Confronting Neutrino-Nucleus Interactions at E_ν~1 GeV with the NuPRISM Detector

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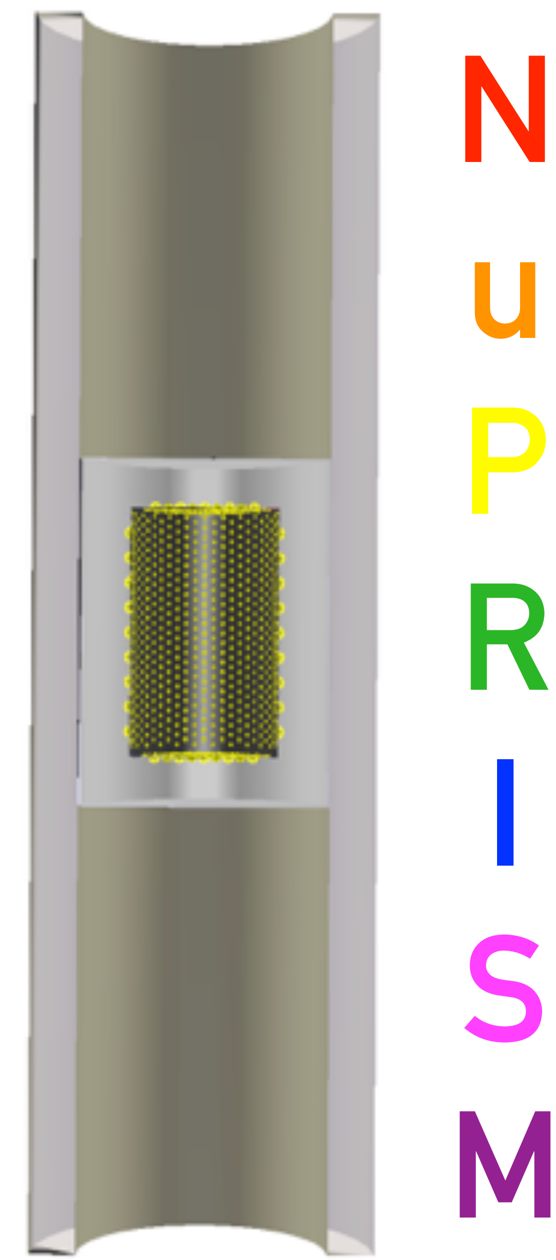
J-PARC Seminar
August 20, 2015



Outline

- Long baseline neutrino experiments
- Challenges in neutrino interaction modeling
- The NuPRISM detector
- Application to muon neutrino disappearance
- Electron neutrino cross section modelling
- Short baseline oscillations at NuPRISM
- Other measurements at NuPRISM

Neutrino Mixing & Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour and mass states related by a unitary mixing matrix.

All three angles have now been measured and we are beginning to constrain the CP phase.

$\theta_{13} = 8.9^\circ \pm 0.4^\circ$

$\theta_{23} = 46.6^\circ \pm 3.2^\circ$

$\theta_{12} = 33.4^\circ \pm 0.9^\circ$

Oscillations depend on the mixing angles and mass squared differences.

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

$|\Delta m^2_{32}| = 2.44 \pm 0.06 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{21} = 7.5 \pm 0.2 \times 10^{-5}\ \mathrm{eV}^2$

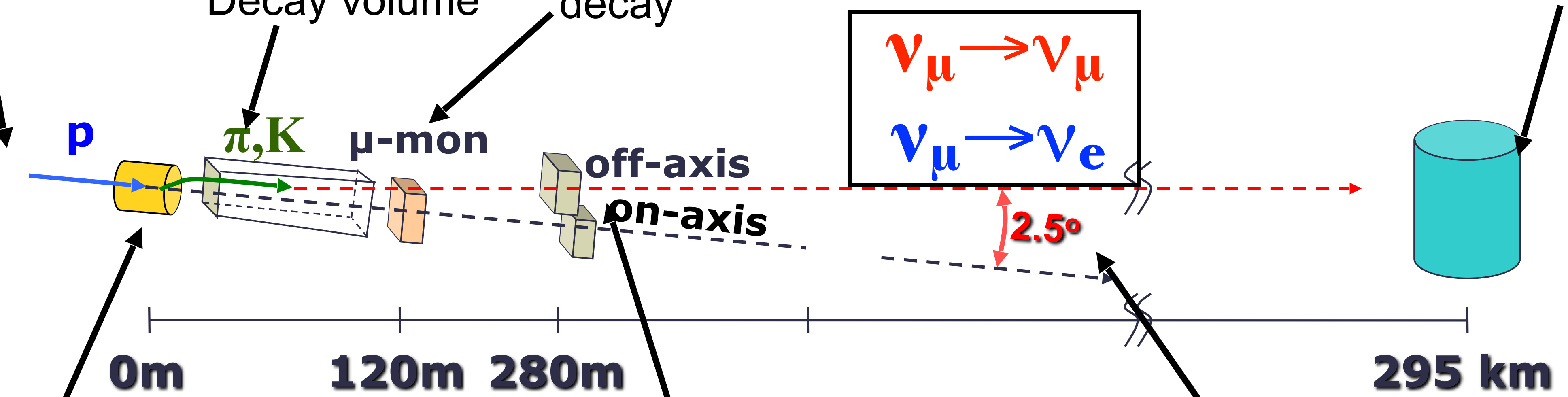
Long Baseline Experiments (T2K & HK)

30 GeV proton beam

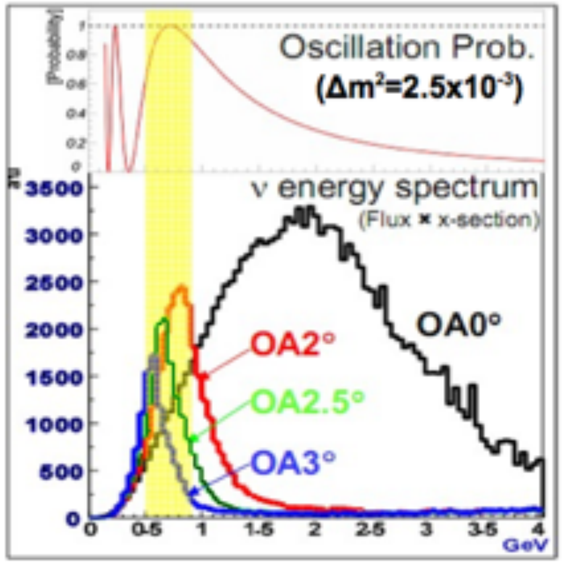
Decay volume

MUMON measures muons from pion decay

Off-axis **far detector** at 295 km: SK (50 kton) or HK (1 megaton) water Cherenkov detector measures oscillated flux



Off-axis = narrow band beam



Beam on graphite target

3 magnetic horns focus positively charged hadrons

Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions

Oscillation Probabilities

$$
\begin{aligned}
P(\nu_\mu \to \nu_\mu) = 1 &- 4(s_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 c_{12}^2 + 2 s_{12} s_{13} s_{23} c_{12} c_{23} \cos\delta) s_{23}^2 c_{13}^2 \sin^2\phi_{31} \\
&- 4(c_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 s_{12}^2 - 2 s_{12} s_{13} s_{23} c_{12} c_{23} \cos\delta) s_{23}^2 c_{13}^2 \sin^2\phi_{32} \\
&- 4(s_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 c_{12}^2 + 2 s_{12} s_{13} s_{23} c_{12} c_{23} \cos\delta) \\
&\times (c_{12}^2 c_{23}^2 + s_{13}^2 s_{23}^2 s_{12}^2 - 2 s_{12} s_{13} s_{23} c_{12} c_{23} \cos\delta) \sin^2\phi_{21},
\end{aligned}
$$

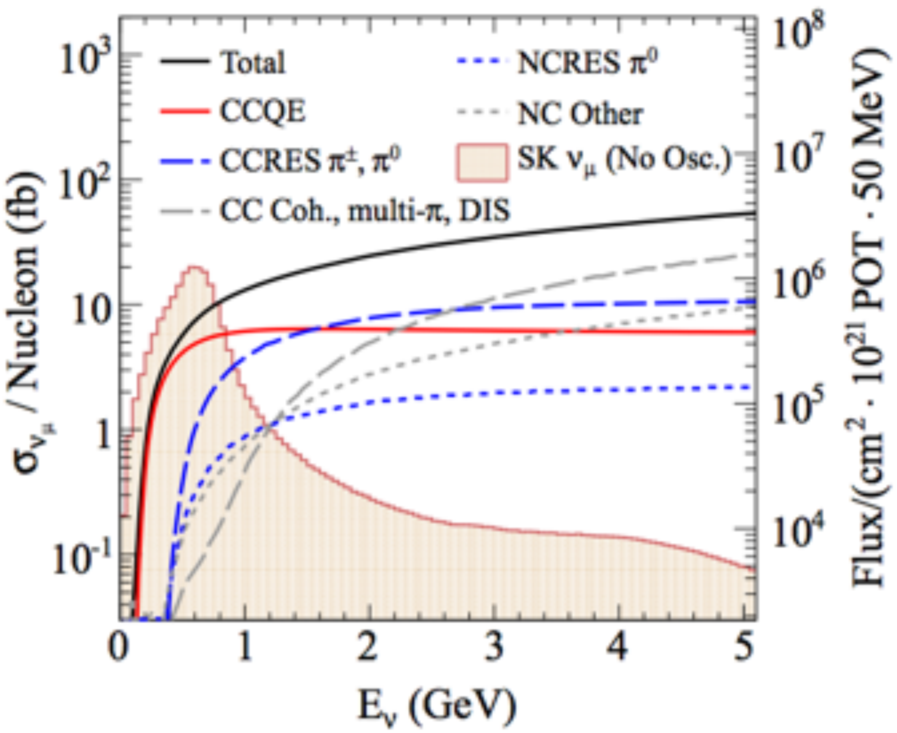
$$\phi_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2 s_{13}^2)\right) + 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\phi_{23} \sin\phi_{31} \sin\phi_{21} \\
& \boxed{- 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\phi_{32} \sin\phi_{31} \sin\phi_{21}} \\
& + 4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2\phi_{21} \\
& - 8 c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2 s_{13}^2) \frac{aL}{4E_\nu} \cos\phi_{32} \sin\phi_{31}. \qquad (18)
\end{aligned}
$$

CP violation enters here, sign flips for antineutrinos

This is what we ultimately want to measure

Neutrino Interactions



In T2K and Hyper-K, the signal are charged current quasi-elastic (CCQE) candidates

Only a single visible ring the the water Cherenkov detector

Oscillations depend on the neutrino energy

The beam is wide enough that we don't know the incident neutrino's energy

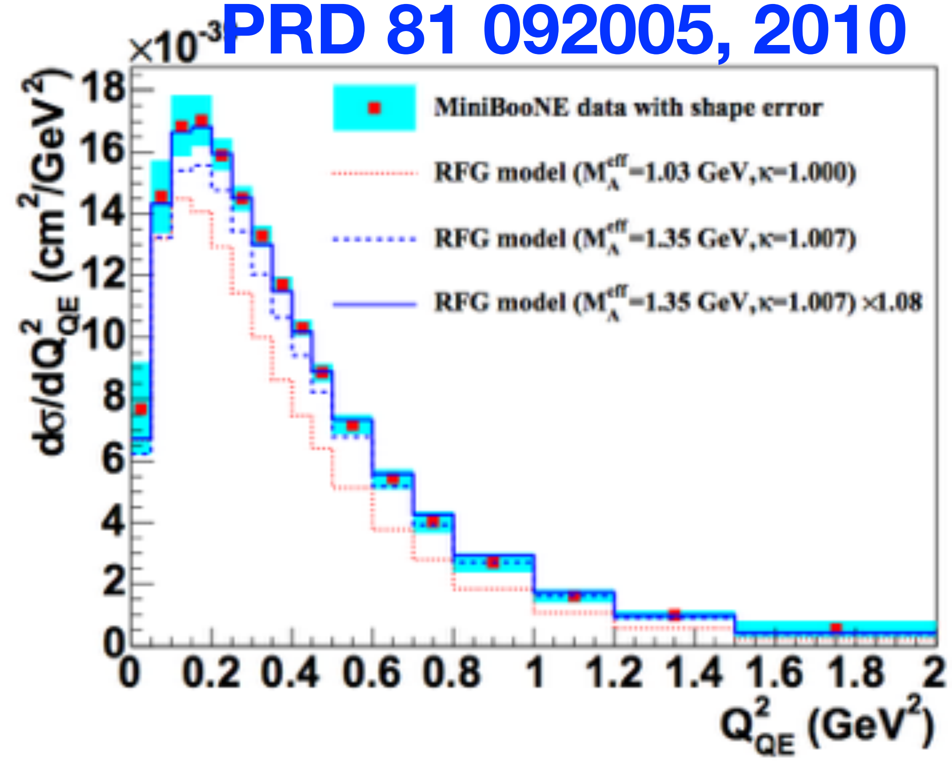
Neutrino interaction model:
observed final state lepton kinematics ↔ neutrino energy

Use reconstructed energy variable: $$E_\nu^{\text{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

The CCQE Cross Section Puzzle

- MiniBooNE published a measurement of the CCQE cross section that seem to prefer a large axial mass (consistent with K2K) of 1.35 GeV
- Why does MiniBooNE M_A deviate from the value measured in neutrino-deuterium interactions and π electroproduction?

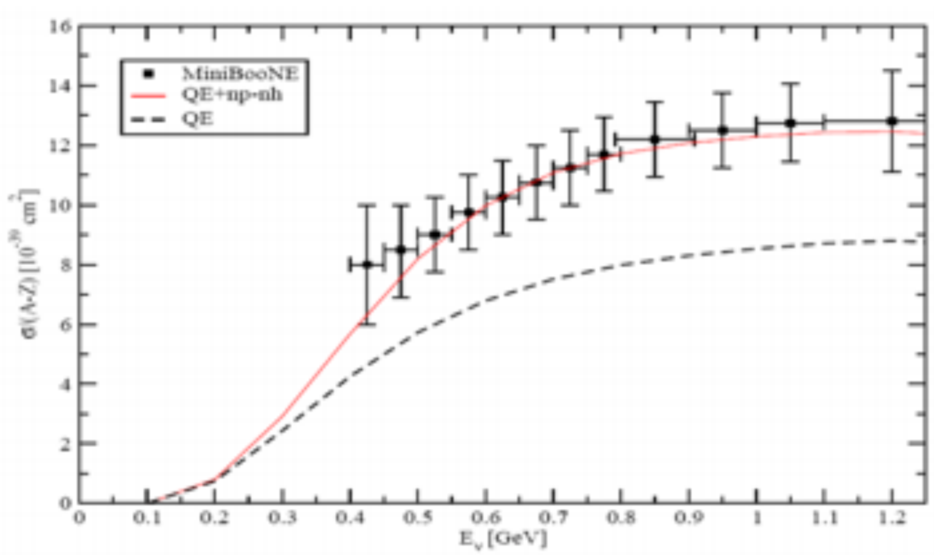
PRD 81 092005, 2010

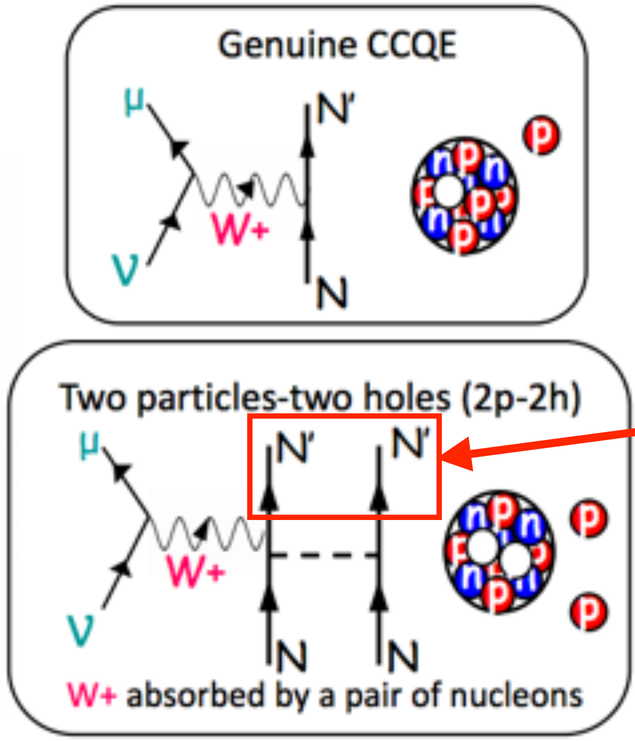


Solution:

M. Martini NuFact 2015

Inclusion of the multinucleon emission channel (np-nh)





Not detected in a water Cherenkov detector

M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Significant Work on np-nh in Recent Years

M. Martini NuFact 2015

Theoretical calculations on np-nh contributions to ν-nucleus cross sections

M. Martini, M. Ericson, G. Chanfray, J. Marteau (Lyon, IPNL)

Phys. Rev. C 80 065501 (2009) ν σtotal
Phys. Rev. C 81 045502 (2010) ν vs antiν (σtotal)
Phys. Rev. C 84 055502 (2011) ν $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. D 85 093012 (2012) impact of np-nh on ν energy reconstruction
Phys. Rev. D 87 013009 (2013) impact of np-nh on ν energy reconstruction and ν oscillation
Phys. Rev. C 87 065501 (2013) antiν $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. C 90 025501 (2014) inclusive ν $d^2\sigma$
Phys. Rev. C 91 035501 (2015) combining ν and antiν $d^2\sigma$, $d\sigma/dQ^2$

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas, F. Sanchez, R. Gran (Valencia, IFIC)

Phys. Rev. C 83 045501 (2011) ν, antiν σtotal
Phys. Lett. B 707 72-75 (2012) ν $d^2\sigma$
Phys. Rev. D 85 113008 (2012) impact of np-nh on ν energy reconstruction
Phys. Lett. B 721 90-93 (2013) antiν $d^2\sigma$
Phys. Rev. D 88 113007 (2013) extension of np-nh up to 10 GeV

J.E. Amaro, M.B. Barbaro, T.W. Donnelly, G. Megias, I. Ruiz Simo et al. (Superscaling)

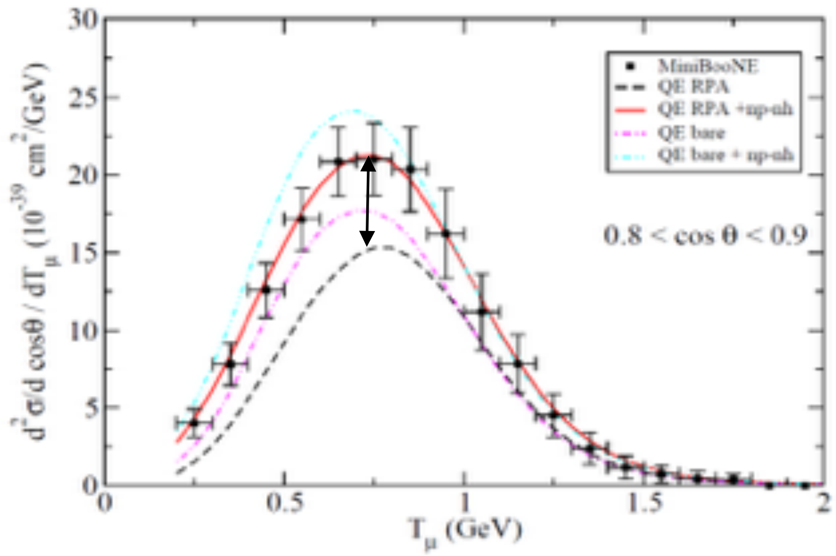
Phys. Lett. B 696 151-155 (2011) ν $d^2\sigma$
Phys. Rev. D 84 033004 (2011) ν $d^2\sigma$, σtotal
Phys. Rev. Lett. 108 152501 (2012) antiν $d^2\sigma$, σtotal
Phys. Rev. D 90 033012 (2014) 2p-2h phase space
Phys. Rev. D 90 053010 (2014) angular distribution
Phys. Rev. D 91 073004 (2015) parametrization of vector MEC
arXiv 1506.00801 (2015) inclusive ν $d^2\sigma$

10/8/2015 M. Martini, NuFact15 18

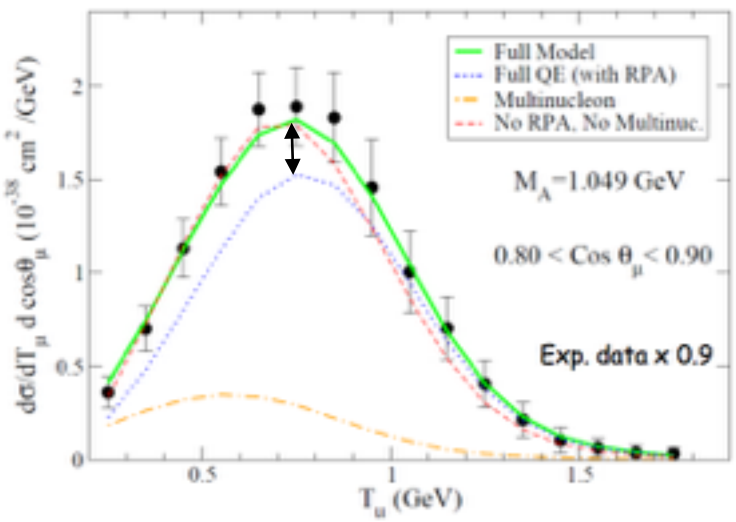
Difference in Models

ν

Martini et al.

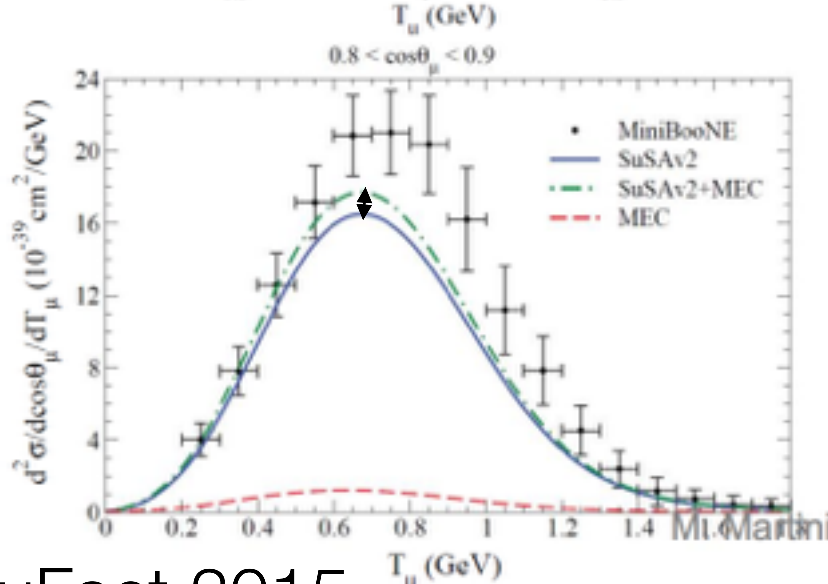


Nieves et al.



Amaro et al.

[Megias talk]



10/8/2015

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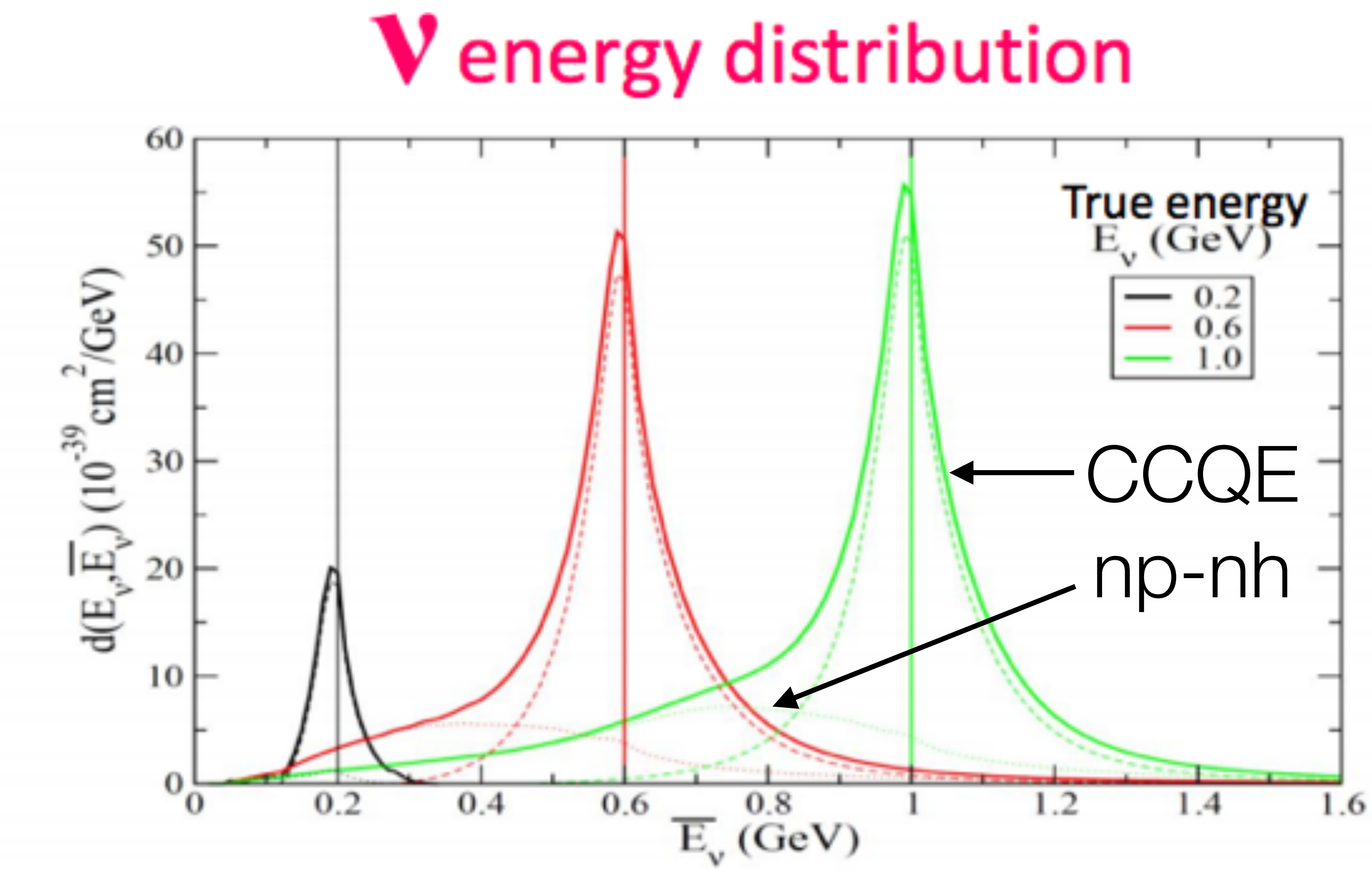
- The np-nh contributions vary by more than a factor of 2 in the energy range of interest
- Both the Martini et al. and Nieves et al. calculations are consistent with MiniBooNE data within the MiniBooNE flux uncertainties
- The super scaling model of Amaro et al. is missing MEC in the axial and vector-axial interference terms

The CCQE Energy Reconstruction Problem

- MiniBooNE CCQE puzzle solved by a large contribution of np-nh to the cross section
- But the reconstructed energy for the np-nh contribution is different from CCQE



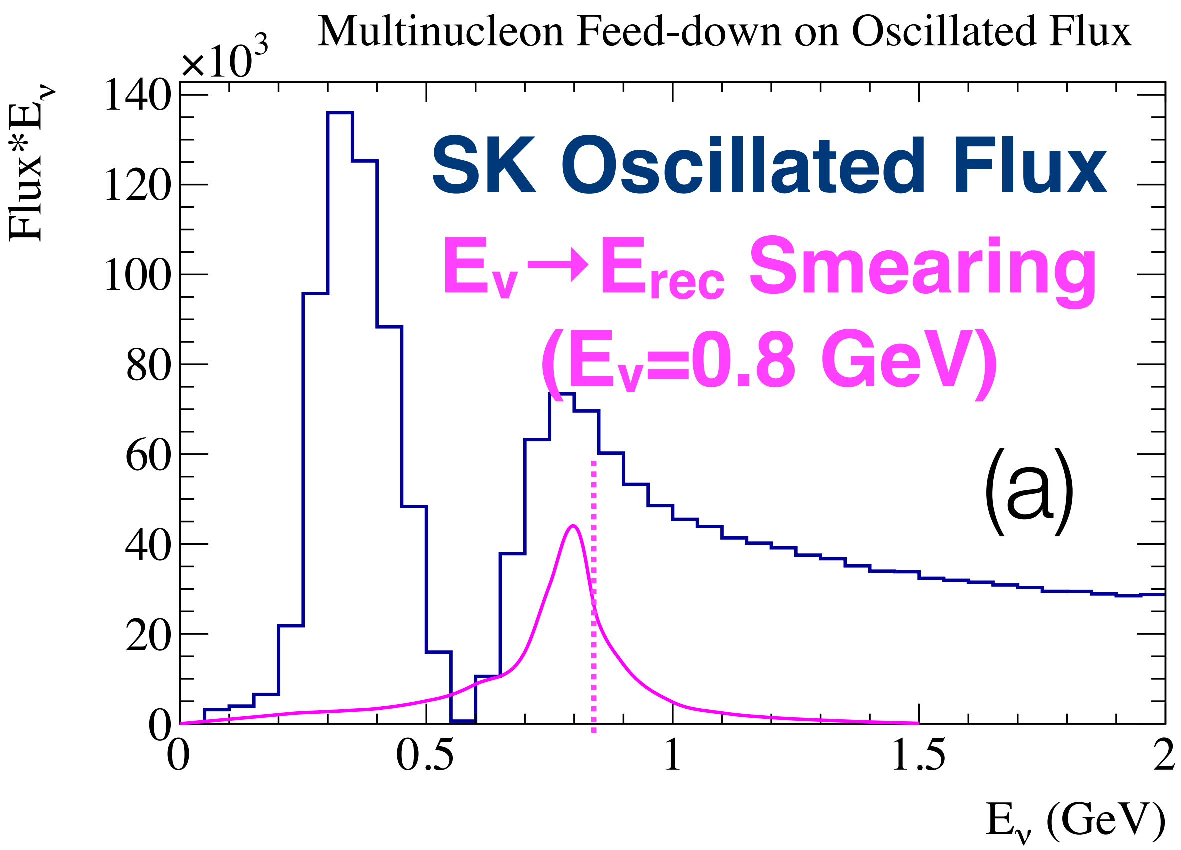
np-nh introduces a large tail of events with reconstructed energy less than the true energy

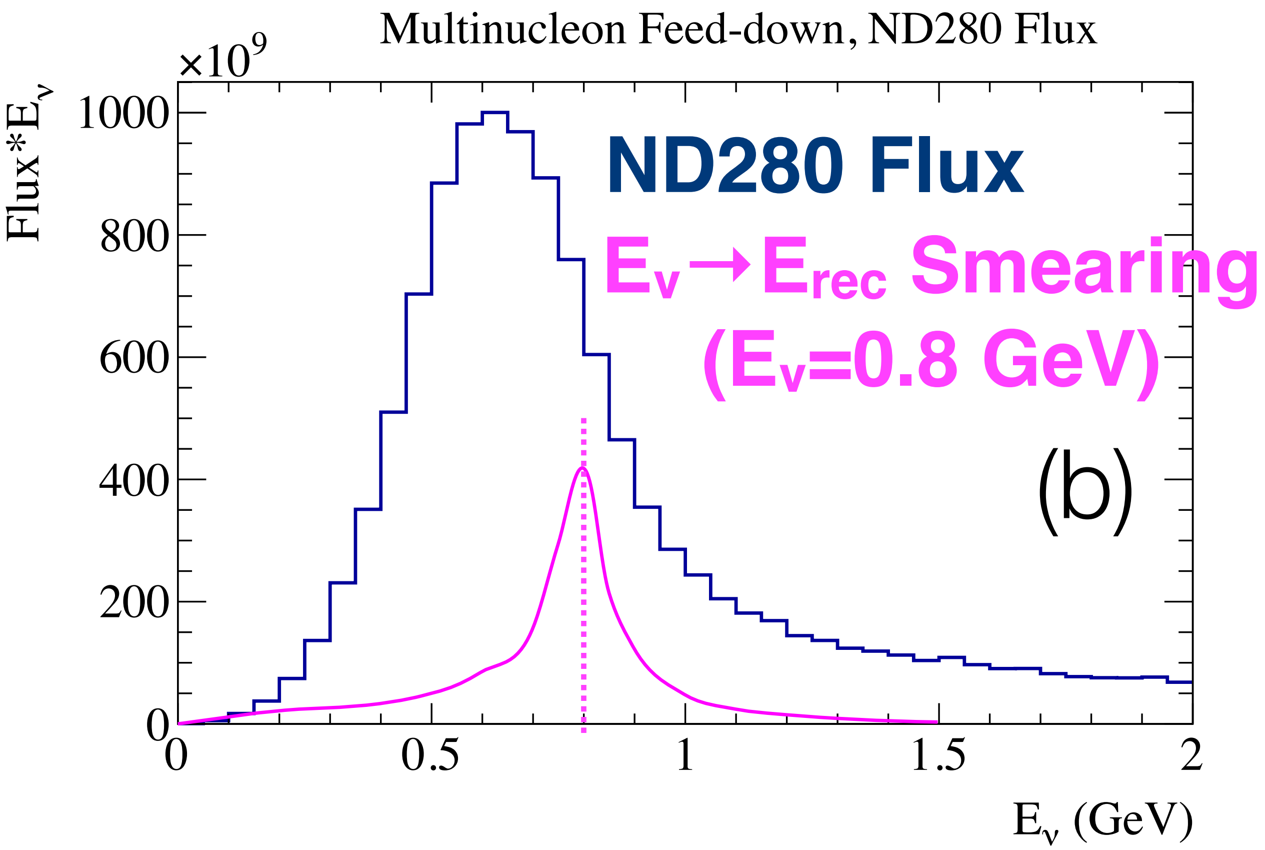
M. Martini, M. Ericson, G. Chanfray, Phys. Rev. D 85 093012 (2012)

- Modelling this is critical since neutrino oscillations depend on the energy
- Calculations on the market can vary by a factor 2 in predicting the np-nh contribution
- Are we saved by using near detector data?

Near Detector Constraints

- Oscillations → different flux at near and far detectors

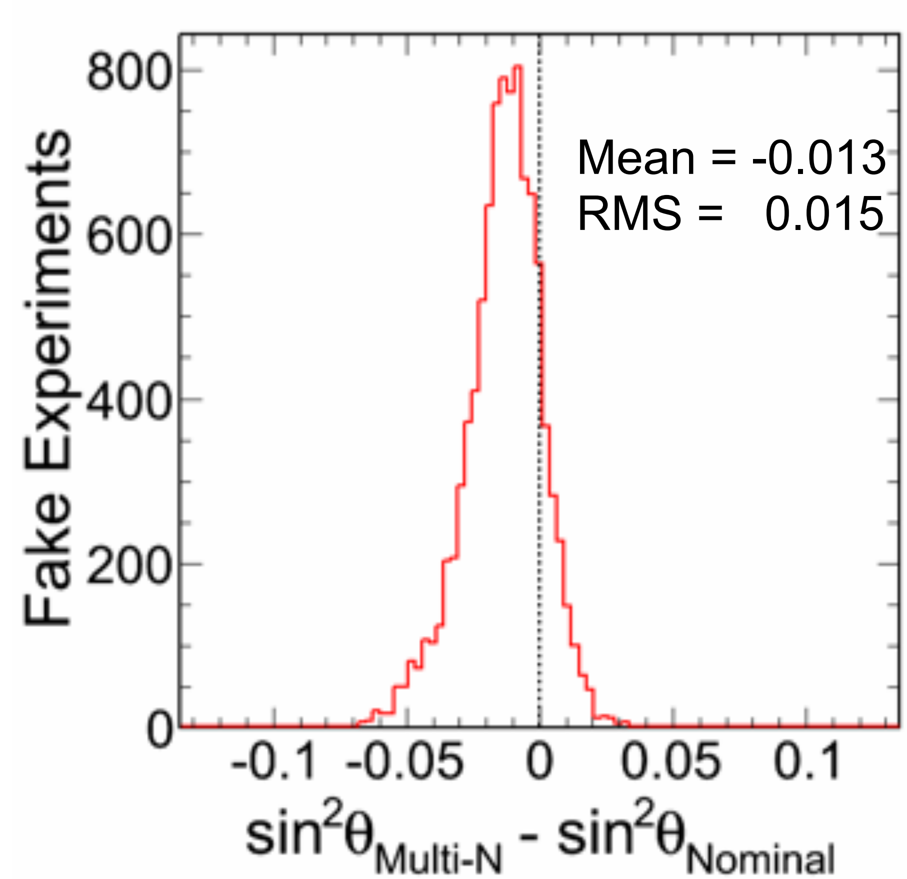




- Energy smear that may be a large effect in the far detector (a) may be a relatively small effect in the near detector (b)
- Mis-modelling can lead to large systematic effects in the extraction of oscillation parameters

T2K np-nh Mis-modelling Study

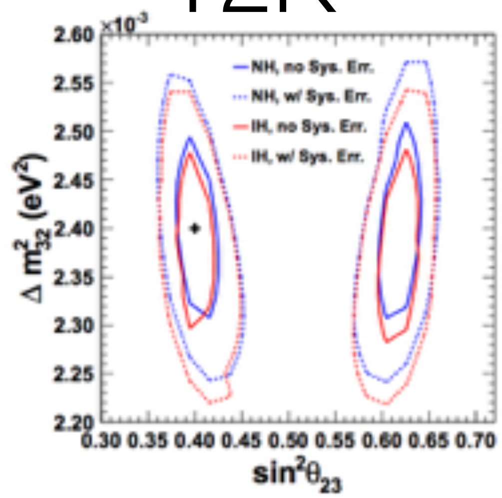
- T2K study of bias induced by np-nh mis-modelling
  - Generate toy data with np-nh models (Nieves et al. and "ad-hoc" model that looks similar to Martini et al.) for both near and SK detector
    - Far detector toy data has oscillations applied
  - Fit the near and far detector toy data with the model in NEUT 5.1.4.2
  - Evaluate the bias on the oscillation parameters
- $\sin^2\theta_{23}$ biased by 3% with uncertainty on bias of 3%
- Would assign a **systematic error of 4.2%**
- But this is only the comparison of 2 models!



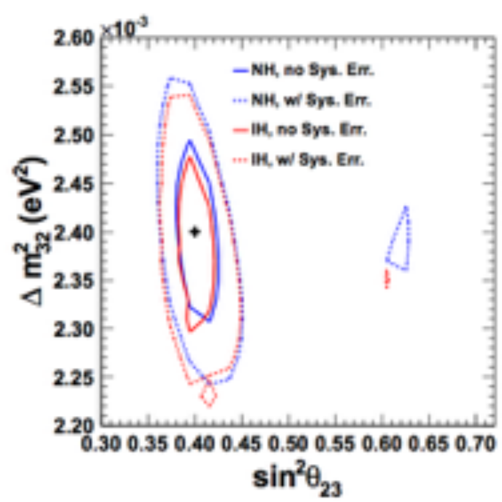
T2K/HK $\sin^2\theta_{23}$ Sensitivity

- Does the ~4% uncertainty on $\sin^2\theta_{23}$ matter?
- 3 cases: T2K full exposure, T2K x3 exposure, Hyper-K exposure

T2K



(b) 50% ν-, 50% $\bar{\nu}$-mode.



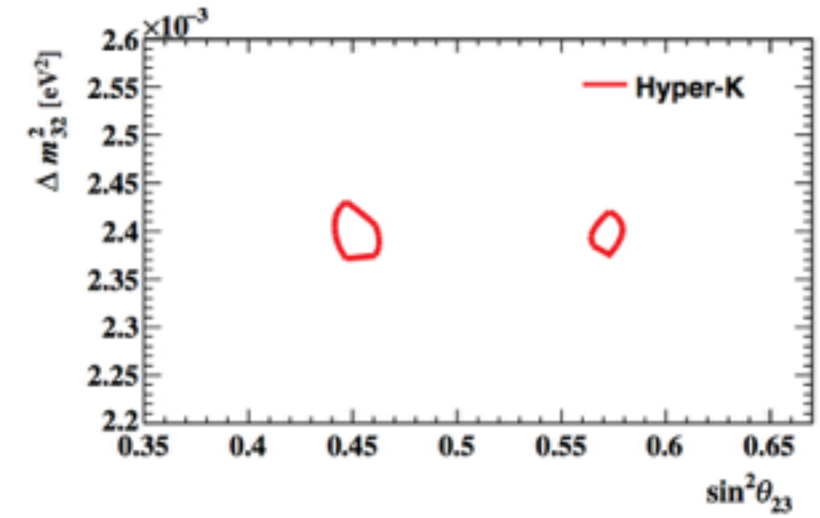
(d) 50% ν-, 50% $\bar{\nu}$-mode, with ultimate reactor error.

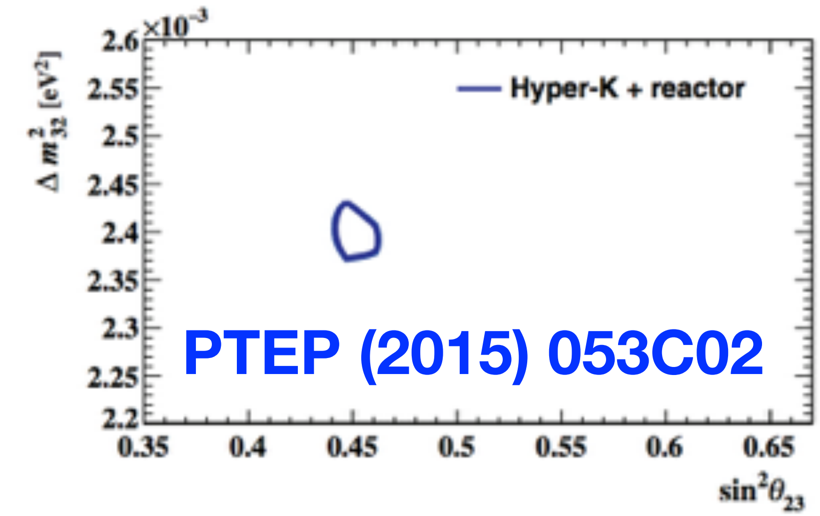
PTEP (2015) 043C01

~10% Statistical Error

Expect ~6% statistical error for 3x T2K exposure

Hyper-K



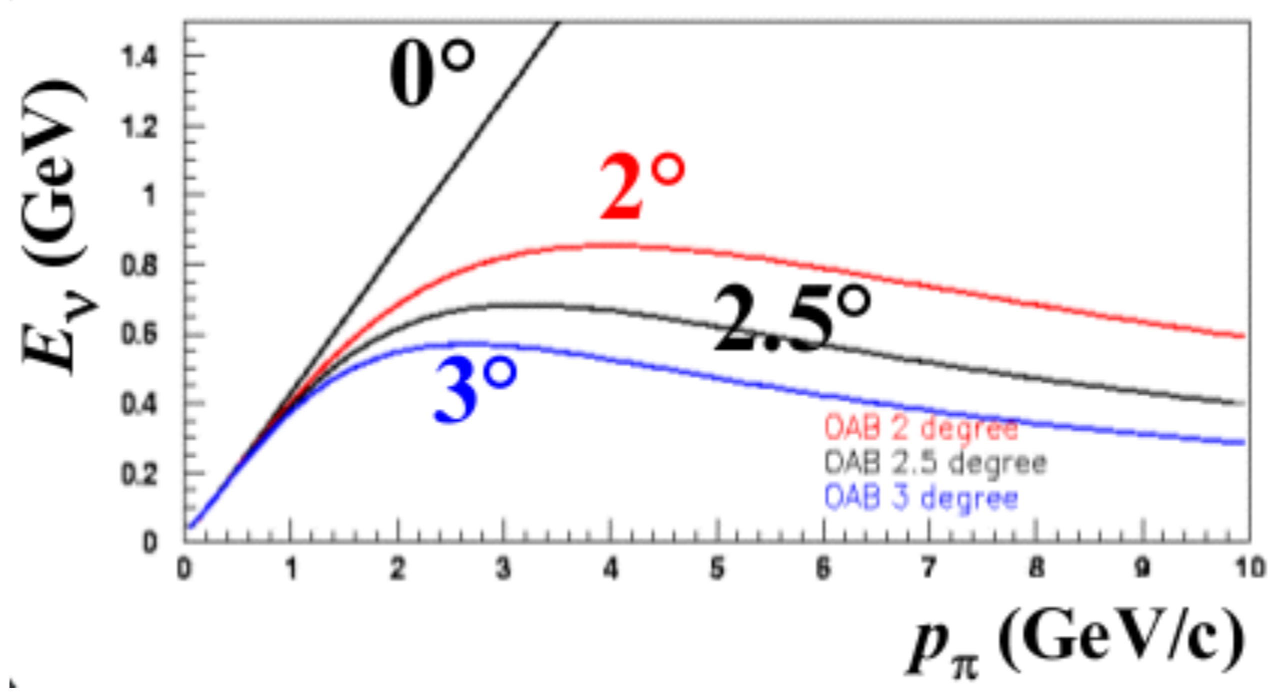


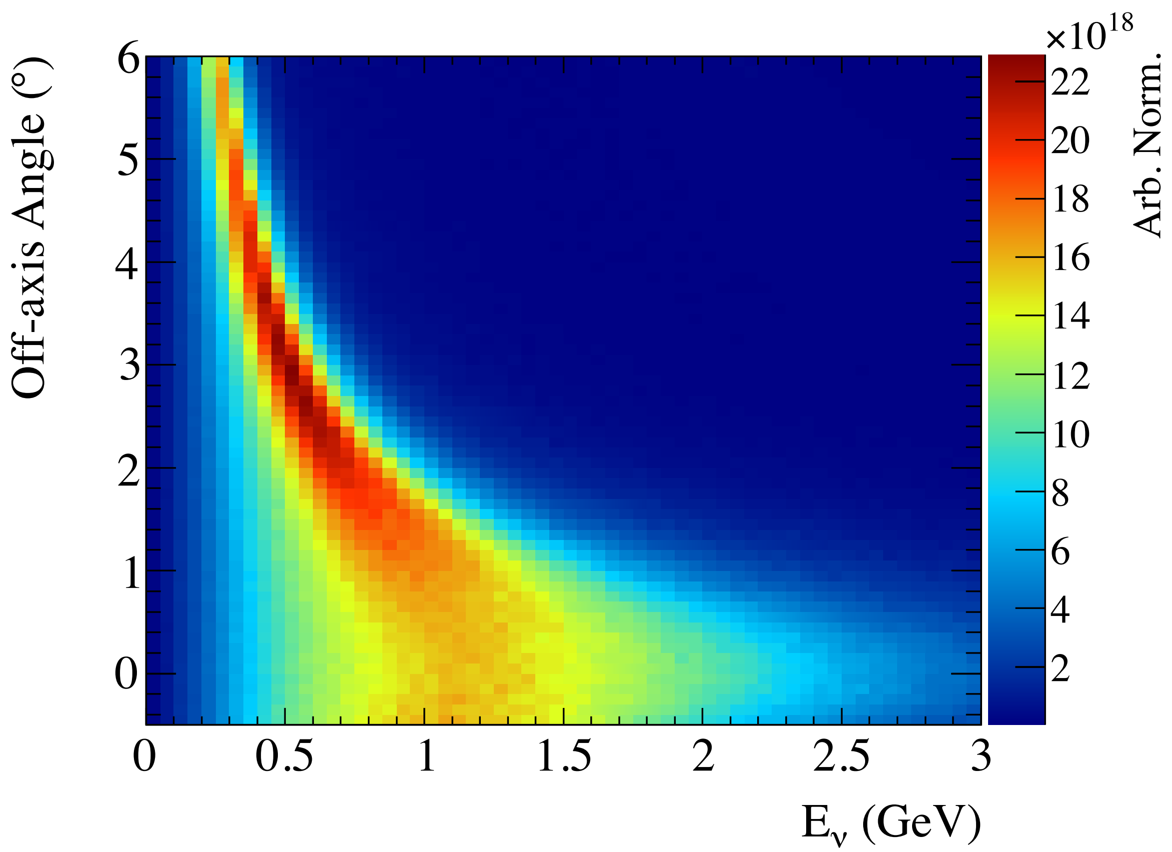
PTEP (2015) 053C02

~1% Statistical Error

Solving the Energy Reconstruction Problem

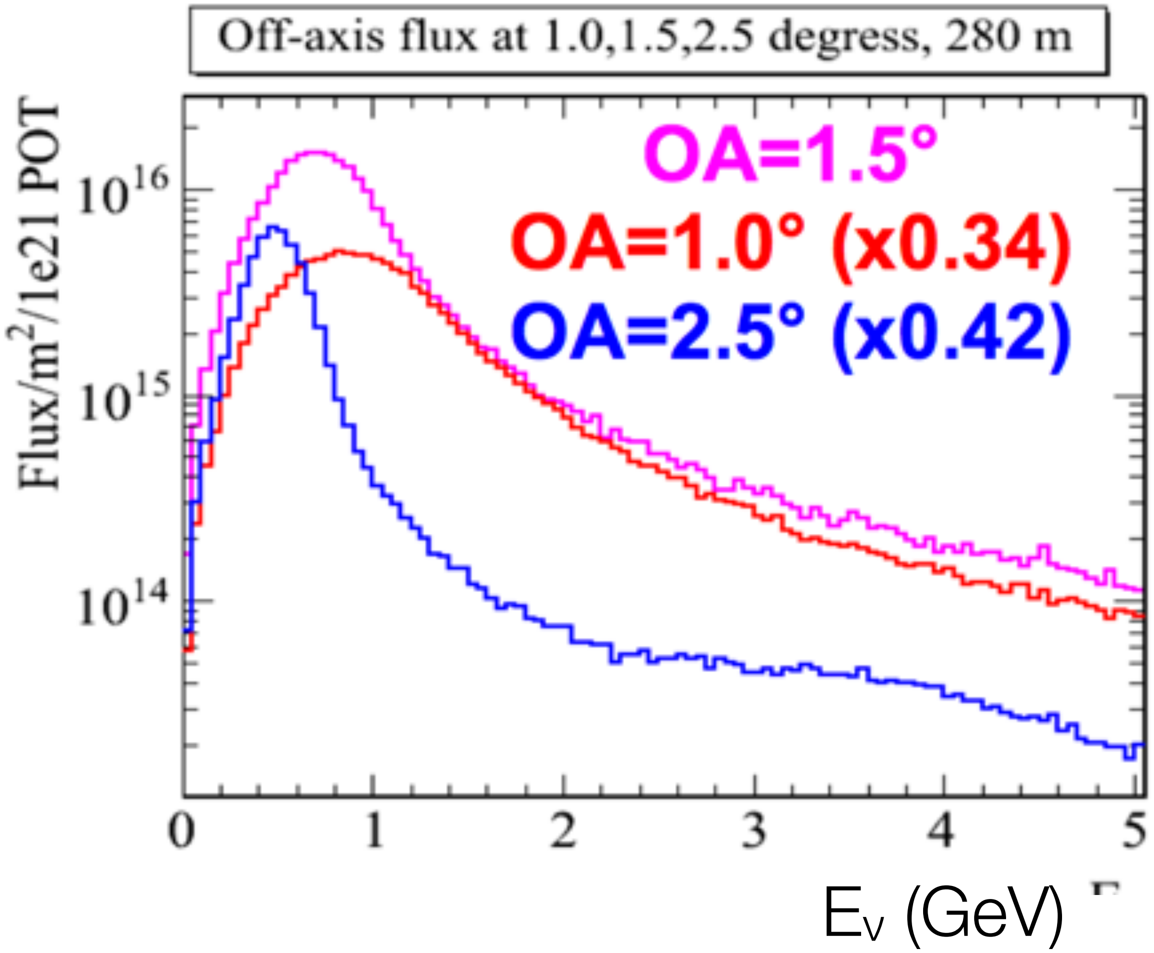
- The best way to solve the energy reconstruction problem:
  - Produce mono-energetic neutrino beams
  - Measure the charged lepton response for each neutrino energy (or 4 momentum transfer)
- Difficult to make a high intensity mono-chromatic neutrino beam from pion decays
- But we can take advantage of the off-axis effect
  - Energy dependence of flux with off-axis angle is governed by the pion decay kinematics
  - Used by T2K on-axis INGRID detector

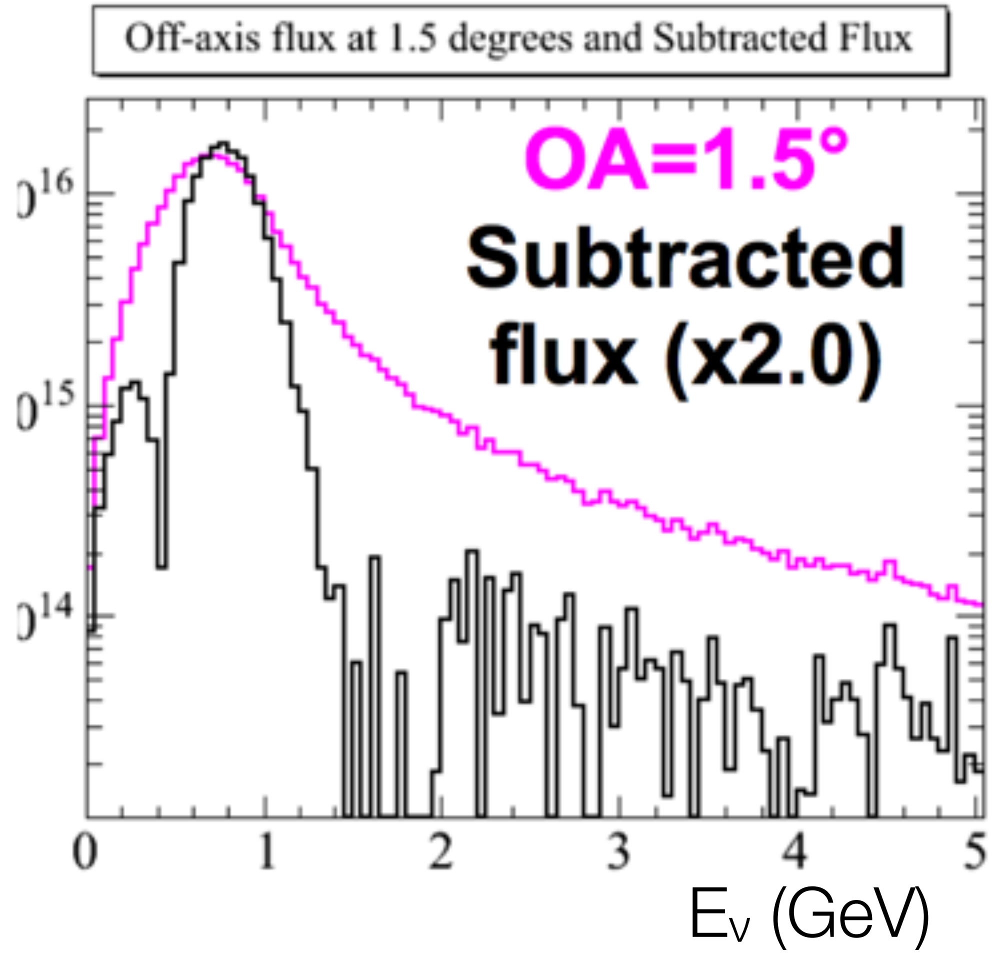




Subtracting Flux Tails

* Can do a pretty good job reproducing the high energy and low energy fluxes with simple linear combinations of nearby angles: $\varphi_{sub} = \varphi(1.5^{\circ}) - 0.34\varphi(1.0^{\circ}) - 0.42\varphi(2.5^{\circ})$

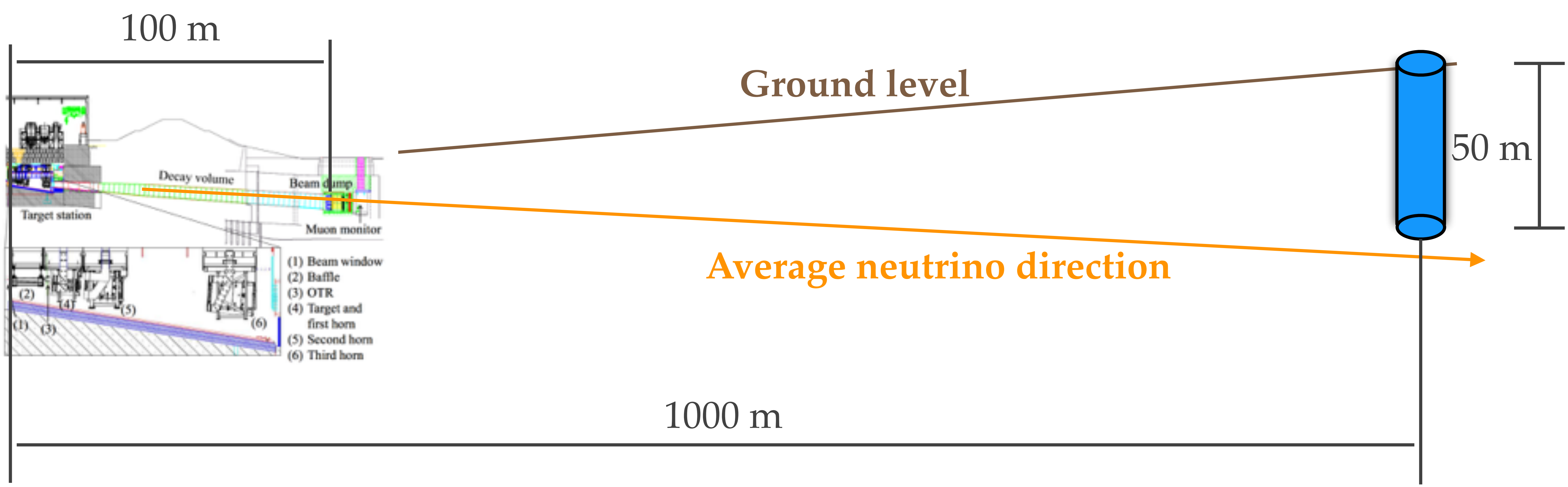




Measurements at just 3 off-axis angles can be used to produce a narrow band spectra by subtracting the low and high energy tails

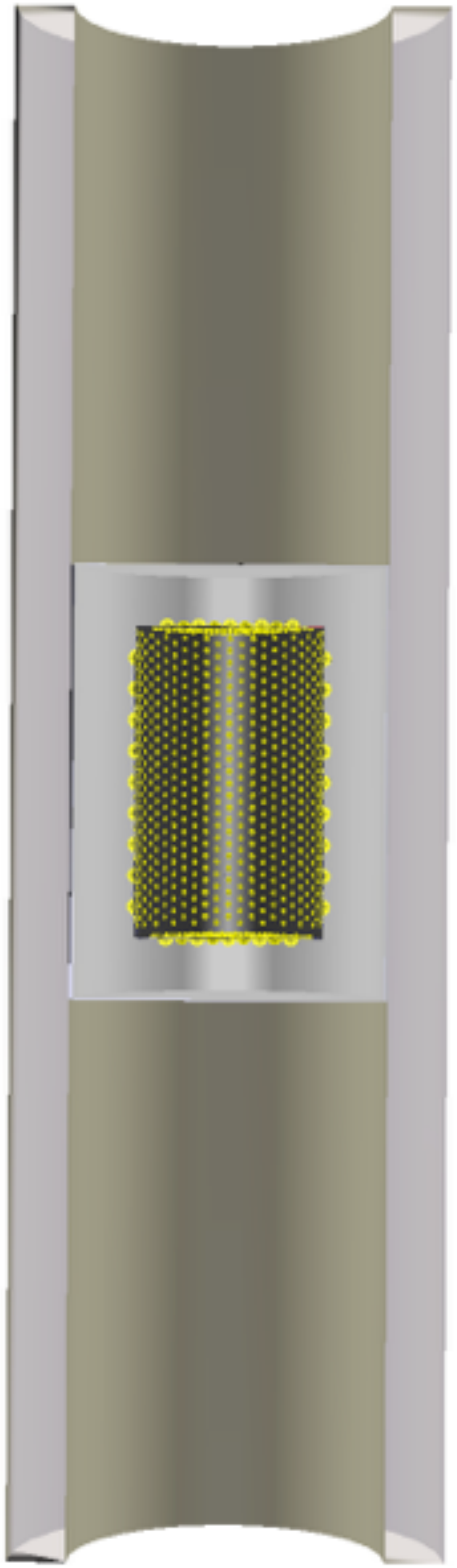
The NuPRISM Detector

- How do we build a detector to take advantage of the off-axis fluxes?
- NuPRISM is a water Cherenkov detector located ~1 km from the target
- 50 m tall detector excavated from ground level downward covers an off-axis range of 1-4 degrees (~70 m to go on-axis)
    - Beam is pointed downward by 3.6 degrees

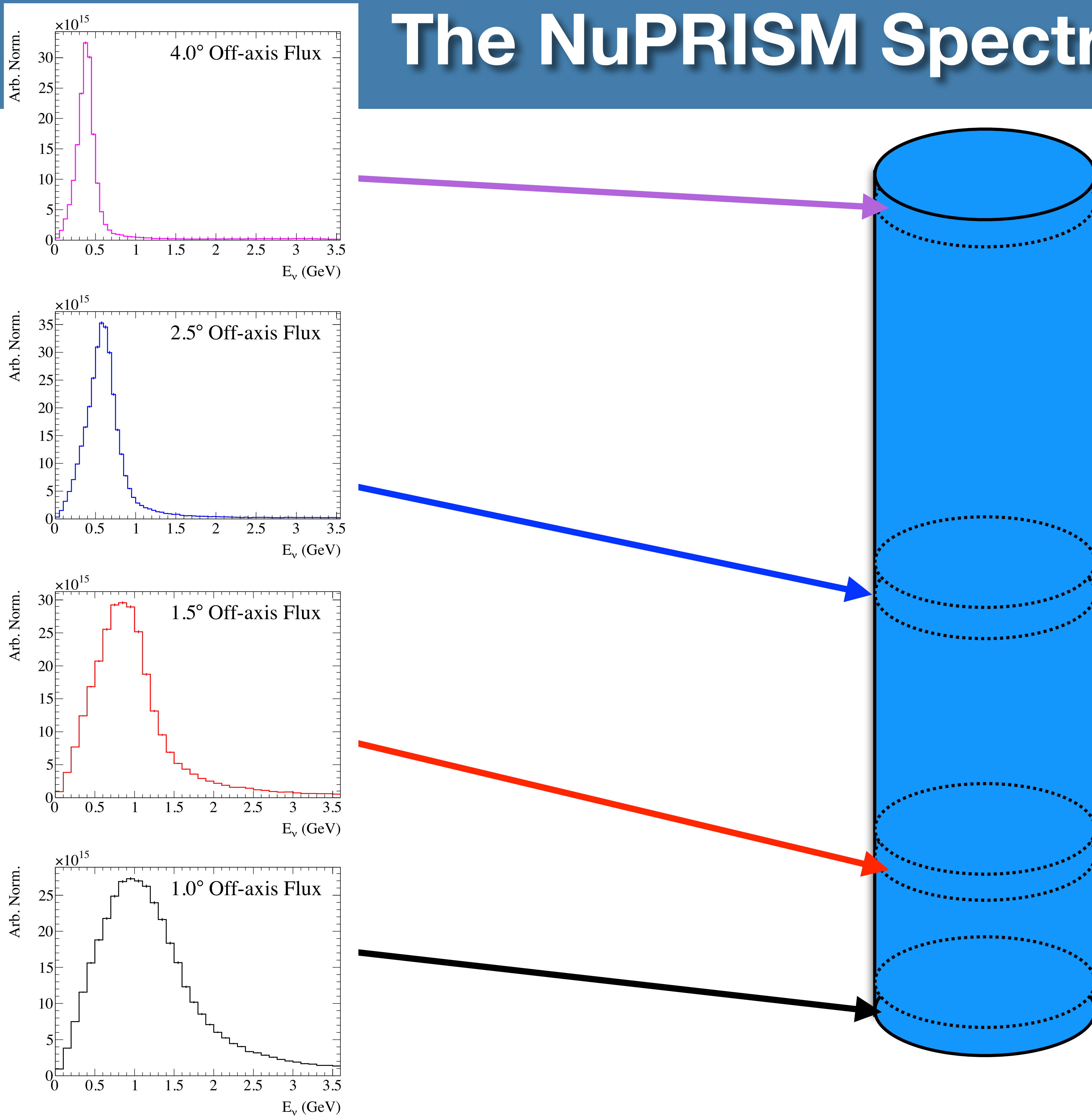


More NuPRISM Details

- Baseline from T2K target is ~1 km
    - Pile-up rate is low enough, beam is more point-like
- 50 m tall extending from ground level downward.
    - 1-4 degrees off-axis
- 10 m diameter
    - Up to ~1.5 GeV/c muon acceptance depending on outer detector design
- Water Cherenkov detector = same nuclear target as SK/HK
- Optimization of PMT size, photo-coverage and out detector is ongoing
- Initial design if NuPRISM: 10 m tall inner-detector frame that can be move to different positions in the pit



The NuPRISM Spectra



Each interaction in NuPRISM has a reconstructed off-axis angle based on its position in the detector

Hence, each interaction has a corresponding neutrino spectrum predicted by the flux model

The neutrino spectra are peaked from 400-1000 MeV

Event Rates in NuPRISM

- We simulated events rates for single electron or muon ring selections in NuPRISM
  - Assuming 20 inch PMTs (not optimal) and 40% photo-coverage
  - 8m diameter ID
  - 4.5e20 protons on target for each NuPRISM light position

Table I. The νPRISM candidate event rates for single ring muon and electron like samples for 4.5e20 protons on target in the J-PARC beam assuming a 8 m diameter ID (500 ton movable ID).

Off-axis Range	$\nu_\mu(\nu_e)$ Peak Energy Range	1 Ring μ Cand.	CC ν_μ Purity	1 Ring e Cand.	CC ν_e Purity
1°-2°	850-710(620-590) MeV	9.4e5	97.3%	6.8e3	35.9%
2°-3°	710-610(590-500) MeV	4.9e5	97.6%	3.4e3	57.4%
3°-4°	610-530(500-490) MeV	2.2e5	97.0%	2.0e2	68.2%

- Large CC ν_e samples with high purity at larger off-axis angles
  - Expect even higher purity with finer granularity of PMTs and optimization of inner detector size

Using NuPRISM Data

- We start by treating the off-axis fluxes as a set of basis functions
- Then we find a linear combination of the off-axis fluxes that gives a function of interest:

$$F(E_\nu) = \sum_{i=1}^{N_{OA}} c_i \boxed{\Phi^{\nu P}_{\nu_\mu, i}(E_\nu)}$$

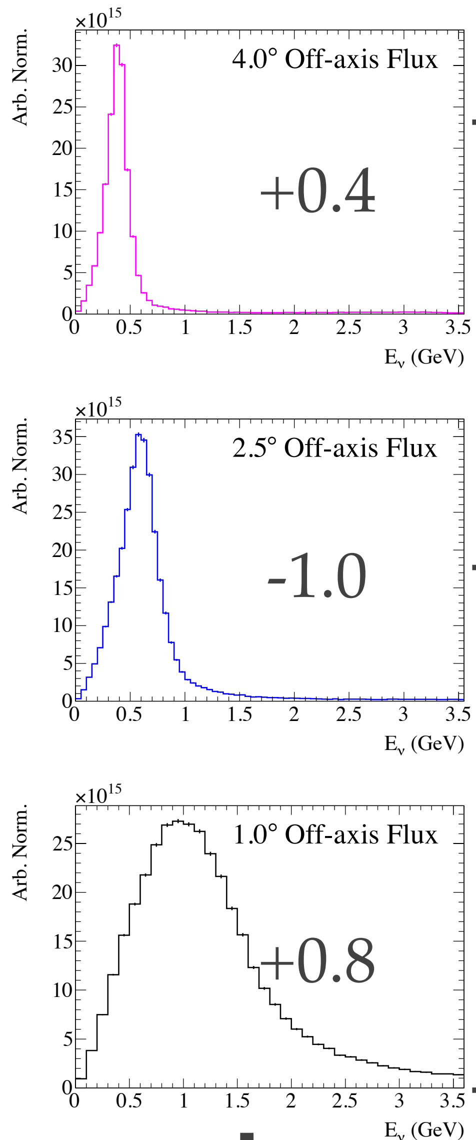
NuPRISM flux in each off-axis angle bin

- Here ***F*** can be a narrow Gaussian at some energy or a flux with oscillation probabilities applied
  - Finding the $\boldsymbol{c_i}$ depends on accurate prior knowledge of the neutrino flux
- The sum over observed event rates gives the expected event rate for the ***F*** flux

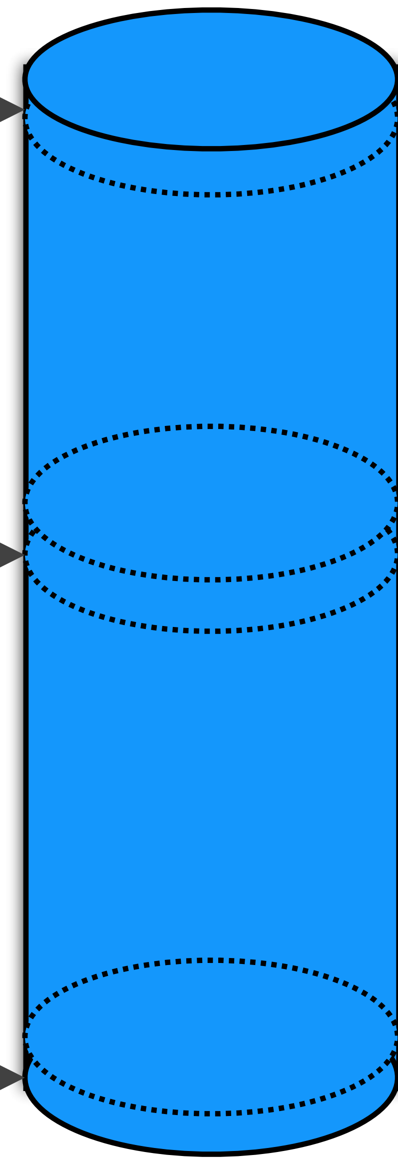
$$N^F(p_\mu, \theta_\mu | E_\nu) = \sum_{i=1}^{N_{OA}} c_i \boxed{N^{\nu P}_{\nu_\mu, i}(p_\mu \theta_\mu | E_\nu)}$$

NuPRISM observed event rates in each off-axis angle bin

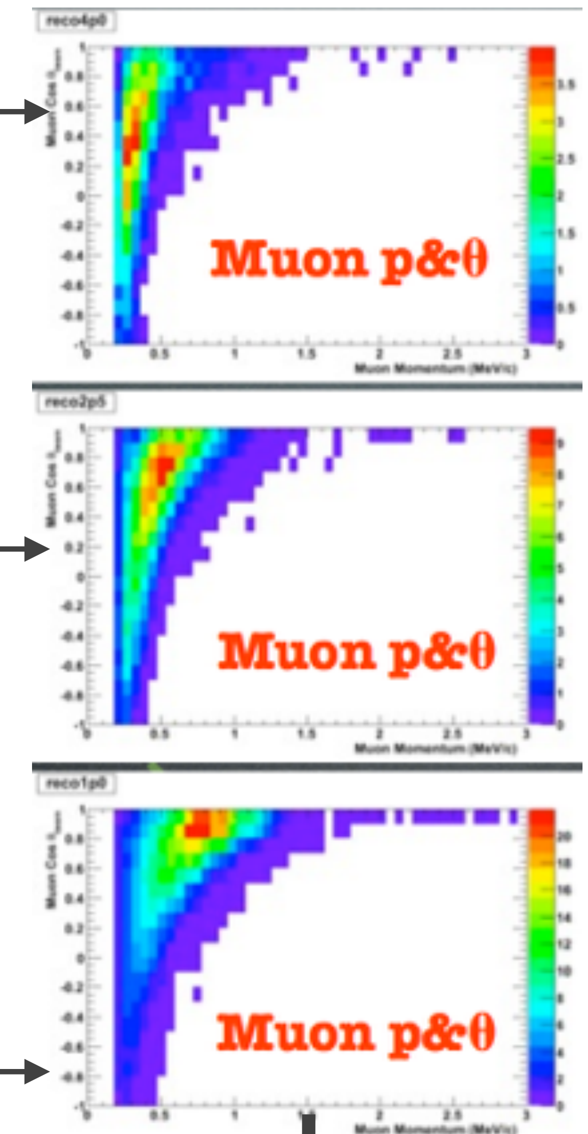
Linear Combination Example

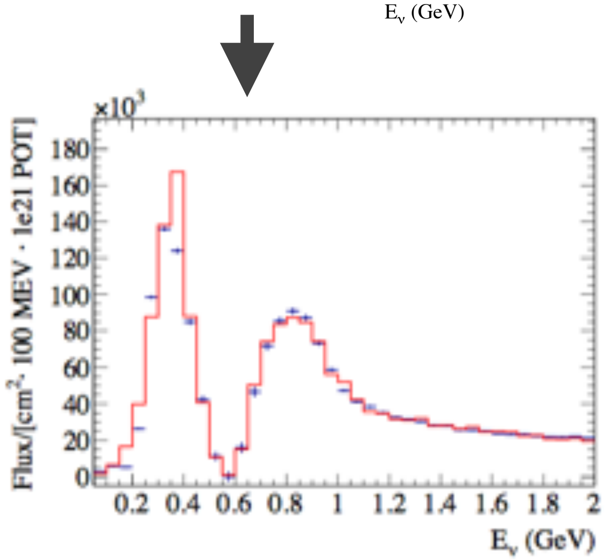


Spectra at at each off-axis bin

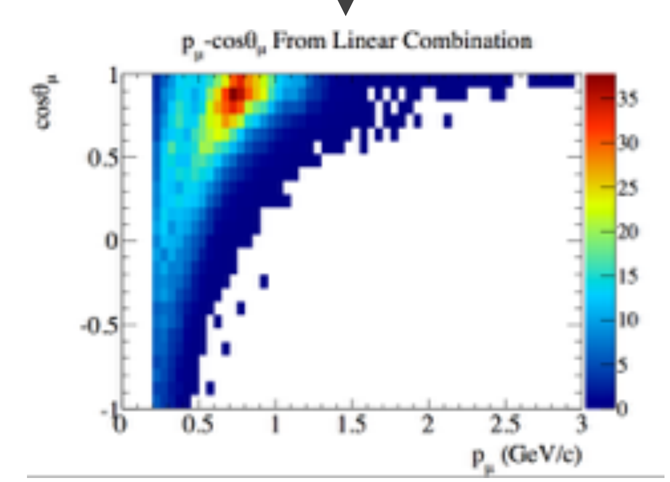


Observed muon kinematic distributions



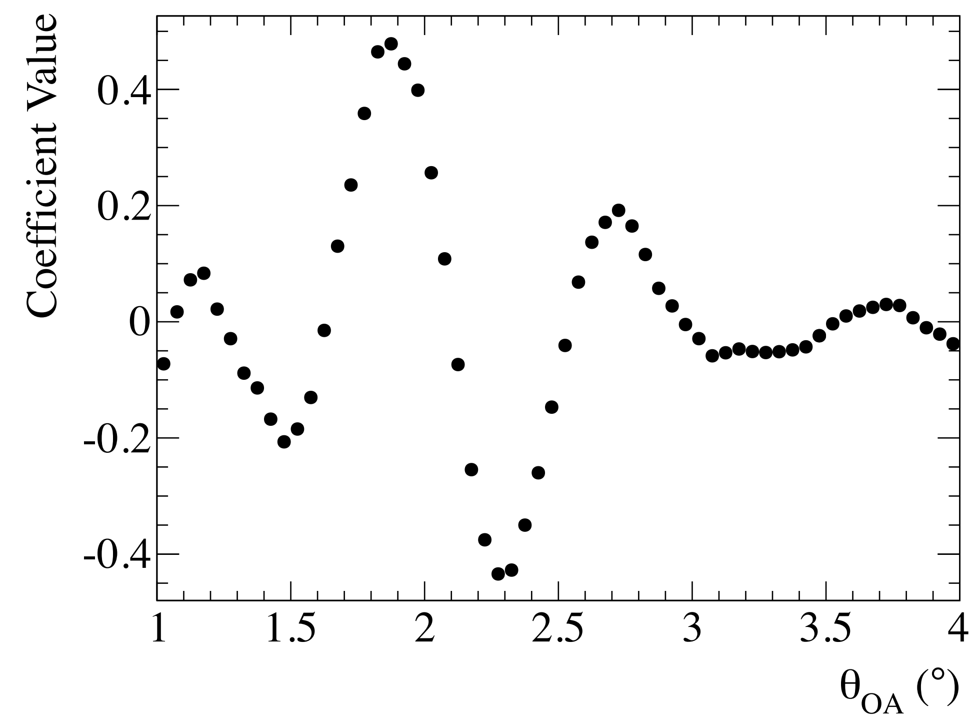


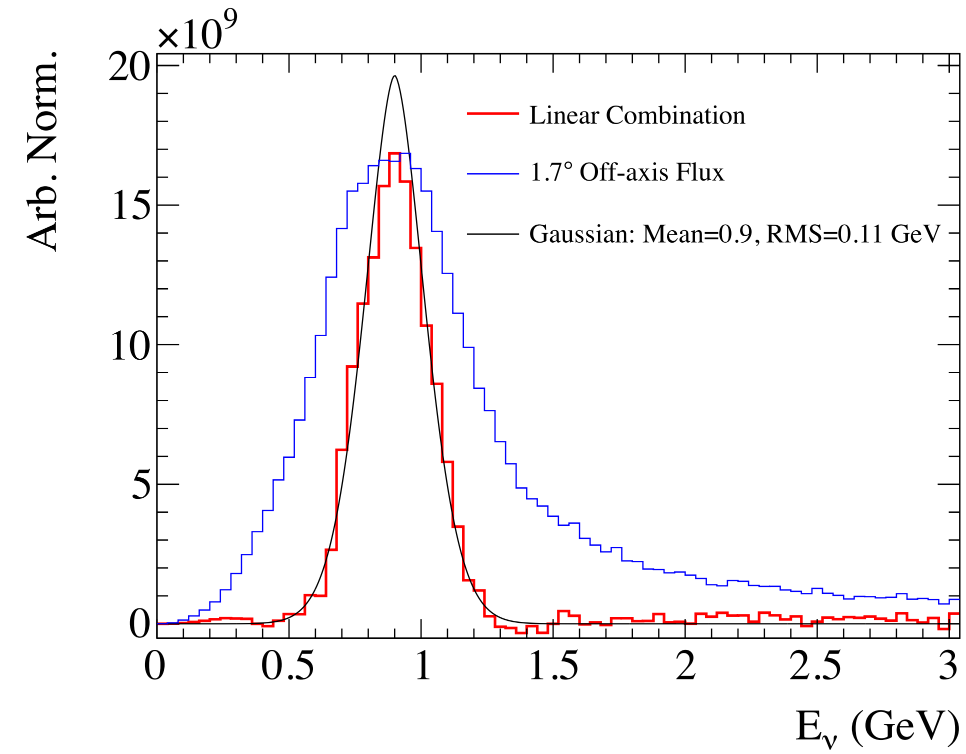
Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



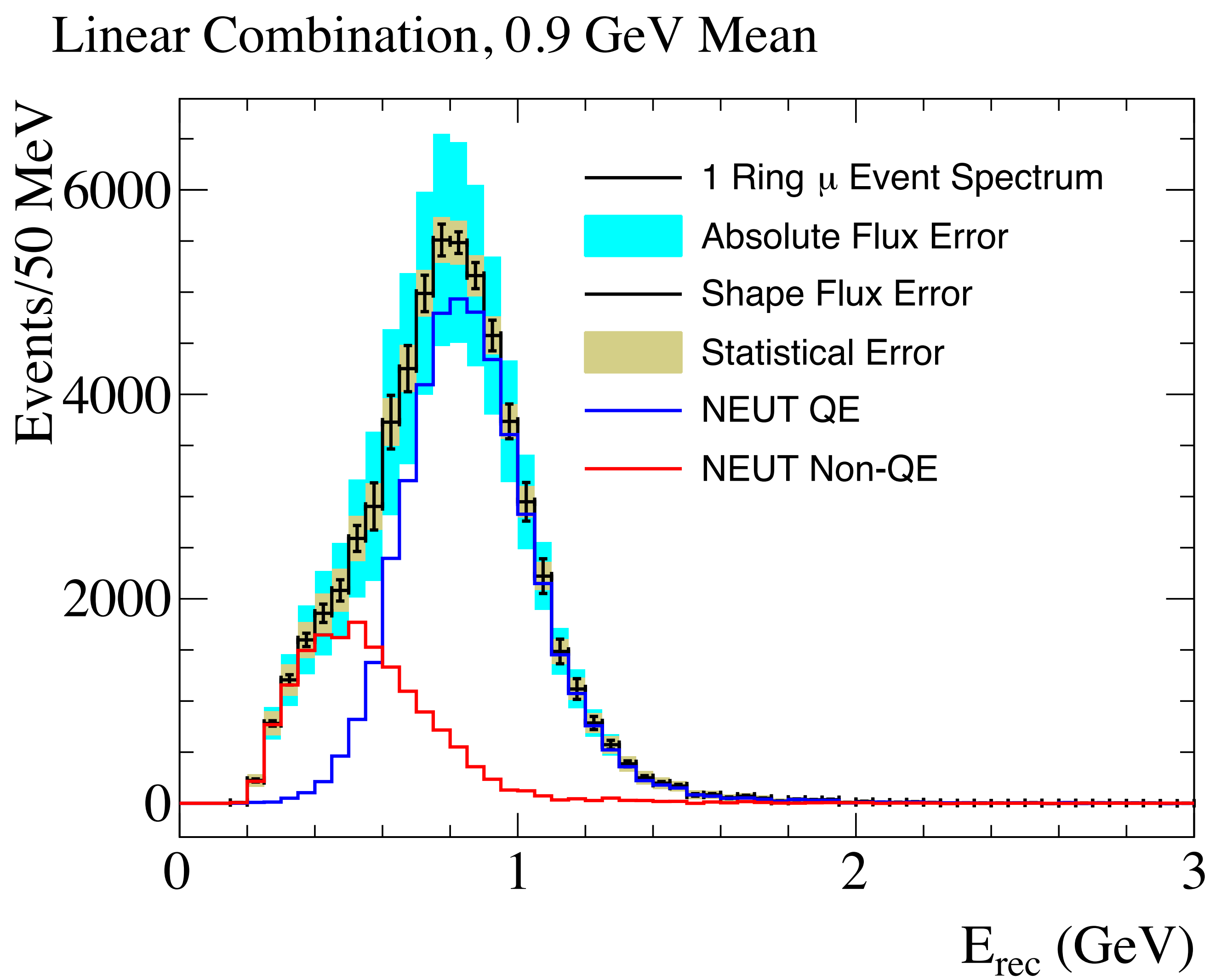
Mono-energetic Flux Example

- Using the flux model, we find coefficients for the off-axis fluxes that give a narrow spectrum peaked at 900 MeV
- The high and low energy tails are removed from the spectrum
- The narrow spectrum (red) is significantly narrower than the off-axis flux peaked at the same energy
    - RMS of 110 MeV is less than fermi momentum → can probe nuclear effects
- Next we apply those coefficients to reconstructed events binned in E_{rec}





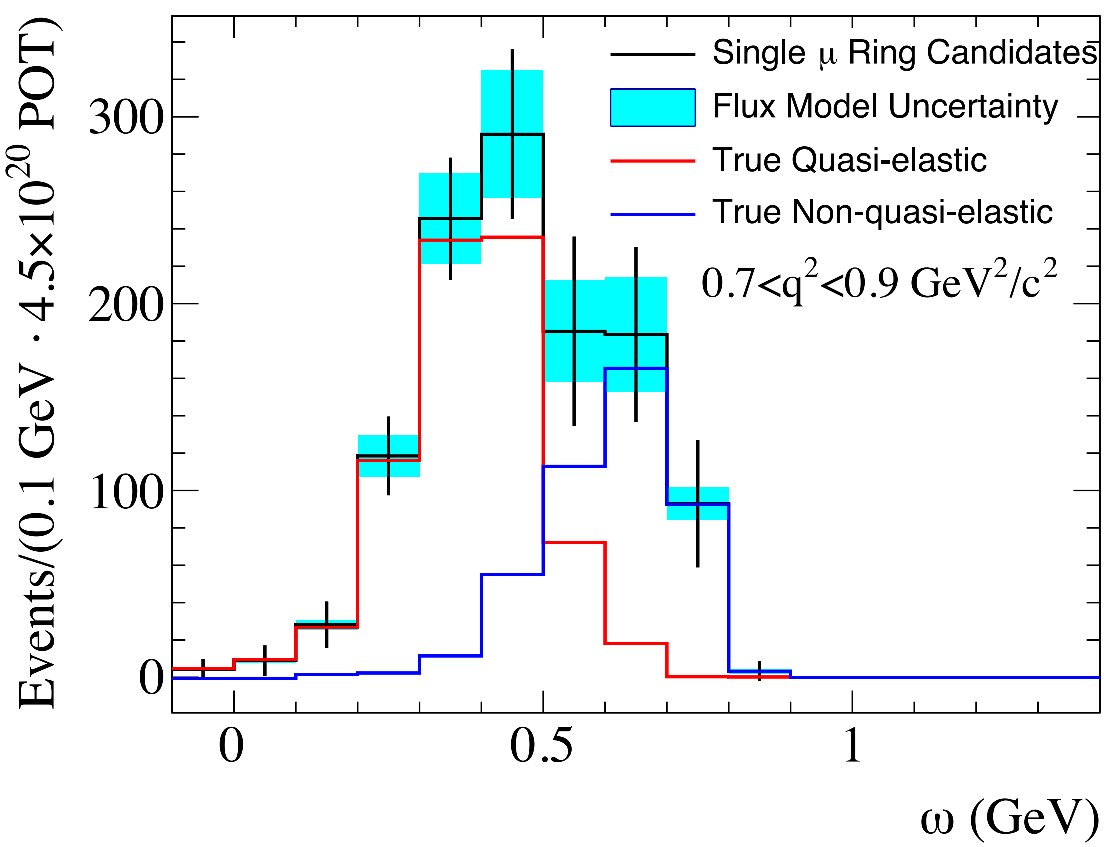
Measuring the Reconstructed Energy



- Simulated reconstructed energy distribution for single muon candidates after applying the 900 MeV linear coefficients
- Separation between the quasi-elastic peak and the non-quasi-elastic tail
  - Even when accounting for flux systematic uncertainties and statistical uncertainties

Energy, Momentum Transfer Variables

- Linear combination give narrow neutrino energy band
- Neutrino direction is know based on decay region and reconstructed vertex in detector
- Lepton momentum is measured
- We can measure the interaction rate as a function of the energy and 3 momentum transfer

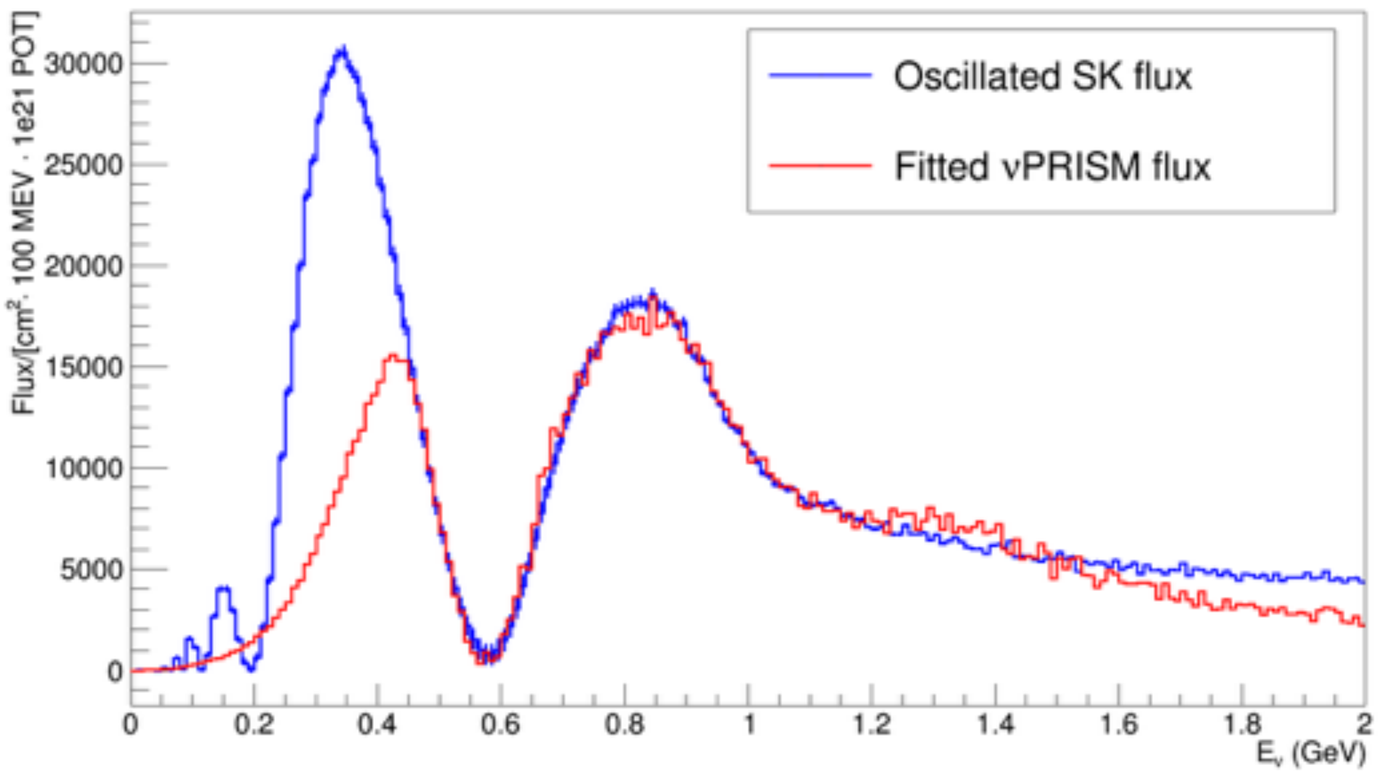


Muon Neutrino Disappearance

- Instead of finding a linear combination to produce a mono-chromatic beam, can we find one to produce an oscillated flux?

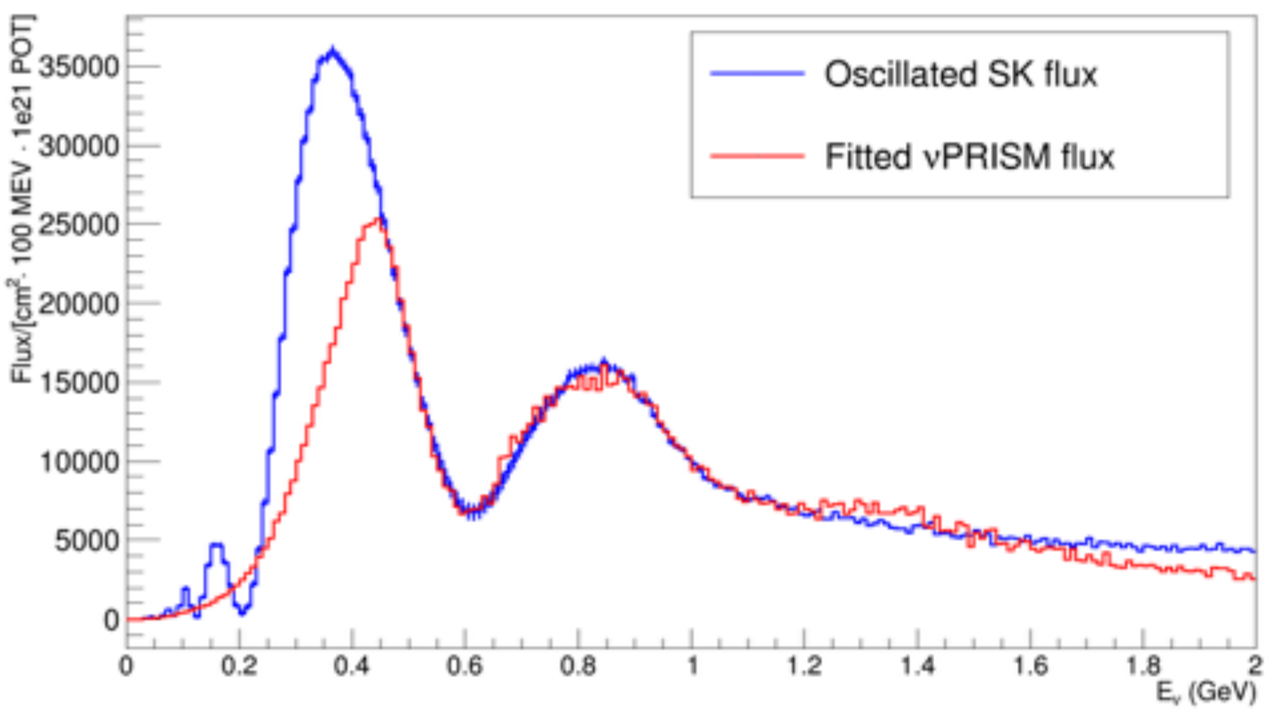
$$\Phi_{SK} P_{\nu_\mu \to \nu_\mu}(E_\nu; \theta_{23}, \Delta m^2_{32}) = \sum_i^{\text{Off-axis Bins}} C_i(\theta_{23}, \Delta m^2_{32}) \Phi_i^{\nu P}(E_\nu)$$

- Yes, we can reproduce the oscillated flux between ~400 MeV and 2 GeV
- For each oscillation hypothesis we want to test, we find a linear combination of the NuPRISM off-axis fluxes to give the oscillated spectrum

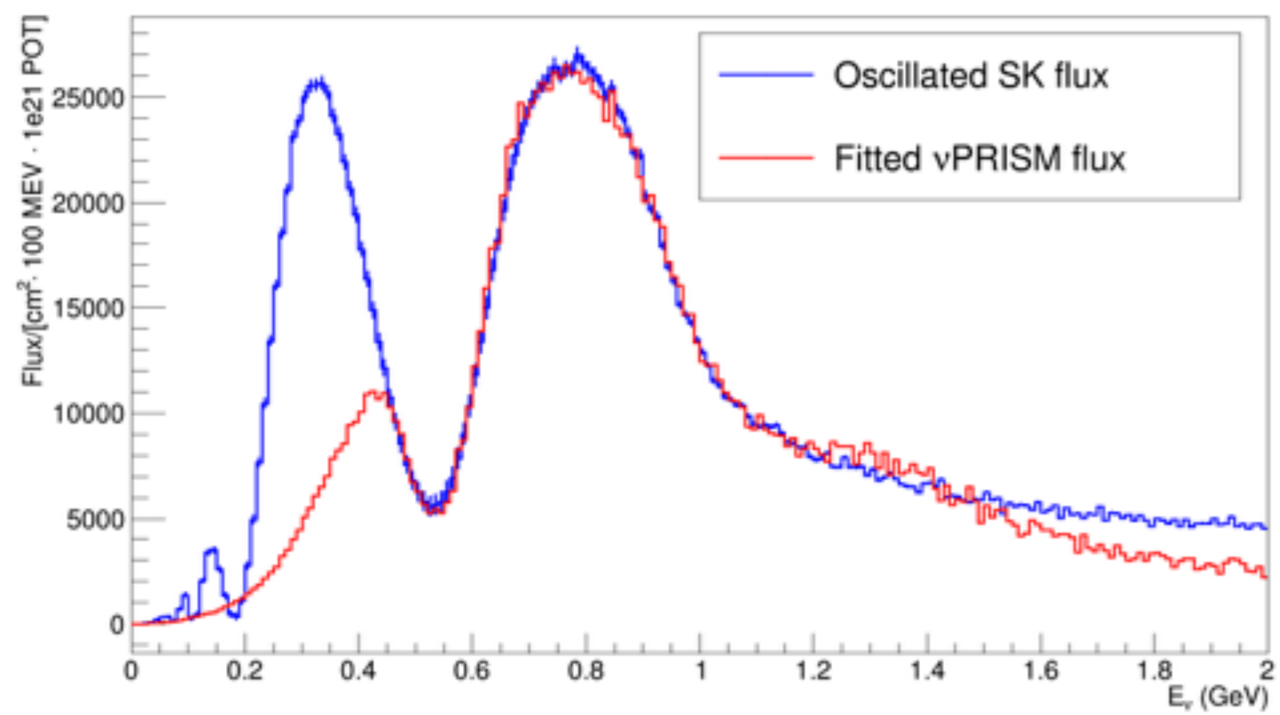


Reproducing the Oscillated Flux

$\sin^2\theta_{23}=0.61,\ \Delta m^2_{32}=2.56\text{e-}3\ \mathrm{eV}^2$



$\sin^2\theta_{23}=0.41,\ \Delta m^2_{32}=2.26\text{e-}3\ \mathrm{eV}^2$



- Between 400 and 1500 MeV the flux can be reproduced for any choice of oscillation parameters
- Outside that range, we rely on the model
  - Still much better than usual ND flux that very different from the oscillated flux

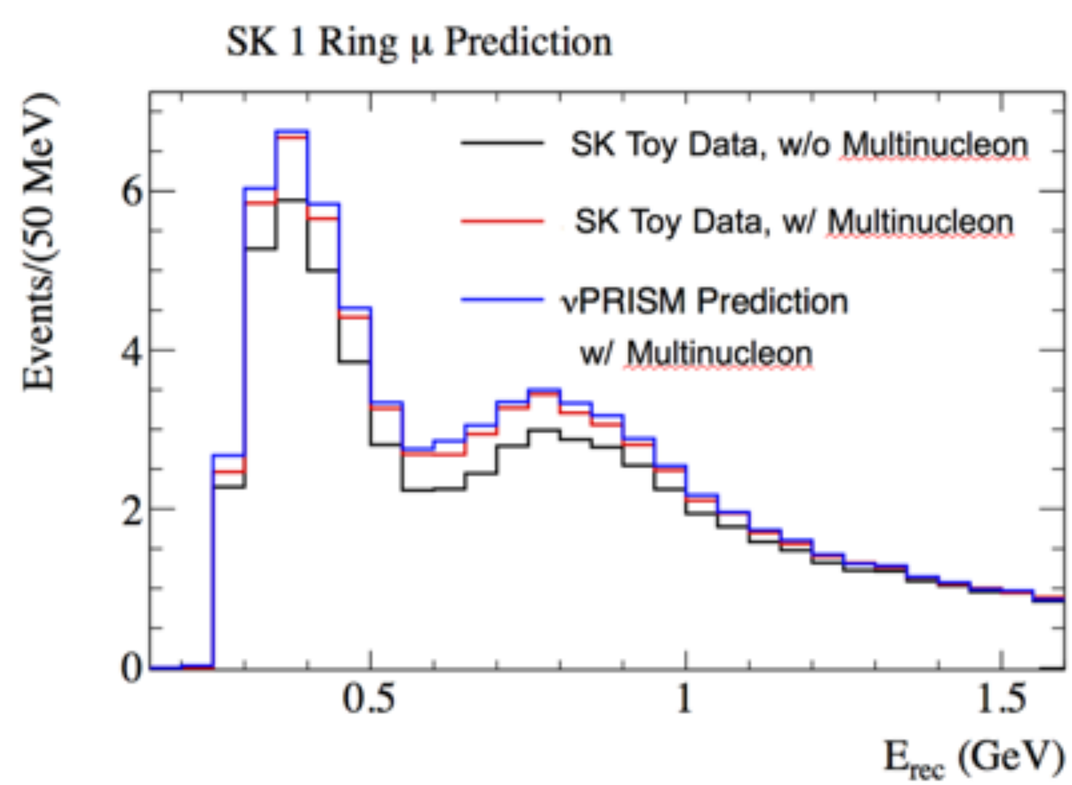
Predicted the Far Detector Response

- The leptonic response at the far detector is derived from the linear combination of observed events at NuPRISM:

$$N_{SK}(E_{rec};\theta_{23},\Delta m^2_{32}) = \sum_{i}^{\text{Off-axis Bins}} C_i(\theta_{23},\Delta m^2_{32})\, N_i^{\nu P}(E_{rec})$$

- Small corrections are applied for efficiency and acceptance differences, imperfect reproduction of the oscillated flux and background subtraction.

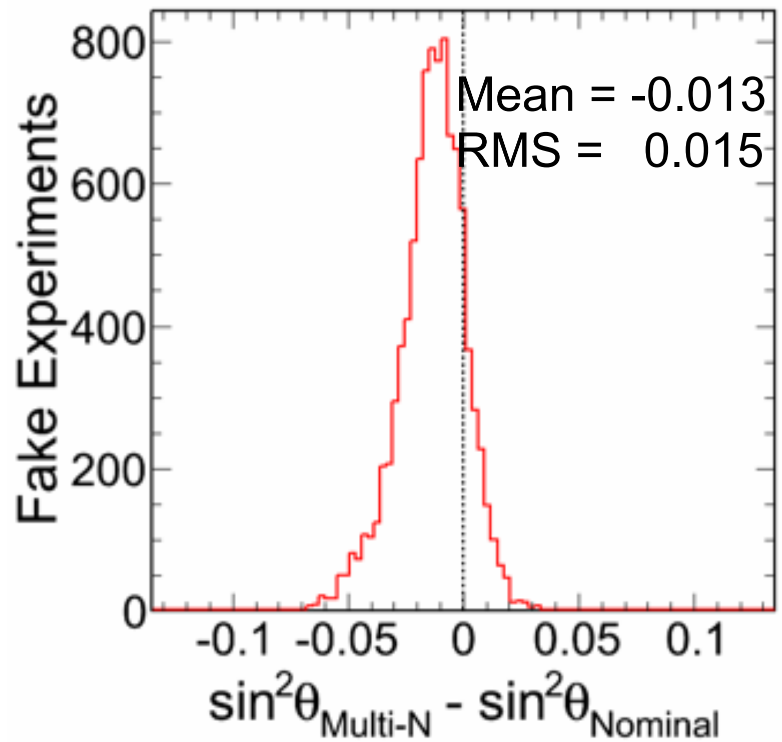
- Model dependent corrections are small → NuPRISM predicts the leptonic response at the far detector accurately in a largely cross-section model independent way.

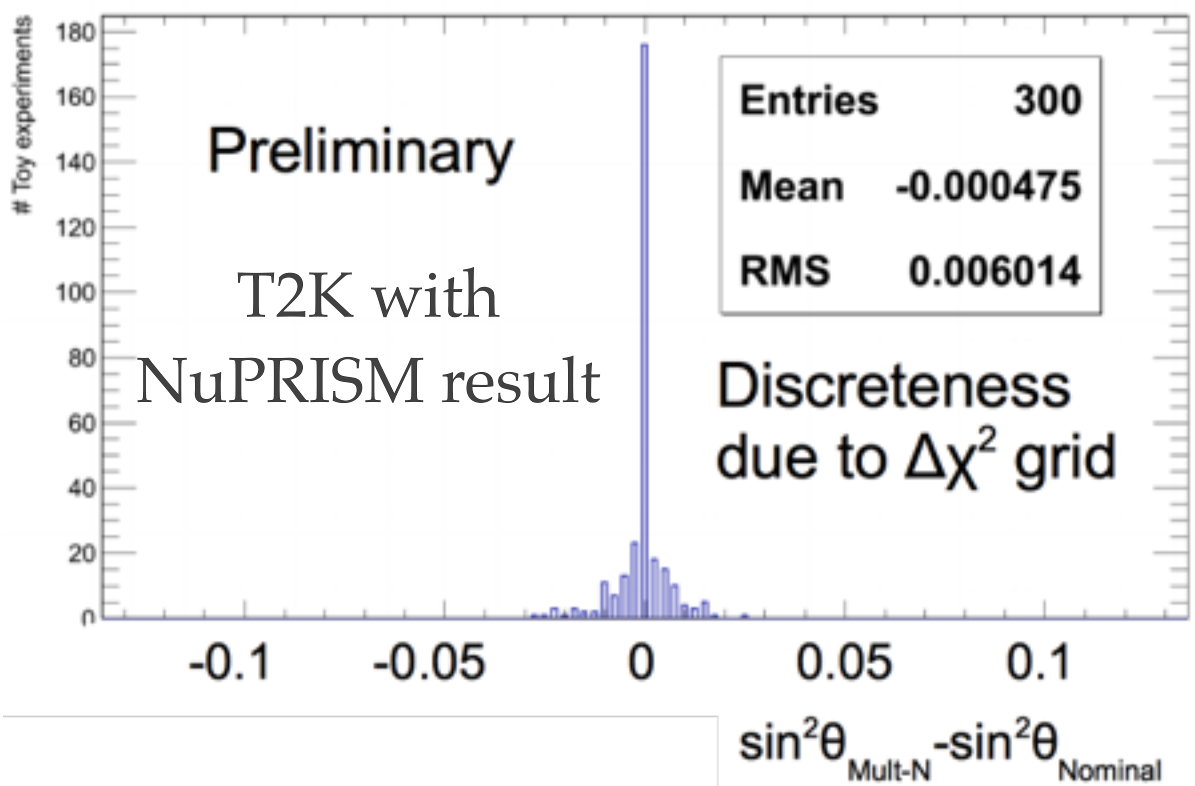


Reproducing T2K Bias Study

- Recall the T2K study of $\sin^2\theta_{23}$ uncertainty from mis-modeling the np-nh part of the cross section found a bias of at least 3%
- The same study is carried out with NuPRISM and realistic exposure in the T2K beam using the same systematic error model as T2K.
- The SK event rate is accurately predicted even when additional np-nh interactions are added to the toy data.
- The $\sin^2\theta_{23}$ bias and uncertainty are reduced to ~1% with the NuPRISM measurement.

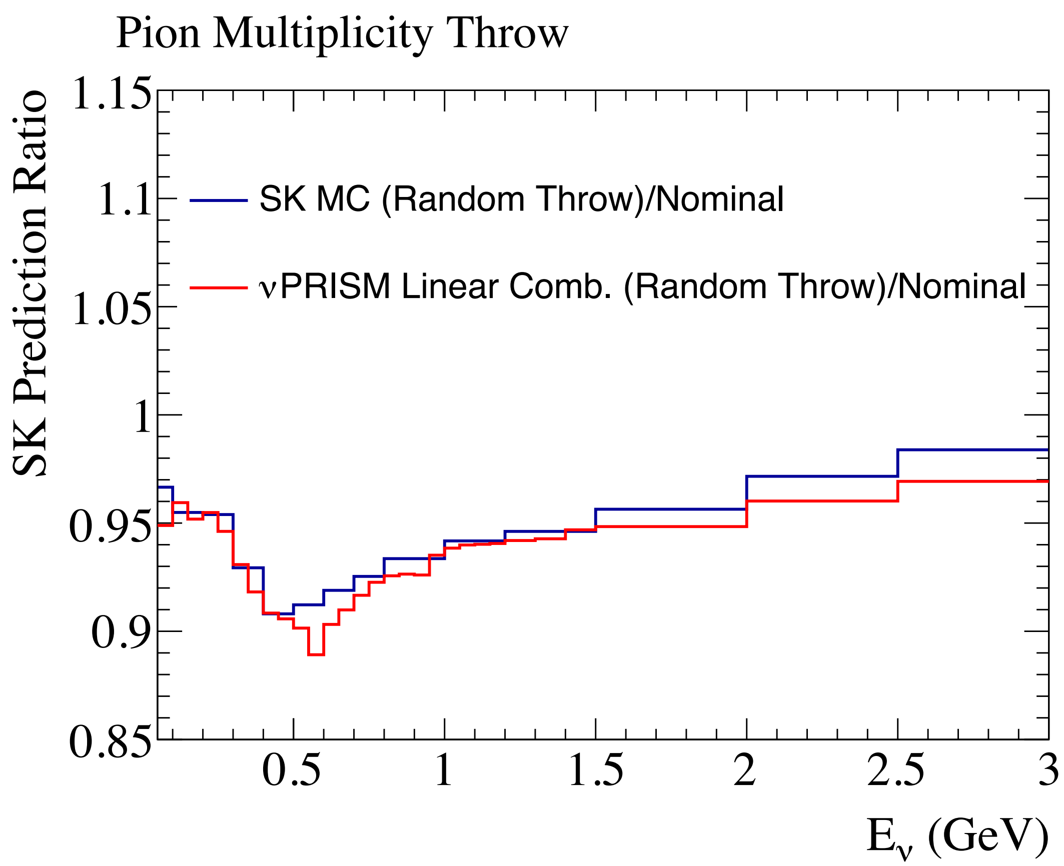
T2K Result



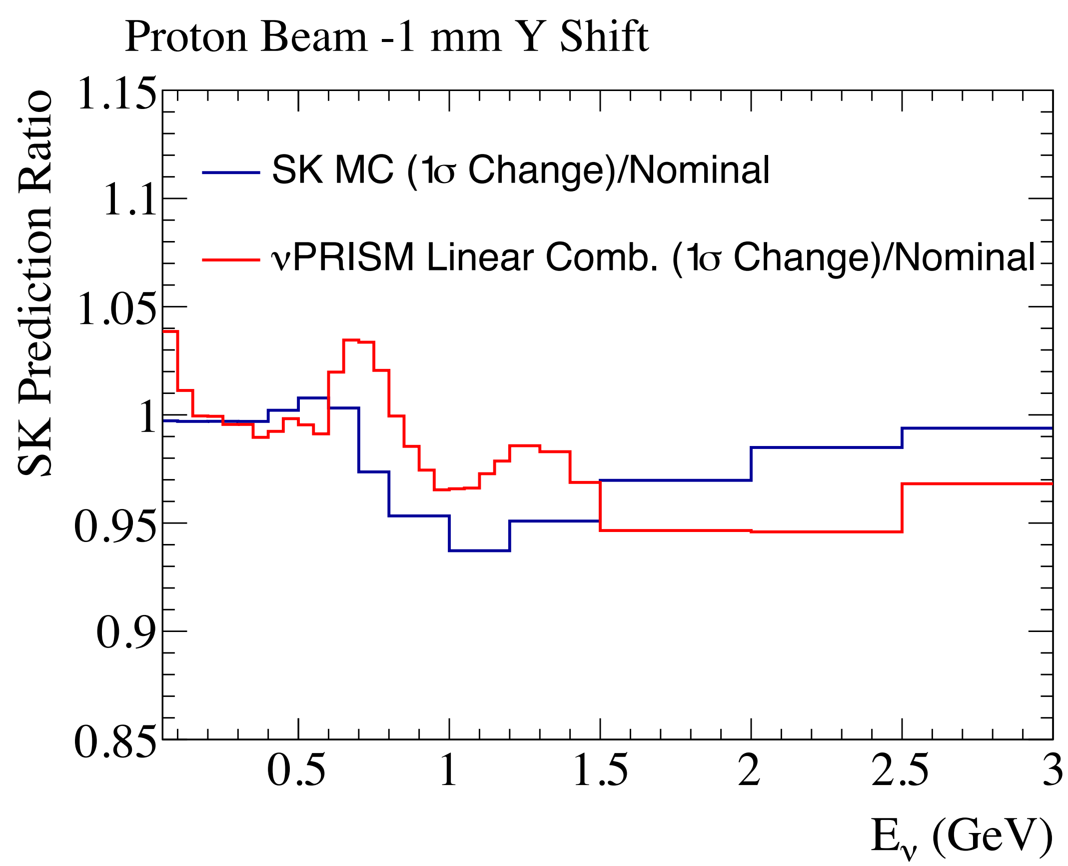


Flux Uncertainties

- We rely on the flux model to predict the off-axis angle dependence of the neutrino spectra - are the uncertainties small enough?
- We apply T2K flux systematic variations to the NuPRISM and SK fluxes to see how well NuPRISM linear combination reproduces the change to the SK flux



Changes from the hadron production model are reproduced in the NuPRISM prediction.



Dominant systematic comes from changes that affect the observed off-axis angle.

Electron Neutrino Appearance

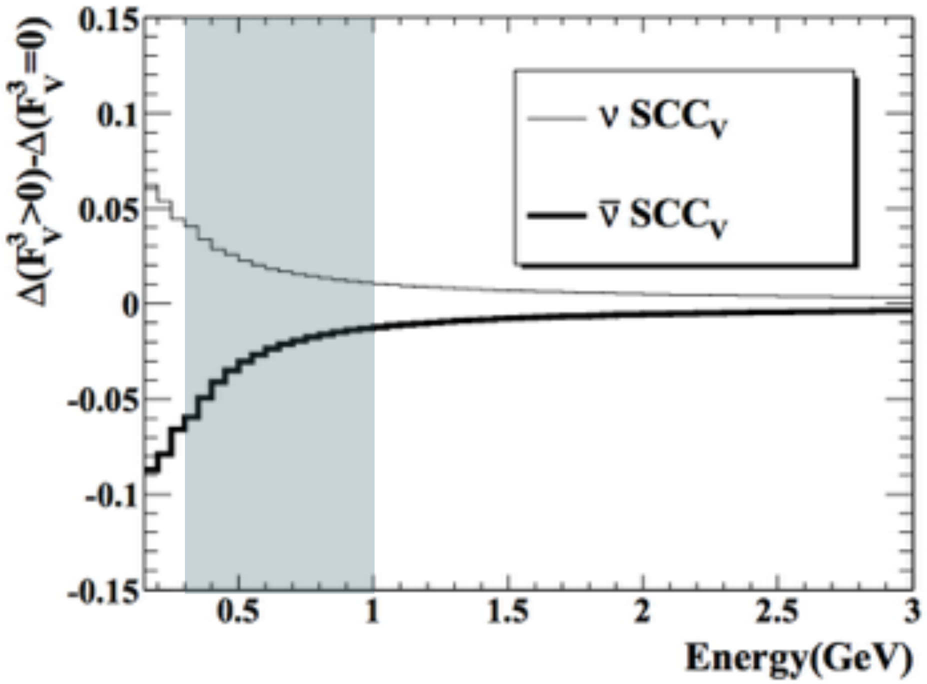
- Energy reconstruction is important for the muon neutrino disappearance analysis
  - We need NuPRISM to control the related systematic error
- What about the electron (anti)neutrino appearance measurement?
  - The energy reconstruction is also important
  - **But most important systematic effect may be the uncertainty on the electron (anti)neutrino cross section**
- We measure the rates of muon (anti)neutrinos in our near detectors
- To predict the electron (anti)neutrino appearance rate at the far detector we must
  - Model the change in the flux spectrum due to oscillations
  - **Model the change in the cross section due to the change from muon to electron (anti)neutrinos**

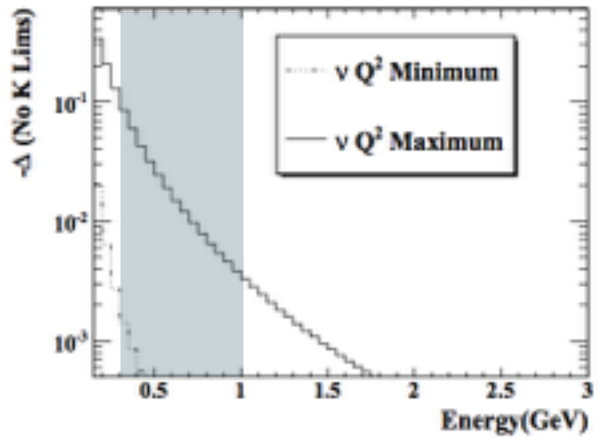
ν_e and $\bar{\nu}_e$ Cross Section Uncertainties

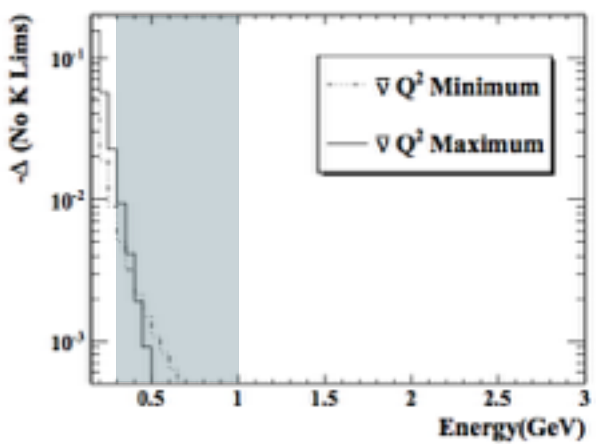
- Sources of theoretical uncertainty are consider by Day & McFarland (Phys.Rev. D86 (2012) 053003)
  - Inclusion of second class currents can change the cross section ratio by 2% at the flux peak
  - The kinematically allowed region is different

$$Q^2_{\substack{max \\ min}} = -m^2 + \frac{s - M^2}{\sqrt{s}} \left(E^*_\ell \pm |p^*_\ell|\right)$$

    - Effect is significant at the maximum Q^2 for neutrinos
  - Radiative corrections - should be calculated







Impact for CP Violation Measurement

- To measure CP violation, we measure the asymmetry:

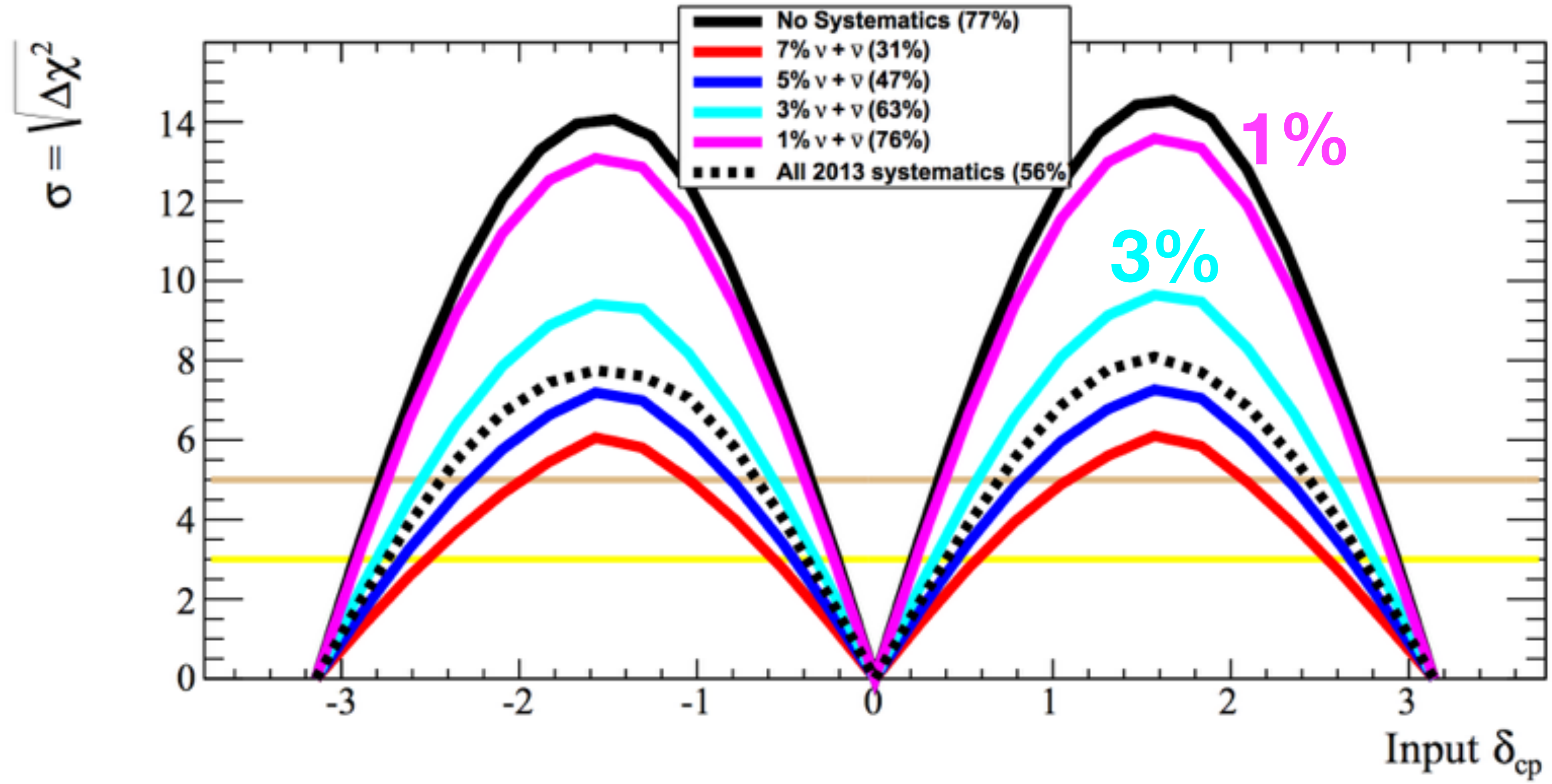
$$A_{CP} = \frac{P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e}}$$

- Most important uncertainties are those that affect the electron neutrino and antineutrino rates differently
- The important uncertainty is on the double ratios of cross sections:

$$(\sigma_{\nu_e}/\sigma_{\nu_\mu})/(\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu})$$

$\nu_e,\bar{\nu}_e$ Cross Section Sensitivity Impact (HK)

- Perform sensitivity study where the ν_e and $\bar{\nu}_e$ cross sections are assigned two uncorrelated normalization systematic parameters
- The uncertainties on the normalization parameters are varied and the impact on the CPV sensitivity is studied.



- The systematic uncertainty should be controlled to <1-2% to minimize the impact on the CPV discovery sensitivity

Direct measure of $\nu_e,\bar{\nu}_e$ Cross Sections

- Ideal place for measurement would be nuSTORM, but can we measure the cross sections in our conventional beam?
- The beam includes an intrinsic electron neutrino component from muon and kaon decays (0.5% at the peak)

Can increase ν_e purity by going further off-axis

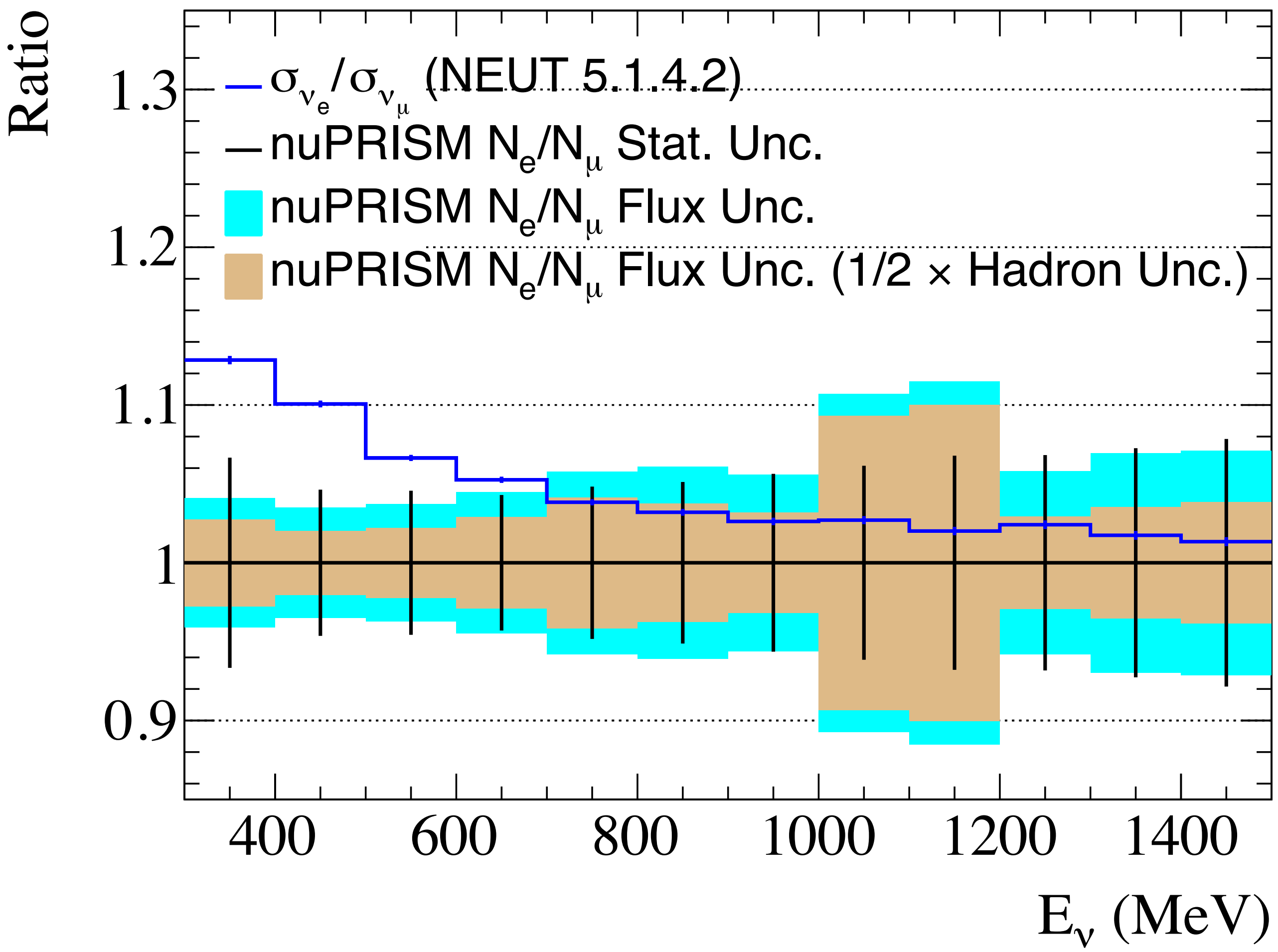
Off-axis angle (º)	ν_e Flux 0.3-0.9 GeV	ν_μ Flux 0.3-5.0 GeV	Ratio ν_e/ν_μ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

At 2.5º, SK has 77% purity in the absence of oscillations

RUN1-4 6.570×10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}=0$					Data
	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	BG total	Signal	
fiTQun π^0	0.07	3.50	0.96	4.53	0.40	28

$\nu_e,\bar{\nu}_e$ Cross Section Precision

- We estimated flux model and statistical errors for a $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ measurement in NuPRISM

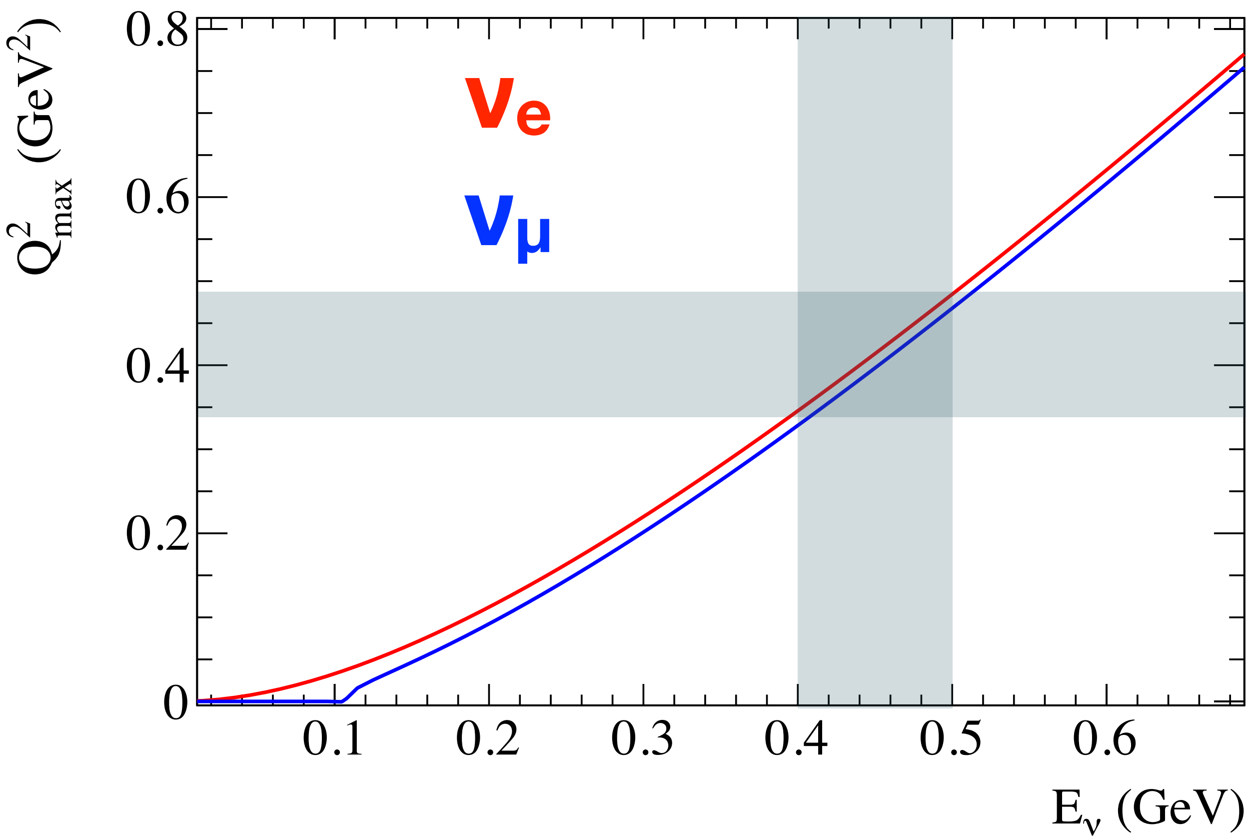


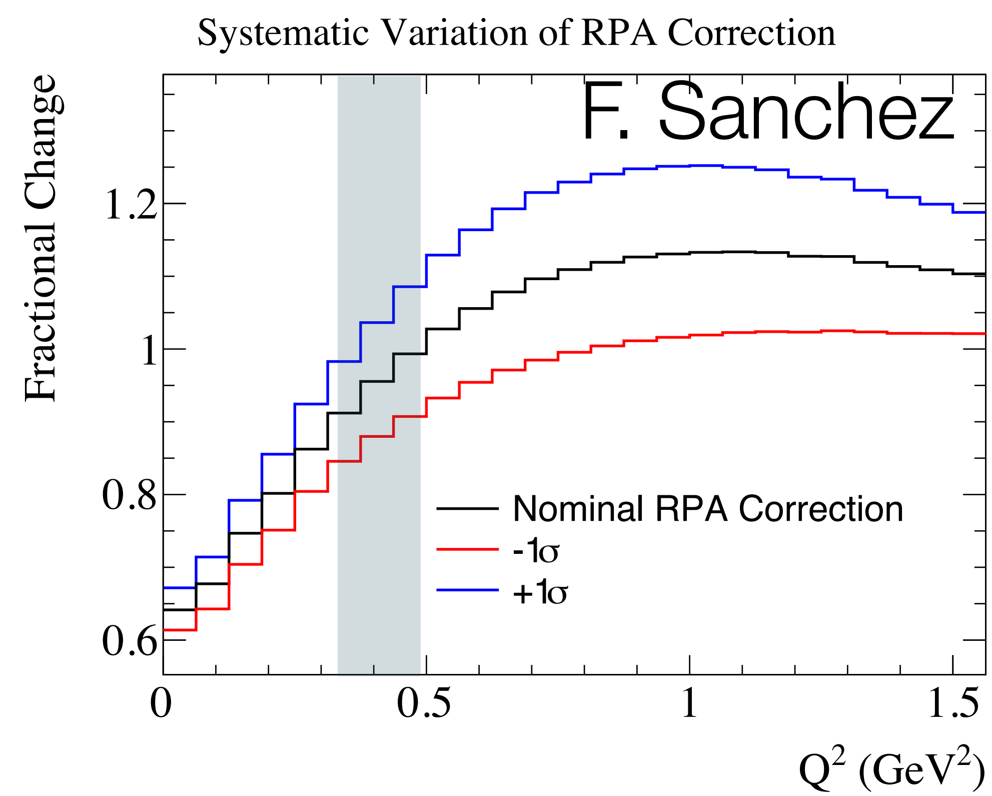
	Flux Error	Hadron x1/2	Stat. Error
300-600 MeV	3.2%	1.7%	2.9%
600-900 MeV	5.2%	3.4%	2.7%

- Preliminary study suggests that a 3% measurement or better is plausible.
- Further studies are ongoing.

Phase Space Difference

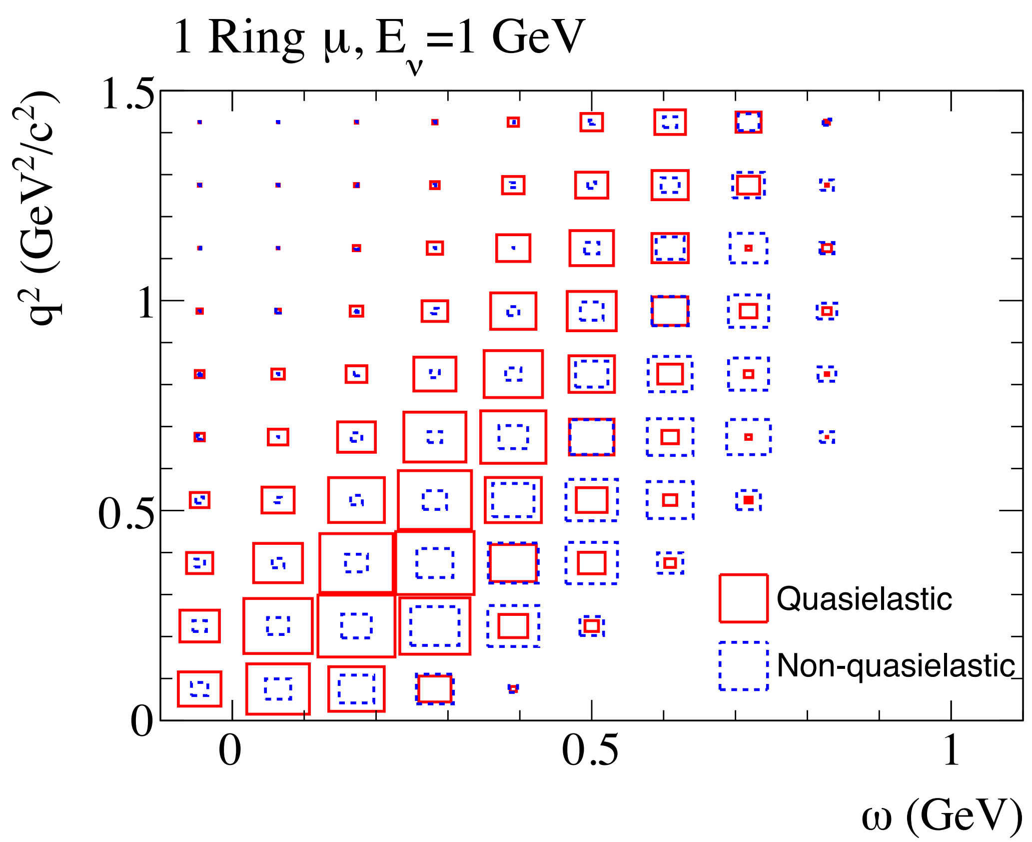
- The kinematic limit difference between muon and electron neutrinos = potential source of uncertainty
  - Error on the cross section in the extra kinematically allowed space for electron neutrinos?
- For energies of interest, Q^2 region of 0.35 to 0.5 GeV^2 is important
- There are potential sources of uncertainty in this Q^2 region including the correction for long-range correlations in the nuclear model (RPA)





Probing the Kinematic Limit

- With NuPRISM mono-energetic beams, we can measure the response to the four momentum transfer at a each neutrino energy

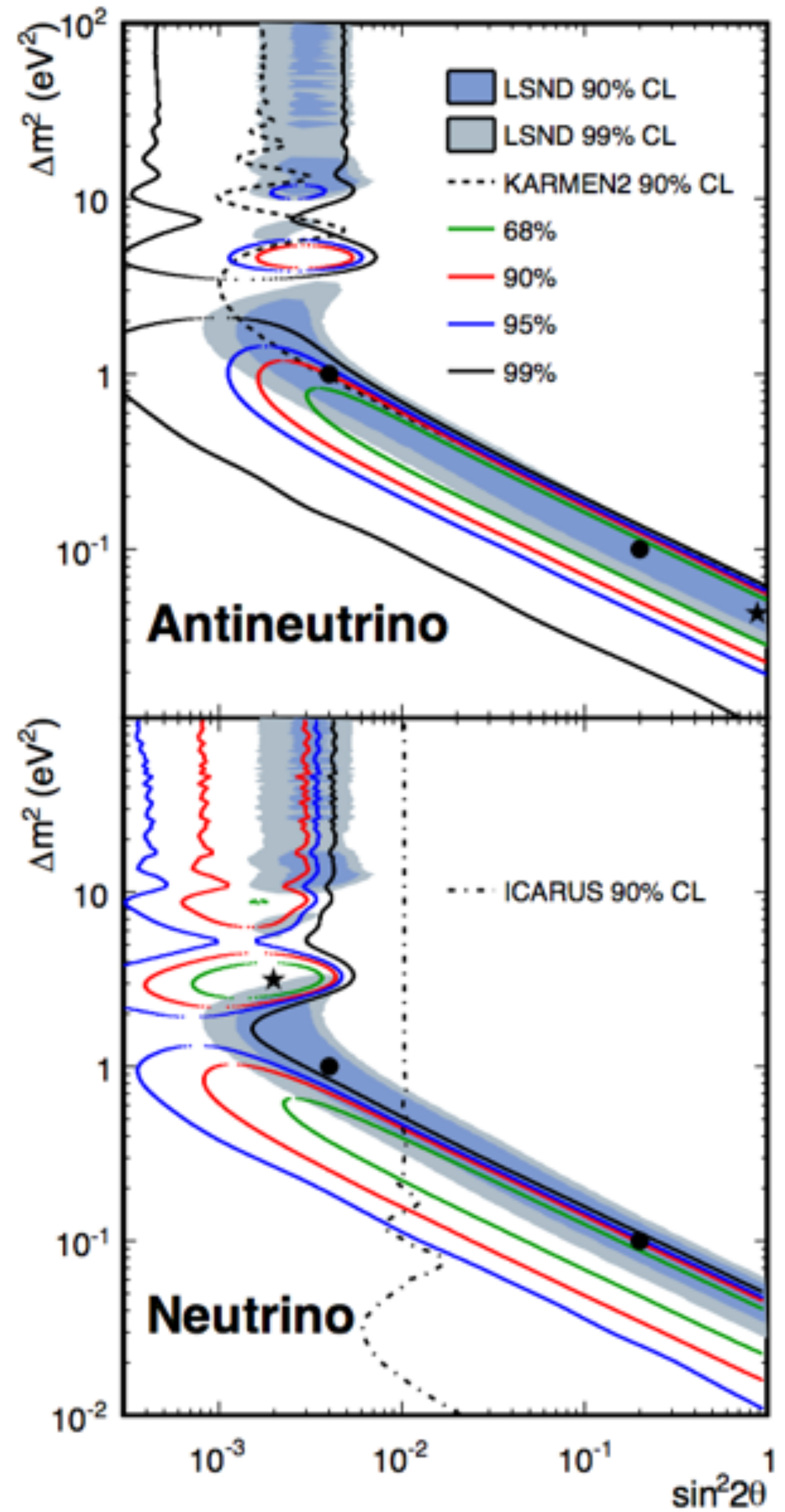


- Can probe the region above the kinematic limit with muon neutrinos by increasing the neutrino energy

- Studies on how this can reduce the electron neutrino cross section uncertainty are ongoing

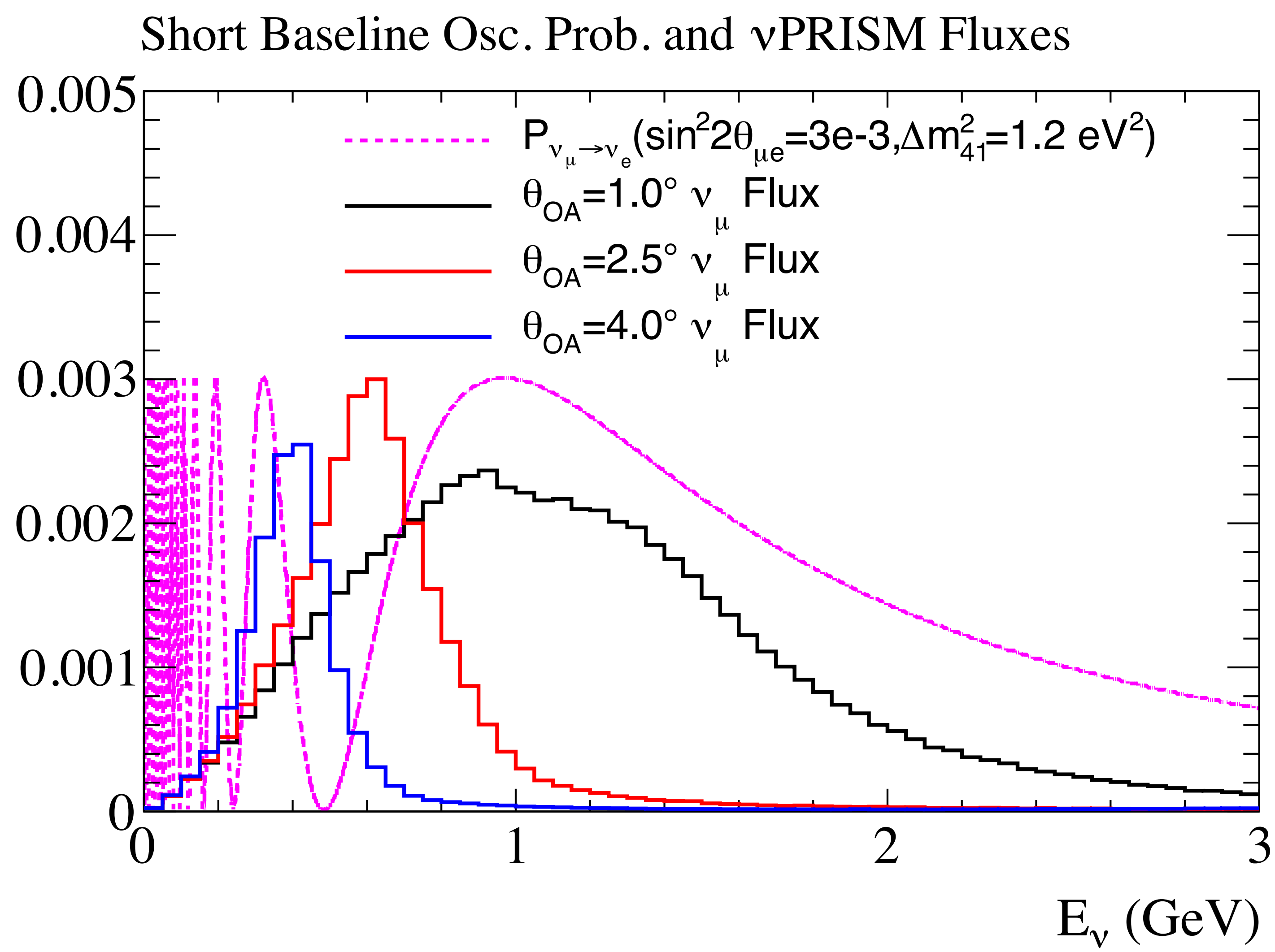
Short baseline Oscillations

- To measure the ν_e cross section, we should confirm that there is no evidence of short baseline ν_e oscillations
- At 1 km baseline, ~1 GeV energy, NuPRISM is ideal for probing short baseline oscillations through sterile neutrinos in the ν_e appearance channel, consistent with MiniBooNE & LSND anomalies.



Phys. Rev. Lett. 110, 161801

Unique to NuPRISM



- **The flux varies across NuPRISM giving it unique capabilities:**
- Can directly probe the energy dependence of the oscillations without relying on reconstructed energy.
- NC or CC backgrounds that feed-down in reconstructed energy will effect different off-axis slices differently

Analysis Method

- We simulate the ν_e oscillation signal by reweighting our ν_e background flux to the oscillated ν_e flux in the 3+1 model
- Expected oscillation signal candidates in 4.5e20 proton on target exposure:

TABLE II. Expected number of events in the ν_e selection for each oscillation hypothesis, and for the two detector inner diameters being considered.

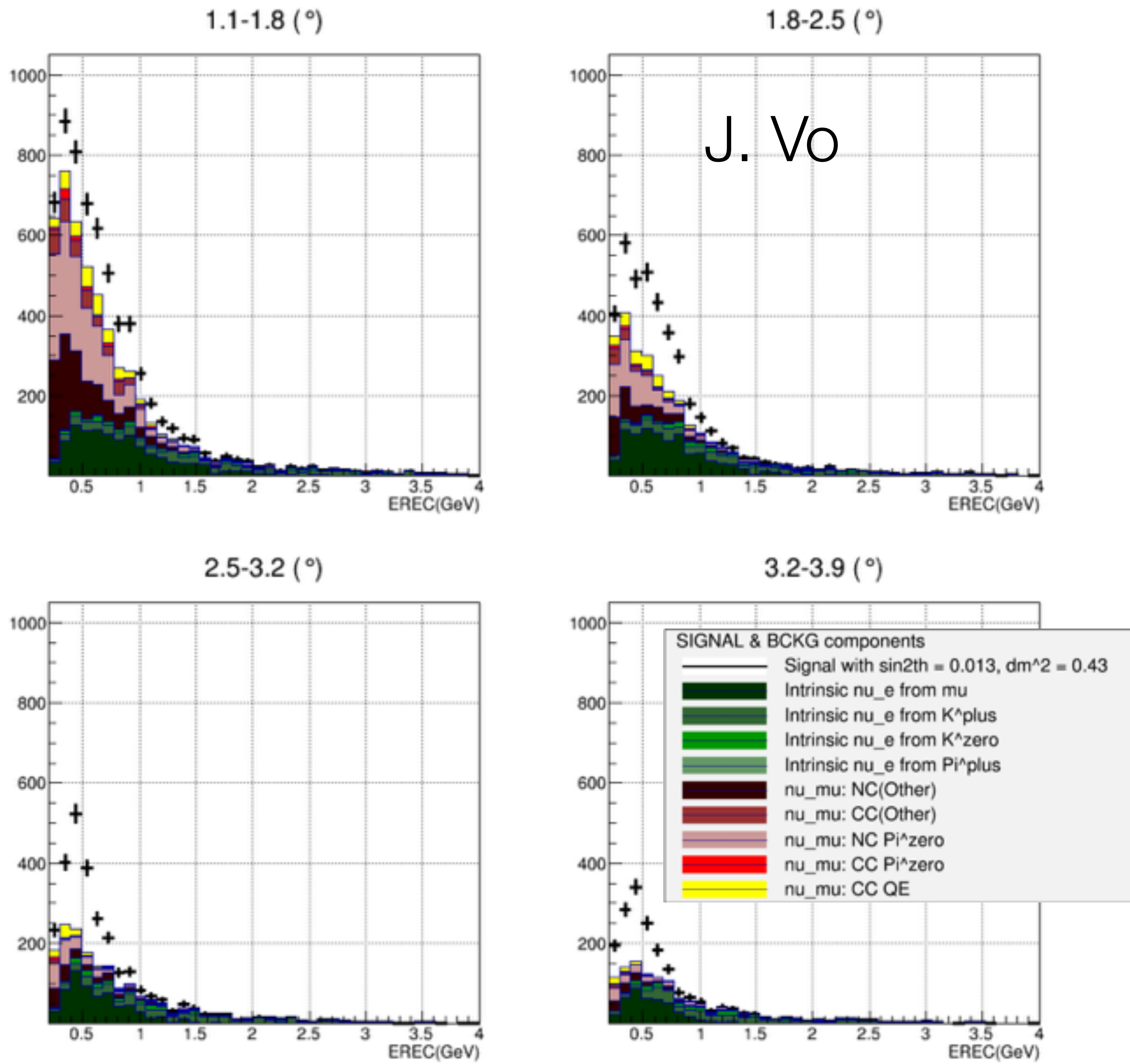
	$(\sin^2(2\theta_{\mu e}), \Delta m^2_{41})$	3 m radius	4 m radius
$\nu_\mu \rightarrow \nu_e$ Signal	$(0.001, 1\ eV^2)$	87.6	484.3
	$(0.005, 1eV^2)$	437.8	2421.7
	$(0.01, 10eV^2)$	635.2	3521.0
	$(0.001, 10eV^2)$	63.5	352.1
Background	ν_e	1076.2	6695.5
	ν_μ	983.8	4700.7

Almost half of the background is neutral current or misidentified muons - significant room for improvement!

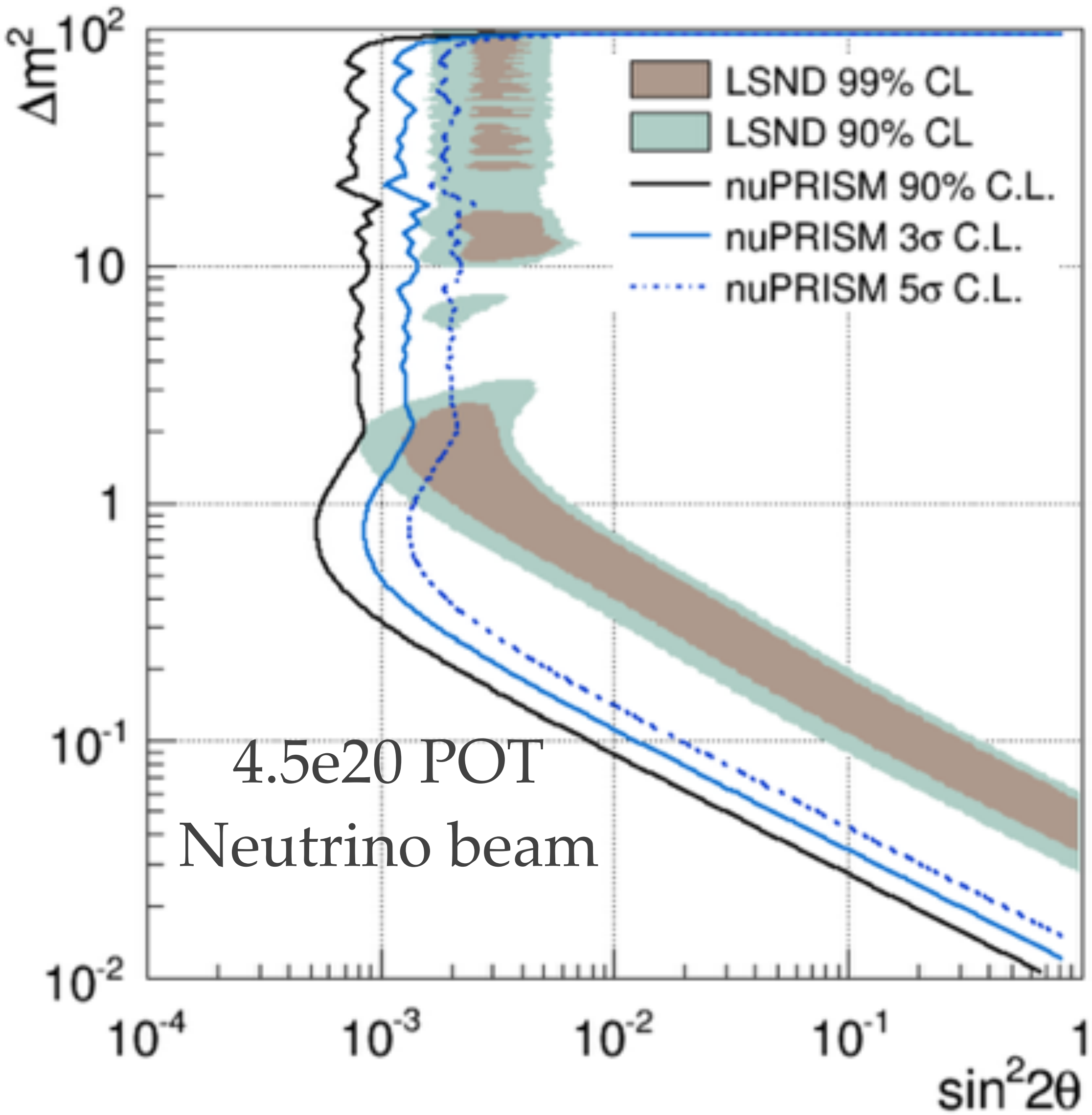
- T2K based flux and interaction model uncertainties are applied
- The data are binned in 10x10 bins of reconstructed energy and off-axis angle
- A simultaneous fit to muon candidates reduces the systematic uncertainties

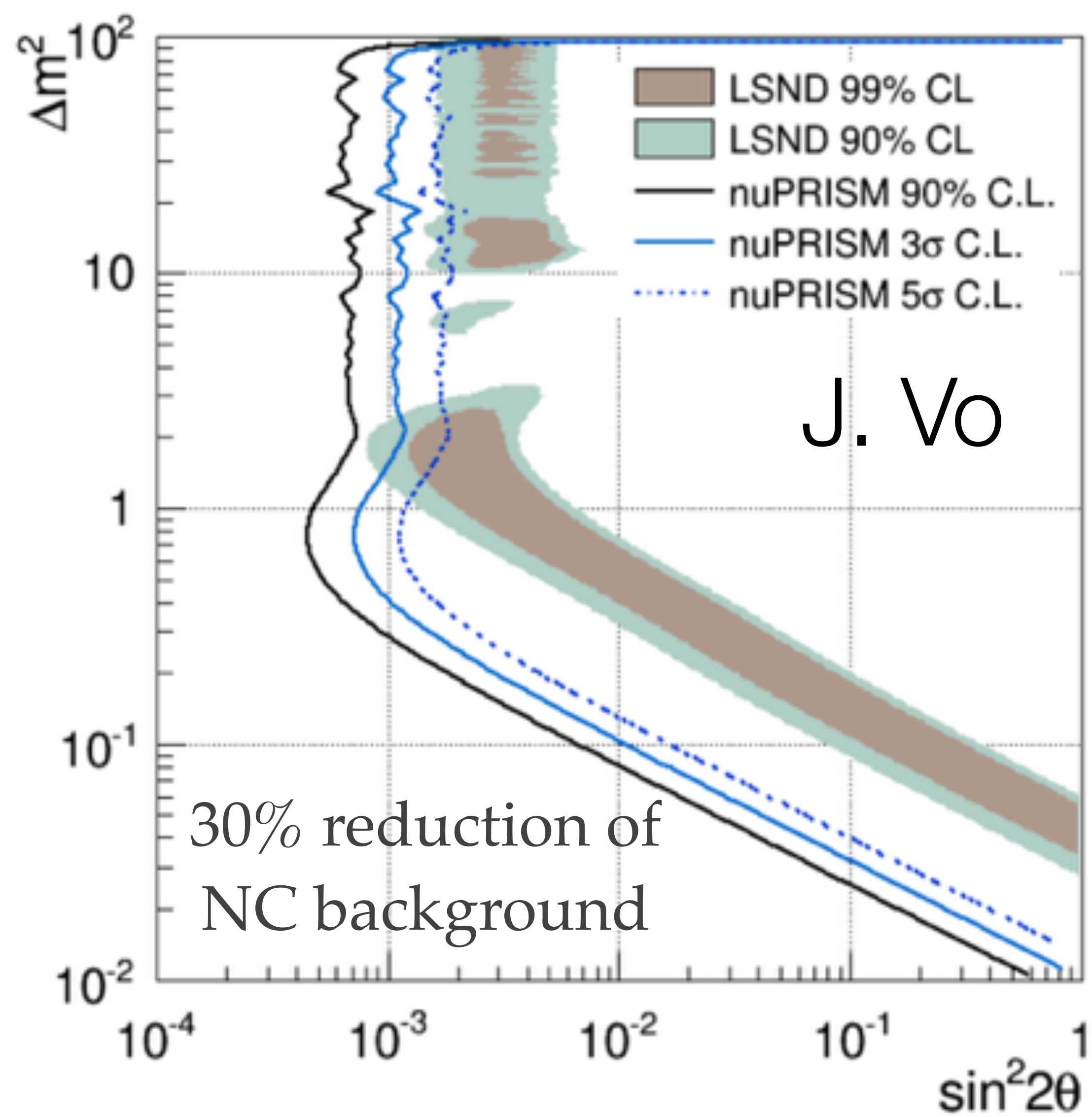
Signal & Background vs. Off-axis Angle

- The predicted signal and background vary differently with off-axis angle
- More on-axis bins are dominated by NC backgrounds
- More off-axis bins are dominated by intrinsic beam electron neutrino background



Exclusion Sensitivity Contours





- Exclusion regions are promising for 4.5e20 POT (1/3 HK exposure)
- Expected improvements: x3 stats for HK exposure, combination with ND280, better ν_e selection after PMT optimization, measurement with antineutrino data

Other Physics

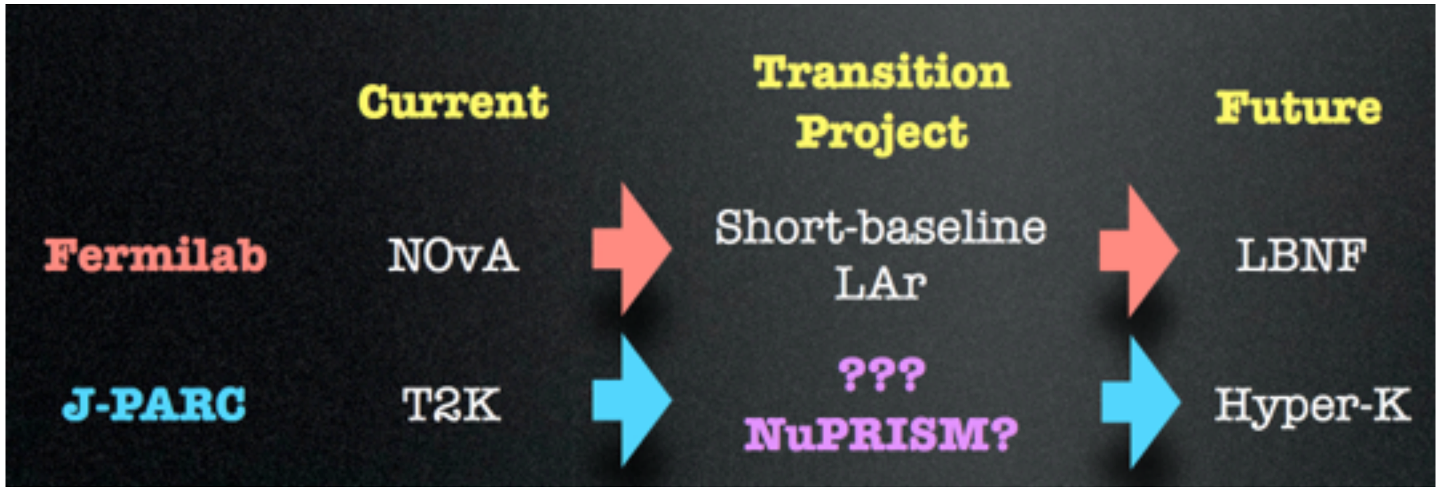
- The NuPRISM mono-energetic beams provide a method to study the energy dependence of NC interactions
- Precision measurements of sub-GeV neutrino cross sections are critical inputs for atmospheric neutrino analyses
  - There can be a statistically significant CP effect in the sub-GeV atmospheric neutrino samples, but it is currently washed out by systematic uncertainties
- Loading NuPRISM with Gd allows for the detection of neutron captures
  - Can measure the neutron multiplicities from (anti)neutrino interactions
  - Important inputs to proton decay or atmospheric neutrino analyses that will used neutron captures on Gd
- Can measure the rates for important backgrounds to proton decay measurements (CCπ^0 and kaon production)

Building NuPRISM

- At a 1 km baseline, NuPRISM is off of the J-PARC site: would need to acquire land.
- NuPRISM is designed with proven technologies so no significant R&D is necessary.
- Cost drivers are PMTs/electronics, civil construction of 50 m deep pit and new surface building.
- PMT costs can be minimized by using a movable frame and only partially instrumenting the pit. (~$3 million USD for 8 inch PMTs)
- At 10 m diameter, caisson methods maybe used for the pit excavation, reducing the cost.
  - Companies have calculated costs as low as $6 million + α
  - α is the unknown cost of unexpected problems during the excavation
- Total cost is in the ~$15-20 million. Will depend on detailed survey for excavation

NuPRISM in the J-PARC Neutrino Program

- NuPRISM can provide a bridge for the the Japanese neutrino program between T2K and Hyper-K (along with extended T2K running)



- Provide valuable inputs to the T2K measurements with the ultimate T2K exposure (or T2K x3 exposure)
- Introduces a new project with new (short base-line) physics potential that collaborators can join while Hyper-K is being built
- Can proved a test-bed for technologies that will be used in Hyper-K with a tank depth similar to what will be used in Hyper-K
- Can be upgraded with more instrumentation for Hyper-K

The Status of NuPRISM

- Have produced a letter of intent with 50 authors
- It is now uploaded to the arXiv: http://arxiv.org/pdf/1412.3086v2.pdf
- We have submitted an experiment proposal at the most rcent J-PARC PAC meeting
- We are forming the NuPRISM collaboration
- If you are interested, now is the time to join!!

Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline

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(Dated: December 16, 2014)

Conclusion

- Achieving the systematic error requirements for current and future long baseline neutrino experiments is a major challenge
- Of particular concerning is the modelling of neutrino interactions
- NuPRISM takes advantage of the off-axis effect in a conventional neutrino beam to measure neutrino interactions in a novel way
- We have shown NuPRISM’s benefits with mono-chromatic beams, in the muon neutrino disappearance measurement and in short baseline oscillations
    - More studies of the physics potential are in the pipeline
- NuPRISM is an exciting project that can provide a bridge from T2K to Hyper-K
- If you are interested, please join us!!

Thank you.