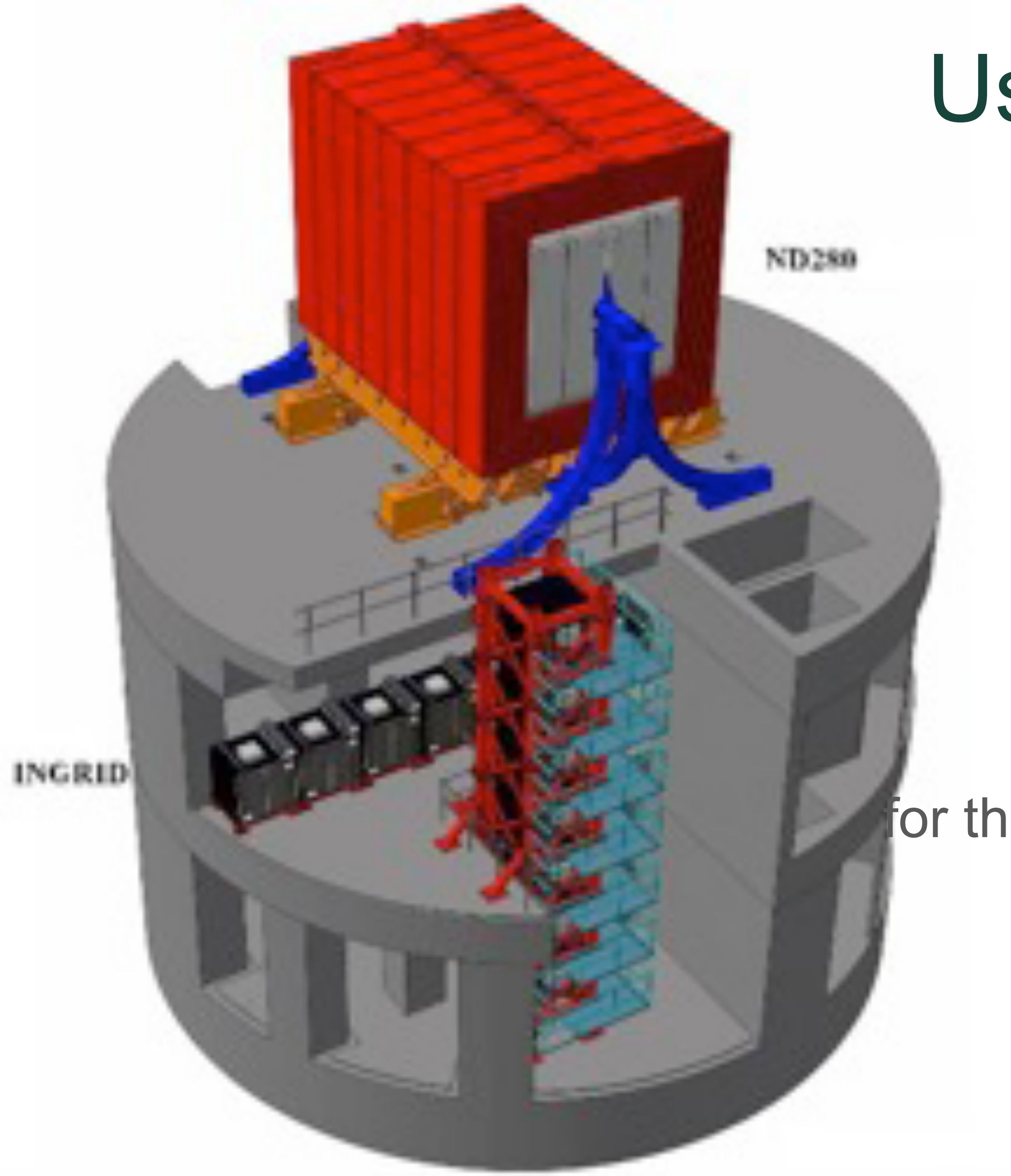
MICHIGAN STATE UNIVERSITY



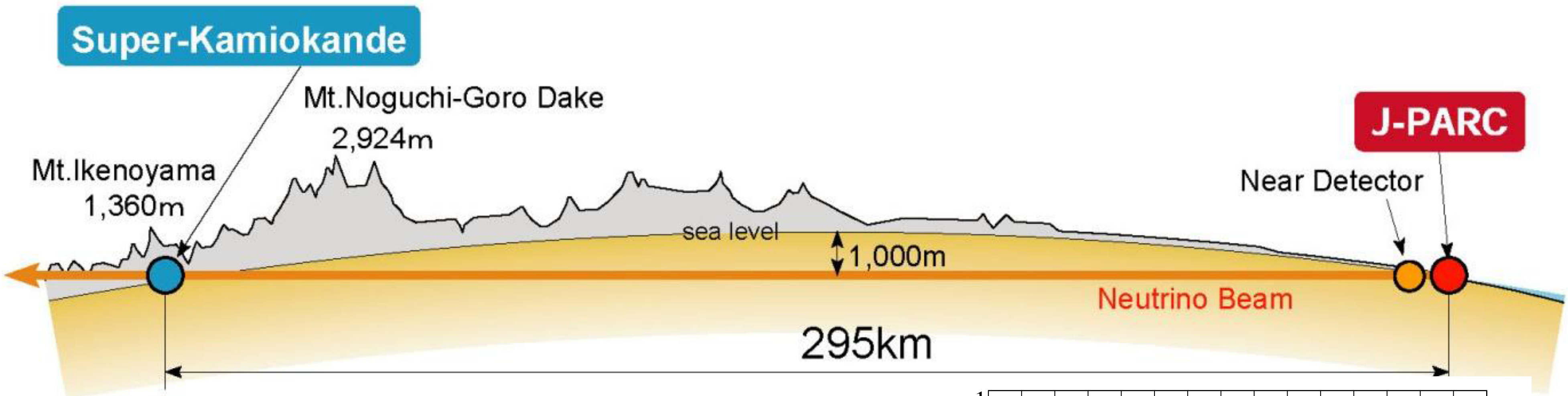
Use of near detectors in oscillation analyses: T2K, SciBooNE +MiniBooNE

Kendall Mahn
for the T2K, SciBooNE and MiniBooNE collaboration

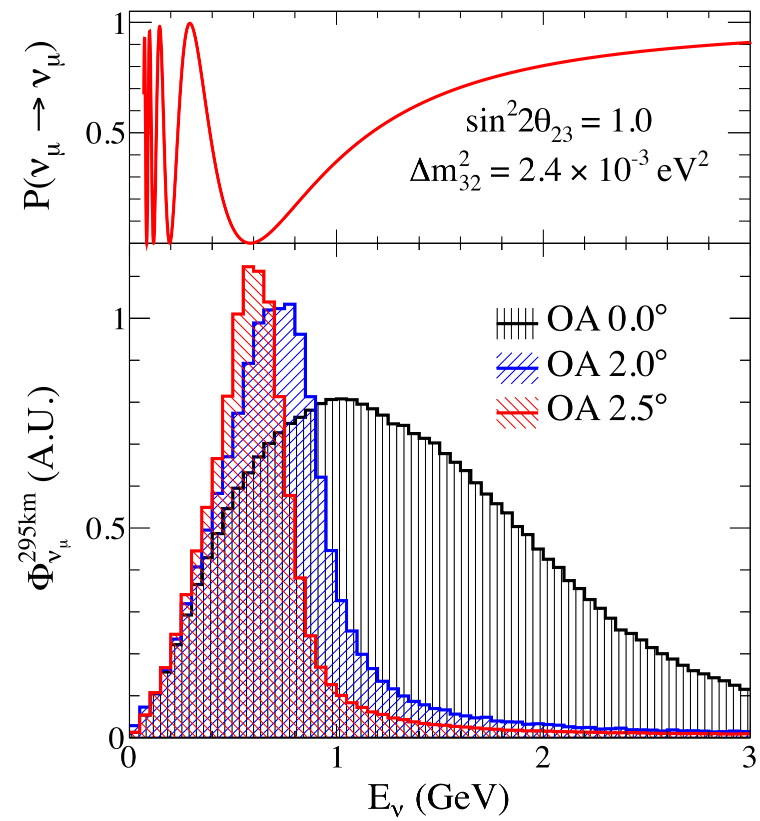
Michigan State University

The Tokai-to-Kamioka experiment

MICHIGAN STATE UNIVERSITY



Measurements so far:



ν_μ to ν_e (and $\overline{\nu}_\mu$ to $\overline{\nu}_e$) appearance:

- Discovery of ν_e appearance (2013)
- Search for presence of appearance with antineutrinos; necessary step toward future CPV searches

ν_μ, $\overline{\nu}_\mu$ disappearance:

- World's best measurement of θ_{23}
- With antineutrinos: test of NSI or CPT theorem

T2K oscillation analyses overview

$$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

Fit the observed rate of ν_e or ν_μ to determine the oscillation probability, P. Depends on:

Neutrino flux prediction	Neutrino cross section model	Far detector selection, efficiency

We reduce the error on the rate of ν_μ with the near detector:

$$N_{ND} \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

Neutrino flux prediction	Neutrino cross section model	Near detector selection, efficiency

T2K oscillation analyses overview

MICHIGAN STATE UNIVERSITY

$$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

Fit the observed rate of ν_e or ν_μ to determine the oscillation probability, P. Depends on:

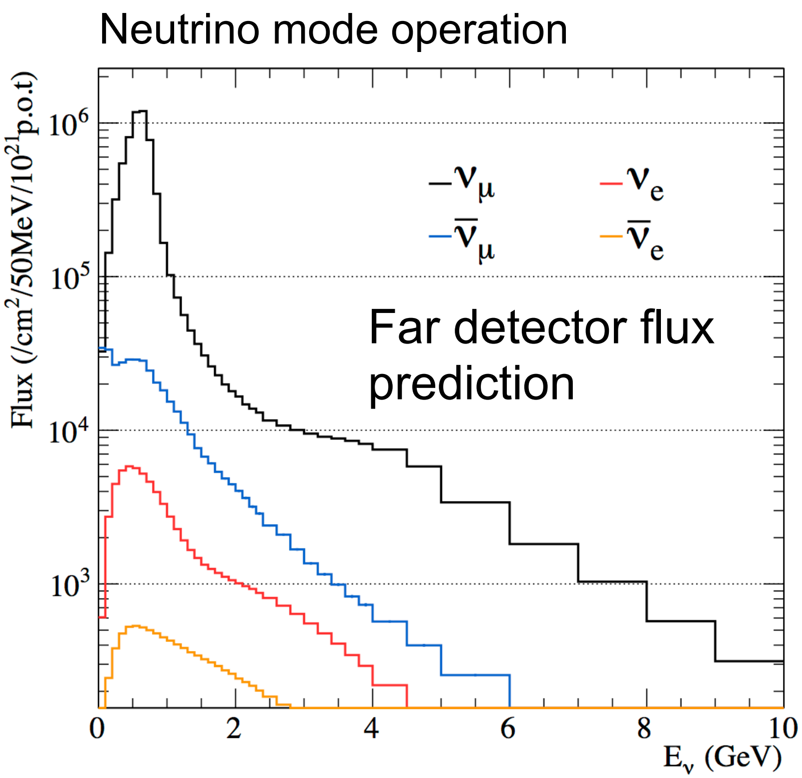
Neutrino | Neutrino cross | Far detector

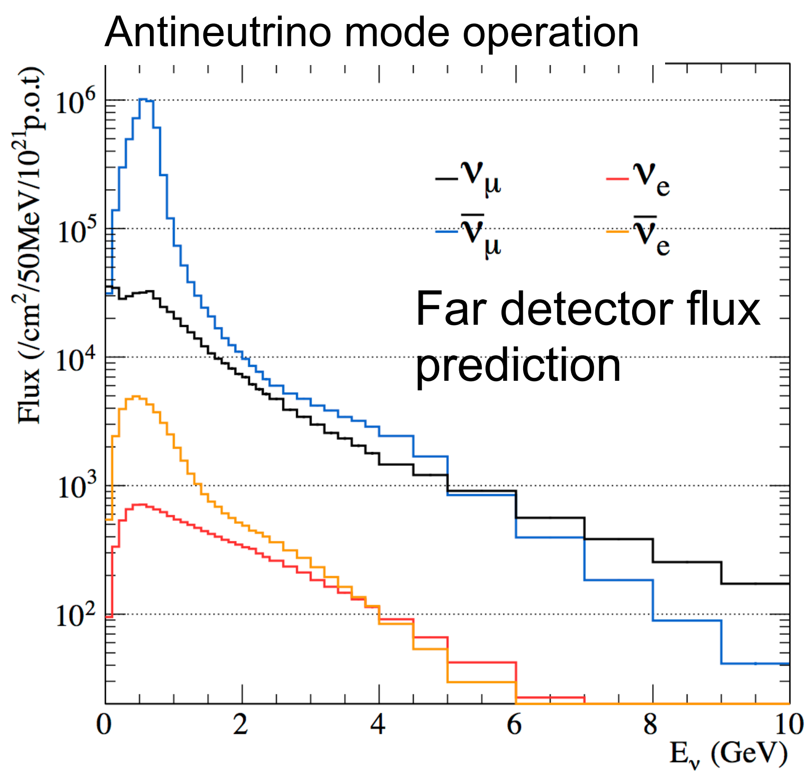
T2K's near to far extrapolation has evolved over the last 5 years

Presentation today will focus on this year's antineutrino analysis and recent improvements to flux, cross section models

Significant background in antineutrino analyses from neutrino interactions motivates inclusion of ND neutrino-mode, antineutrino-mode data sets

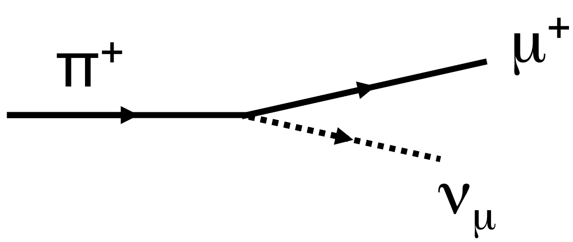
T2K neutrino, antineutrino flux

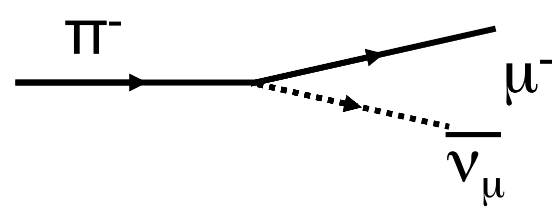




FLUKA/Geant3-based neutrino beam simulation (PRD 87, 012001)

- Significant neutrino component to antineutrino mode beam ("wrong sign" component)



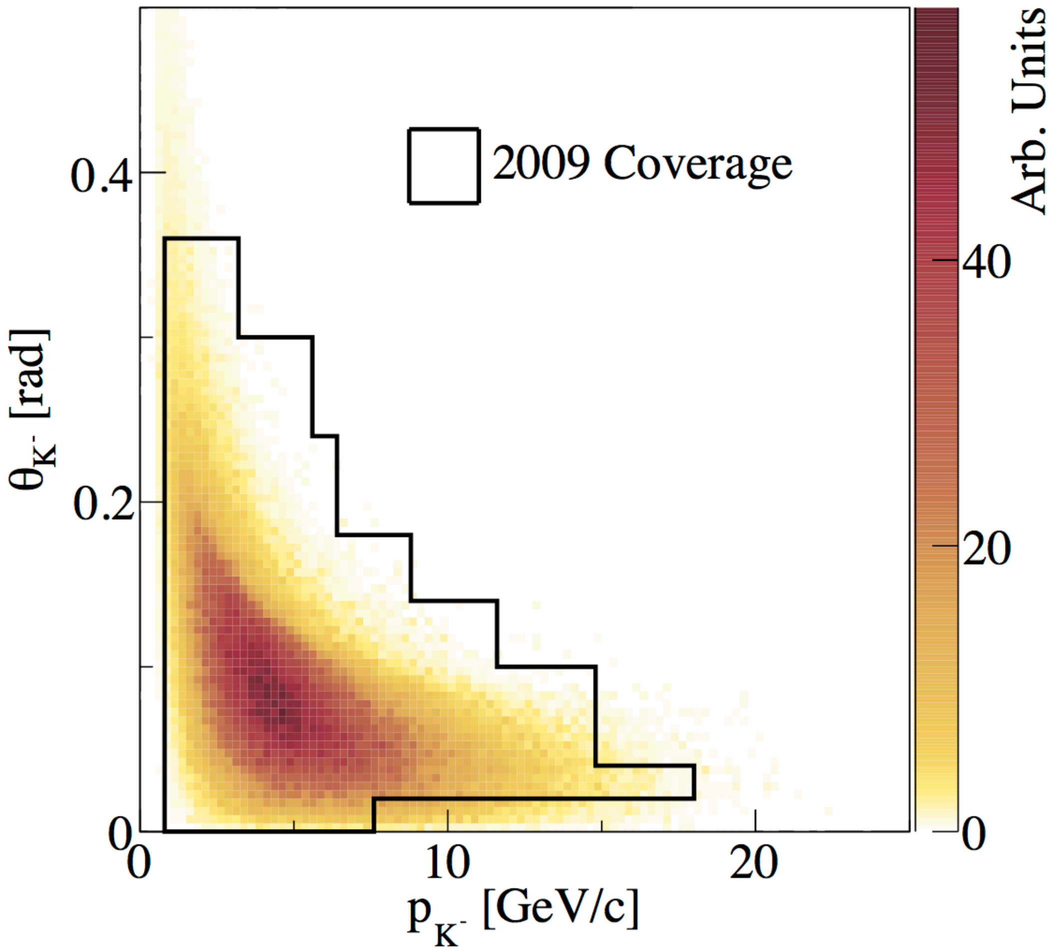


- "Intrinsic" ~0.5% electron (anti)neutrino component

T2K neutrino, antineutrino flux

Prediction based on external or in-situ measurements of:

- proton beam (30 GeV)
- alignment and off-axis angle
- $\pi^{+/-}$, $K^{+/-}$ production from NA61

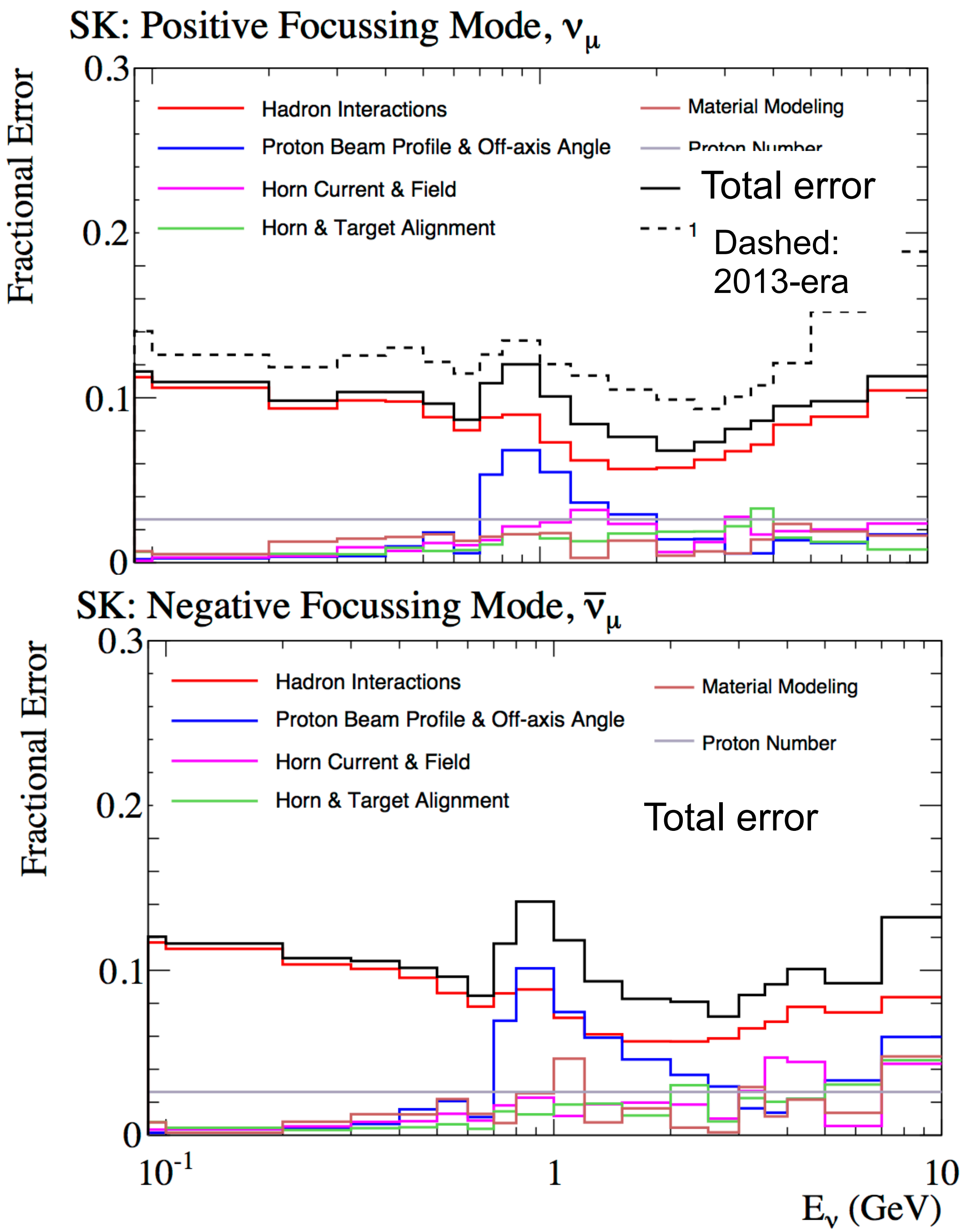


Dedicated hadron-production experiment at CERN

- Thin target data analysed so far, replica target data taken
- Improved results for $\pi^{+/-}$ expand (anti)neutrino production phase space
- New K^- (and K^0_S) measurements
  - K^-: ν_μ production
  - K^0_S: Intrinsic ν_e production

See A. Bravar's talk (NA61 pion analysis) joint WG1,4 talk Thurs 12-12:30

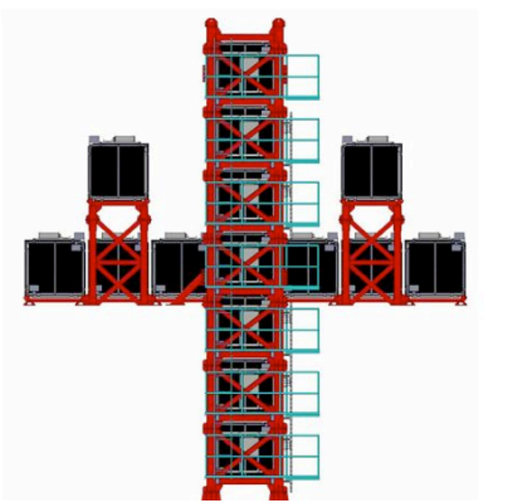
Flux uncertainties

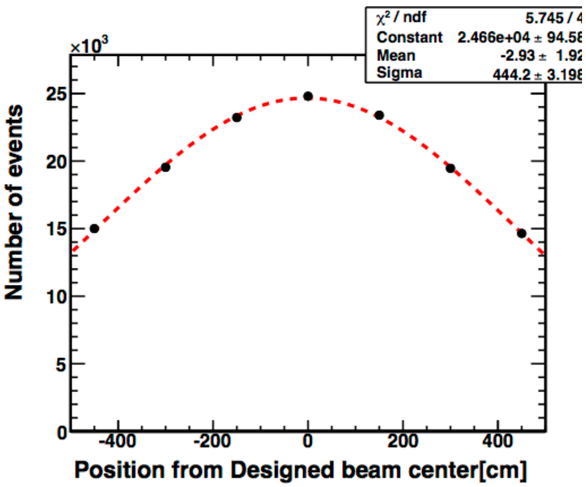


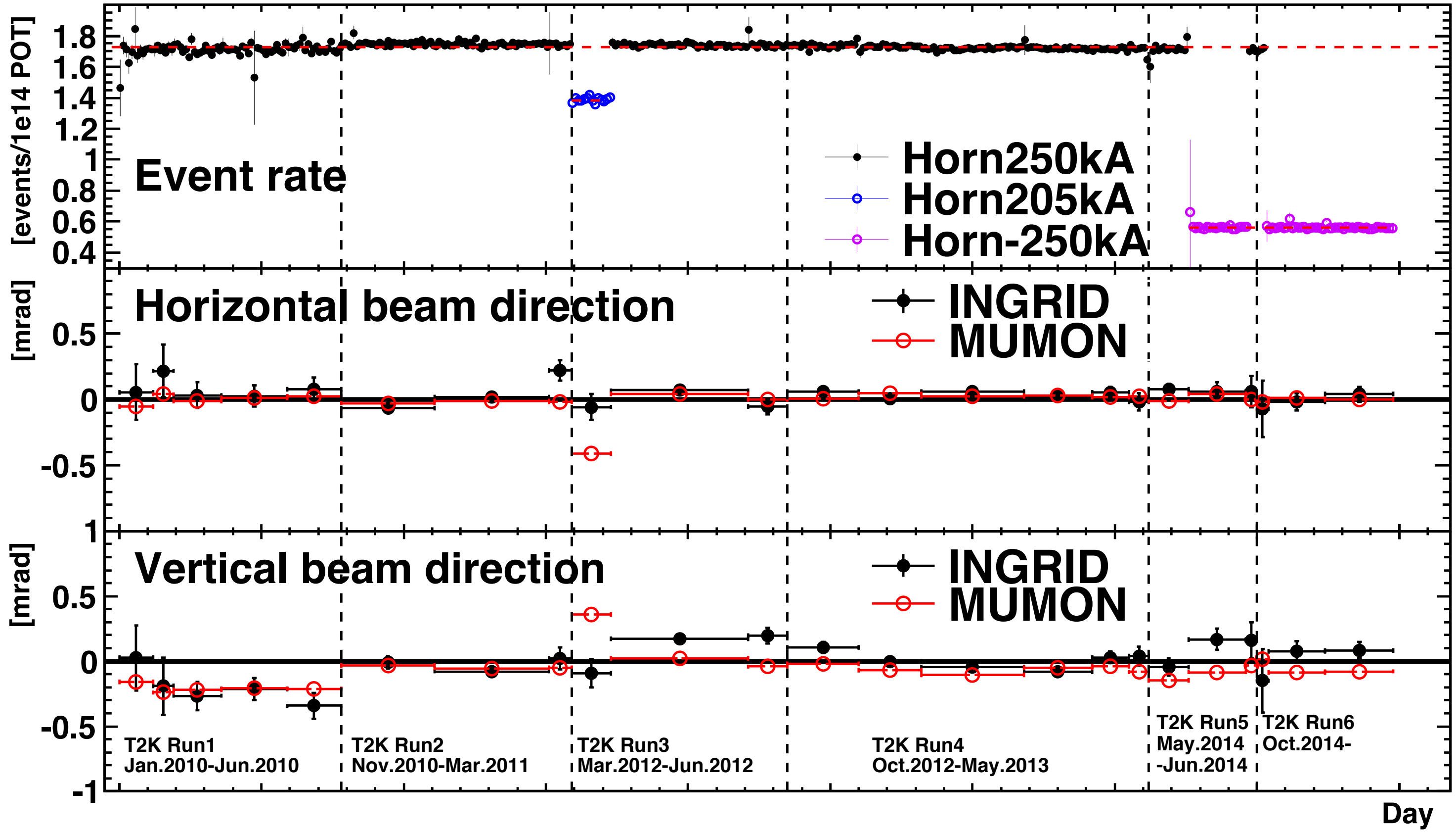
Dominant flux uncertainties are from hadron interactions

Uncertainties are comparable for neutrino mode (top) or antineutrino mode (bottom) operation

Use of on-axis near detector: INGRID







Profile of neutrino beam measured with scintillator/iron detectors placed from 0-0.9 degrees off-axis (INGRID)

- Confirms POT normalized event rate stable (better than 1%)
- Beam direction is stable to within 1mrad; 1mrad corresponds to a 2% shift to peak of the off-axis neutrino energy distribution

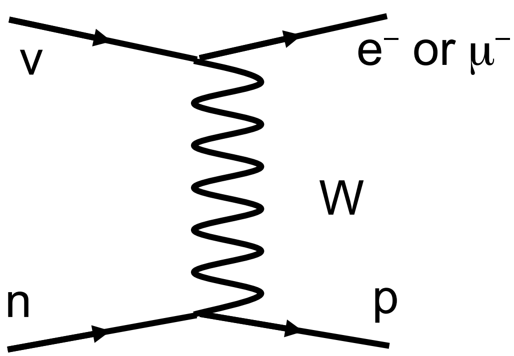
Neutrino interaction model

MICHIGAN STATE UNIVERSITY

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

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

CCQE

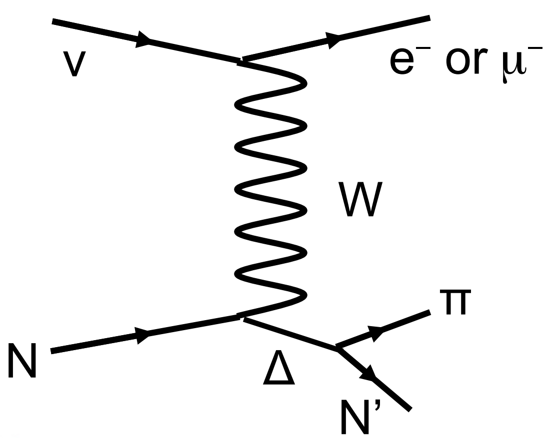


Infer neutrino properties from the lepton momentum and angle:

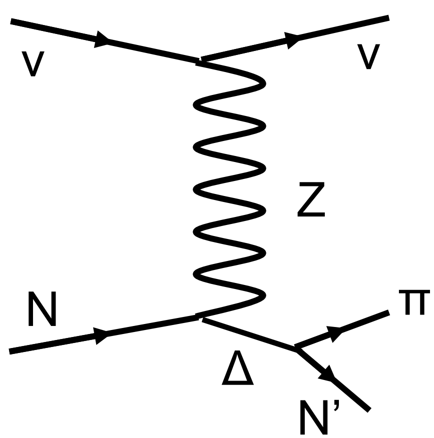
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CCπ



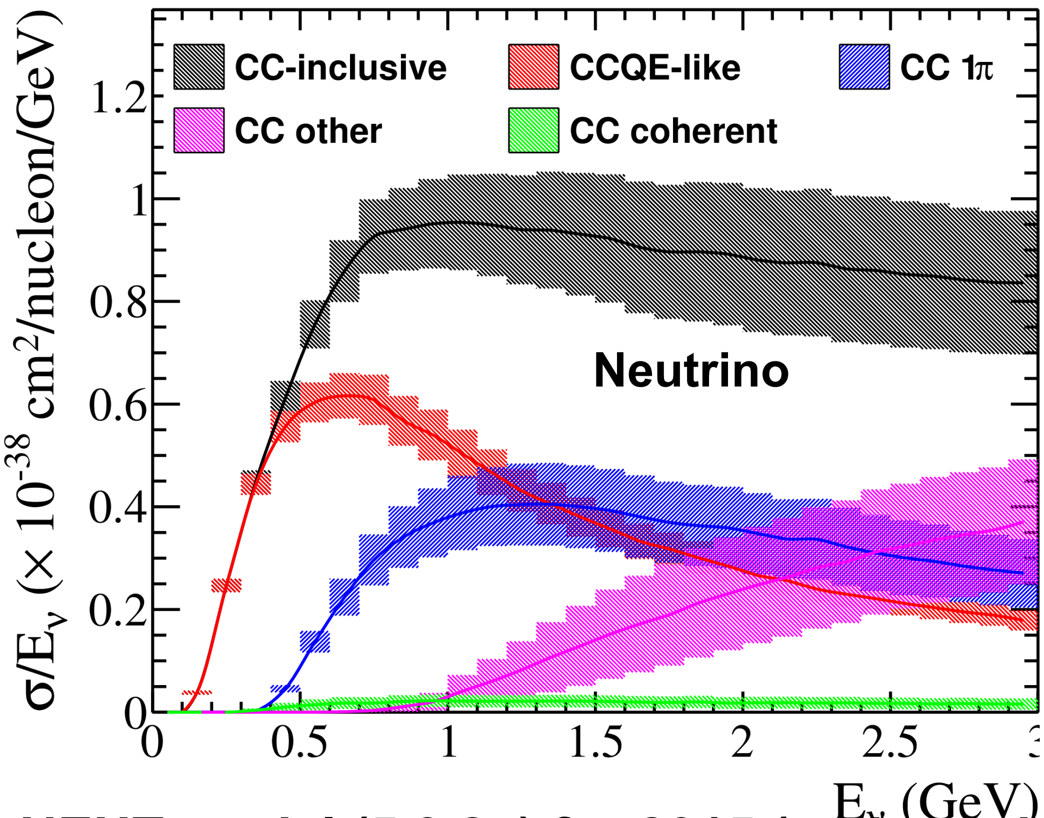
NCπ

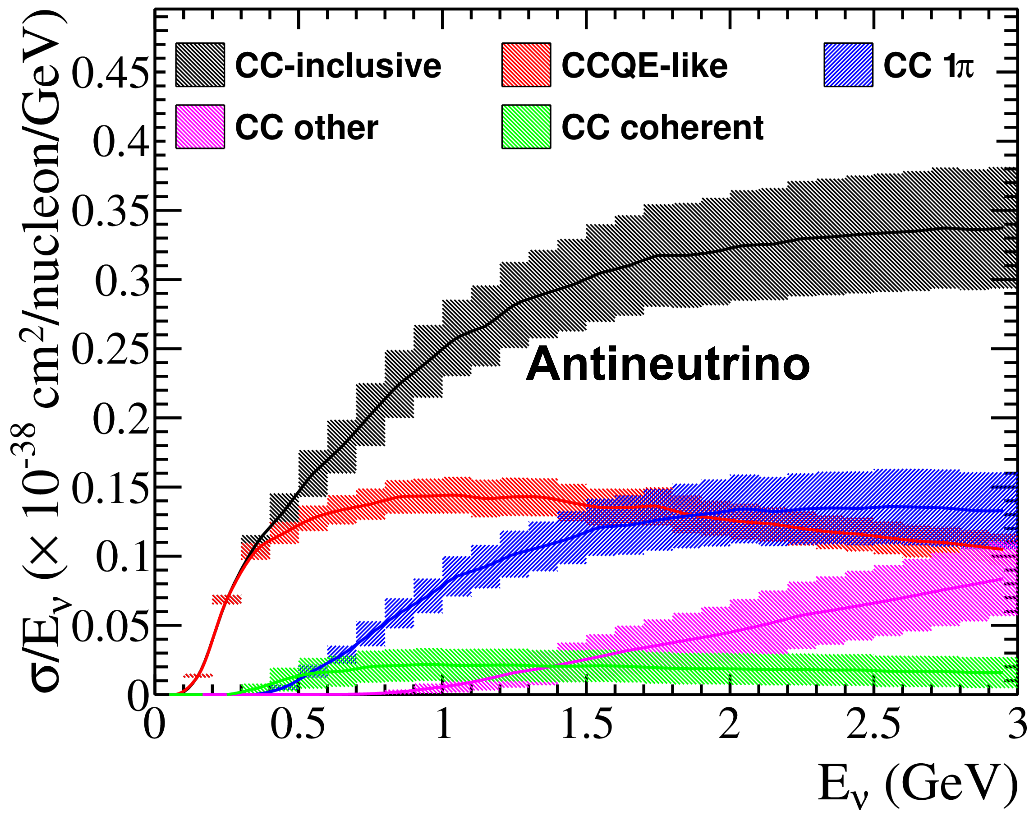


Additional significant processes:

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

Improved neutrino interaction models



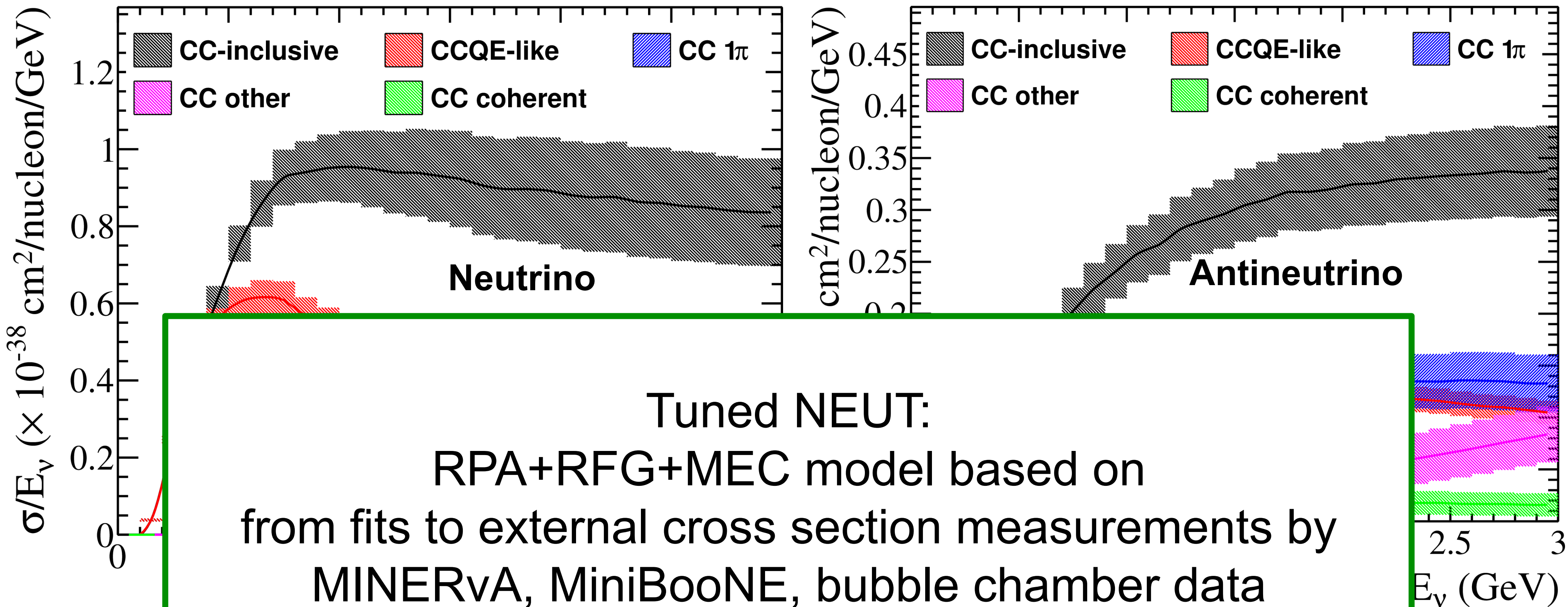


NEUT model (5.3.2+) for 2015 (antineutrino, neutrino+antineutrino) analyses:

- Two new CCQE models implemented for consideration in the analysis:
  - CCQE: Spectral function model (Benhar et al.) M_A^{QE}= 1.2 GeV
  - CCQE: Relativistic Fermi Gas (RFG)+Random Phase Approximation (RPA)
  - New: "Meson exchange current" (MEC) CCQE like scattering from Nieves et. al
- 1π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

Improved neutrino interaction models

MICHIGAN STATE UNIVERSITY



Tuned NEUT:
RPA+RFG+MEC model based on
from fits to external cross section measurements by
MINERvA, MiniBooNE, bubble chamber data

See T. Feusels' talk in WG2, Thurs 15:00-15:30

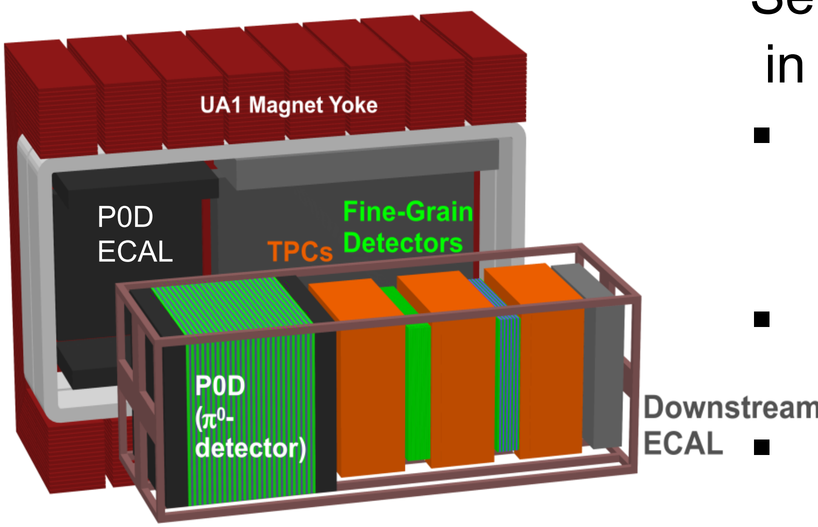
NEUT m … es:

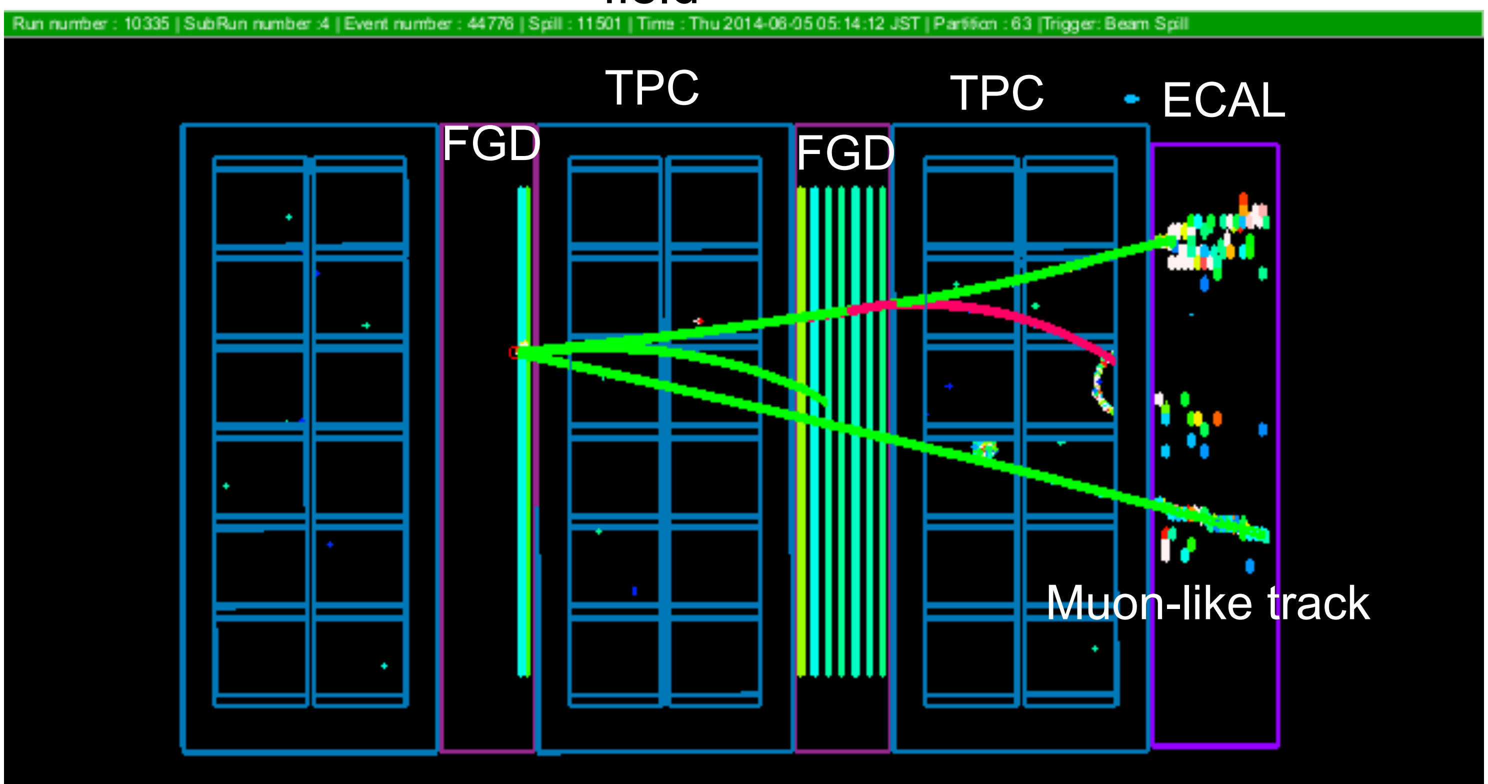
- Two n …
  - C …
  - C … PA)
  - New: "Meson exchange current" (MEC) CCQE like scattering from Nieves et. al
- 1π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

T2K off-axis near detectors: ND280

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

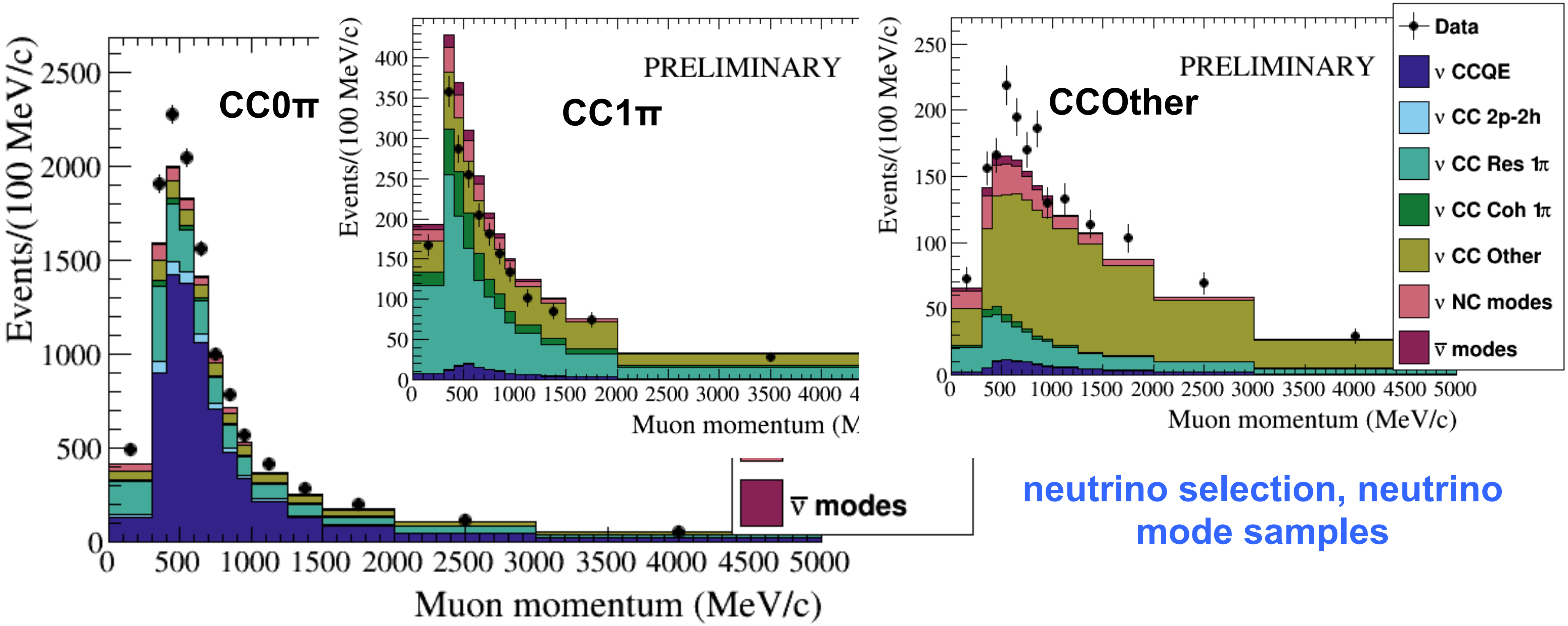
- Neutrino interacts on scintillator or water target in tracking detectors (FGDs), muon tracked through scintillator and TPCs
- Additional scintillator (P0D, SMRD) and calorimeters (ECAL)
- Muon momentum, sign from curvature in magnetic field





Example: neutrino candidate in antineutrino mode

ND280 data samples: neutrino mode



neutrino selection, neutrino mode samples

Select CC ν_μ candidates based on interactions with μ-:

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

Event samples provide information on flux, cross section model

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

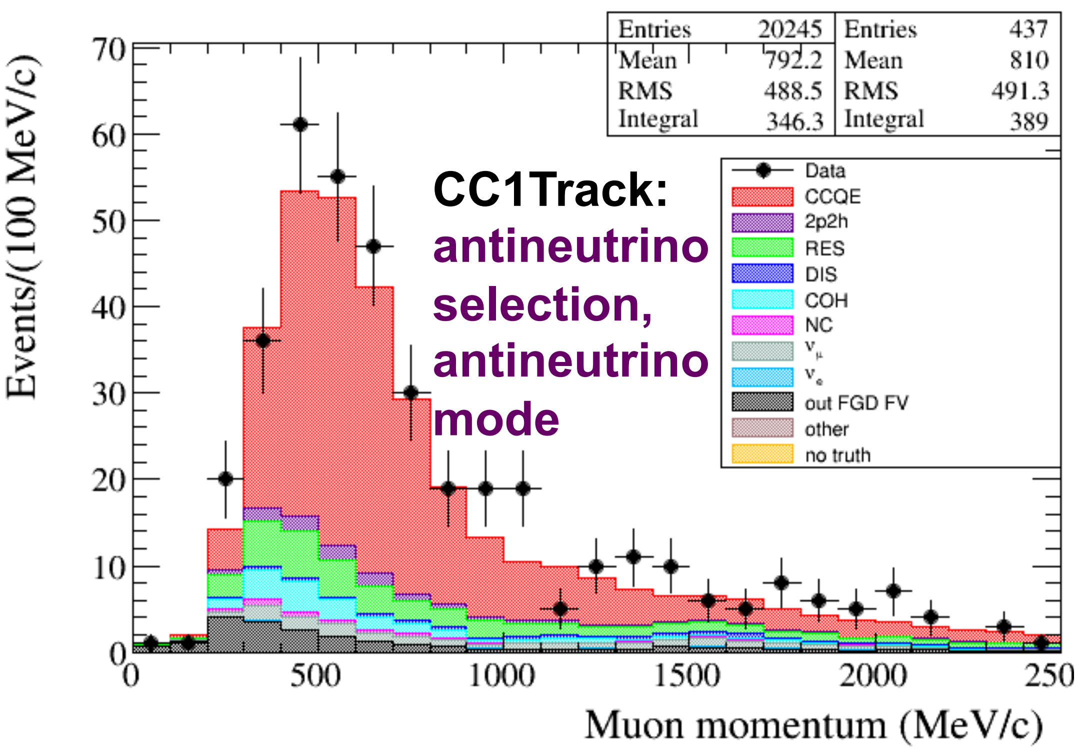
ND280 data samples: antineutrino mode

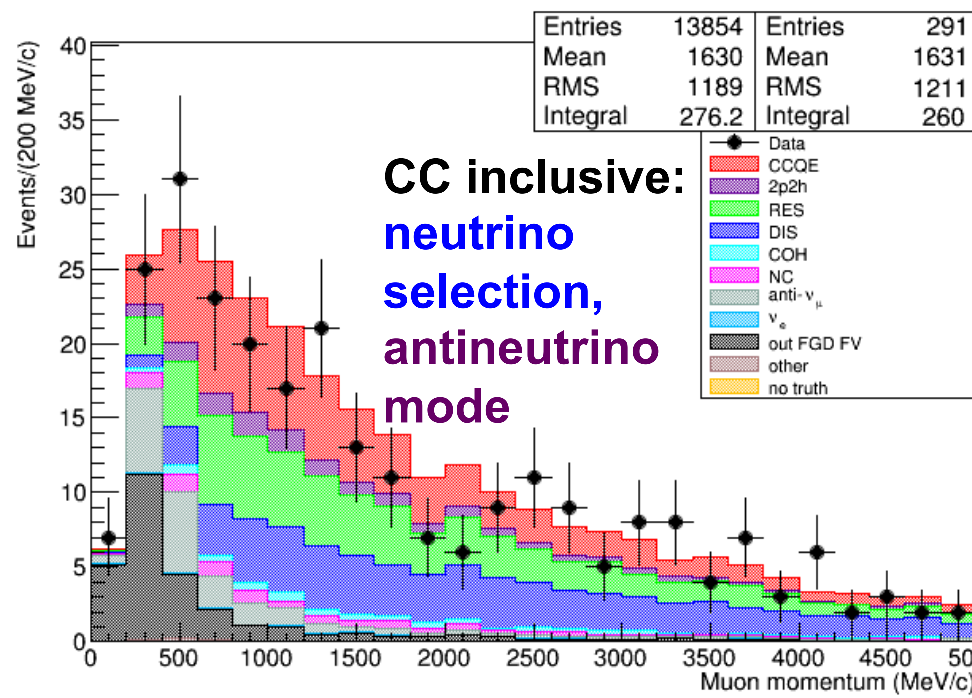
Select CC $\overline{\nu}_\mu$ candidates based on interactions with μ+:

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

Complementary selection of neutrino candidates in antineutrino mode

Include in fit:
neutrino mode neutrino selections
antineutrino mode neutrino and antineutrino selections

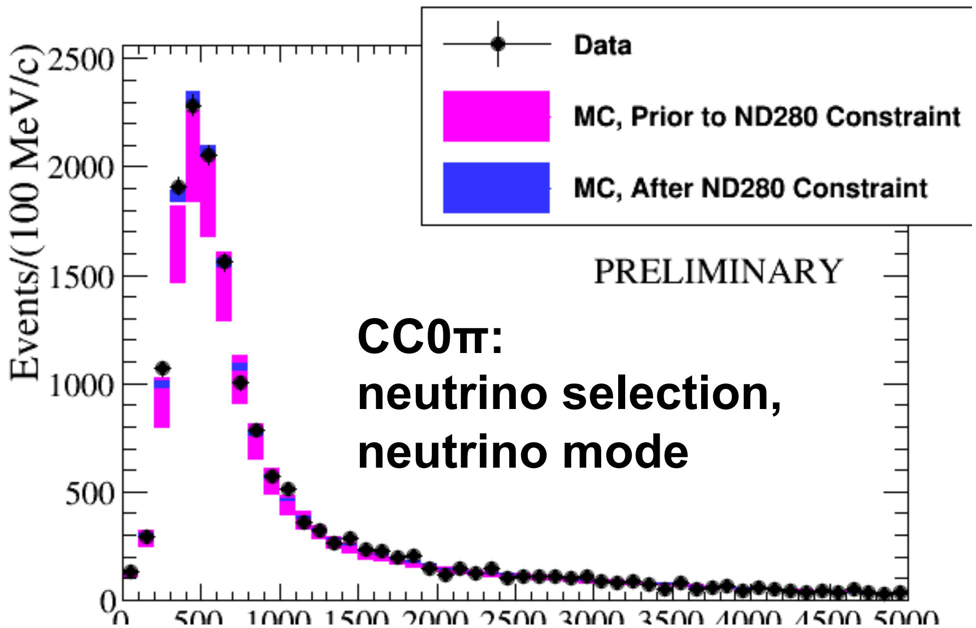


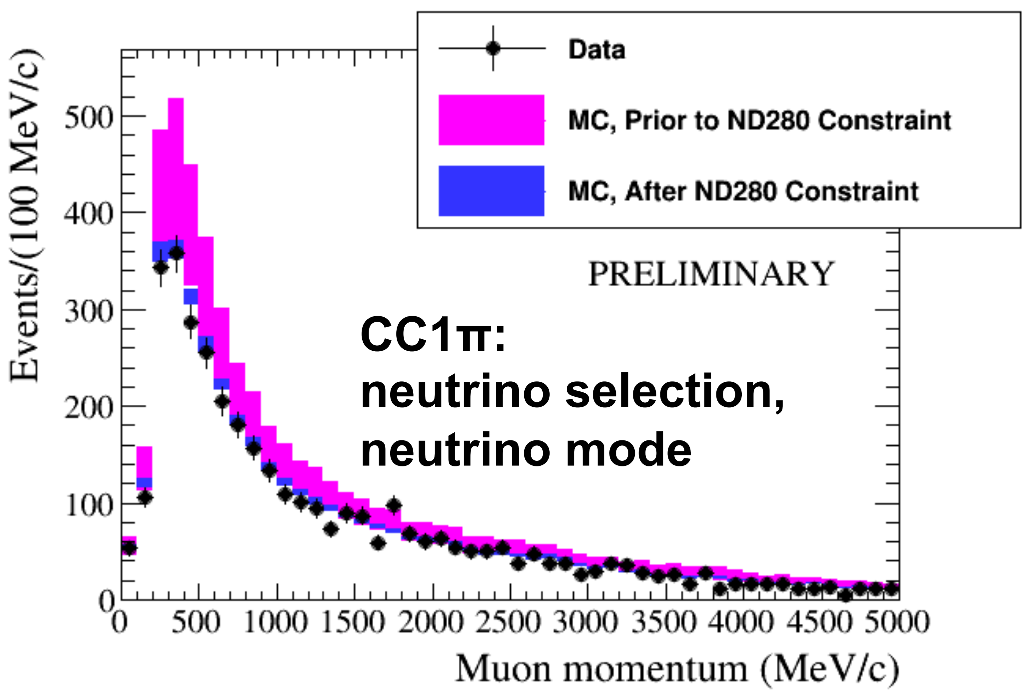


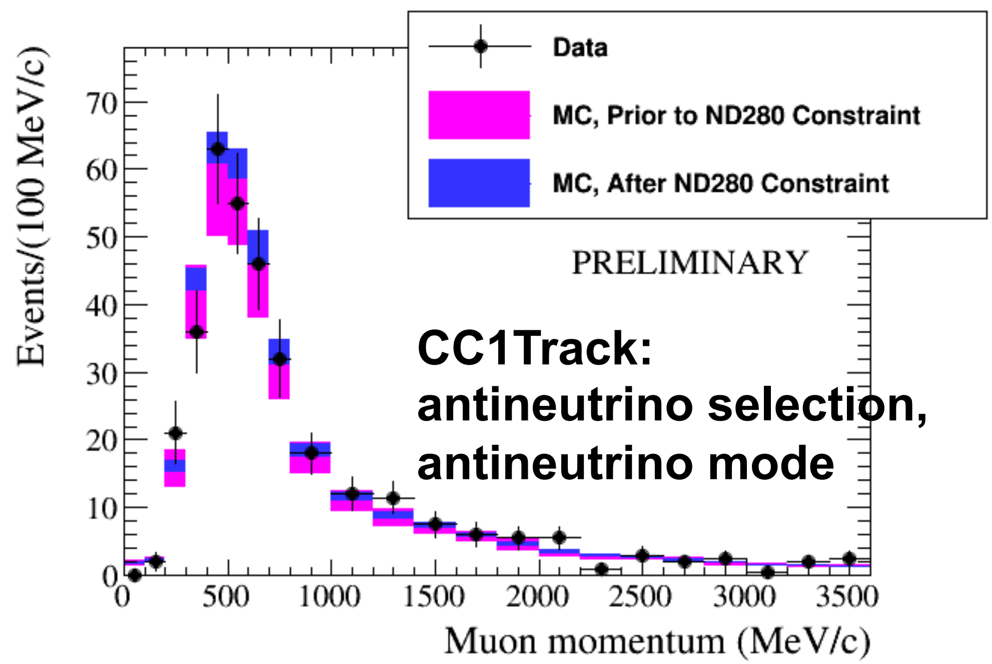
Near detector rate measurement

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

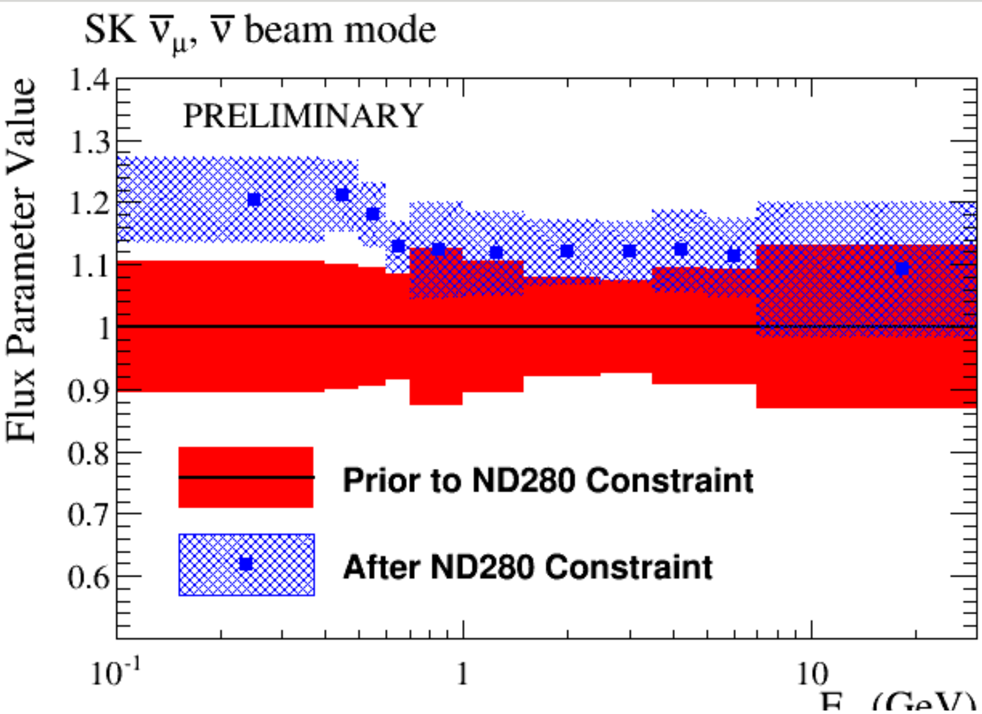
- Fits include ND detector uncertainties
- Flux and cross section model parameters modified

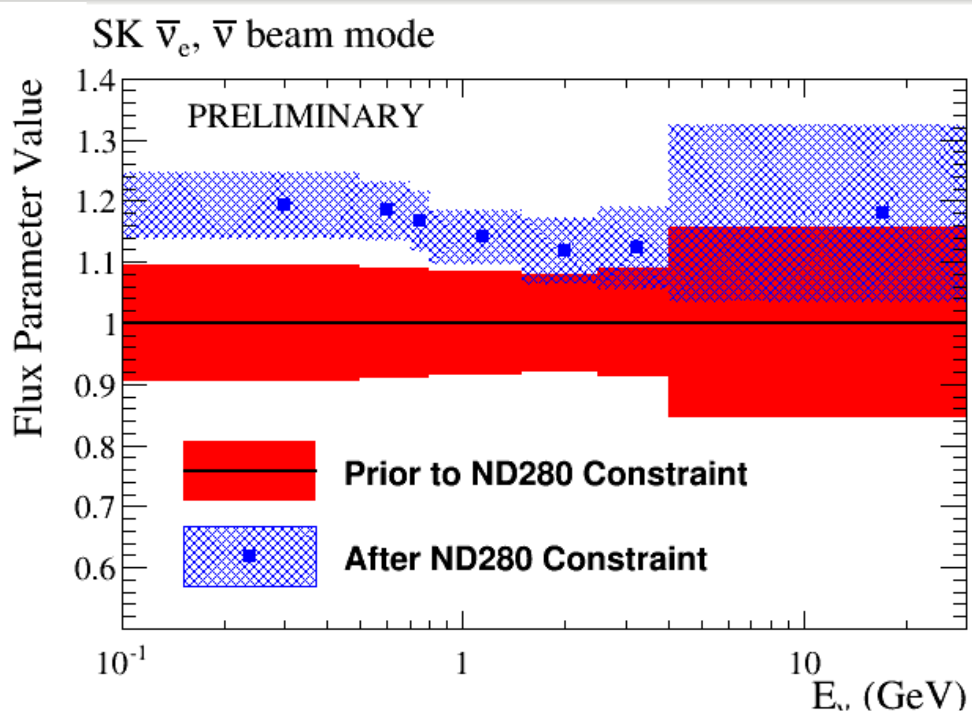


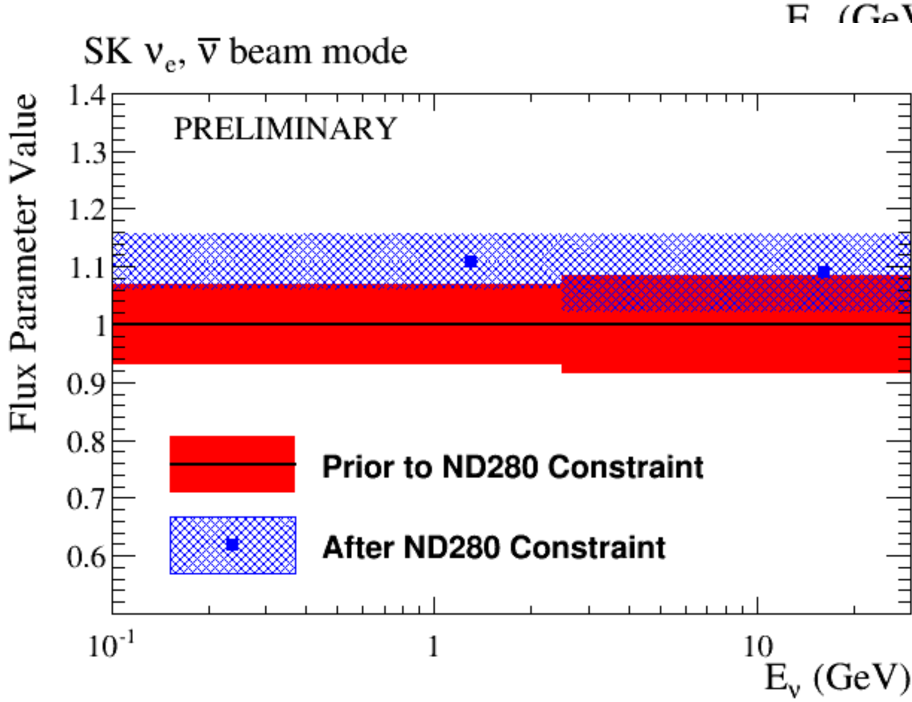


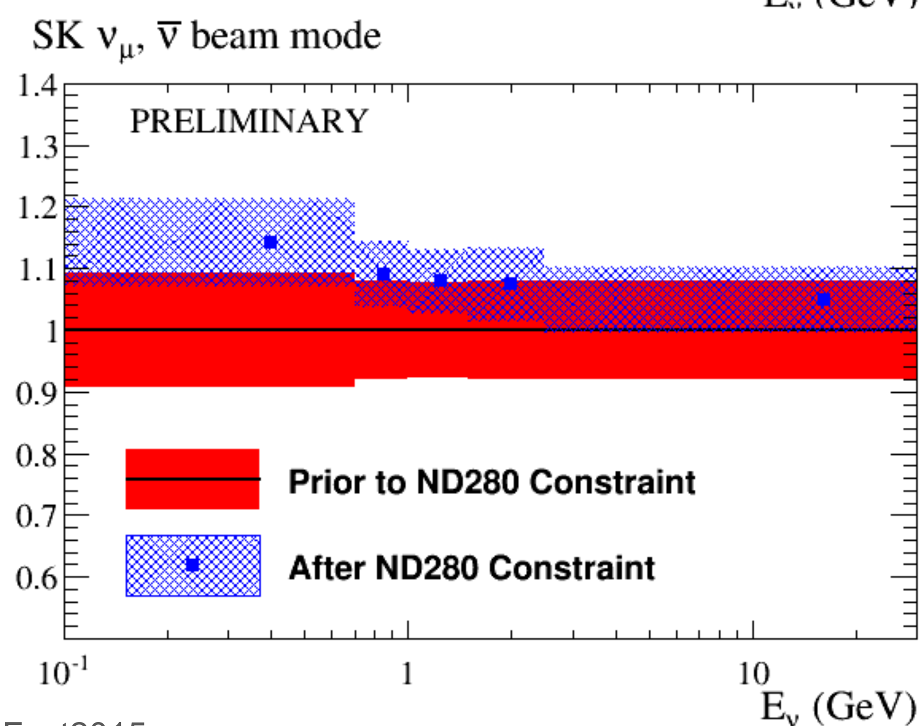


Flux tuning from near detector fit

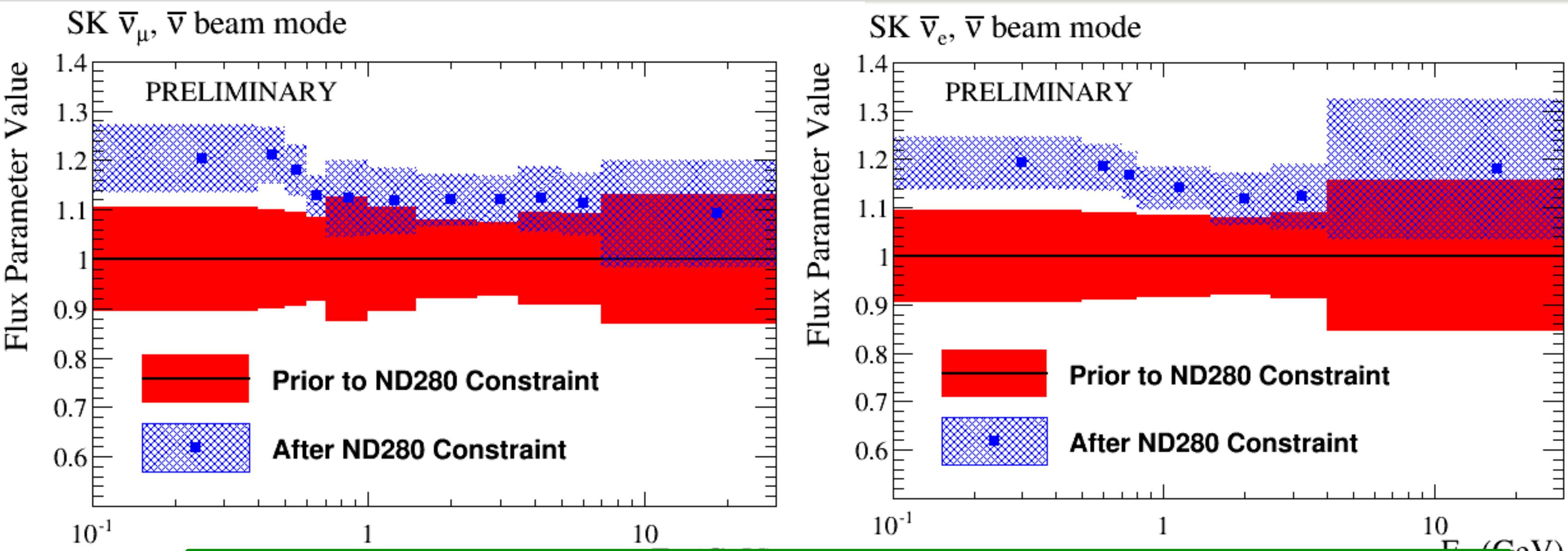








Flux tuning from near detector fit

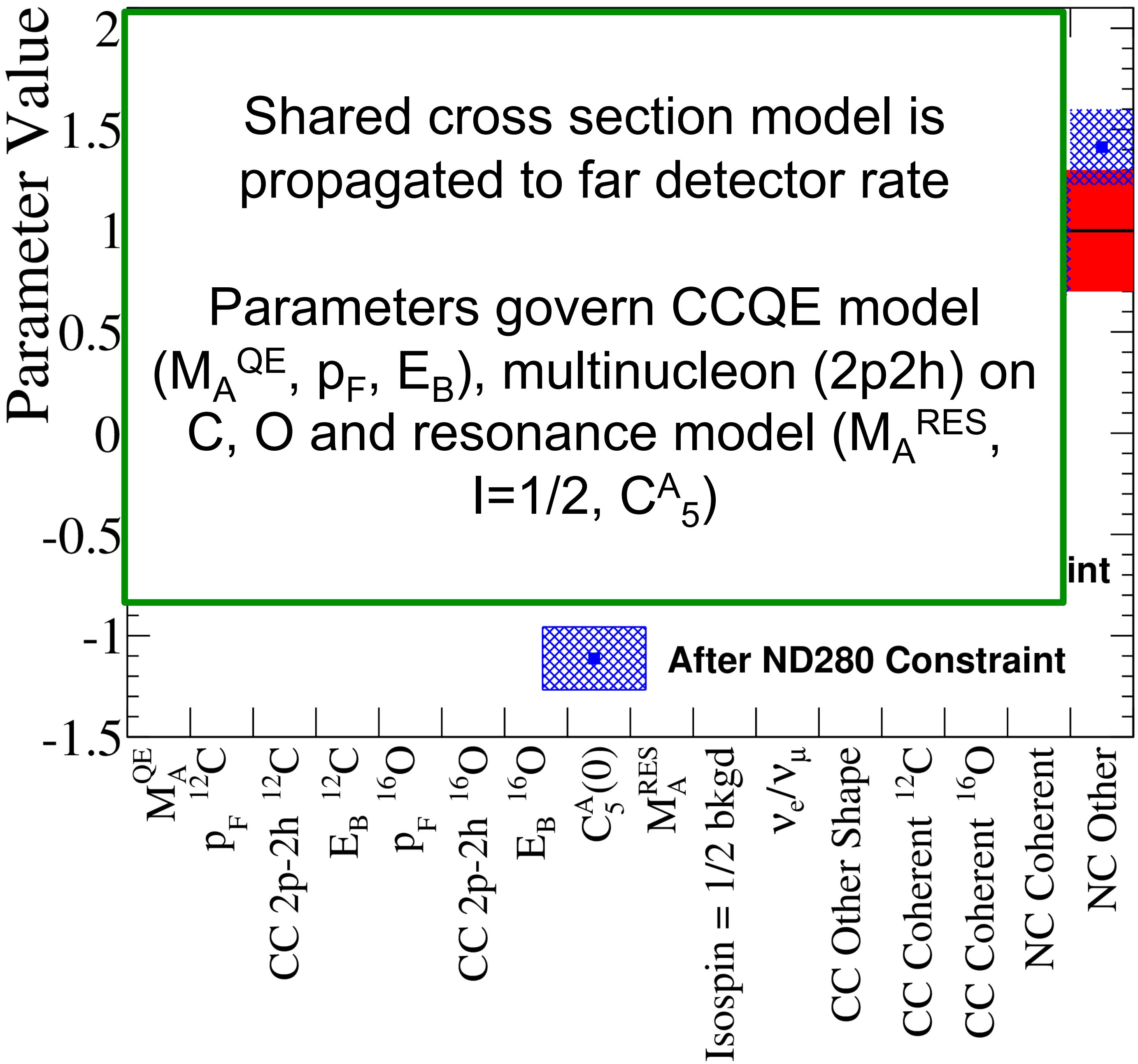


ND muon neutrino/antineutrino data constrains flux parameters

Muon neutrino/antineutrino flux correlates to electron neutrino/antineutrino flux

Increased flux preferred with new cross section model

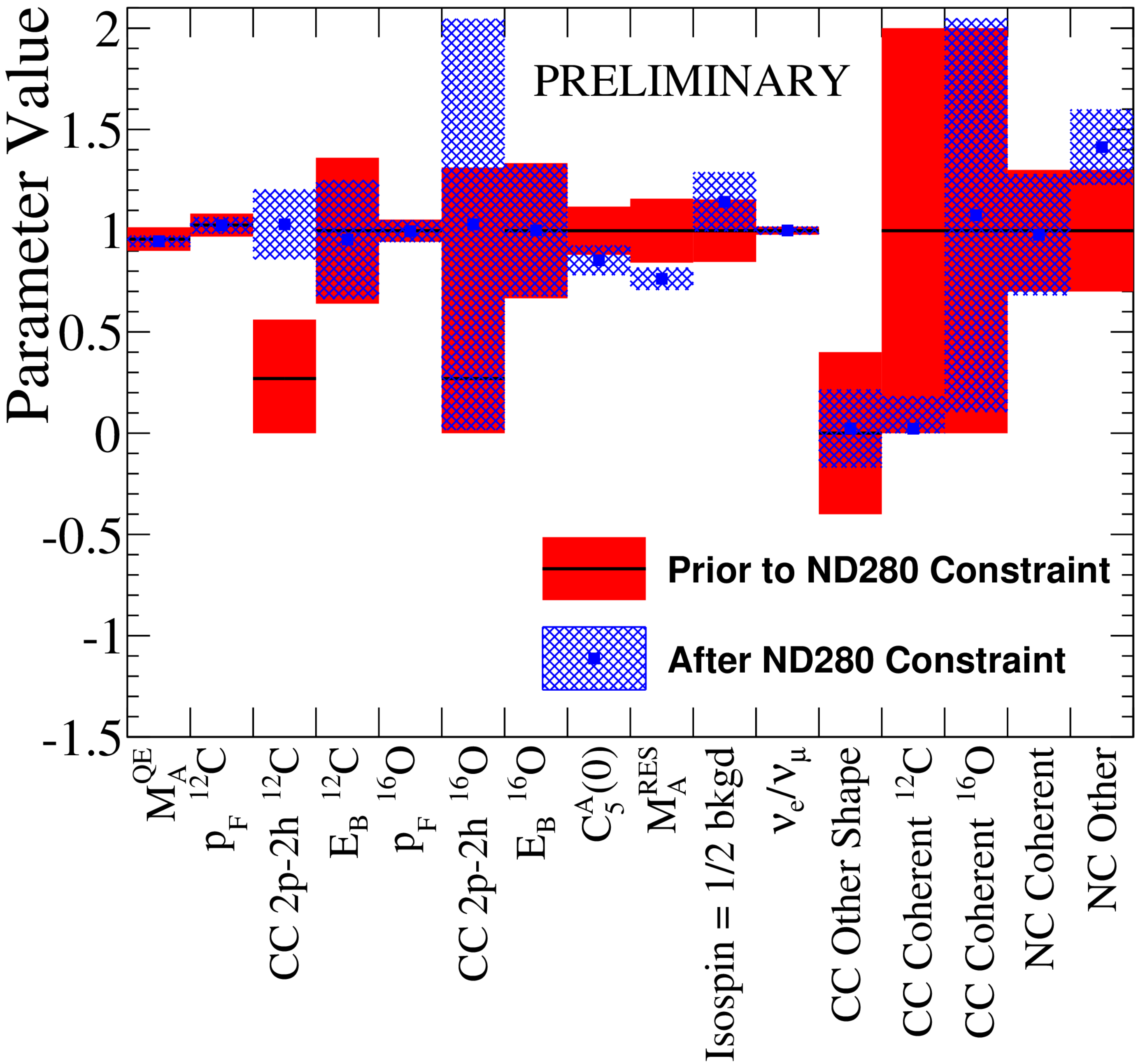
Cross section tuning from near detector fit



Shared cross section model is propagated to far detector rate

Parameters govern CCQE model (M_A^{QE}, p_F, E_B), multinucleon (2p2h) on C, O and resonance model (M_A^{RES}, I=1/2, C^A_5)

Cross section tuning from near detector fit



Some cross section parameters (2p2h on C, M_A^{RES}) changed significantly compared to external data prior

Off-axis near detector measurement

MICHIGAN STATE UNIVERSITY

Expected number of events at the far detector is tuned using a likelihood fit to the near detector samples; substantial reduction to overall uncertainty:

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

Fractional error on number-of-event prediction

Antineutrino oscillation analyses are statistics limited
Efforts to improve multinucleon oxygen uncertainty with FGD2 water samples and C-to-O A scaling studies

The Booster Neutrino Experiments (BooNEs)

MICHIGAN STATE UNIVERSITY

8 GeV/c protons from the Fermilab Booster strike a Be target

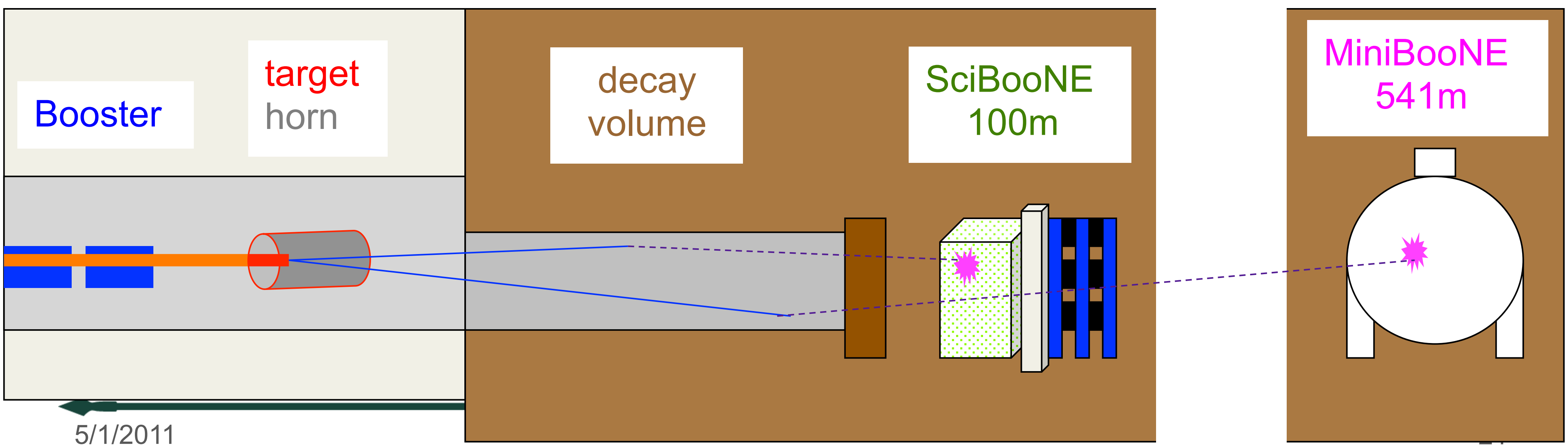
Pions and kaons are produced which decay to produce a neutrino beam

100m from the target are the SciBooNE detectors:

- 14,336 scintillator bar detector read out with WLS fibers attached to 64 channel MA-PMTs (SciBar)
- Lead and scintillator fiber electromagnetic calorimeter (EC)
- Iron and scintillator counter muon range detector (MRD)

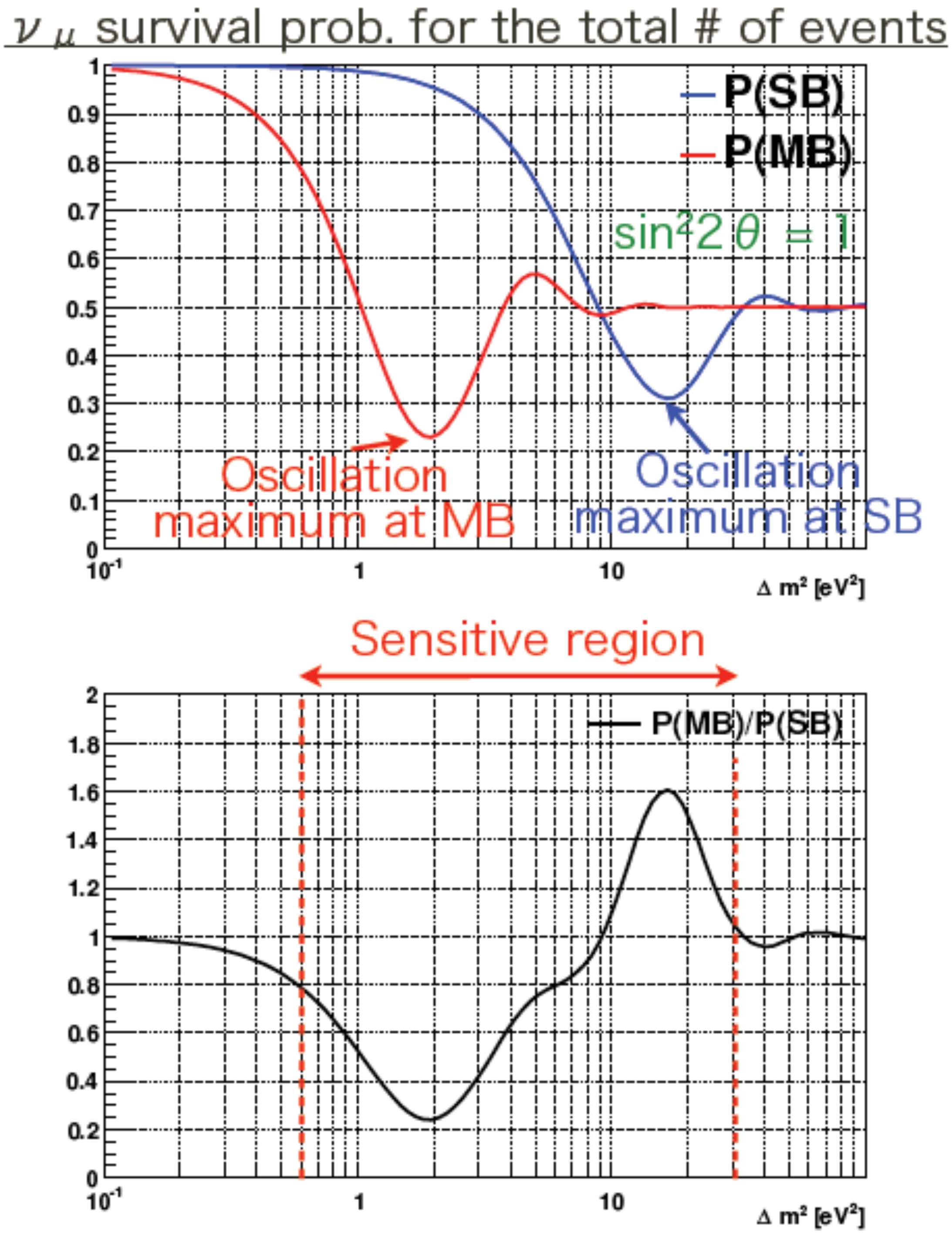
541m from the target is the MiniBooNE detector

- 1kton mineral oil Cherenkov detector
- 1240 inner PMTs, 240 veto PMTs



Short baseline oscillation: not just for far detectors

MICHIGAN STATE UNIVERSITY



Consider a 3+1 oscillation model:

$$P(\nu_\mu \to \nu_{x\neq\mu}) \cong \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

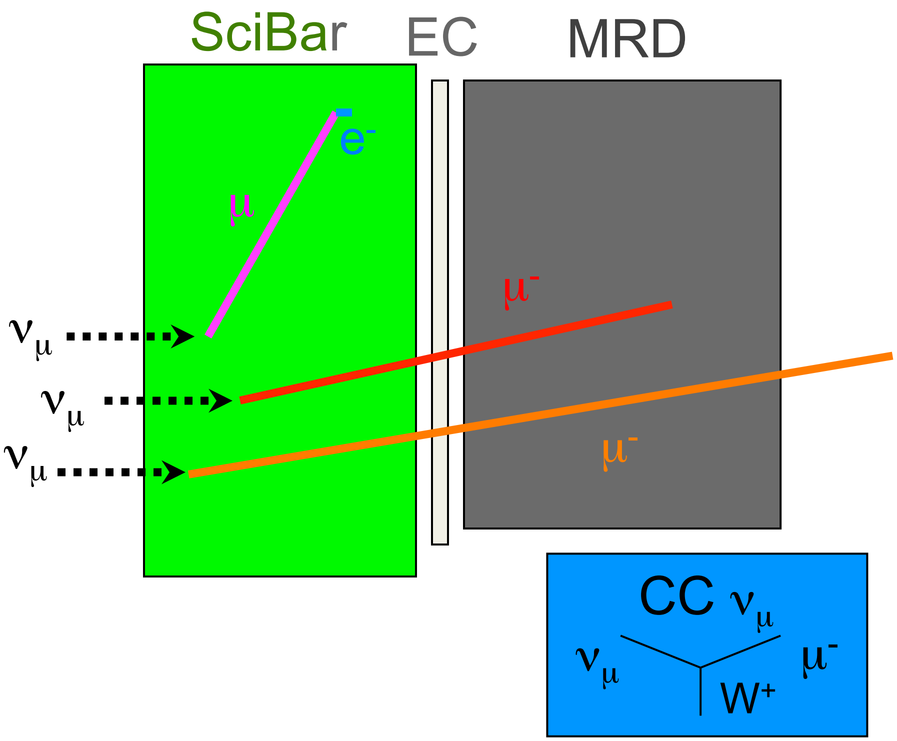
Below Δm^2~0.5 eV^2, ν_μ have not oscillated yet

At 0.5 < Δm^2 < 2 eV^2, events at MiniBooNE undergo oscillation

At 2 < Δm^2 < 30 eV^2, events at SciBooNE also undergo oscillation

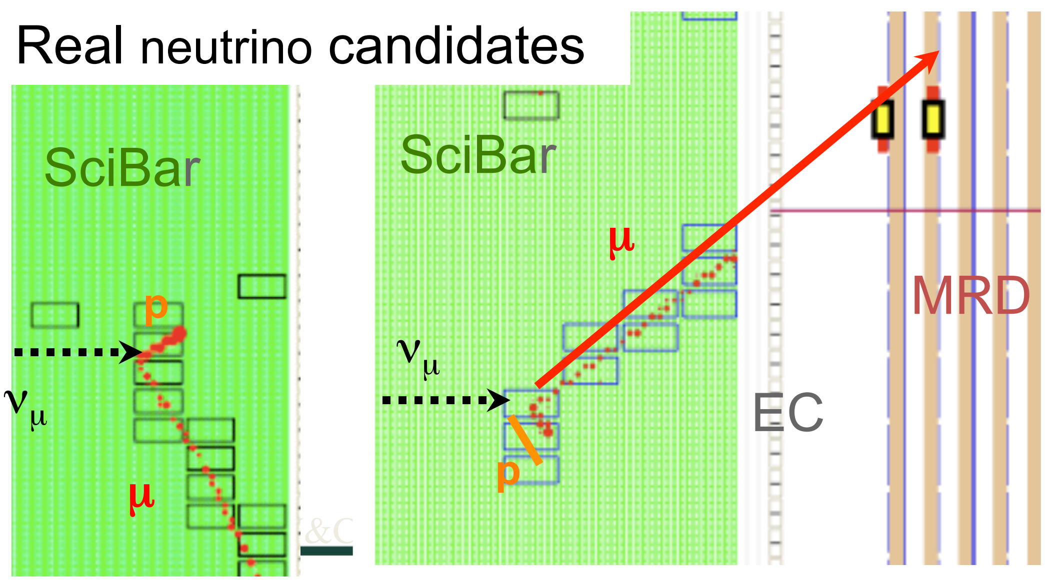
Above Δm^2~30 eV^2, oscillation is an overall normalization change, where MiniBooNE/SciBooNE are insensitive

Selecting CC ν_μ interactions in SciBooNE



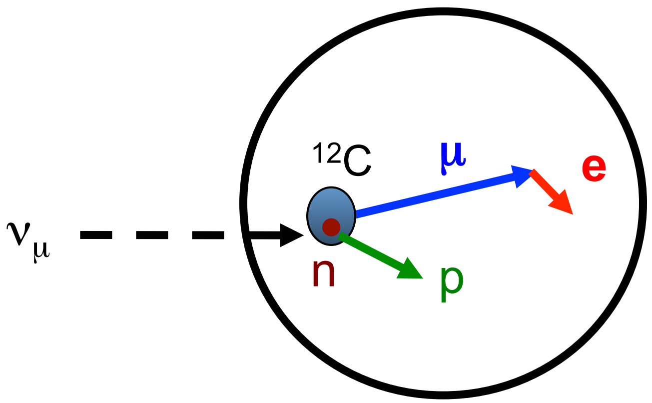
- Select events with the highest momentum track with a vertex in SciBar fiducial volume which pass data quality, beam timing cuts
- Events which also end in SciBar:
  "SciBar contained"
  Use energy loss in scintilator to select muon-like tracks
  p_μ>250 MeV/c reduces NC events

Real neutrino candidates



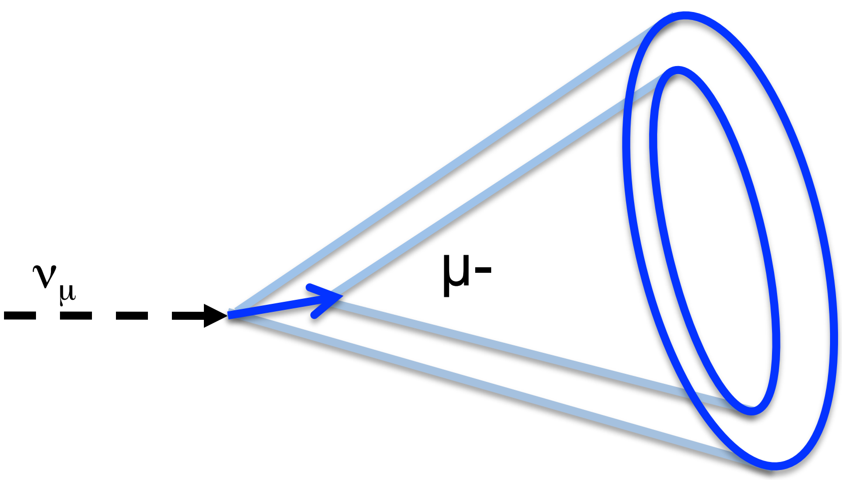
- Events which stop in the MRD:
  "MRD Stopped"
- Events which exit the end of the MRD:
  "MRD Penetrated"
  Angular information only

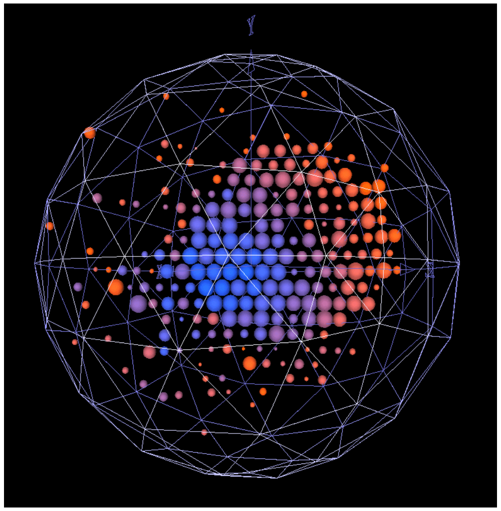
Selecting CCQE ν_μ interactions in MiniBooNE



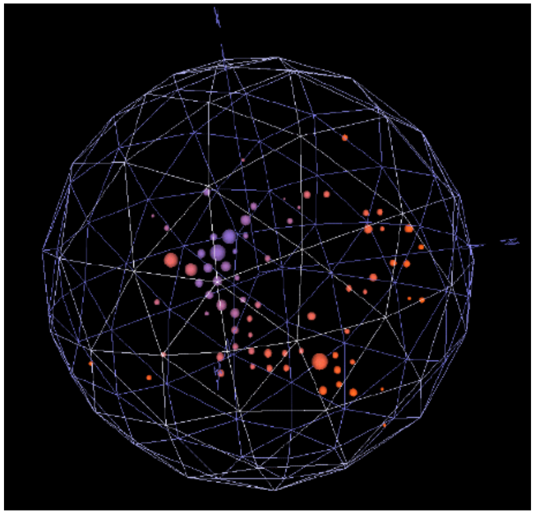
Tag single muon events and their decay electron

- Events produce Cherenkov light recorded by PMTs as hits (charge, time)
- Two sets of hits separated in time (μ, e)
- Minimal hits in the veto
- Require 1st set of hits above decay electron energy endpoint, 2nd set of hits below
- Endpoint of 1st track consistent with vertex of 2nd track
- Also require events within fiducial volume, beam timing and data quality selections





muon candidate



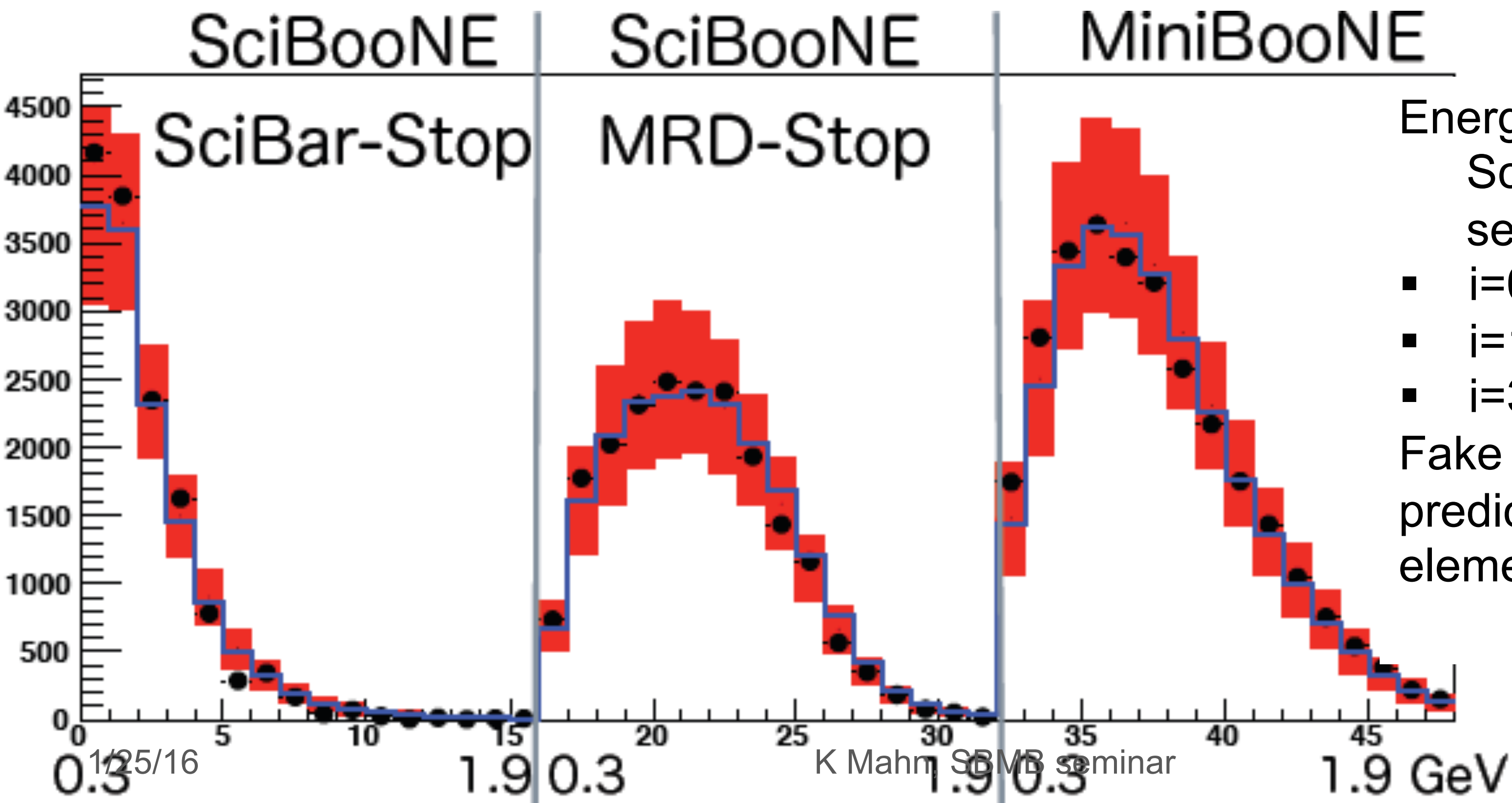
electron candidate

Simultaneous fit

Form a χ^2 to test if data d agrees with prediction p:

$$\chi^2 = \sum_{i,j=1}^{bins} (d_i - p_i) M_{ij}^{-1} (d_j - p_j)$$

- i,j are indices over reconstructed neutrino energy bins
- 3+1 oscillation (Δm^2,$\sin^2 2\theta$) included in prediction p
- Systematic (and statistical) uncertainties in M_{ij} matrix, preserves correlations between energy bin i and j



Energy bins can range over SciBooNE, MiniBooNE selected event samples:

- i=0-15 SciBar stopped
- i=16-31 MRD stopped
- i=32-47 MiniBooNE

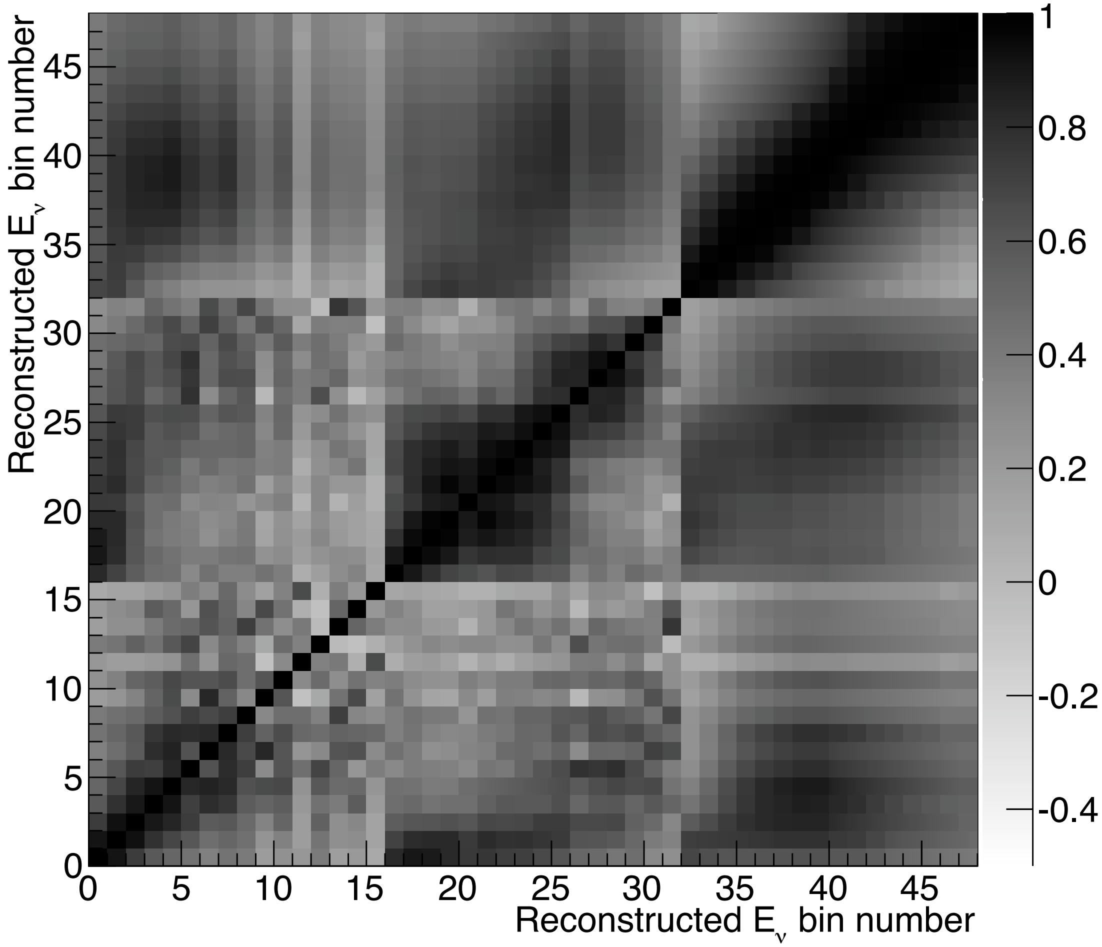
Fake data shown with prediction and diagonal elements of M_{ij}

(MB scaled by 1/7)

Correlations between SciBooNE, MiniBooNE

Systematic (and statistical) uncertainties in M_{ij} matrix

- M_{ij} is the sum of each individual systematic error matrix, e.g:
  M_{ij}(total) = M_{ij} (flux) + M_{ij}(cross section) + M_{ij}(detector)
- 48x48 error matrix (i=0-15 SciBar stopped, 16-31 MRD stopped, 32-47 MiniBooNE

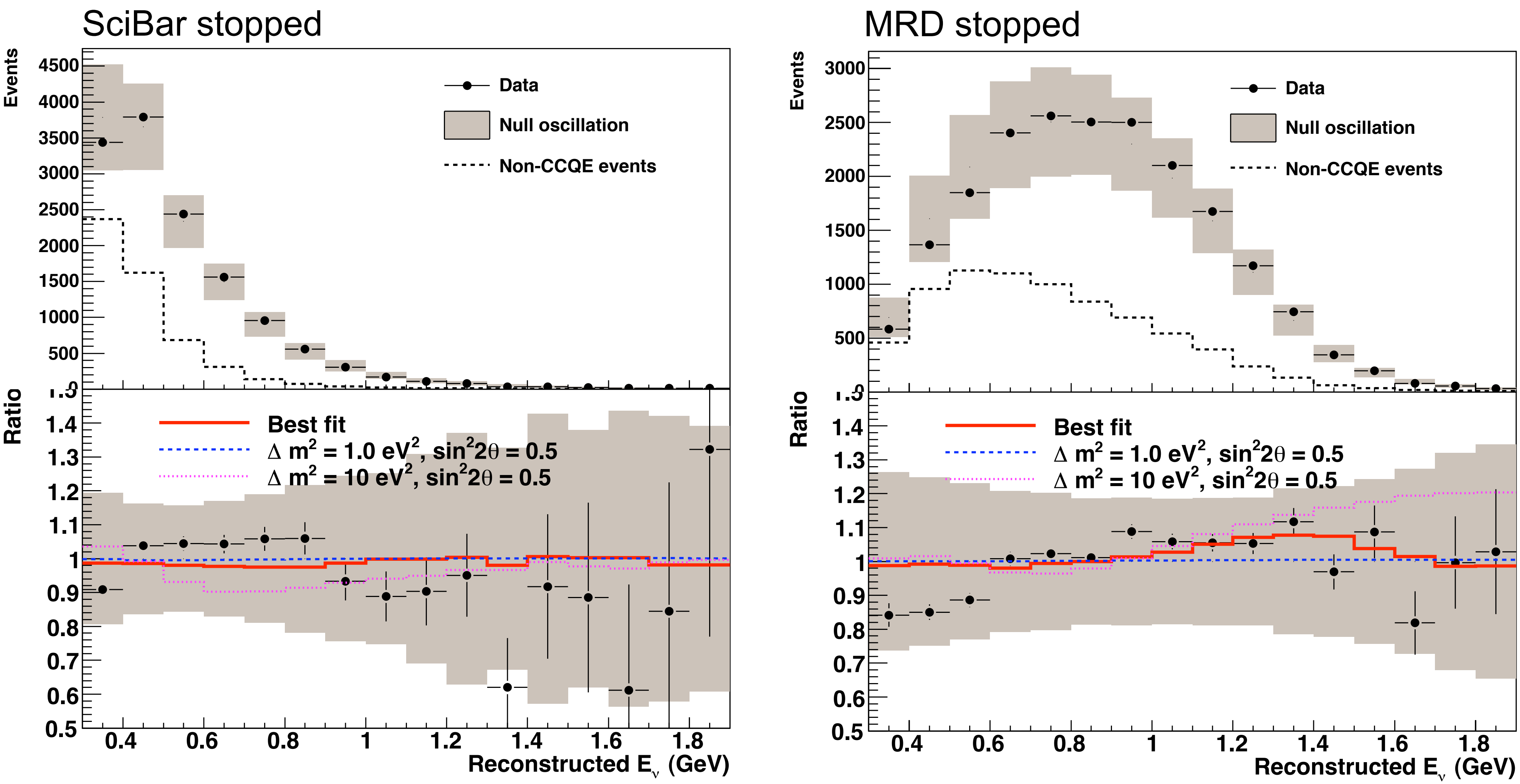


Fit leverages correlations between SciBooNE energy bins to constrain event rate in MiniBooNE bins

- Correlation matrix
  $\rho_{ij} = M_{ij}/\mathrm{sqrt}(M_{ii}\ M_{jj})$ shown
- Uncorrelated uncertainties (different acceptance, detector uncertainties, statistics) degrade this constraint

SciBooNE CC ν_μ data set

MICHIGAN STATE UNIVERSITY



First, test agreement of SciBooNE datasets

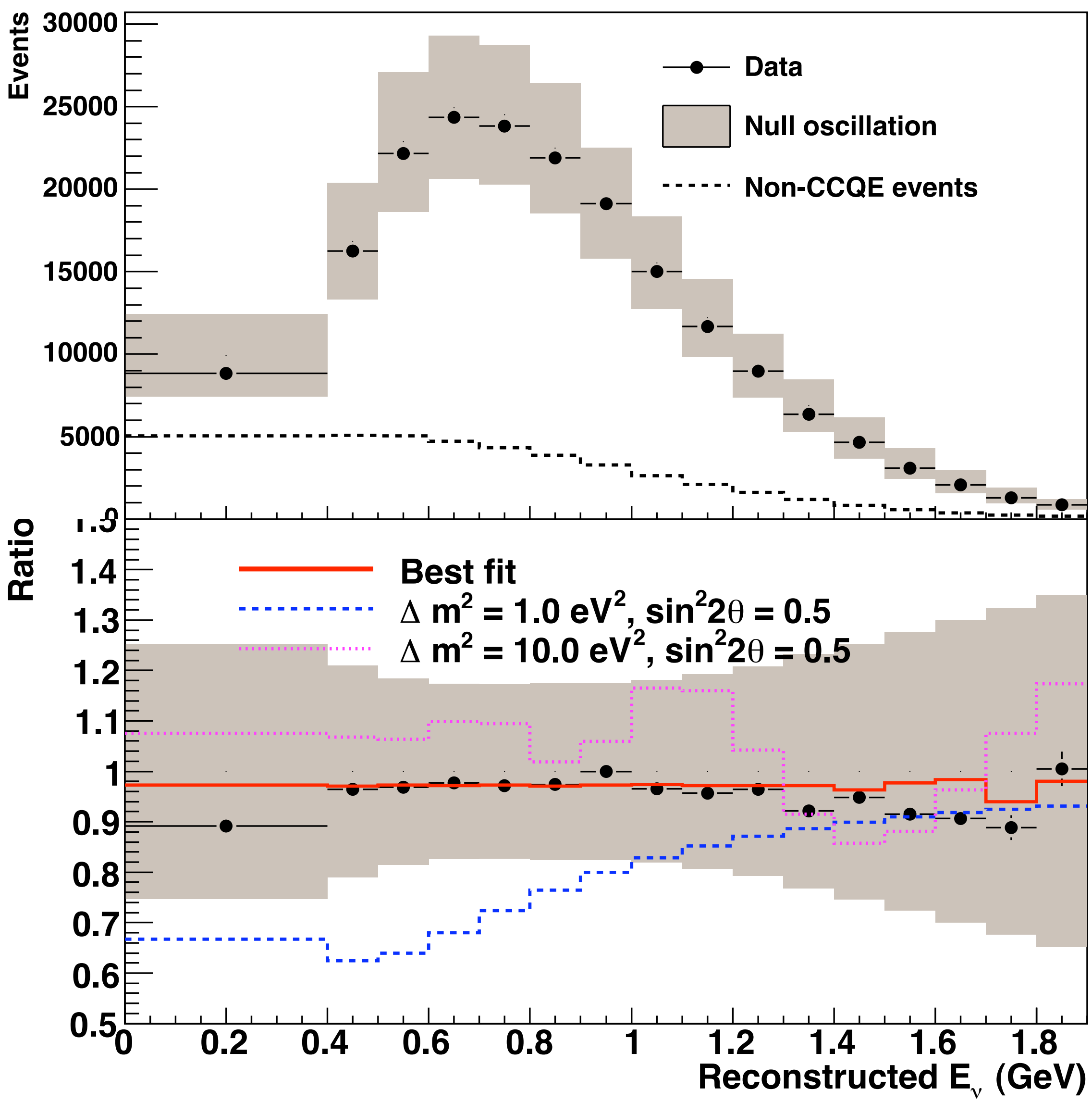
Above $\Delta m^2 > 2$ eV², oscillation is possible at SciBooNE

No evidence for oscillation at SciBooNE

Uncertainties include neutrino flux, cross section and detector uncertainties

MiniBooNE CCQE ν_μ data set

MiniBooNE CCQE ν_μ data set
+ prediction (no oscillation)



Fit 16+16+16 bins in total = 48

χ^2 (null) = 45.1/ 48 (DOF)
χ^2 (best) = 39.5/ 46 (DOF)
At Δm^2 = 43.7 eV^2, $\sin^2 2\theta$ = 0.60

$\Delta\chi^2 = \chi^2(\text{null}) - \chi^2(\text{best})$ = 5.6

$\Delta\chi^2$ (90% CL, null) = 9.3

Feldman Cousins frequentist technique used to determine $\Delta\chi^2$ statistic

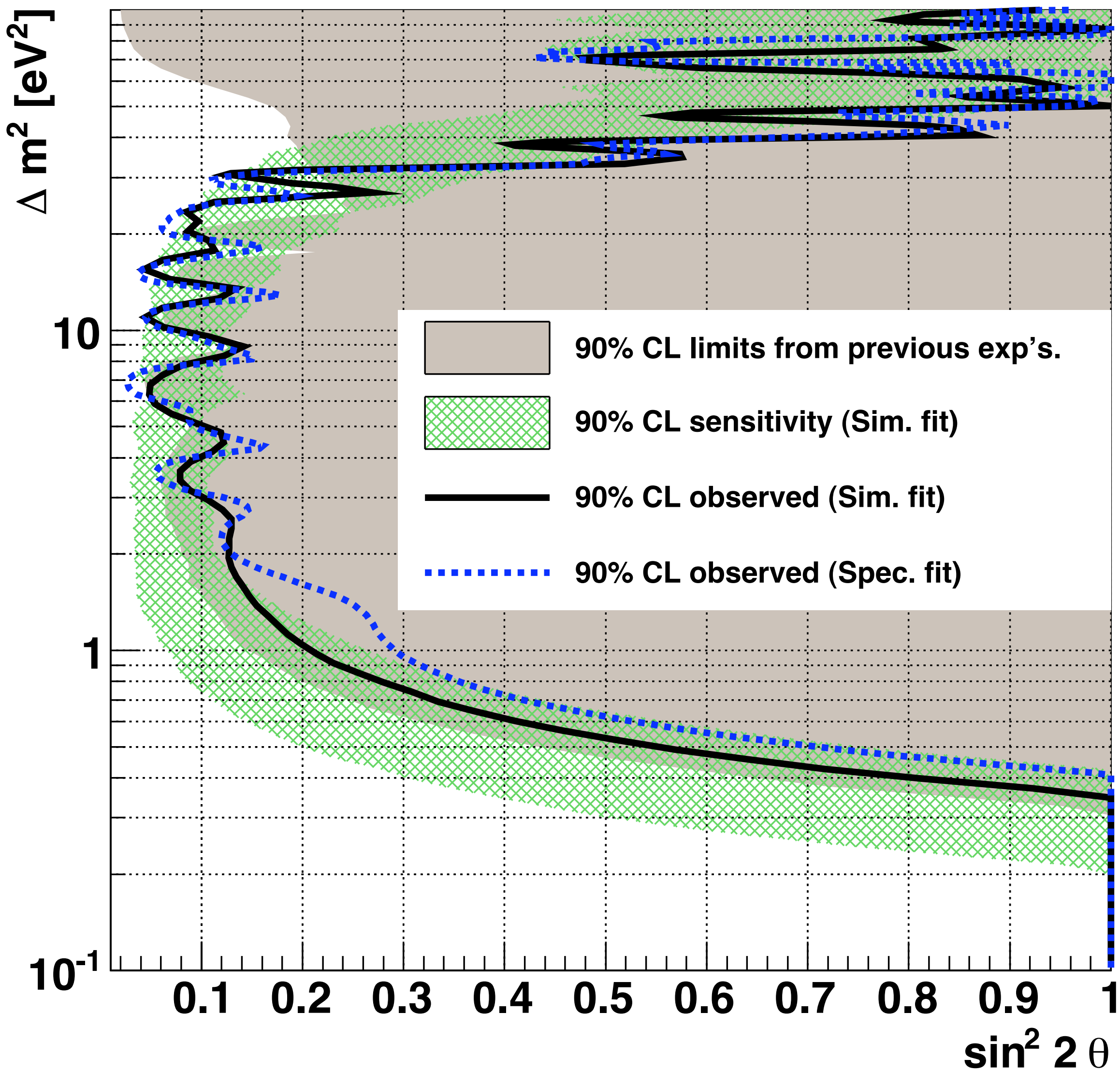
Results of SBL disappearance fit

Limits for simultaneous fit (black) and spectrum fit (blue)

Green hatched region indicates 68% of 90%CL limits to fake data with no underlying oscillation

Average of these limits is sensitivity, comperable for simultaneous and alternate, spectrum fit methods

Largest uncertainty is MiniBooNE detector systematics



No disappearance at 90% CL observed for either method

The joys and challenges of near detectors

MICHIGAN STATE UNIVERSITY

Off-axis near detector data is used in T2K oscillation analyses to constrain parameters associated to the flux, cross section model

- Total uncertainty on far detector muon antineutrino candidates reduced from 14% to 11%. Previous analyses had reductions of 2-3 in systematic uncertainties, similar to SciBooNE/MiniBooNE joint analysis

T2K on-axis detectors, priors on flux and cross section models, are crucial:

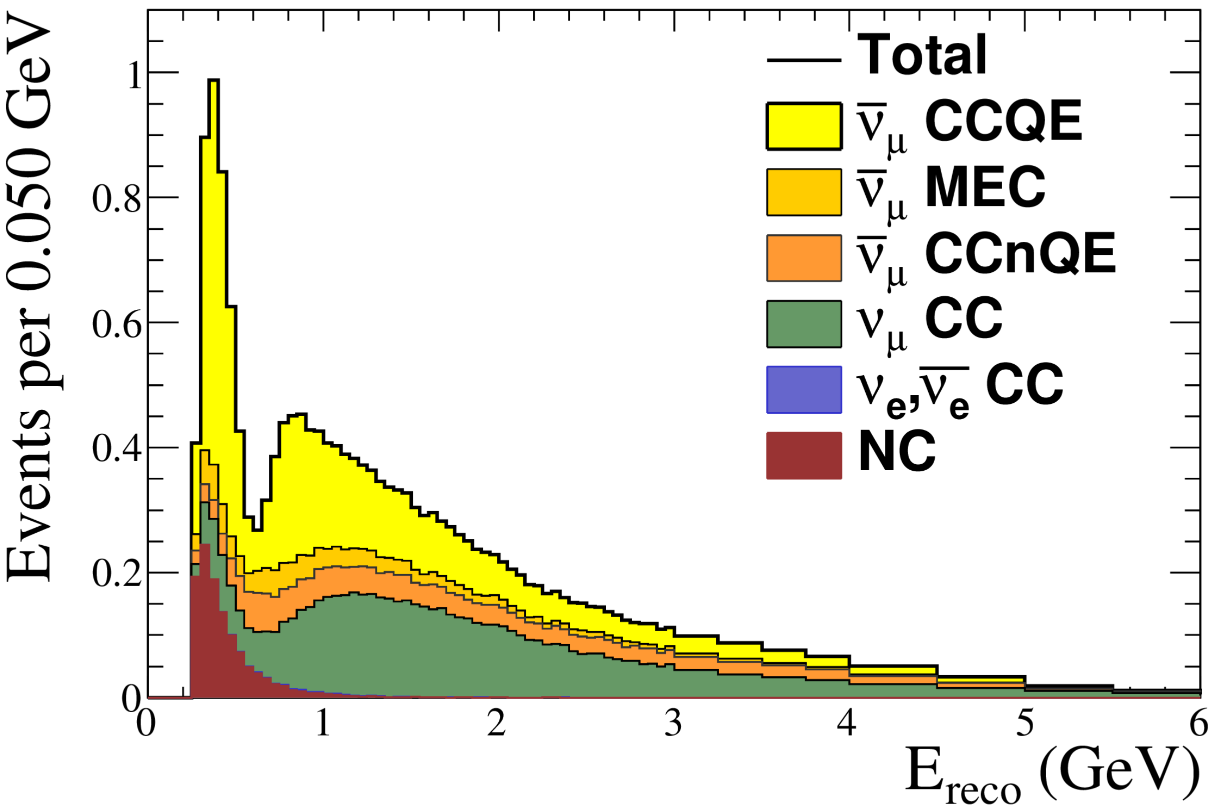
- Monitoring of beam stability, off-axis angle variations with neutrino datasets
- Necessary to develop a suitable parameterization and extrapolation, with correct physical basis for neutrino, antineutrino mode correlations
- Be careful of significant uncertainties (ν_e/ν_μ cross section, multinucleon oxygen uncertainty) which may not be constrained by current T2K ND data sets
    - It's only as good as the model you put in!

Additional lessons from SciBooNE+MiniBooNE:

- Oscillation at SciBooNE reduces the power of the constraint
- Non-cancelling uncertainties from detector, but also acceptance, out of FV backgrounds

Backup slides

Disappearance prediction, event rate



Predominantly antineutrino interactions, but significant components from other channels

- Expect 34.6 (103.6) events with (without) oscillation

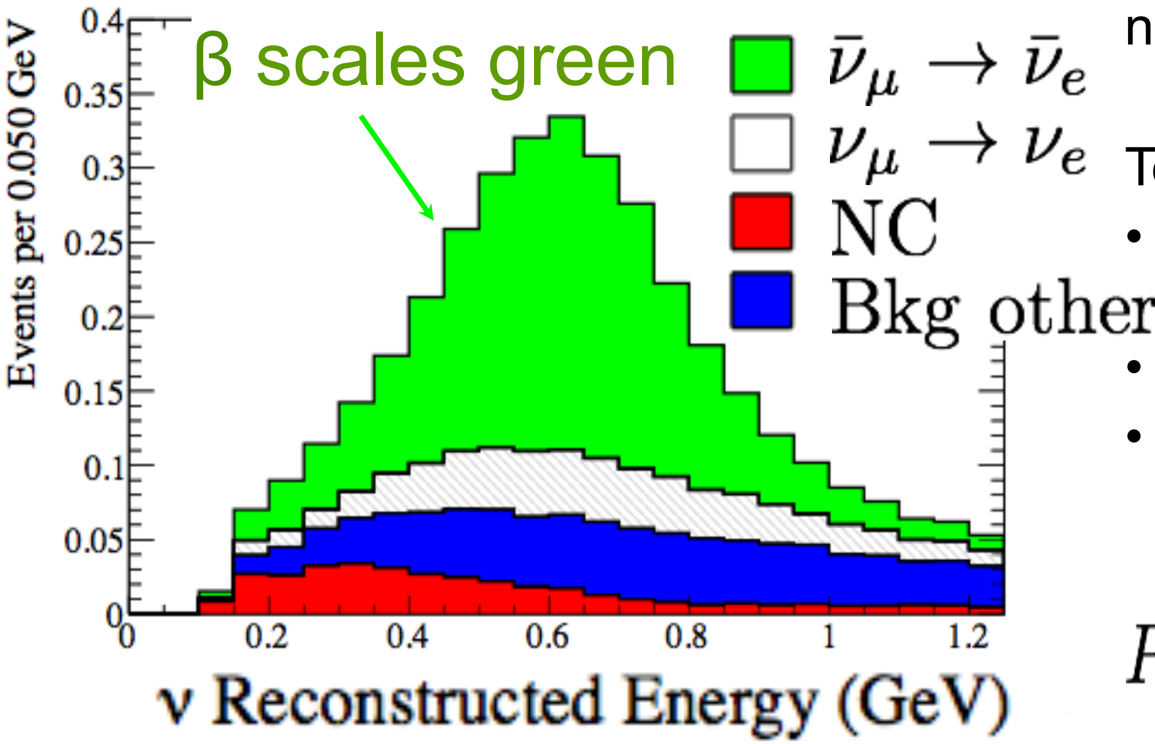
	$\nu_\mu \to \nu_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$
CCQE	6.870	13.258	0.004	0.005	0.007	0.017
MEC	1.578	2.347	0.001	0.001	0.001	0.003
CC1π	2.414	3.046	0.003	0.002	0.003	0.003
CC coherent	0.167	0.696	0.000	0.000	0.000	0.002
CC other	1.222	0.880	0.001	0.000	0.000	0.000
NC1π	0.391	0.428	0.016	0.012	-	-
NC other	0.707	0.420	0.035	0.017	-	-
subtotal	13.349	21.076	0.059	0.038	0.011	0.025
total			34.559			

Antineutrino appearance analysis

MICHIGAN STATE UNIVERSITY

	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288	2.481	3.254	3.939
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389	0.531	0.423	0.341
Bkg NC	0.349	0.349	0.349	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826	0.821	0.821	0.821
Total	3.729	4.315	4.851	4.181	4.848	5.450

Normal hierarchy (columns 2–4) — Inverted hierarchy (columns 5–7)



Expect 3.73 (4.18) events based on normal (inverted) hierarchy

Test of no $\bar{\nu}_e$ appearance hypothesis:

- Significant expected contribution from ν_e appearance
- β=0: no $\bar{\nu}_e$ appearance
- β=1: $\bar{\nu}_e$ appearance

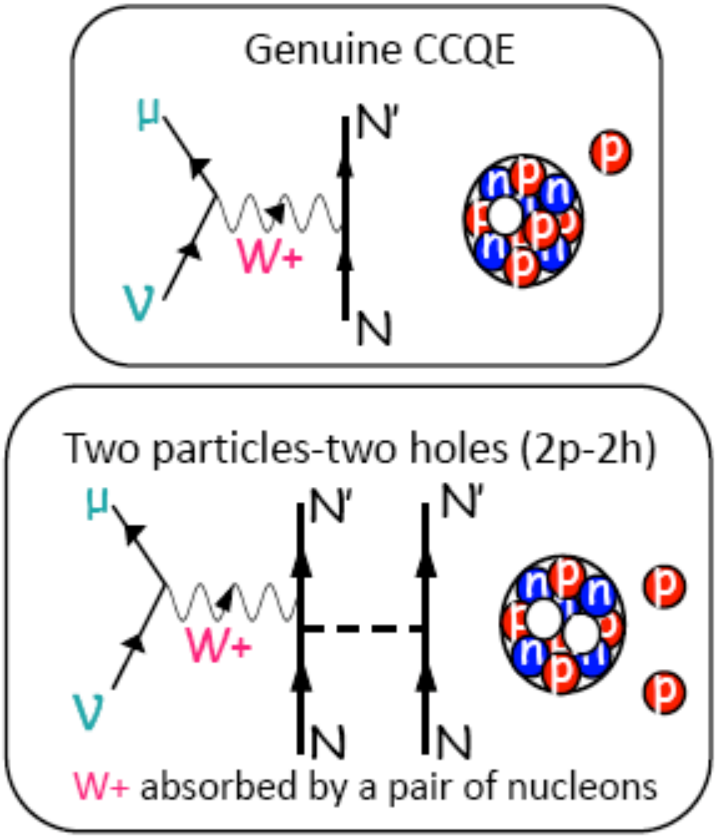
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\bar{\nu}_\mu \to \bar{\nu}_e)$$

Future systematics: cross section model

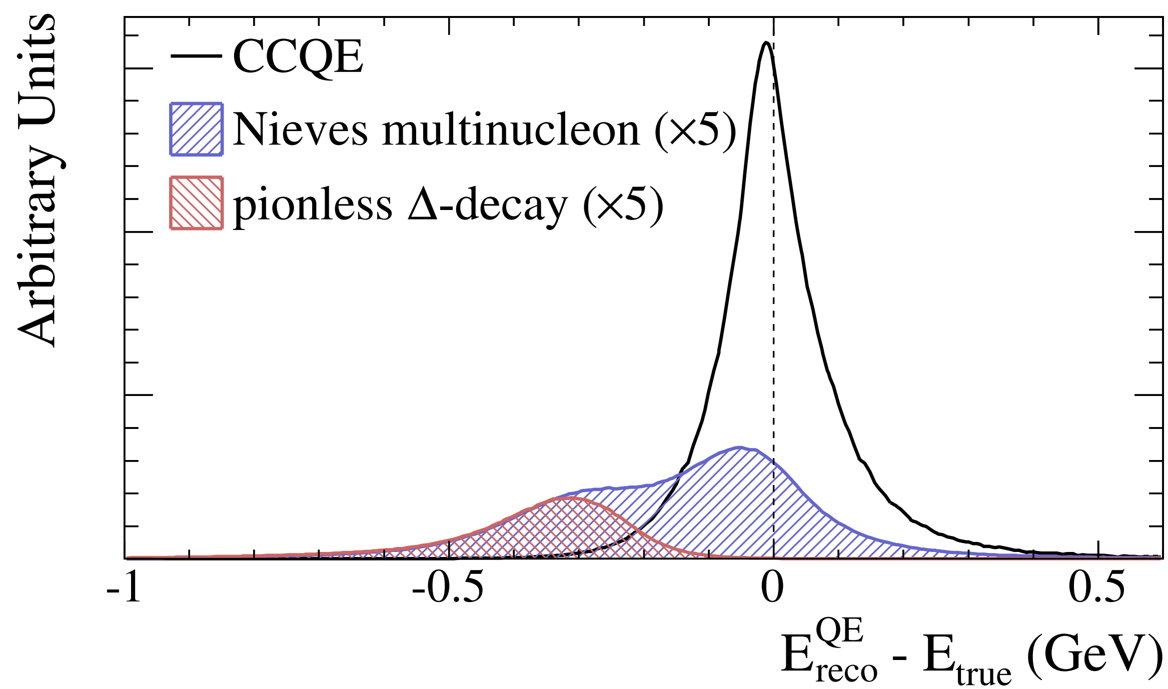
MICHIGAN STATE UNIVERSITY

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

- CCQE interaction simulated as interaction on a single nucleon (1p1h)
- Two models simulate interaction on correlated pair of nucleons (2p2h)
- 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)



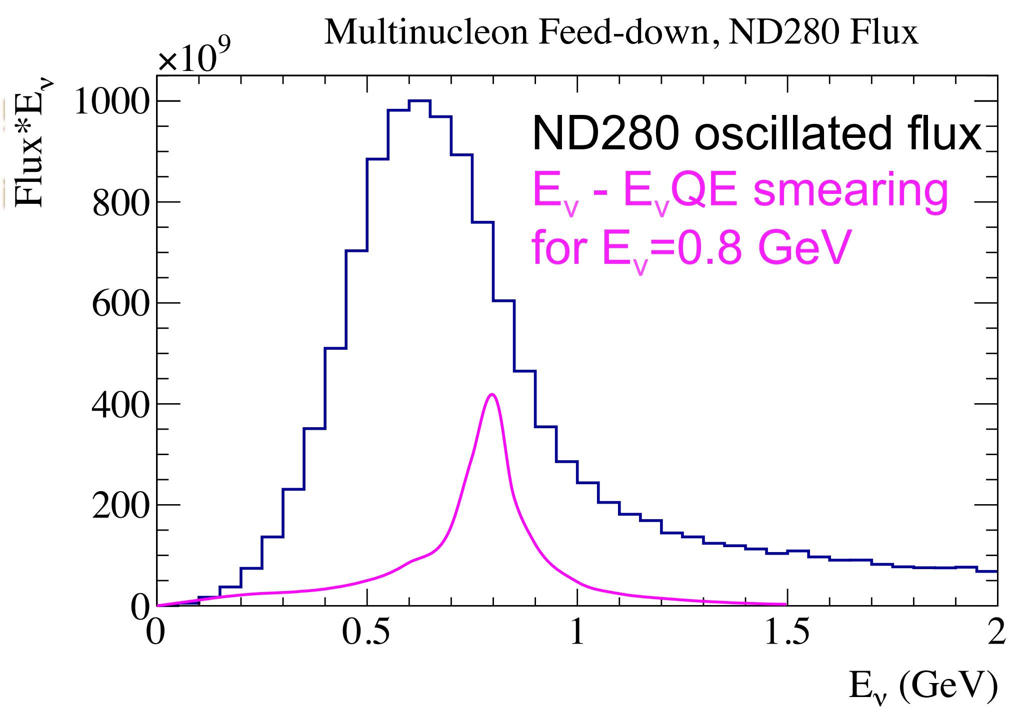
Picture by M. Martini

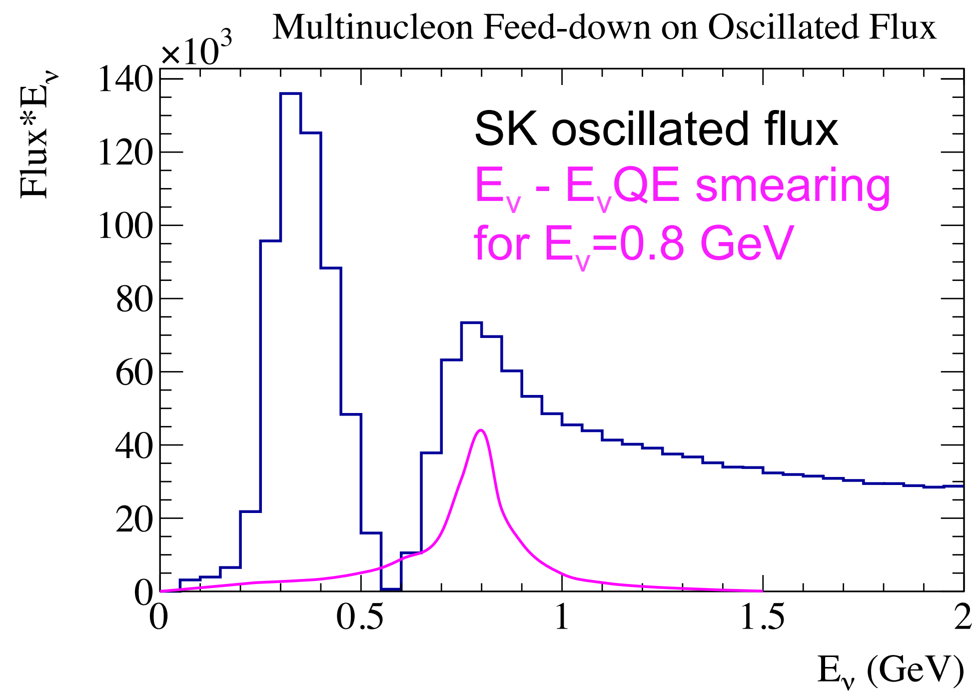


T2K collab PRL 112, 181801 (2014)

Future systematics: cross section model

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





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

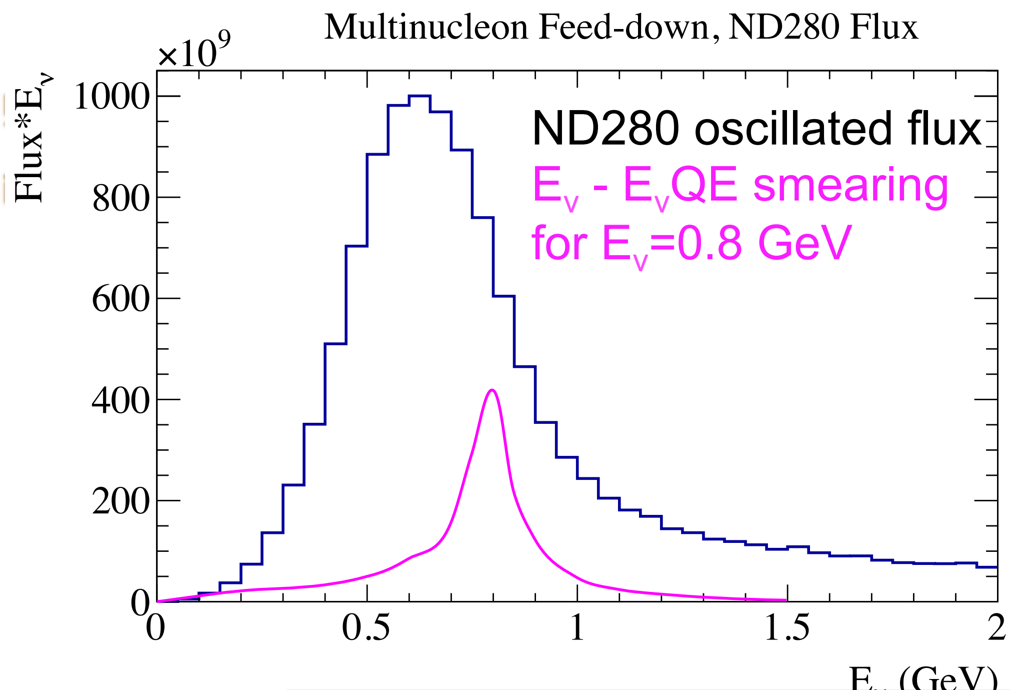
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

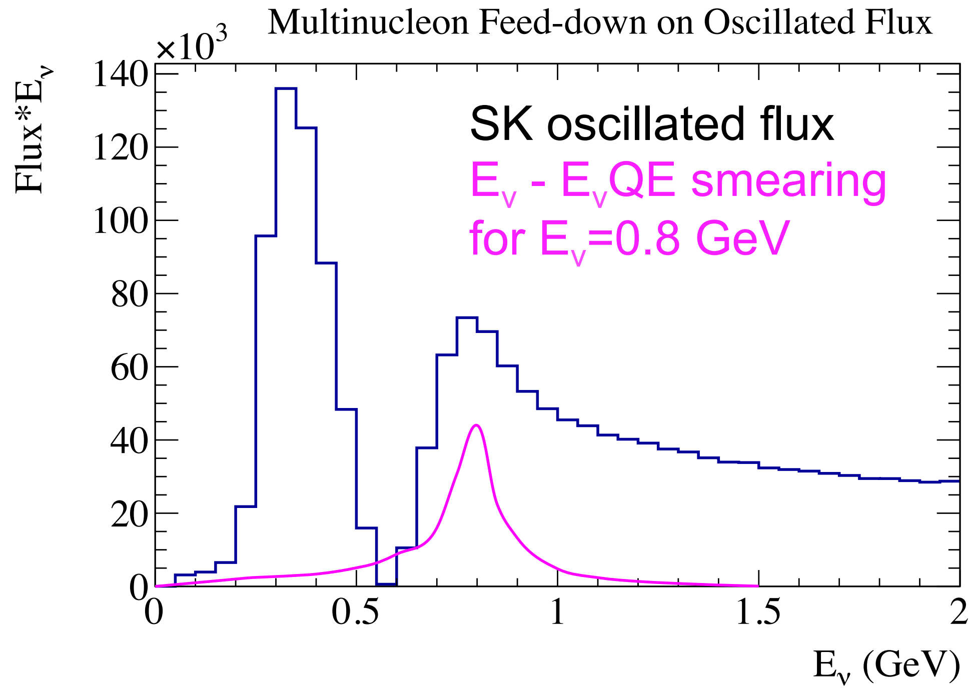
Overall increase to cross section cancels in extrapolation, but any shifts between true to reconstructed E feed down into oscillation dip and are ~degenerate with θ_{23} measurement

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

Future systematics: cross section model

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





$FD(\nu$ ... $n'_n E_\mu$

$ND(\nu$ ... $s\,\theta_\mu)$

Overall inc ... een true to reconstr ... measurem ...

- Similar ... in nucleus ...

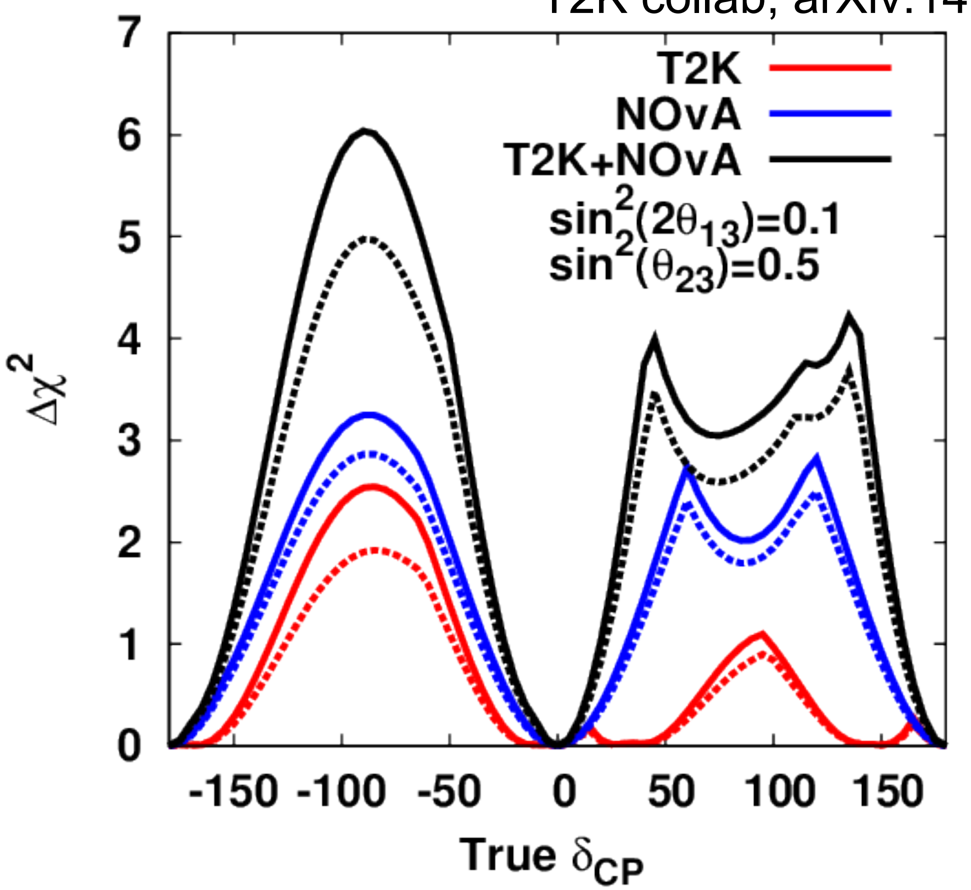
This effect still occurs even if the near and far detectors are the same technology

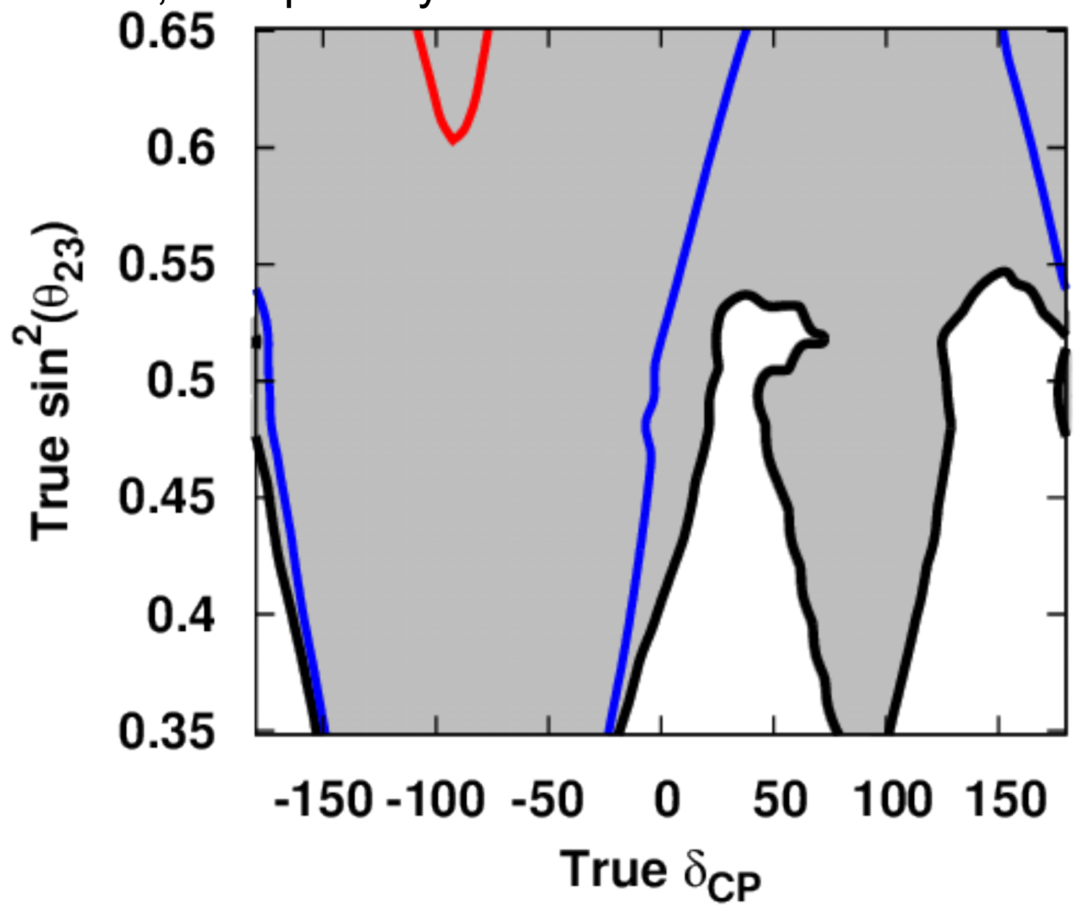
Critical to understand differences between neutrino and antineutrino due to 2p2h/MEC for future measurements

Future of T2K and mass hierarchy

MICHIGAN STATE UNIVERSITY

T2K collab, arXiv:1409.7469, accepted by PTEP





NOvA's higher energy (peak E_ν~2 GeV) and longer baseline (L~810km) has a different dependence on mass hierarchy (MH) through the matter effect

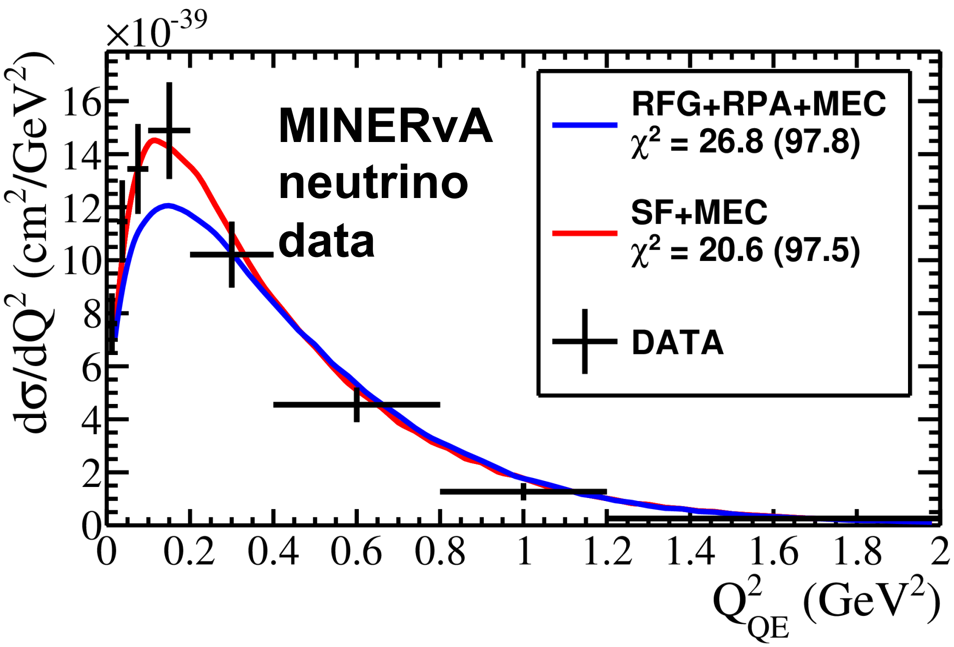
- Gray regions are where the mass hierarchy can be determined to 90% CL for T2K(red), NOvA (blue), and T2K+NOvA (black)

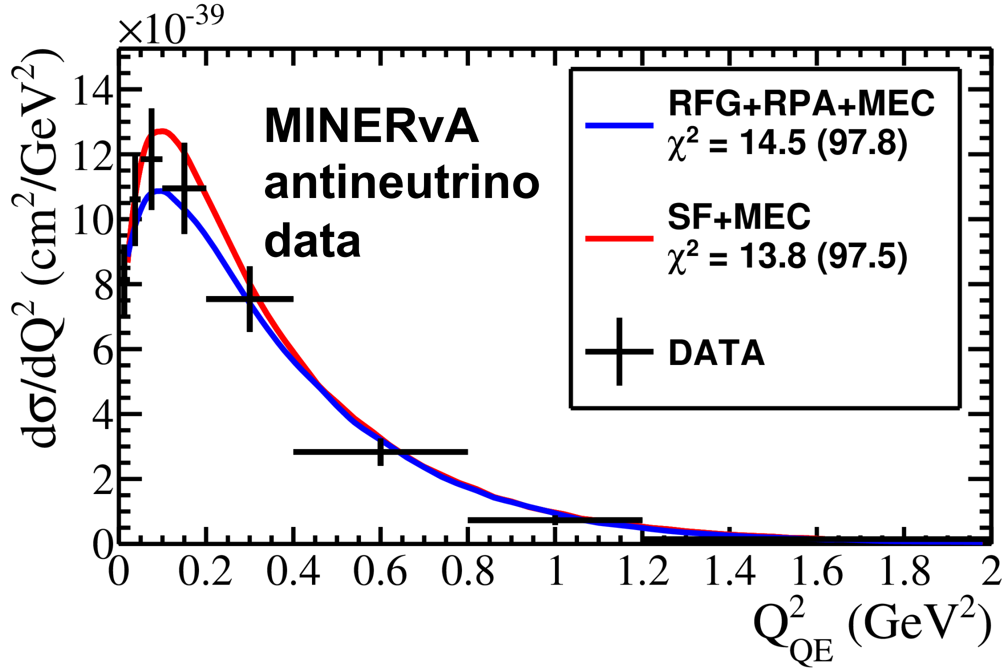
Determination of MH depends on θ_{23}

External data fits

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

- Neutrino and antineutrino datasets fit to determine RPA correction choice and uncertainties on MAQE

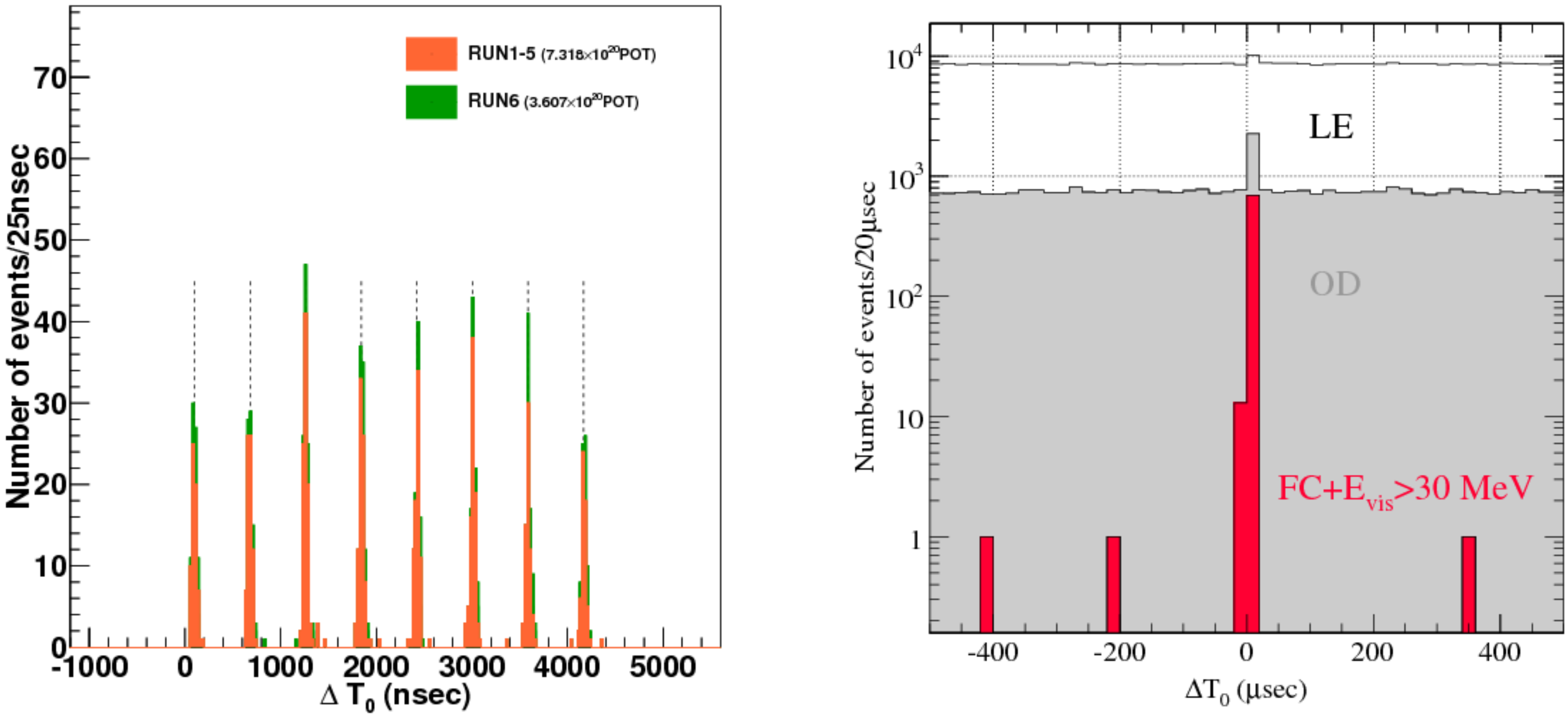




Hope was that Nieves et al model would resolve high MAQE for MiniBooNE. Instead:

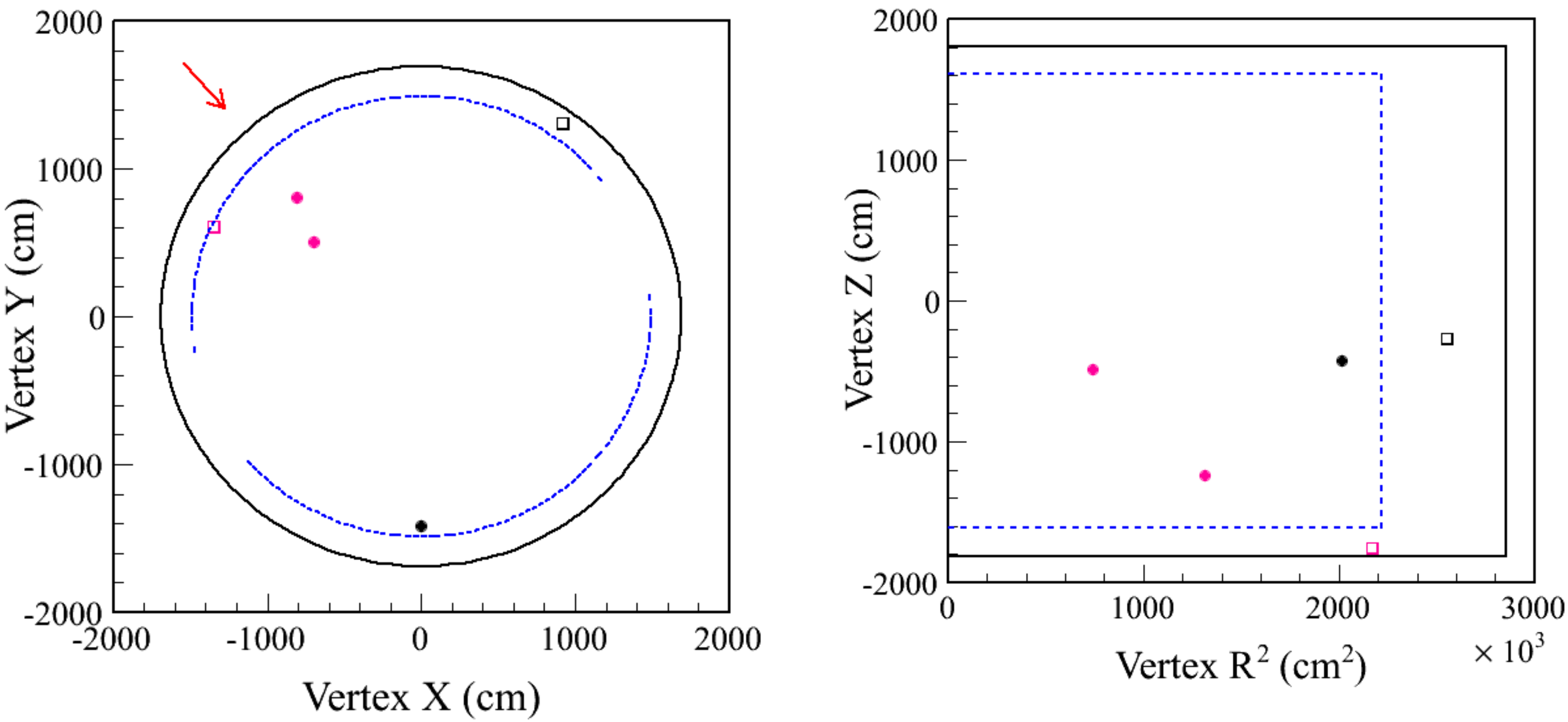
- Forward scattering region for MiniBooNE neutrino model doesn't fit well
- Low Q2 MINERvA nu/nubar disfavors Nieves RPA, suppresses MEC
- MINERvA data are 20% lower than MiniBooNE.
- For now: uncertainties inflated to cover disagreement between datasets
- Next: improve inputs: covariance from MiniBooNE, revisit model parameterization

Beam timing of events at SK



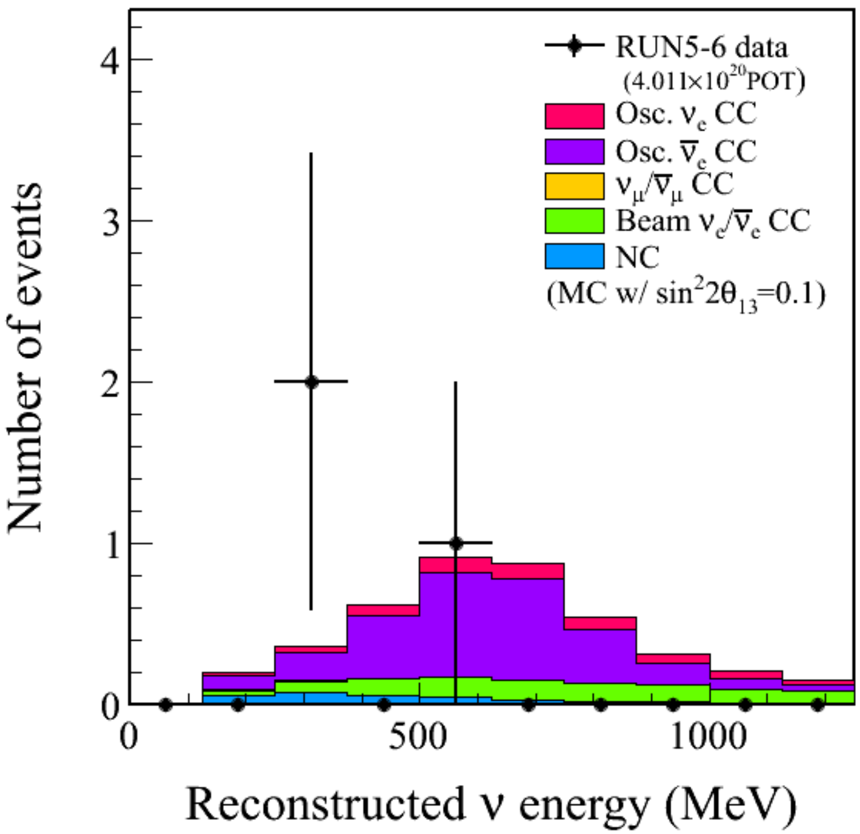
dT0 distribution of all the FC events (zoomed into the spill on-timing window) observed during Run1-5 (orange) and Run6 (green). The eight dotted vertical lines represent the 581 nsec-interval bunch center positions fitted to the observed FC event times albeit with their spacing preserved. The two histograms are stacked.

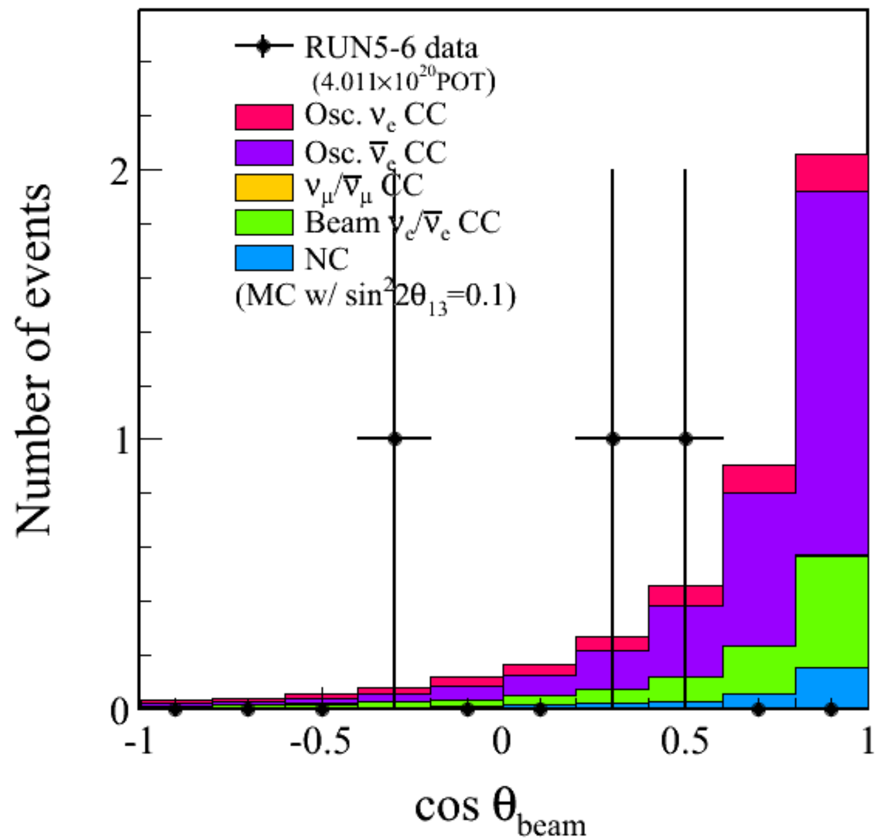
Antielectron neutrino candidates distributions



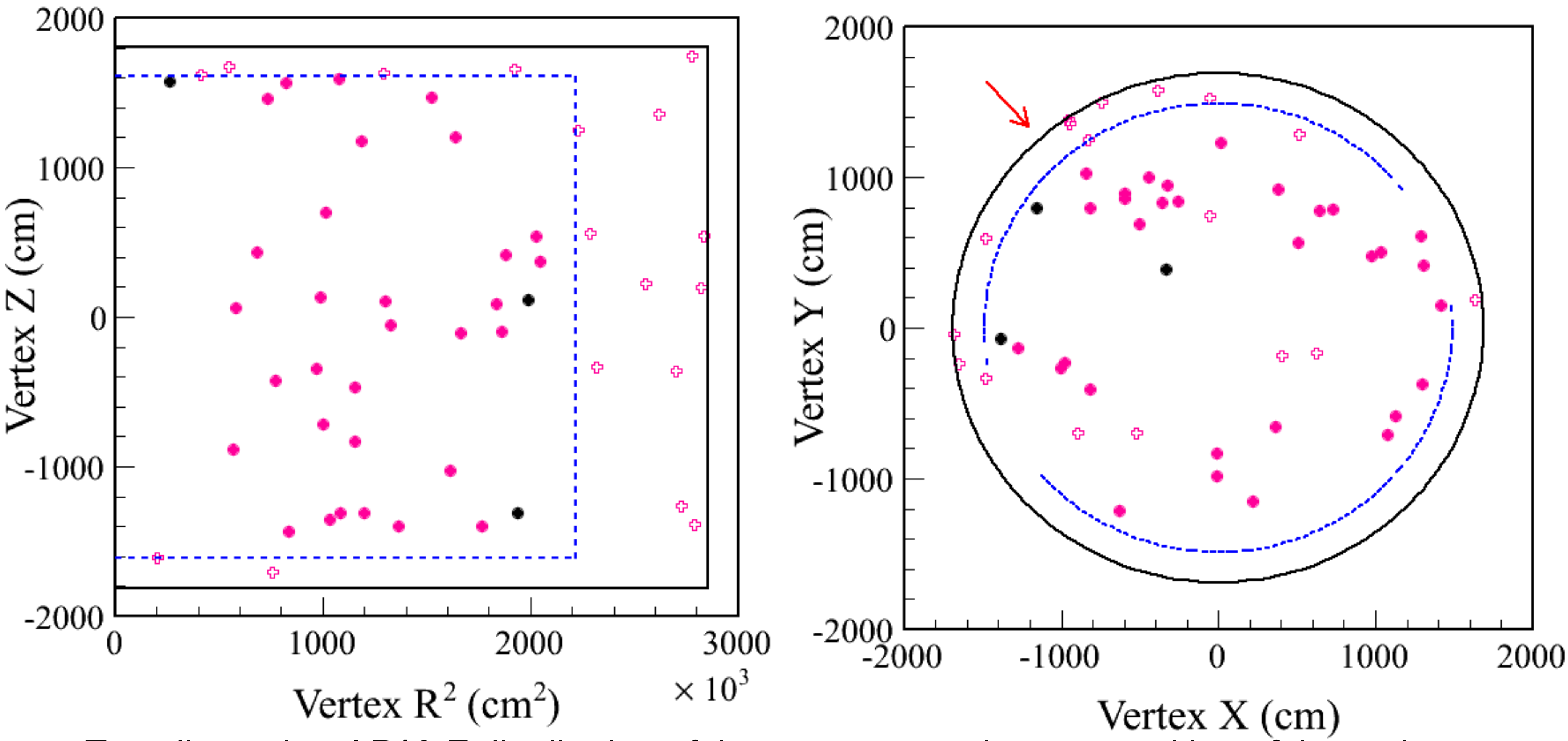
Two-dimensional R^2-Z distribution of the reconstructed vertex position of the anti-nue candidate events. Dashed blue line indicates the fiducial volume boundary. Black markers are events observed during RUN5, and pink markers are events from RUN6. Hollow crosses represent events passing the anti-numu selection cuts other than the fiducial volume cut.

Antielectron neutrino candidates distributions



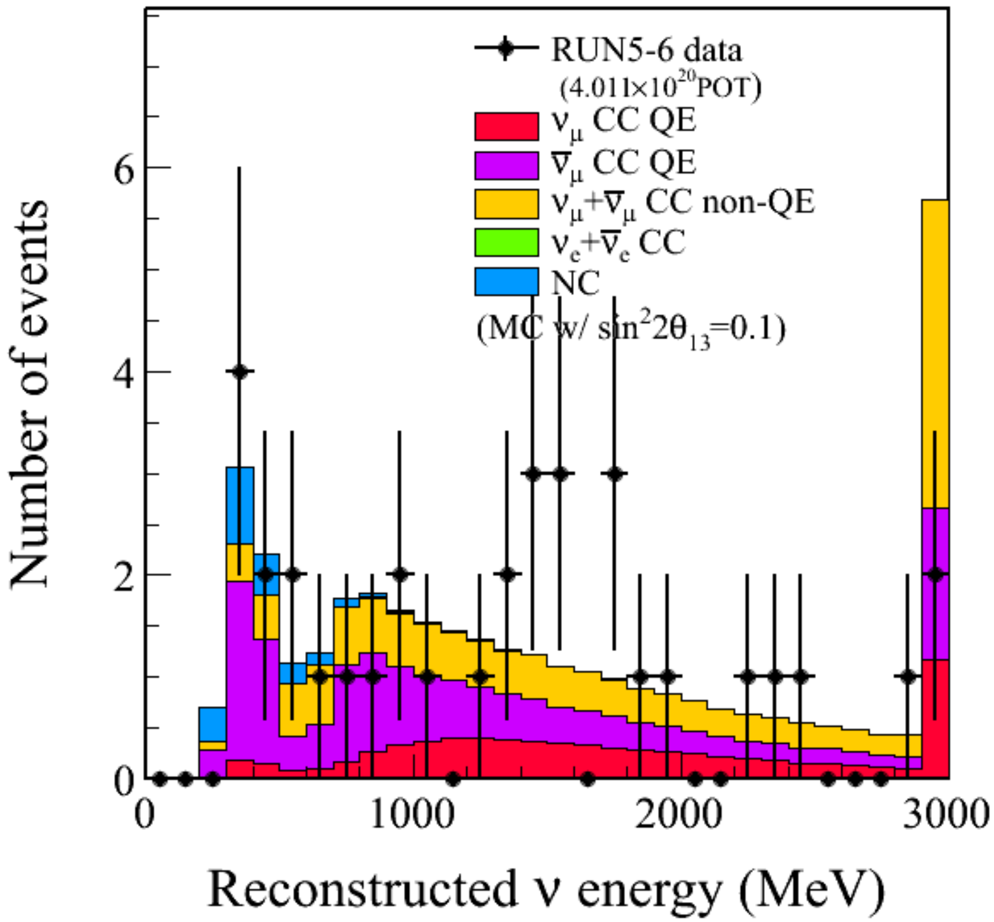


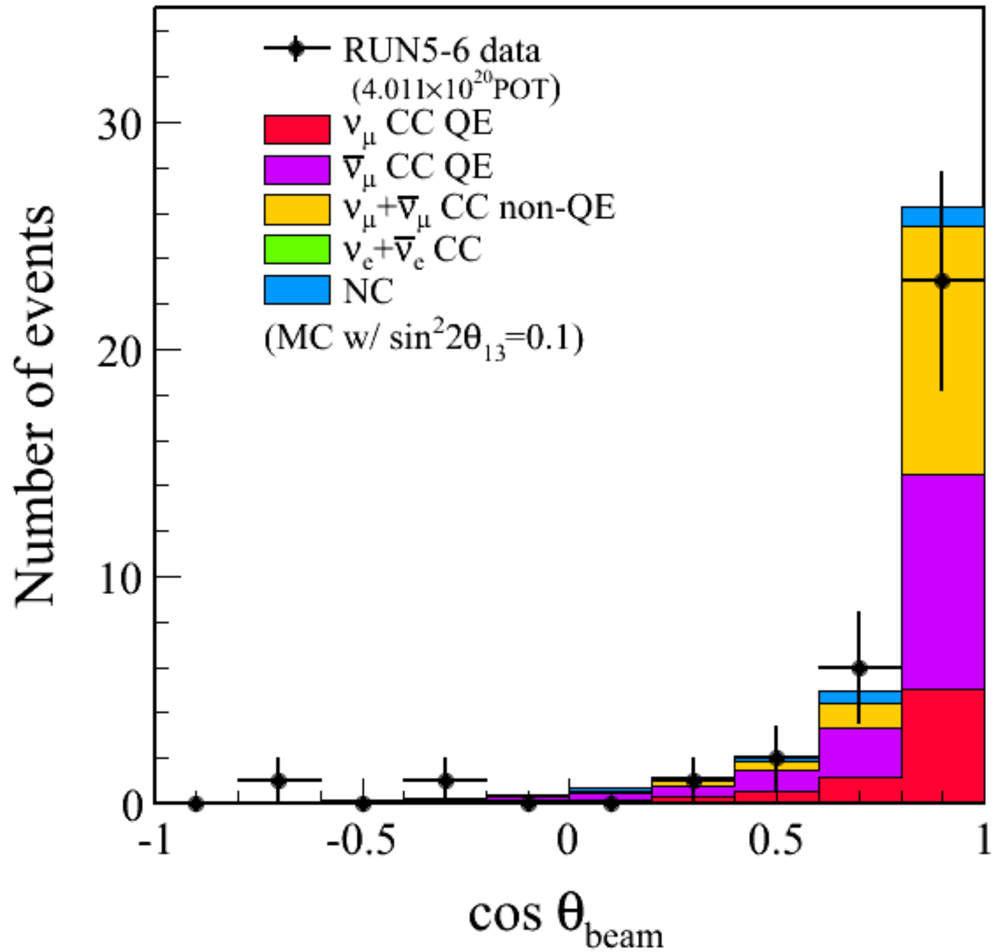
Antimuon neutrino candidates distributions



Two-dimensional R^2-Z distribution of the reconstructed vertex position of the anti-numu candidate events. Dashed blue line indicates the fiducial volume boundary. Black markers are events observed during RUN5, and pink markers are events from RUN6. Hollow crosses represent events passing the anti-numu selection cuts other than the fiducial volume cut.

Antimuon neutrino candidates distributions



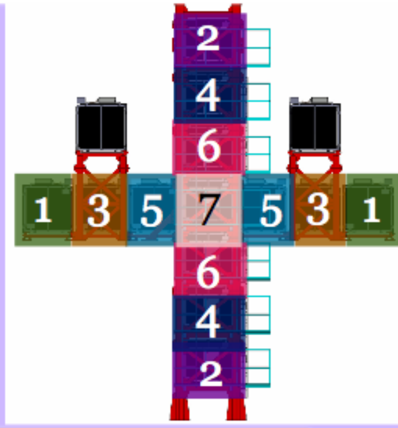


T2K on-axis CC inclusive on Fe

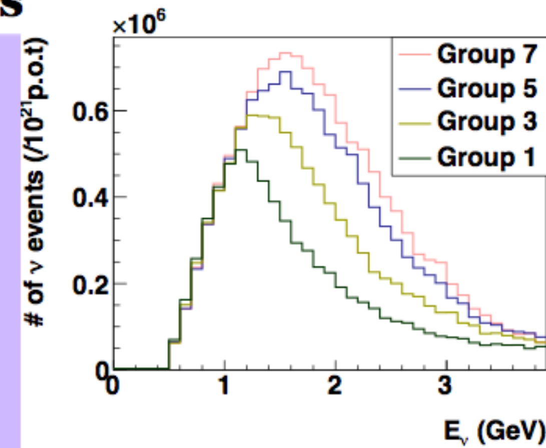
MICHIGAN STATE UNIVERSITY

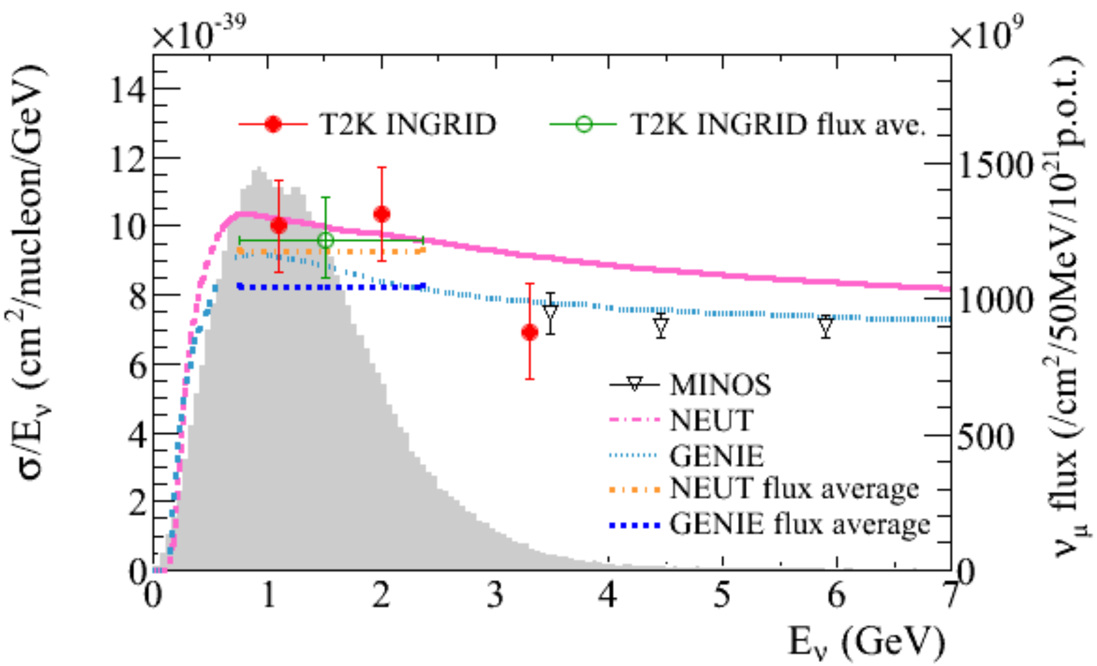
1. Utilize # of event at different modules
   - Different energy spectra at different modules because of different off-axis angles (θ_{OA}=0-0.9°)
2. Group two modules to minimize effects from the variation of the neutrino beam direction
   - 14 modules → 7 groups

Definition of grouping modules



Energy spectra predicted by MC





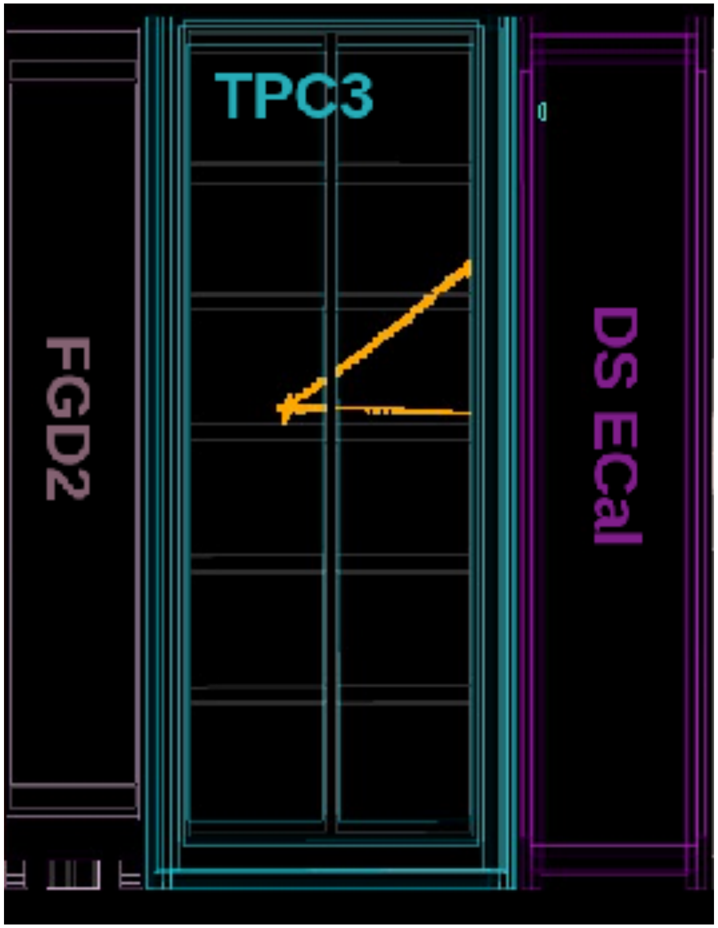
Compare nearby CC inclusive event rate across the on-axis (INGRID) detector:

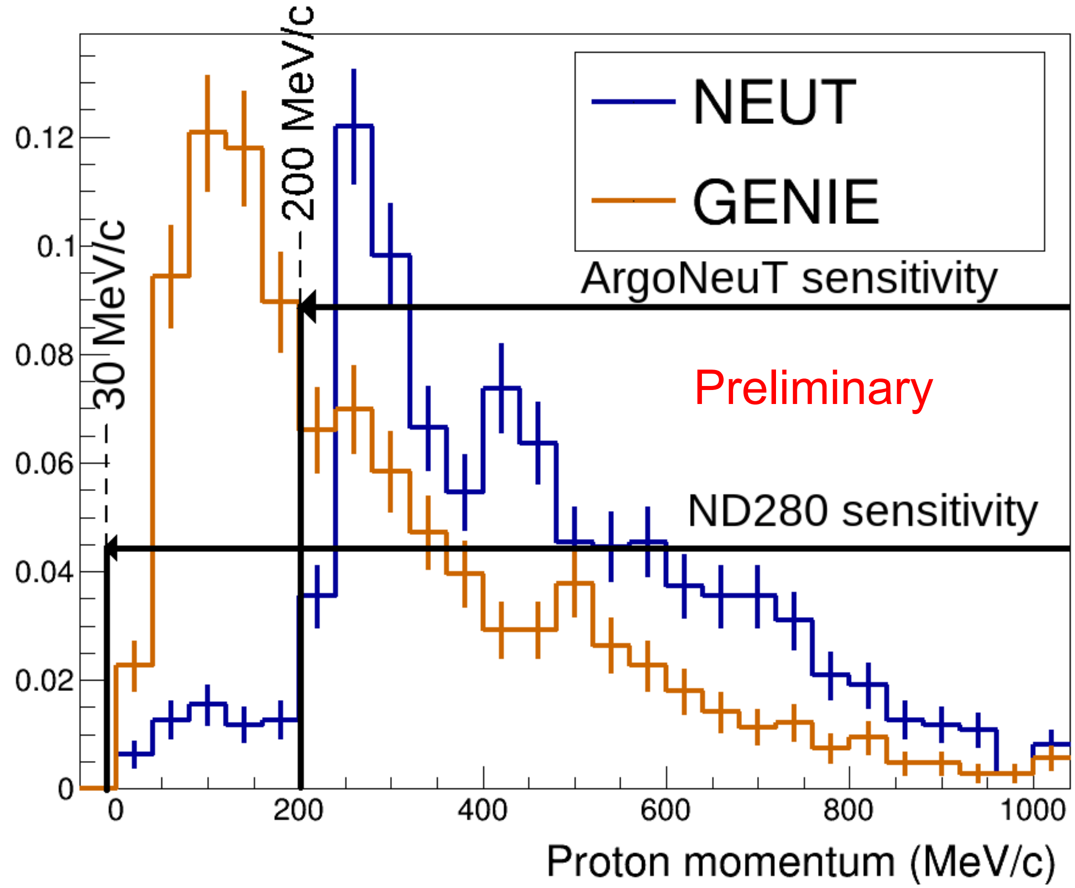
- Target material: Fe
- Flux varies across detector due to off-axis effect
- Infer energy dependence from variation

Cross section tuning from near detector fit

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

T2K as a cross section experiment

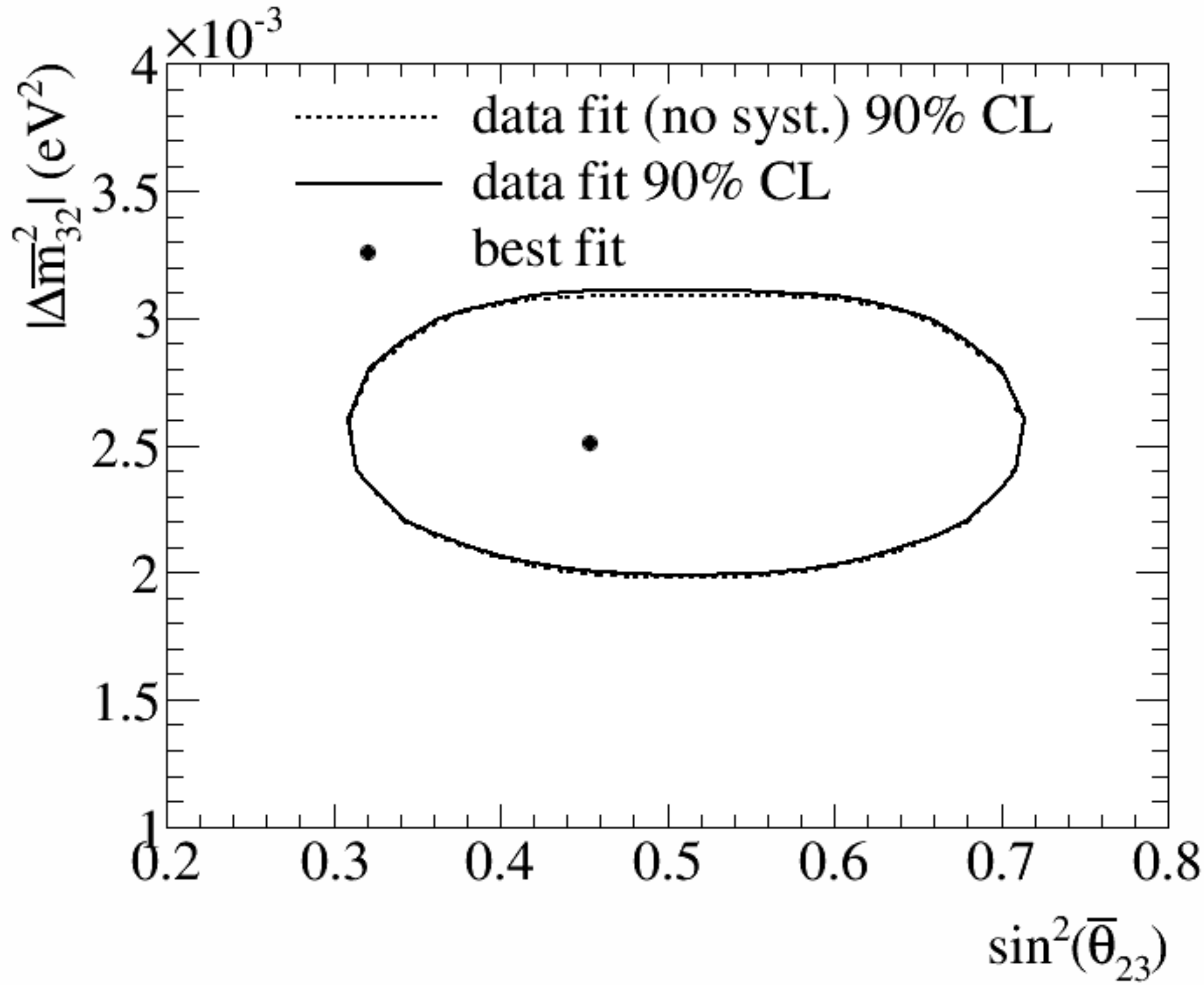




Gaseous TPCs (3 in total) are predominantly Ar gas:

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

Impact of systematic uncertainty



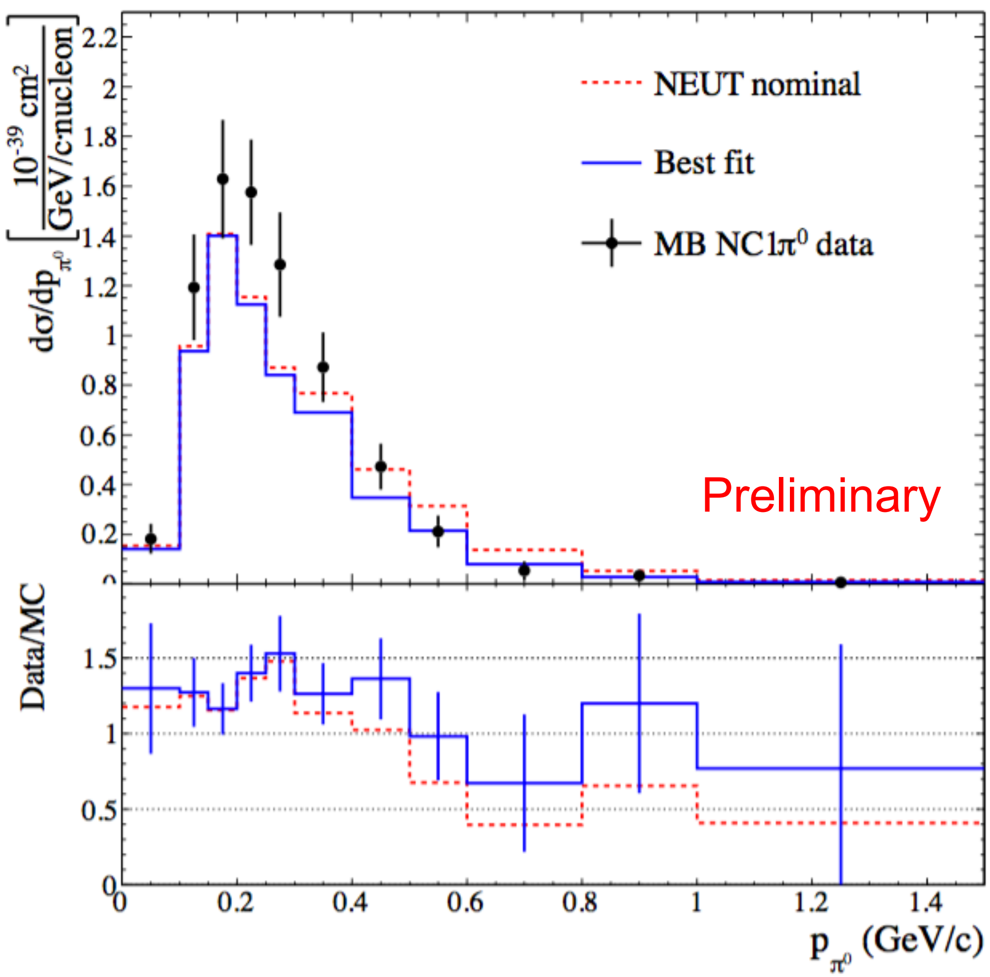
Our antineutrino measurements are statistics limited

- Analysis with and without systematics included barely changes the contours

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)

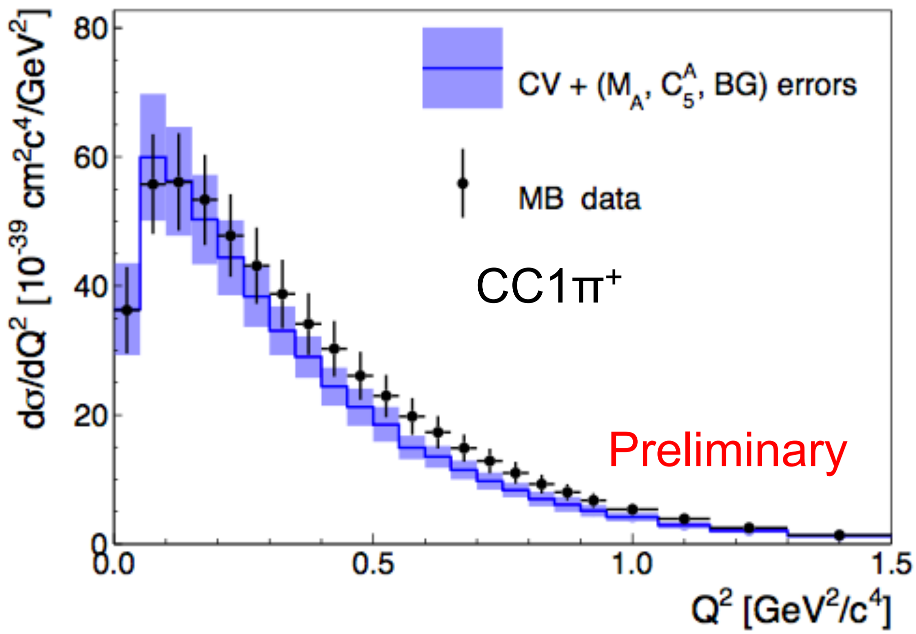
Fit neutrino deuterium channels:

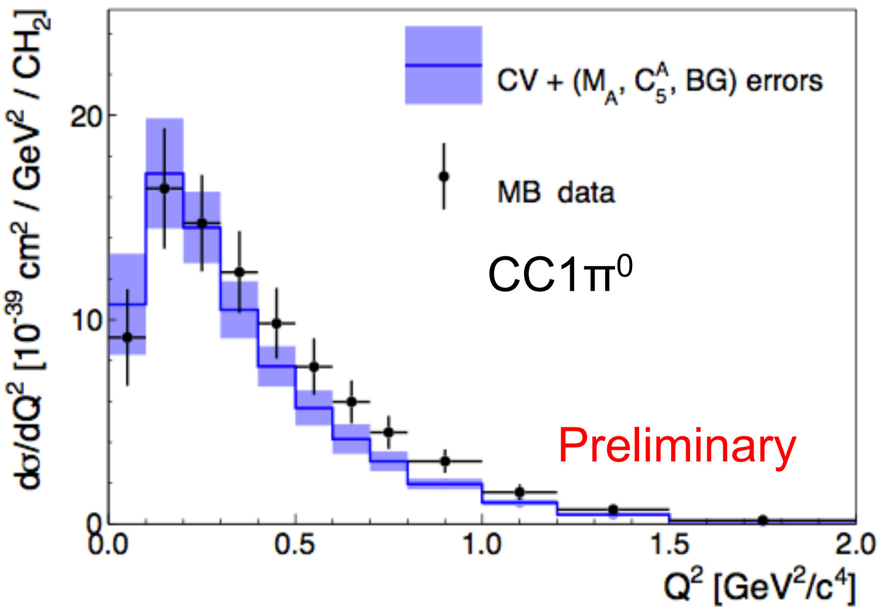
- C^A_5 (0) driven by ANL/BNL disagreement
- MARES (axial form factor mass)
- Non-resonant background scale factor

Results of resonance model retune

MICHIGAN STATE UNIVERSITY

- 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)



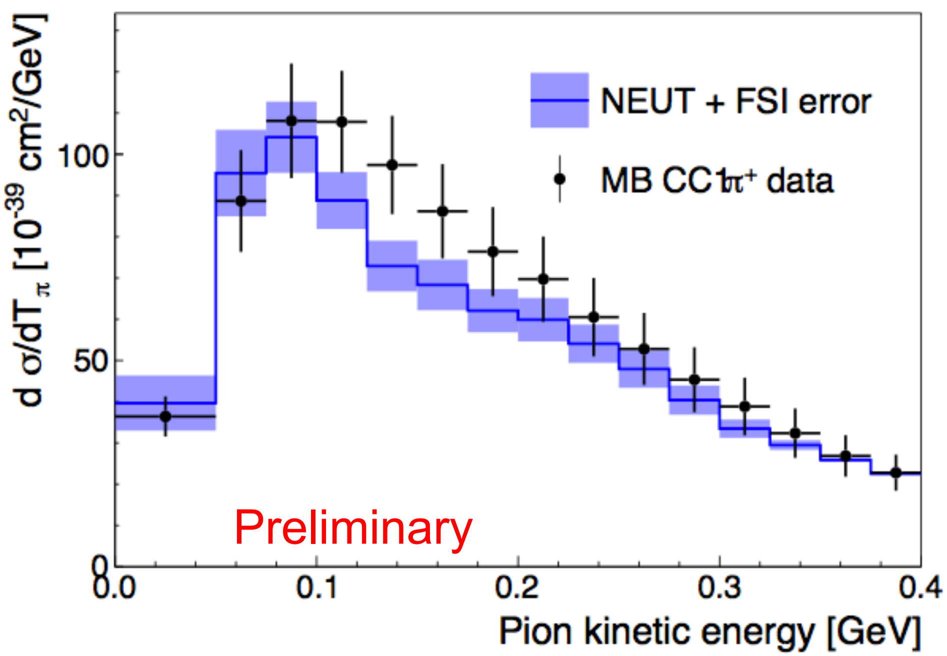


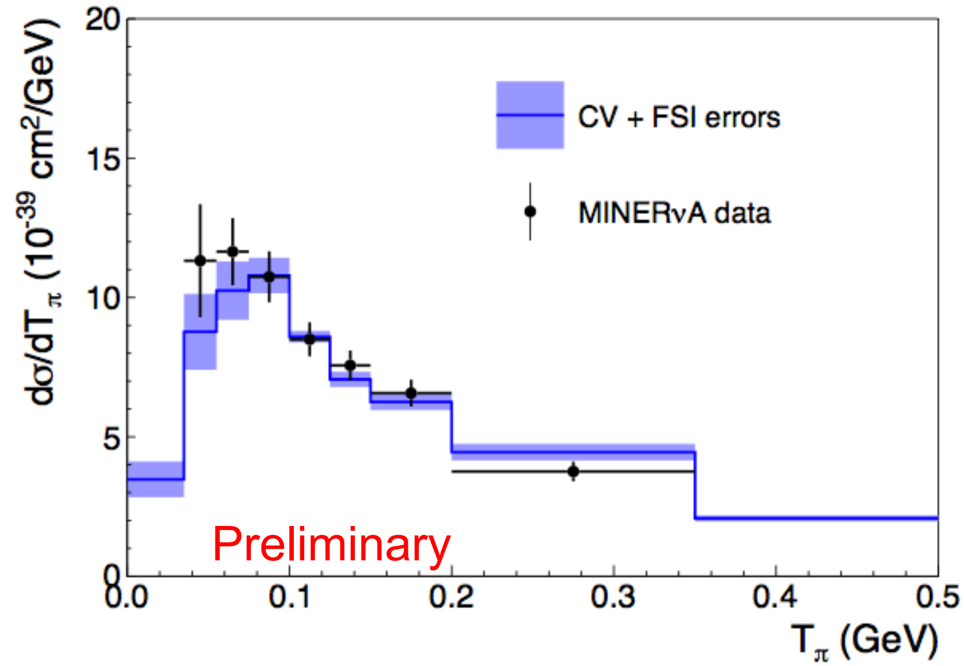
Results of resonance model retune

MICHIGAN STATE UNIVERSITY

- 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



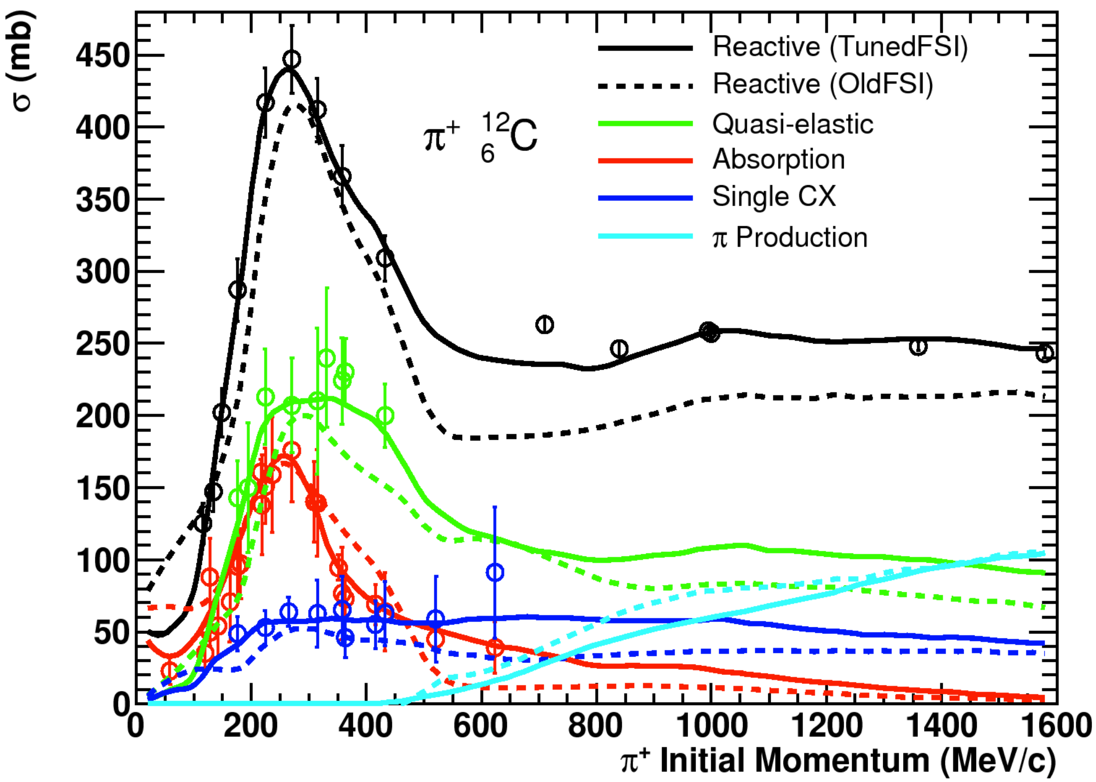


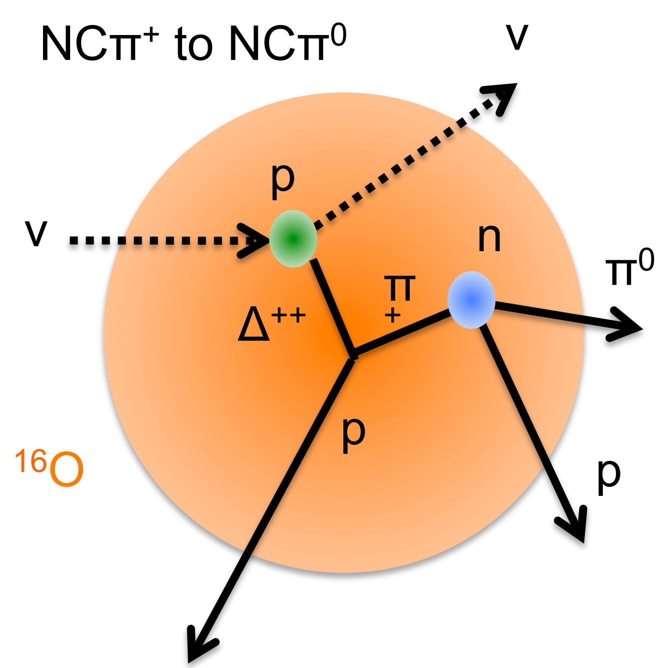
New T2K near detector measurements of pion production coming soon

Final state interaction model

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

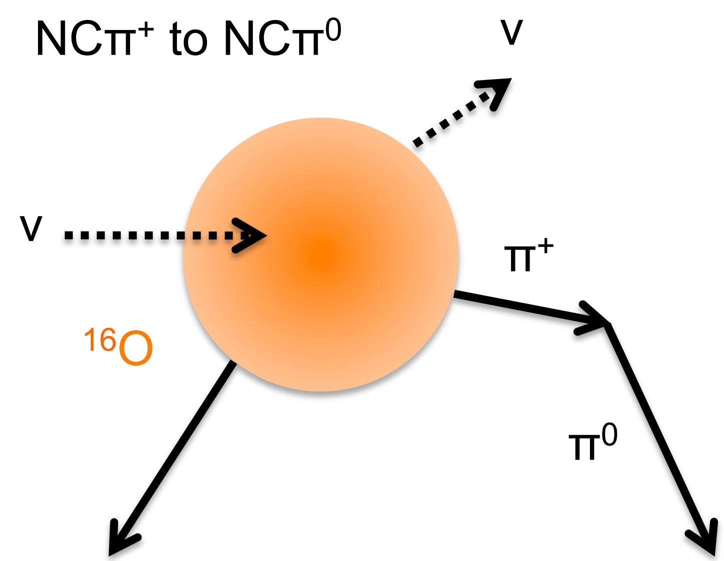
Pion scattering in the detector is a background to cross section understanding of what comes out of the nucleus (``secondary interactions'')

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

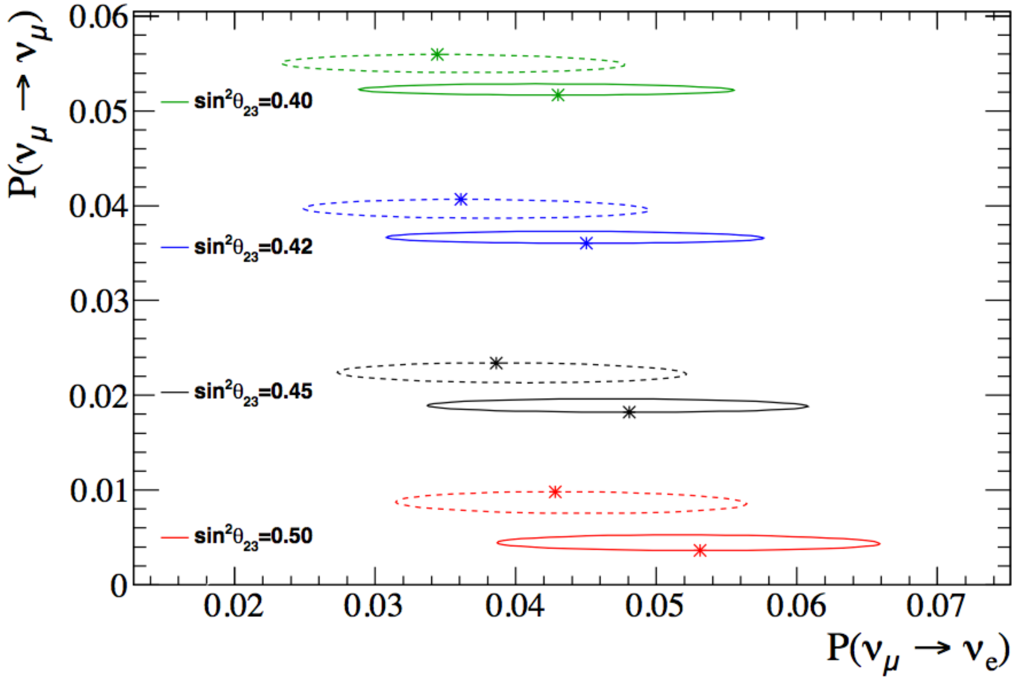
TABLE XI: Minimum and maximum fractional errors among all the (p_μ,$\cos\theta_\mu$) bins, including the largest error sources. The last column shows the fractional error on the total number of events, taking into account the correlations between the (p_μ,$\cos\theta_\mu$) bins.

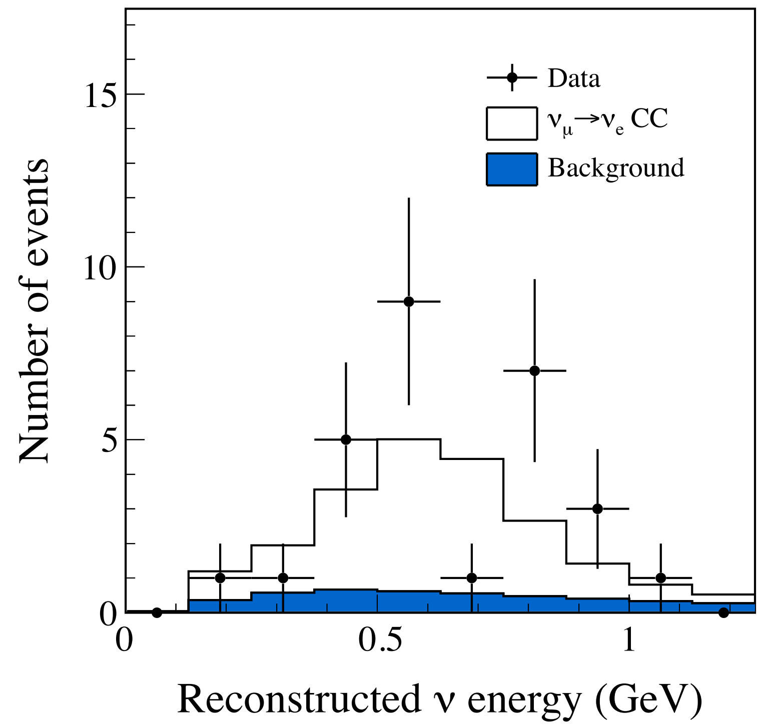
Systematic error	Error Size (%)	
	Minimum and maximum fractional error	Total fractional error
B-Field Distortions	0.3 - 6.9	0.3
Momentum Scale	0.1 - 2.1	0.1
Out of FV	0 - 8.9	1.6
Pion Interactions	0.5 - 4.7	0.5
All Others	1.2 - 3.4	0.4
Total	2.1 - 9.7	2.5

NCπ$^+$ to NCπ^0



T2K results: appearance



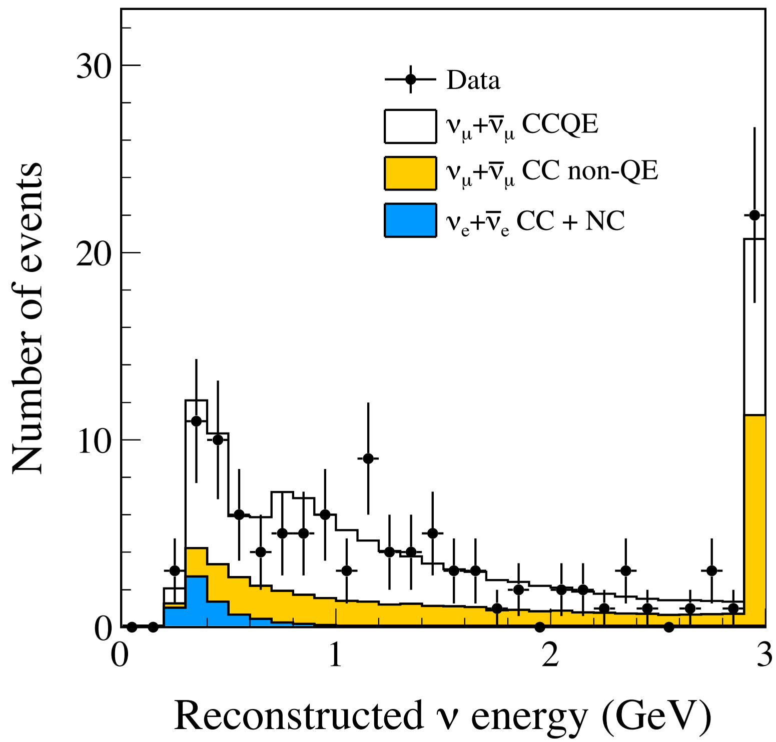


T2K collab, arxiv:1502.01550v1,
PRD 91, 072010 (2015)

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

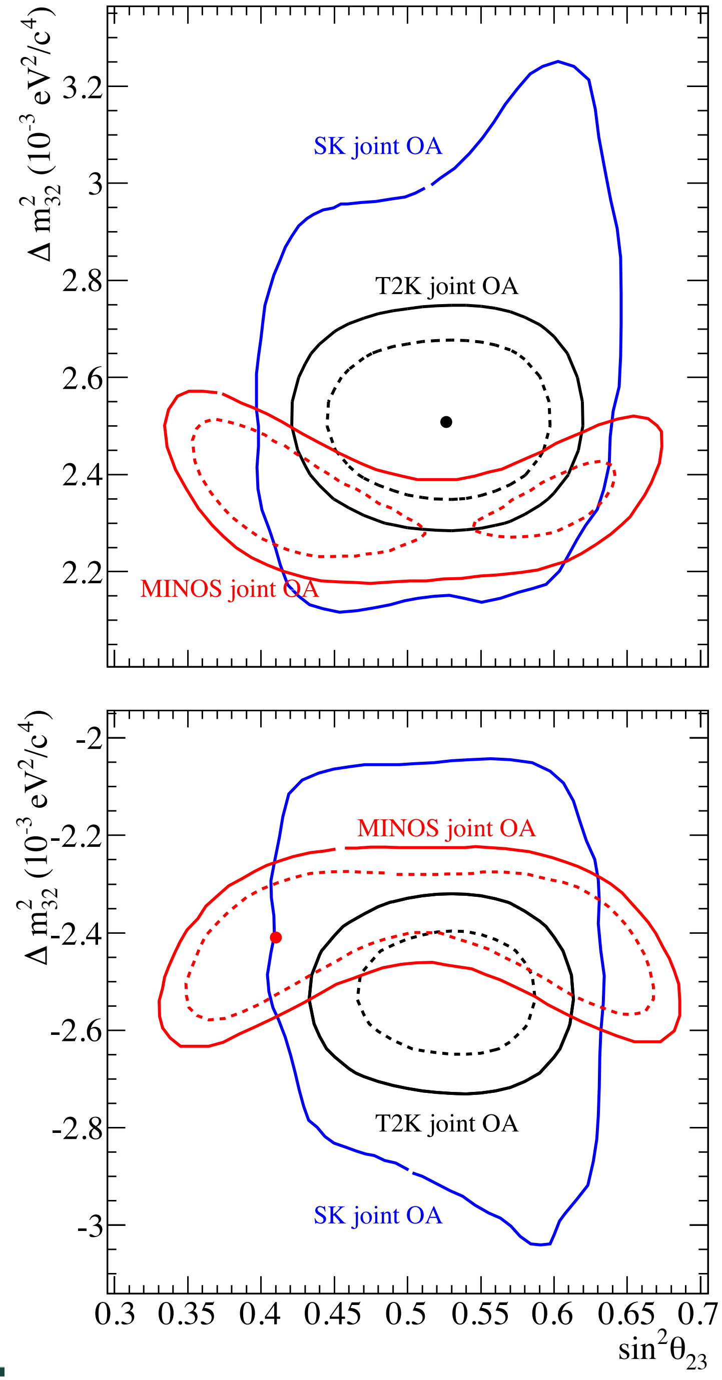


120 candidate ν_μ events observed

- 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

Additional osc-multinucleon studies

MICHIGAN STATE UNIVERSITY

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:

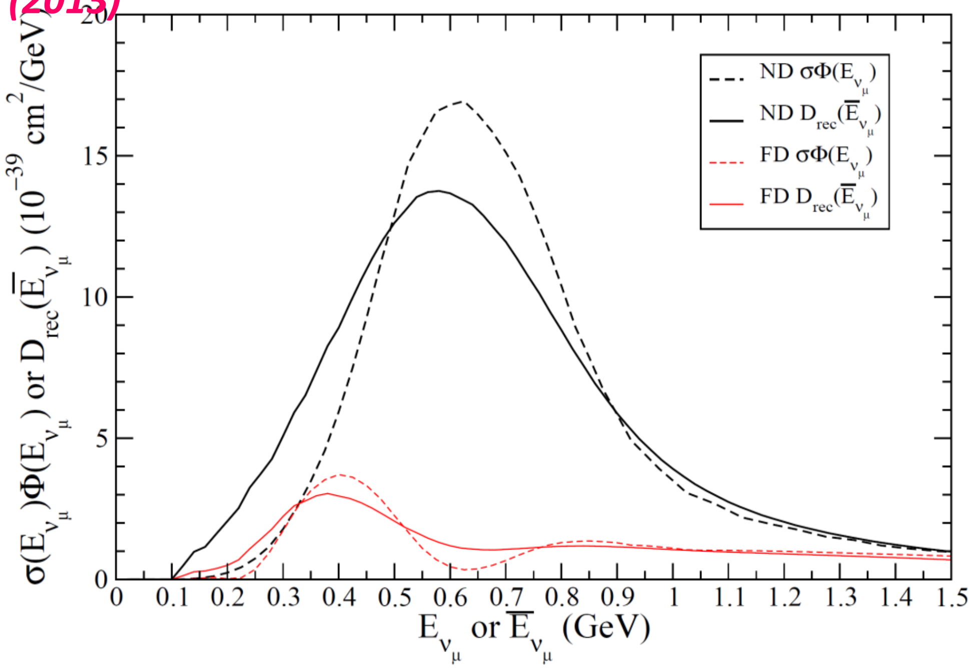
- J. Nieves et al PRD 85, 113008 (2012)
- O. Lalakulich, U. Mosel, and K. Gallmeister, PRC 86, 054606 (2012)
- M. Martini, M. Ericson, and G. Chanfray, PRD 85, 093012 (2012)
- M. Martini, M. Ericson, and G. Chanfray, PRD 87, 013009 (2013)
- D. Meloni and M. Martini, PLB 716, 186 (2012)

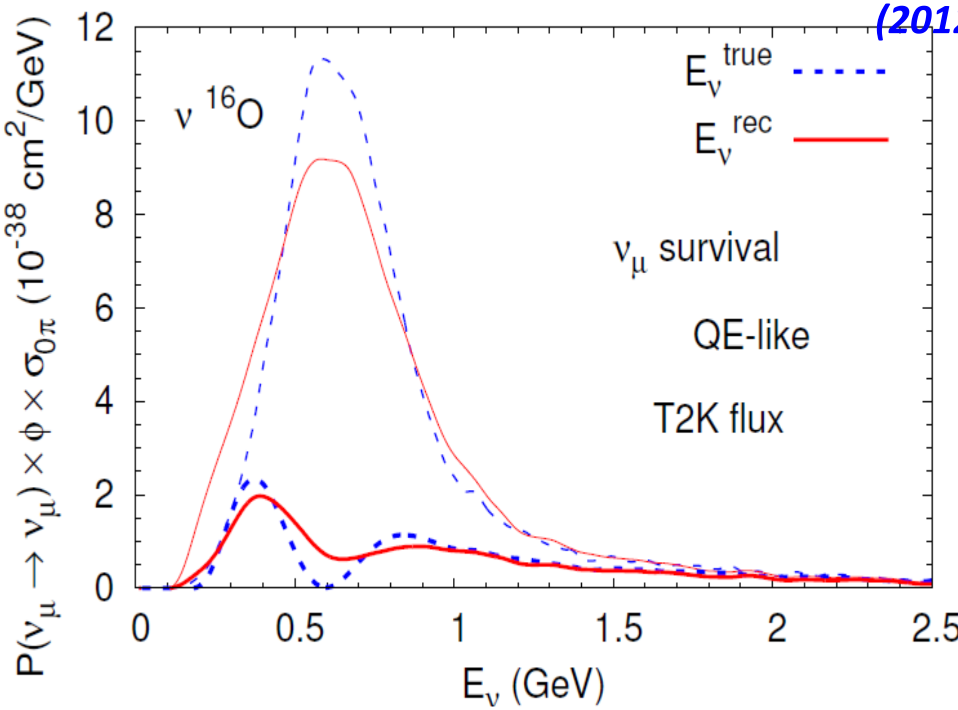
	$\sin^2 2\theta_{13}$	$\theta_{23}(^o)$	Δm^2_{atm} (10^{-3} eV^2)
FG	[0.041-0.211] (0.105)	[40.1-51.3] (47.6)	[2.45-2.67] (2.56)
MECM	[0.023-0.154] (0.092)	[41.1-49.9] (45.4)	[2.49-2.67] (2.60)

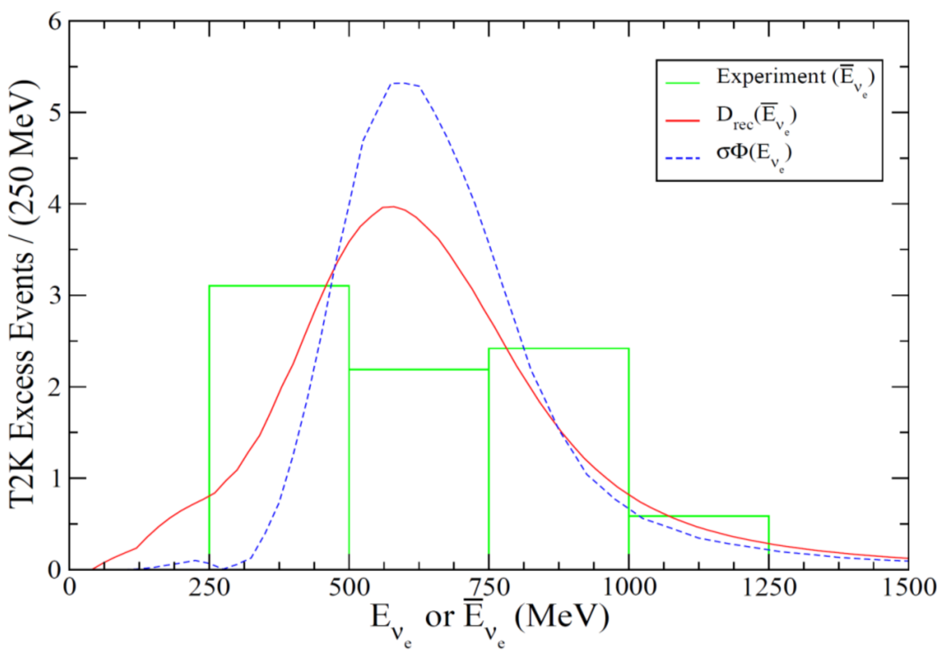
Table 5: *90% intervals for $\sin^2 2\theta_{13}, \theta_{23}$ and Δm^2_{atm}, for the MECM and FG models in the case the current T2K statistics is increased by a factor of 10. In parenthesis, the best fit points.*

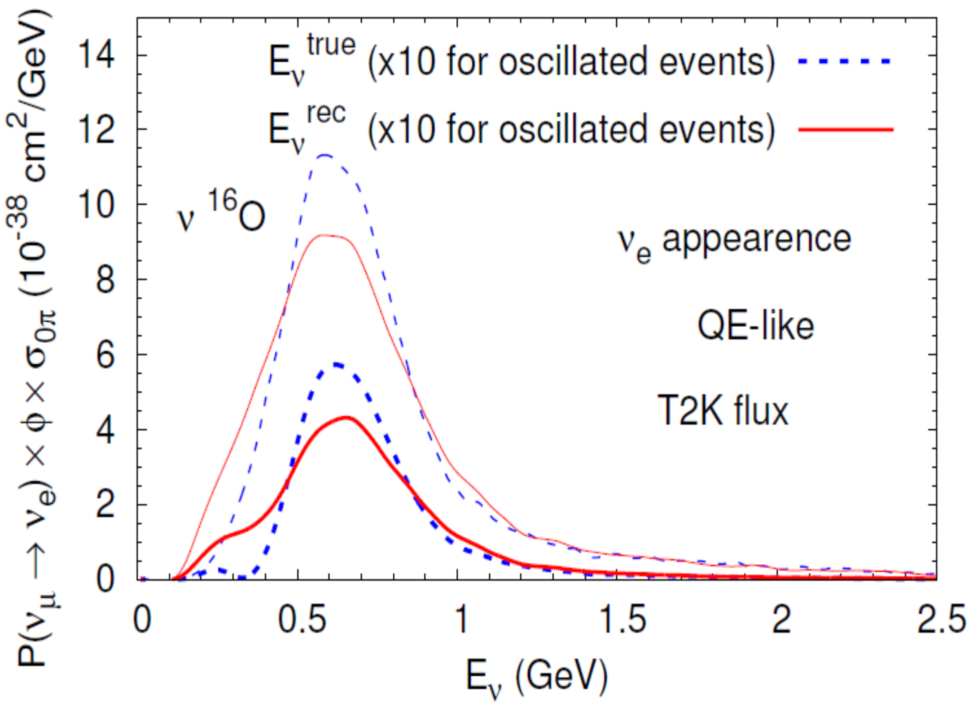
M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

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









Appearance and disappearance

ν_μ to ν_e appearance:

Approximation from M. Freund, PRD 64, 053003

$$P_{\nu_\mu \to \nu_e} = \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2[(A-1)\Delta]$$
$$-(+)\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times$$
$$\sin\delta_{CP} \sin\Delta \sin A\Delta \sin[(1-A)\Delta]$$
$$+\frac{\alpha}{A(1-A)} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times$$
$$\cos\delta_{CP} \cos\Delta \sin A\Delta \sin[(1-A)\Delta]$$
$$+\frac{\alpha^2}{A^2} \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta$$

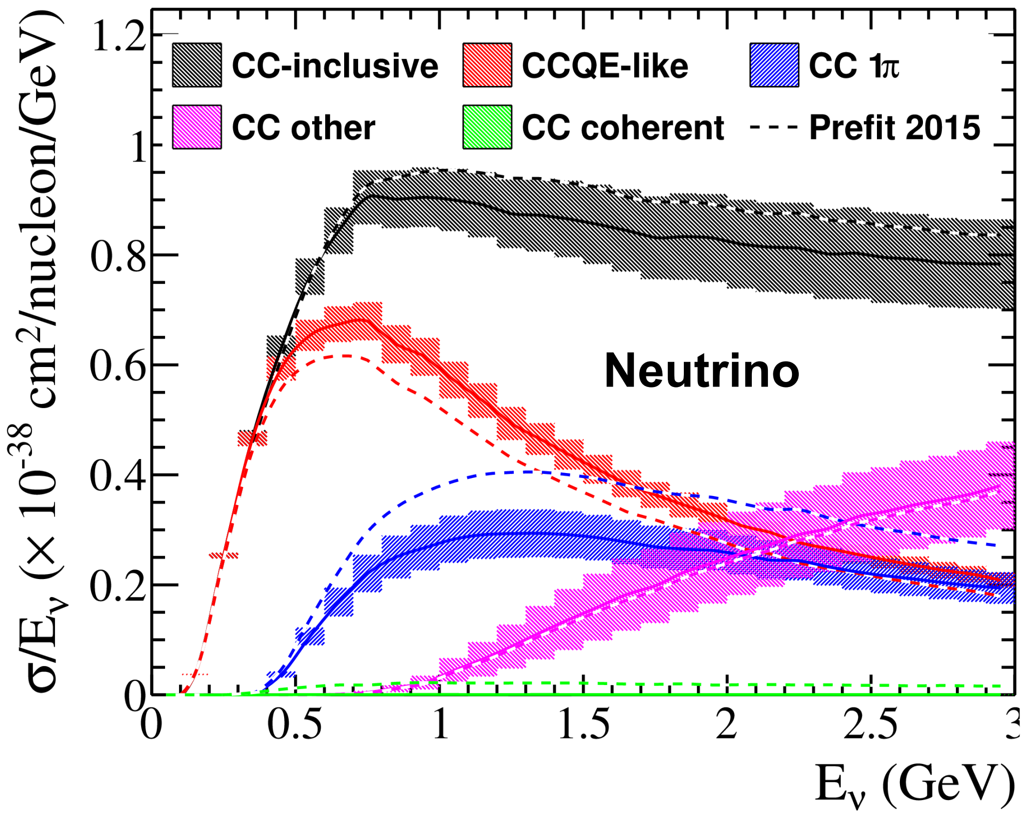
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} << 1,$$
$$\Delta = \frac{\Delta m^2_{32} L}{4E_\nu}$$
$$A = 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$$

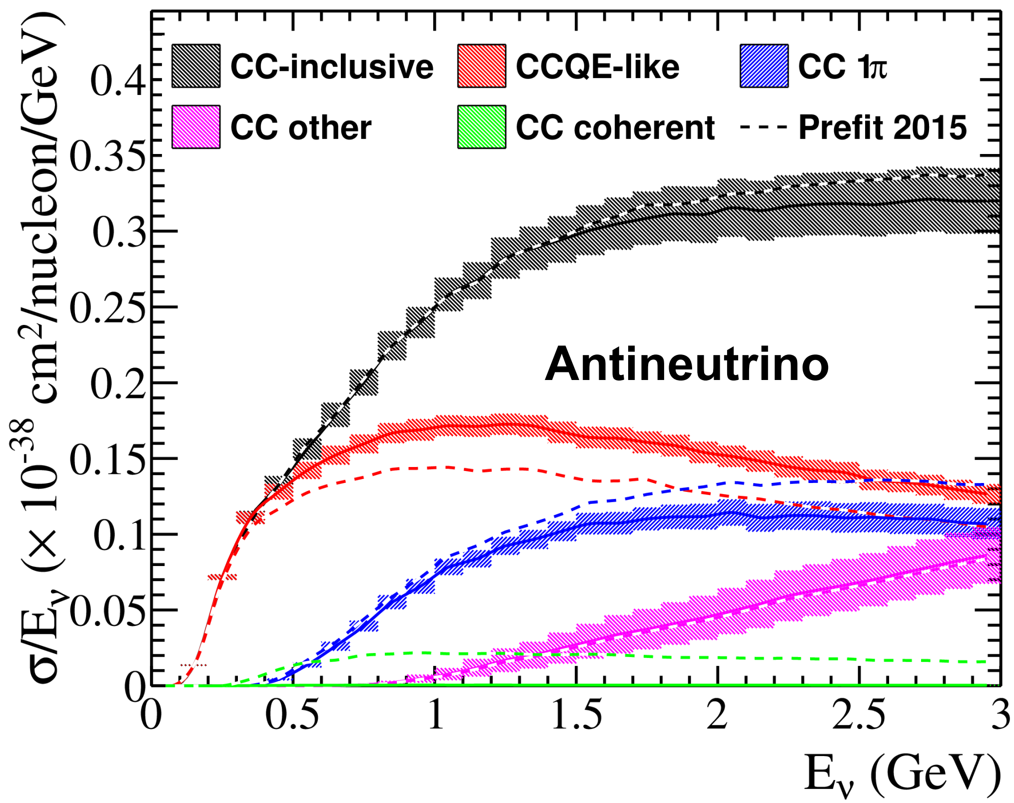
Key players:

- $\Delta m^2_{32} \sim 2.4 \times 10^{-3}$ eV^2 (atmospheric mass splitting), sign enters due to ν_e, ν_μ interactions in matter (matter effects, A terms)
- Mixing angles: θ_{12}, θ_{23}, θ_{13}
- CP-violating phase δ_{CP}

Determine Δm^2_{32}, θ_{23} from measurements of ν_μ disappearance

Improved neutrino interaction models





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

- Two new CCQE models implemented for consideration in the analysis:
  - CCQE: Spectral function model (Benhar et al.) M_A^{QE}= 1.2 GeV
  - CCQE: Relativistic Fermi Gas (RFG)+Random Phase Approximation (RPA)
  - New: "Meson exchange current" (MEC) CCQE like scattering from Nieves et. al
- 1π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

Short baseline oscillation: not just for far detectors

Disappearance observable as a deficit and distortion to neutrino energy spectrum

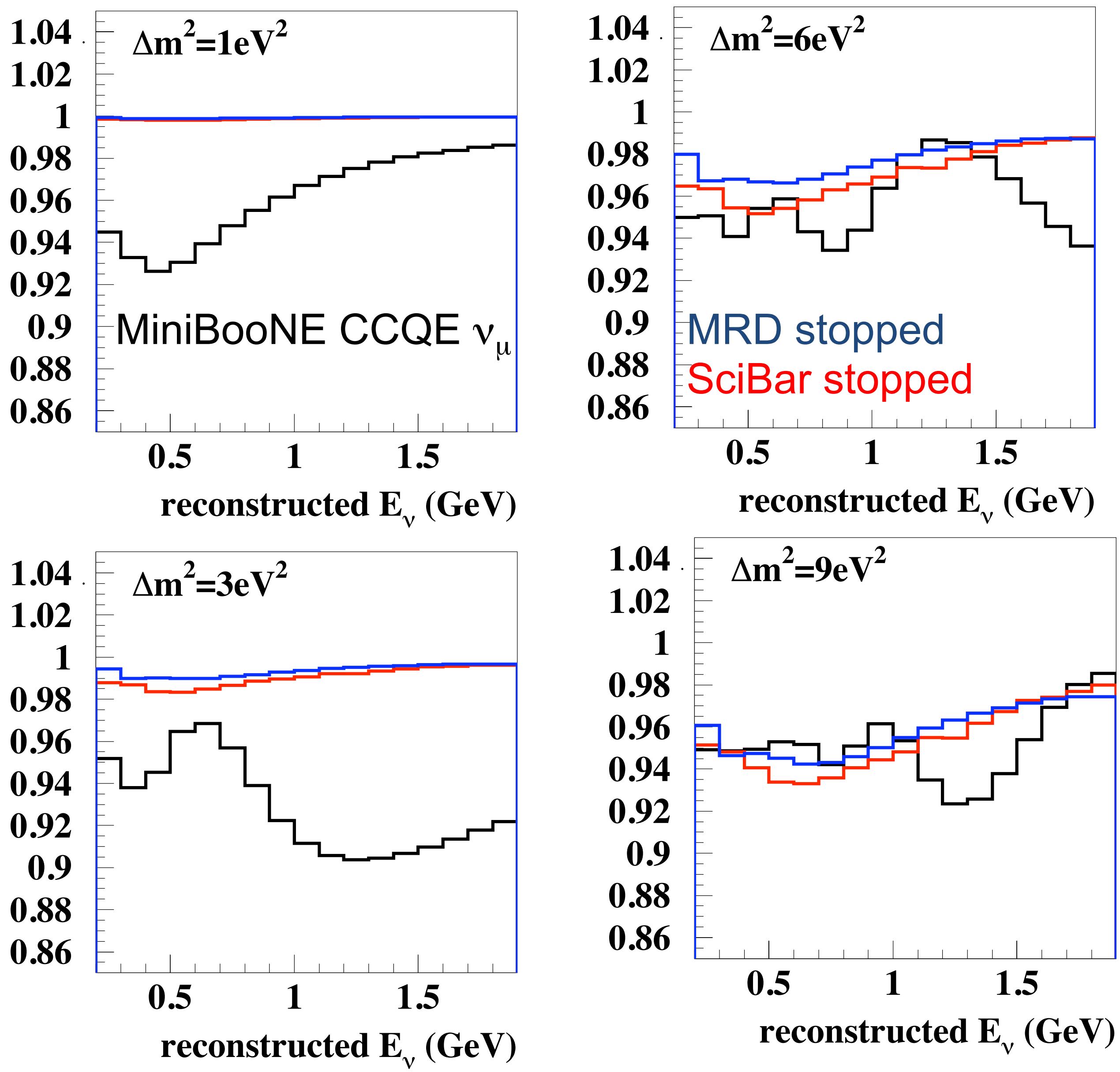
Includes:

- Oscillation of all CC ν_μ interactions at SciBooNE and MiniBooNE
- Distribution of distance travelled by neutrinos (L)

	Mean L
SciBooNE	~76m
MiniBooNE	~520m

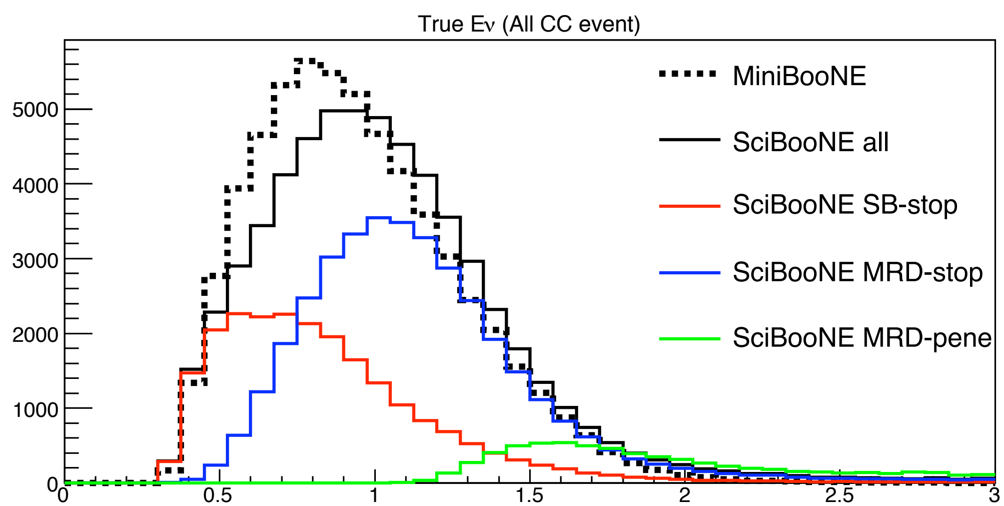
~50m spread in L due to finite decay volume

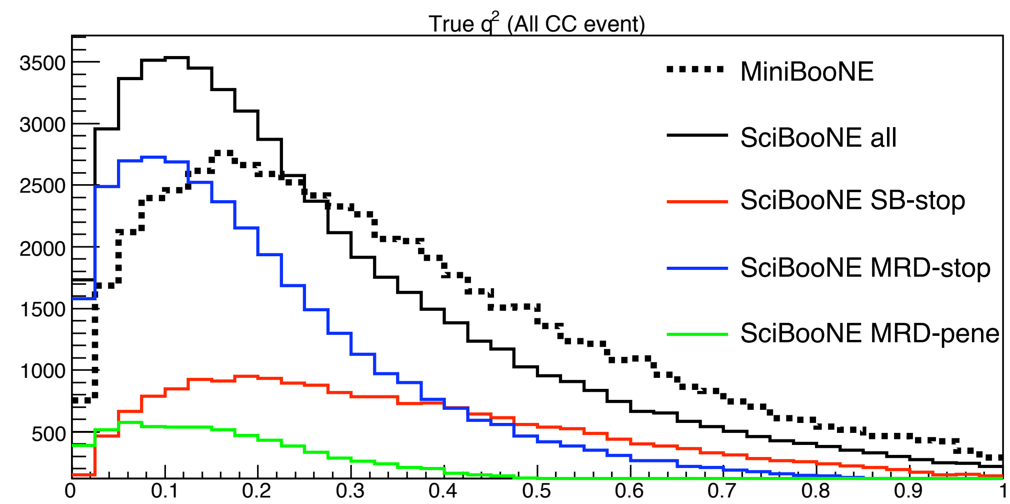
Ratio of oscillated spectrum to unoscillated ($\sin^2 2\theta = 0.10$)

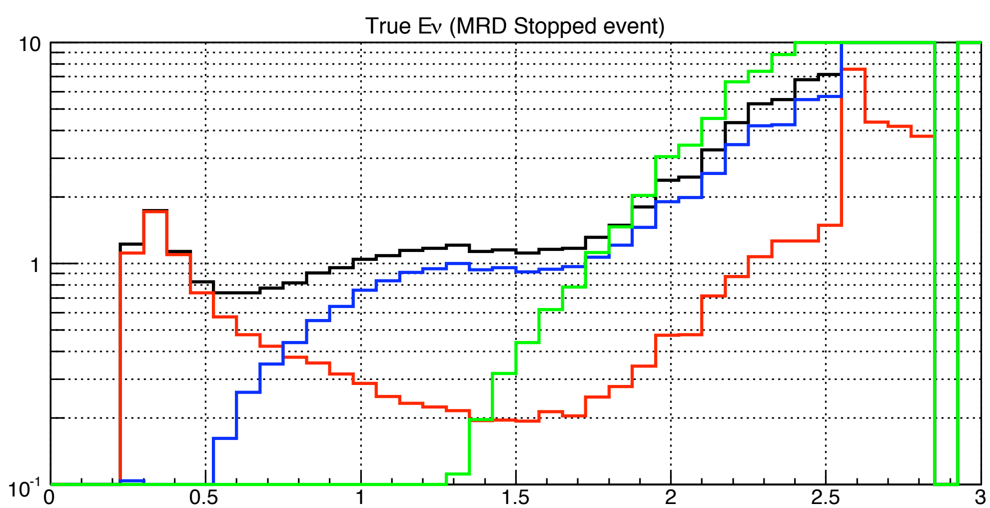


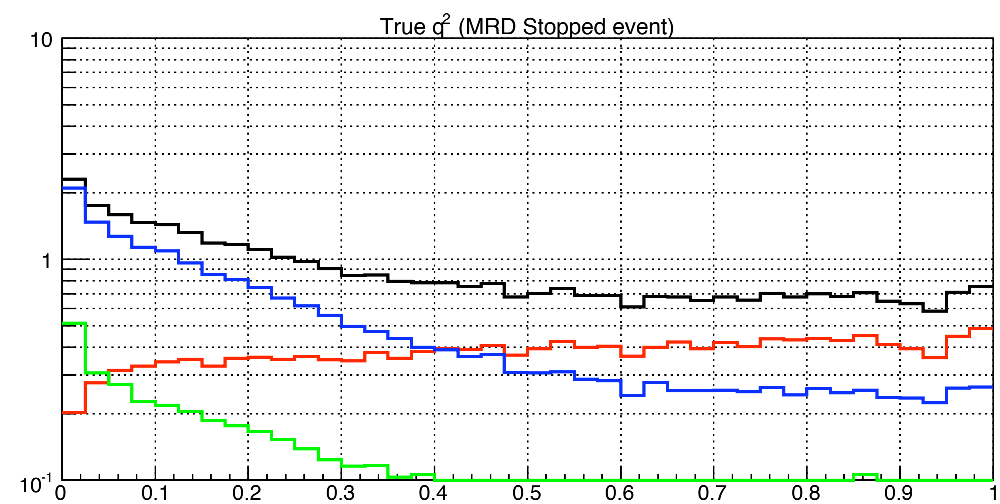
SciBooNE samples cover relevant flux (E_ν) and cross section (Q^2) for MiniBooNE

- SciBar stopped: 49% CCQE, 30% CC1π; MRD stopped: 54% CCQE, 34% CC1π
- MiniBooNE: 74% CCQE, 25% CC1π

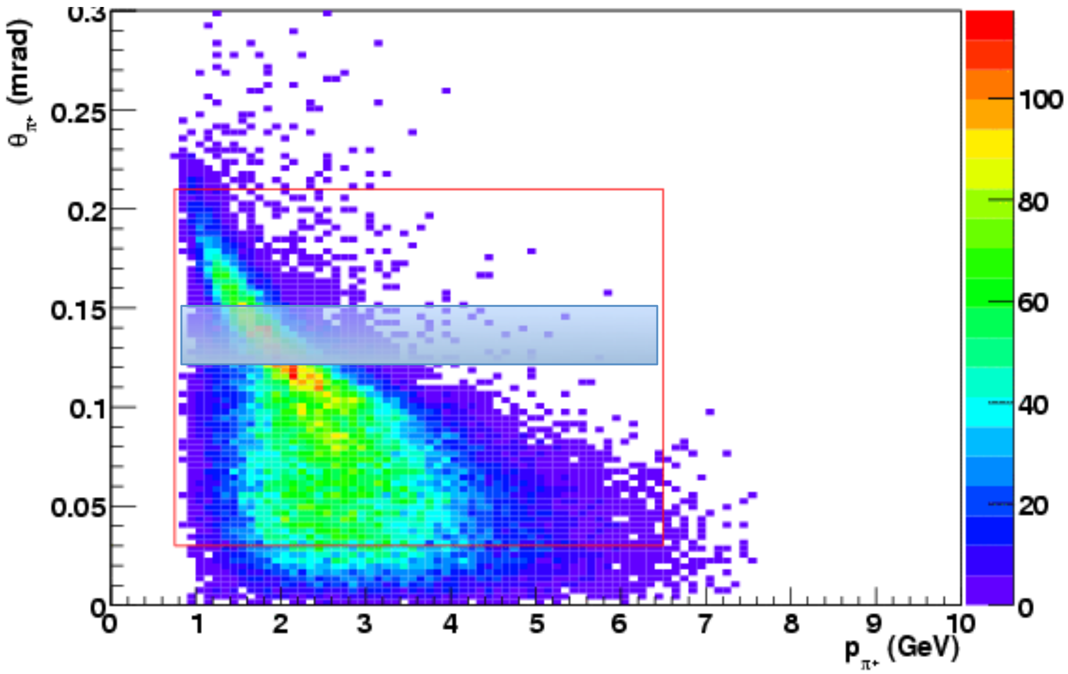


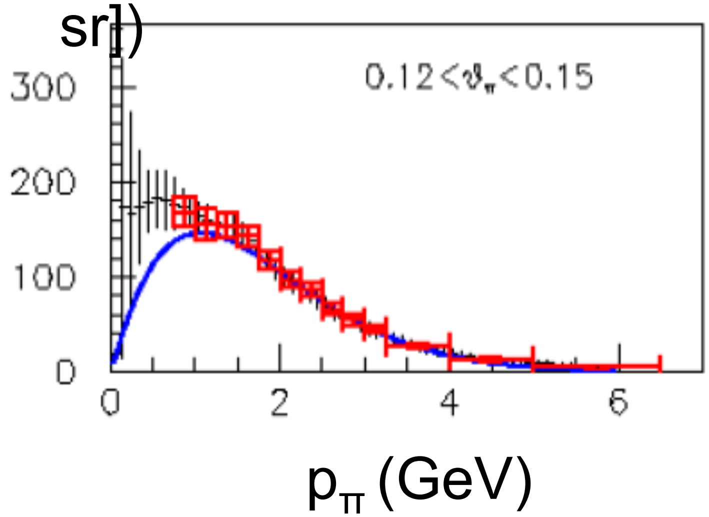






Flux systematics





HARP data with errors in θ_π bins

MiniBooNE flux parameterization

Included as systematic error:

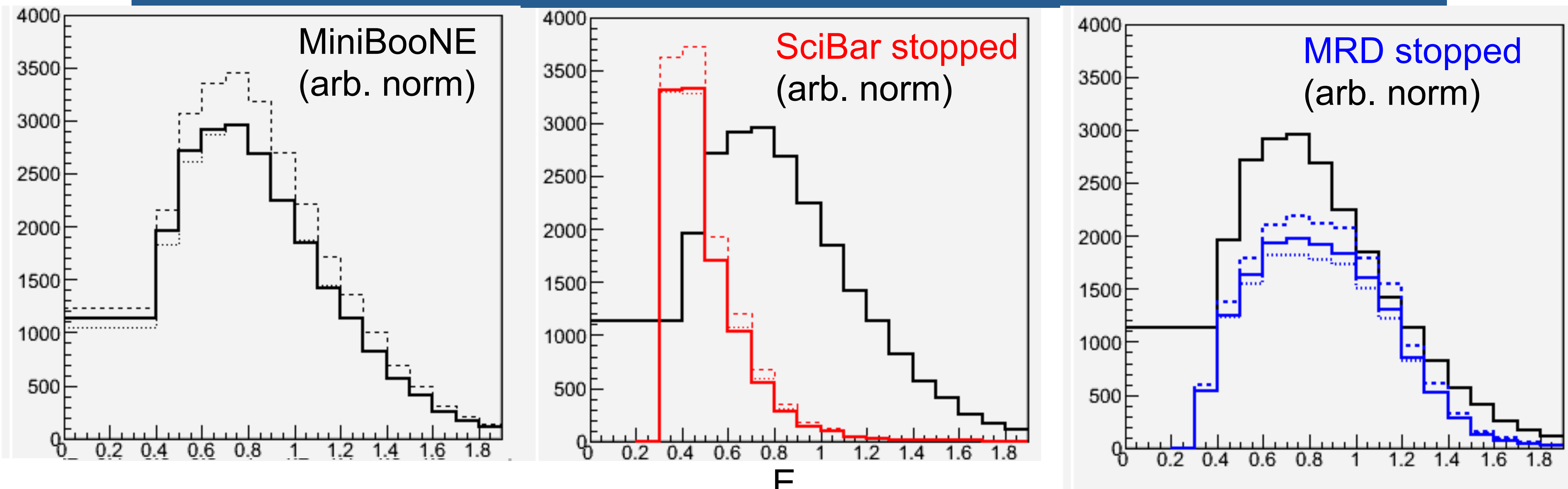
1. Beam optics and targeting efficiency
2. p+Be elastic and inelastic cross sections
3. Production of mesons ($\pi^{+/-}$, $K^{+/-}$) from pBe interactions (dominant)
4. Horn magnetic field

The HARP experiment measured p+Be production of π^+/ π^- (hep-ex/0702024)

Use the HARP data and errors to produce different fluxes consistent with HARP

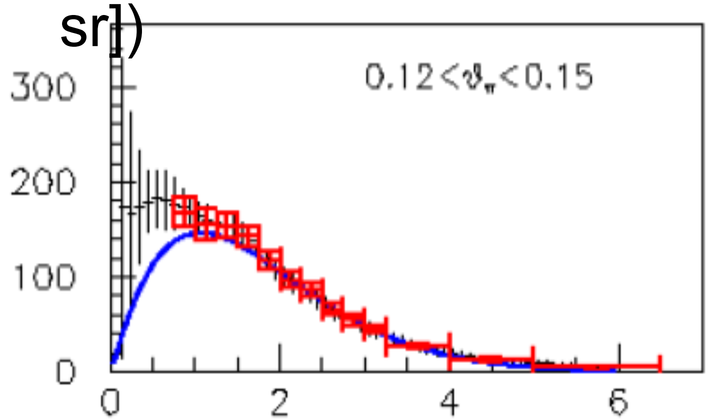
Propagate the new fluxes through to the neutrino spectrum

Flux systematics



E_ν

dσ/dpdW (mb c/[GeV sr])



p_π (GeV)

HARP data with errors in θ_π bins

MiniBooNE flux parameterization

Propagate the new fluxes through to the neutrino spectrum

Example variations (dotted, dashed) to E_νQE spectrum at 3 experiments

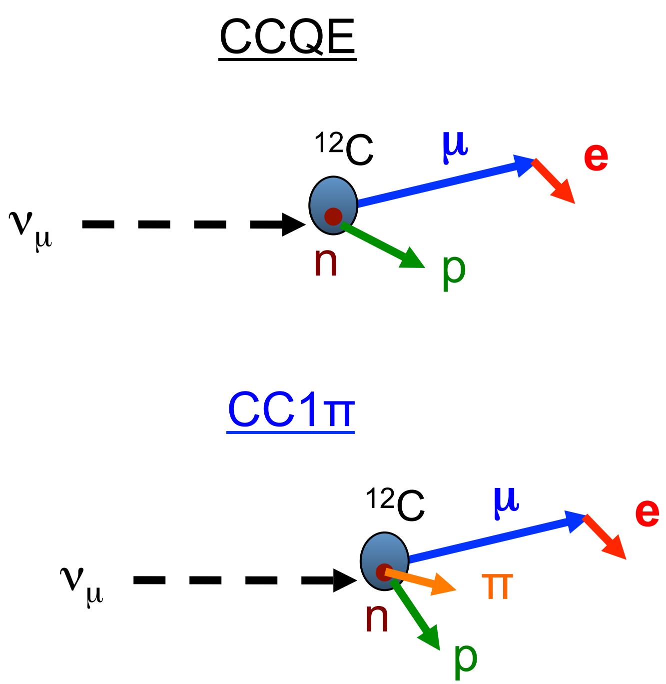
Create covariance:

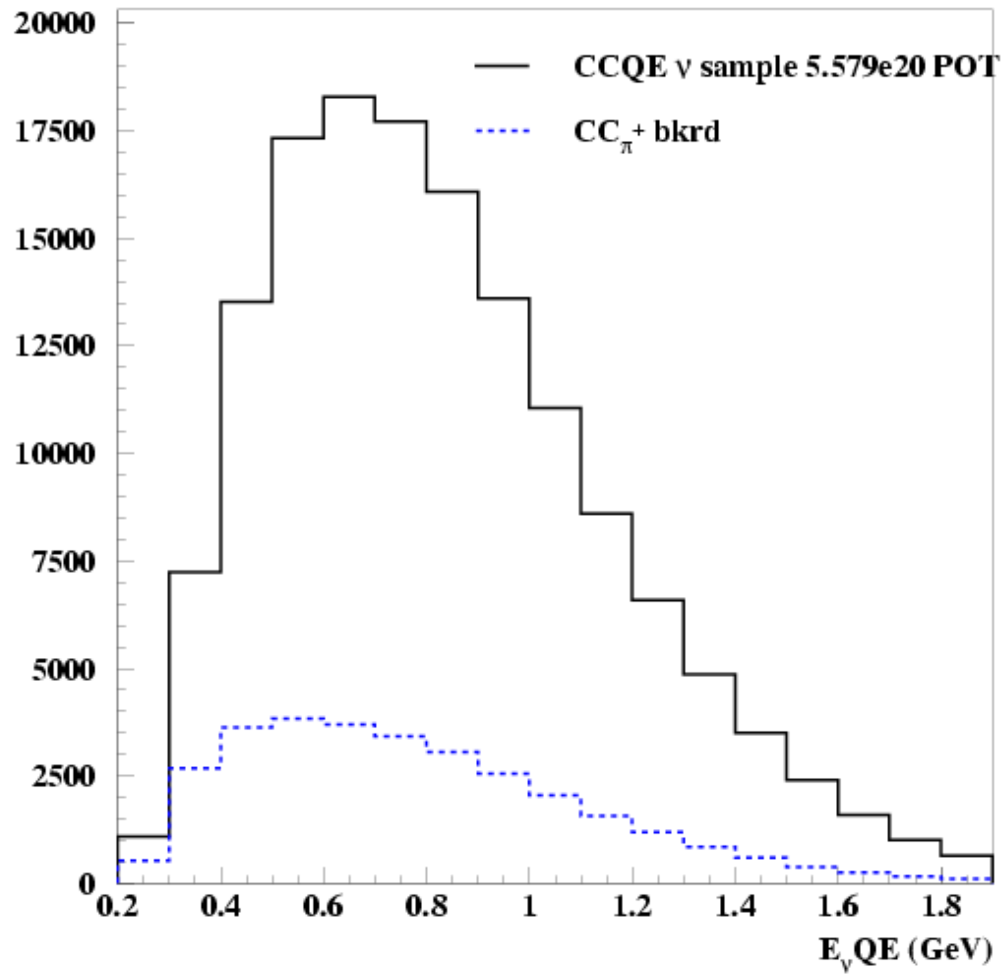
$$M_{ij}^{\pi+prod} = \frac{1}{throws} \sum_{k=1}^{throws} (N_{cv} - N_k)_i (N_{cv} - N_k)_j$$

Cross section systematics

Uncertainties on the cross sections include:

- Uncertainties on the base cross section model (CCQE, CC1π)
- Uncertainties on model dependence (relativistic Fermi Gas to spectral function)
- Uncertainties on the propagation of pions, protons out of the nucleus (final state interactions)





Detector systematics

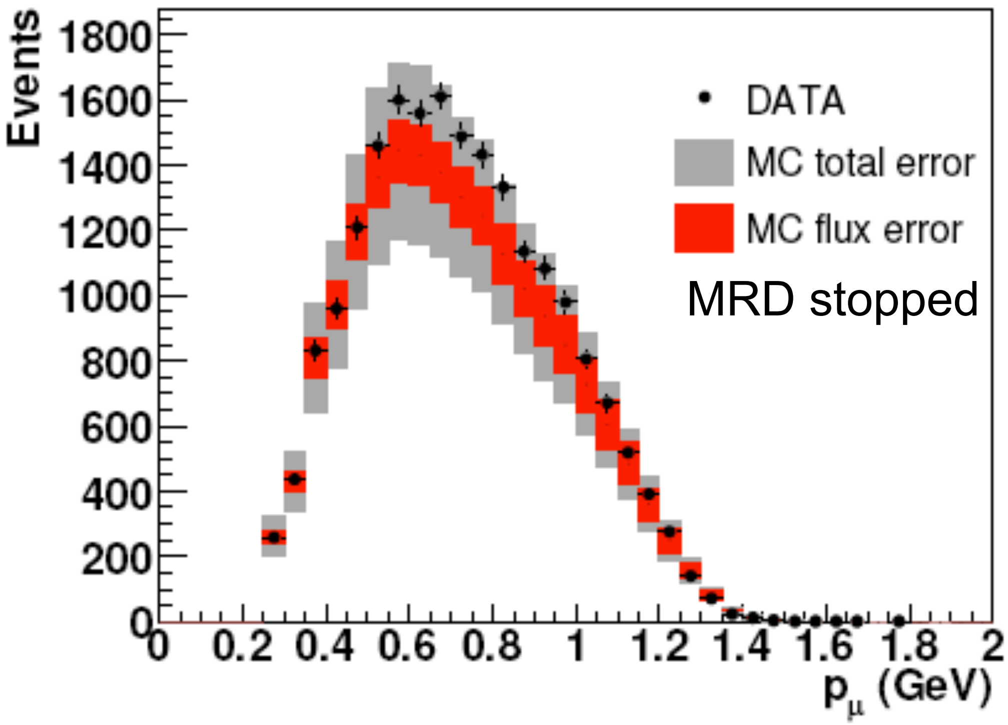
Detector uncertainties which affect our muon momentum scale affect reconstructed neutrino energy

MiniBooNE detector uncertainties include:
light propagation through the mineral oil, scattering, detection and PMT response (see Nucl. Instr. Meth. A599, 28 (2009))

SciBooNE detector uncertainties include:
energy loss of the muons through scintillator and iron, light attenuation in the WLS fibers and PMT response

	Muon momentum resolution	Angular resolution
MiniBooNE	35 MeV/c (@ 500 MeV)	5°
SciBar stopped	15 MeV/c	0.9°
MRD stopped	60 MeV/c	0.9°

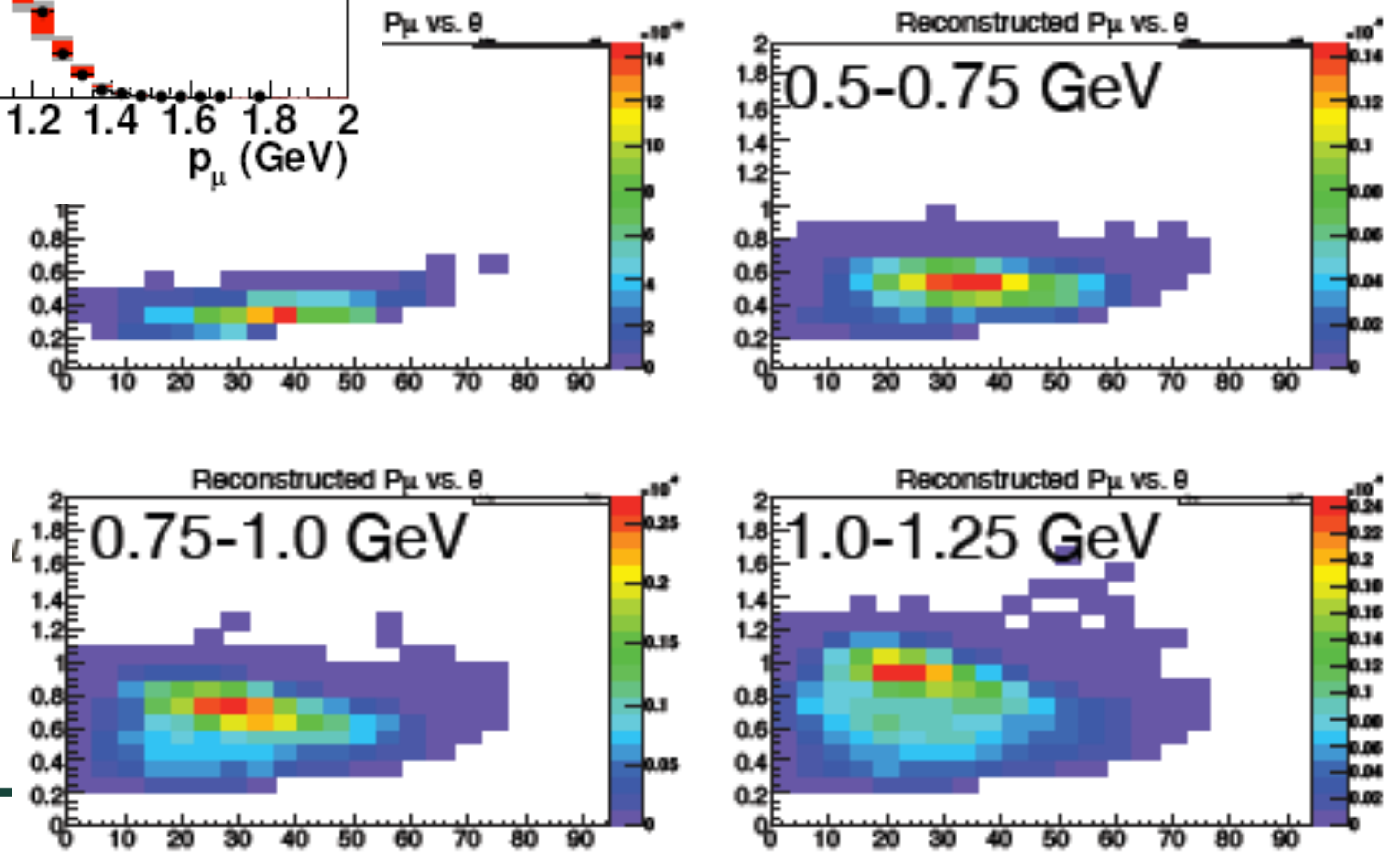
Spectrum fit method



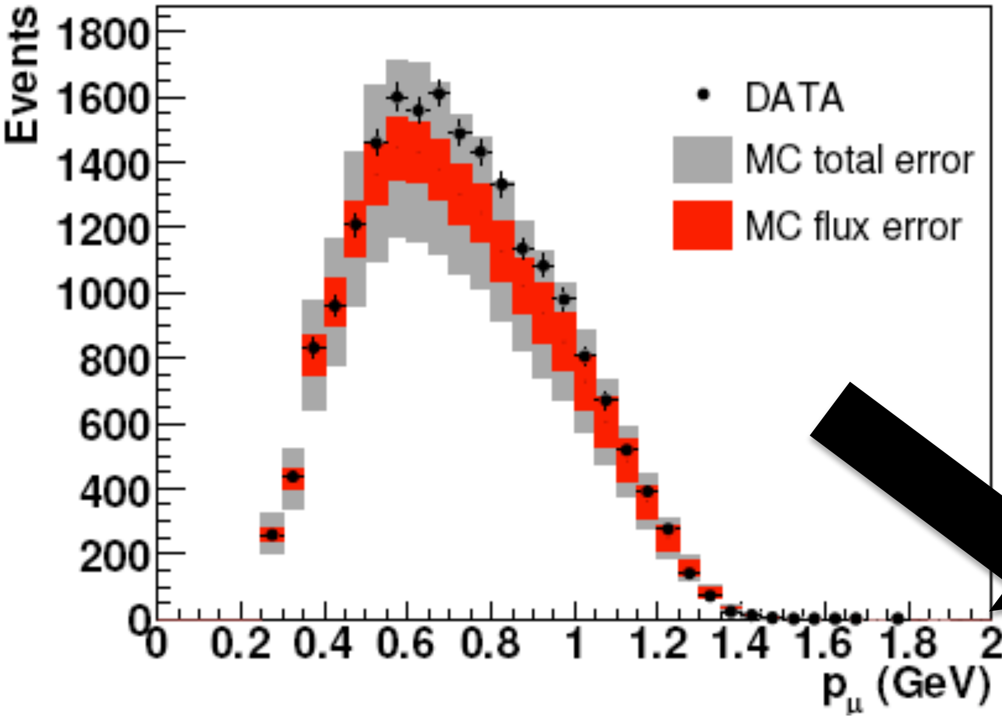
Use SciBooNE samples to determine $f(E_\nu)$ correction factors (with uncertainties)

Template fit to p_μ-θ_μ-E_ν slices

- SciBar stopped, MRD stopped and MRD penetrated samples are used
- Same analysis used to calculate CC interaction rate (Phys. Rev. D 83, 012005 (2011))



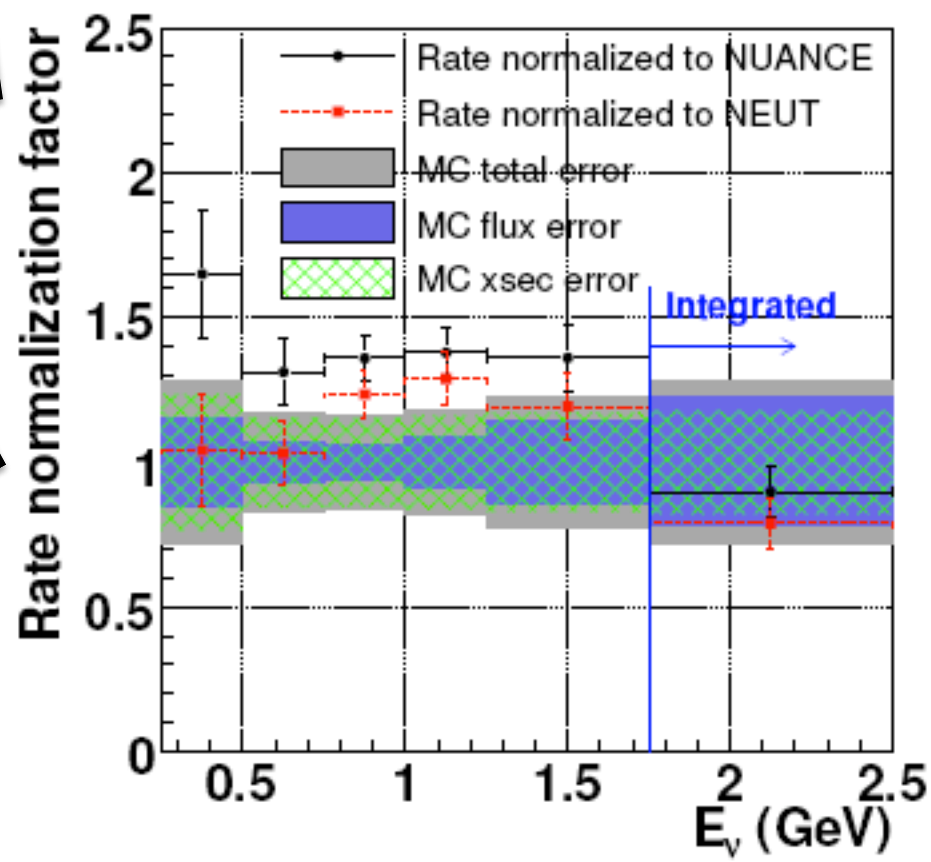
Spectrum fit method

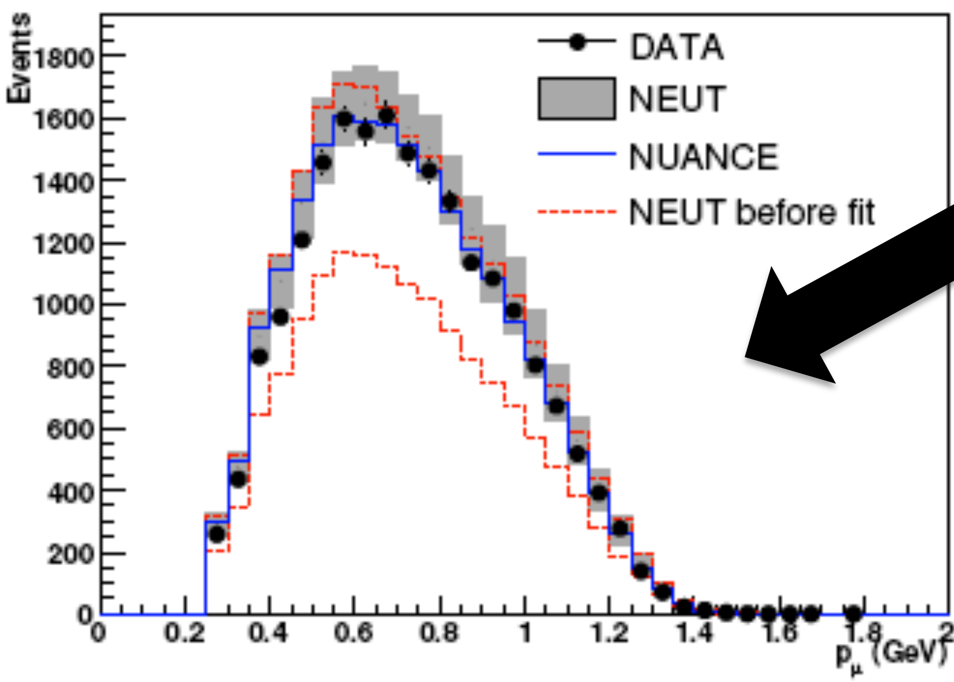


Use SciBooNE samples to determine f(E_ν) correction factors (with uncertainties)

Template fit to p_μ-θ_μ-E_ν slices

- SciBar stopped, MRD stopped and MRD penetrated samples are used
- Same analysis used to calculate CC interaction rate (Phys. Rev. D 83, 012005 (2011))

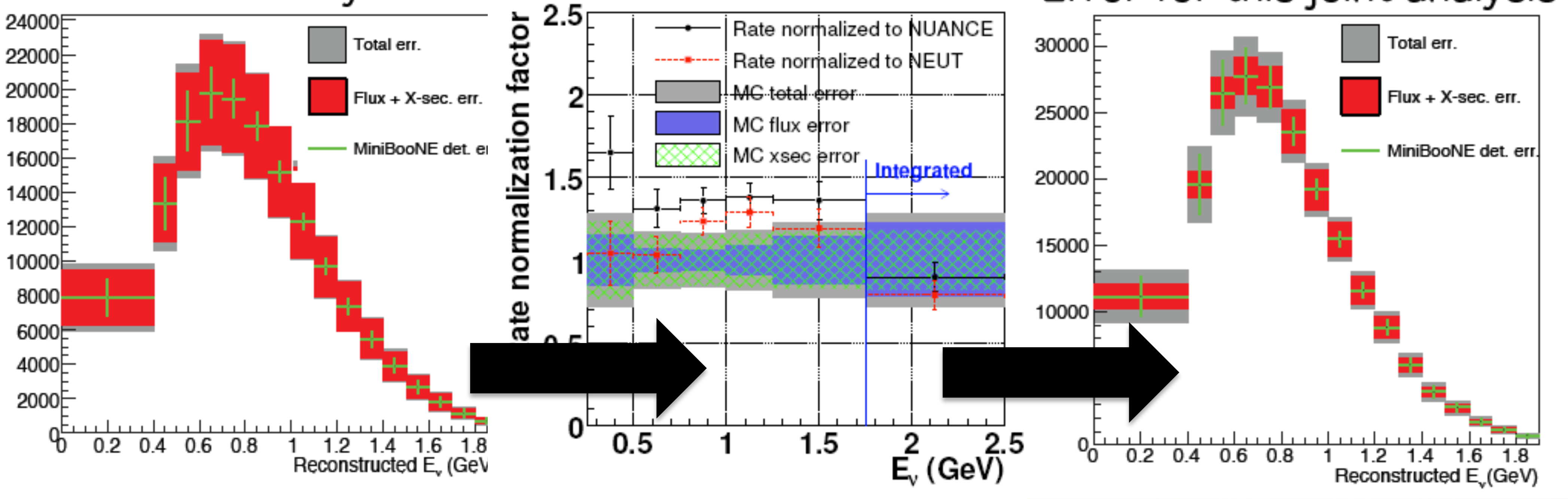




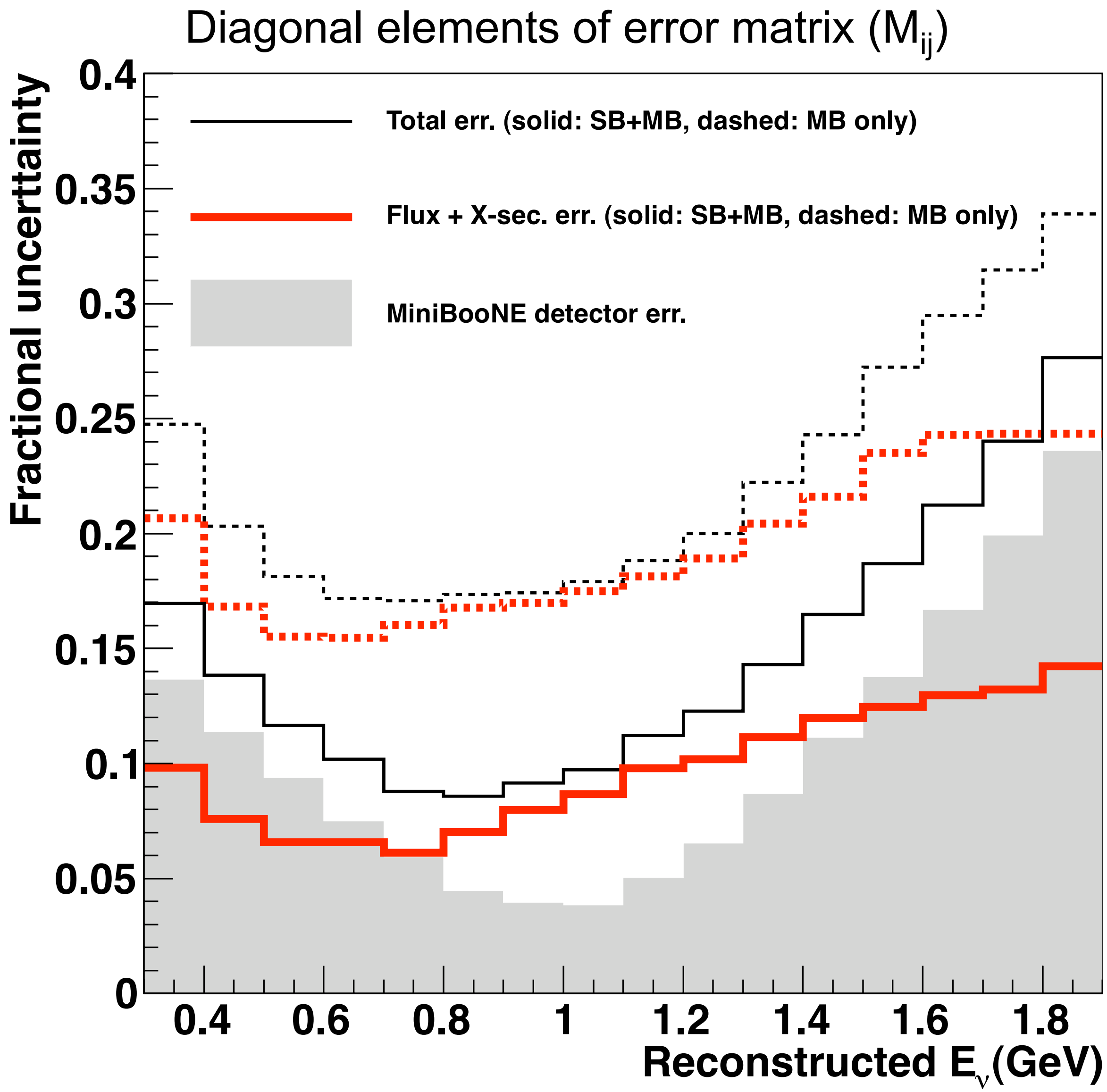
Effect of spectrum fit constraint at MiniBooNE

MiniBooNE only error

Error for this joint analysis



Effect of spectrum fit constraint at MiniBooNE



Rate constraint reduces flux and cross section uncertainties by approximately a factor of 2

Spectrum fit results

Fit MiniBooNE data only, for SB/MB run periods and MB only period
(16+16 bins in total = 32)

Best fit: Δm^2 =41.5 eV^2
$\sin^2 2\theta$ = 0.51

χ^2 (null) = 41.5/ 32 (DOF)
χ^2 (best) = 35.6/ 30 (DOF)

$\Delta\chi^2 = \chi^2(\text{null}) - \chi^2$ (best) = 5.9

$\Delta\chi^2$ (90% CL, null) = 8.4
(estimated from frequentist techniques)

No significant oscillation observed

MiniBooNE CCQE ν_μ dataset
+ prediction corrected from SciBooNE datasets (spectrum fit, reduced errors)