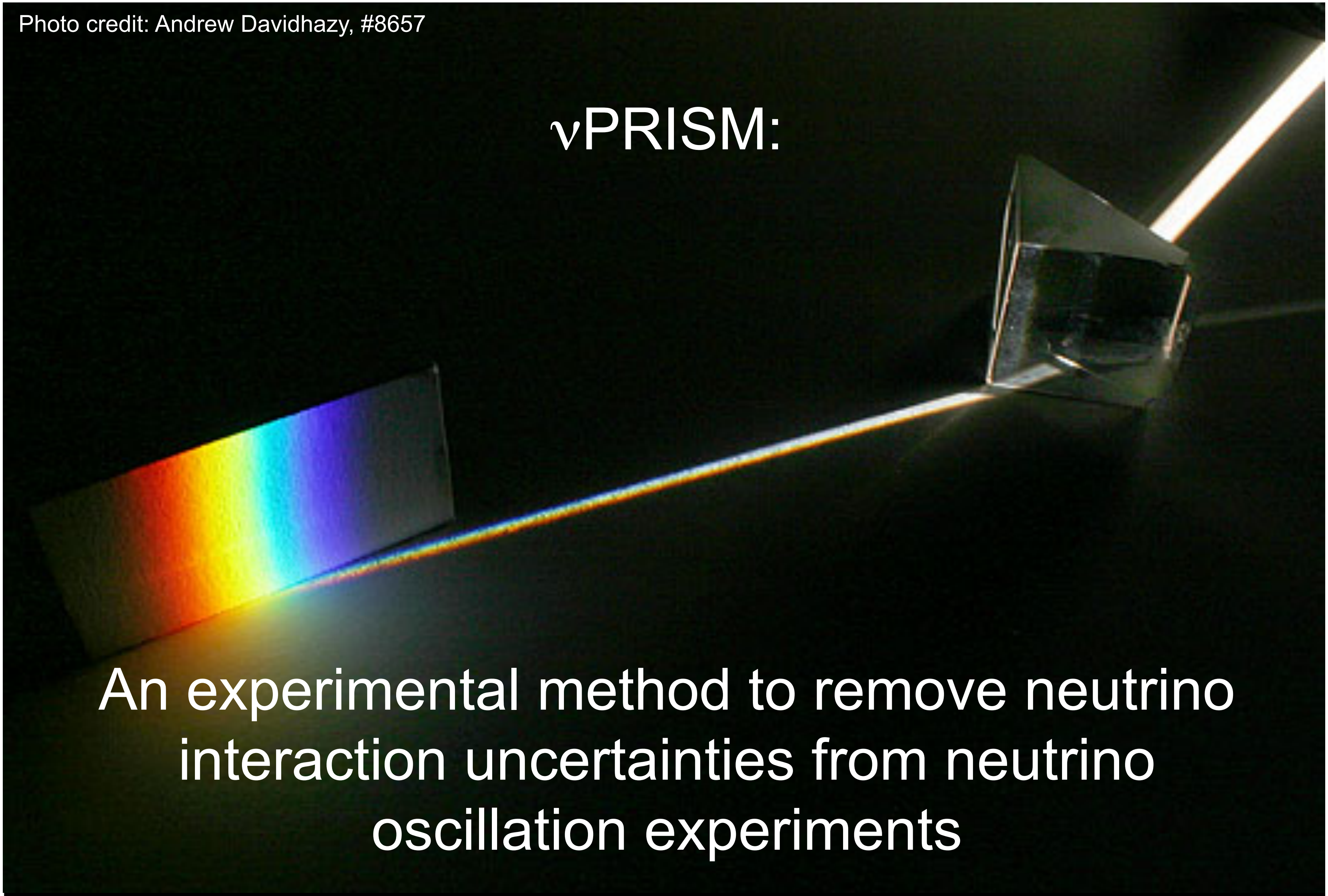


Photo credit: Andrew Davidhazy, #8657

νPRISM:

An experimental method to remove neutrino interaction uncertainties from neutrino oscillation experiments

Kendall Mahn
Michigan State University
For νPRISM working group

What is neutrino oscillation?

Evidence of massive neutrinos comes from the observation of neutrino oscillation, the interference between the flavor and mass eigenstates.

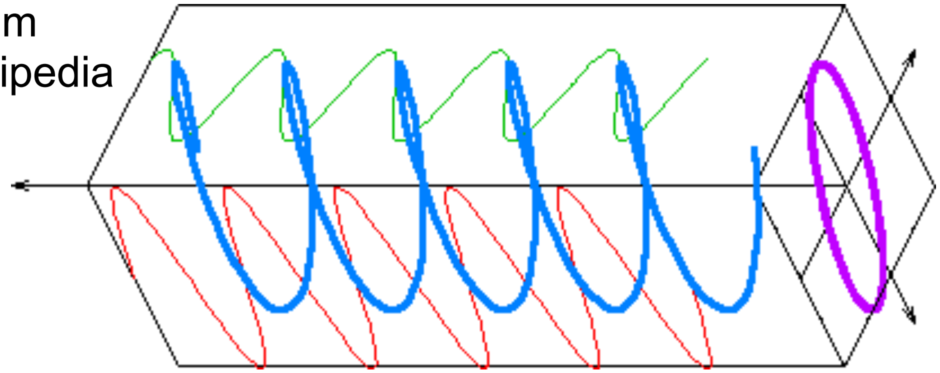
If we start with two neutrino flavor (ν_e, ν_μ) and two mass states (ν_1, ν_2) then:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ \text{-}\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

The flavor state evolution in time is like an elliptically polarized wave:

$$|\nu_\mu(t)\rangle = -\sin\,\theta\; e^{-iE_1 t}\,|\nu_1\rangle + \cos\,\theta\; e^{-iE_2 t}\,|\nu_2\rangle$$

From wikipedia



Starting polarized along the x-axis (like starting in ν_μ state) then:

- Some time later polarization is along y-axis (ν_ε)
- Or back to the x-axis (ν_μ)

Open questions about neutrino mixing

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

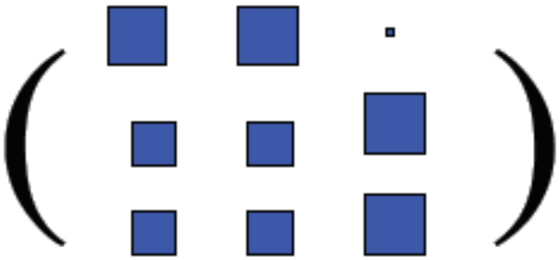
Three observed flavors of neutrinos (ν_e, ν_μ , ν_τ) means U is represented by three independent mixing angles (θ_{12}, θ_{23}, θ_{13}) and a CP violating phase δ

$$\theta_{12} = 33.6^\circ \pm 1.0^\circ$$

$$\theta_{23} = 45^\circ \pm 6^\circ \quad (90\%\mathrm{CL})$$

$$\theta_{13} = 9.1^\circ \pm 0.6^\circ$$

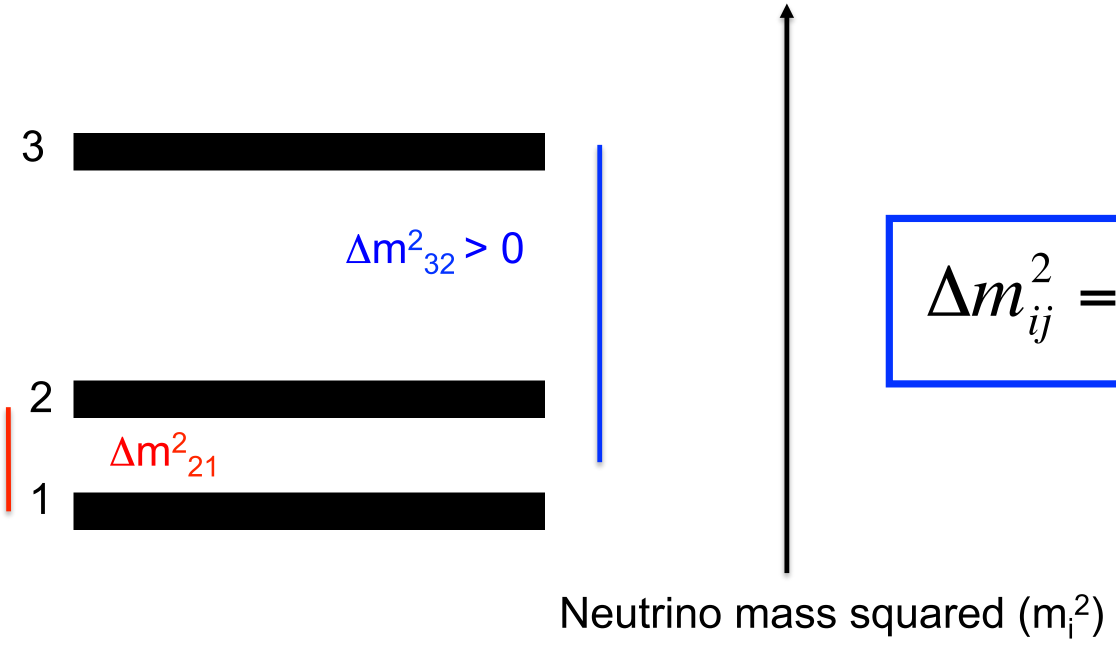
PDG2012



Is θ_{23} mixing maximal (45°?)

Is there CP violation (non-zero δ?)

Open questions about neutrino mixing



$$\boxed{\Delta m^2_{ij} = m^2_i - m^2_j}$$

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

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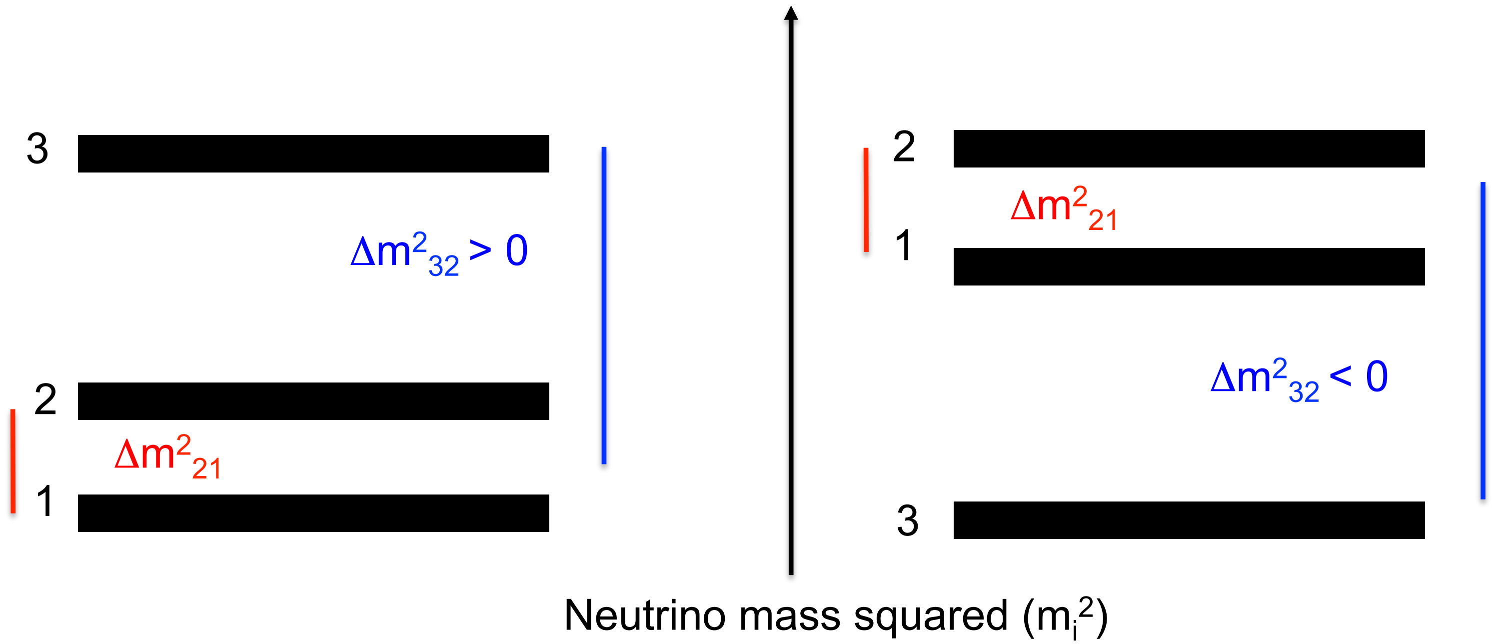


The sign of Δm^2_{32}, or the "mass hierarchy" is still unknown

- 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

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

A small amount of ν_e will "appear"

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

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

Only leading order terms shown

Oscillation probabilities

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

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

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"

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

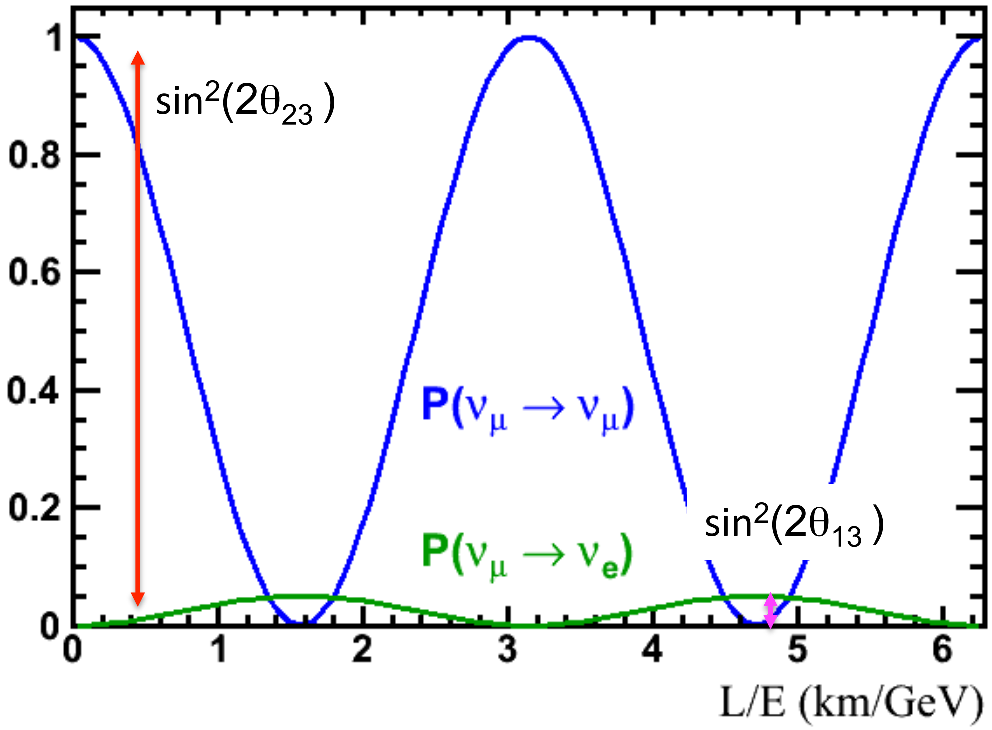
$$\boxed{P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right)}$$

Only leading order terms shown

Toy oscillation experiment

We infer the values of oscillation parameters from:

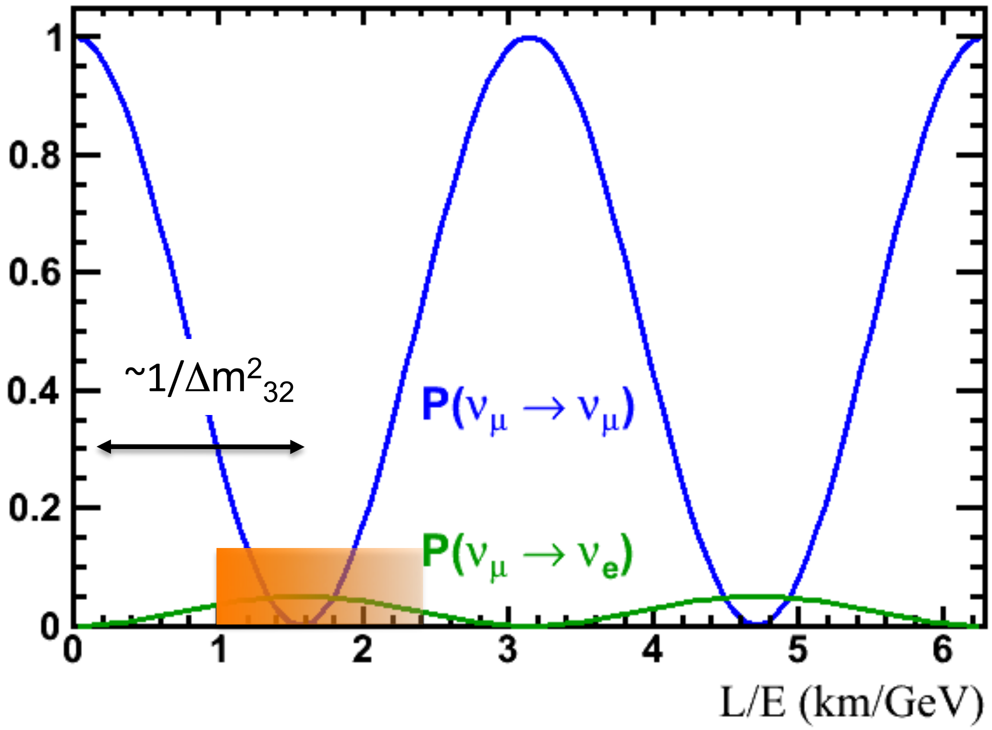
- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)



Toy oscillation experiment

We infer the values of oscillation parameters from:

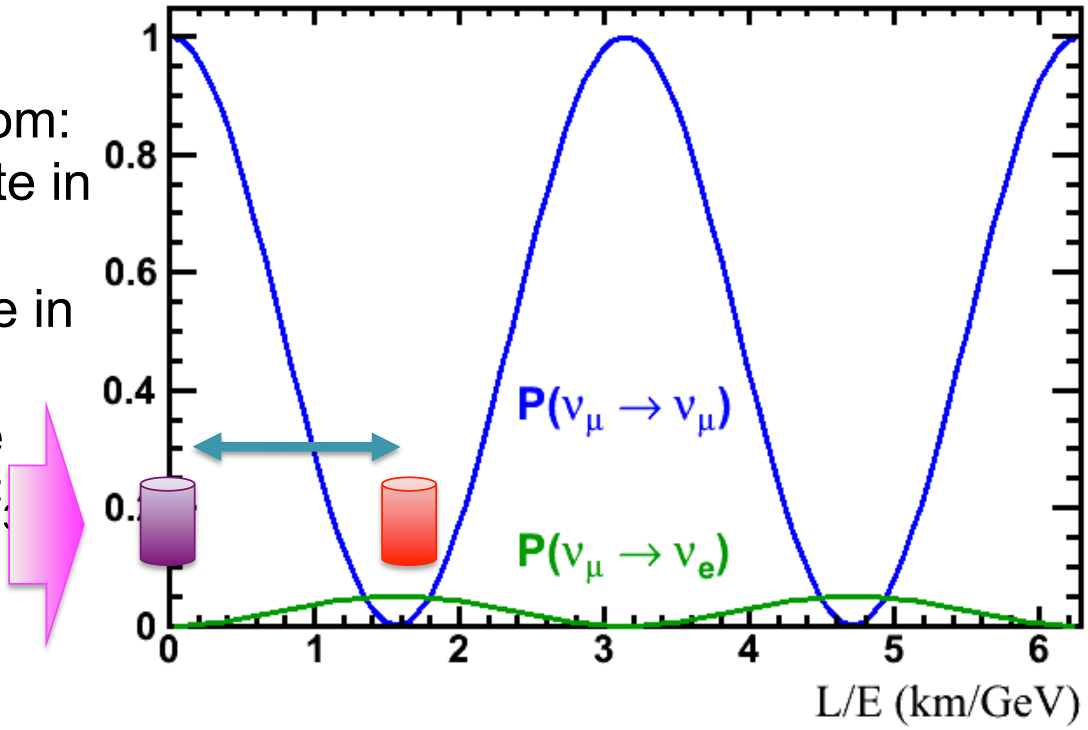
- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)
- and the distortion to the neutrino spectrum (Δm^2_{32})



Toy oscillation experiment

We infer the values of oscillation parameters from:

- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)
- and the distortion to the neutrino spectrum (Δm^2



To search for neutrino oscillation, we need:

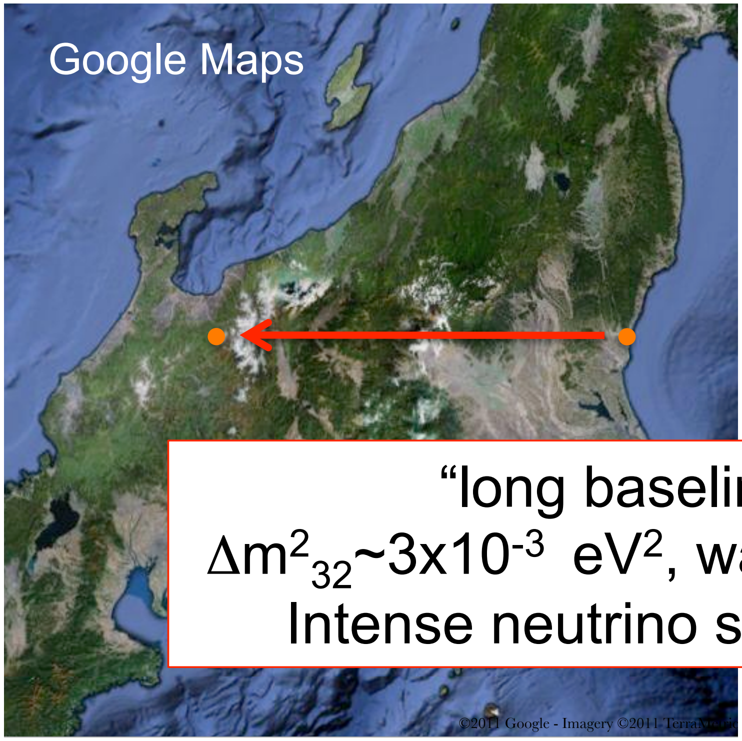
1) An intense neutrino source of muon neutrinos
2) A sufficient distance for oscillation to occur
3) A “near detector” measurement of unoscillated ν_μ (and ν_e background) rate at L~0
4) A “far detector” measurement of ν_μ, ν_e at L~ oscillation maximum

Long-baseline experiments

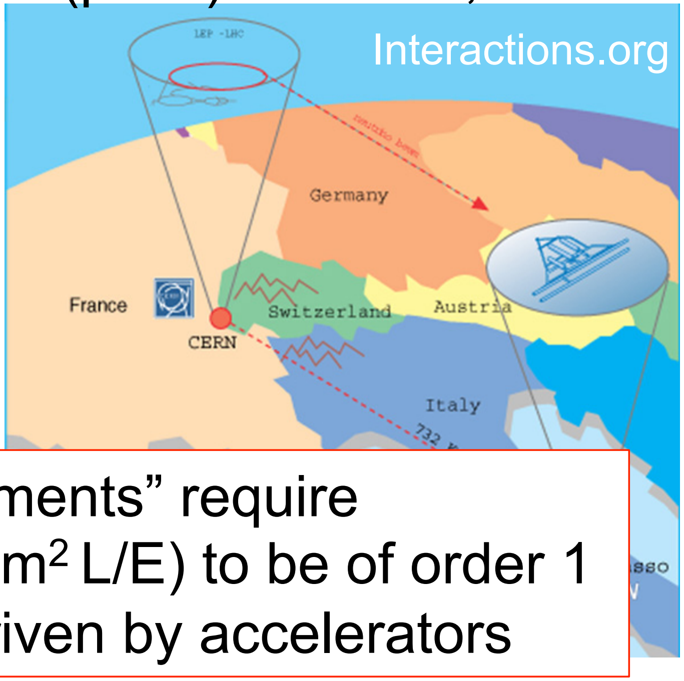
The oscillation probability, P, for ν_μ to oscillate is sinusoidal and depends on the distance L (km) the neutrinos travel and their energy E (GeV):

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

Tokai To Kamioka (T2K) experiment:
Eν(peak) ~0.6GeV, L=295km

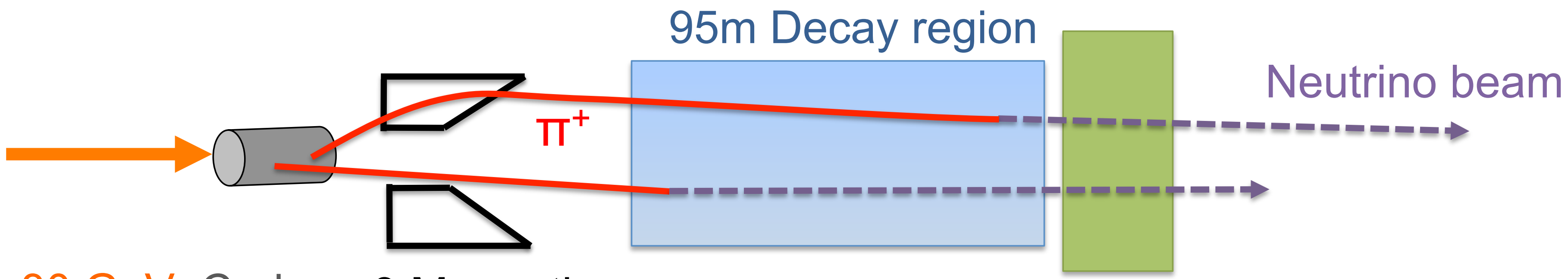


OPERA experiment:
Eν(peak) ~17 GeV, L=730km



"long baseline experiments" require
Δm^2_{32}~3×10^{-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



95m Decay region

Neutrino beam

π^+

30 GeV Proton beam

Carbon Target

3 Magnetic focusing ``horns”

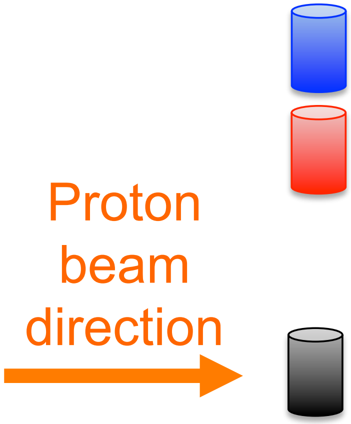
Pions and kaons decay to neutrinos

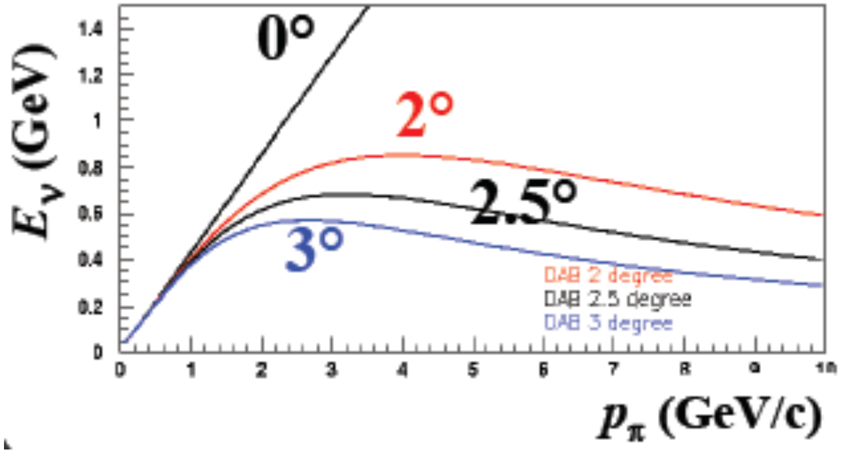
Beam dump

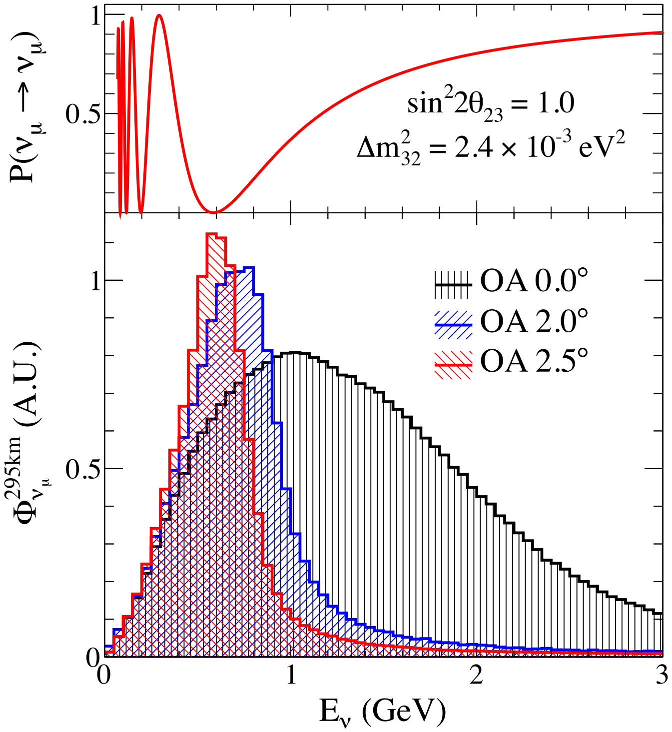
Neutrinos are produced as a tertiary beam:

1. Protons hit a target, producing pions and kaons which decay to neutrinos
2. Resulting beam is >99% muon neutrino flavor, small ν_e component from muon, kaon decay; ~7% antineutrino component
3. Can switch magnetic horn polarization to focus π^- and produce an predominantly antineutrino beam (with a ~30% neutrino component)

Accelerator-based neutrino sources







PRD 88, 032002 (2013)

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

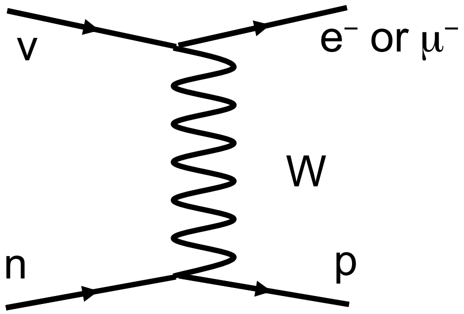
- Proton beam energy
- Position of the detector relative to the proton beam direction
- T2K uses an “off axis” (2.5°) beam, peaked at E_ν~0.6 GeV to maximize the oscillation probability

T2K oscillation analyses

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

Oscillation probability depends on neutrino energy
For T2K's neutrino spectrum, dominant process is Charged Current Quasi-Elastic:

CCQE

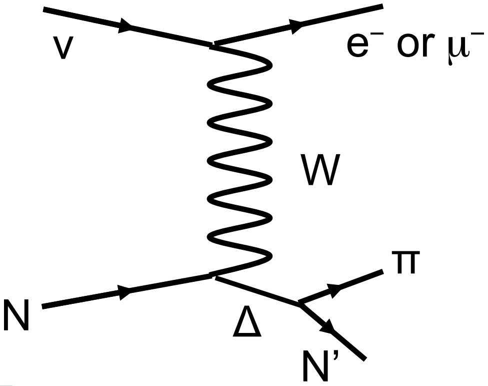


Infer neutrino properties from the lepton momentum and angle:

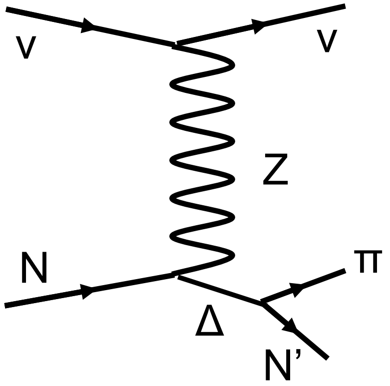
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CCπ



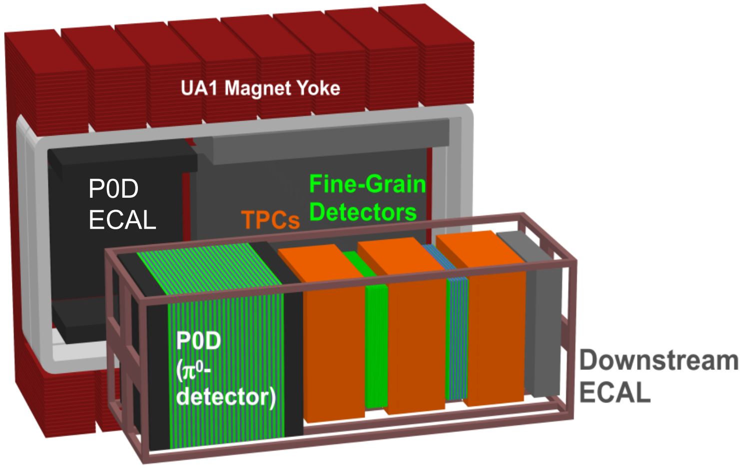
NCπ



Background processes are:

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

T2K event selection

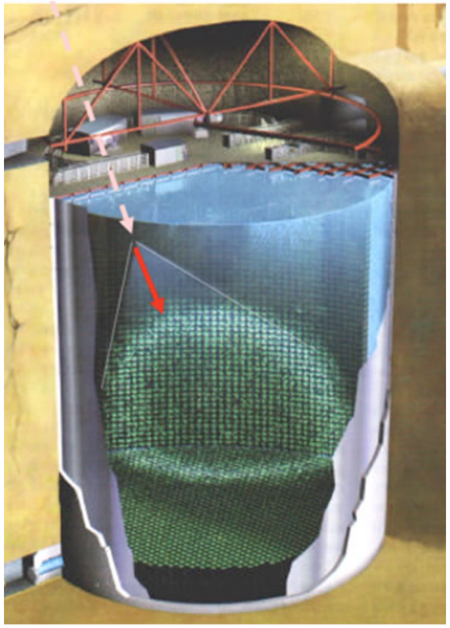


Select CC ν_μ candidates prior to oscillations in an off-axis tracking detector (ND280)

- 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

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



Use of near detectors on T2K

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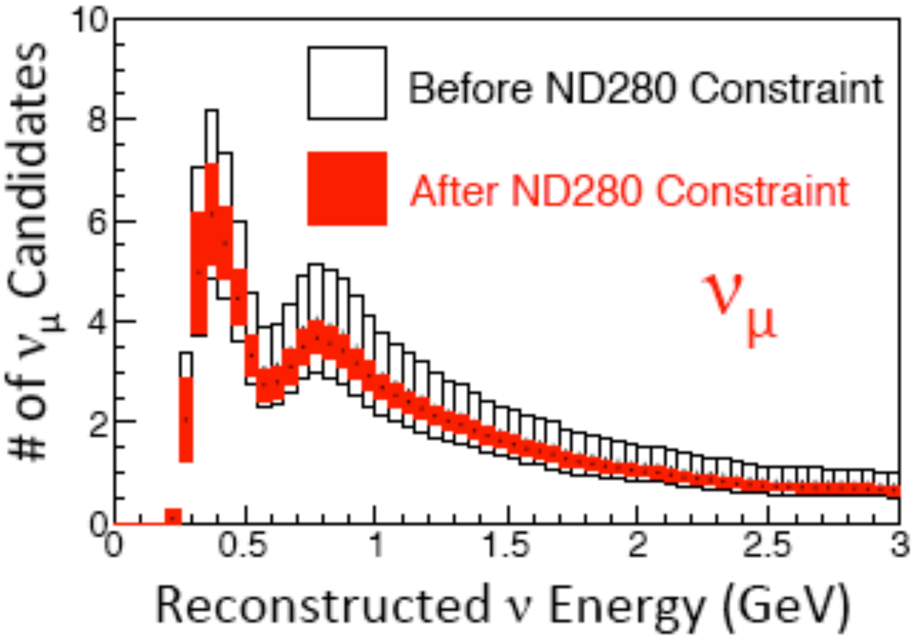
Expected number of events at the far detector is tuned based on near detector information. Near detector also provides a substantial constraint on the uncertainties of ν_e and ν_μ events:

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

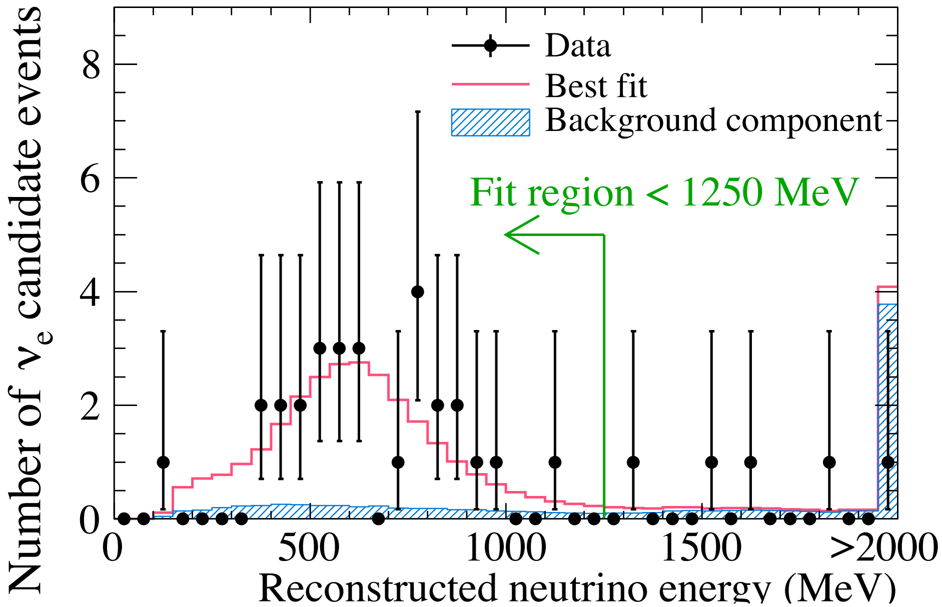
uncertainties for ν_e appearance	**ν_e sig+bkrd**	**ν_e bkrd**
ν flux+xsec (before) after ND constraint	(25.9%) ±2.9%	(21.7%) ±4.8%
ν unconstrained xsec	±7.5%	±6.8%
Far detector	±3.5%	±7.3%
Total	(27.2%) ±8.8%	(23.9%) ±11.1%

After ND: expect 21.6 ν_e candidates
(background only: 4.92)



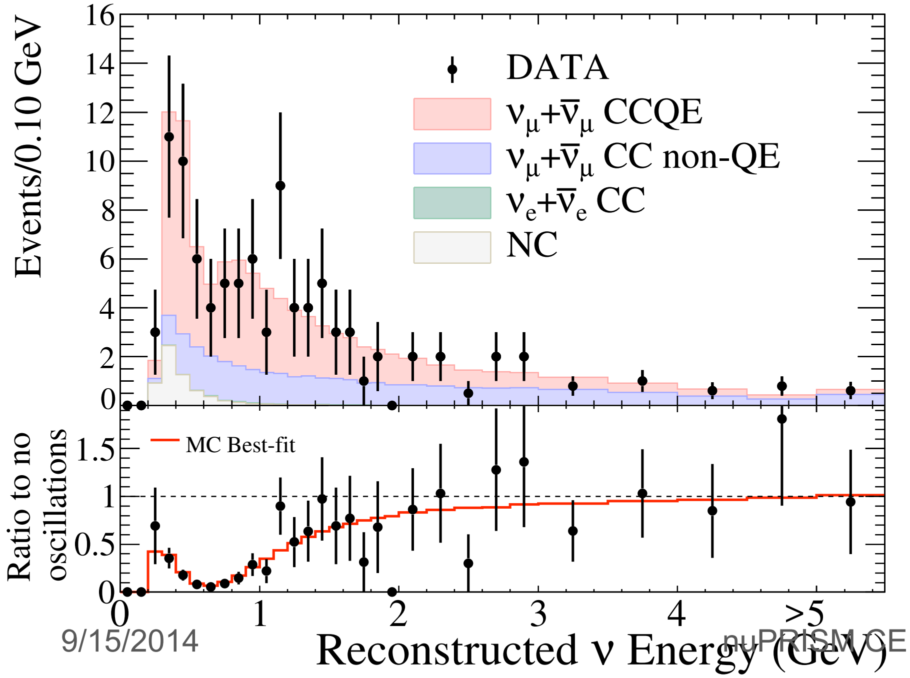
After ND: expect 124.8 ν_μ events

T2K observed event distributions



28 candidate ν_e events observed

- First observation of CC ν_e appearance
  - 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})



120 candidate ν_μ events observed

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

Fit both ν_e and ν_μ samples simultaneously, include solar, reactor determinations of Δm^2_{21}, θ_{12}, θ_{13}

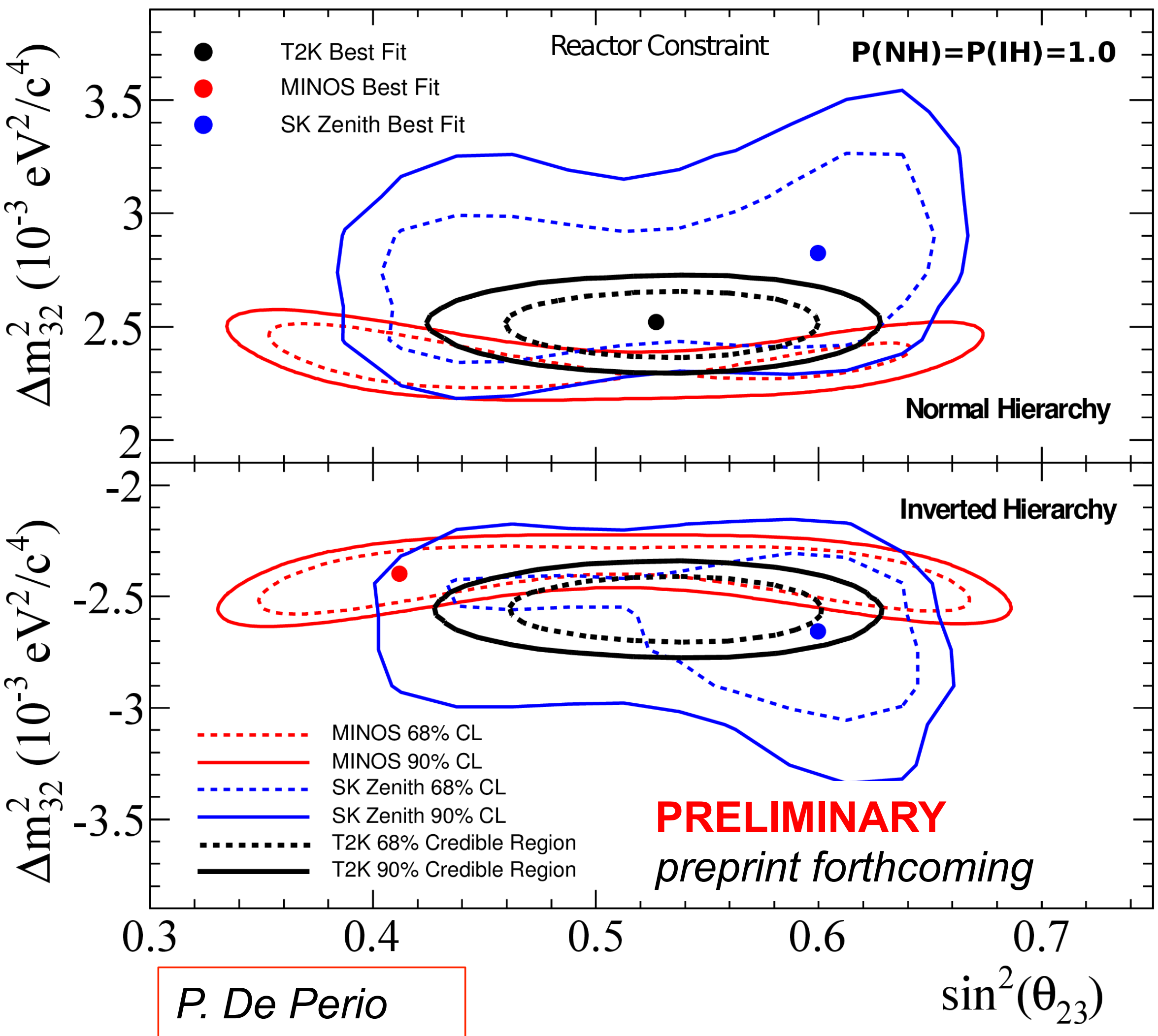
T2K joint ν_μ-ν_e fit results: Δm^2_{32}, $\sin^2\theta_{23}$

Markov Chain Monte Carlo-based analysis

- Simultaneous fit to near detector ν_μ, far detector ν_μ, ν_e samples
- Includes correlations between ν_μ, ν_e samples

T2K data favors maximal disappearance

- Provides best constraint on θ_{23} to date, consistent with maximal (45°) mixing
- Caveat: Baysian analysis, credible regions are shown with confidence intervals from other experiments
- T2K CL are similar to CI regions



P. De Perio
Moriond 2014

T2K joint ν_μ-ν_e fit: δ_{CP} and mass hierarchy

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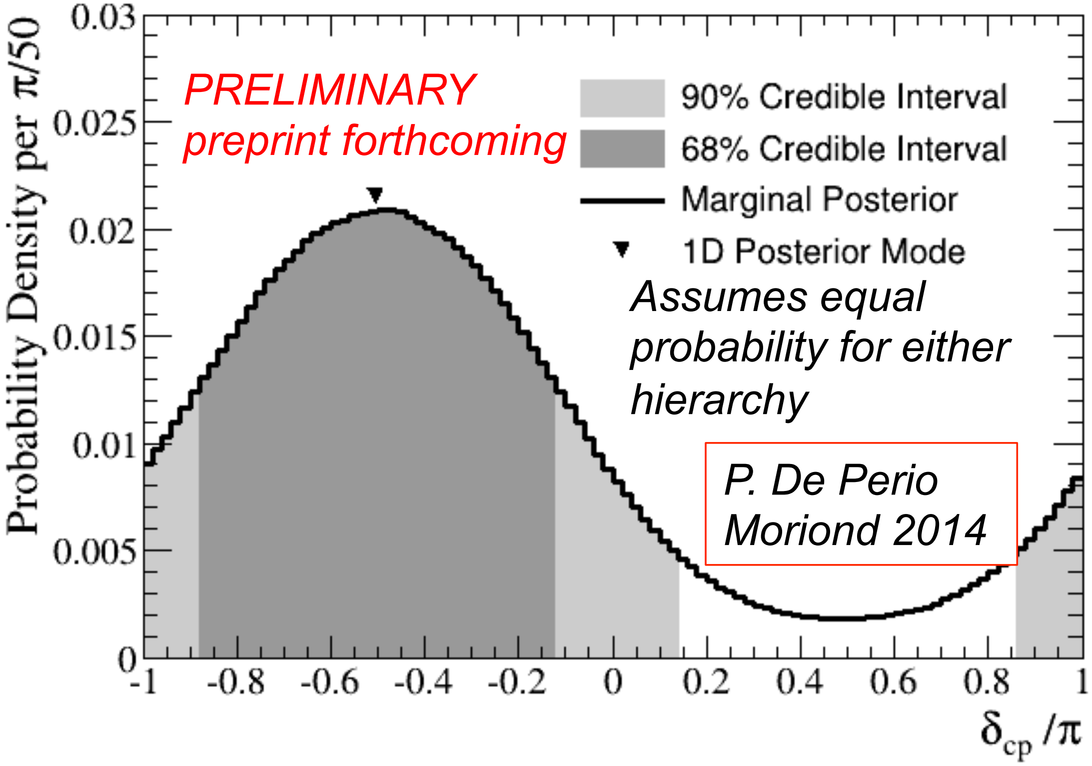


90% credible interval, removes dependence on all other oscillation parameters

- Excludes δ_{CP} values near ~π/2

Comparison of probabilities for each combination of θ_{23} octant, mass hierarchy:

Probability	$\Delta m^2_{32}>0$	$\Delta m^2_{32}<0$	Sum
$\sin^2\theta_{23} \leq 0.5$	18%	8%	26%
$\sin^2\theta_{23} > 0.5$	50%	24%	74%
Sum	68%	32%	

What is needed to measure δ_{CP}?

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

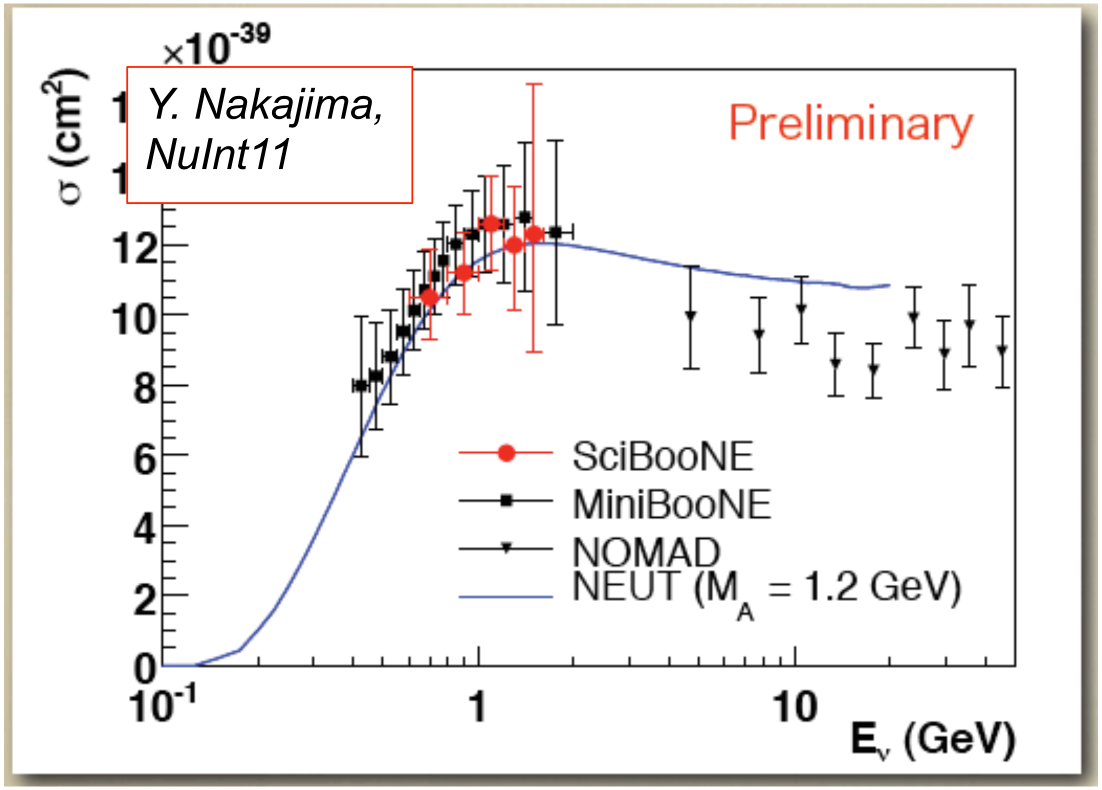
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

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

- LBNE(F) experiment goals:1% signal uncertainties / 5% background uncertainties: http://arxiv.org/abs/1307.7335
- Hyper-Kamiokande statistical precision: 2%, required systematics 3% on ν_e appearance: http://j-parc.jp/researcher/Hadron/en/pac_1405/pdf/P58_2014_2.pdf

How do we achieve <5% systematics?

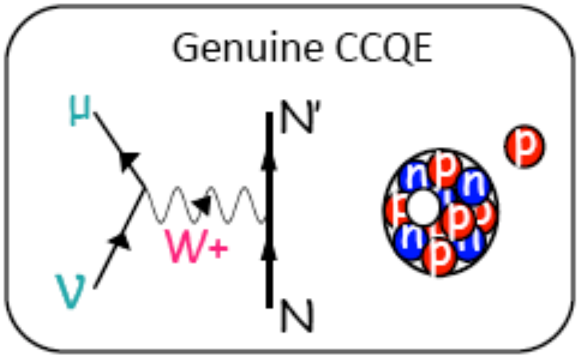
Uncertainties	ν_e sig+bkrd
ν flux+xsec (constrained by ND280)	±2.9%
ν xsec (unconstrained by ND280)	±7.5%
Far detector	±3.5%
Total	±8.8%

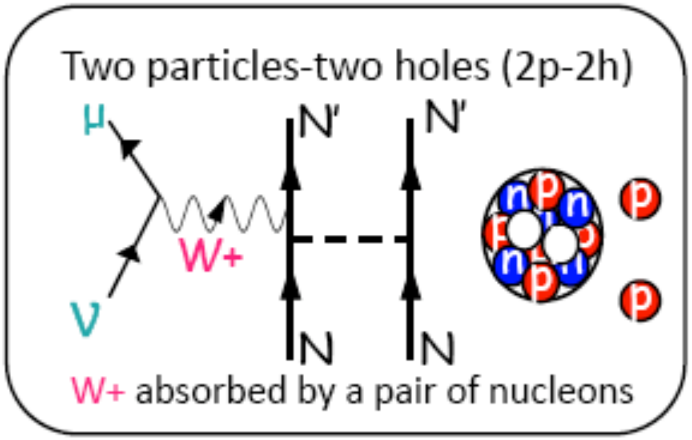


The largest systematic uncertainties currently on the T2K oscillation analyses are from uncertainties on the CCQE, CC1π neutrino interaction models

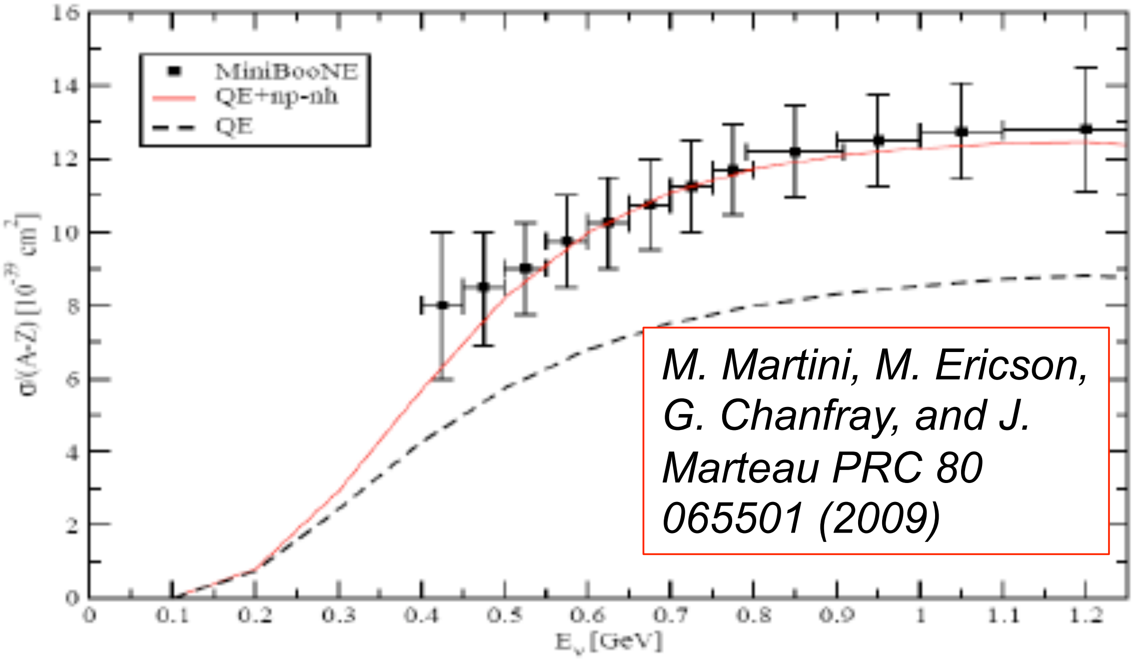
- Disagreements between models and existing neutrino experiment data (e.g. MiniBooNE, SciBooNE, NOMAD)
- Differences between new theoretical models and those currently used by T2K

Are we really measuring “CCQE”?


Genuine CCQE


Two particles-two holes (2p-2h)

W+ absorbed by a pair of nucleons

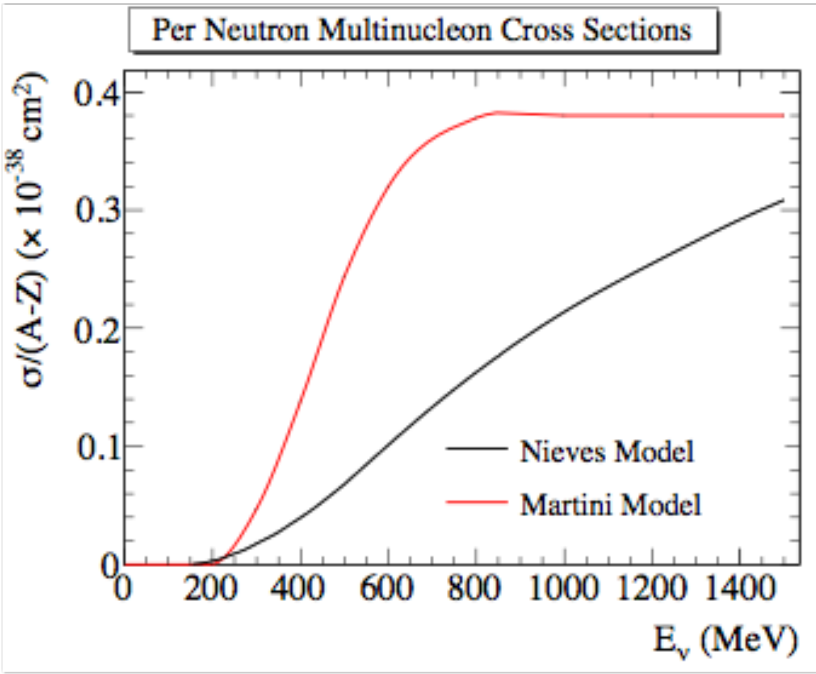


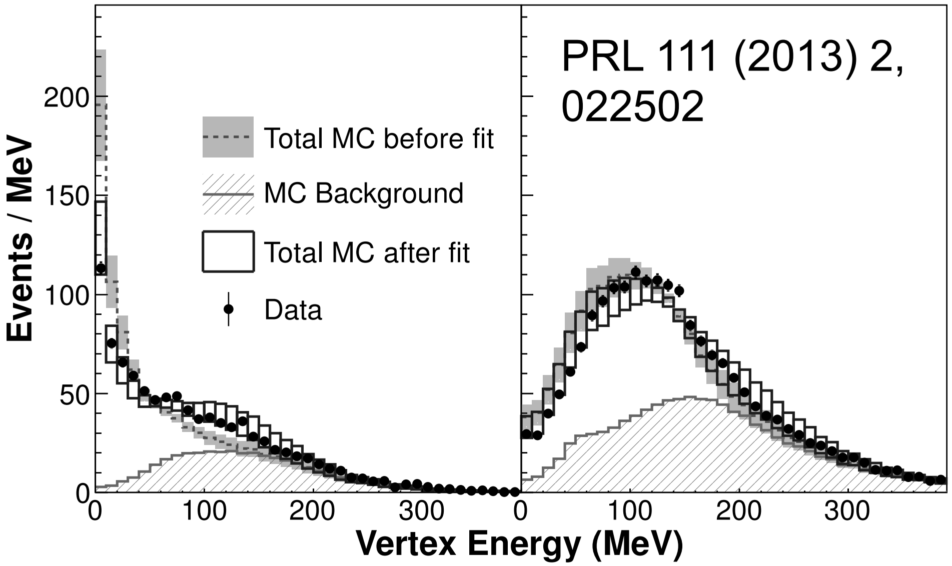
M. Martini, M. Ericson, G. Chanfray, and J. Marteau PRC 80 065501 (2009)

“Multinucleon” processes may explain the enhanced CCQE cross section observed by MiniBooNE, SciBooNE experiments

- Neutrino can also interact on a correlated pair of nucleons
- CCQE interaction simulated as interaction on a single nucleon (1p1h)

Complications of multinucleon models




PRL 111 (2013) 2, 022502

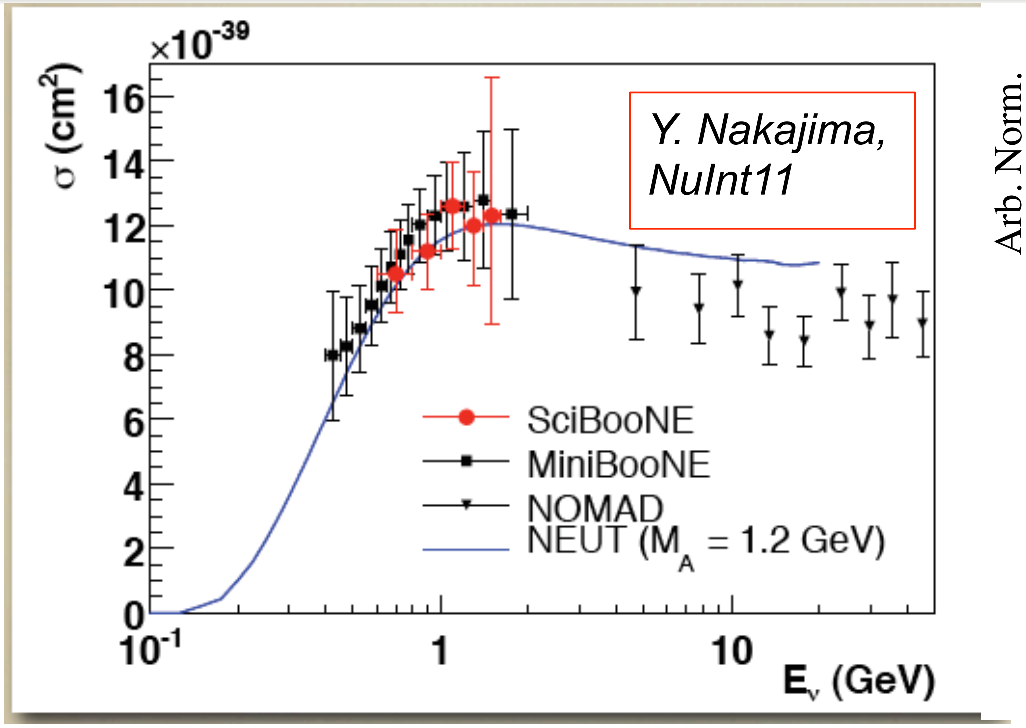
Significant differences between models... new interest over last ~5 years in MiniBooNE results; **theory effort needs support:**

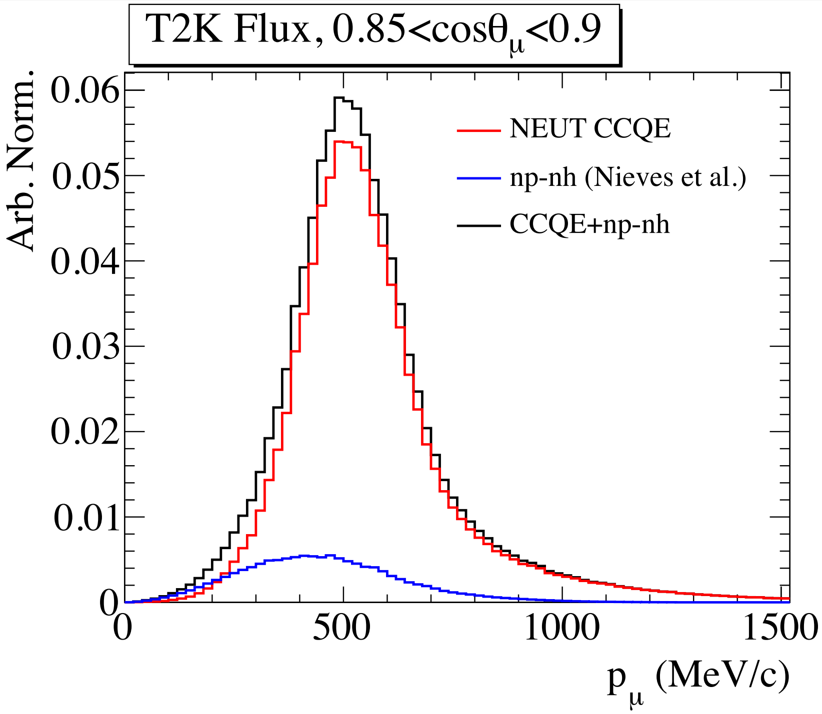
- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011)
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)

Challenges:

- MINERvA observation of extra charge near vertex implies extra proton in final state, but no clear theoretical insight to kinematics, multiplicity of protons
- Models are also limited to certain ranges of validity

Complications of multinucleon models





Significant differences between models… and experiments

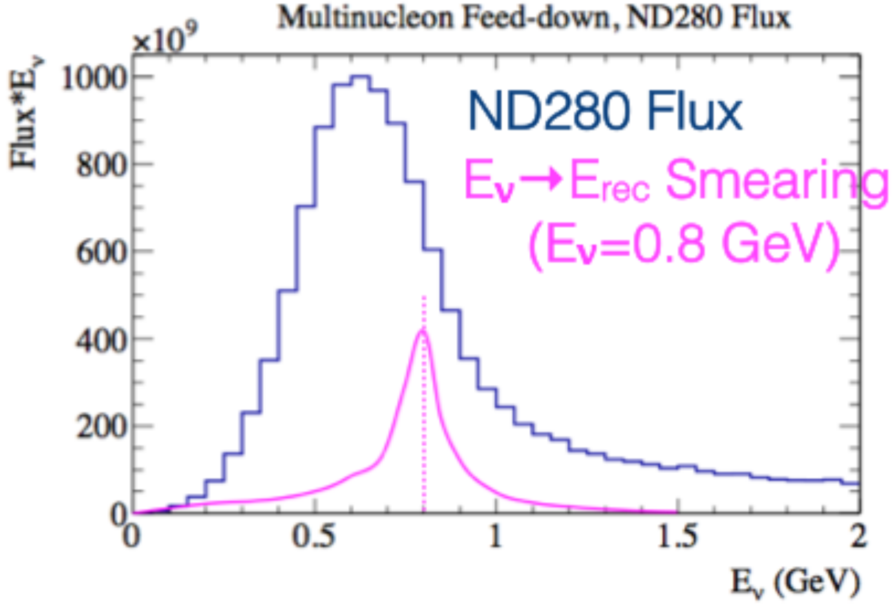
- Enhanced cross section not seen by NOMAD, why?

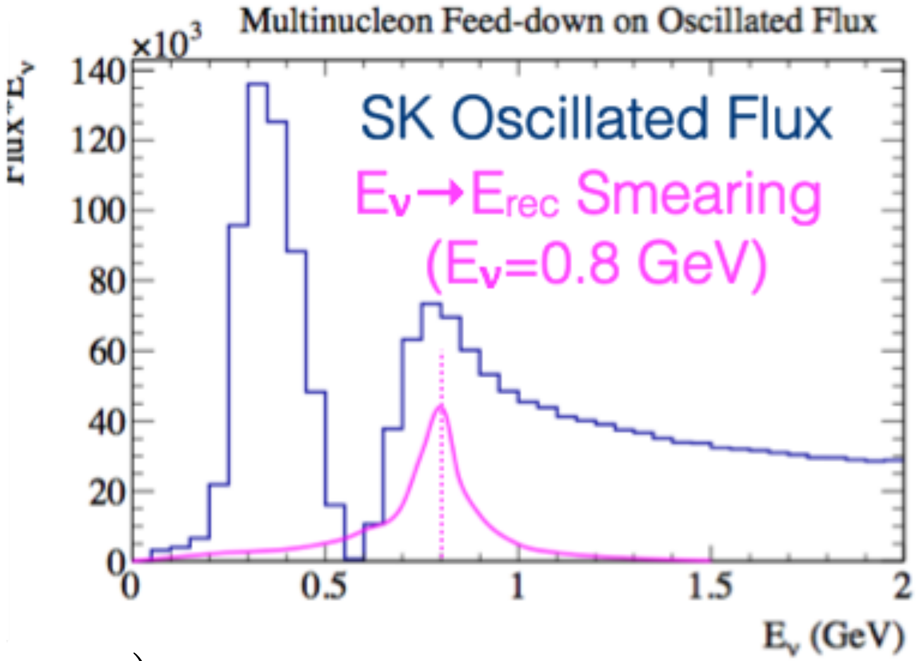
Difficult to probe experimentally, though T2K ND, MINERvA, NOvA ND will try

- Is extra charge due to feeddown from CC1π, DIS interactions? CCQE FSI?
- Multinucleon interactions are hidden under the flux peak and (dominant) CCQE interactions

Limitations of current ND constraints

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





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

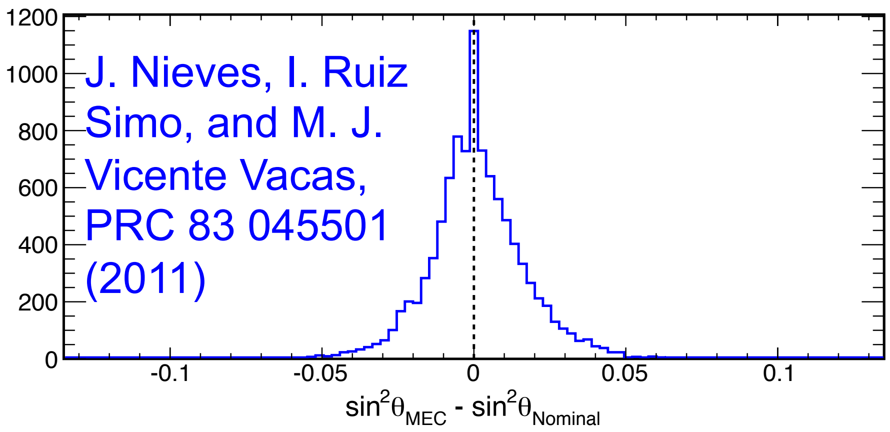
$$ND(\nu_\mu) = \boxed{\Phi \times \sigma} \times \epsilon_{ND}$$

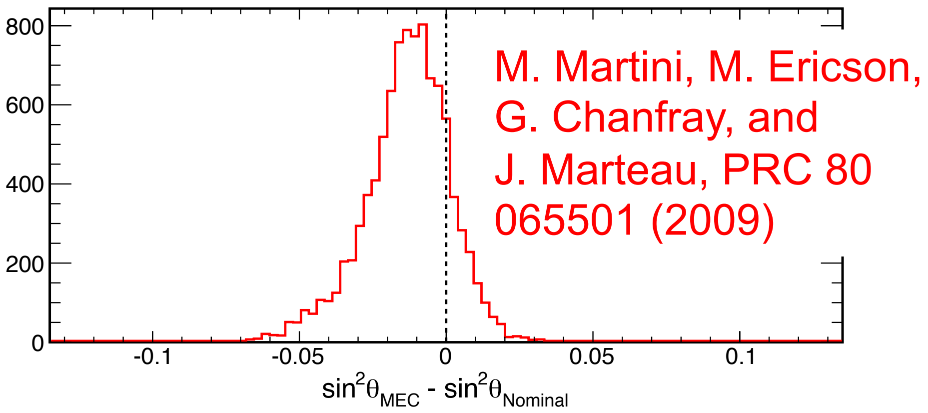
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

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)

Multinucleon effect on T2K analysis





Tested possible bias on T2K disappearance measurement

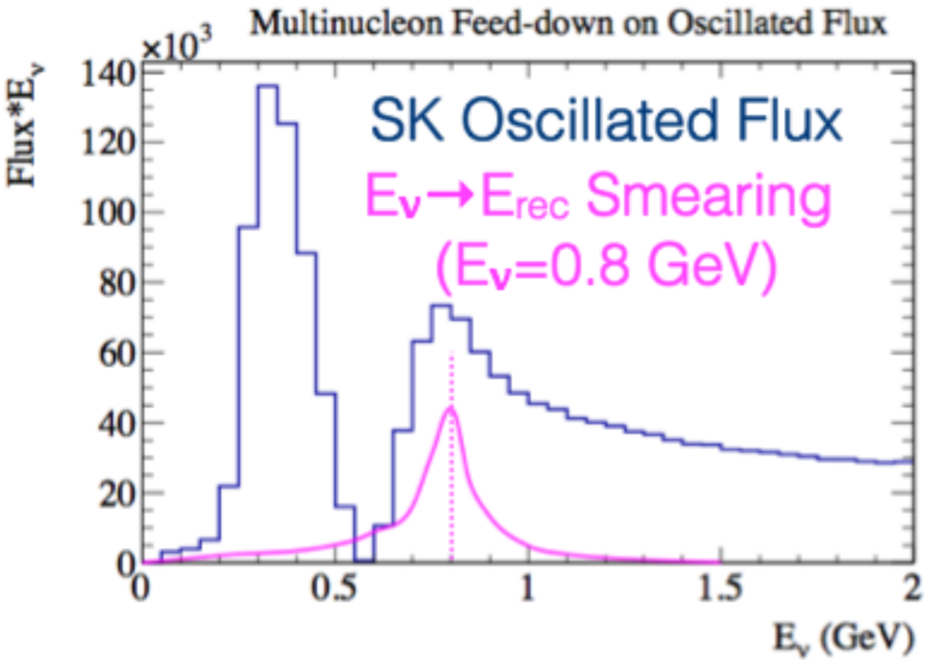
- Generate fake data under flux, detector, cross section variations, and perform full oscillation analysis including ND constraint
- For each fake data set, compare fitted θ_{23} with and without a 2p2h model present

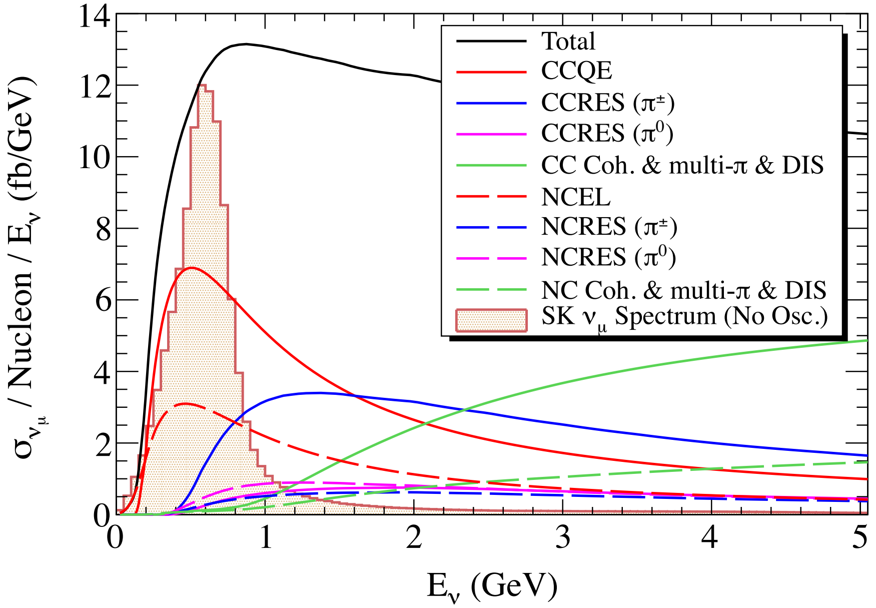
Nieves et al model: 0.3% mean, 3.2% RMS
“increased Nieves” = Martini model: -2.9% mean, 3.2% RMS

Significant relative to current systematic uncertainty on disappearance analysis (vs. 4.9% non-cancelling cross section uncertainty, 8.1% total)

Important for future long baseline program (1-5% uncertainties)

Summary of multinucleon challenges





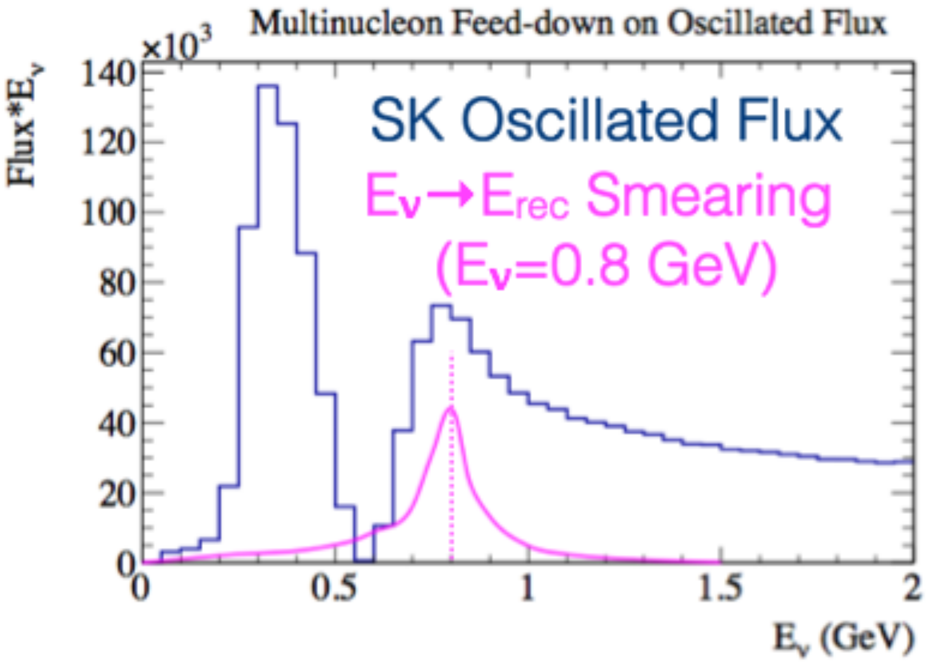
Challenges of neutrino interactions at 1 GeV

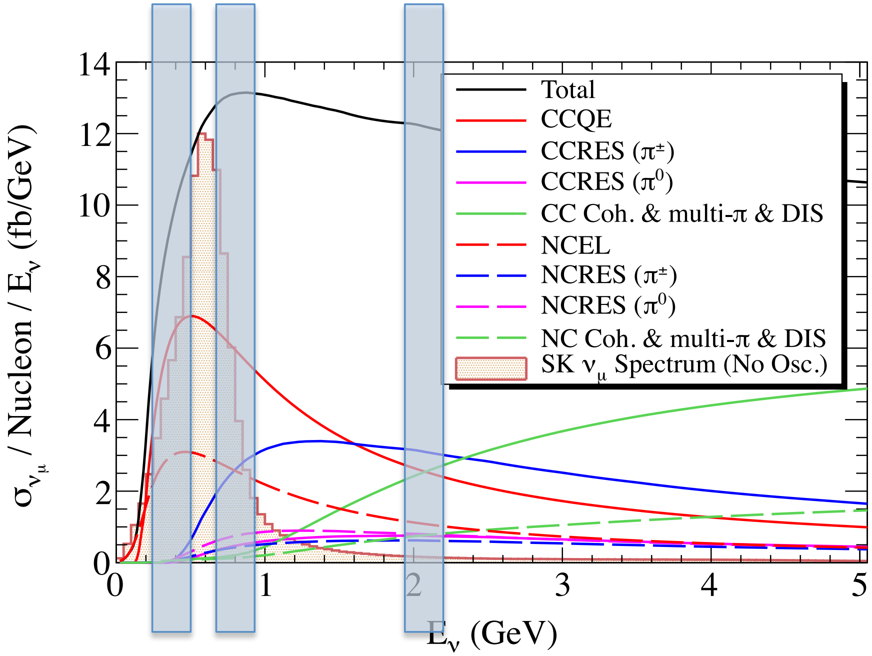
- Are we seeing new multinucleon processes? Issues with CCQE,1π model?

Difficult to isolate a control sample of multinucleon events

- Measure a particular topology (CC with no pions) integrated over the flux, which includes multiple processes
- Flux is not identical at near and far detectors, if only just from oscillation

Summary of multinucleon challenges





Challenges of neutrino interactions at 1 GeV

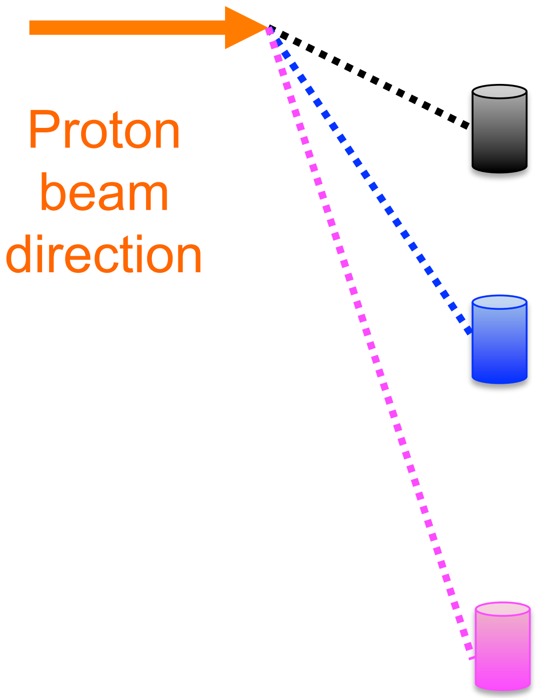
- Are we seeing new multinucleon processes? Issues with CCQE,1π model?

Difficult to isolate a control sample

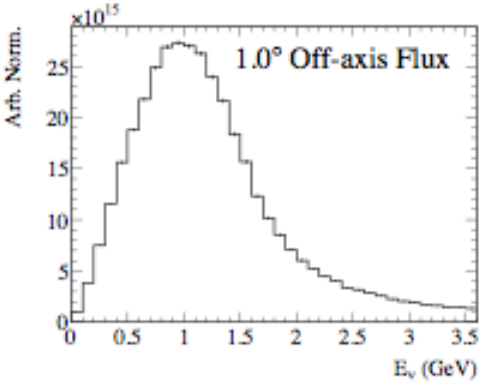
- Measure a particular topology (CC with no pions) integrated over the flux, which includes multiple processes
- Flux is not identical at near and far detectors, if only just from oscillation

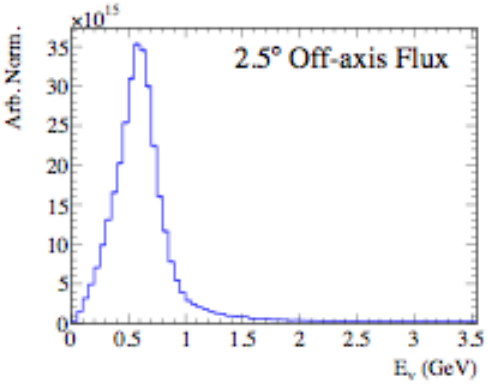
If we had a direct probe– a "monoenergetic" neutrino beam– we could isolate different processes independently

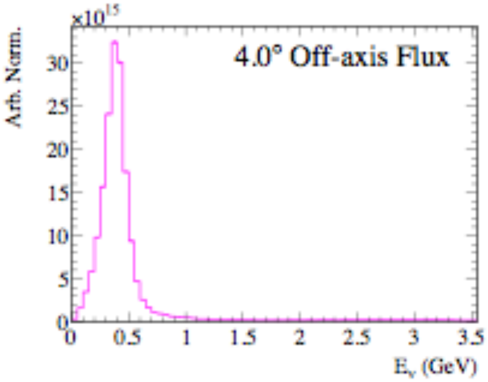
Revisiting off-axis beams



Proton beam direction

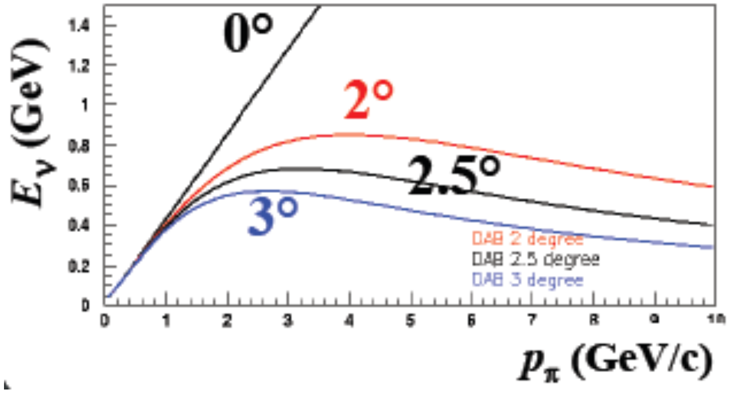




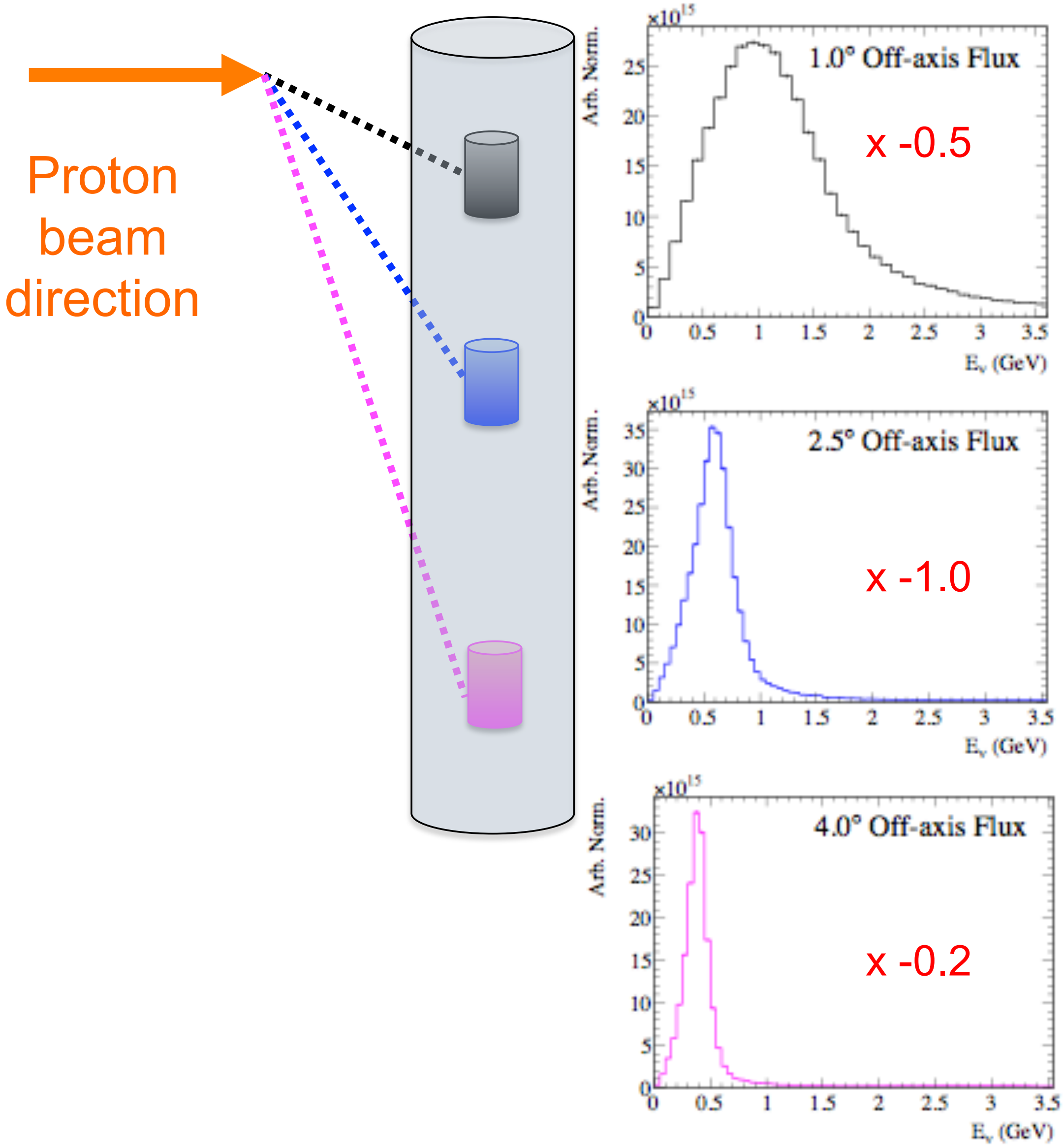


Example using T2K beamline

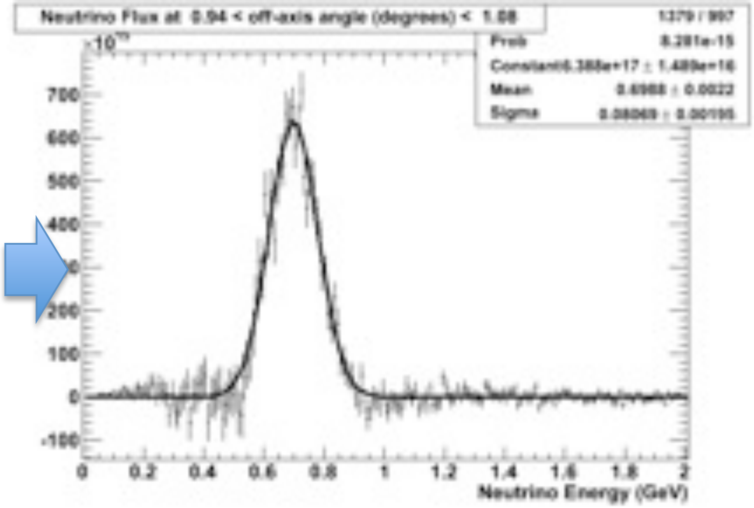
As off-axis angle increases, flux spectrum narrows and peak shifts down, due to the kinematics of pion decay



Combining different off-axis angles



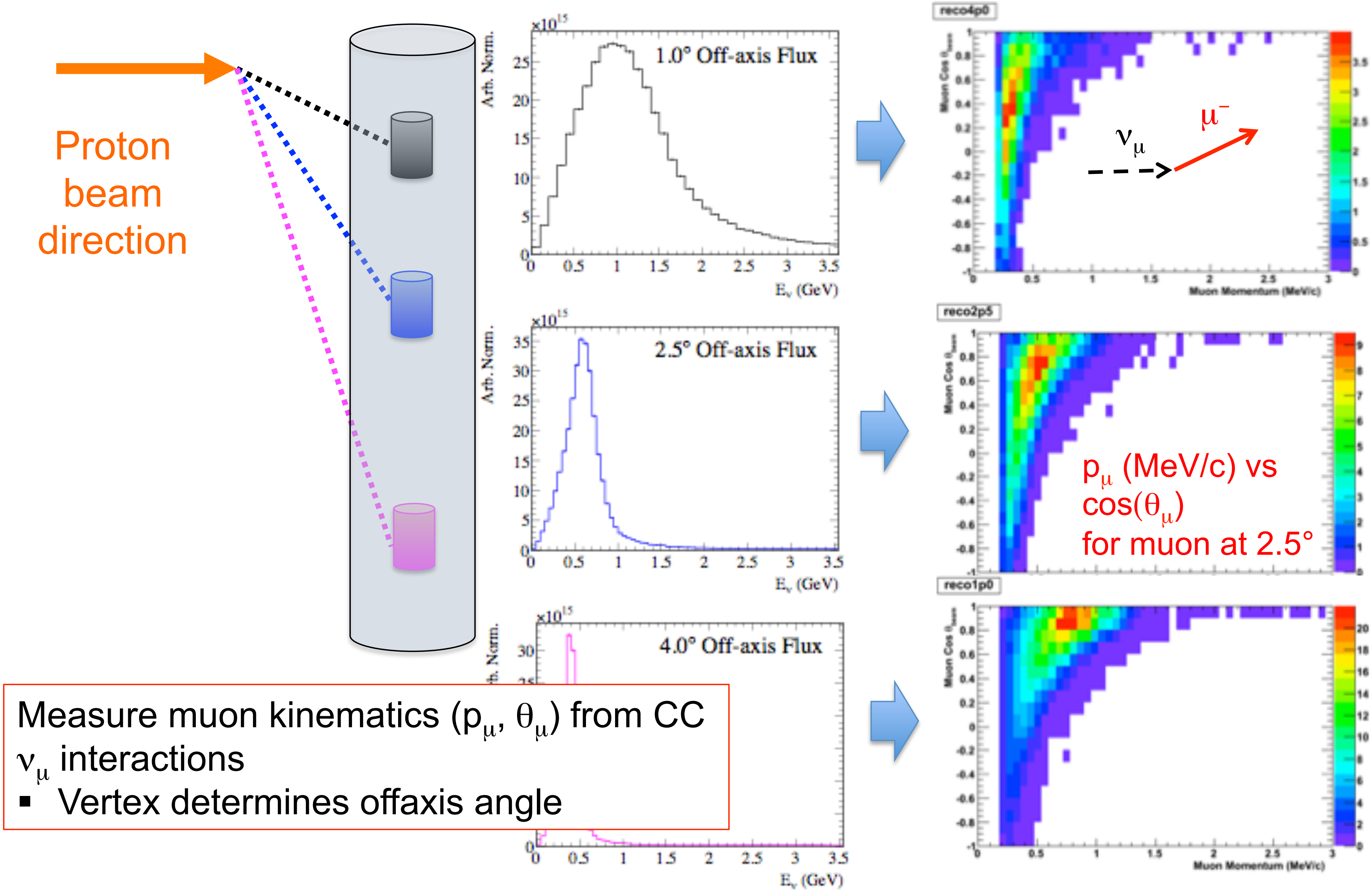
$$\Phi(E_\nu) = \sum_{i=0^\circ}^{\theta_{max}} C_i \; \phi_i(E_\nu)$$



For a Gaussian beam peaked at 700 MeV, use linear combination of 30 offaxis angles:

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

Relating observables to true E_ν



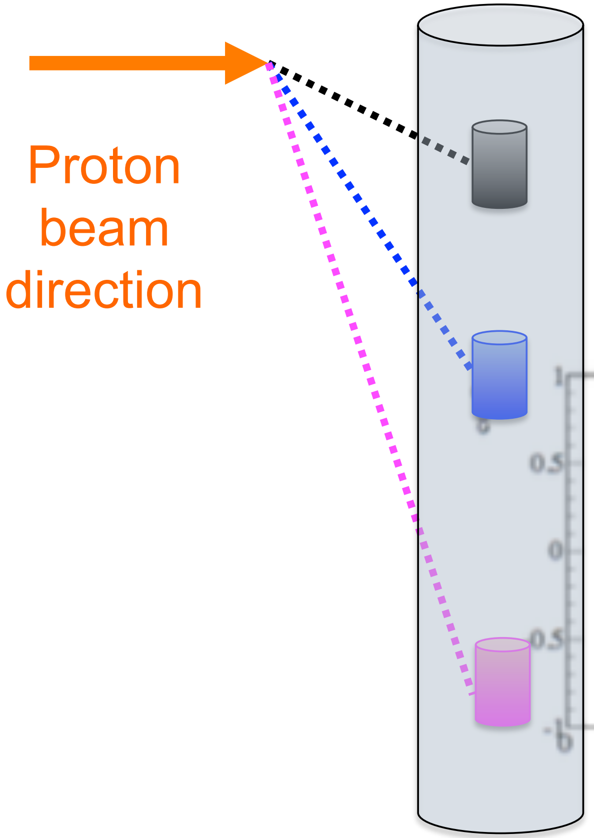
Proton beam direction

p_μ (MeV/c) vs $\cos(\theta_\mu)$ for muon at 2.5°

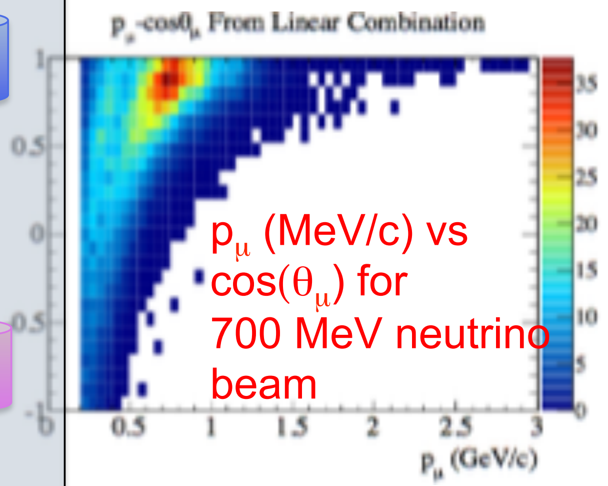
Measure muon kinematics (p_μ, θ_μ) from CC ν_μ interactions

- Vertex determines offaxis angle

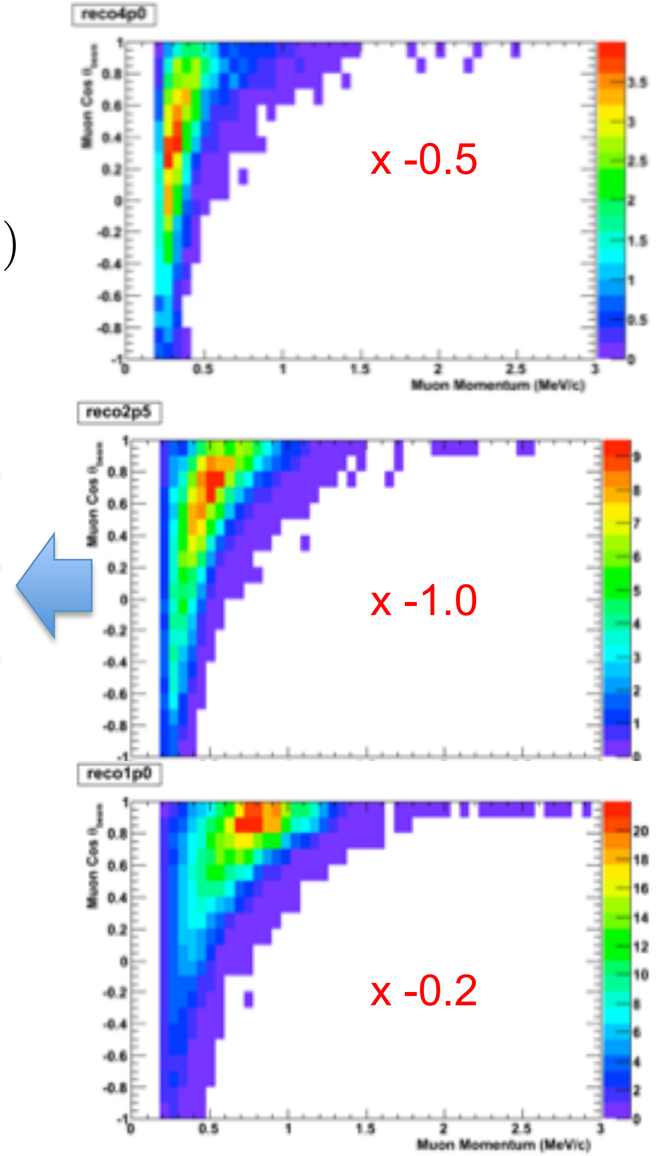
Relating observables to true E_ν



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


p_μ-$\cos\theta_\mu$ From Linear Combination

p_μ (MeV/c) vs $\cos(\theta_\mu)$ for 700 MeV neutrino beam


reco4p0

x -0.5

reco2p5

x -1.0

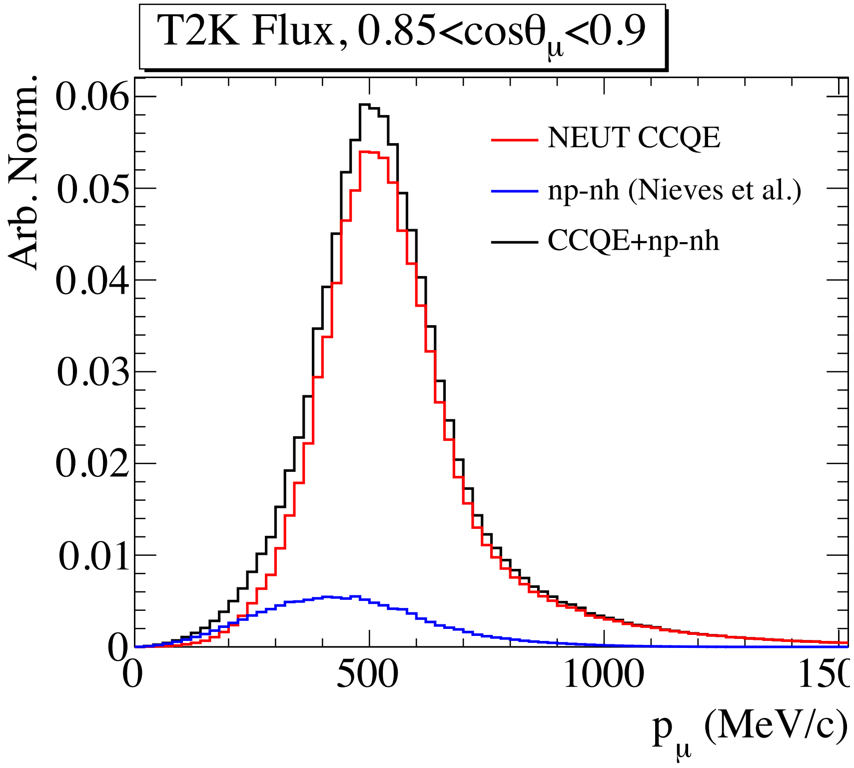
reco1p0

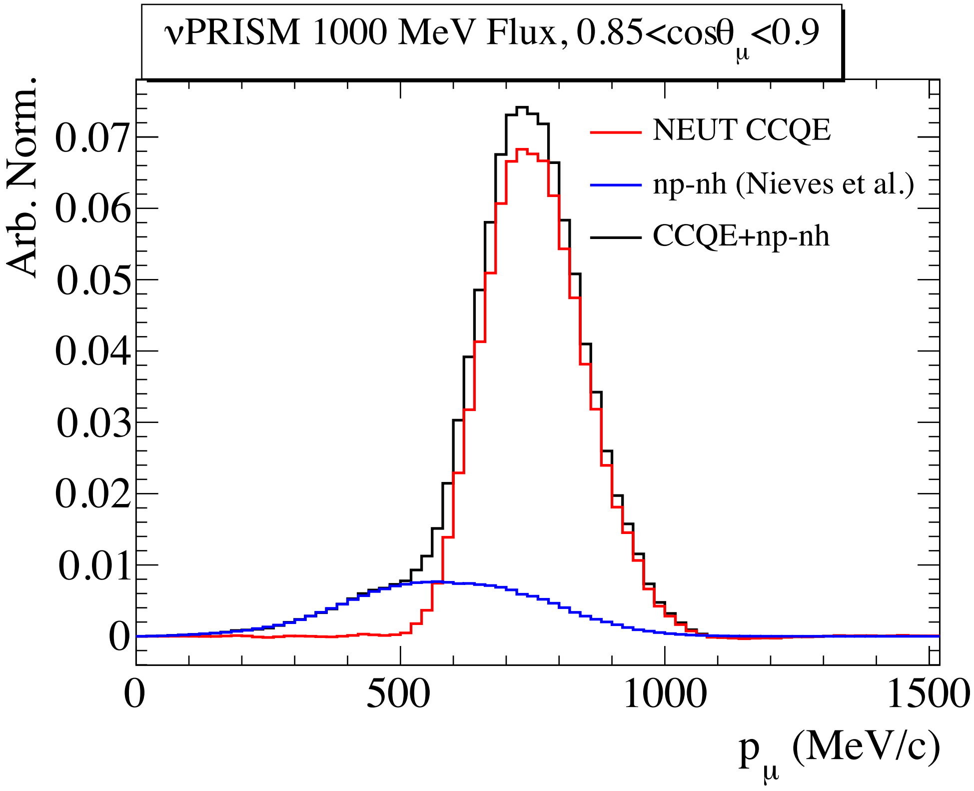
x -0.2

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



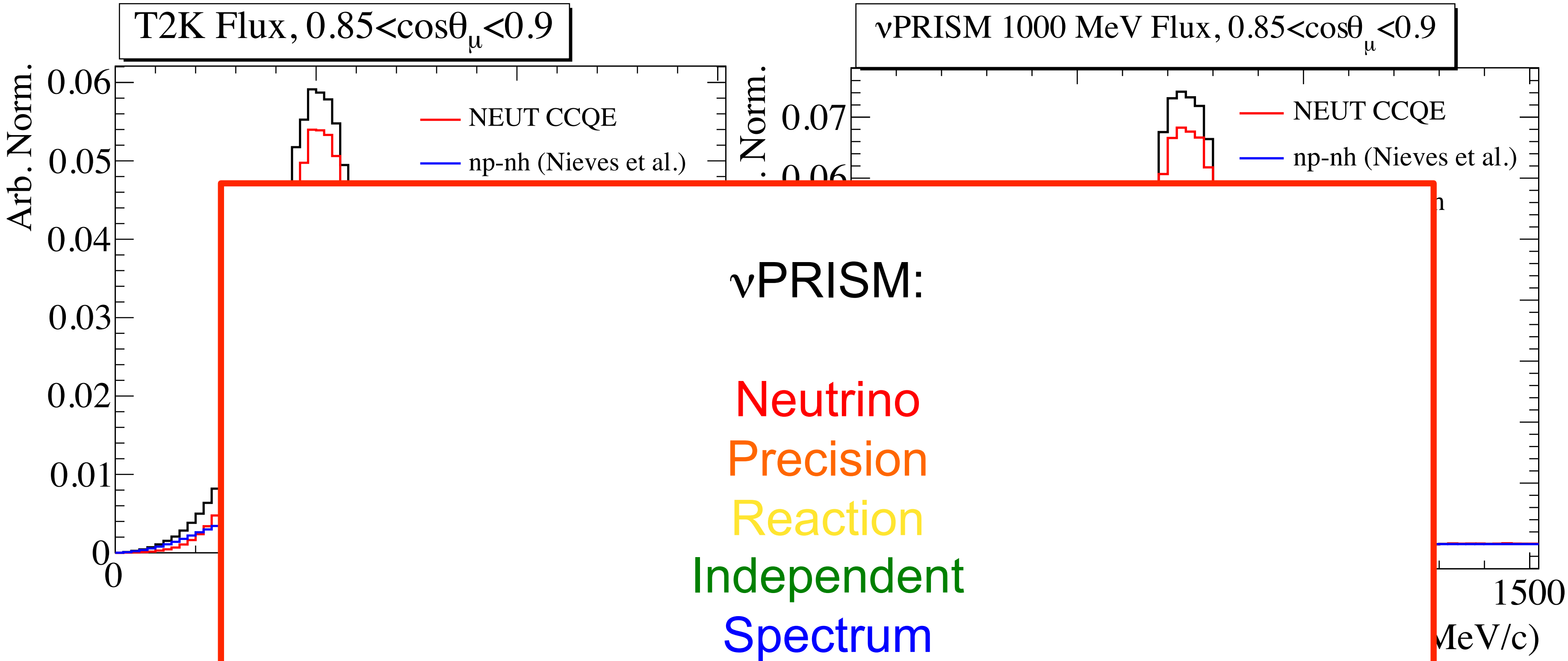


With the T2K flux, multinucleon (npnh) interactions from higher E_ν feed down into same momentum region as CCQE.

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

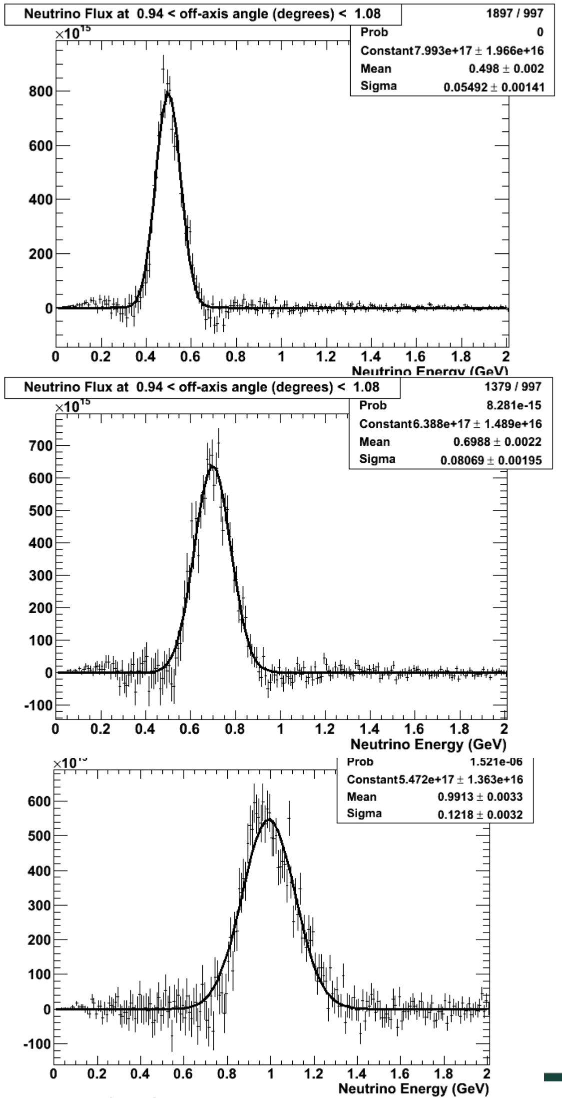
With the … into
same mo

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

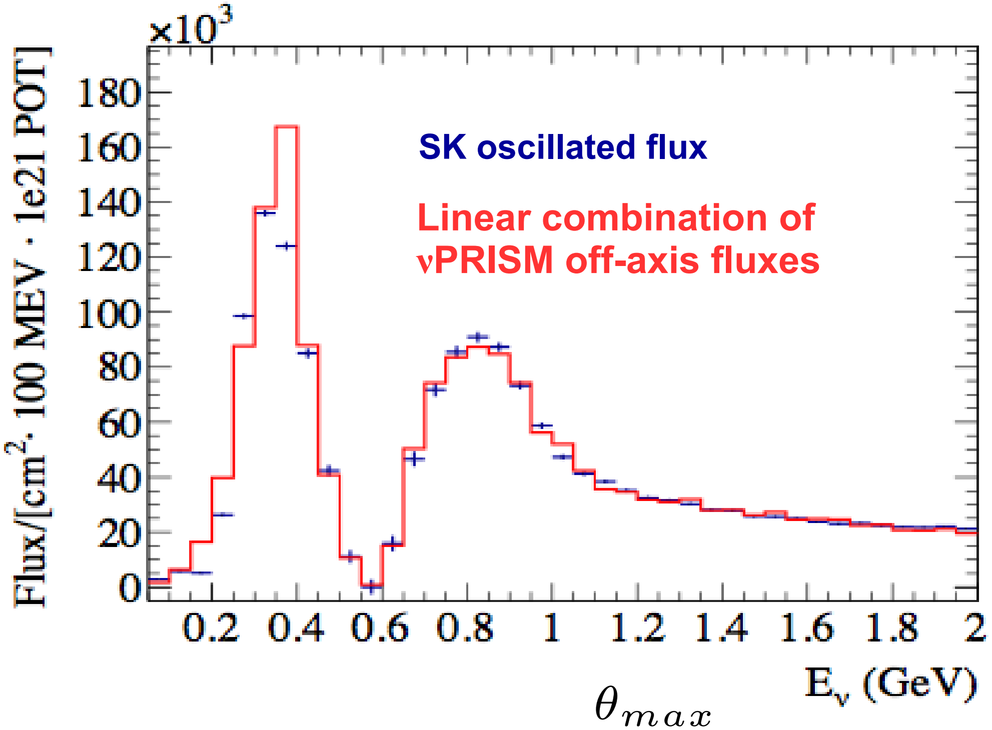
- Combinations of nearby monoenergetic fluxes provide energy dependence of cross section

Effect on oscillation analysis

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



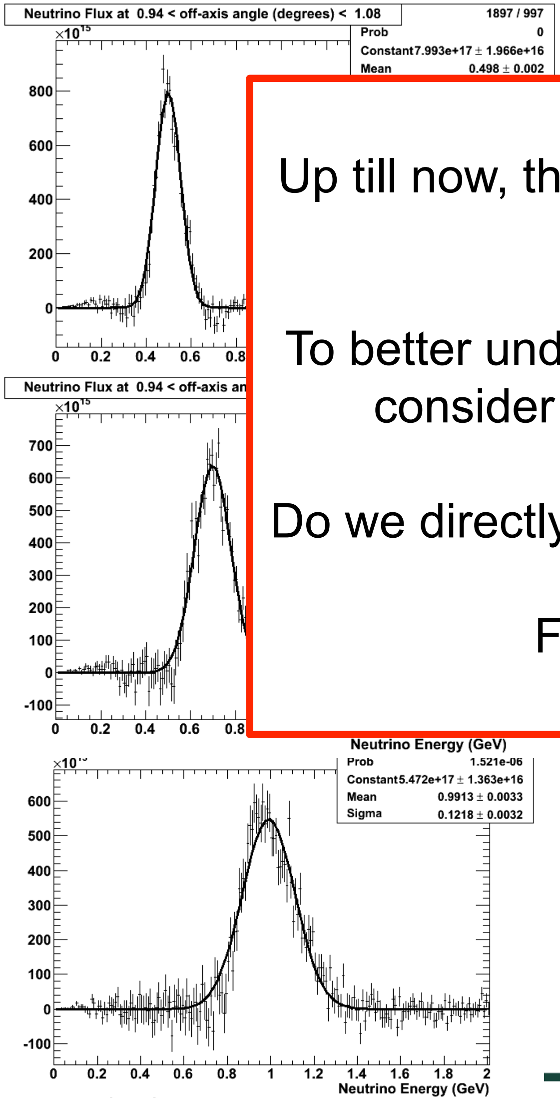
Use linear combination technique to generate oscillated spectrum from different offaxis angles



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

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

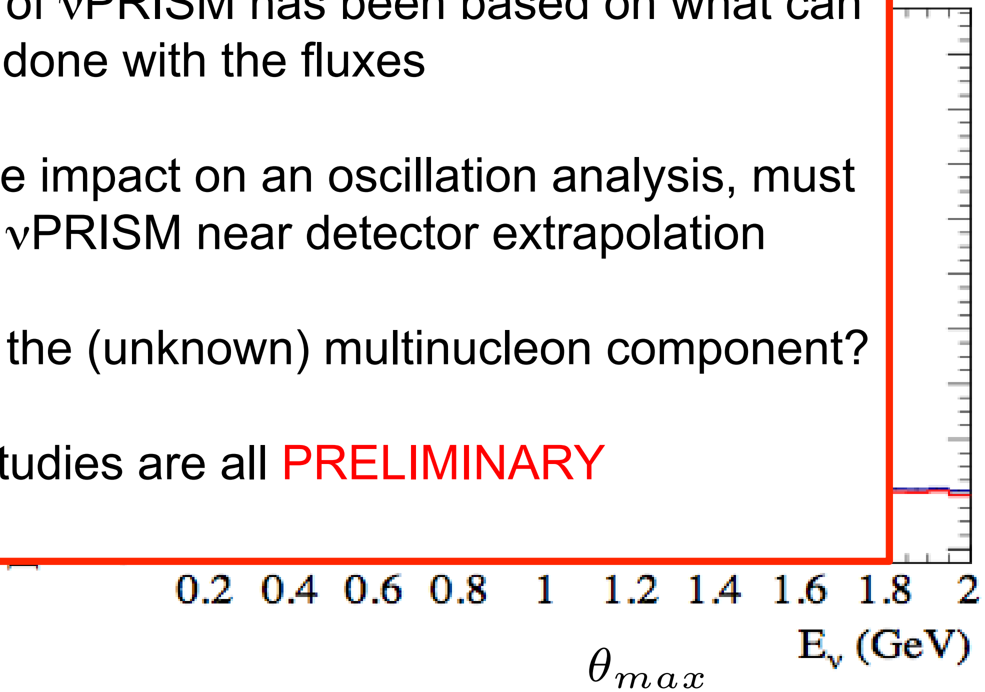
angles

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

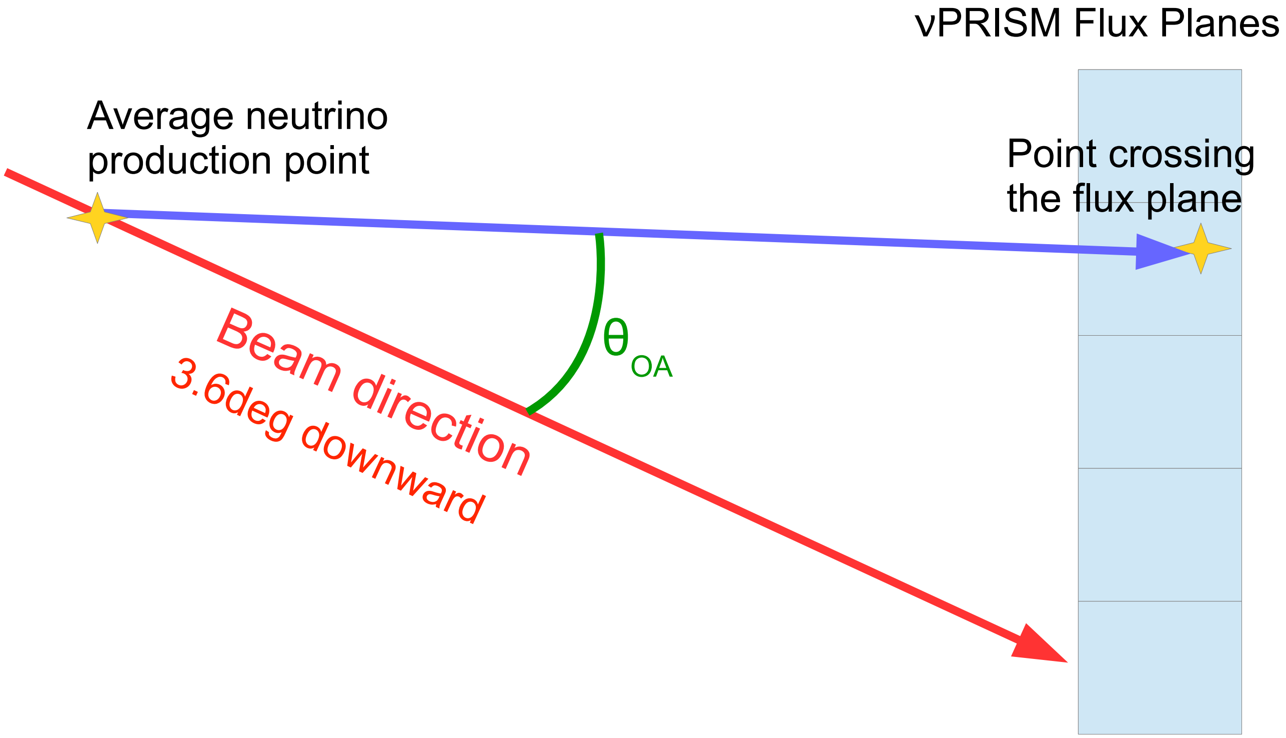
Do we directly measure the (unknown) multinucleon component?

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



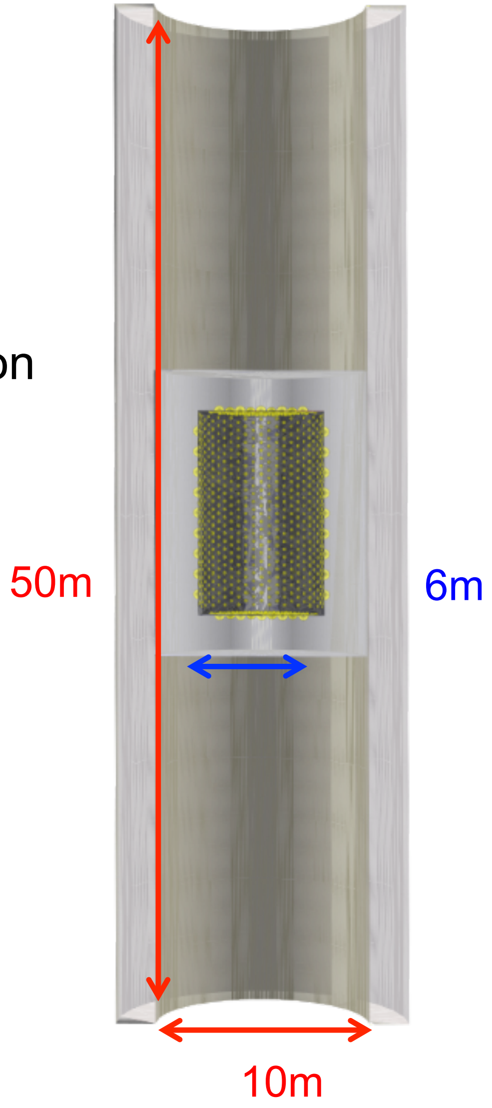
Detector needs to be placed ~1km away from T2K neutrino target

- 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

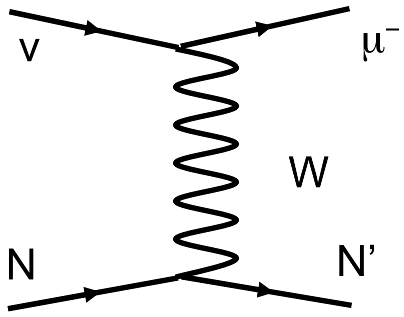
- Analysis considers a 50m high volume from 1-4° off-axis as the necessary E_ν region for the T2K oscillation analysis
    - 4° peaks at 380MeV
- Water Cherenkov detector with ~40% PMT coverage
    - Further cost reduction by instrumenting a movable portion of the detector
- Detector assumes containment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



νPRISM selection

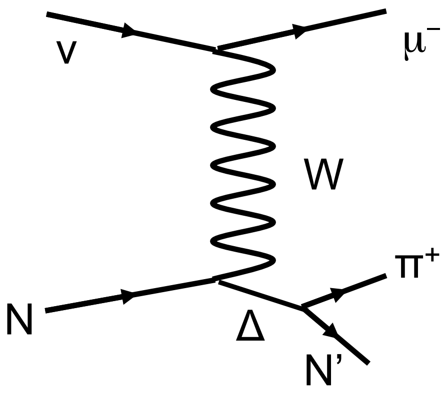
Signal: measure outgoing μ kinematics

CCQE



1p1h or 2p2h

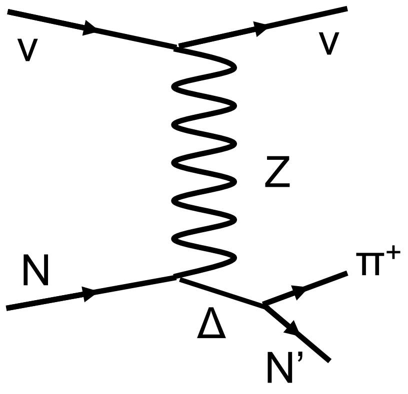
CCπ⁺



π absorbed in nucleus,
or below Cerenkov threshold

Background:

NCπ⁺



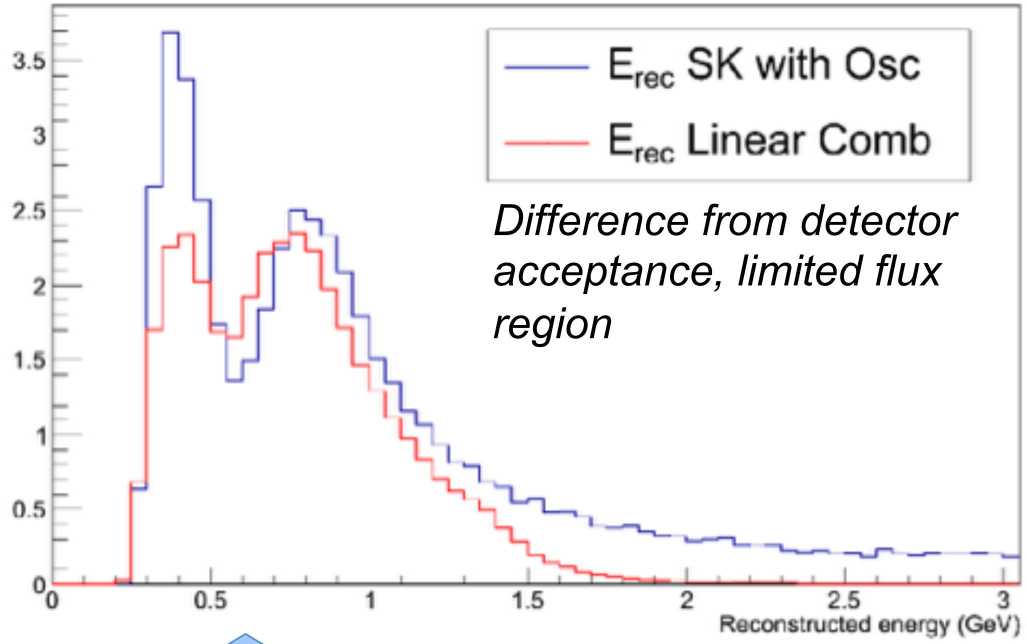
Select CCQE-like ν_μ candidates at νPRISM, correct for detector efficiency

- 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

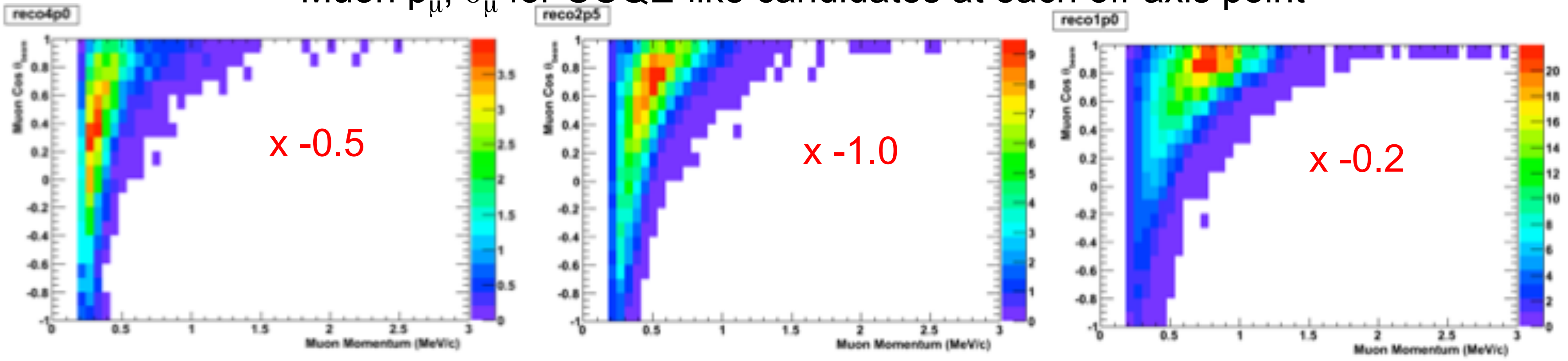


Difference from detector acceptance, limited flux region

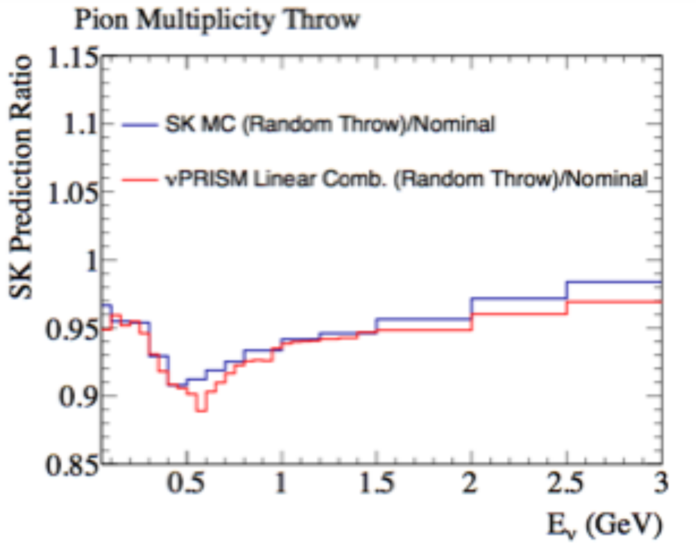
Build reconstructed E distribution (1D p_μ, θ_μ observable) for each Δm^2_{32}, θ_{23}

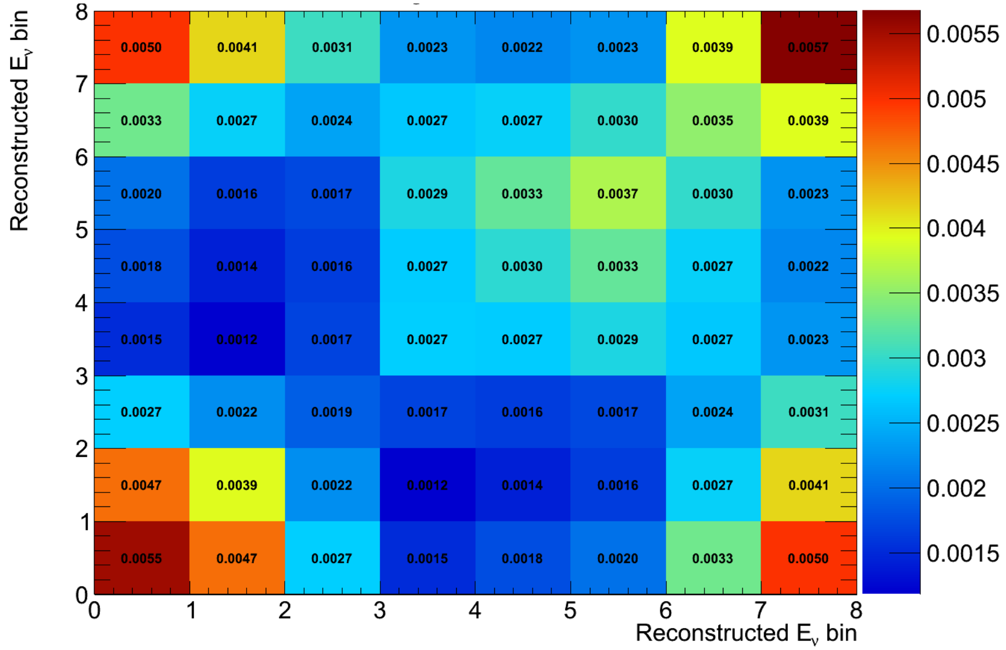
Include all statistical uncertainties and flux, cross section, detector uncertainties

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



νPRISM ND extrapolation to FD





0.0050	0.0041	0.0031	0.0023	0.0022	0.0023	0.0039	0.0057
0.0033	0.0027	0.0024	0.0027	0.0027	0.0030	0.0035	0.0039
0.0020	0.0016	0.0017	0.0029	0.0033	0.0037	0.0030	0.0023
0.0018	0.0014	0.0016	0.0027	0.0030	0.0033	0.0027	0.0022
0.0015	0.0012	0.0017	0.0027	0.0027	0.0029	0.0027	0.0023
0.0027	0.0022	0.0019	0.0017	0.0016	0.0017	0.0024	0.0031
0.0047	0.0039	0.0022	0.0012	0.0014	0.0016	0.0027	0.0041
0.0055	0.0047	0.0027	0.0015	0.0018	0.0020	0.0033	0.0050

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

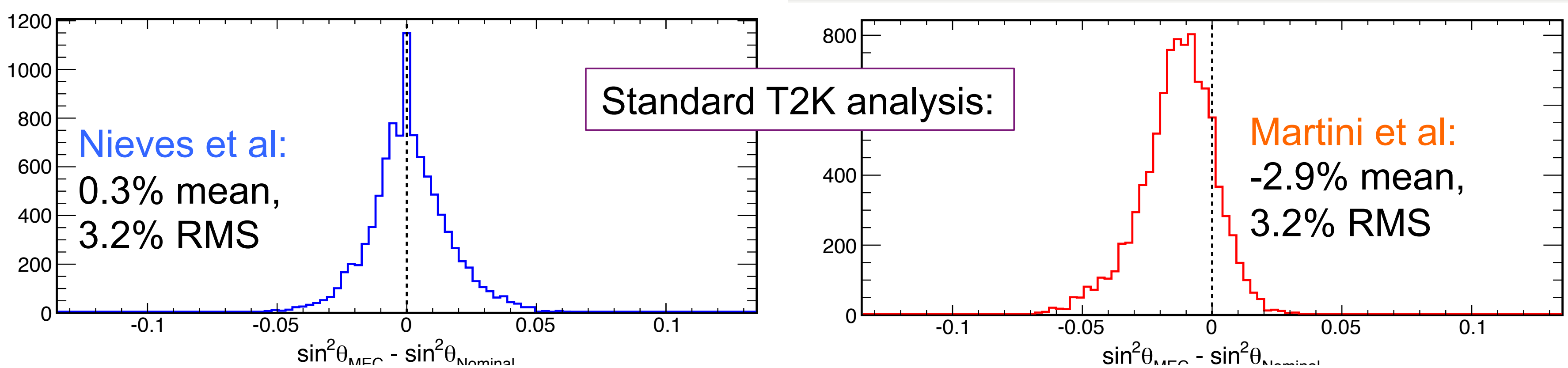
Include all statistical uncertainties and flux, cross section, detector uncertainties

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

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

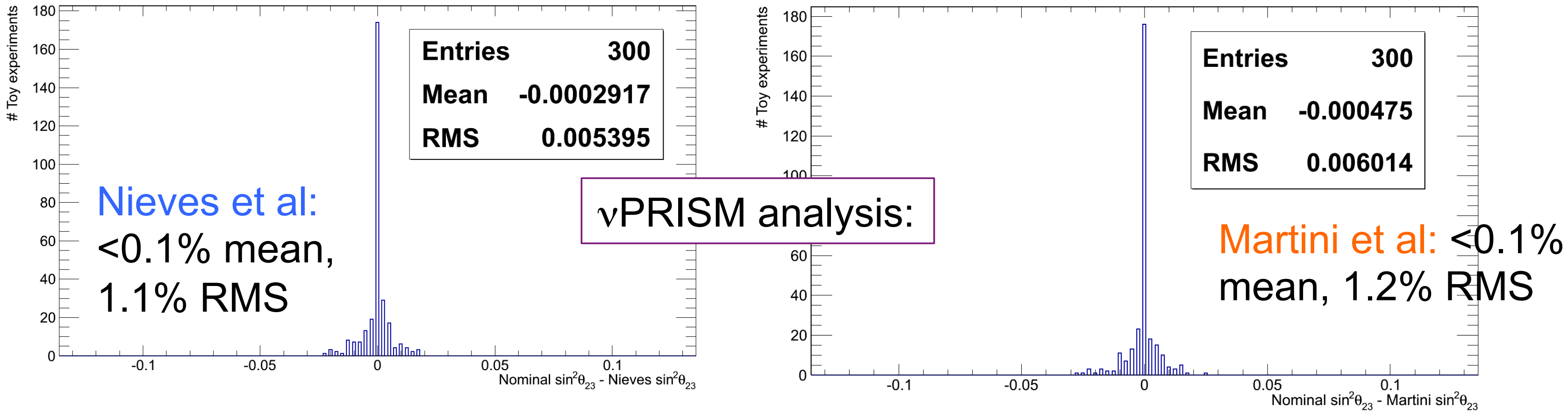
Revisiting bias tests with νPRISM



Standard T2K analysis:

Nieves et al:
0.3% mean,
3.2% RMS

Martini et al:
-2.9% mean,
3.2% RMS



νPRISM analysis:

Nieves et al:
<0.1% mean,
1.1% RMS

Martini et al: <0.1%
mean, 1.2% RMS

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

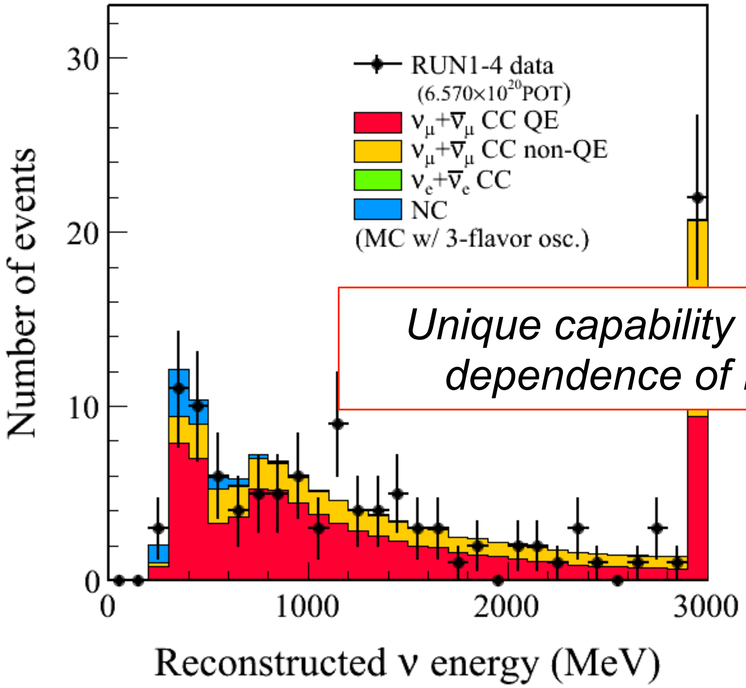
νPRISM cross section measurements

A monoenergetic neutrino beam is interesting for cross section physics

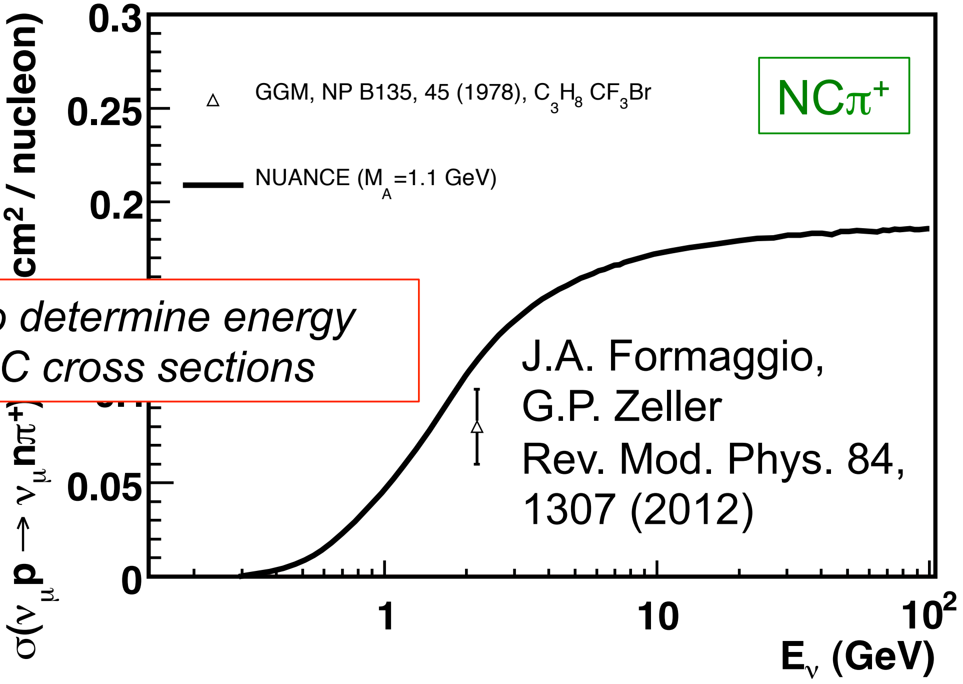
- All cross section measurements are averaged over (wide) fluxes
- Direct test of energy dependence for “CCQE”, characterize multinucleon processes

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

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



Unique capability to determine energy dependence of NC cross sections

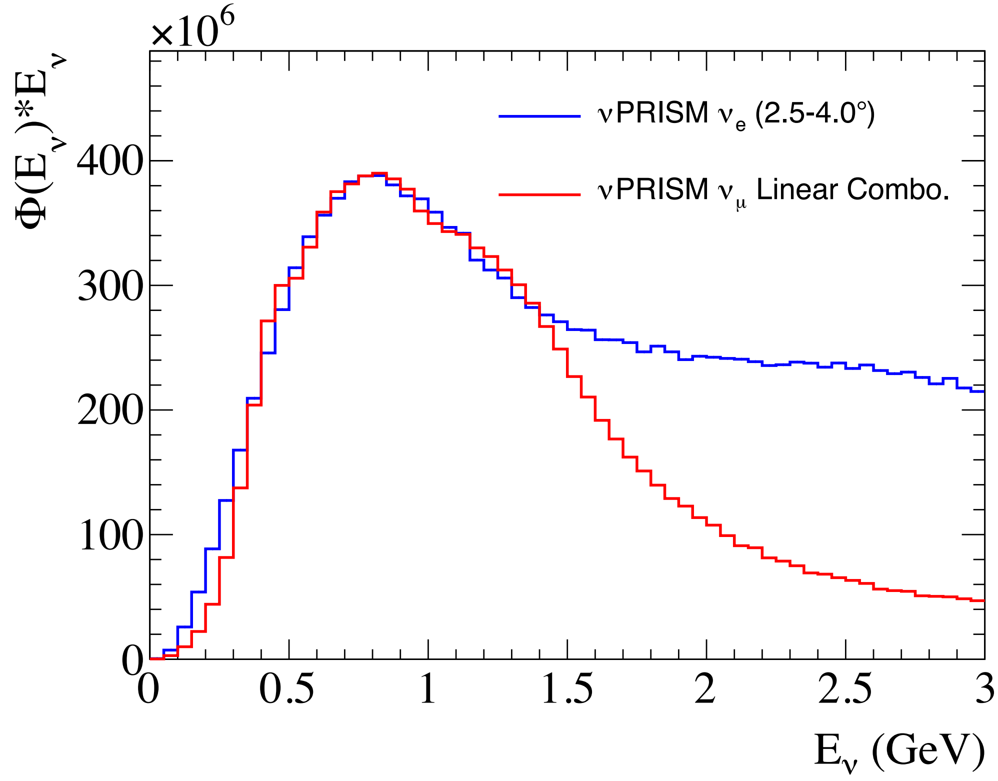


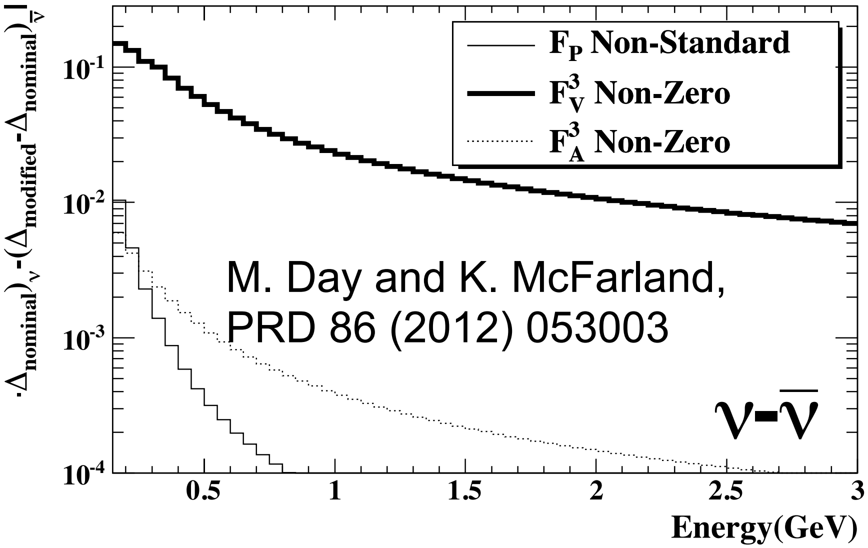
J.A. Formaggio, G.P. Zeller Rev. Mod. Phys. 84, 1307 (2012)

ν_e/ν_μ cross section at νPRISM

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%





M. Day and K. McFarland, PRD 86 (2012) 053003

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

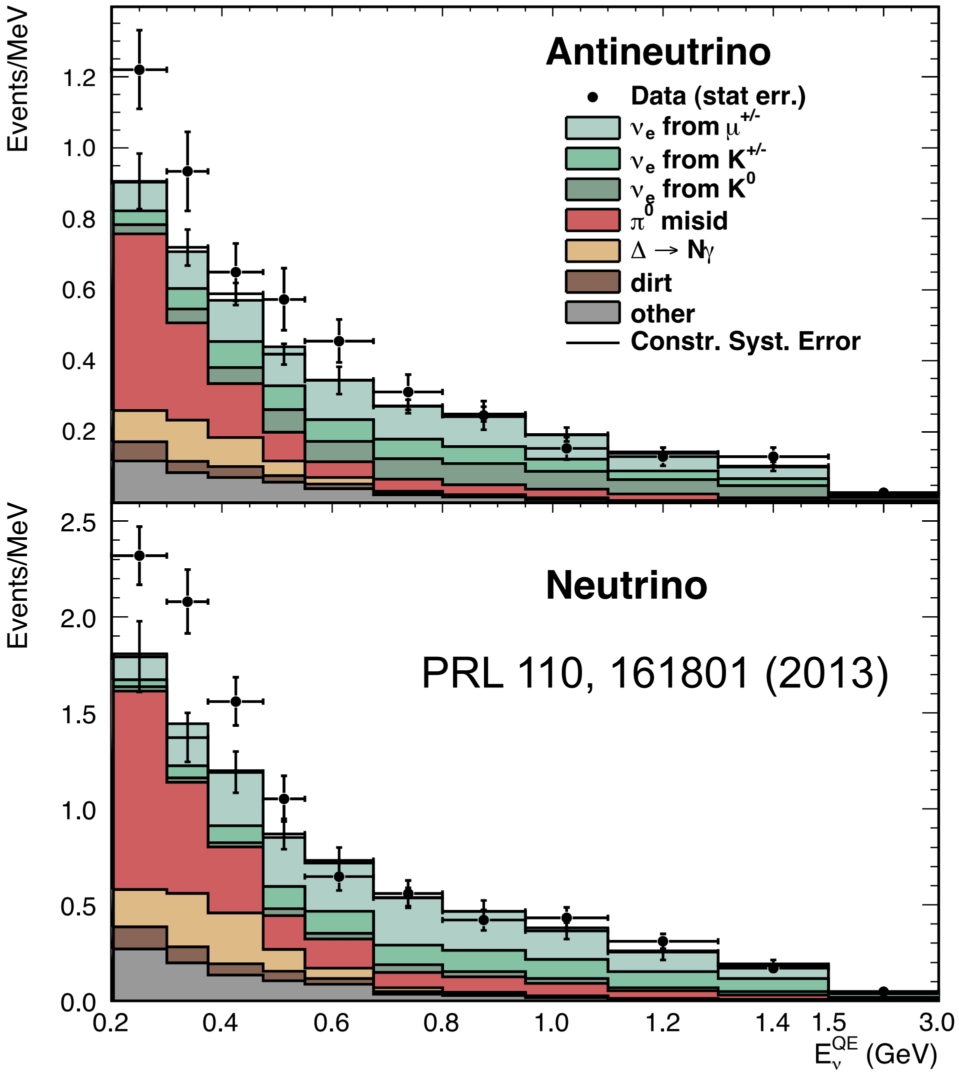
- Measurement ν_e/ν_μ ratio by matching intrinsic ν_e flux spectrum

Direct measurement of intrinsic ν_e background for appearance

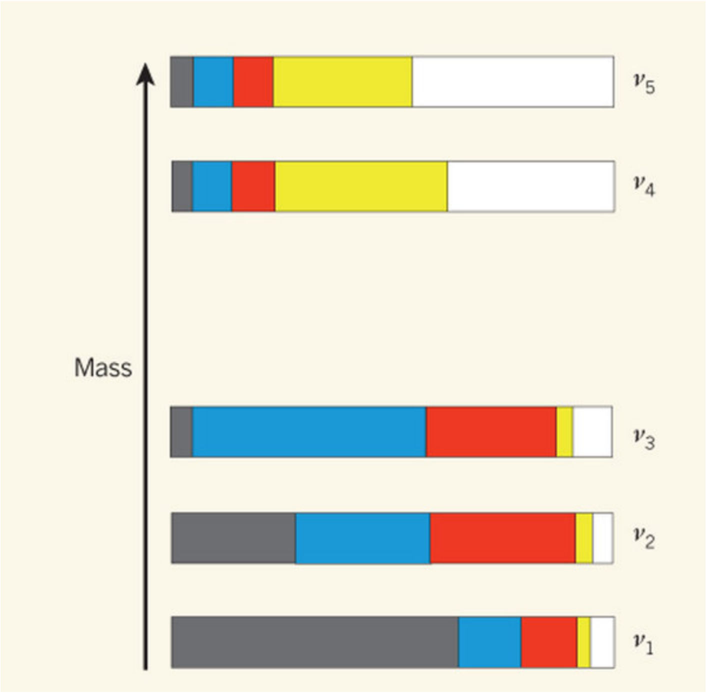
Constrains signal ν_e cross section

Is the three flavor paradigm complete?

Evidence of additional oscillation inferred from short-baseline LSND, MiniBooNE $\nu_e, \overline{\nu}_e$ appearance signals Δm^2~0.1-1eV^2 (E~1 GeV, L~0.5km)

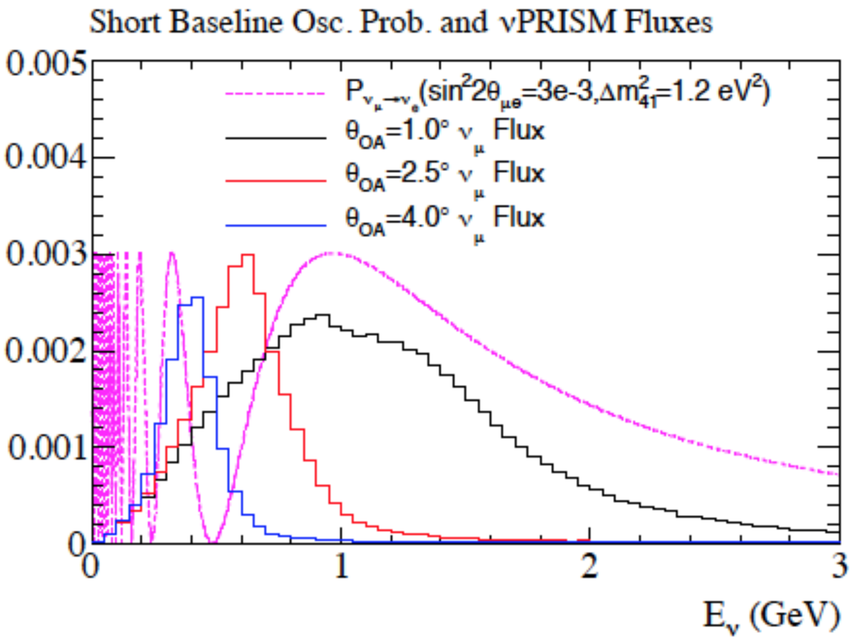


PRL 110, 161801 (2013)



W.C. Louis,
Nature, Volume: 478,
Pages: 328–329

Short baseline oscillations at νPRISM



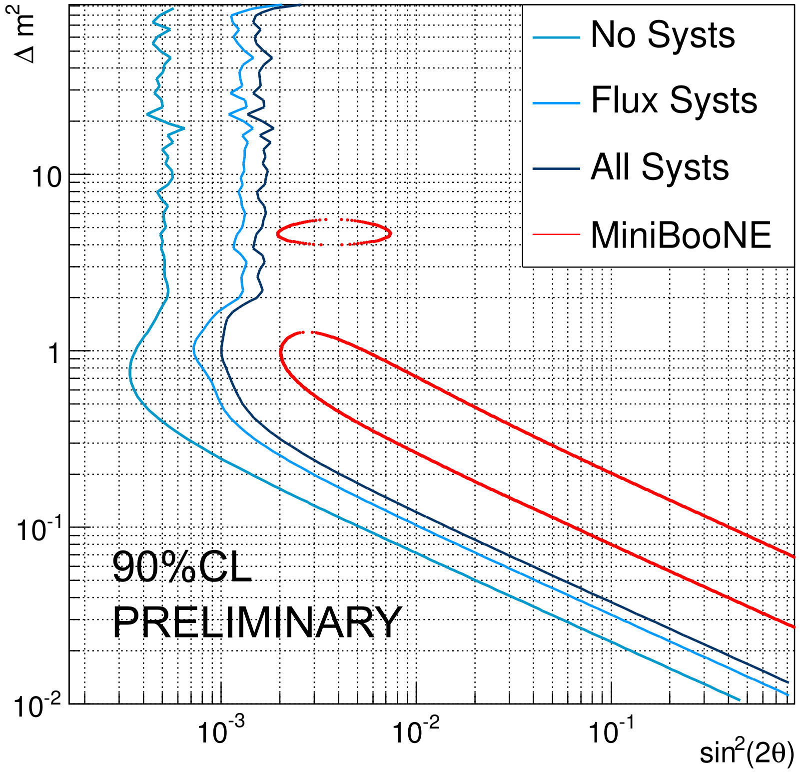
Direct test with νPRISM if oscillation follows L/E energy dependence

- Test relationship between inferred and true E_ν
- Backgrounds are measureable (e.g. $NC\pi^0$, intrinsic ν_e)

With 4.6e20 POT, νPRISM resolves MiniBooNE anomaly at 90%CL

Caveats:

- ν_e signal sensitive to inner diameter volume. Assumes 4m radius instead of 3; to be optimized with full simulation
- Does not include existing 280m T2K near detector information which will improve sensitivity



Summary

We are entering the precision era of neutrino physics

- Is there a symmetry between ν_μ and ν_τ? Is θ_{23} maximal?
- What is the ordering of the mass eigenstates? Is Δm^2_{32} positive or negative?
- Is there CP violation in the leptonic sector?

To achieve these goals, future long baseline programs require tight control of systematics (~1%) on few GeV neutrino beams

- Near detectors are enormously helpful; T2K reduces systematics by nearly a factor of 3
- However, near detector measures unoscillated flux. Predicting oscillated flux therefore relies on the cross section model.

The νPRISM concept provides a data driven method to address uncertainties on the cross section model by using a combination of fluxes in a single detector

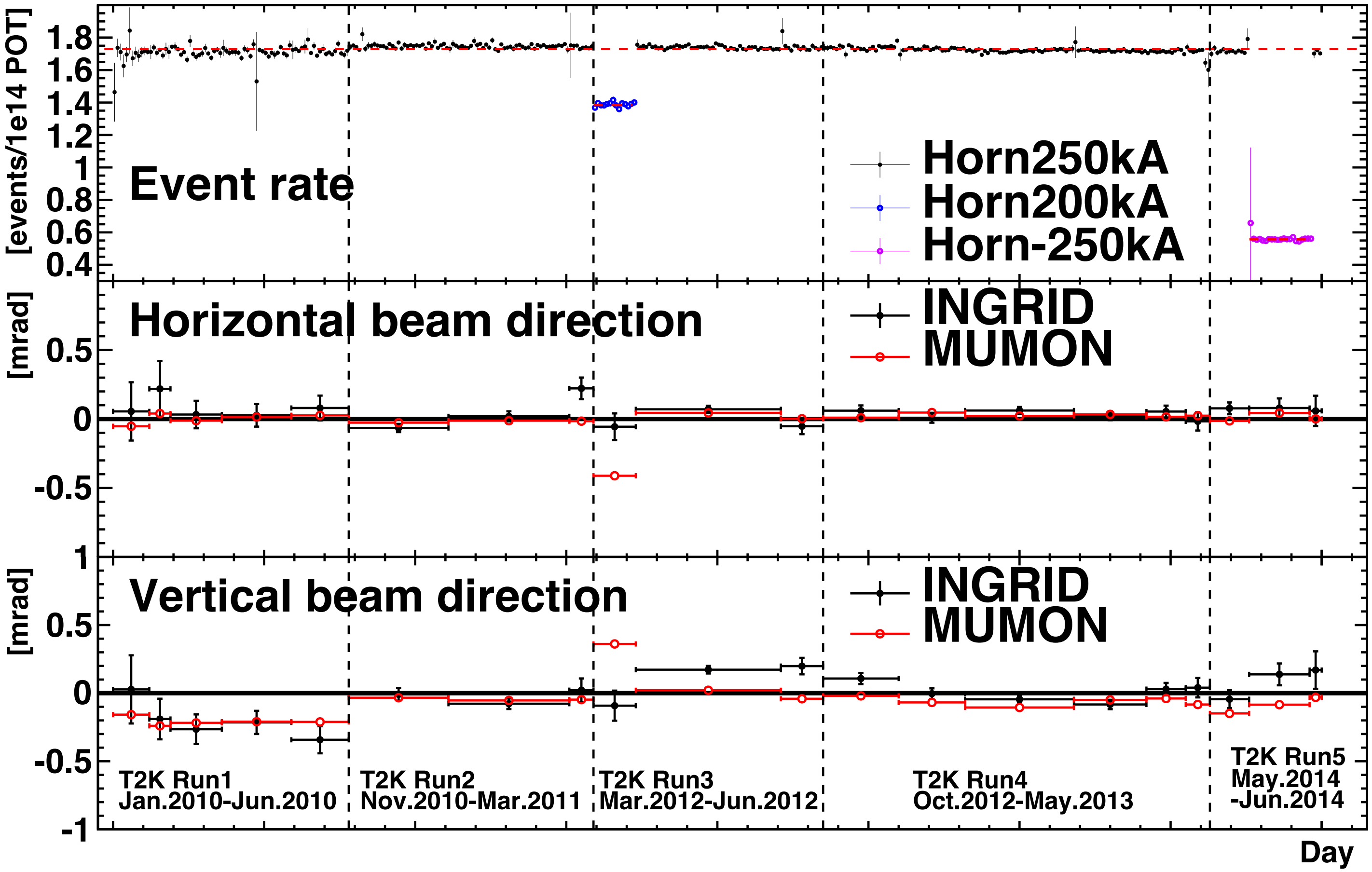
- Can create a monoenergetic neutrino beam or an oscillated flux
- Preliminary studies indicate significant reduction to bias in a realistic T2K-style analysis and beam over current program
    - To be studied for antineutrinos as
- Novel cross section program and sterile search capability

Thank you for your attention!

Backup slides

T2K run periods

MICHIGAN STATE UNIVERSITY



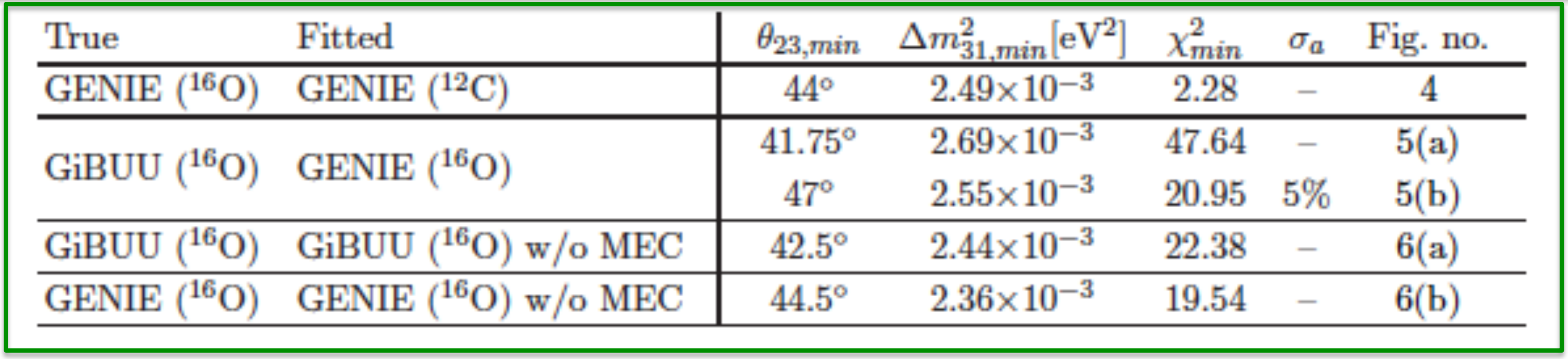
Run 1-4 POT: 6.63x10^{20} POT taken

- 6.57x10^{20} for analysis, ~8% of design POT

Run 5 (2014)

- Neutrino commissioning run
- Pilot antineutrino run

Additional osc-multinucleon studies



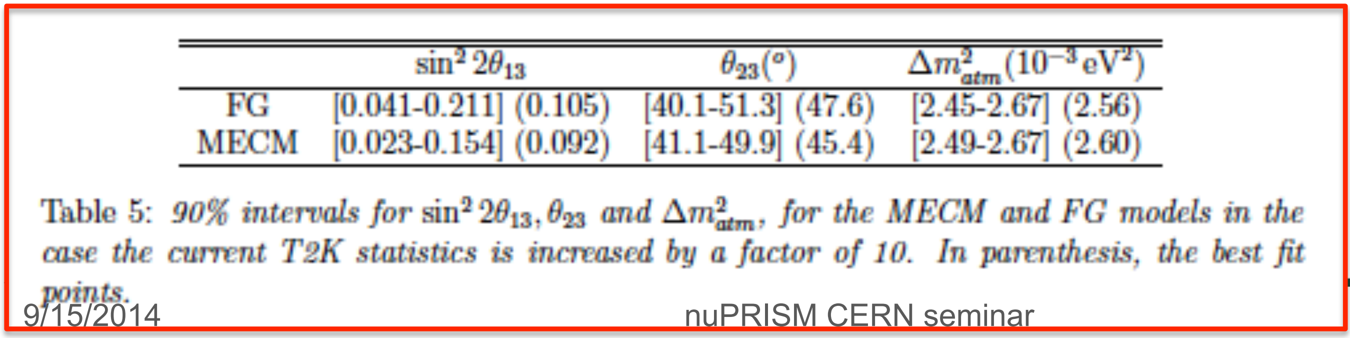
True	Fitted	$\theta_{23,min}$	$\Delta m^2_{31,min}[\mathrm{eV}^2]$	χ^2_{min}	σ_a	Fig. no.
GENIE (^{16}O)	GENIE (^{12}C)	44°	2.49×10^{-3}	2.28	–	4
GiBUU (^{16}O)	GENIE (^{16}O)	41.75°	2.69×10^{-3}	47.64	–	5(a)
		47°	2.55×10^{-3}	20.95	5%	5(b)
GiBUU (^{16}O)	GiBUU (^{16}O) w/o MEC	42.5°	2.44×10^{-3}	22.38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

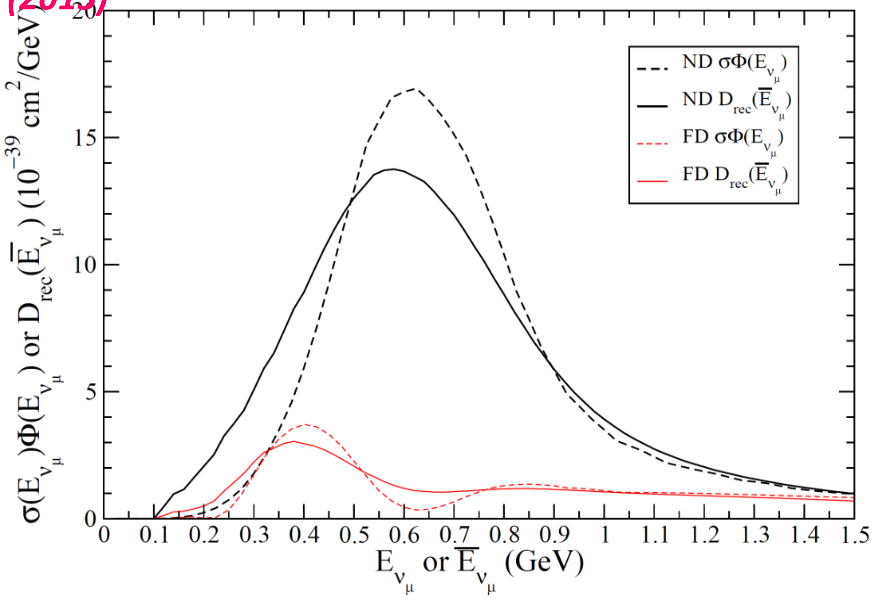


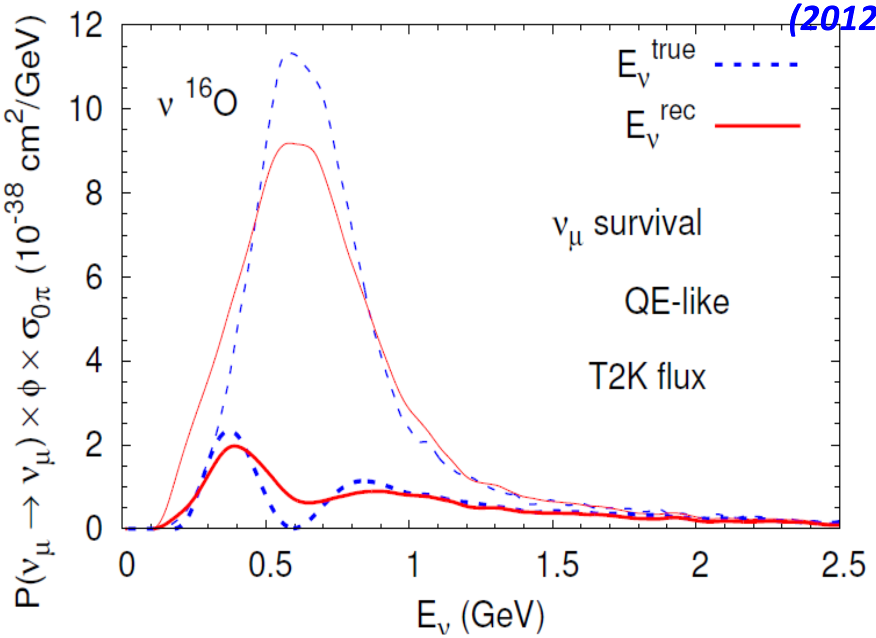
	$\sin^2 2\theta_{13}$	$\theta_{23}(^\circ)$	$\Delta m^2_{atm}(10^{-3}\,\mathrm{eV}^2)$
FG	[0.041-0.211] (0.105)	[40.1-51.3] (47.6)	[2.45-2.67] (2.56)
MECM	[0.023-0.154] (0.092)	[41.1-49.9] (45.4)	[2.49-2.67] (2.60)

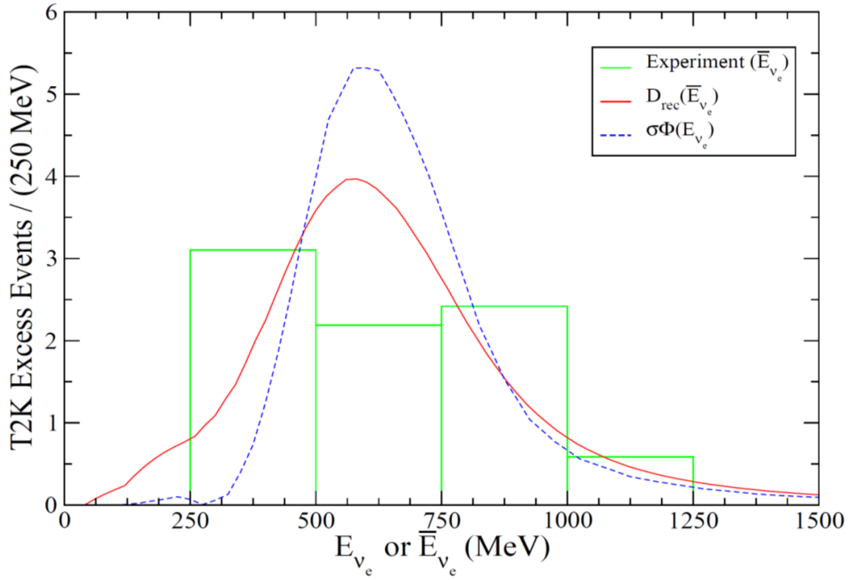
Table 5: *90% intervals for* $\sin^2 2\theta_{13}, \theta_{23}$ *and* Δm^2_{atm}, *for the MECM and FG models in the case the current T2K statistics is increased by a factor of 10. In parenthesis, the best fit points.*

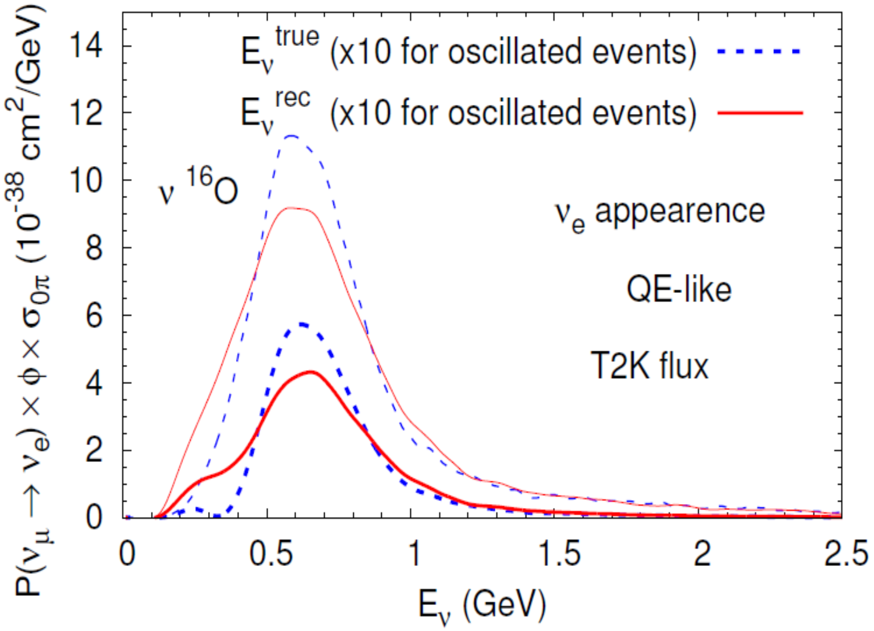
M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

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



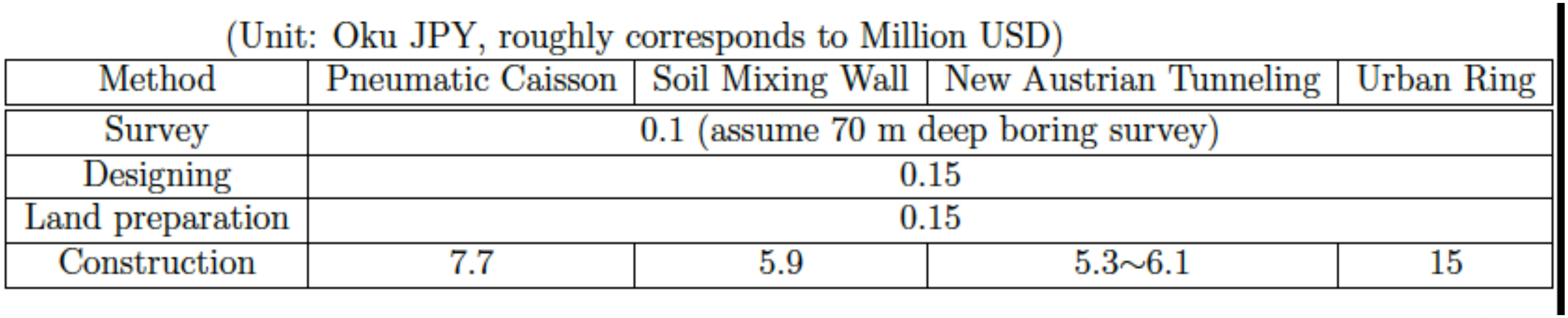






Civil construction and costing

MICHIGAN STATE UNIVERSITY



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

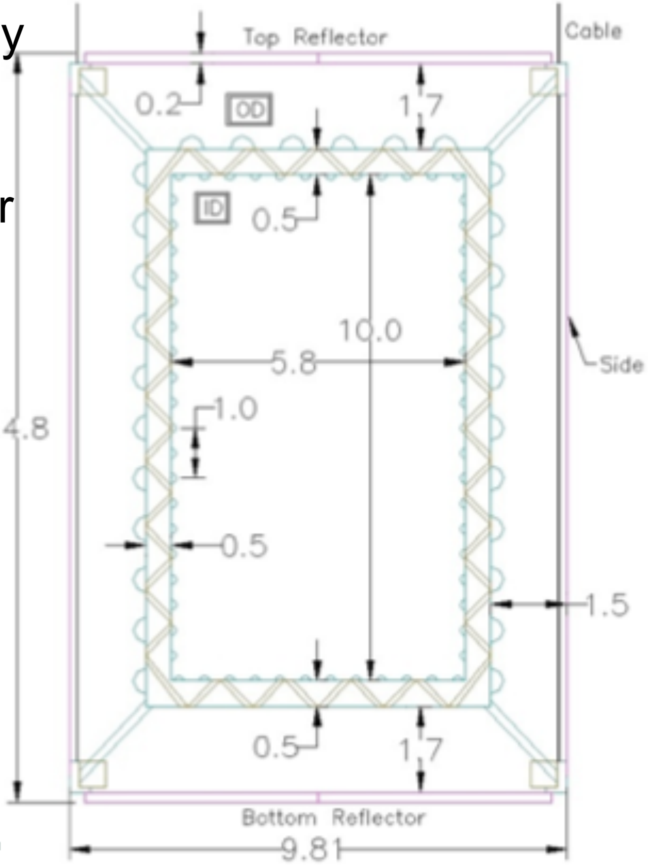
Method	Pneumatic Caisson	Soil Mixing Wall	New Austrian Tunneling	Urban Ring
Survey	0.1 (assume 70 m deep boring survey)			
Designing	0.15			
Land preparation	0.15			
Construction	7.7	5.9	5.3∼6.1	15

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

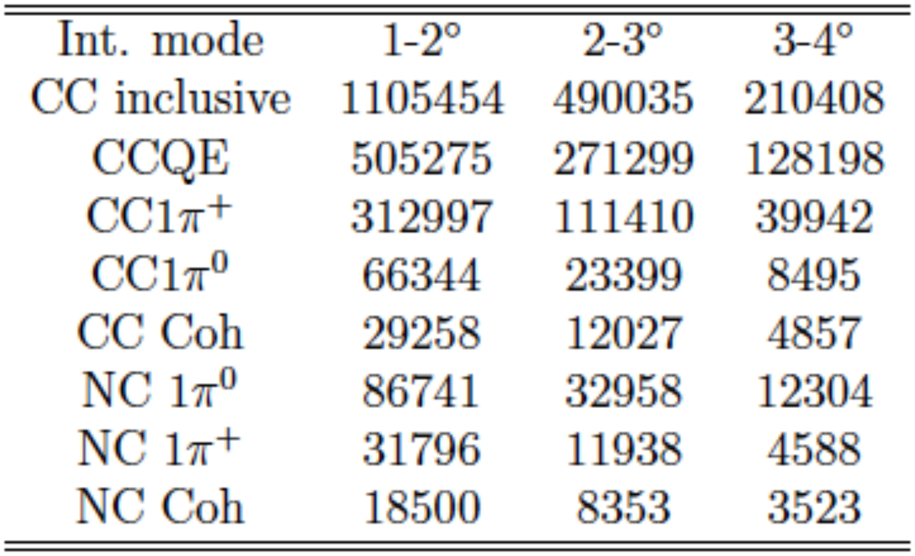


Simulation and event rate

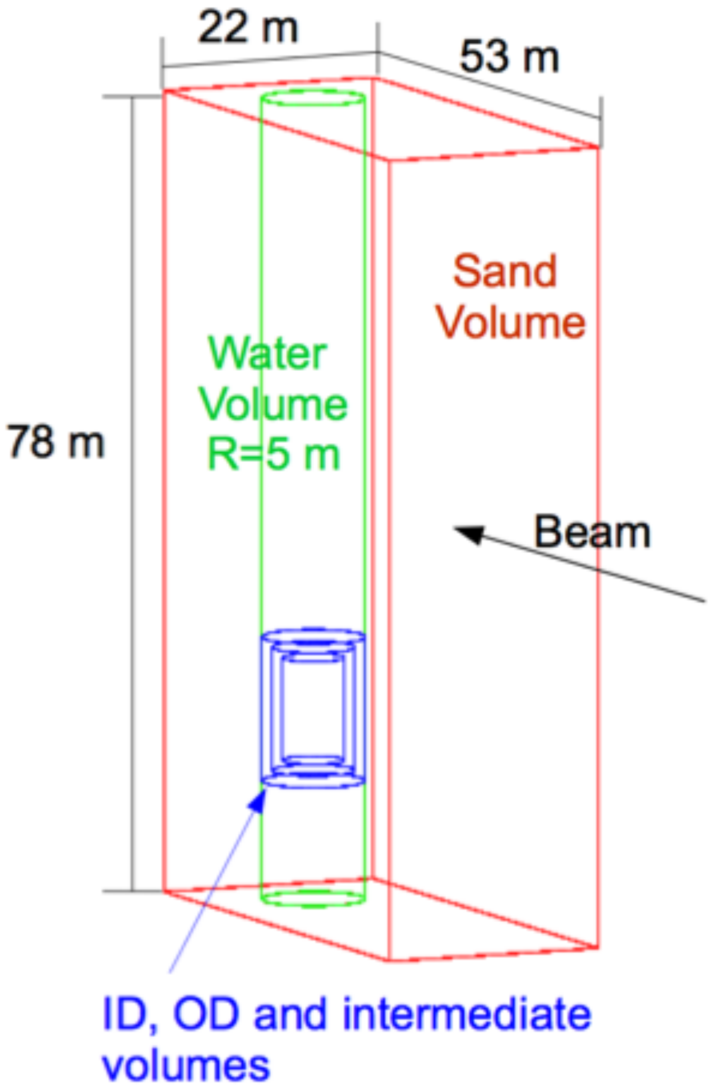
Full GEANT4 simulation of water, surrounding sand

- 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:



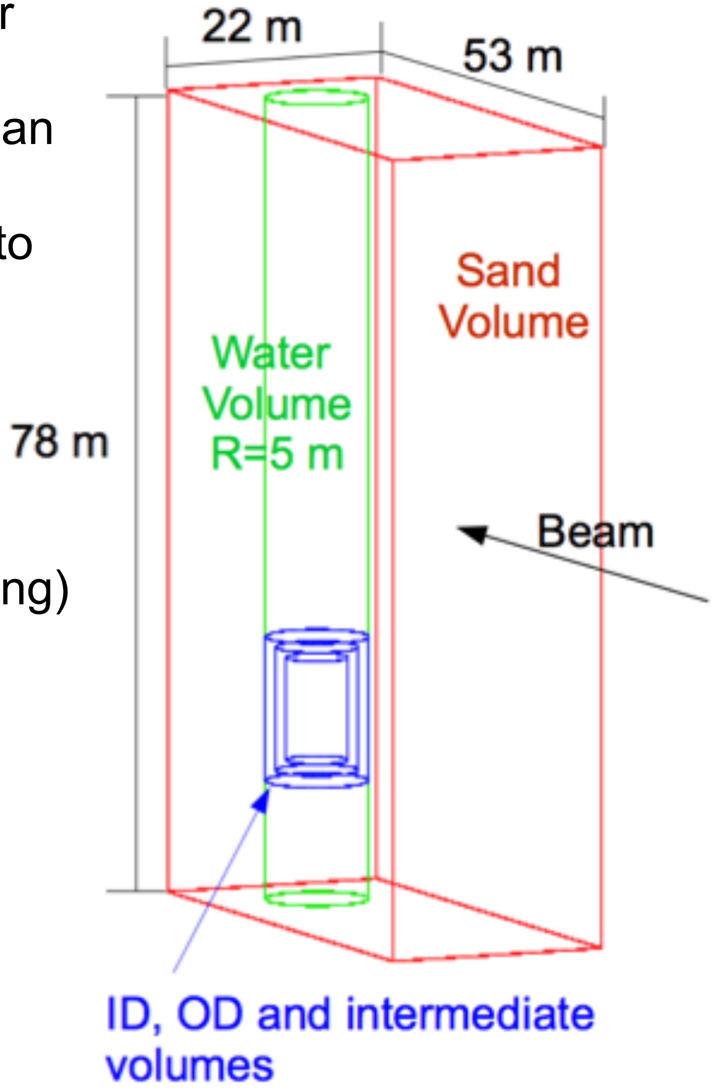
Int. mode	1-2°	2-3°	3-4°
CC inclusive	1105454	490035	210408
CCQE	505275	271299	128198
CC1π^+	312997	111410	39942
CC1π^0	66344	23399	8495
CC Coh	29258	12027	4857
NC 1π^0	86741	32958	12304
NC 1π^+	31796	11938	4588
NC Coh	18500	8353	3523



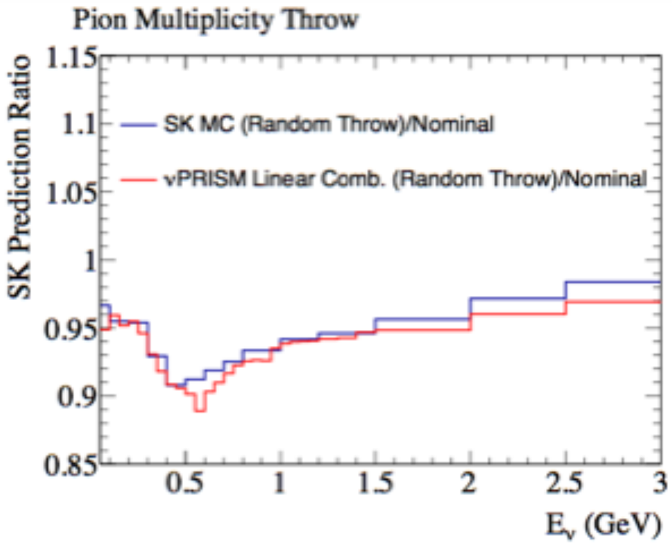
Pile-up and vetoing

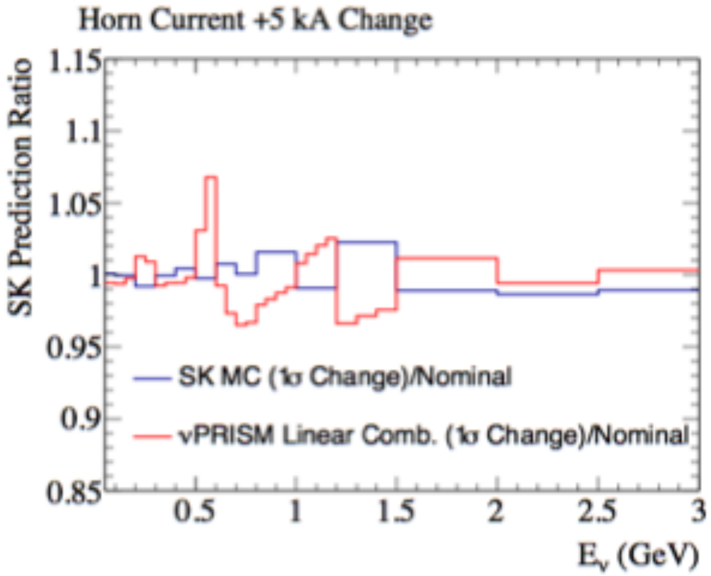
Beam consists of 8 bunches per spill, consider multiple neutrino interactions in ID, OD

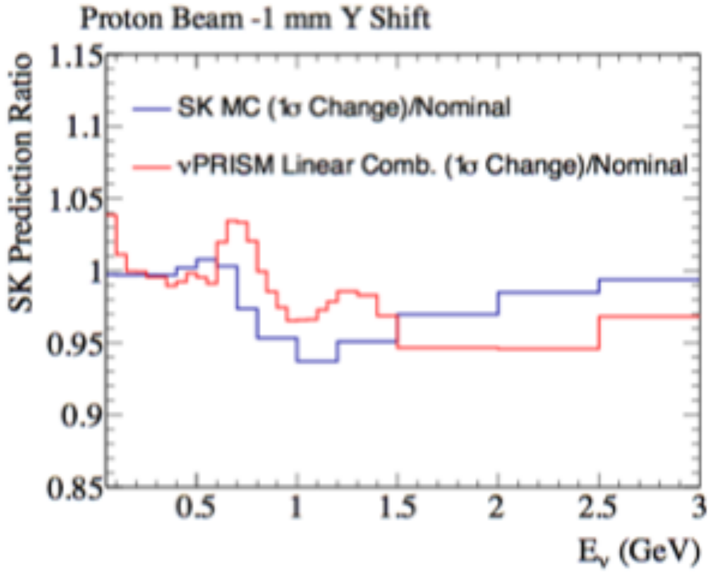
- 41% chance of in-bunch OD activity during an ID-contained event
    - Consider scintillator panels in addition to OD activity
- 17% of bunches have ID activity from more than 1 interaction (10% with no OD)
    - Full MC studies planned
    - New FD reconstruction works well with multiple particles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



Flux uncertainties

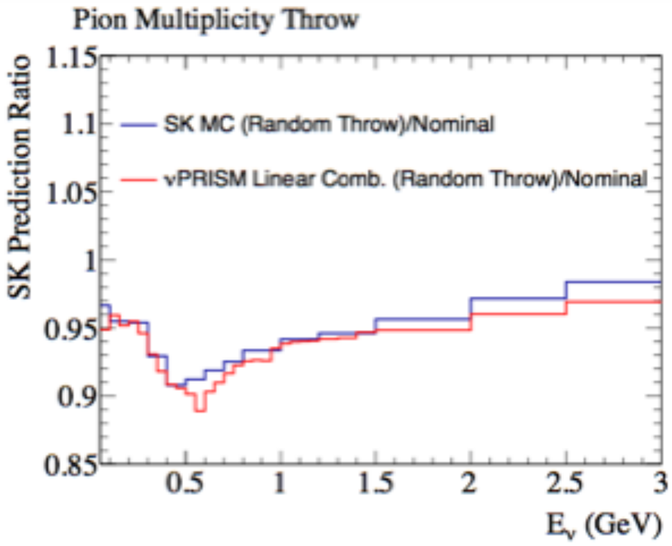

Pion Multiplicity Throw

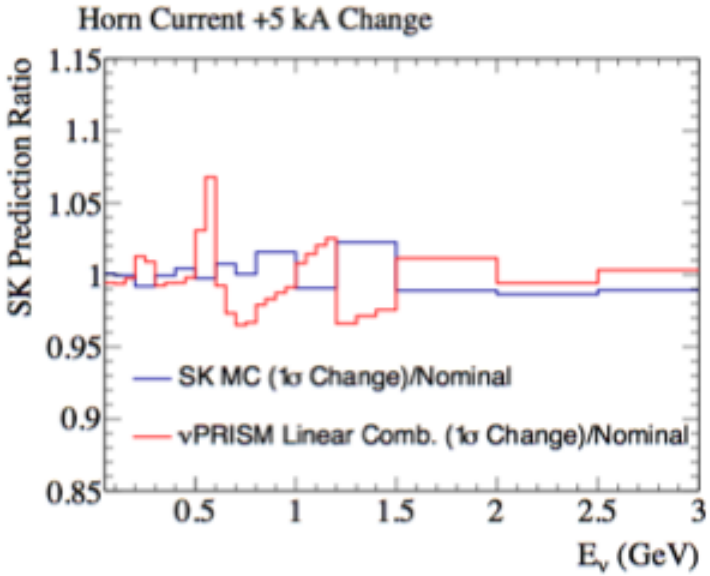

Horn Current +5 kA Change

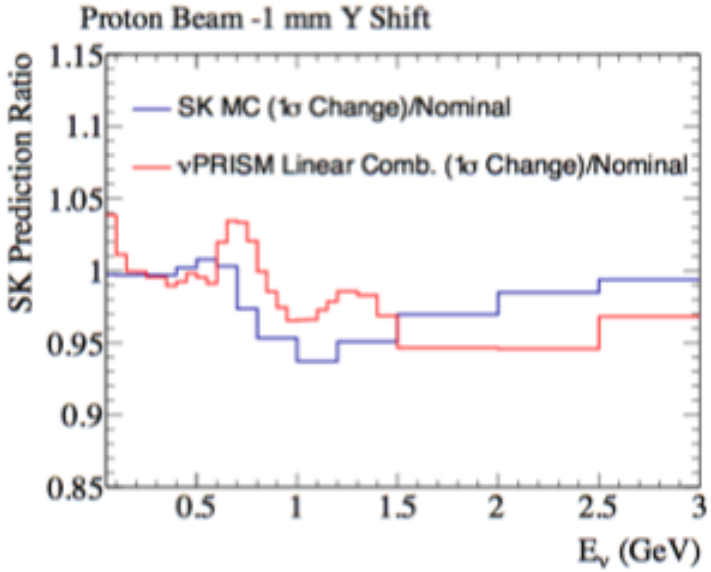

Proton Beam -1 mm Y Shift

- 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







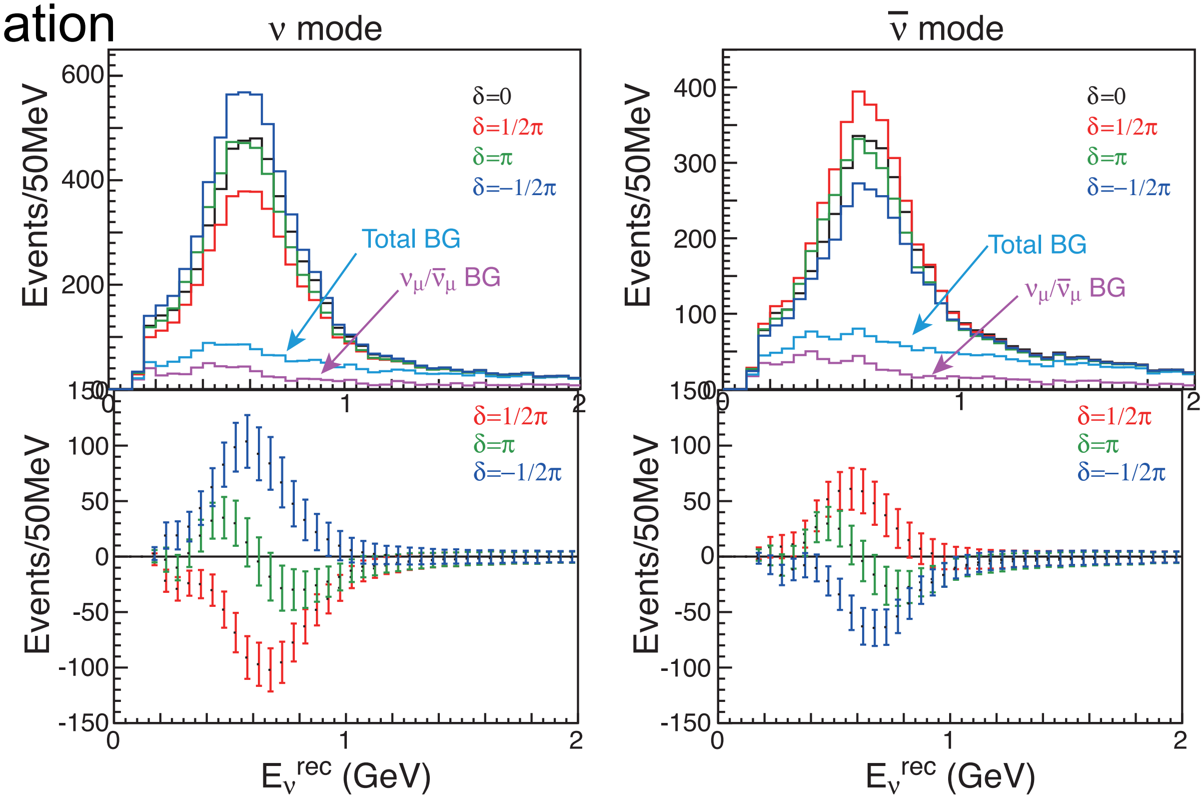
- Dominant flux uncertainty (pion production) affects νPRISM ND and FD flux similarly
- Proton beam and horn current affect off-axis angle
- ~10% change becomes 1% on $\sin^2\theta_{23}$

T2HK: Hyper-Kamiokande

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

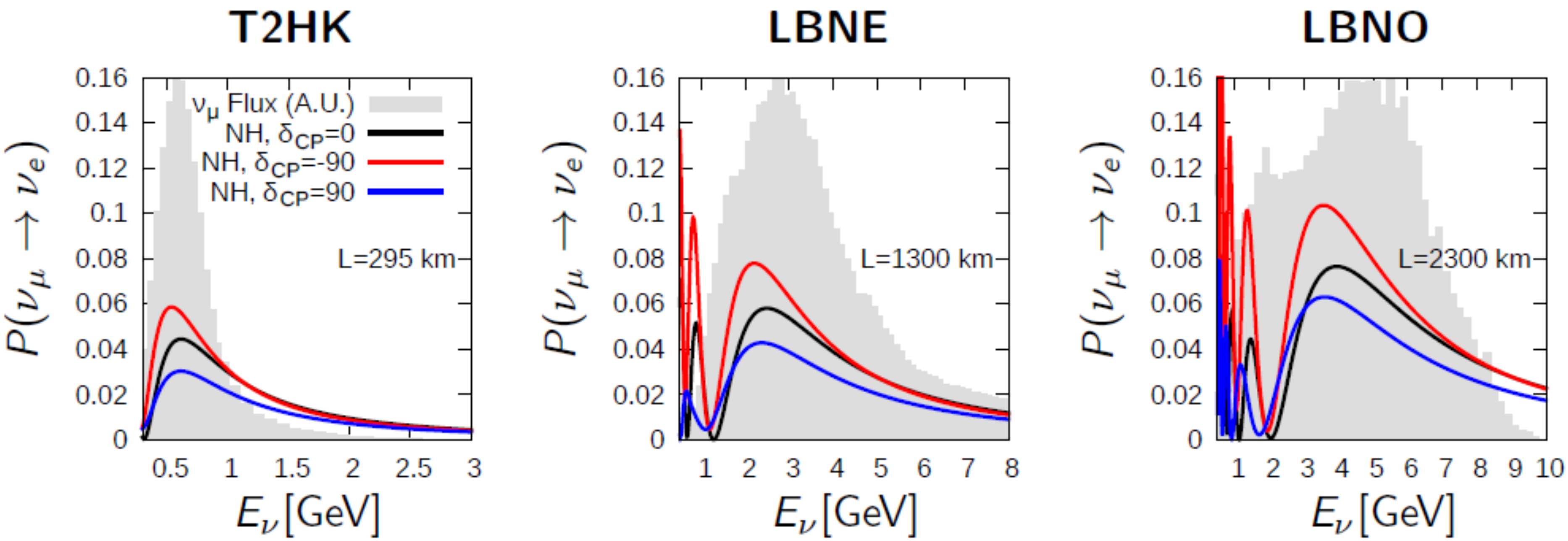


Hyper-Kamiokande LOI: arXiv:1109.3262

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