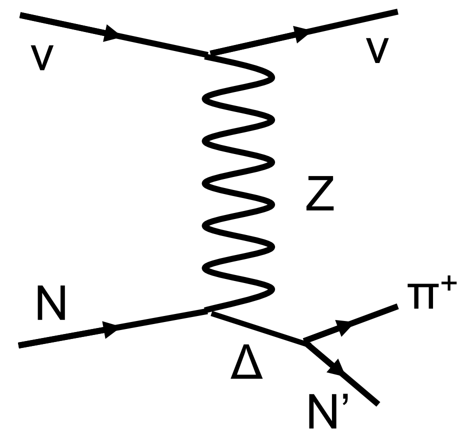
CCπ+



π absorbed in nucleus,
or below Cerenkov threshold

Background:

NCπ+



Select CCQE-like ν_μ candidates at νPRISM, correct for detector efficiency

- Signal includes true CCQE, multinucleon and CC1π^+ with absorbed pion
- Each component is also present at far detector under oscillation, so former "background" is also propagated

Subtract NC, external backgrounds from sample as these do not undergo oscillation

- Model dependence, but NC background is measureable (see later)

νPRISM ND extrapolation to FD

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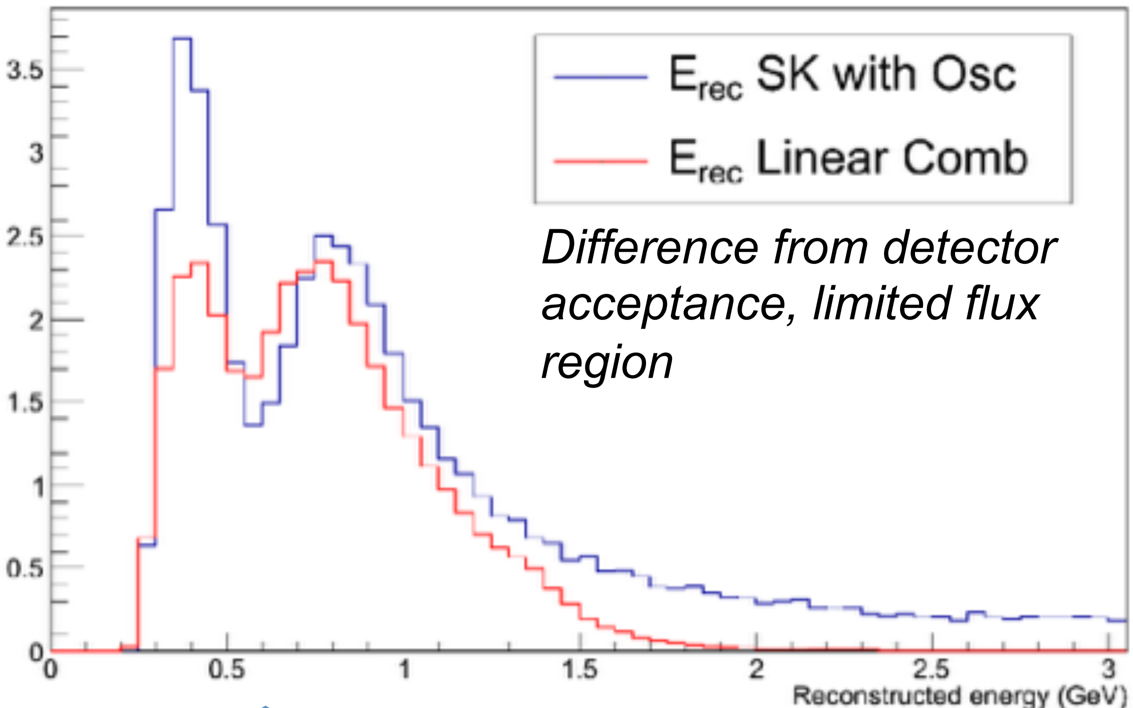
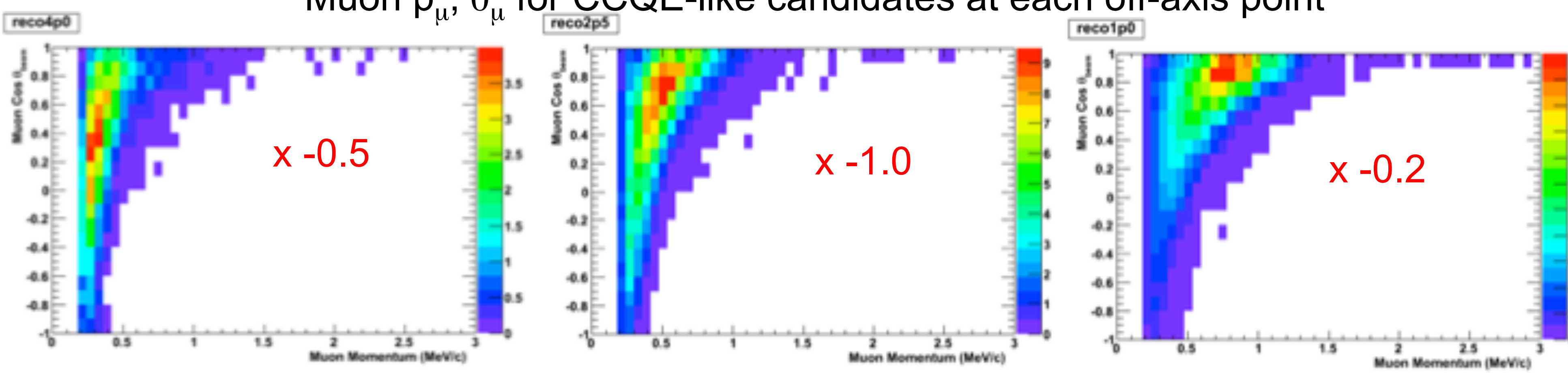


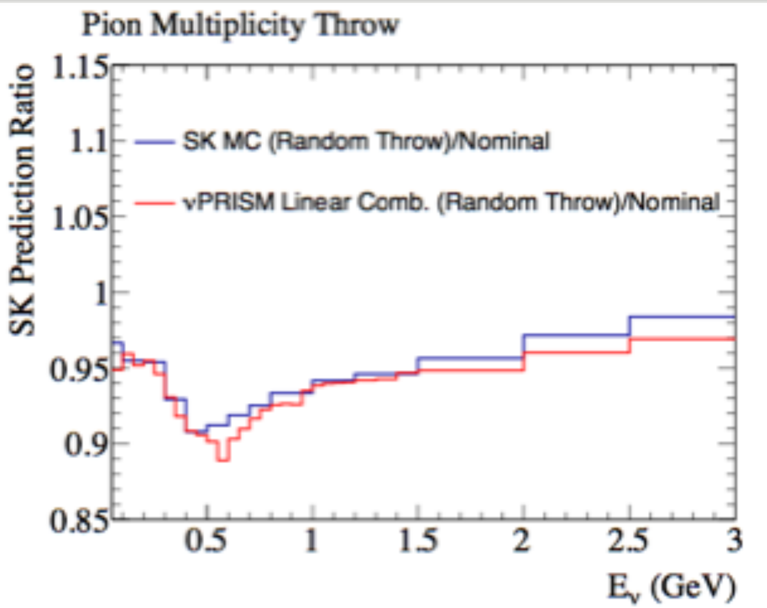
Build reconstructed E distribution (1D p_μ, θ_μ observable) for each Δm^2_{32}, θ_{23}

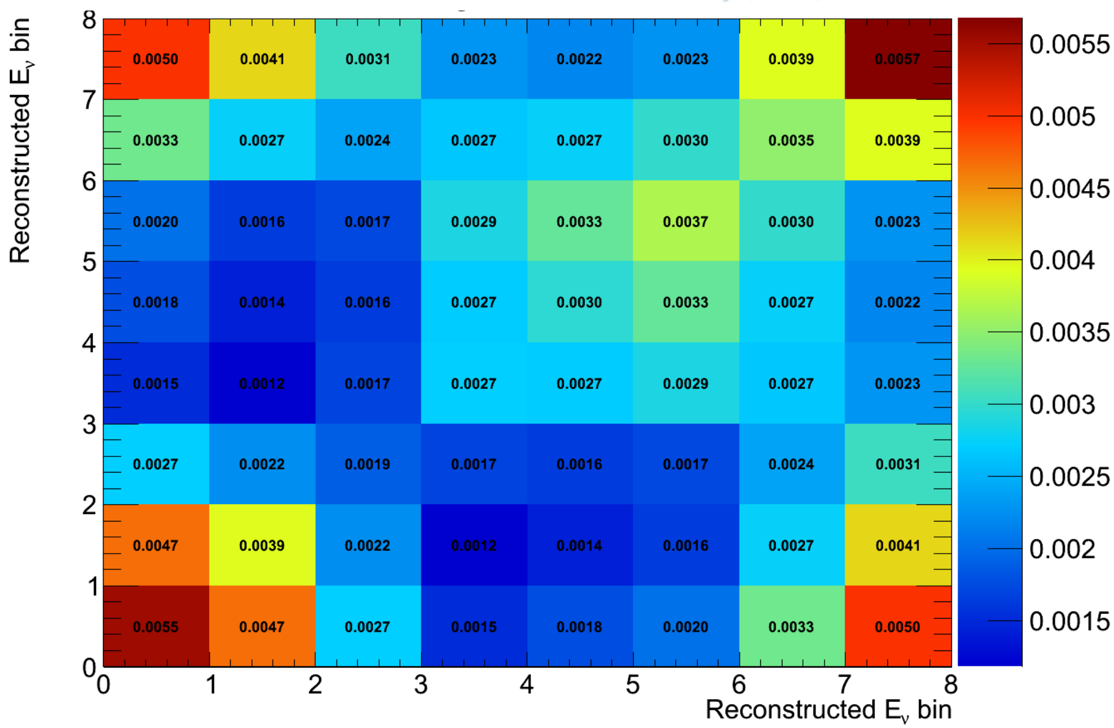
Include all statistical uncertainties and flux, cross section, detector uncertainties

Muon p_μ, θ_μ for CCQE-like candidates at each off-axis point



νPRISM ND extrapolation to FD





0:0.0-0.4 1:0.4,0.5 2:0.5,0.6 3:0.6,0.7 4:0.7,0.8 5:0.8,1.0 6:1.0,1.25 7:1.25,1.5 8:1.5,3.5 GeV

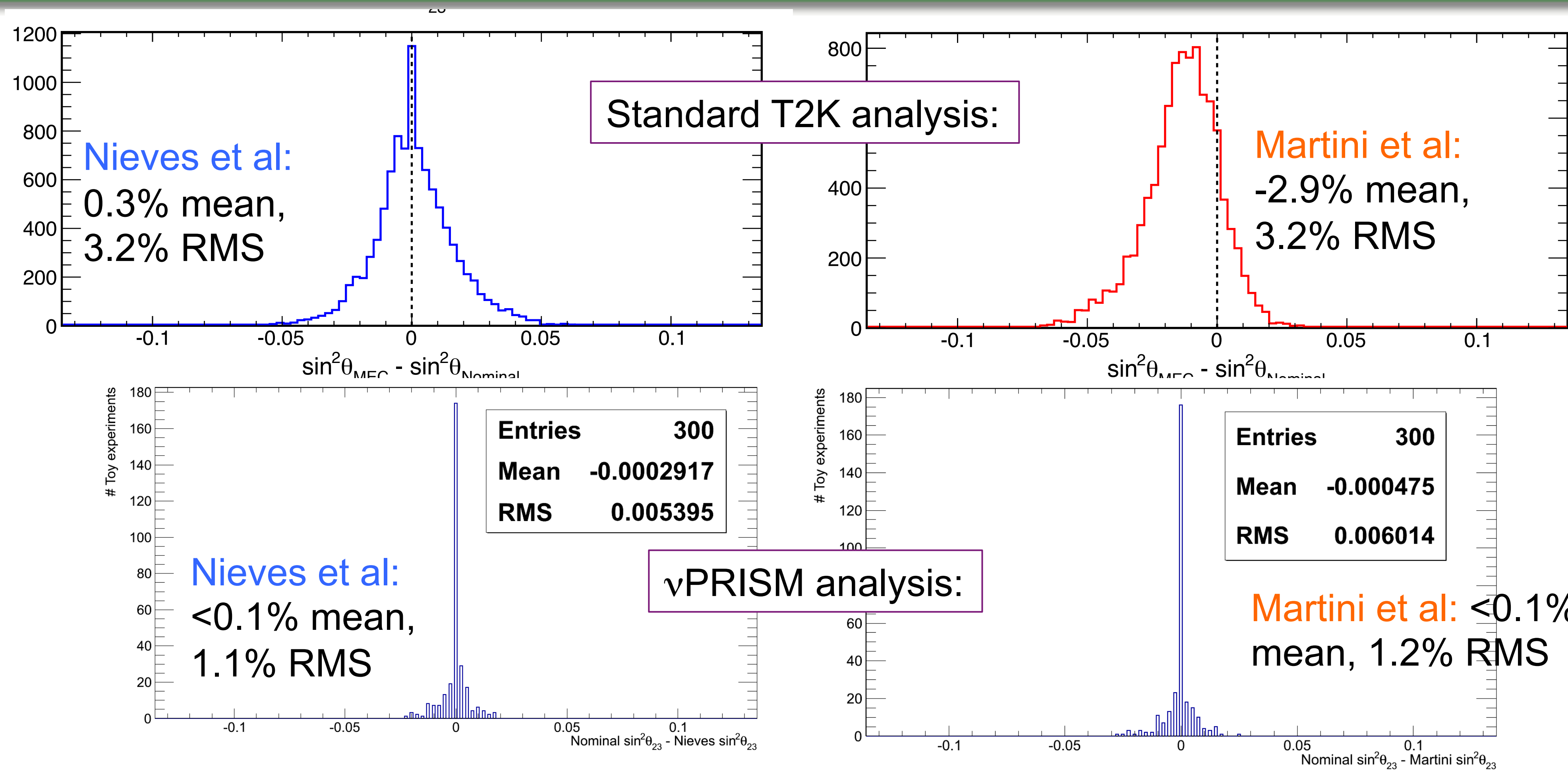
Build reconstructed E distribution (1D p_μ, θ_μ observable) for each Δm^2_{32}, θ_{23}

Include all statistical uncertainties and flux, cross section, detector uncertainties

Substantial constraint on predicted spectrum's flux uncertainties where νPRISM is sensitive

- Dominant flux uncertainty (pion production) affects νPRISM ND and FD flux similarly
- Flux uncertainties increase as expected where νPRISM has no constraint
  - νPRISM cannot predict spectrum above 1.5 GeV or below 0.4 GeV

Revisiting bias tests with νPRISM



Reminder: tested possible bias on 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

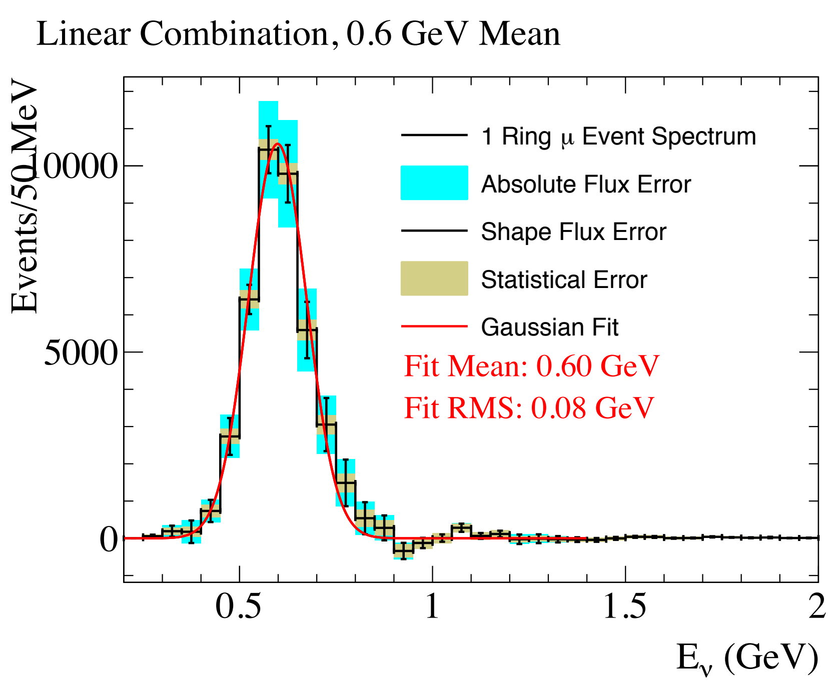
Bias replaced by data driven measurement

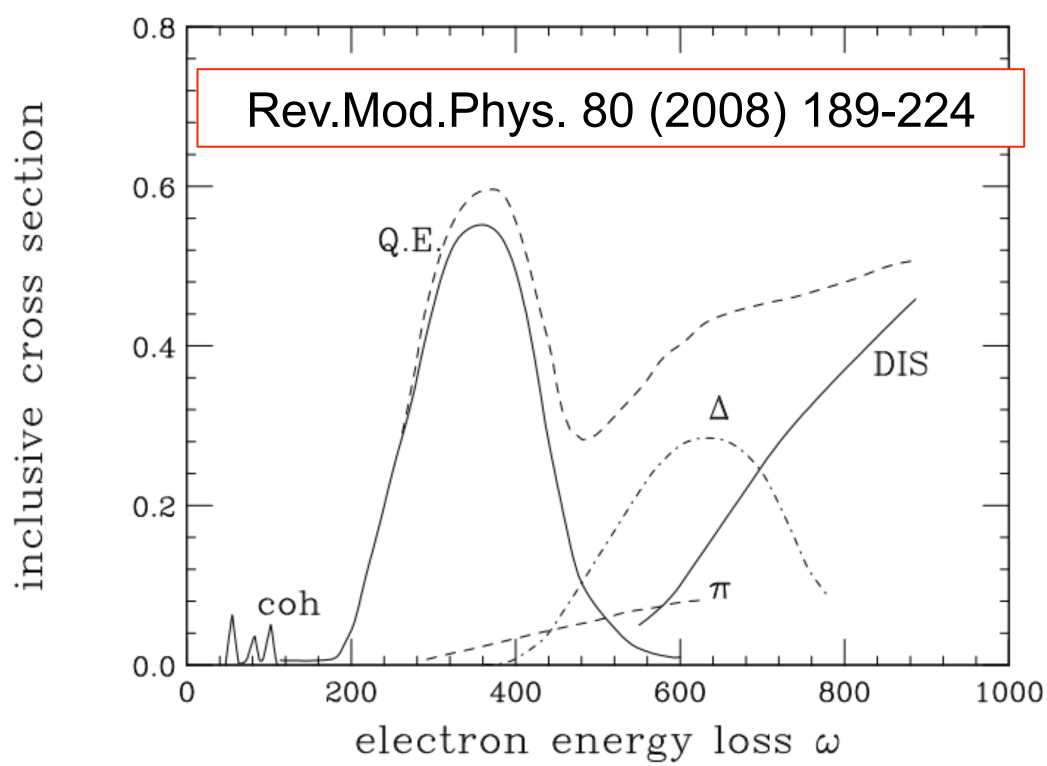
νPRISM cross section measurements

A monoenergetic (anti) neutrino beam is interesting for cross section physics
- All cross section measurements are averaged over (wide) fluxes
- Neutrino and antineutrino interactions of axial structure of the nucleus

Similar physics as electron scattering:
- Neutrino energy known (on average, to 10%)
- Outgoing lepton kinematics determine QE, instead of selection cuts
- nuPRISM probes pion production around Δ peak

Unique probe of NC interactions





ν_e/ν_μ cross section at νPRISM

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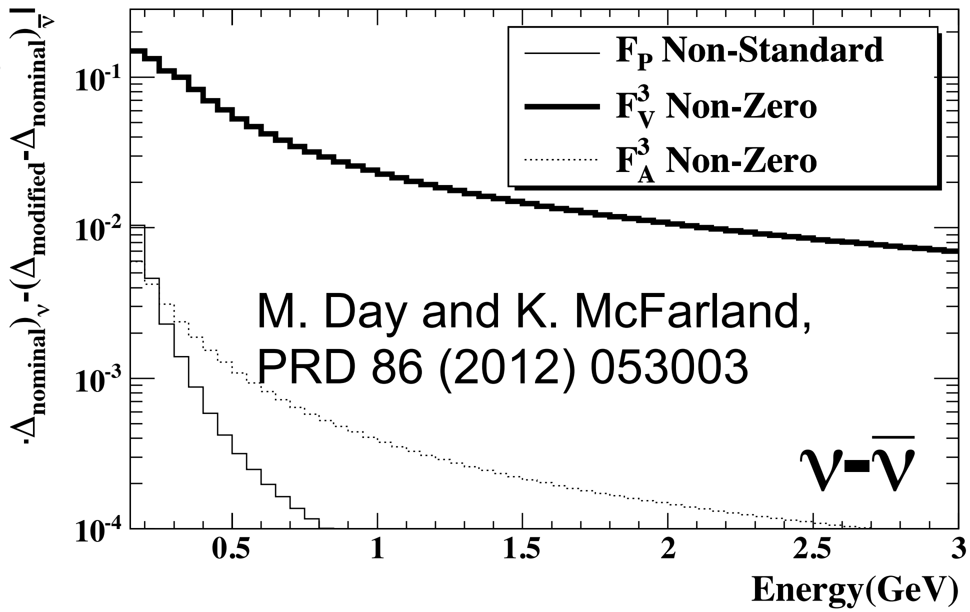
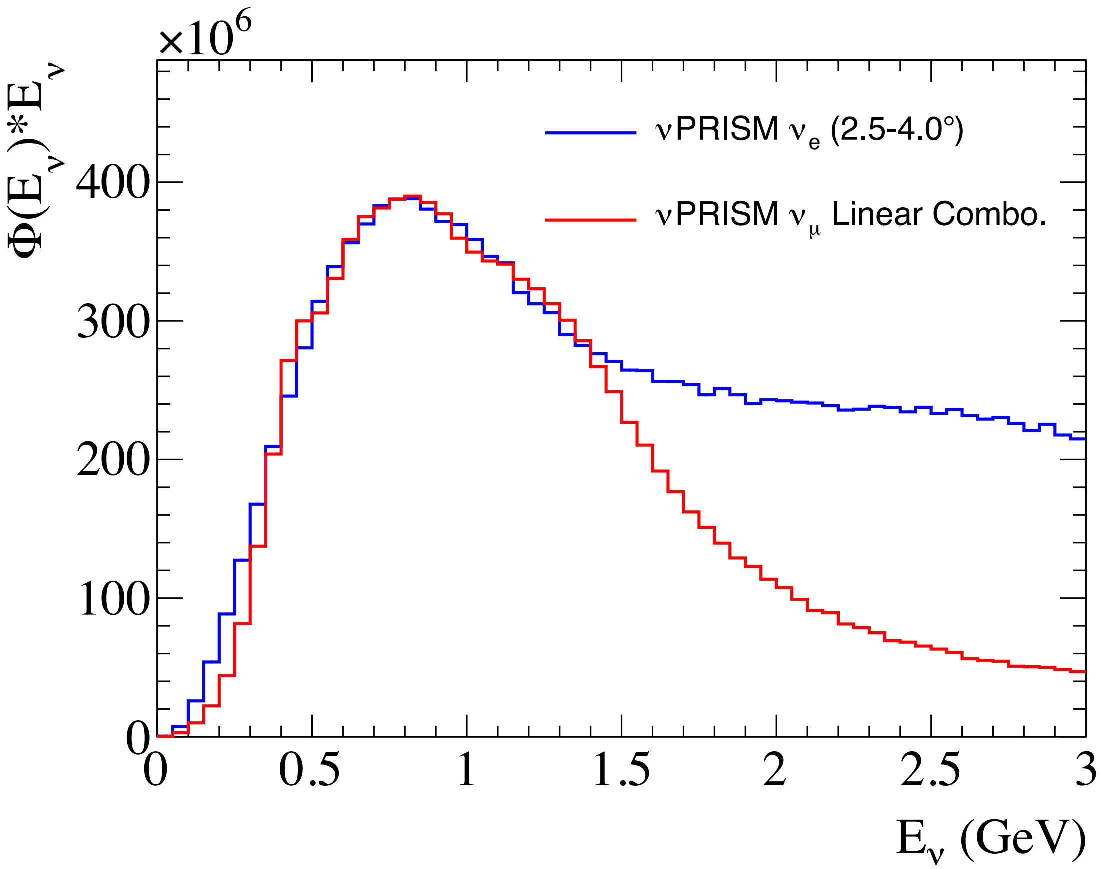
Differences between ν_e and ν_μ cross sections difficult to probe experimentally, but significant for for future program

- ν_μ cross section used to infer ν_e from ND
- T2K uncertainty on ν_e/ν_μ xsec is 3%





0.5% of T2K beam is ν_e, not possible to make mono-energetic beam

- Measurement ν_e/ν_μ ratio by matching intrinsic ν_e flux spectrum

Direct measurement of intrinsic ν_e background for appearance

Studies at MSU underway with undergraduates

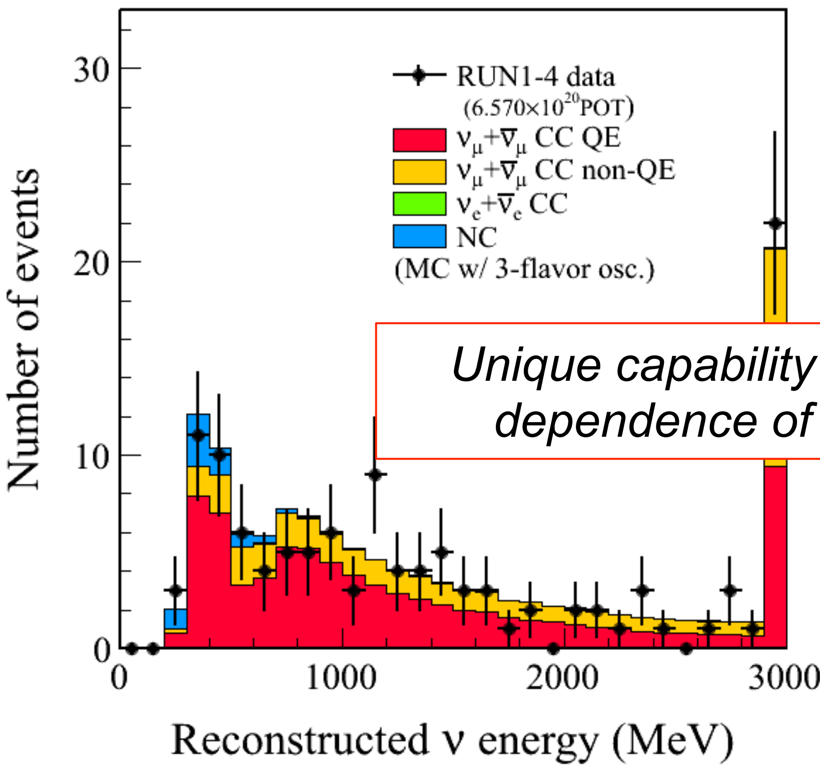
νPRISM cross section measurements

A monoenergetic neutrino beam is interesting for cross section physics

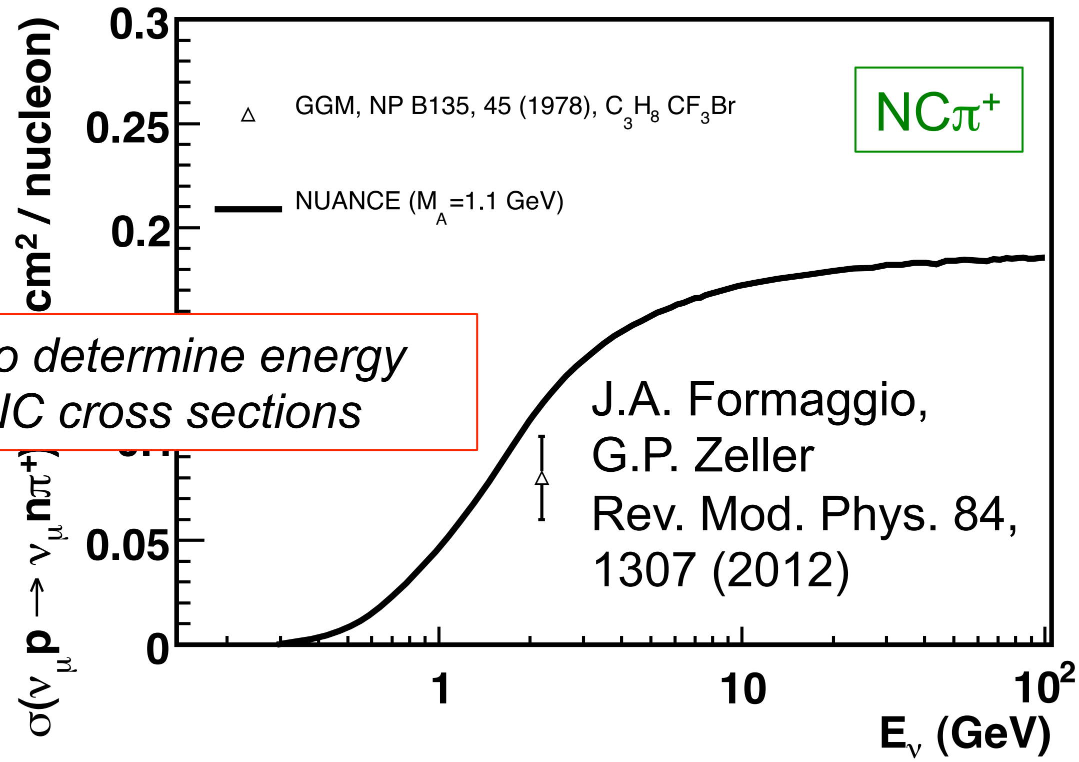
- All cross section measurements are averaged over (wide) fluxes
- Direct test of energy dependence for “CCQE”, characterize multinucleon processes

Other backgrounds to oscillation experiments come from NC processes:
$NC\pi^0$ (T2K ν_e appearance analysis) and $NC\pi^+$ (T2K disappearance analysis)

- Cross section vs. energy difficult to probe due to lack of measurements, no final state leptonic information
- Selection already possible for $NC\pi^0$, new fitter will be able to measure π^+



Unique capability to determine energy dependence of NC cross sections



Additional osc-multinucleon studies

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True	Fitted	$\theta_{23,min}$	$\Delta m^2_{31,min}$[eV^2]	χ^2_{min}	σ_a	Fig. no.
GENIE (^{16}O)	GENIE (^{12}C)	44°	2.49×10^{-3}	2.28	–	4
GiBUU (^{16}O)	GENIE (^{16}O)	41.75°	2.69×10^{-3}	47.64	–	5(a)
		47°	2.55×10^{-3}	20.95	5%	5(b)
GiBUU (^{16}O)	GiBUU (^{16}O) w/o MEC	42.5°	2.44×10^{-3}	22.38	–	6(a)
GENIE (^{16}O)	GENIE (^{16}O) w/o MEC	44.5°	2.36×10^{-3}	19.54	–	6(b)

Significant variations to determination of θ_{23}, Δm^2_{32} if a different simulation is used to generate fake data and fit (Coloma et al, PRD 89, 073015 (2014))

- Significant bias if multinucleon (MEC) component is not considered

Also noted in theoretical publications discussing multinucleon effects, including:

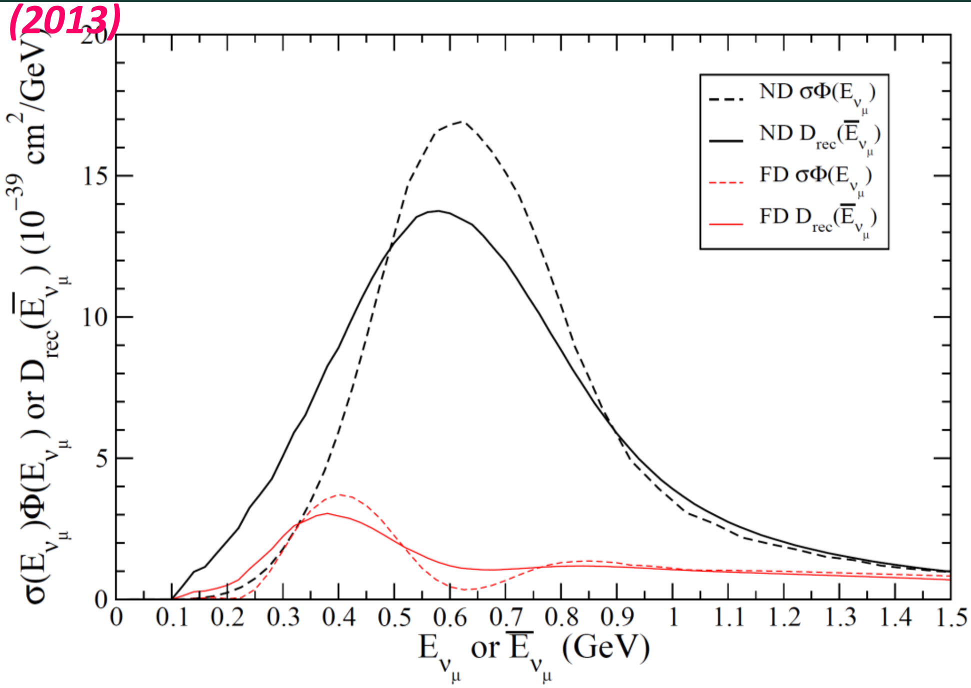
- J. Nieves et al PRD 85, 113008 (2012)
- O. Lalakulich, U. Mosel, and K. Gallmeister, PRC 86, 054606 (2012)
- M. Martini, M. Ericson, and G. Chanfray, PRD 85, 093012 (2012)
- M. Martini, M. Ericson, and G. Chanfray, PRD 87, 013009 (2013)
- D. Meloni and M. Martini, PLB 716, 186 (2012)

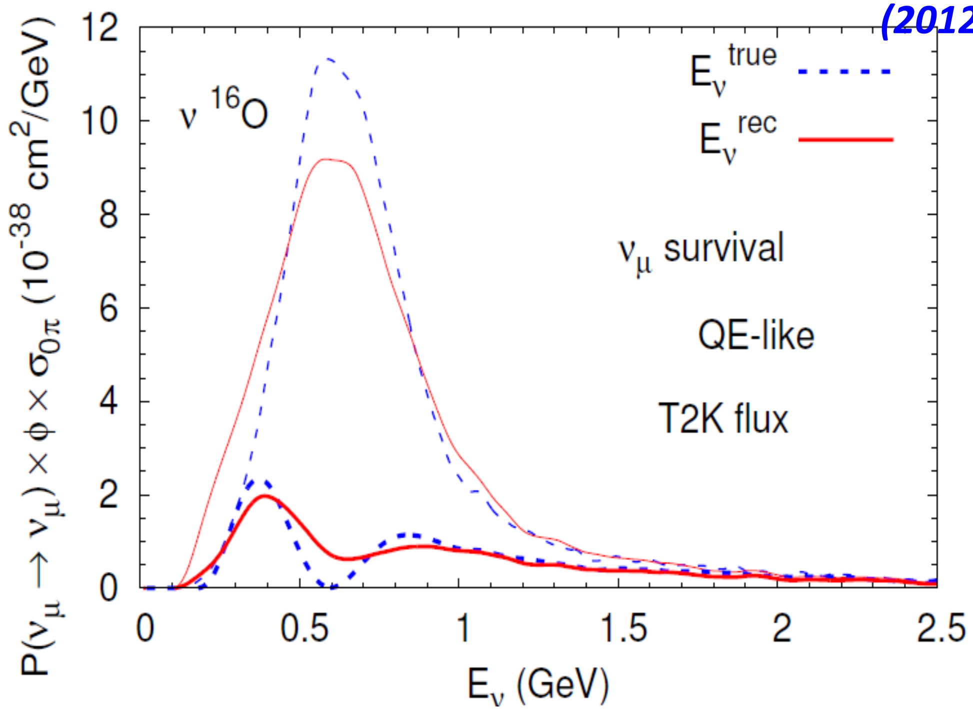
	$\sin^2 2\theta_{13}$	$\theta_{23}(^o)$	Δm^2_{atm} (10^{-3}eV^2)
FG	[0.041-0.211] (0.105)	[40.1-51.3] (47.6)	[2.45-2.67] (2.56)
MECM	[0.023-0.154] (0.092)	[41.1-49.9] (45.4)	[2.49-2.67] (2.60)

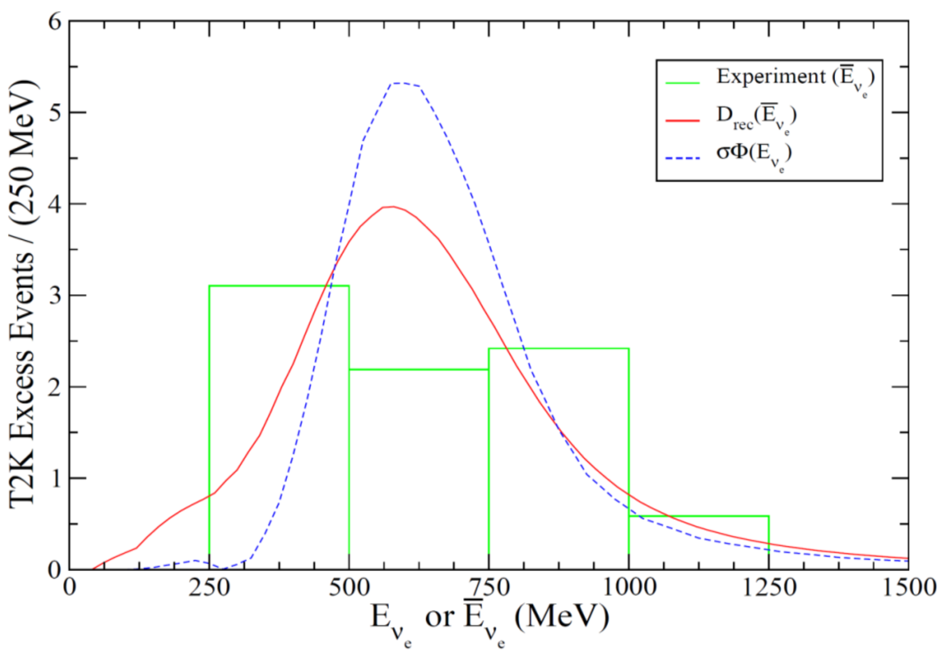
Table 5: *90% intervals for* $\sin^2 2\theta_{13}, \theta_{23}$ *and* Δm^2_{atm}, *for the MECM and FG models in the case the current T2K statistics is increased by a factor of 10. In parenthesis, the best fit points.*

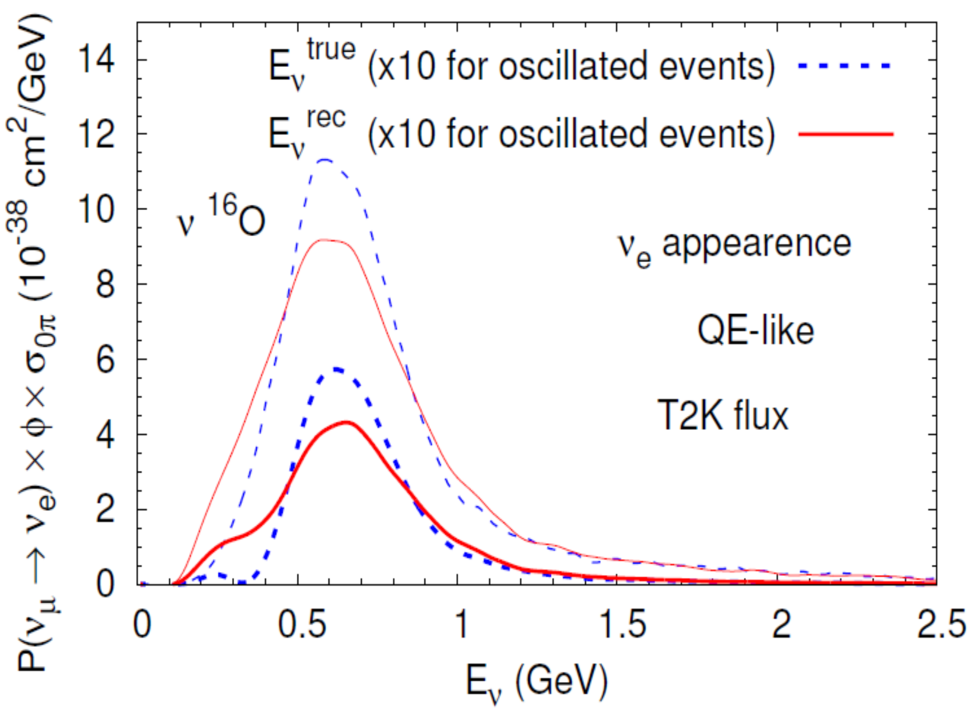
M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

O. Lalakulich, U. Mosel, K. Gallmeister, PRC 86 054606 (2012)









Civil construction and costing

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(Unit: Oku JPY, roughly corresponds to Million USD)

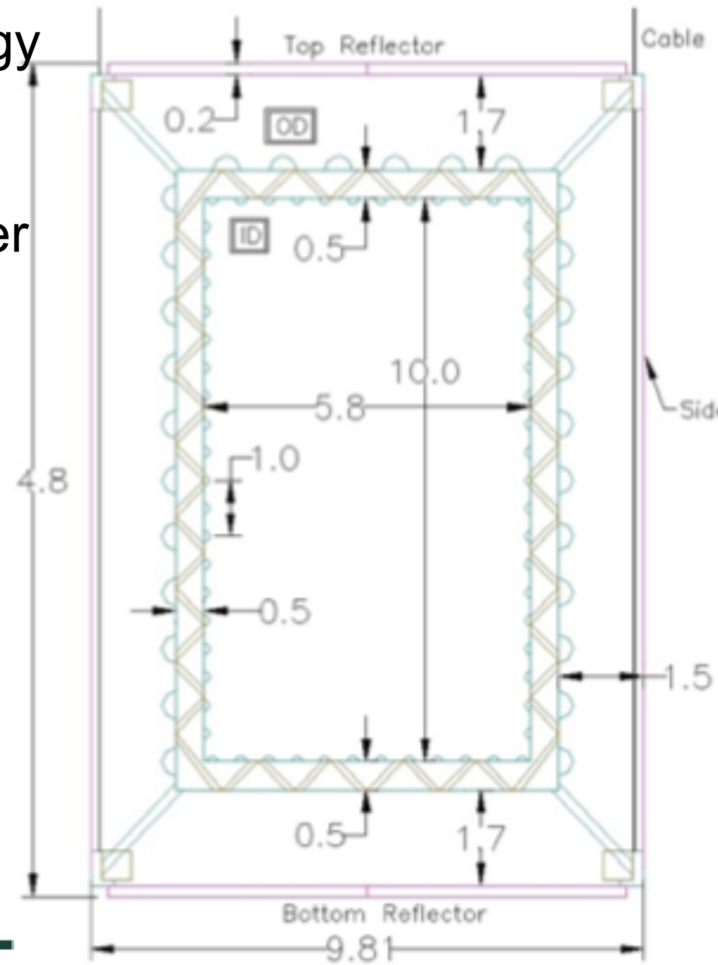
Method	Pneumatic Caisson	Soil Mixing Wall	New Austrian Tunneling	Urban Ring
Survey	0.1 (assume 70 m deep boring survey)			
Designing	0.15			
Land preparation	0.15			
Construction	7.7	5.9	5.3~6.1	15

Construction method would depend on exact site geology

- ~5-8M$ USD for 10m diameter, 50m pit

Cost of PMTs, electronics are other significant cost driver

- Instrument a movable frame
  - Complete initial design, considers water flow and maintenance
- For 3,000 PMTs, 4.3M$USD
  - Considering 8”,5” normal and high quantum efficiency
  - Also looking at borrowing existing PMTs
- ~3 year timescale from approval to completion
  - Lead time needed to secure site



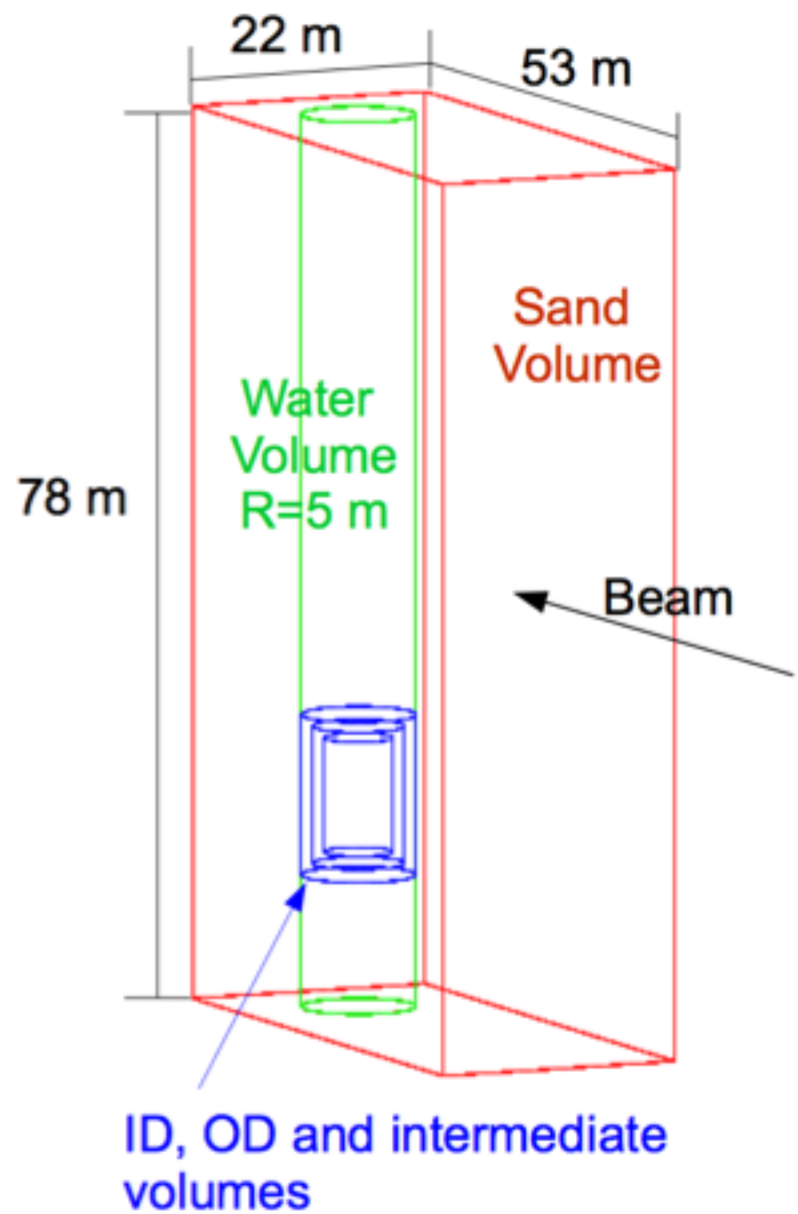
Simulation and event rate

Full GEANT4 simulation of water, surrounding sand

- Includes T2K flux and NEUT interaction generator inside and outside detector
- Simplified detector response, efficiency applied for ν_μ, ν_e events

- For 4.5 x10^{20} POT:

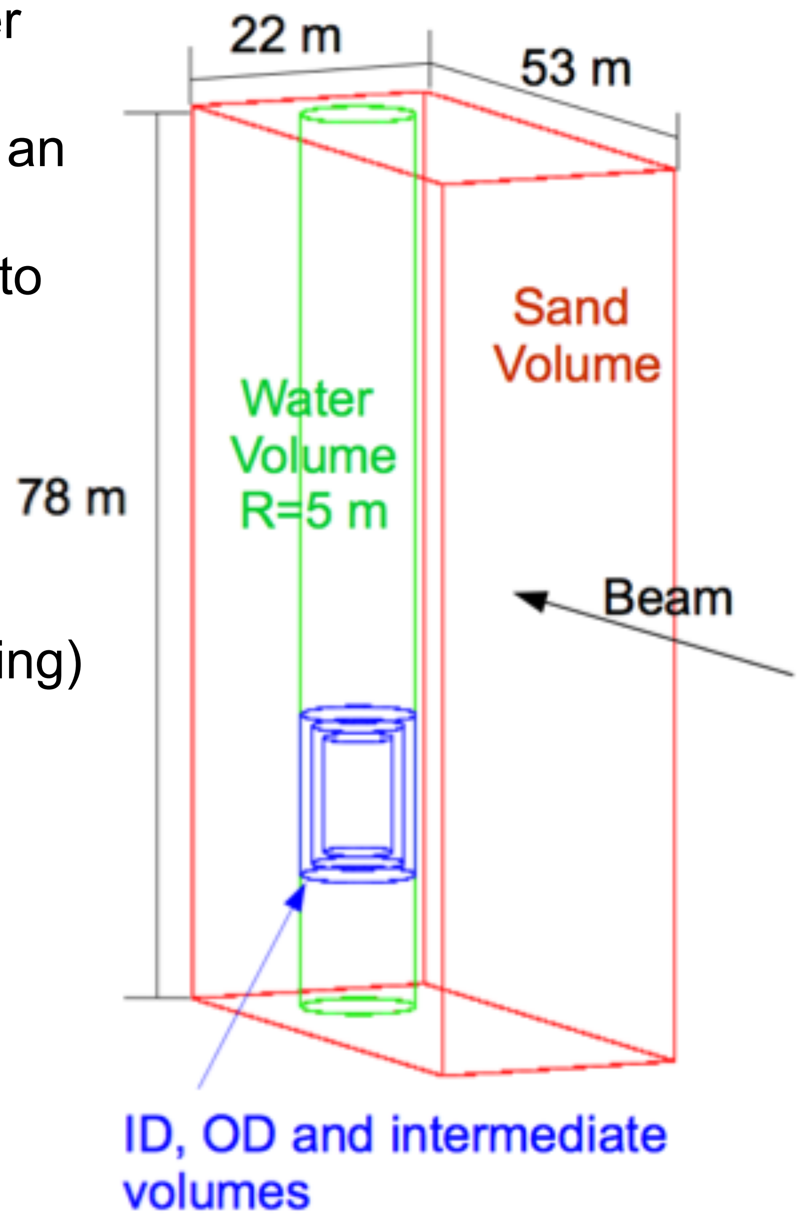
Int. mode	1-2°	2-3°	3-4°
CC inclusive	1105454	490035	210408
CCQE	505275	271299	128198
CC1π^+	312997	111410	39942
CC1π^0	66344	23399	8495
CC Coh	29258	12027	4857
NC 1π^0	86741	32958	12304
NC 1π^+	31796	11938	4588
NC Coh	18500	8353	3523



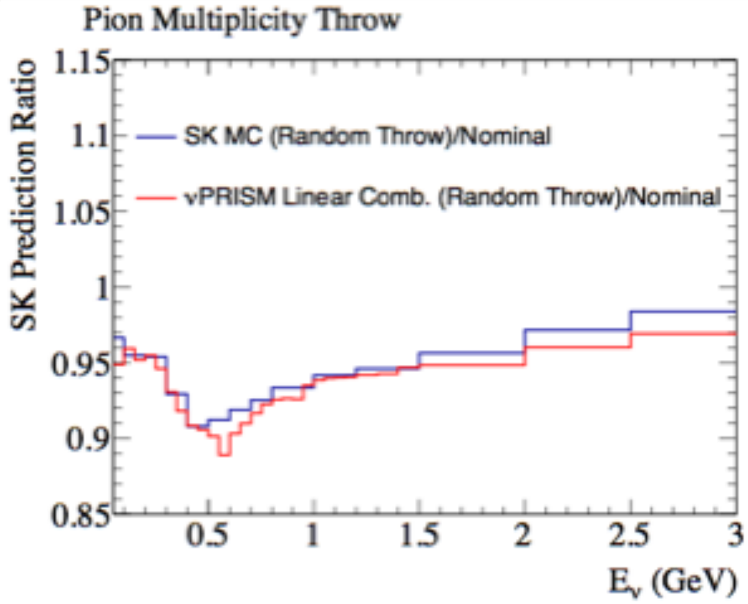
Pile-up and vetoing

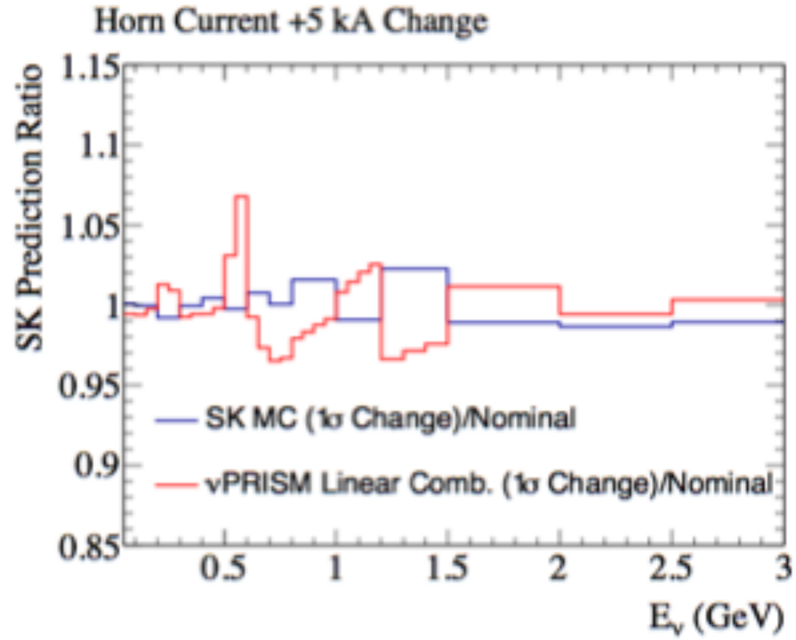
Beam consists of 8 bunches per spill, consider multiple neutrino interactions in ID, OD

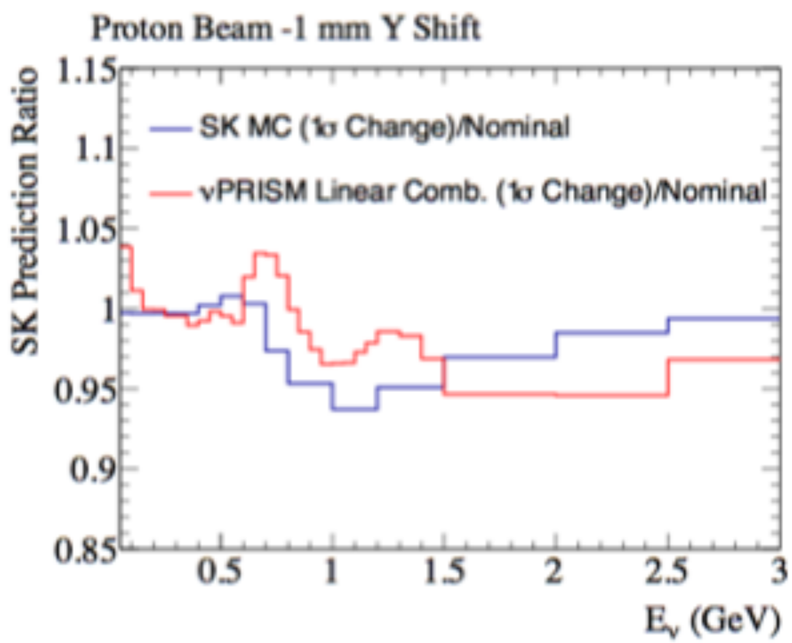
- 41% chance of in-bunch OD activity during an ID-contained event
  - Consider scintillator panels in addition to OD activity
- 17% of bunches have ID activity from more than 1 interaction (10% with no OD)
  - Full MC studies planned
  - New FD reconstruction works well with multiple particles in same event (multiring)



Flux uncertainties

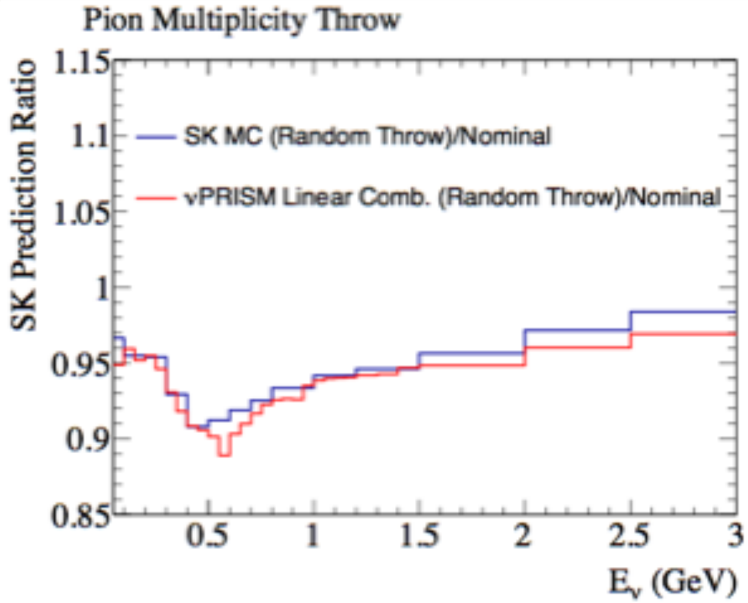


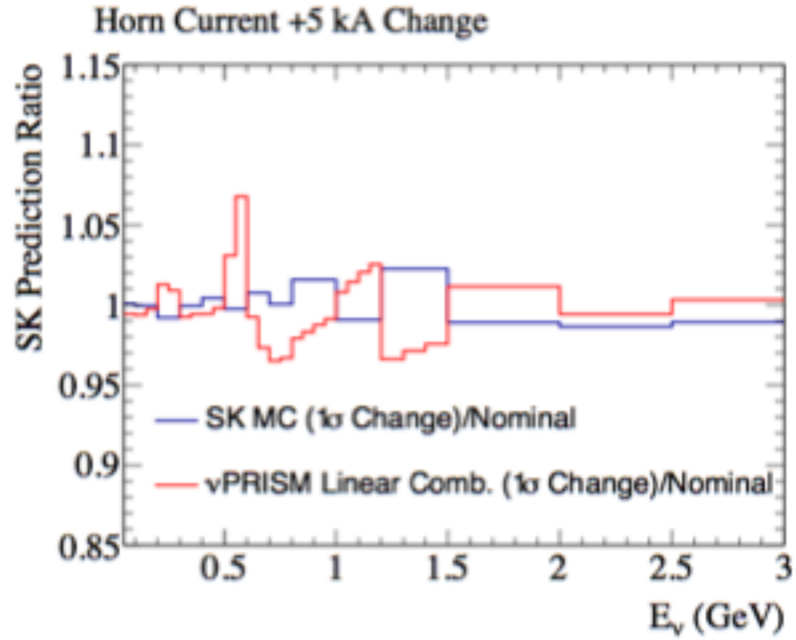


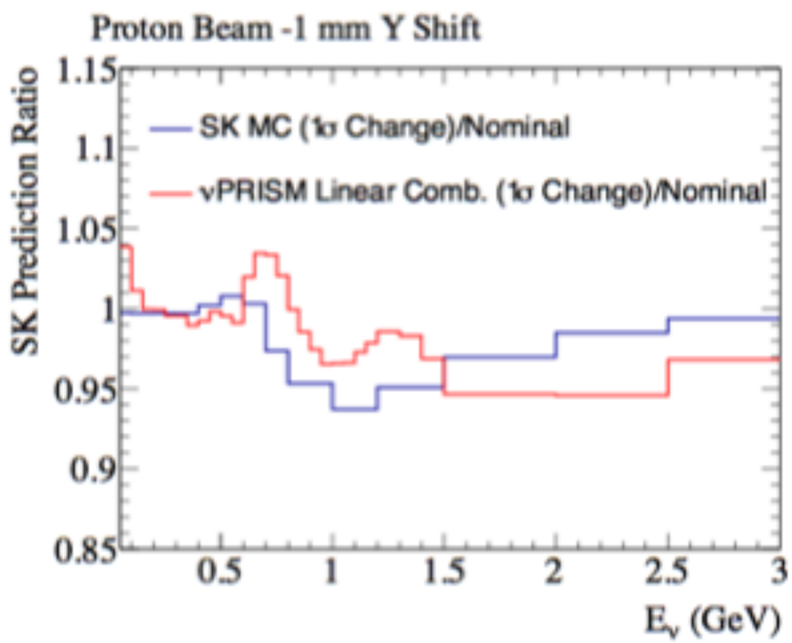


- Dominant flux uncertainty (pion production) affects νPRISM ND and FD flux similarly
- Proton beam and horn current affect off-axis angle
- ~10% change becomes 1% on $\sin^2\theta_{23}$

Flux uncertainties







- Dominant flux uncertainty (pion production) affects νPRISM ND and FD flux similarly
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- ~10% change becomes 1% on $\sin^2\theta_{23}$

T2HK: Hyper-Kamiokande

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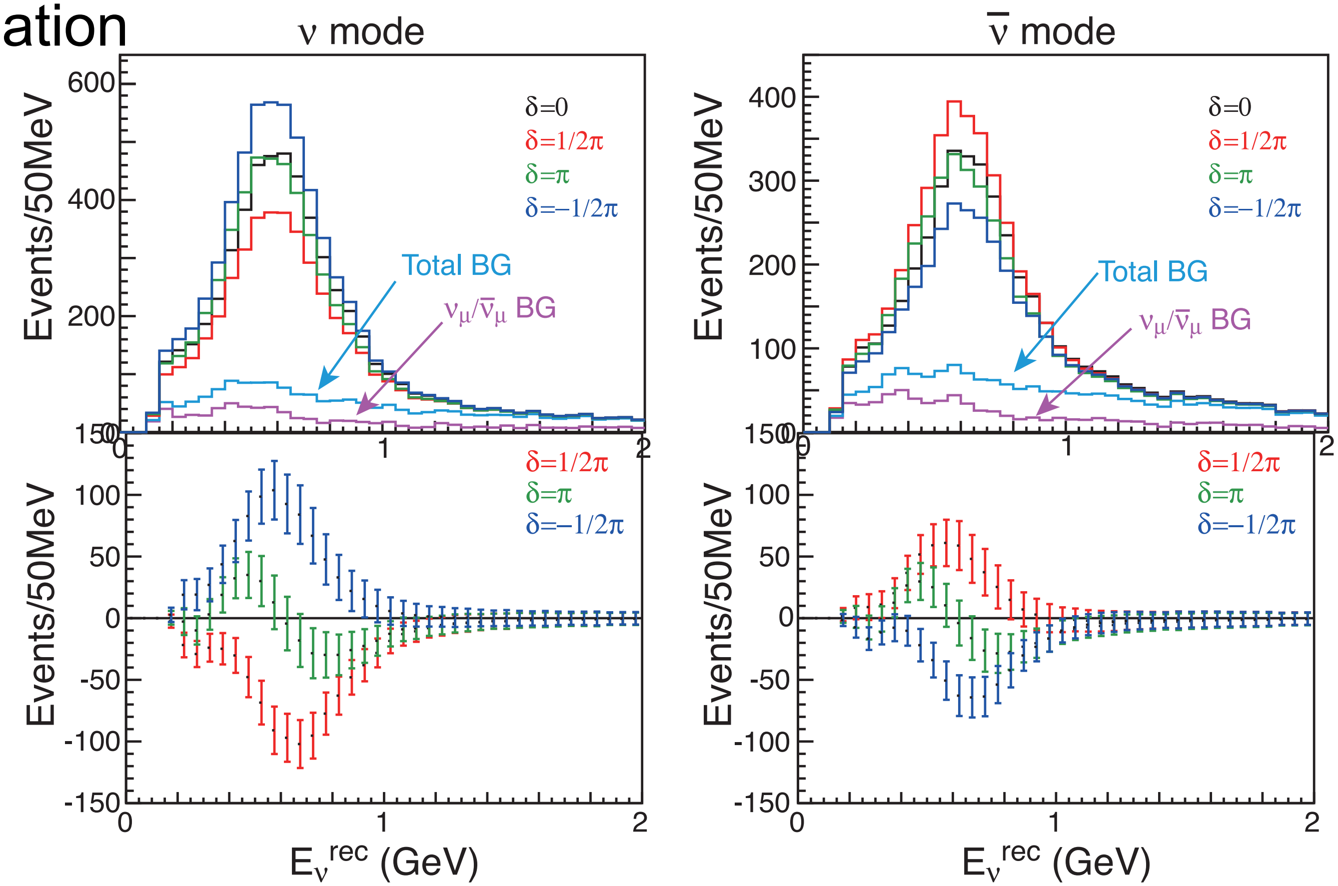
T2HK: same neutrino beamline and off-axis angle as T2K

Would use a new detector (Hyper-Kamiokande) in a different cavern

- Event rate enhanced over T2K's with a much larger ~1Mton far detector (approximately 25x T2K's current far detector)
- Technique requires mass hierarchy is known, assuming determined from cosmology, 0νββ, atmospheric neutrinos, or T2K-NoVA combination

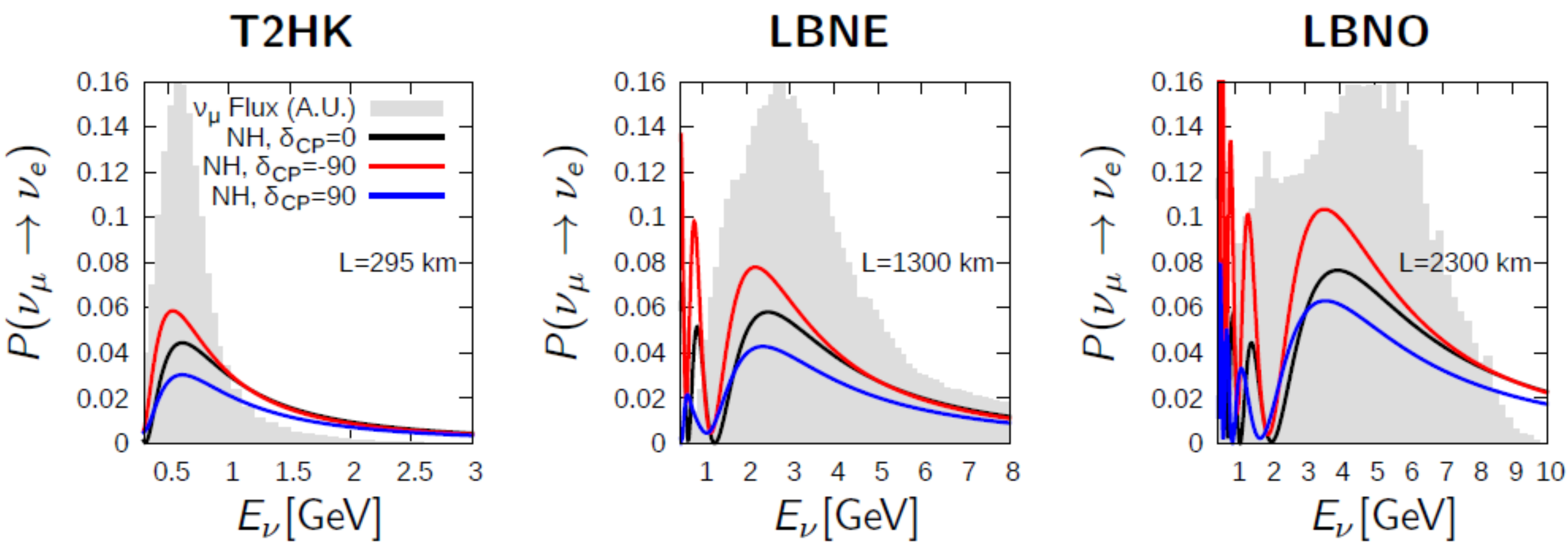


Hyper-Kamiokande LOI: arXiv:1109.3262

Future LBL experiments

Wide band (on-axis) beams can be used to directly test energy dependence of oscillation and determine the mass hierarchy and δ_{CP} simultaneously

- LBNE (now LBNF): 1300km distance (FNAL to South Dakota),
- LBNO/LAGUNA: 2300km distance (CERN to Finland)



M. Bass, NuInt2014