New antineutrino oscillation and other results from the T2K experiment

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Outline

- Introduction
- T2K experimental setup
- Oscillation analysis methodology
- **Updated anti-ν_μ disappearance**
- **First look at anti-ν_e appearance**
- A look toward future oscillation analyses
- Highlights from additional T2K physics: new cross section results

What is neutrino oscillation?

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

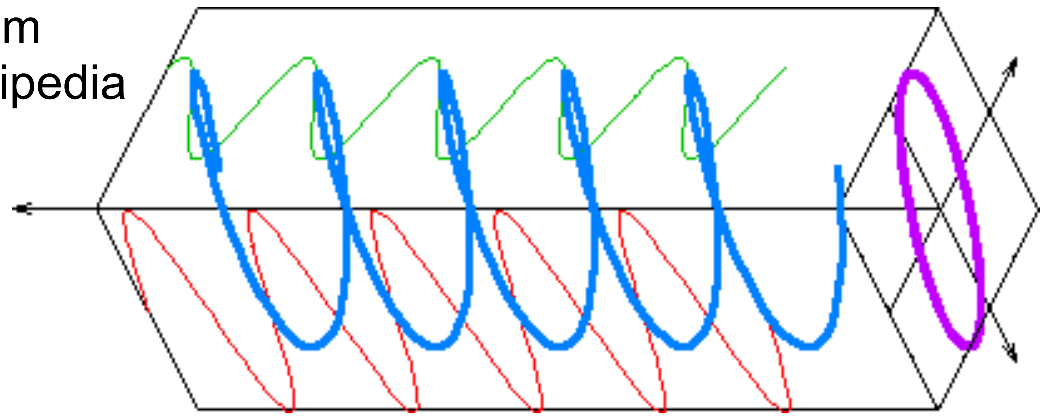
If we start with two neutrino flavor (ν_e, ν_μ) and two mass states (ν_1, ν_2) then:

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

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

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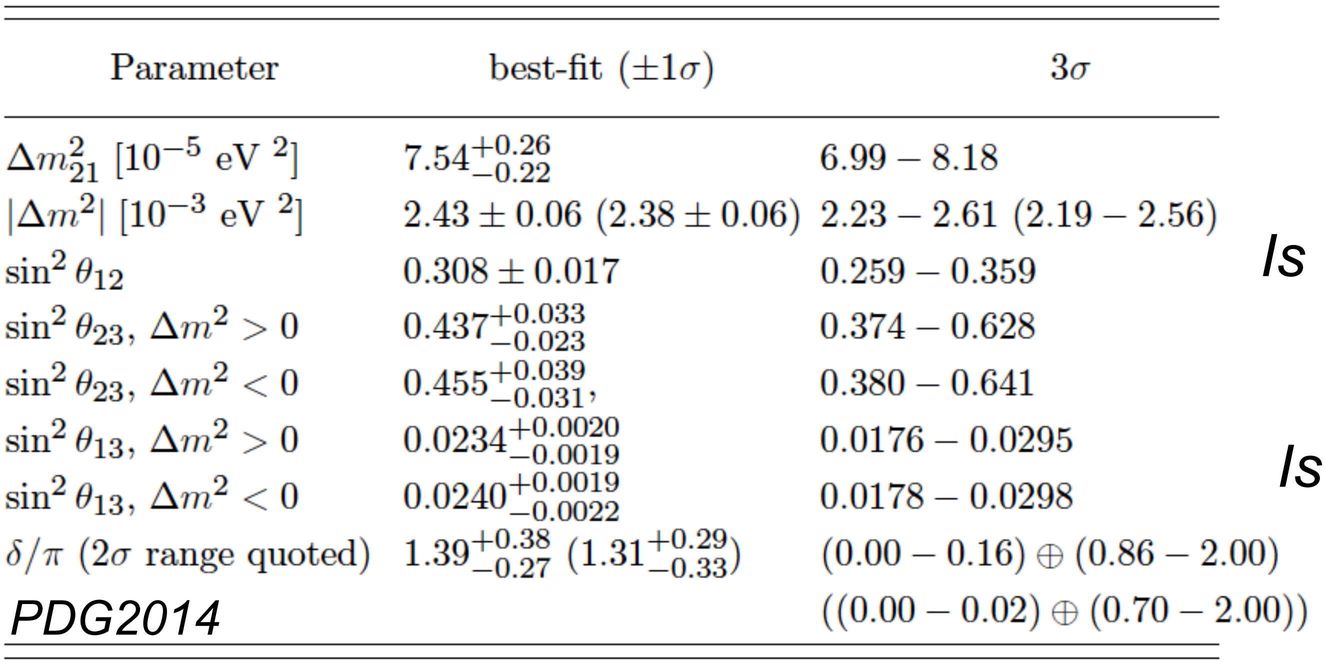
Flavor eigenstates (coupling to the W)

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

Mass eigenstates (definite mass)

Unitary PMNS mixing matrix

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



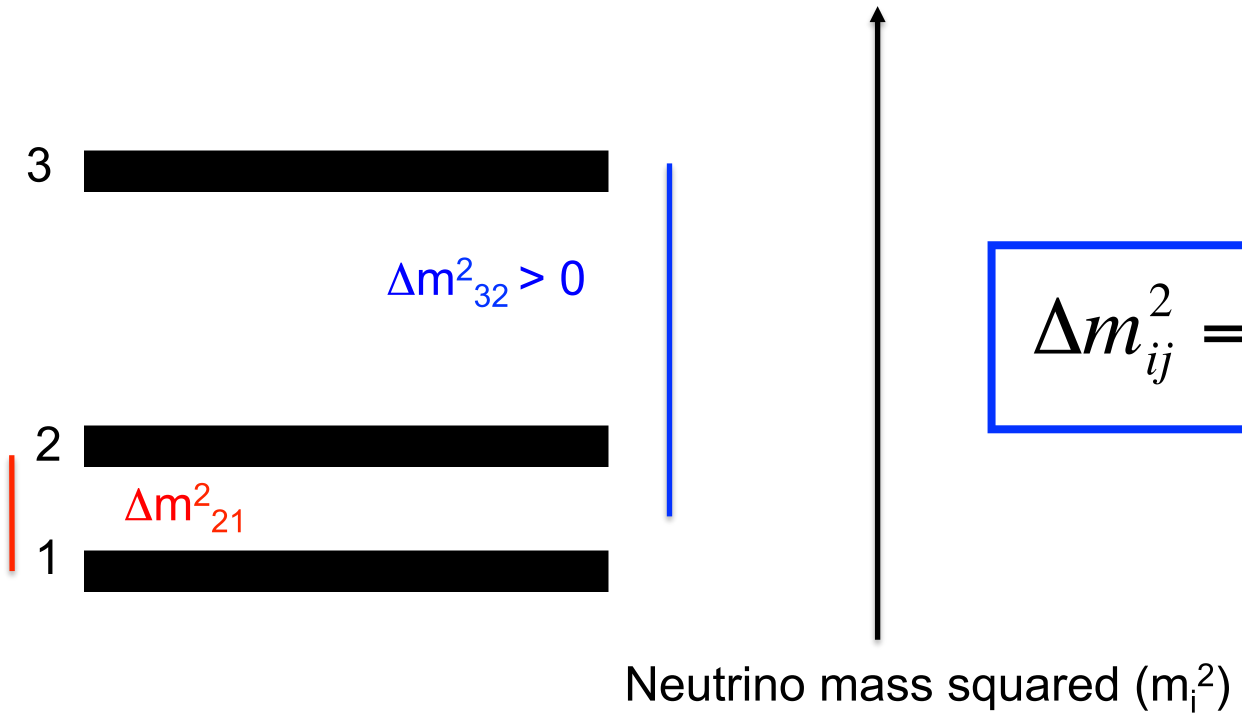
Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$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

PDG2014

Is θ_{23} mixing maximal (θ_{23}=46°±3°)

Is there CP violation (non-zero δ?)

Open questions about neutrino mixing



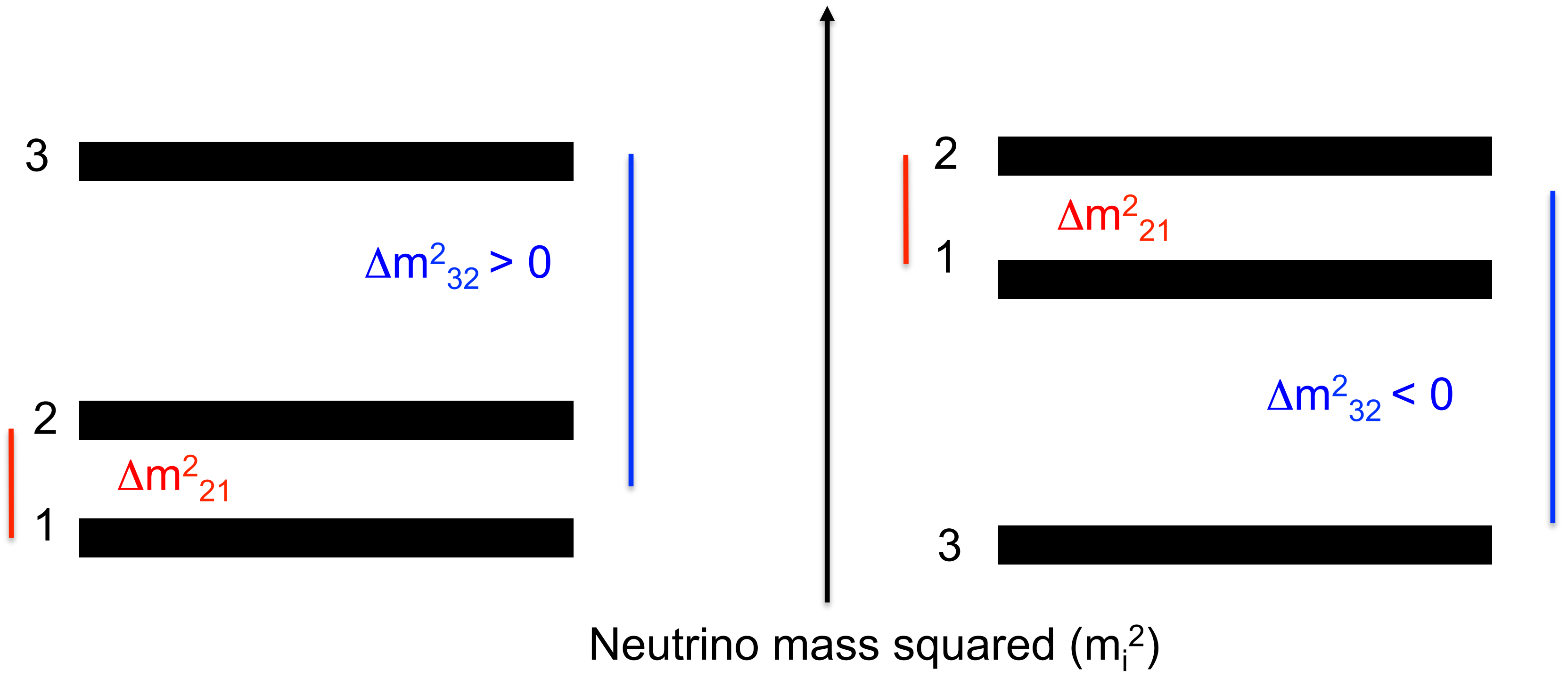
$$\boxed{\Delta m^2_{ij} = m^2_i - m^2_j}$$

Neutrino oscillation measurements are sensitive to the interference of the mass eigenstates (Δm^2)

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

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

Open questions about neutrino mixing



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

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

What is the mass hierarchy?

Oscillation probabilities

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

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

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

ν_μ "disappear" into ν_e, ν_τ

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

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

ν_μ to ν_e appearance probability expansion:

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

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} << 1,$$

$$\Delta = \frac{\Delta m^2_{32}L}{4E_\nu}$$

$$A = 2\sqrt{2}G_F N_e\frac{E_\nu}{\Delta m^2_{32}}$$

Key players:

- $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2 (atmospheric mass splitting)
- Mixing angles: θ_{12}, θ_{23}, θ_{13}
- CP-violating phase δ_{CP}

Approximation from
M. Freund, PRD 64, 053003

Neutrinos vs. antineutrinos probability depends on δ_{CP}, mass hierarchy (sign of Δm^2_{32})

- Mass hierarchy is determined through energy dependence of ν_e, ν_μ interactions in matter (matter effects, A terms)

Oscillation probabilities

ν_μ to ν_e appearance probability expansion:

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

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

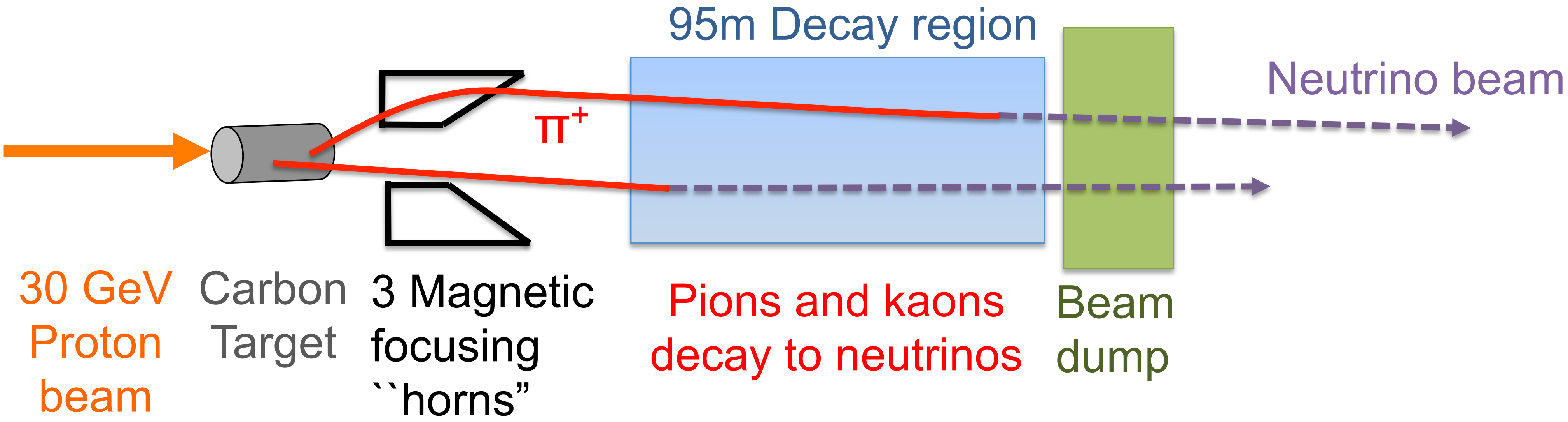
Key players:

- $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2 (atmospheric mass splitting)

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} (disappearance) and Δm^2_{21}, θ_{12} and θ_{13}

Measurements of ν_μ to ν_e (and $\overline{\nu_\mu}$ to $\overline{\nu_e}$) appearance are sensitive to currently unknown physics

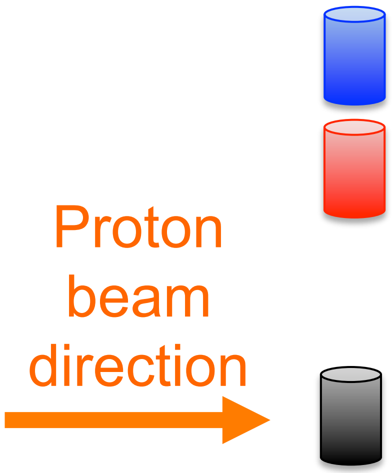
Accelerator-based neutrino sources



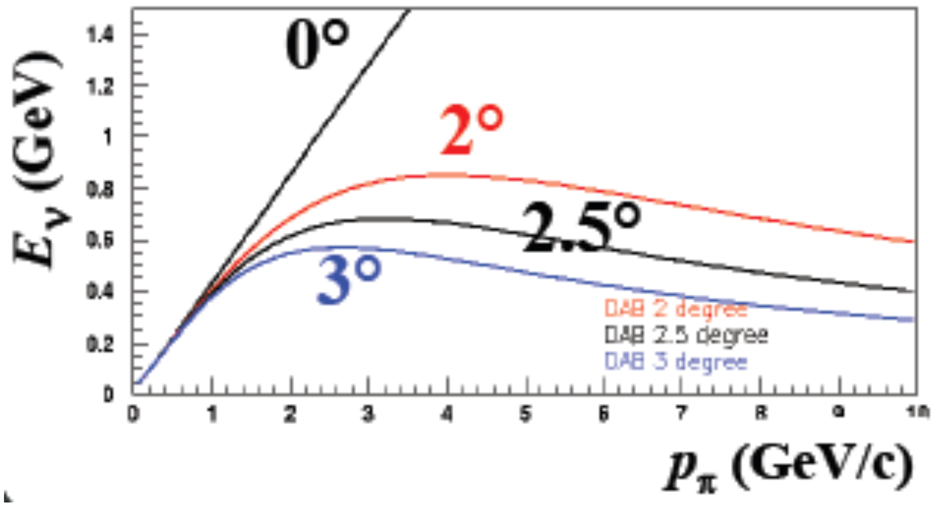
Neutrinos are produced as a **tertiary beam**:

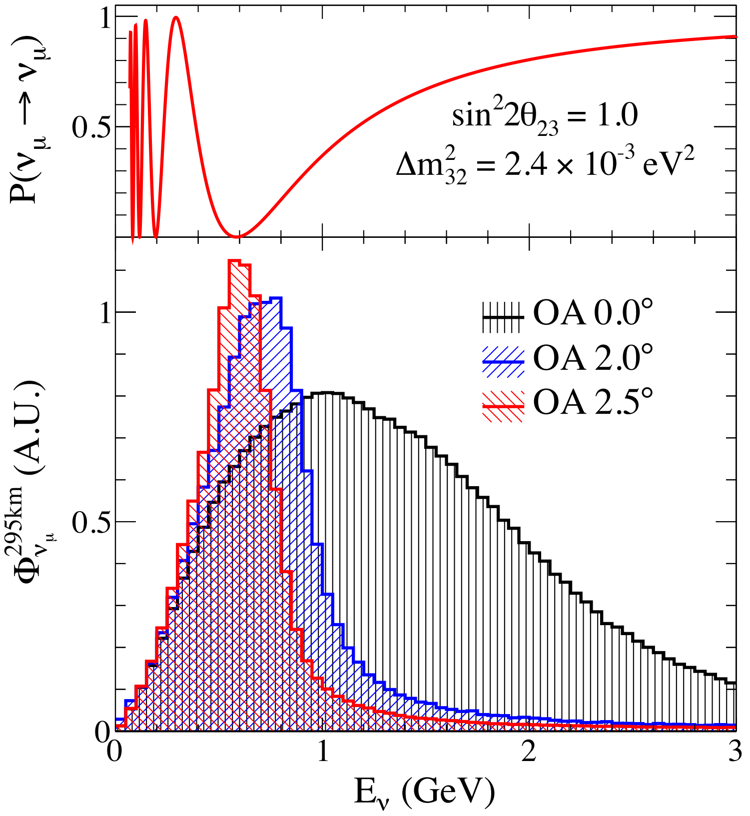
1. Protons hit a target, producing pions and kaons which decay to neutrinos
2. Resulting **beam is >99% muon neutrino flavor,** small ν_e component from muon, kaon decay; ~7% antineutrino component
3. Can switch magnetic horn polarization to focus π^- and produce an **predominantly antineutrino** beam (with a ~10% neutrino component)

Accelerator-based neutrino sources



Proton beam direction





PRD 88, 032002 (2013)

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

- Proton beam energy
- Position of the detector relative to the proton beam direction
- "Off axis" beams maximize the event rate at the point of expected oscillation

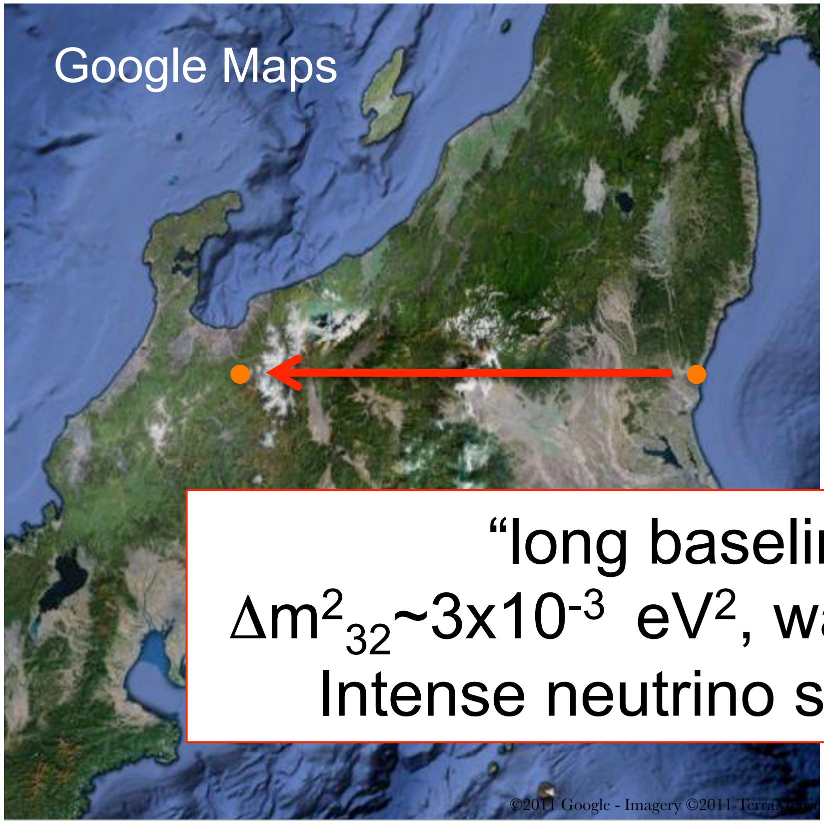
Long-baseline experiments

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):

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

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

MINOS experiment: On-axis Eν(peak) ~3 GeV, L=735km



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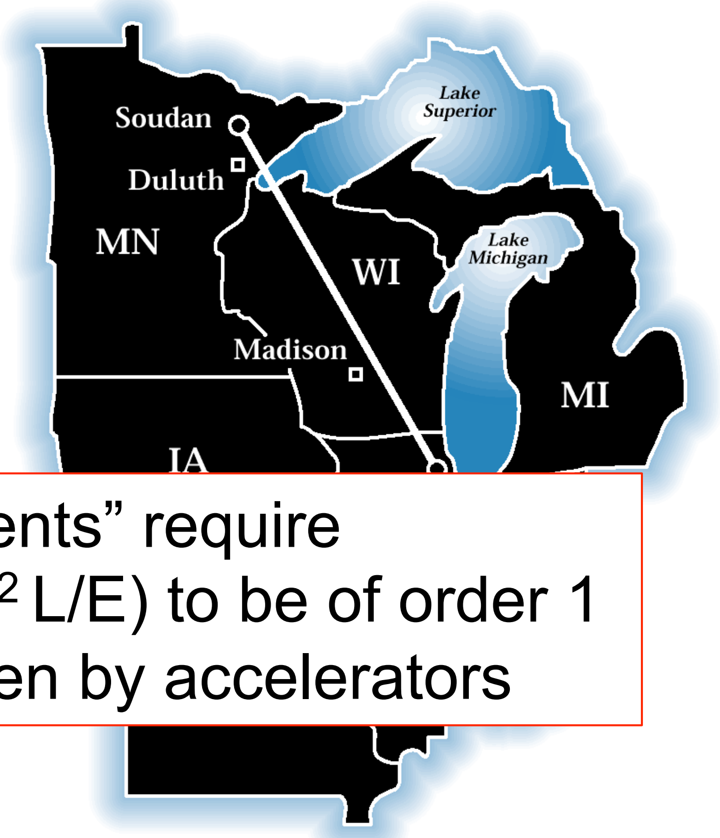


"long baseline experiments" require

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

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):

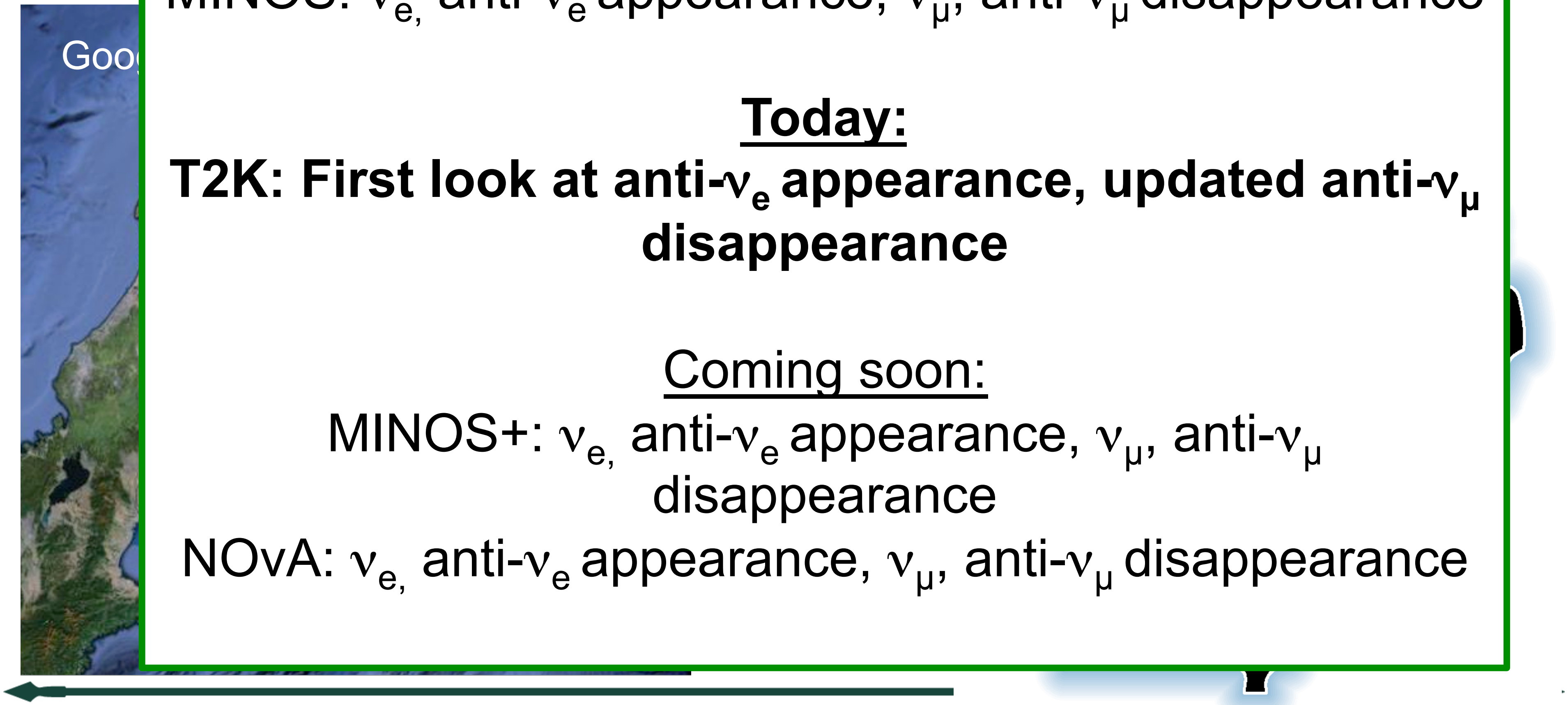
$$\left(1.27\Delta m^2_{32}L\right)$$

Tokai To

Off-axis

kis

m



<u>Recent long baseline measurements:</u>

T2K: ν_e appearance, ν_μ disappearance

MINOS: $\nu_{e,}$ anti-ν_e appearance, ν_μ, anti-ν_μ disappearance

<u>Today:</u>

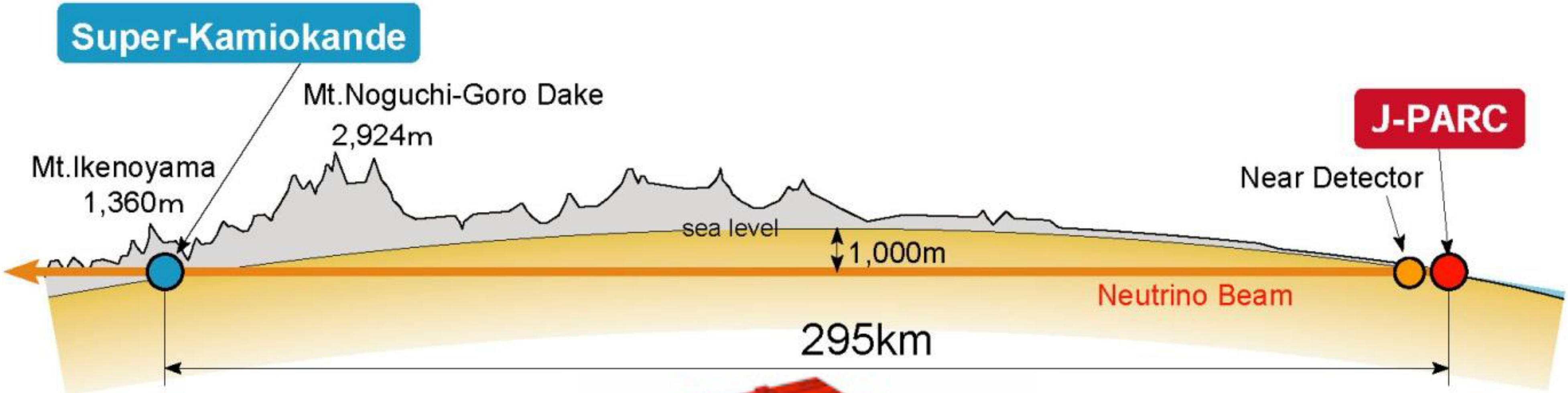
T2K: First look at anti-ν_e appearance, updated anti-ν_μ disappearance

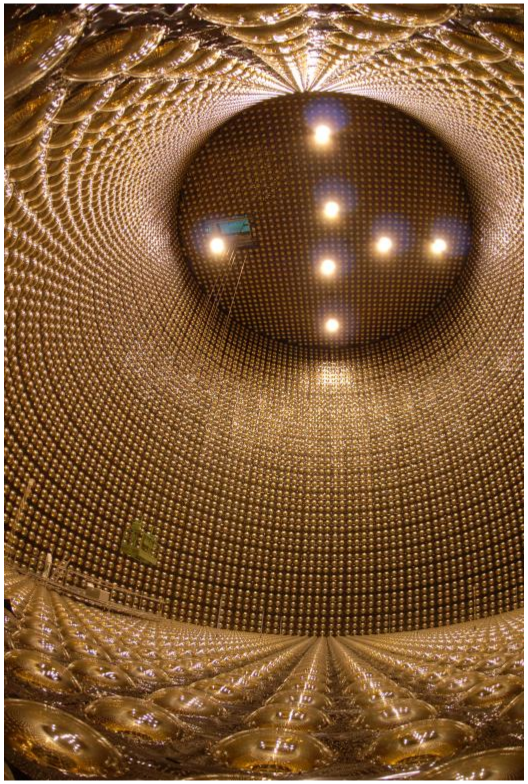
<u>Coming soon:</u>

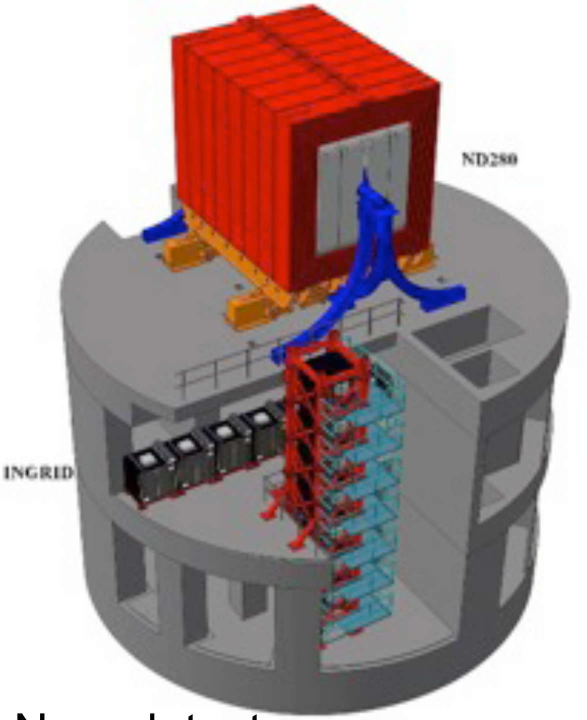
MINOS+: $\nu_{e,}$ anti-ν_e appearance, ν_μ, anti-ν_μ disappearance

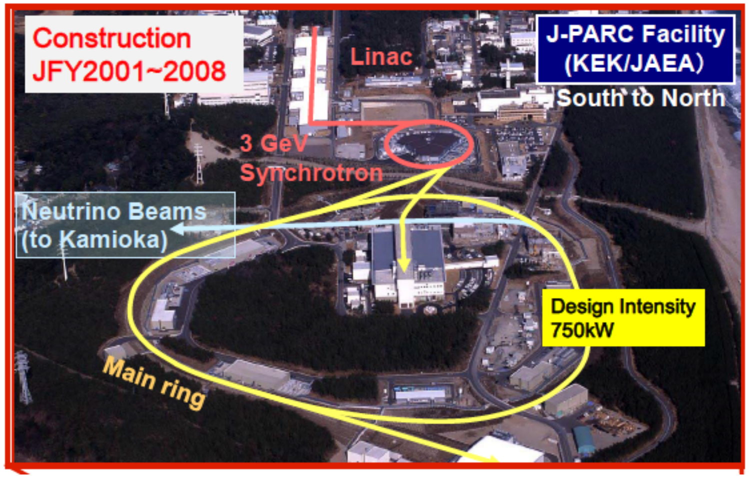
NOvA: $\nu_{e,}$ anti-ν_e appearance, ν_μ, anti-ν_μ disappearance

T2K experimental overview







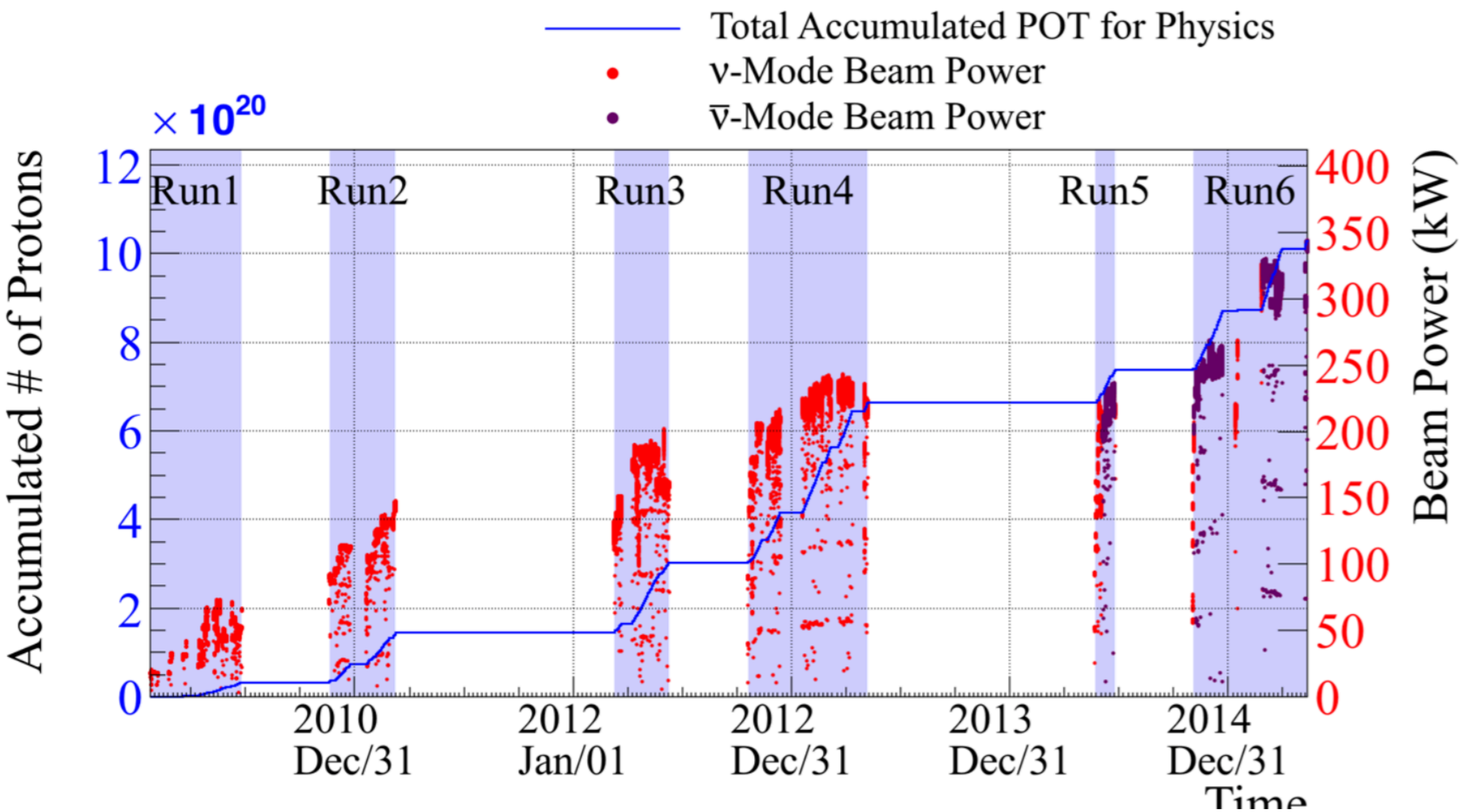


J-PARC accelerator

Near detectors
Off-axis: ND280 On-axis: INGRID

Far detector

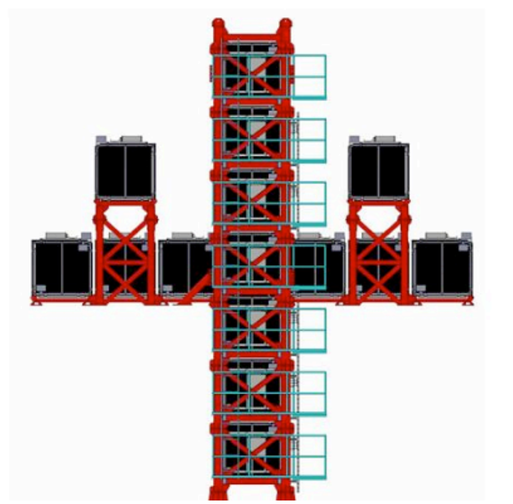
T2K data periods

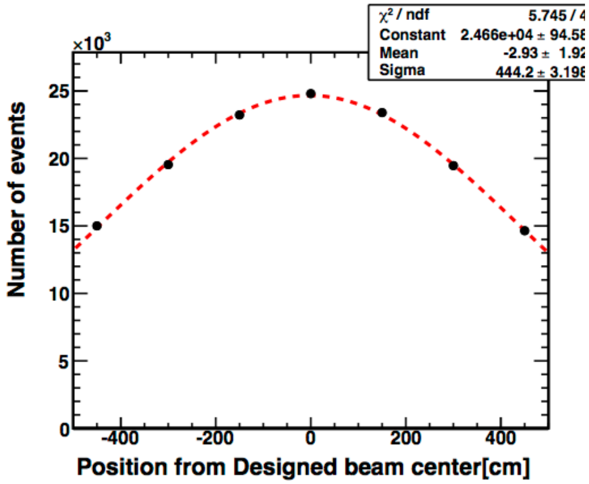


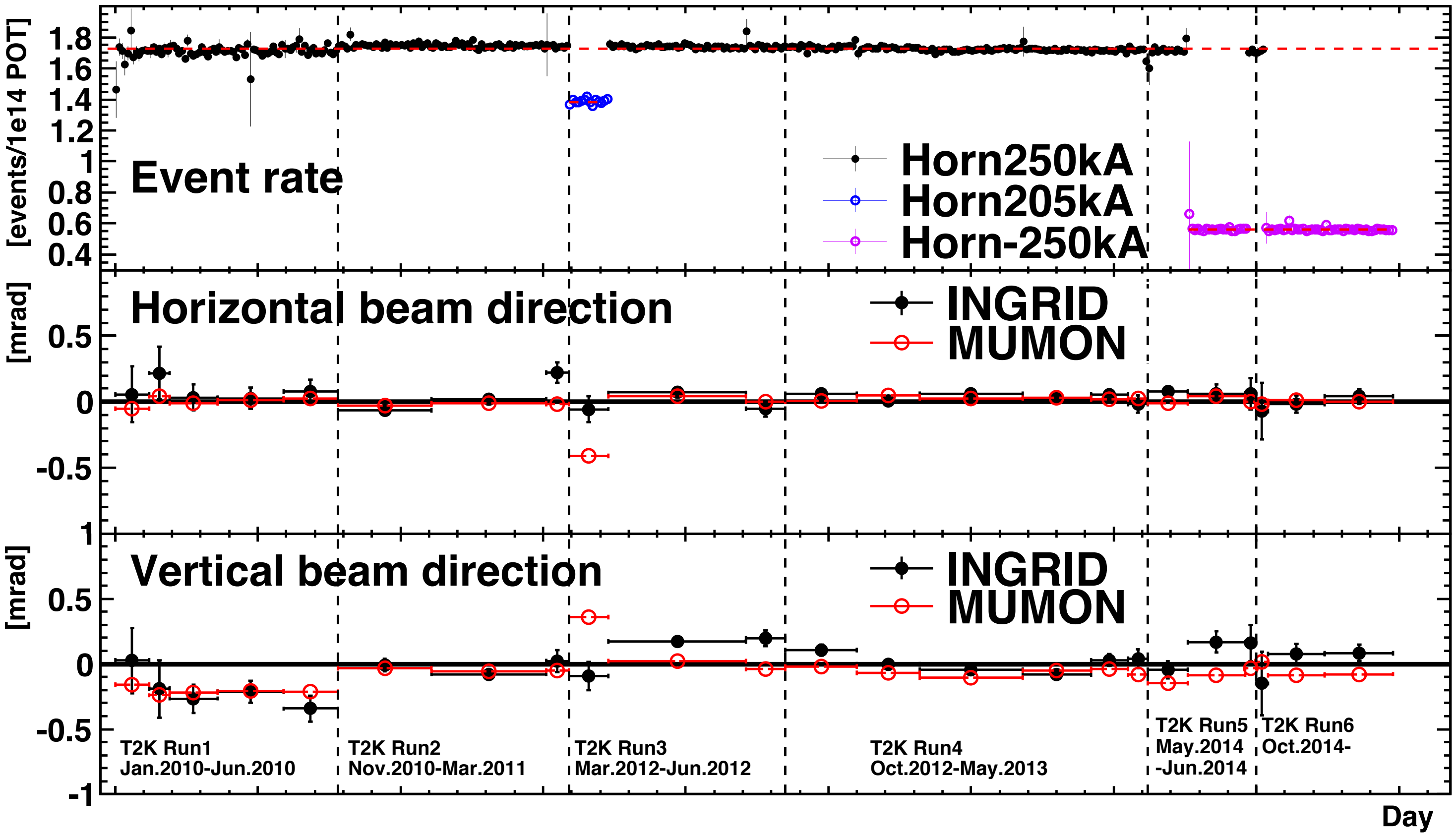
Protons on Target (POT) for the antineutrino analyses today:

- Run 5c+6 datasets for far detector, Super-Kamiokande: 4.0 x 10^{20} POT
- Run 5c datasets for off-axis near detector, ND280: 4.3 x 10^{19} POT

T2K beam stability







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

- POT normalized event rate stable to 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

T2K oscillation analyses overview

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

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:

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

Neutrino flux prediction

Neutrino cross section model

Near detector selection, efficiency

T2K oscillation analyses overview

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

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

Neutrino cross

Far detector

Even with state of the art antineutrino beams, analyses presented today are statistics limited

However, significant background to antineutrino analyses from *neutrino* interactions motivates consistent treatment and inclusion of neutrino data in analysis

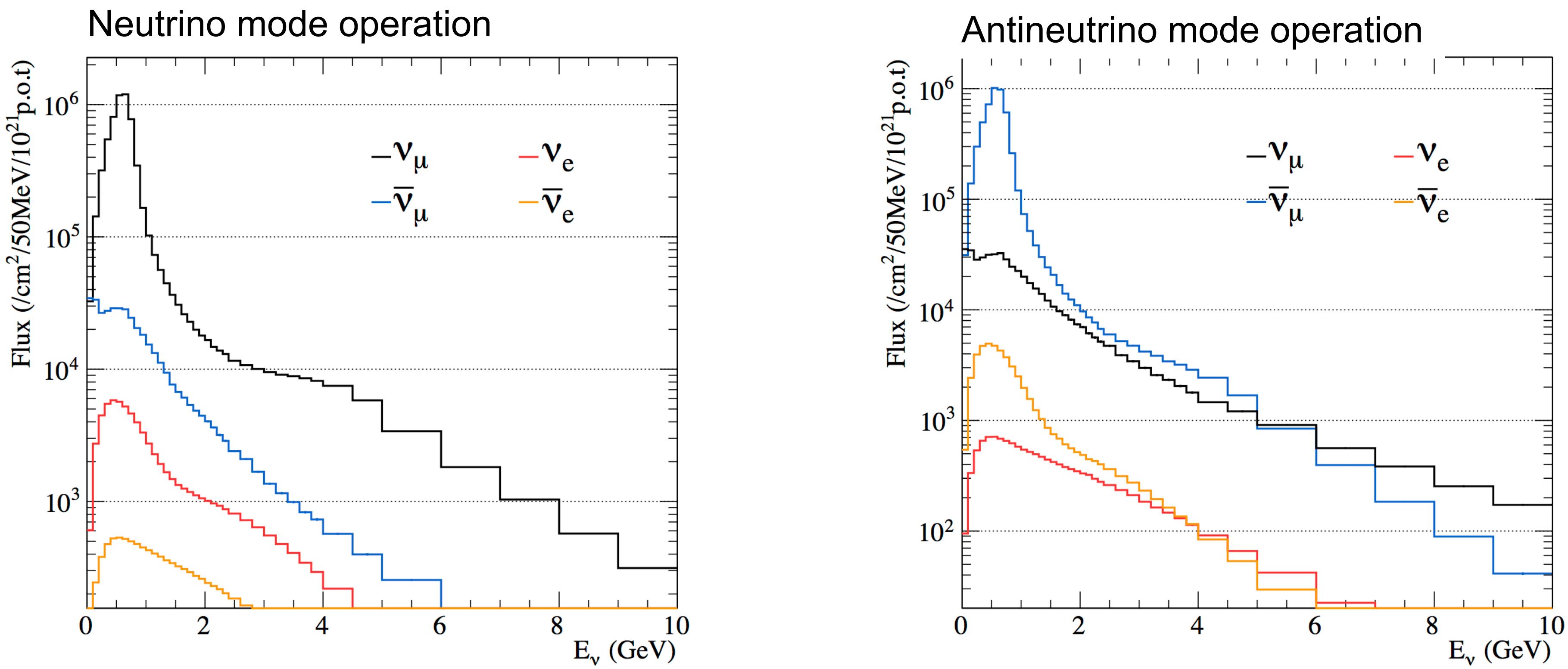
N

prediction

model

efficiency

T2K neutrino, antineutrino flux


Neutrino mode operation

Antineutrino mode operation

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

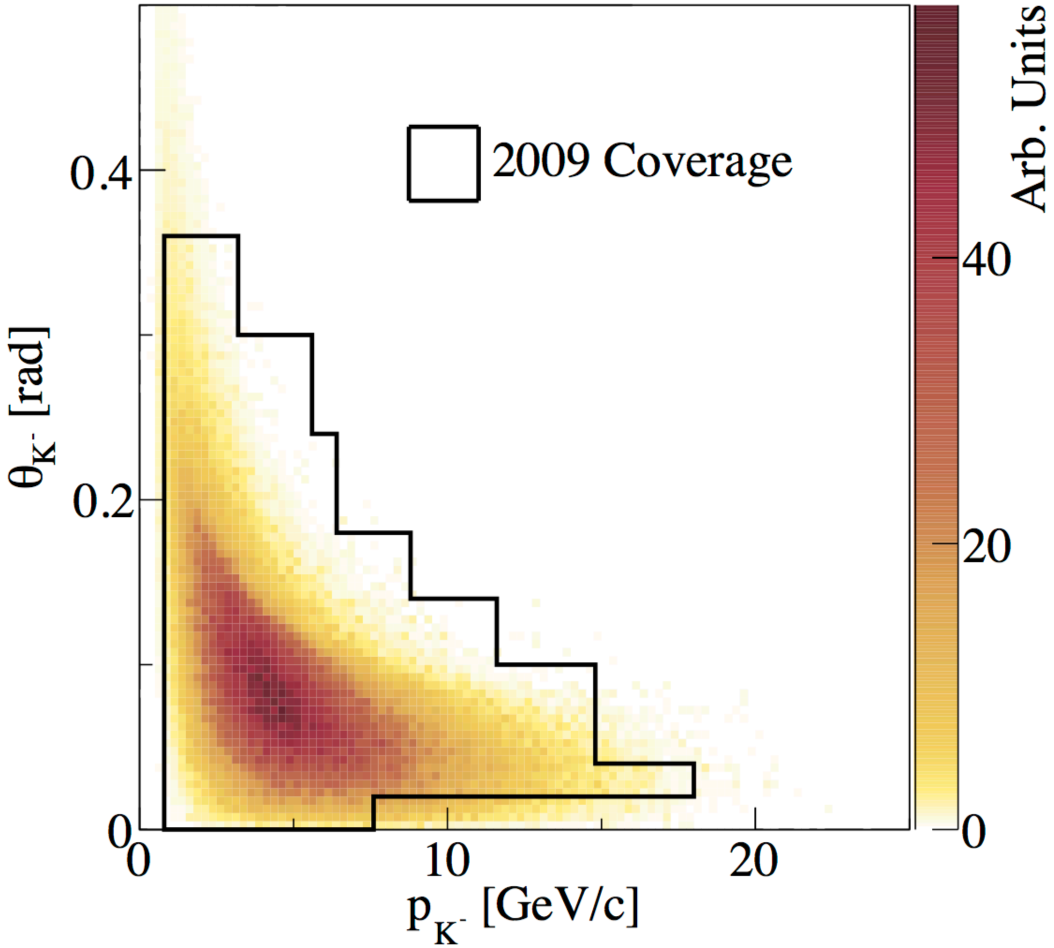
- Significant neutrino component to antineutrino mode beam
  - Increases in event rate due to lower antineutrino cross section
- Also called “wrong sign” component:

- “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

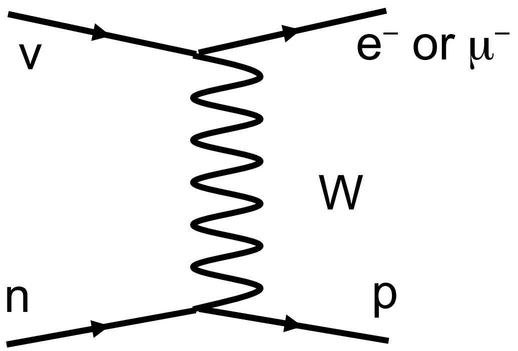
Uncertainties are comparable for neutrino or antineutrino mode operation (10-15%)

Neutrino interaction model

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

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

CCQE

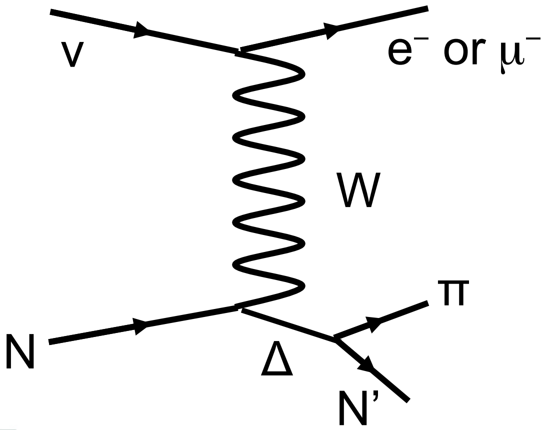


Infer neutrino properties from the lepton momentum and angle:

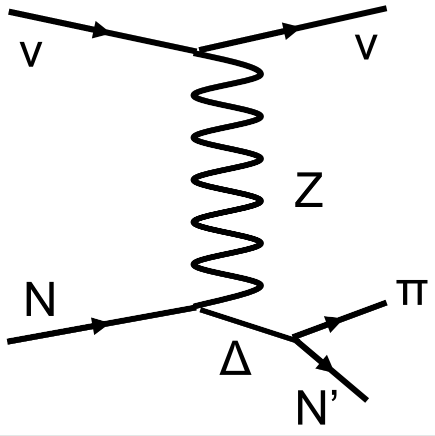
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

CCπ



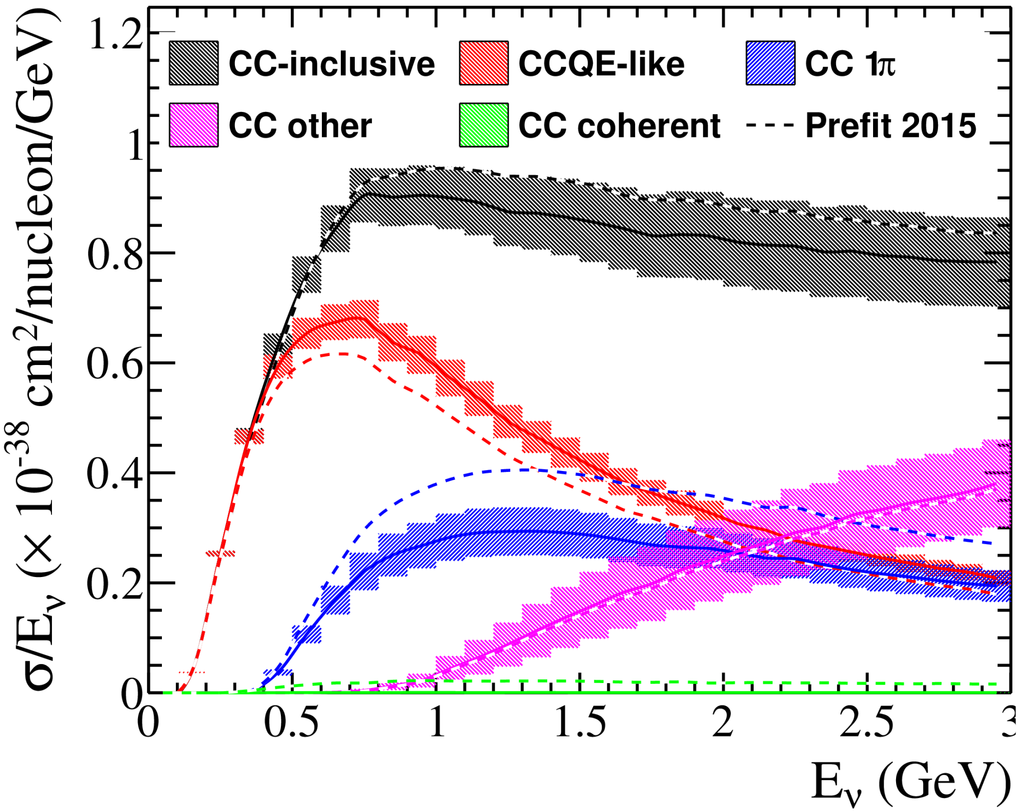
NCπ

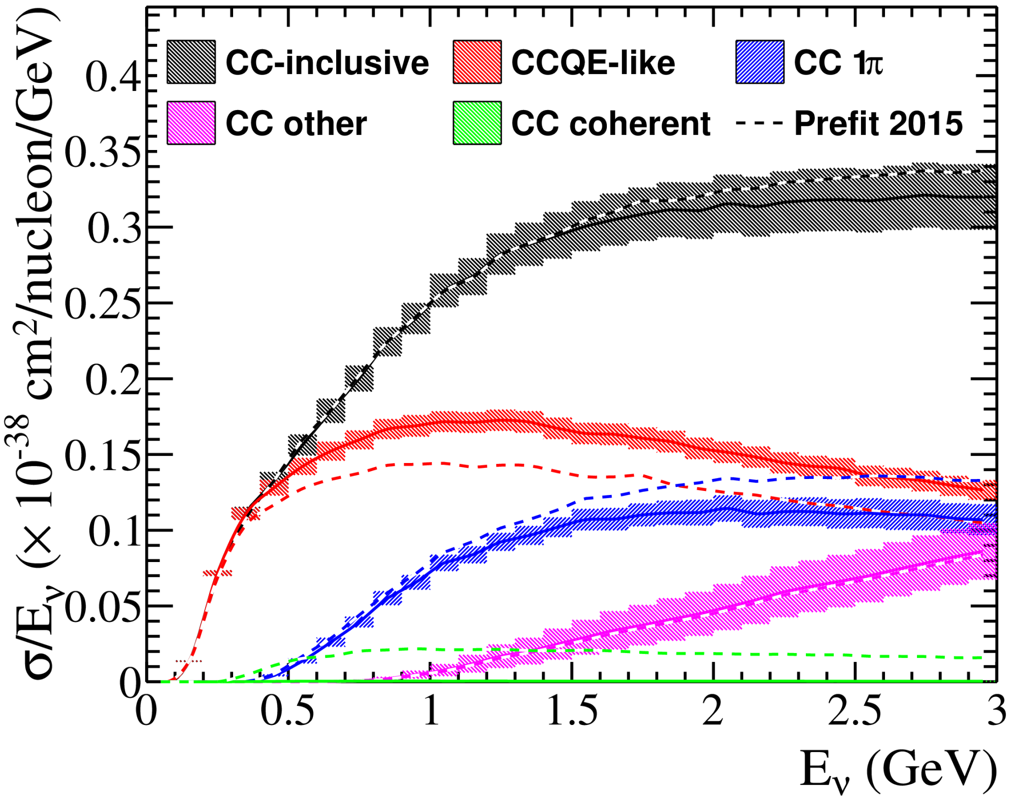


Additional significant processes:

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

Improved interaction models

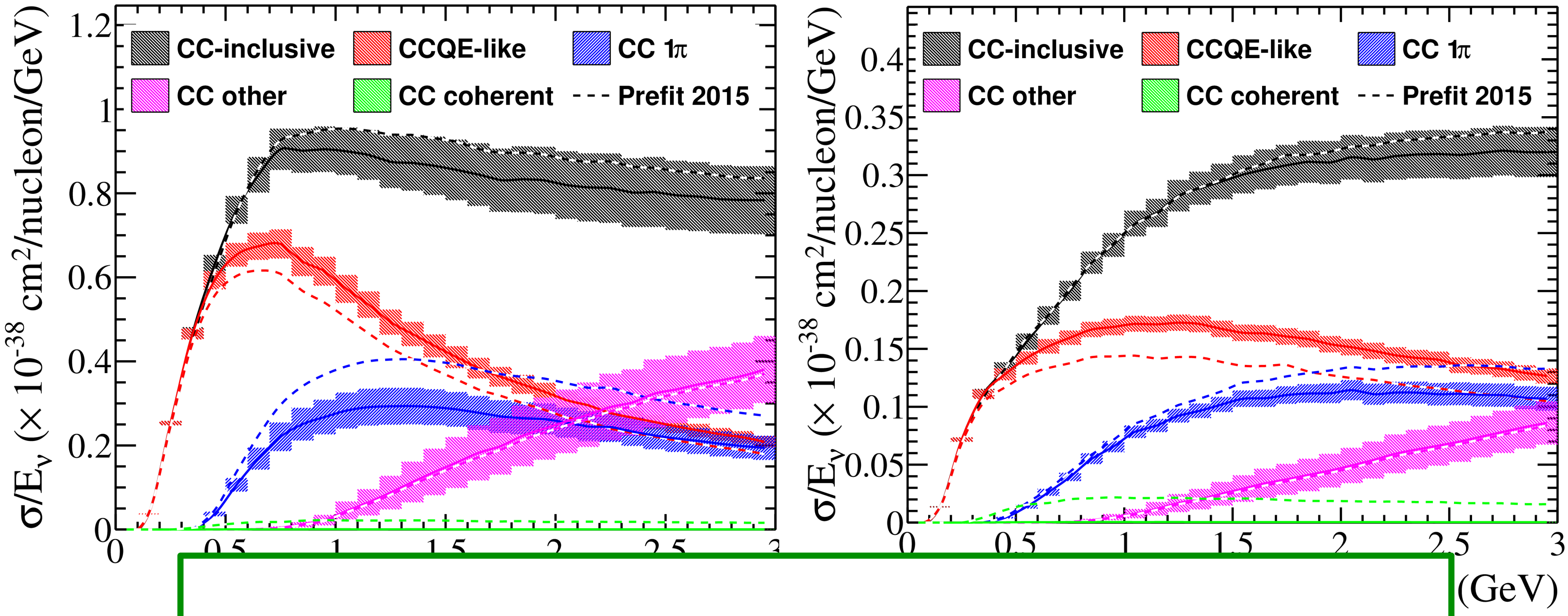




NEUT model (5.3.2+) for 2015 (antineutrino, neutrino+antineutrino) analyses:

- 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 interaction models



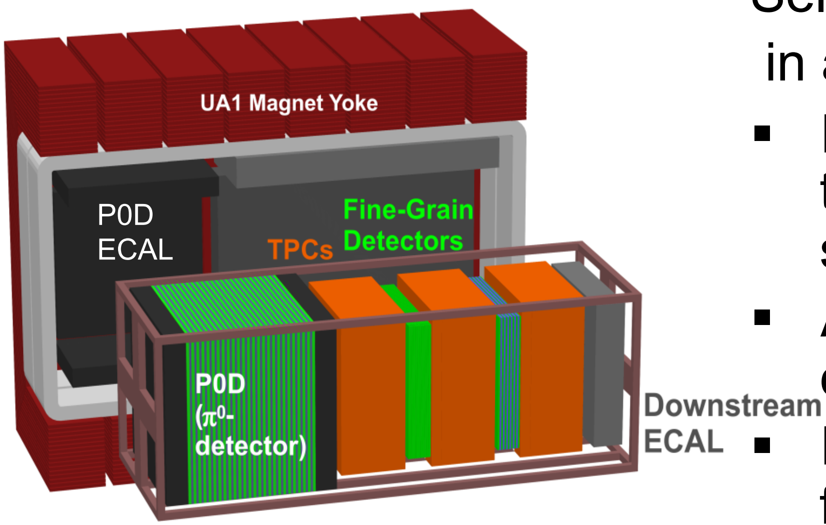
NEUT m **es:**

- Two ne
  - CC GeV/c2.
  - CC
  - Ne
- 1π (N Delta.

No pio

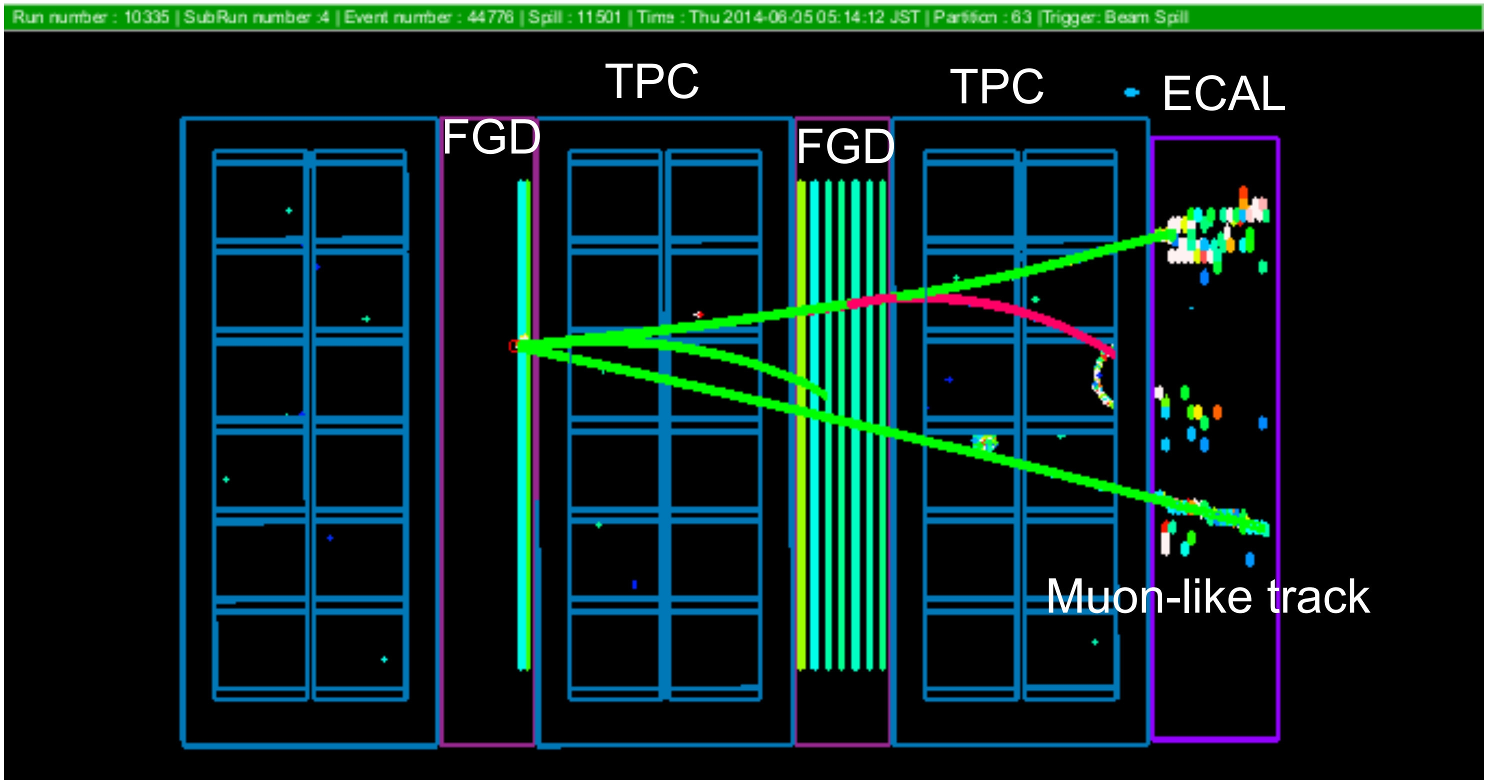
Tuned NEUT
(dashed, prefit 2015, RPA+RFG+MEC model based on from fits to external cross section measurements by MINERvA, MiniBooNE, bubble chamber data) compared to NEUT with near detector data tuning (solid with associated errors)

T2K off-axis near detectors: ND280



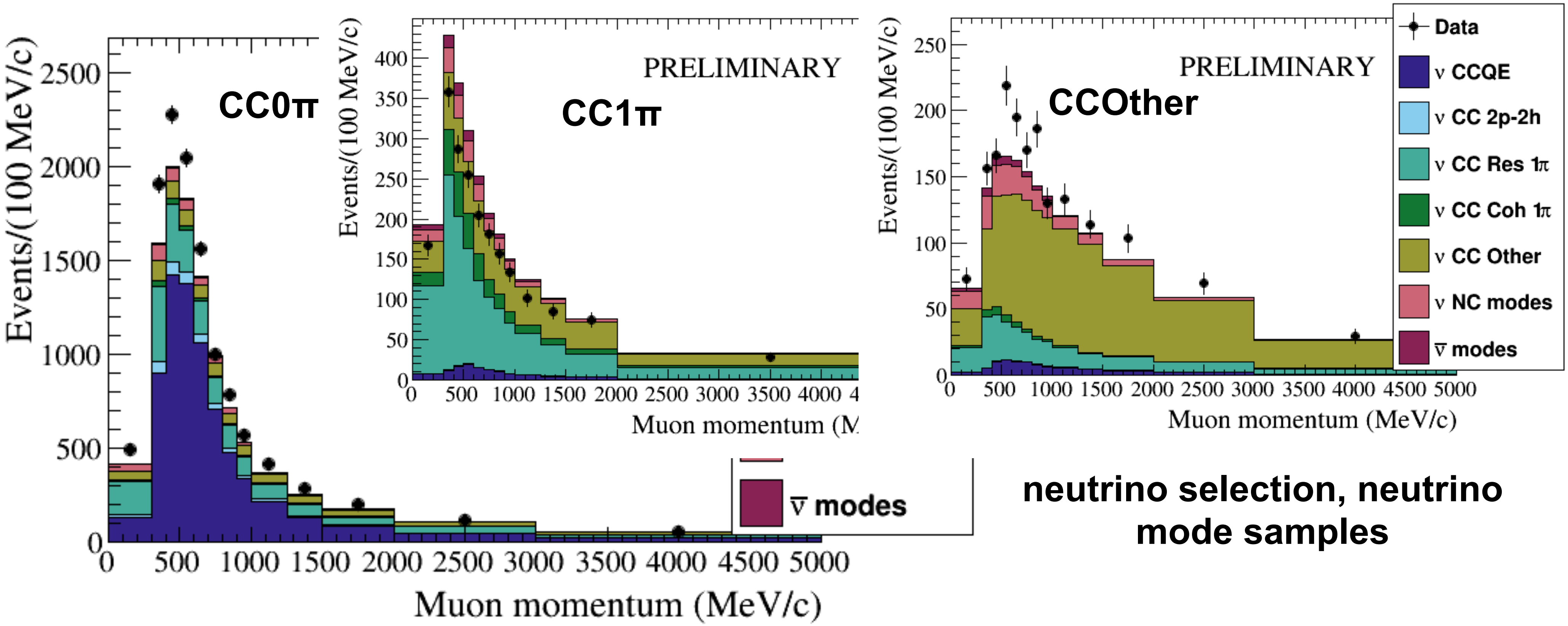
Select CC ν_μ, $\overline{\nu_\mu}$ candidates prior to oscillations in an off-axis tracking detector (ND280)

- 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

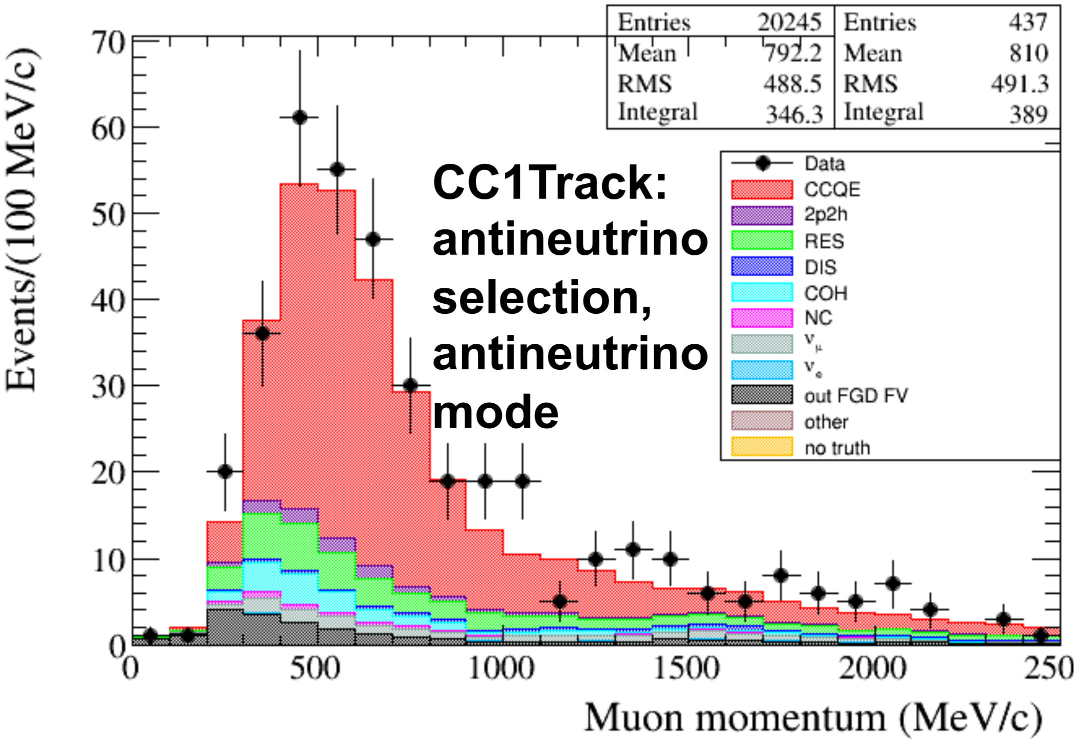
ND280 data samples: antineutrino mode

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

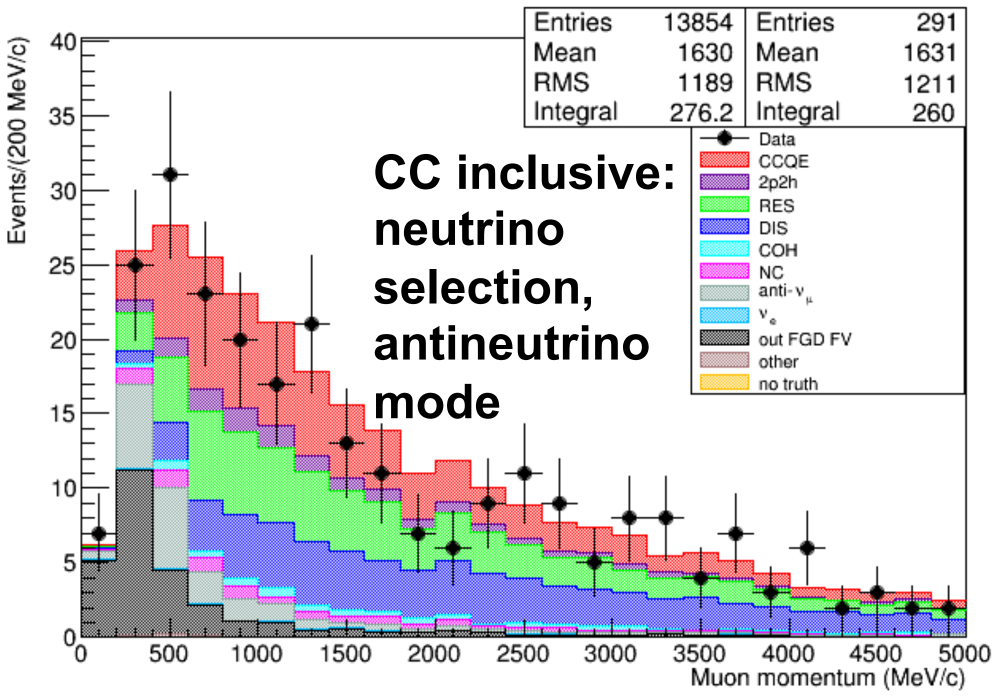
- Select highest momentum track with positive charge, and PID consistent with a muon
- Two sub-samples based on track multiplicity: CC1-Track, CC>1 Track

Complementary selection of neutrino candidates in antineutrino mode

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

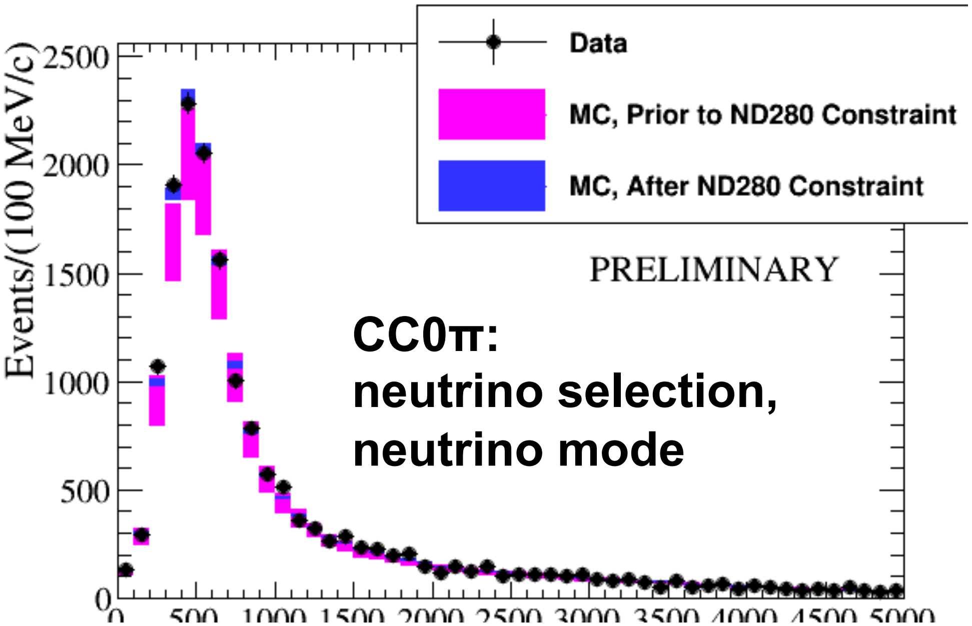


CC1Track: antineutrino selection, antineutrino mode



CC inclusive: neutrino selection, antineutrino mode

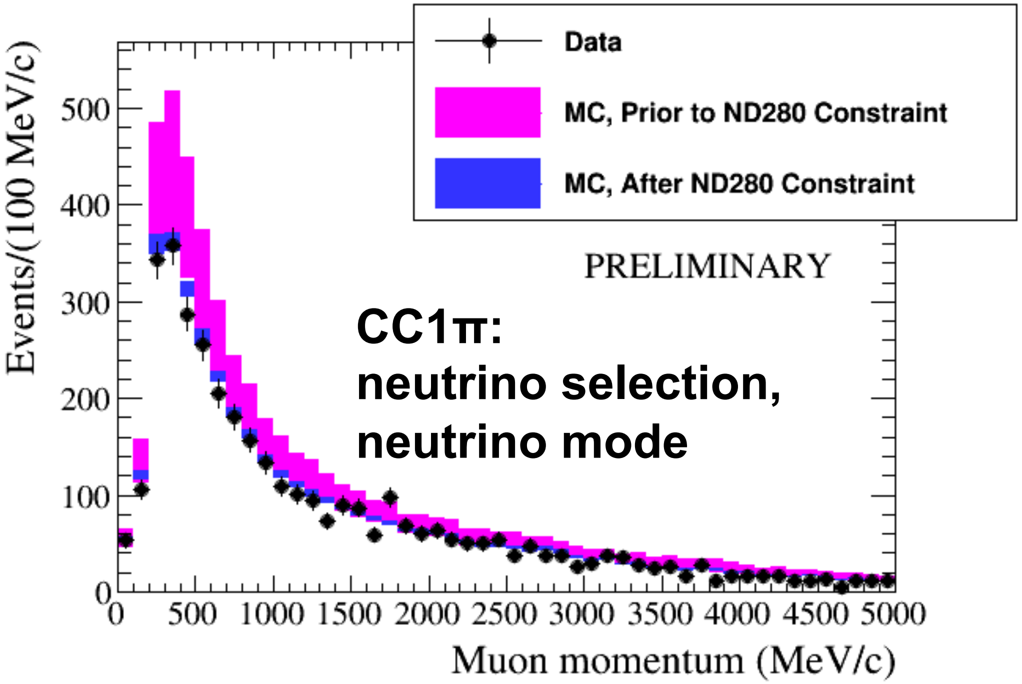
Near detector rate measurement



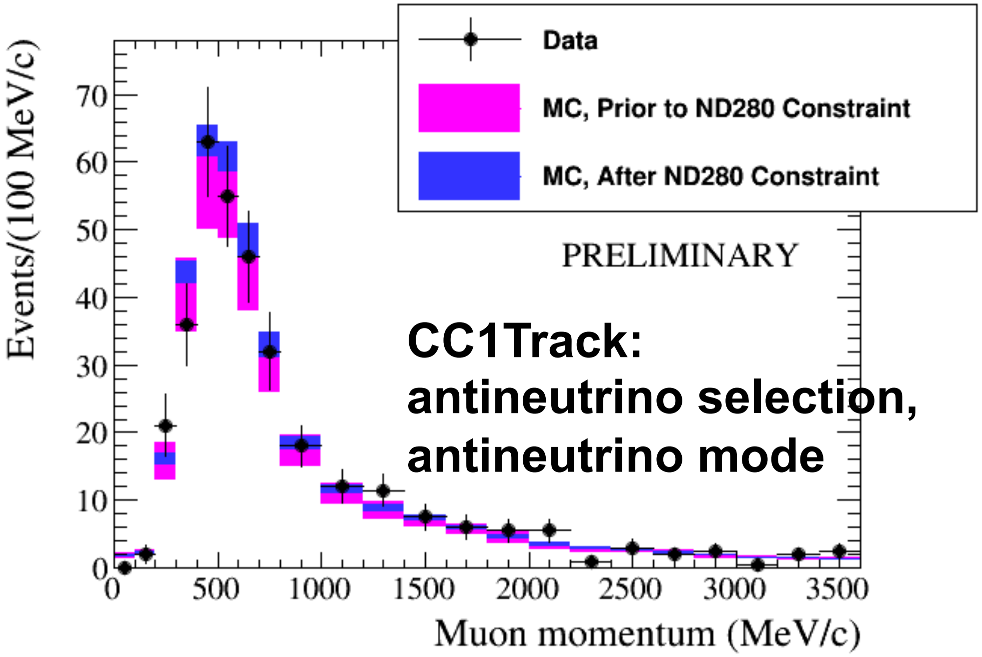
CC0π: neutrino selection, neutrino mode

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

- Neutrino, antineutrino fluxes are highly correlated between near and far detectors
- Cross sections are also correlated
- Significant reduction to overall uncertainties

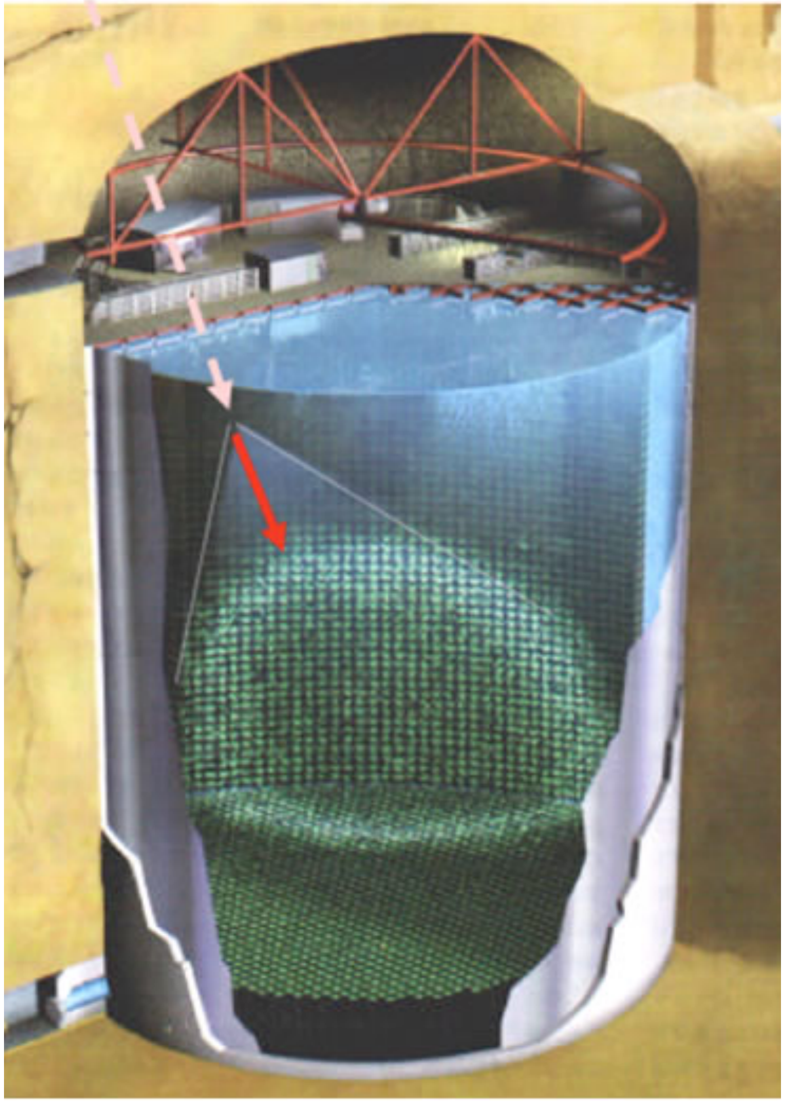


CC1π: neutrino selection, neutrino mode



CC1Track: antineutrino selection, antineutrino mode

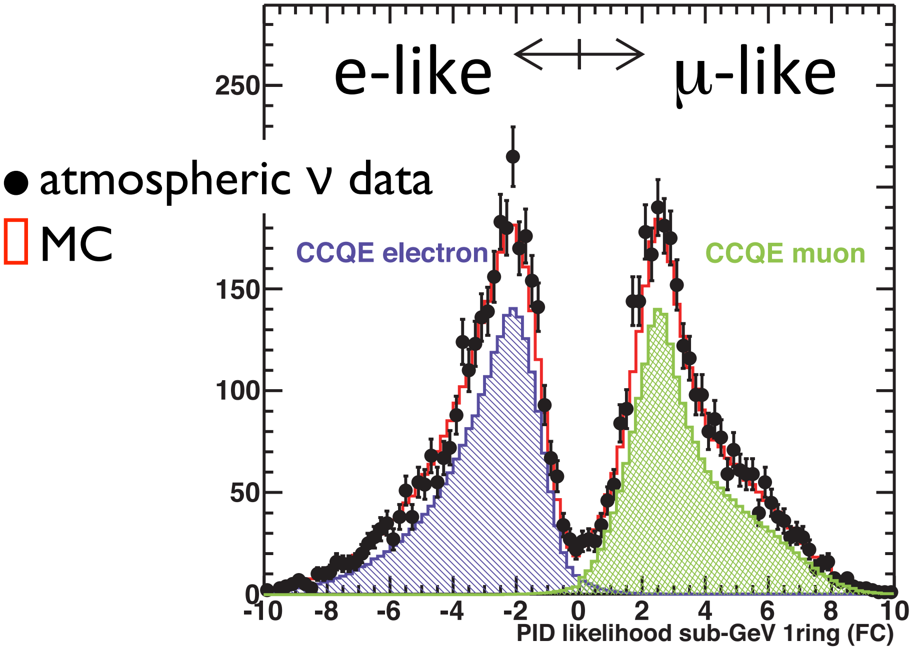
T2K far detector: Super-Kamiokande



Example atmospheric neutrino interaction

Select CC $\overline{\nu}_e$ and $\overline{\nu}_\mu$ candidates, in a 50kton water Cherenkov detector (Super-Kamiokande)

- Efficient for (CCQE-like) interactions
    - Select single ring (only lepton above threshold)
    - Decay electron (from below threshold μ or π final state) tagging capability
- Determine lepton flavor based on ring topology
    - Excellent muon-electron separation; 1% rate of mu identified as e
- Lacks sign selection separation of $\nu, \overline{\nu}$



Antineutrino oscillation analyses

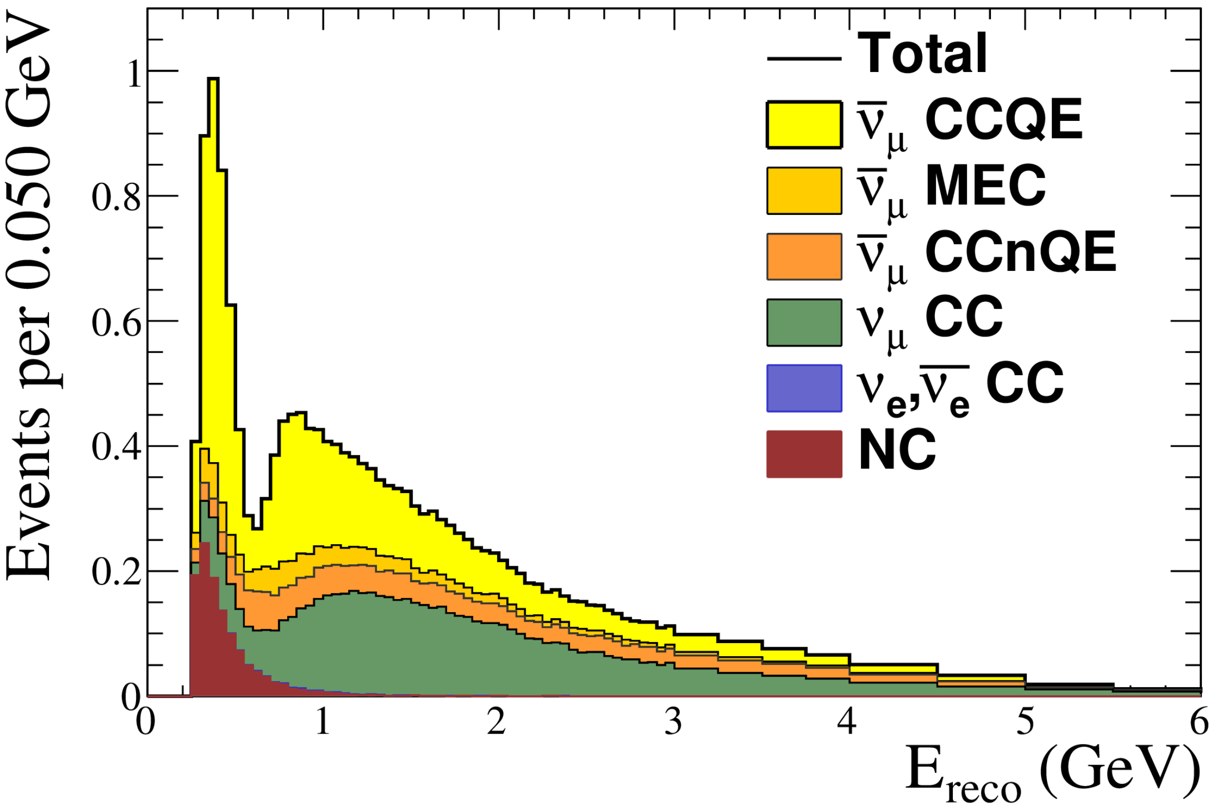
Muon antineutrino disappearance:

- Fit for $\bar{\theta}_{23}$ and $\overline{\Delta m^2}_{32}$
- Use separate parameters for neutrino interactions
- Other oscillation parameters fixed to T2K neutrino data and PDG2014
- Test of NSI or CPT theorem

Electron antineutrino appearance:

- Search for presence of appearance with antineutrinos
- Necessary step toward future CPV searches

Disappearance prediction, event rate

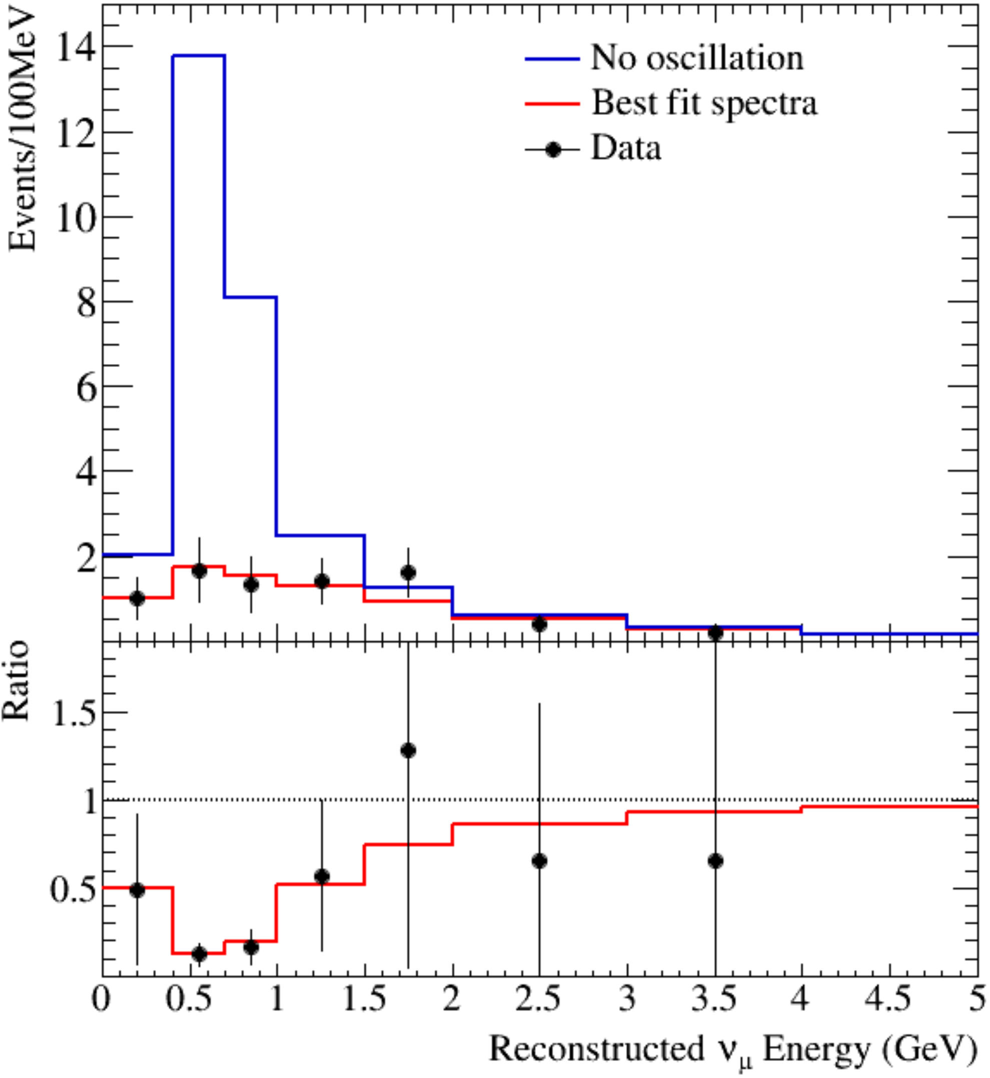


Predominantly antineutrino interactions, but significant components from other channels

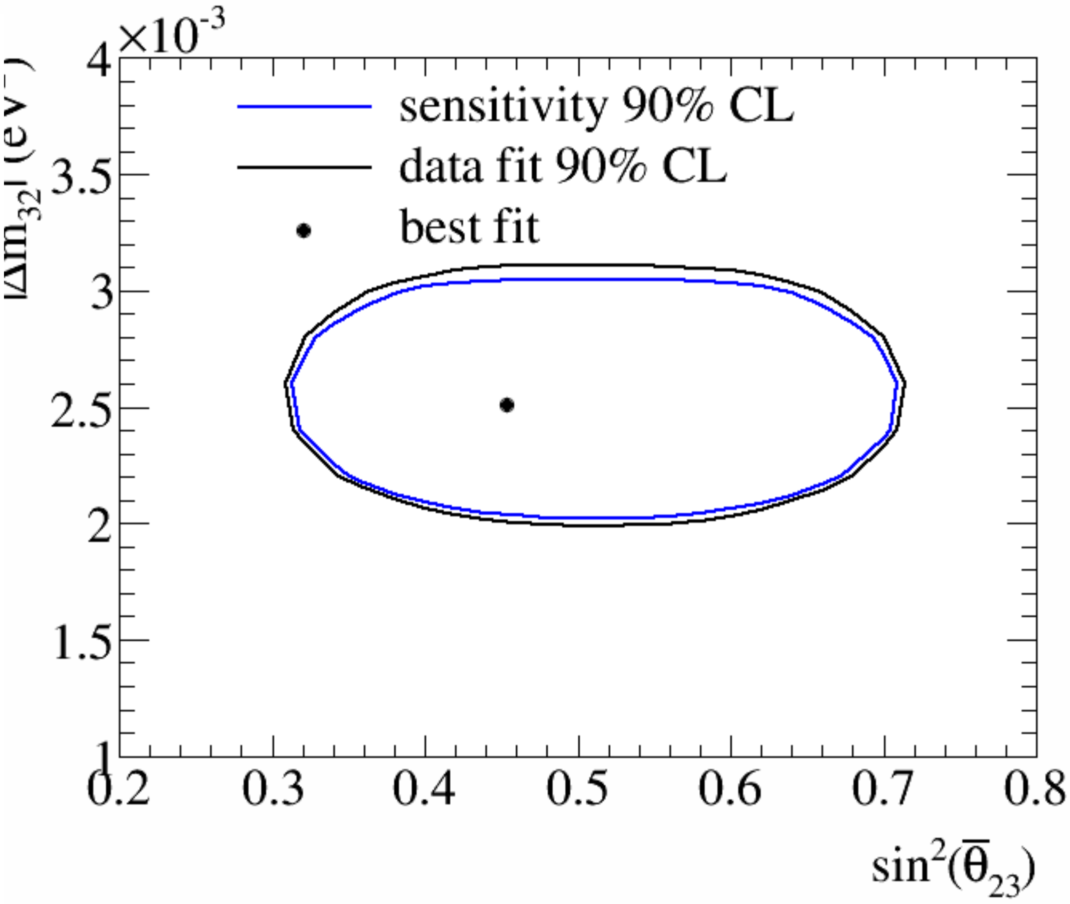
- Expect 34.6 (103.6) events with (without) oscillation

	$\nu_\mu\to\nu_\mu$	$\overline{\nu}_\mu\to\overline{\nu}_\mu$	$\nu_e\to\nu_e$	$\overline{\nu}_e\to\overline{\nu}_e$	$\nu_\mu\to\nu_e$	$\overline{\nu}_\mu\to\overline{\nu}_e$
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 disappearance results!



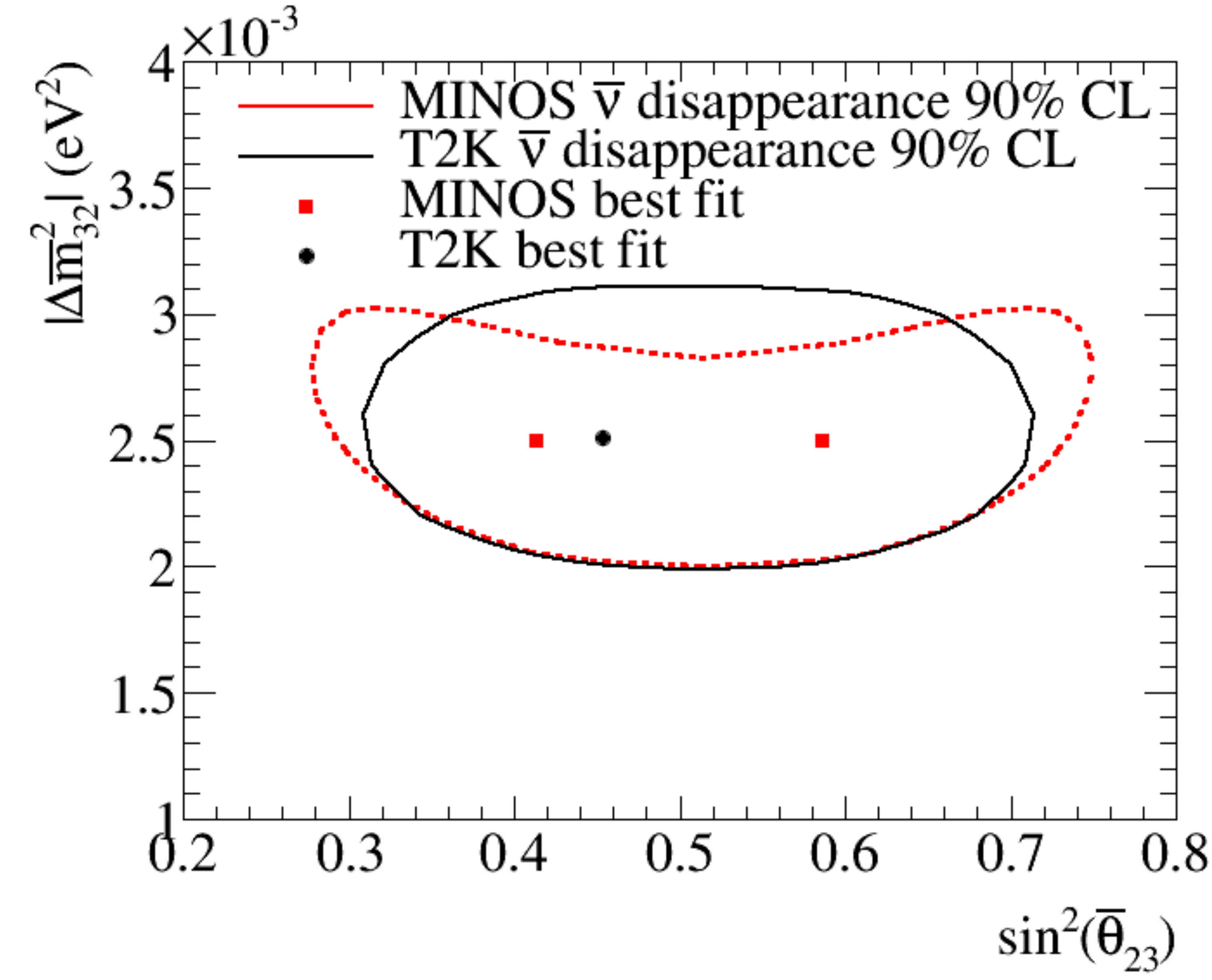
34 events observed



Likelihood based estimation of oscillation parameters

- Binned in reconstructed neutrino energy
- Other oscillation parameters fixed to T2K neutrino data and PDG2014
- Best fit near maximal disappearance

Comparison to MINOS



Results compatible with MINOS combined beam+atm

- P. Adamson et al., Phys. Rev. Lett. 110 (2013) 25, 251801

Comparison to T2K neutrino mode results

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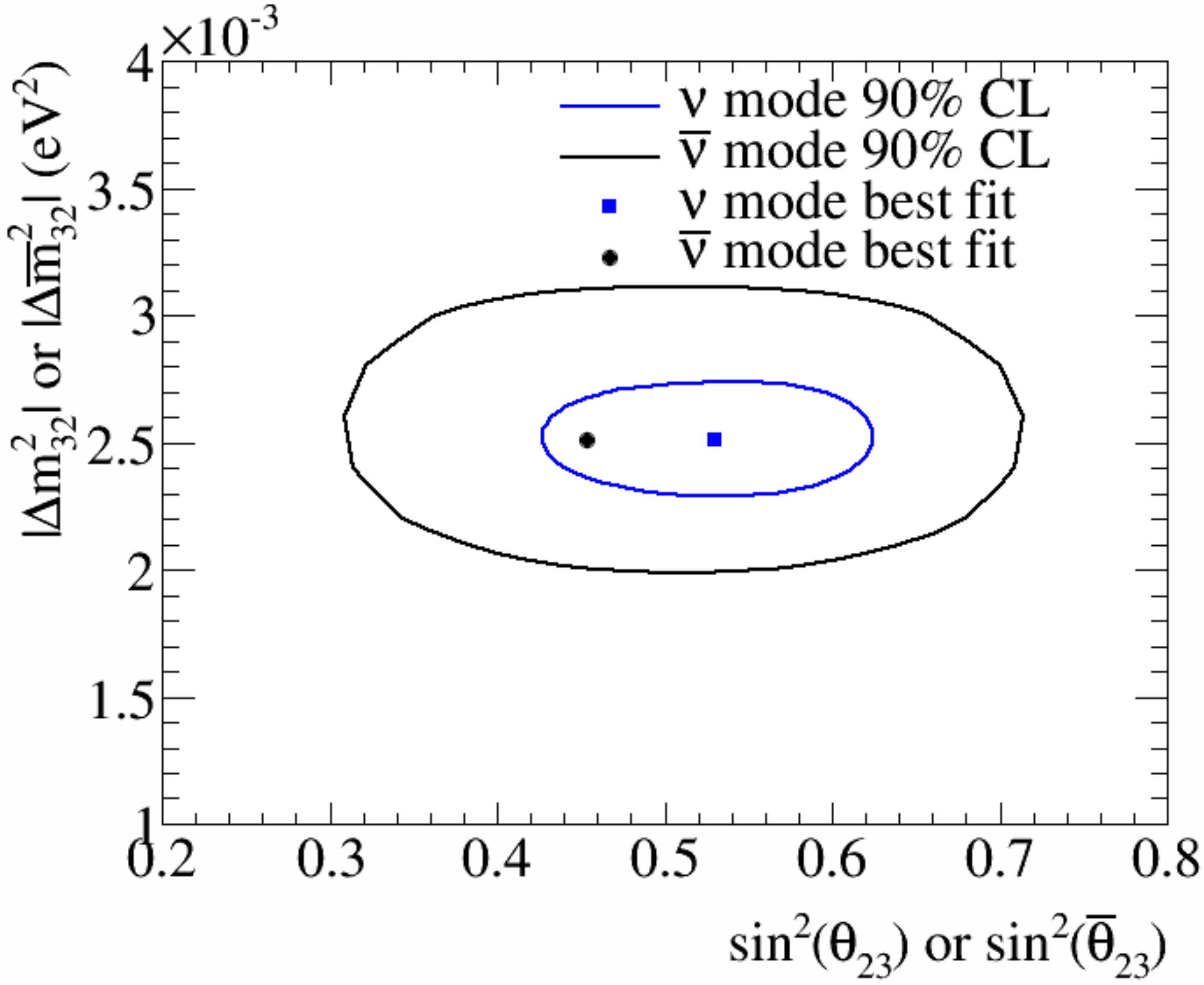


Consistency also between T2K neutrino and antineutrino data estimation of θ_{23}

Antineutrino appearance analysis

Signal: CC $\overline{\nu}_e$ from $\overline{\nu}_\mu$ to $\overline{\nu}_e$ oscillation

Background: CC $\overline{\nu}_{e,}$ ν_e

Irreducible beam $\overline{\nu}_{e,}\nu_e$

ν_e from oscillation

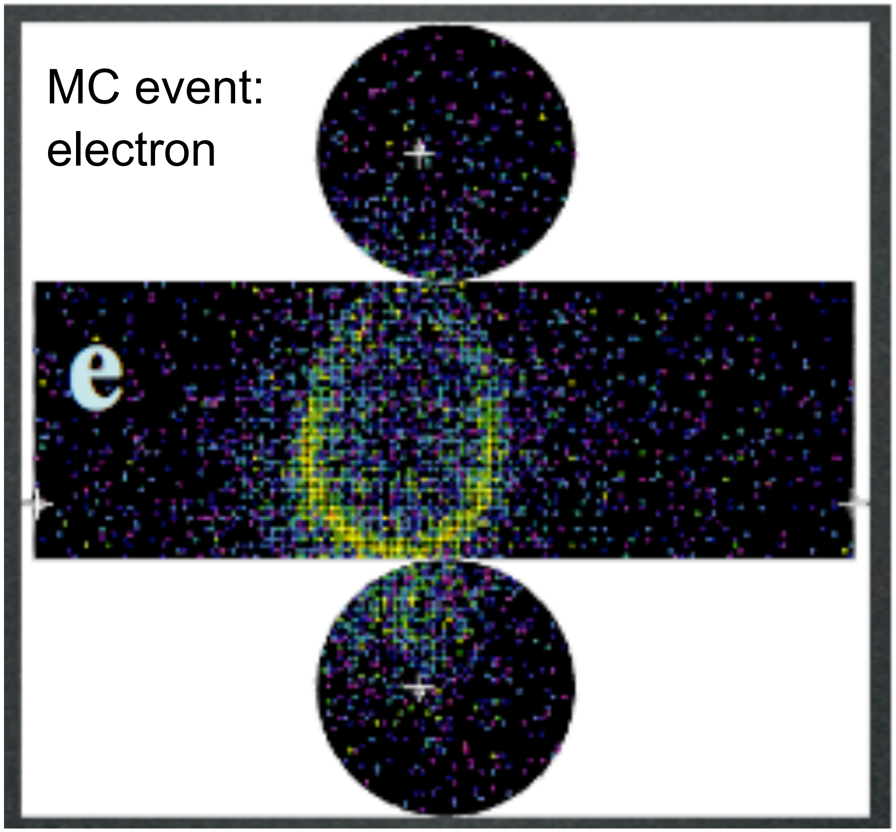
Background:

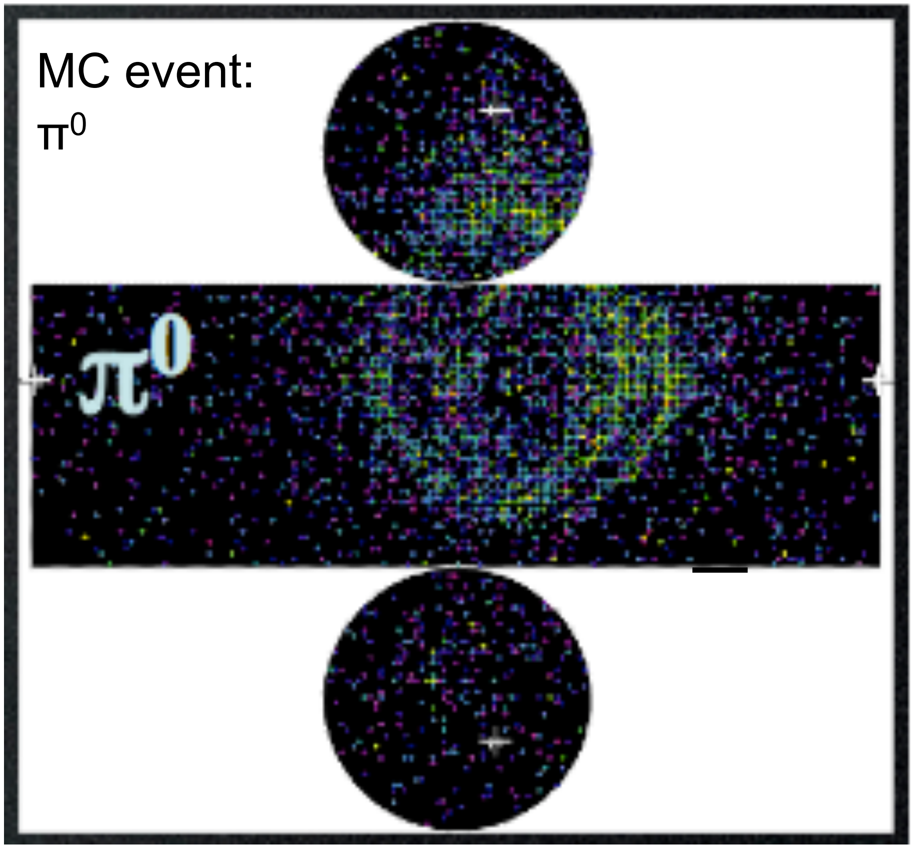
NCπ^0 $\nu_{\mu,}$ $\overline{\nu}_\mu$

Mimics CC ν_e

A π^0 from a NC interaction will decay to two photons (two electron-like rings)

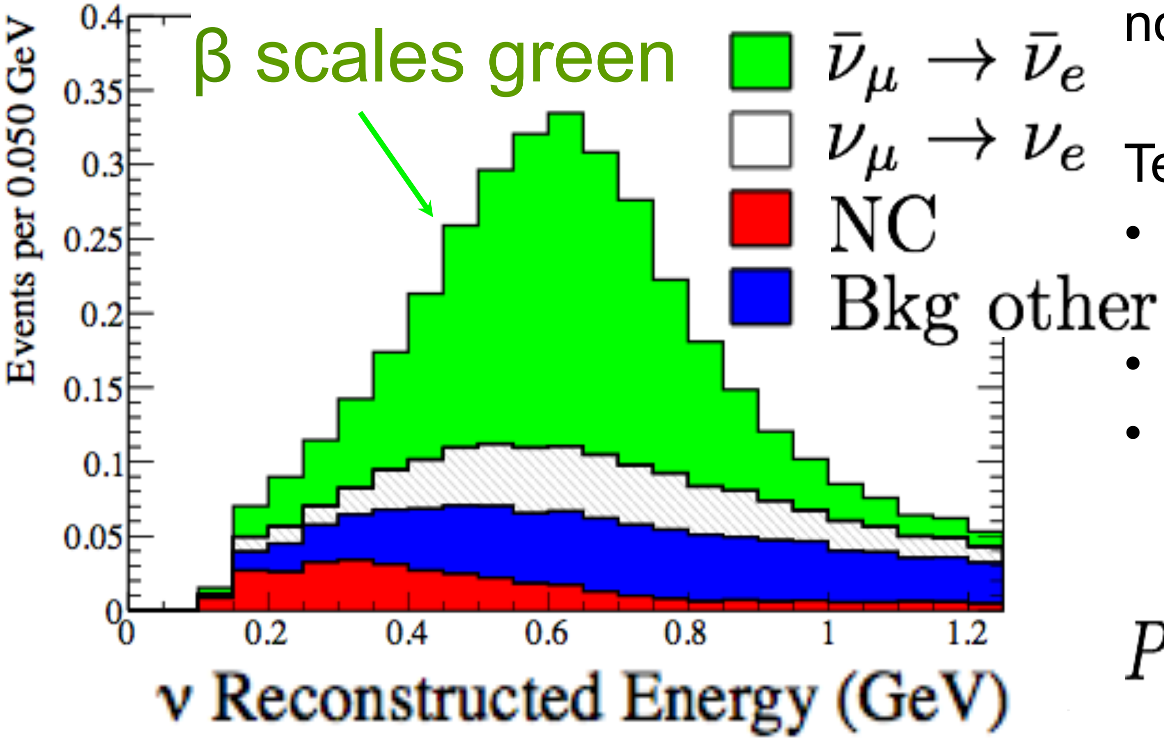
- Search for 2nd ring
- Calculate invariant mass
- Reject events consistent with π^0 invariant mass


MC event: electron


MC event: π^0

Antineutrino appearance analysis

	Normal hierarchy			Inverted hierarchy		
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
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



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

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

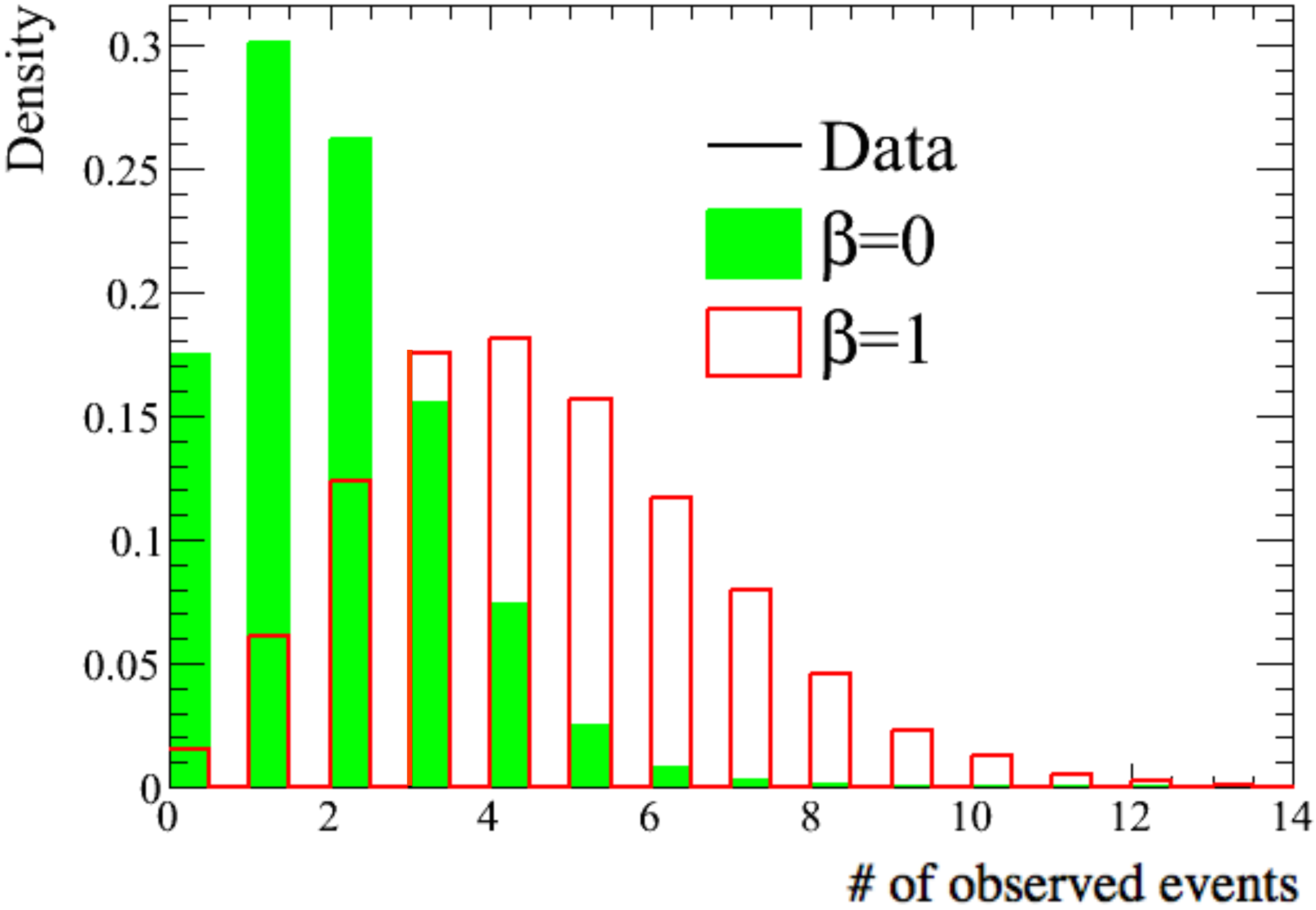
- Significant expected contribution from ν_e appearance
- β=0: no $\bar{\nu}_e$ appearance
- β=1: $\bar{\nu}_e$ appearance

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

Rate only p-value and sensitivity

Generate an ensemble of test experiments with β=0 (no $\overline{\nu}_e$ appearance)

- p-value: fraction of test experiments that have as many or more candidate events as T2K data
- Sensitivity: mean p-value for an ensemble of fake data experiments with β=1

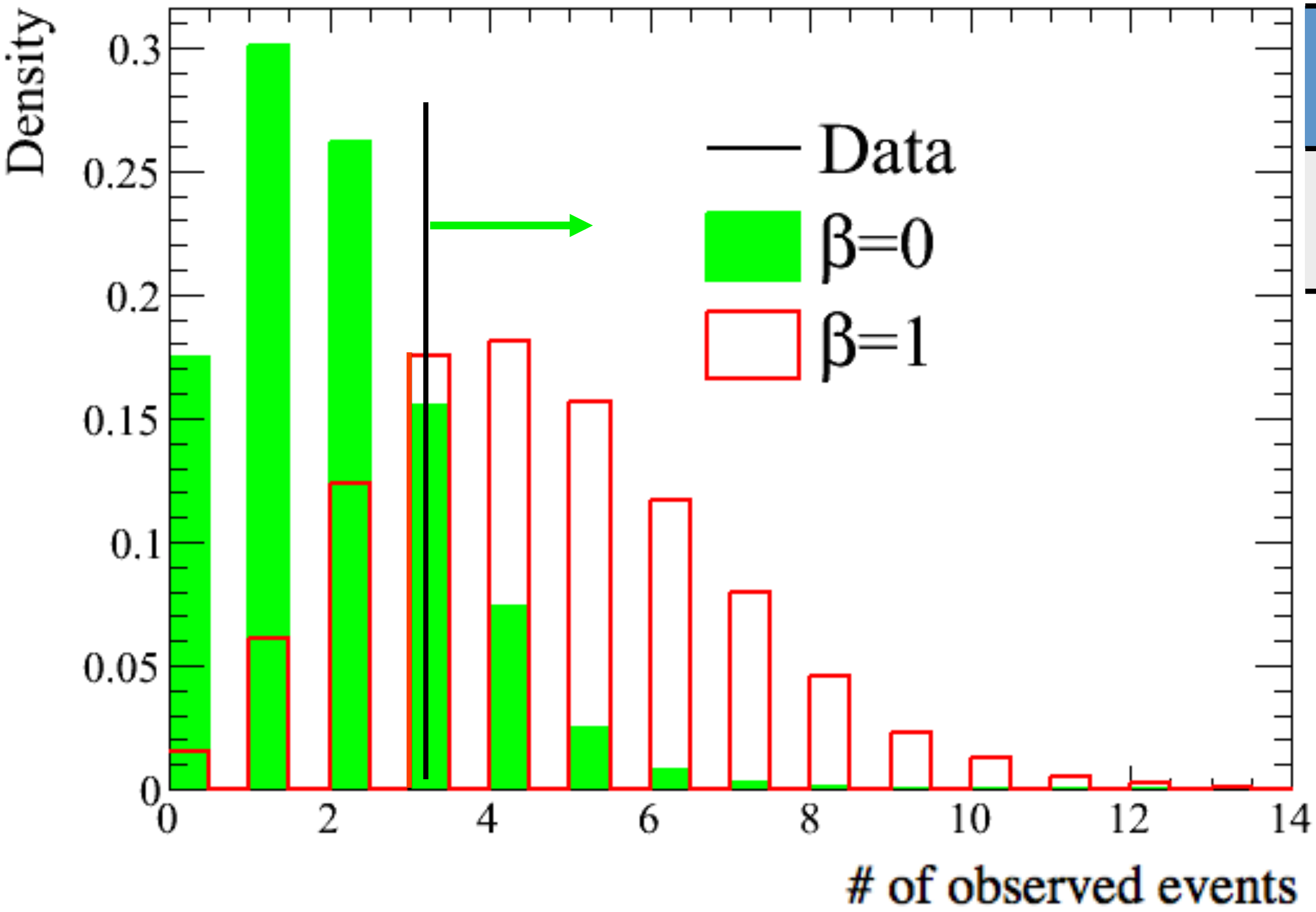


Rate only	p-value
Mean p-value	0.20

Rate only p-value and sensitivity

Generate an ensemble of test experiments with β=0 (no $\overline{\nu}_e$ appearance)

- p-value: fraction of test experiments that have as many or more candidate events as T2K data
- Sensitivity: mean p-value for an ensemble of fake data experiments with β=1



Rate only	p-value	Likelihood ratio
Data: 3 events	0.26	0.9

Likelihood ratio:
L(β=0)/L(β=1) is close to 1

Data does not favor or disfavor $\overline{\nu}_e$ appearance

Shape information

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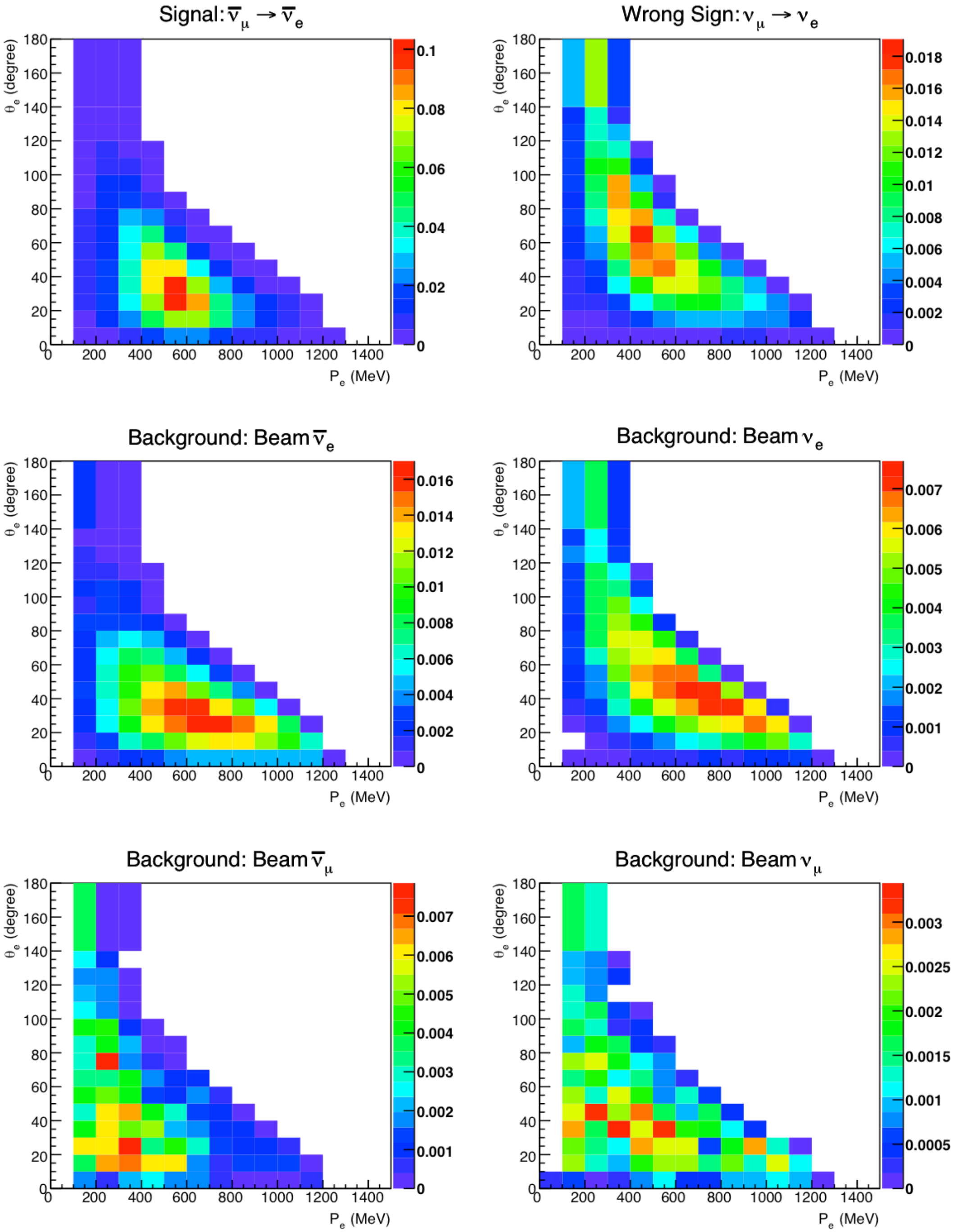
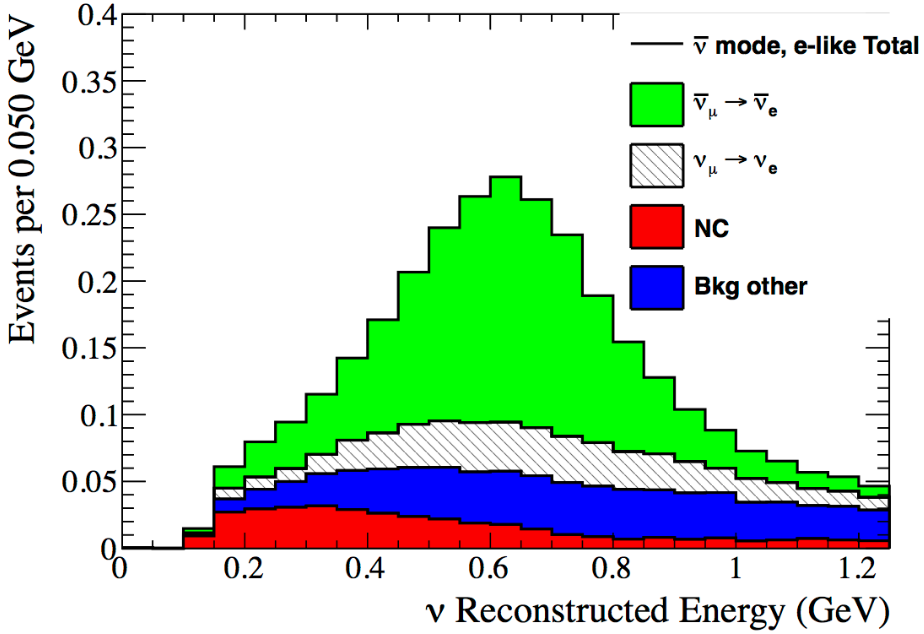


Include distribution of events in kinematic variables in calculation of p-value

- Momentum, angular distribution (p-θ) are different for signal, background events
- Similar for EvQE (Erec) distribution

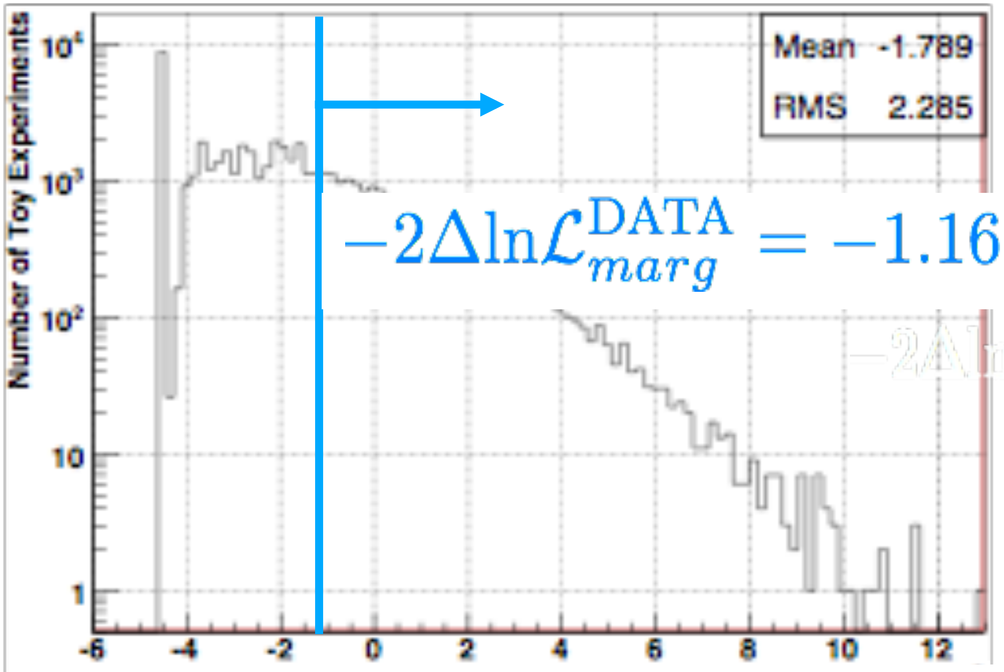


Rate+shape p-value and sensitivity

Form a likelihood with shape, normalization information:

- Shape information from p-θ or EvQE distribution
- Marginalize likelihood over all systematic, oscillation parameters except β and define a test statistic:

$$-2\Delta\ln\mathcal{L} = -2\ln\frac{\mathcal{L}_{marg}(\beta=0)}{\mathcal{L}_{marg}(\beta=1)}$$

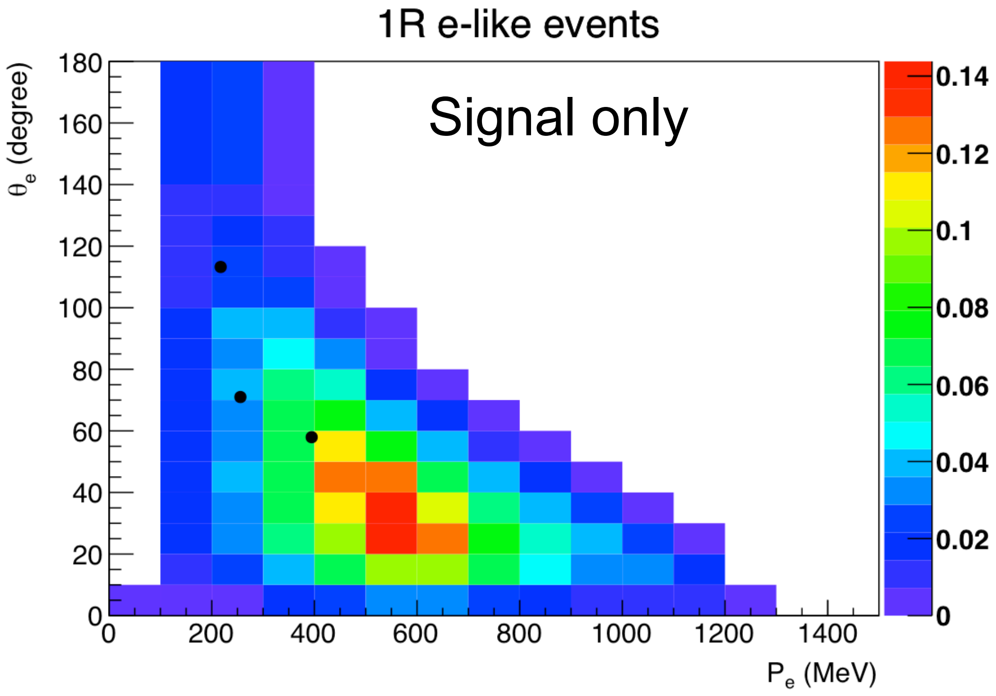


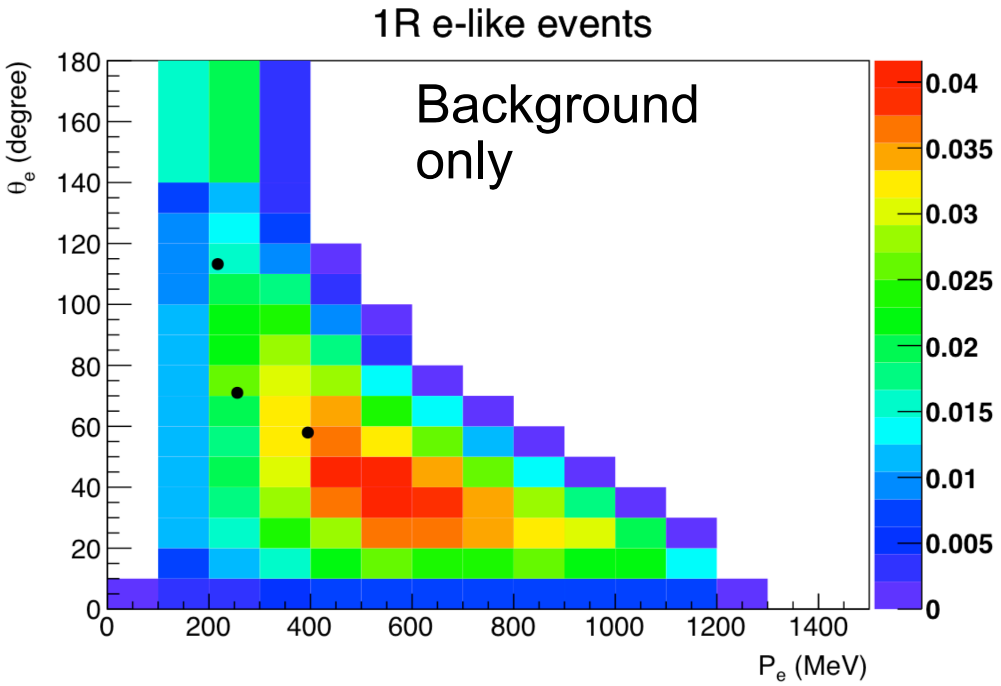
$$-2\Delta\ln\mathcal{L} = -2[\ln\mathcal{L}_{marg}(\beta=0) - \ln\mathcal{L}_{marg}(\beta=1)]$$

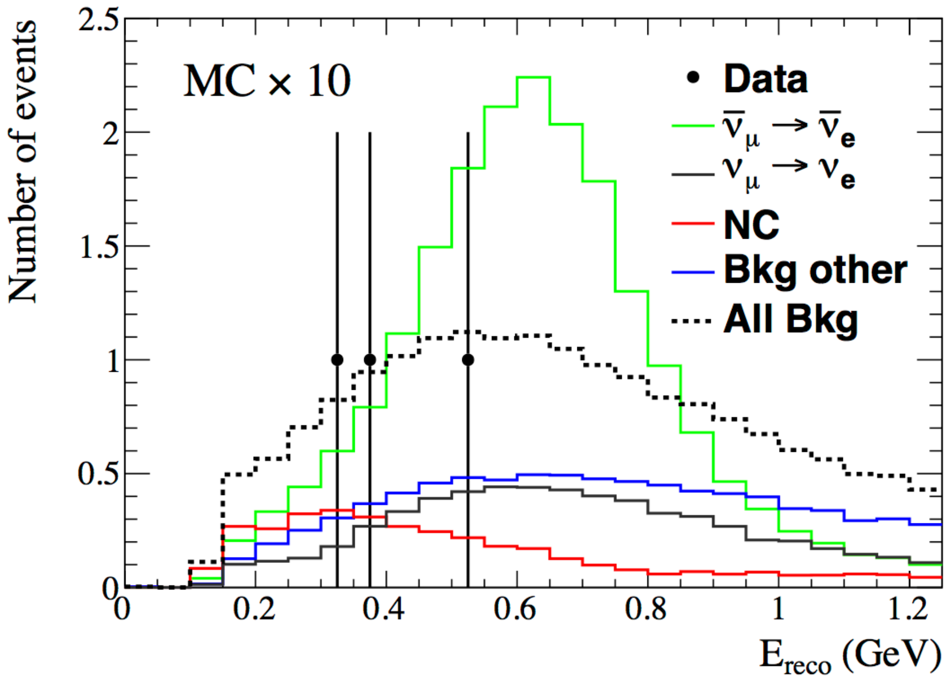
Use an ensemble of fake data experiments to estimate the mean p-value

Rate+shape	Mean p-value	Likelihood ratio	-2ΔlnL(marg) Data	Data p-value
p-θ	0.13	1.8	-1.16	0.34
EvQE	0.14	0.9	0.16	0.16

Rate+shape distribution of candidate events







Data does not favor or disfavor $\overline{\nu}_e$ appearance

A look toward the future for T2K

So far, 14% of T2K design POT taken

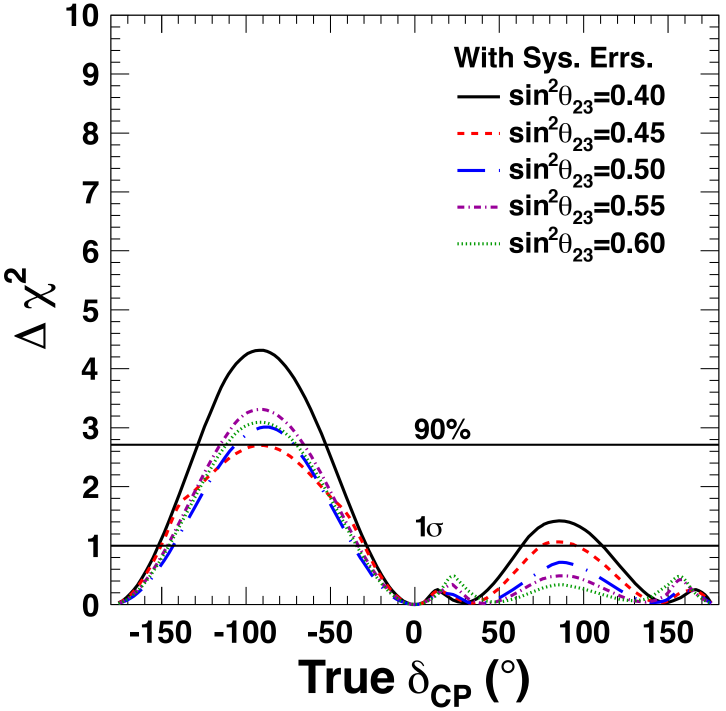
- ν mode: 6.9 x 10^{20} POT;
- $\bar{\nu}$ mode: 4.0 x 10^{20} POT

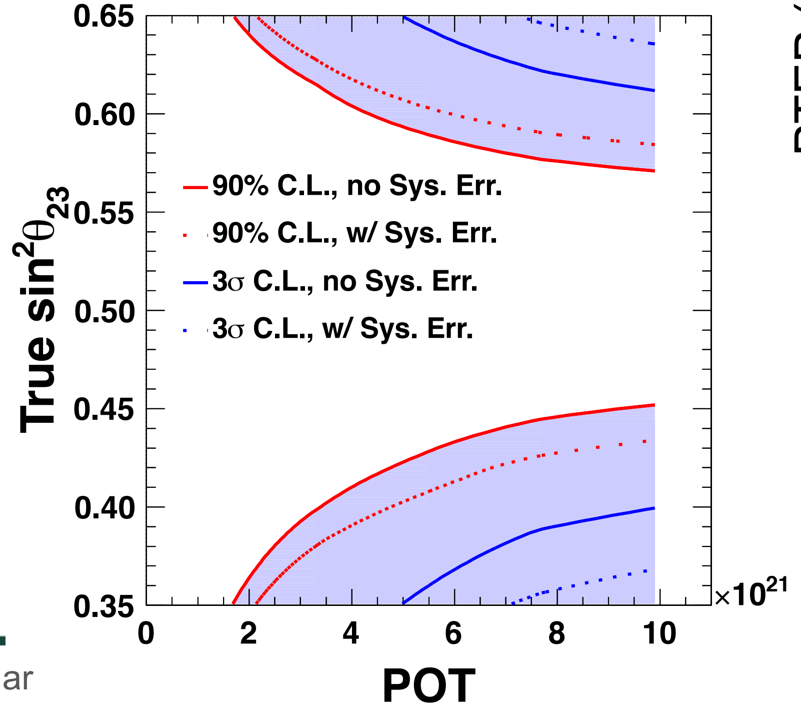
Short term (1 year) goal: ~9.5 x 10^{20} POT

- ~2σ level rejection of no $\bar{\nu}_e$ appearance
- ~60% chance of 99%CL observation

Long term (full run) goal: 8 x 10^{21} POT

- ~10x statistics in $\bar{\nu}$ mode
- 50% ν, 50% $\bar{\nu}$ run plan
- May exclude δ_{CP}=0 at ≥90%CL
- Combined app. and disap. channels to infer octant (and reactor measurements)



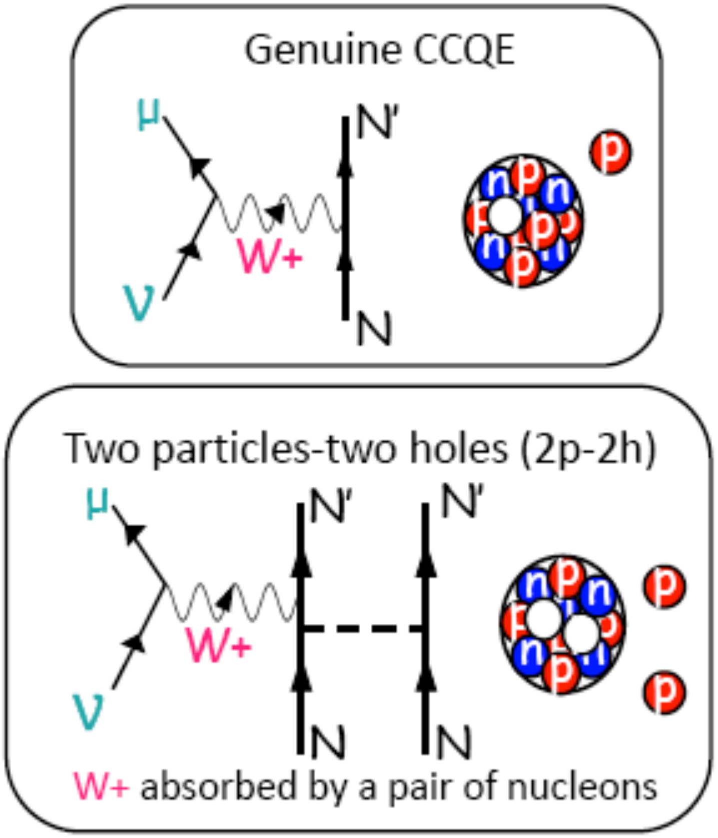


PTEP (2015) 043C01

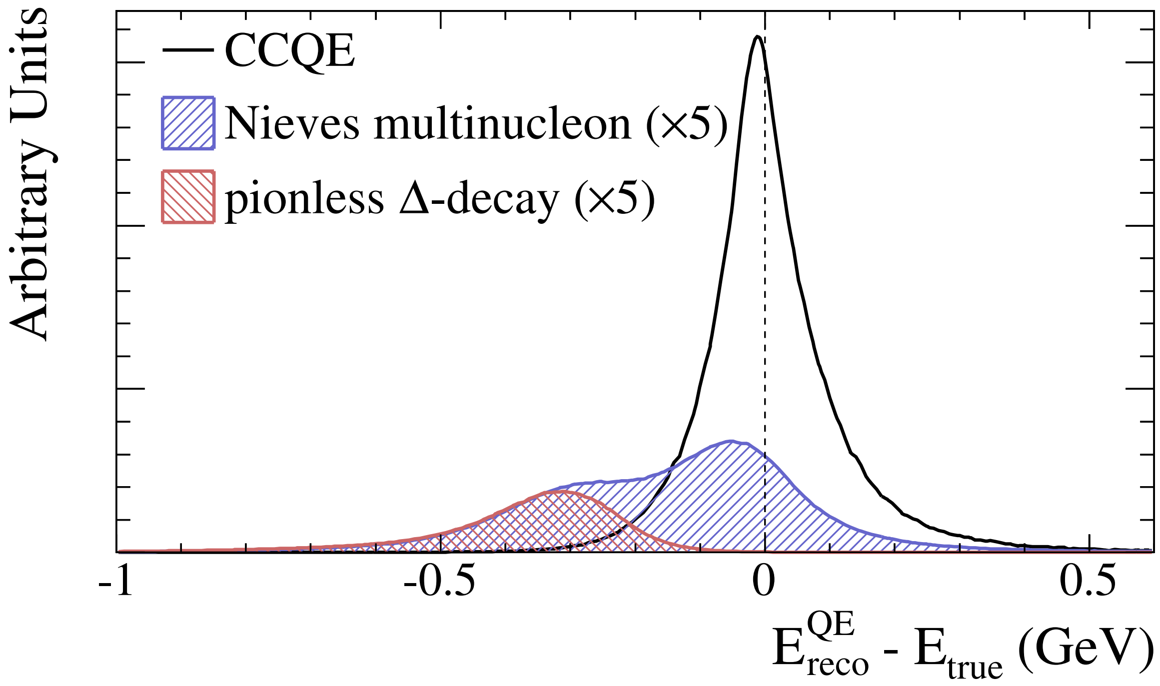
Future systematics: cross section model

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)



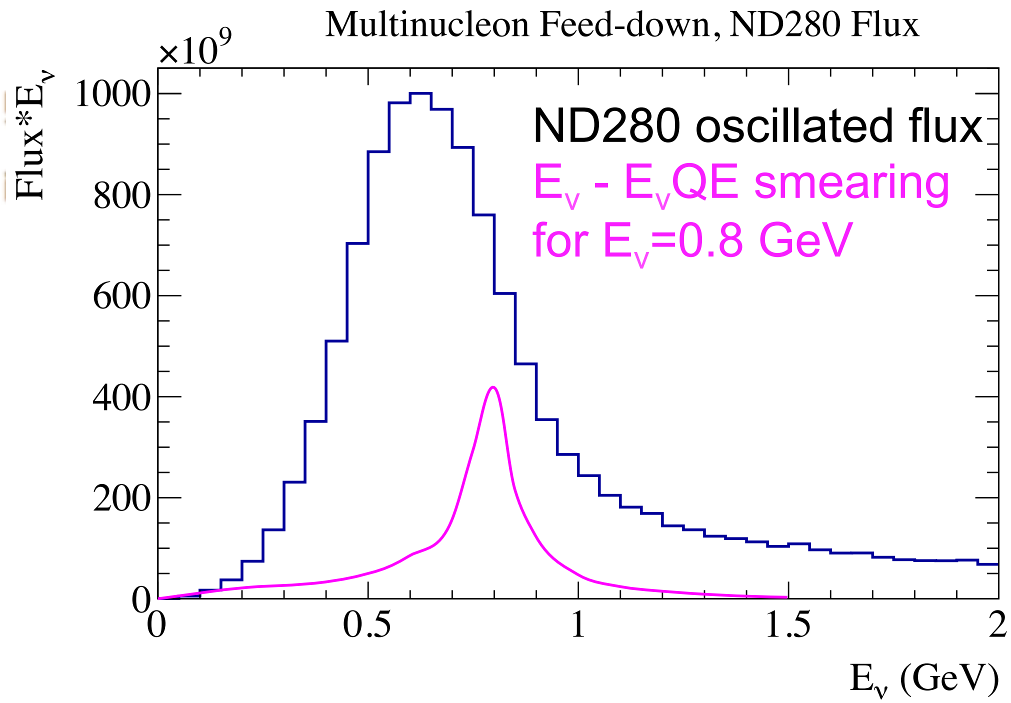
Picture by M. Martini

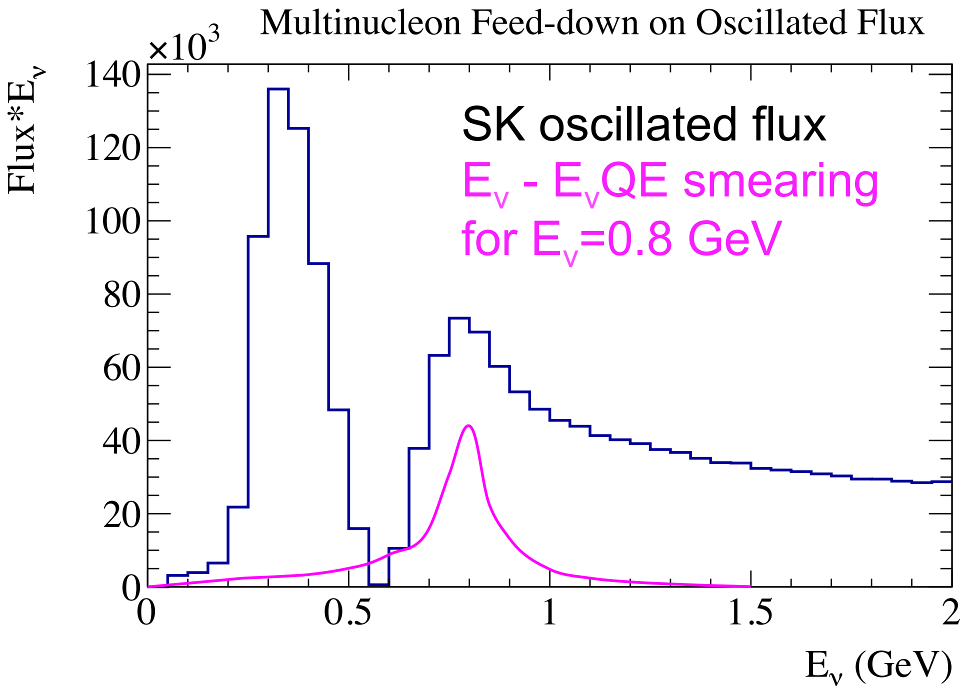


T2K collab PRL 112, 181801 (2014)

Future systematics: cross section model

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





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

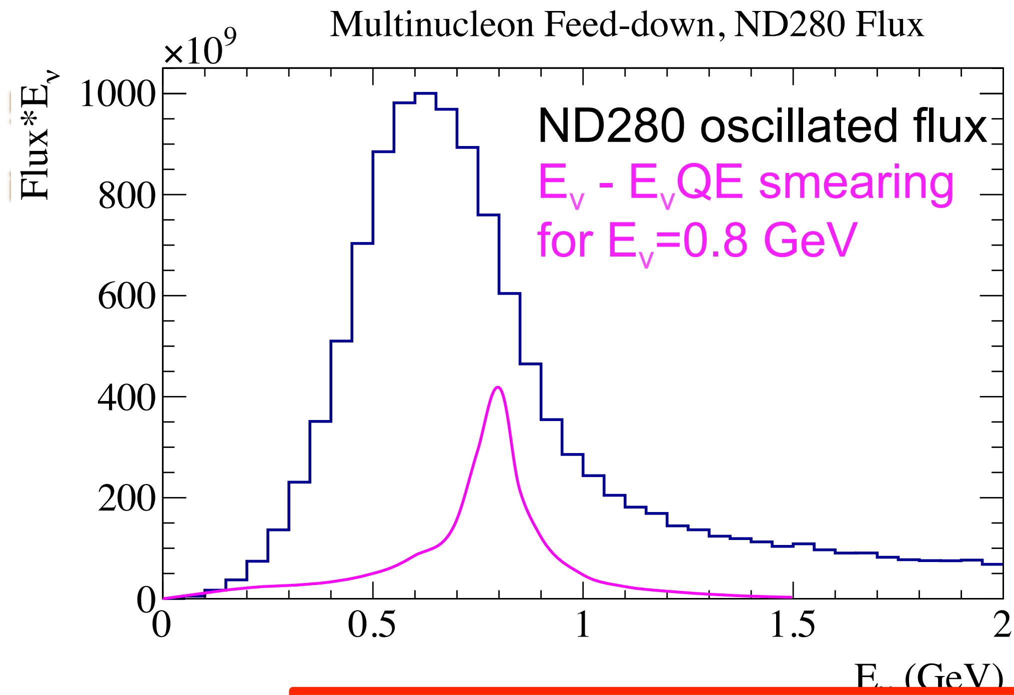
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

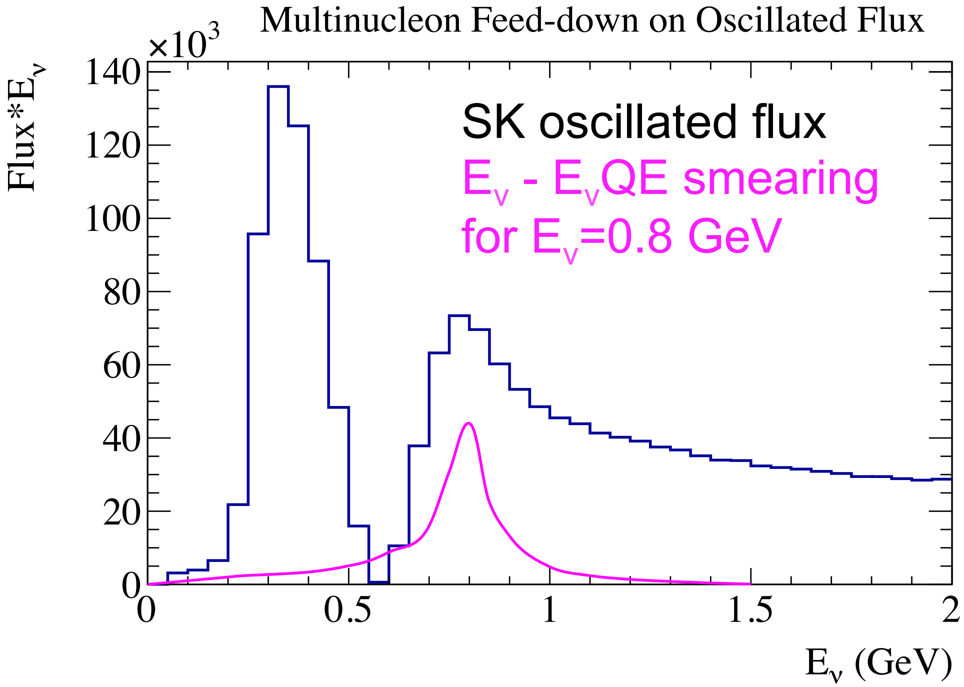
Overall increase to cross section cancels in extrapolation, but any shifts between true to reconstructed E feed down into oscillation dip and are ~degenerate with θ_{23} measurement

- 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


Multinucleon Feed-down, ND280 Flux


Multinucleon Feed-down on Oscillated Flux

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

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

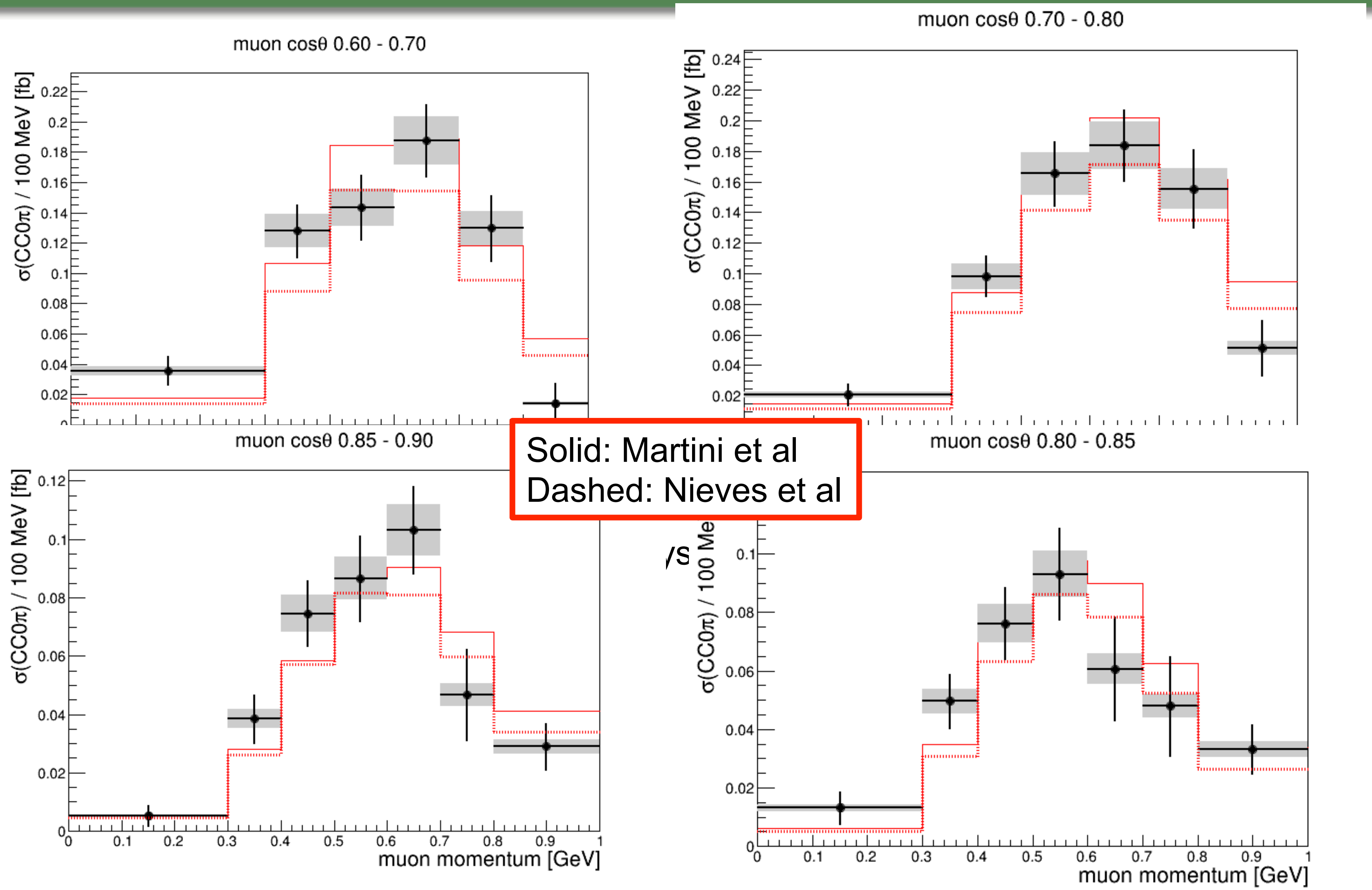
Overall inc een true to reconstr 3 measurem

- 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

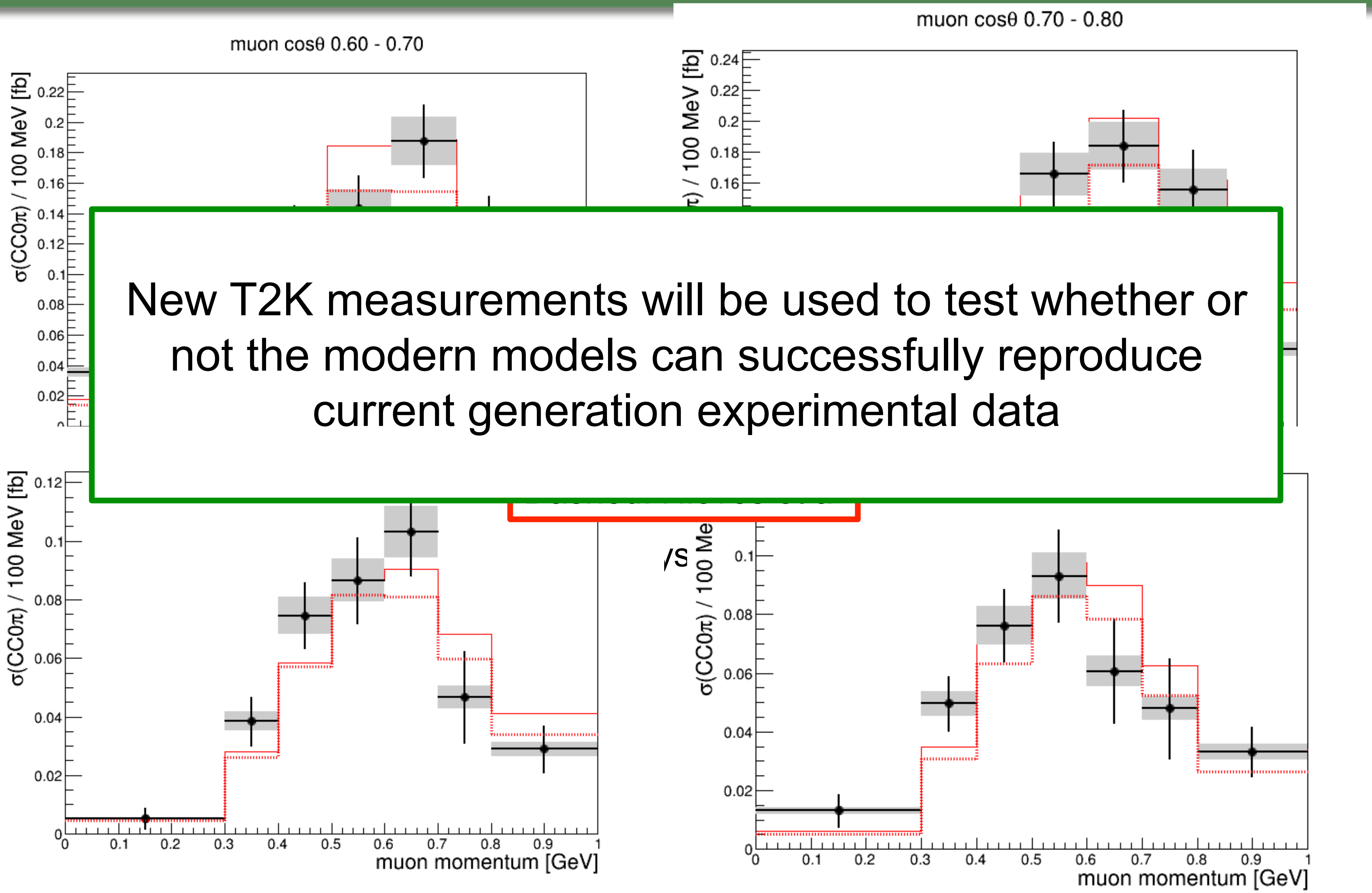
T2K CC0π differential measurement on CH



Solid: Martini et al
Dashed: Nieves et al

New measurement muon kinematics for muon, muon+proton, both with no pion in final state from ND280 off-axis beam

T2K CC0π differential measurement on CH



New T2K measurements will be used to test whether or not the modern models can successfully reproduce current generation experimental data

New measurement muon kinematics for muon, muon+proton, both with no pion in final state from ND280 off-axis beam

Bonus physics! from T2K detectors

Cross section measurements	Target	Reported in	Detector
ν_μ CC inclusive	CH	PRD 87, 092003 (2013)	ND280, Tracker
ν_μ CCQE	CH	Accepted by PRD	ND280, Tracker
ν_e CC inclusive	CH	PRL 113, 241803 (2014)	ND280, Tracker
ν_μ NC π^0	CH/Water	Publication in progress	ND280, P0D
ν_μ NC elastic	Water	PRD 90, 072012 (2014)	SK
ν_μ CC inclusive	CH/Fe	PRD 90, 052010 (2014)	INGRID
ν_μ CCQE	CH	PRD 91, 112002 (2015)	INGRID
ν_μ CC coherent	CH	Publication in progress	INGRID
ν_μ CC coherent	CH	Publication in progress	ND280, Tracker
ν_μ CCπ^+	Water	Publication in progress	ND280, Tracker
ν_μ CC0π	CH	Publication in progress	ND280, Tracker

Cross section measurements with both off-axis and on-axis fluxes

Additional measurements of Lorenz violation, sterile oscillation, and neutrino mass

Conclusion

T2K presents first results with antineutrino data: 4.0 x 10^{20} POT

- **anti-ν_μ disappearance results**
  - Updated with full antineutrino run
  - 34 events used for world leading determination of $\bar{\theta}_{23}$
- **Search for anti-ν_e appearance:**
  - 3 candidate events observed
  - Data does not favor or disfavor the appearance hypothesis
- Both analyses are statistics limited
- Next step: joint neutrino+antineutrino beam mode analysis

Additional physics from T2K:

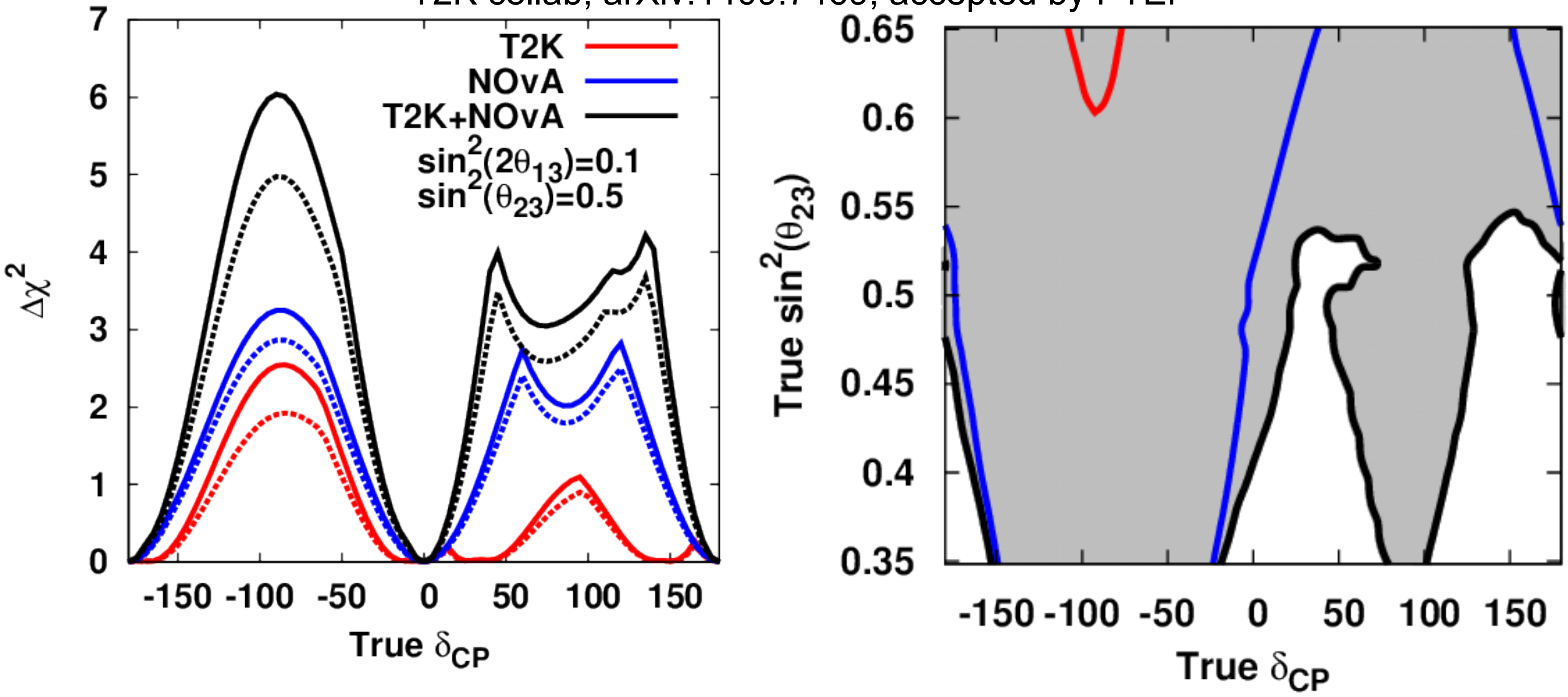
- 13 papers from 2014-2015 so far on oscillation, cross section, and sterile oscillation

Thank you for your attention!

Backup slides

Future of T2K and mass hierarchy

T2K collab, arXiv:1409.7469, accepted by PTEP

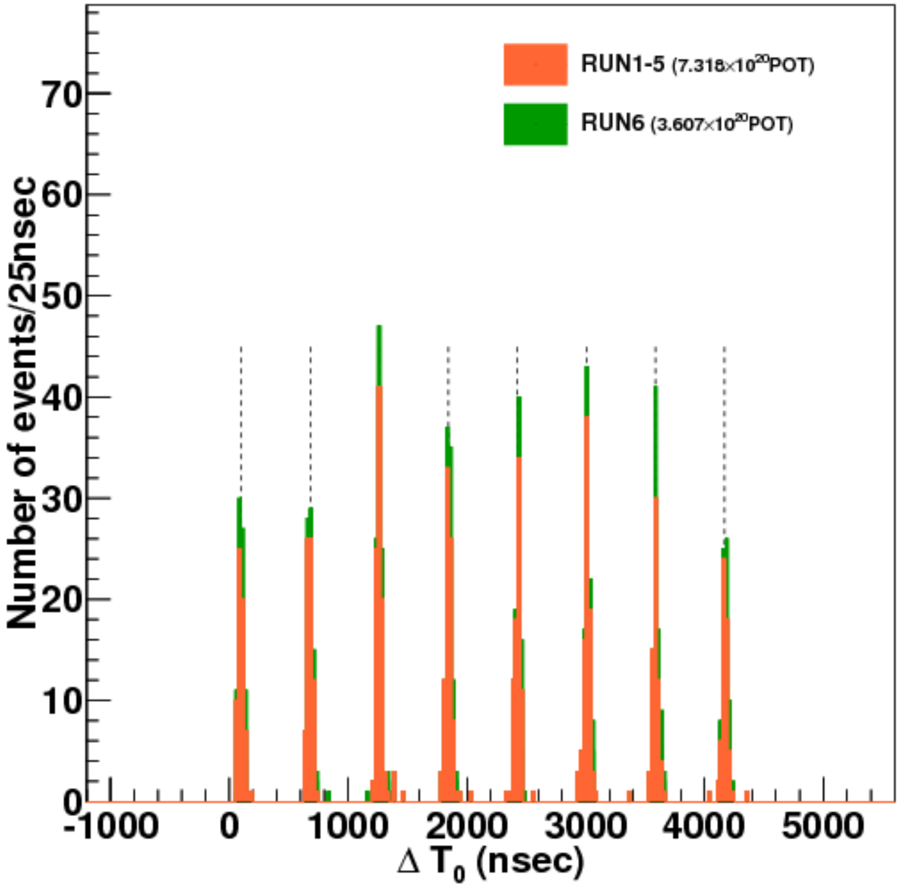


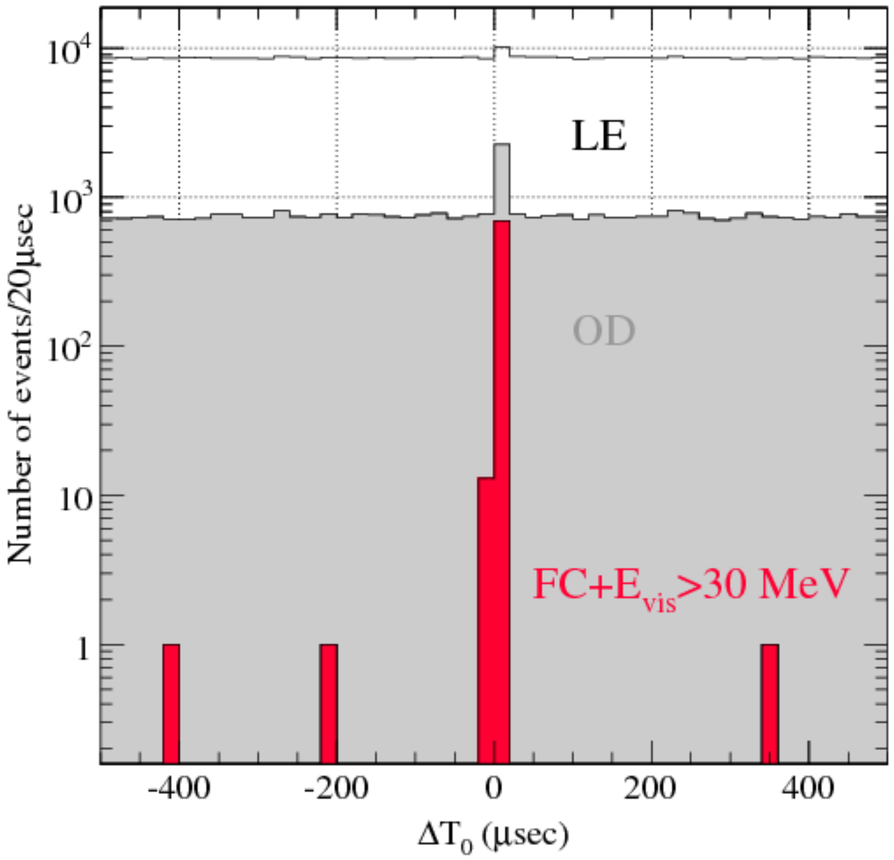
NOvA's higher energy (peak E_ν~2 GeV) and longer baseline (L~810km) has a different dependence on mass hierarchy (MH) through the matter effect

- 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}

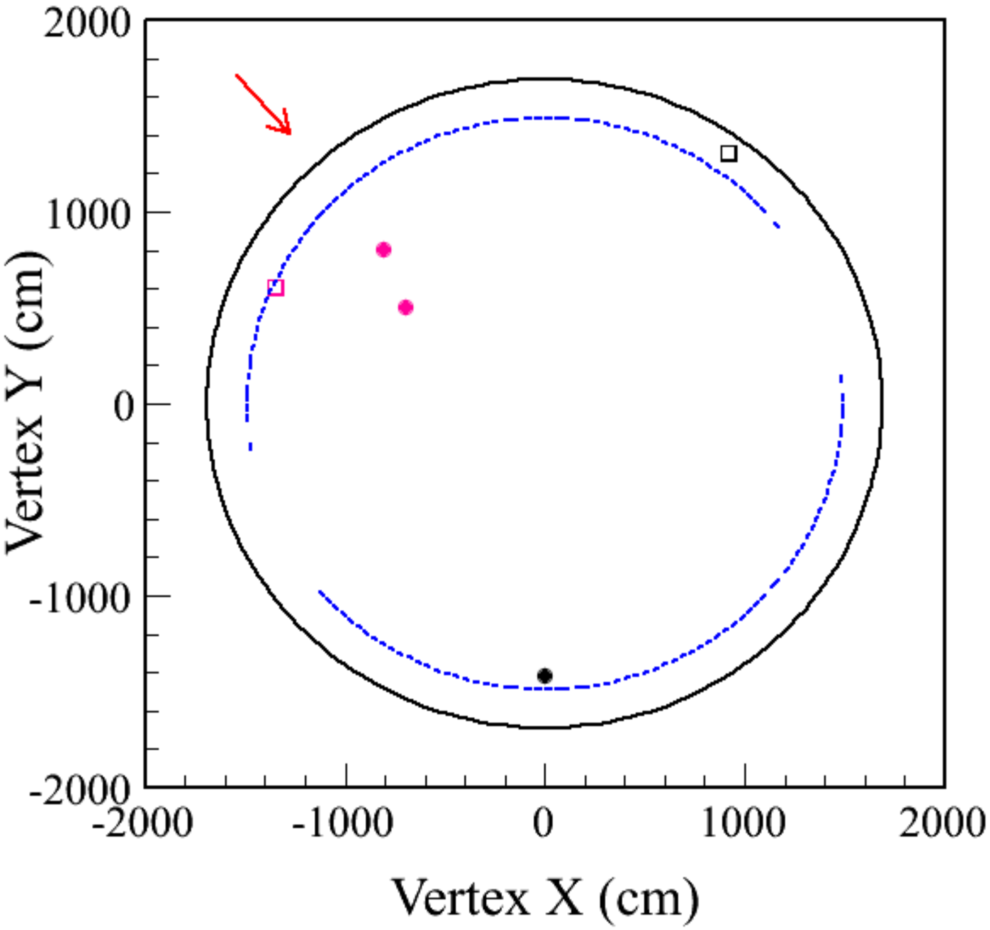
Beam timing of events at SK

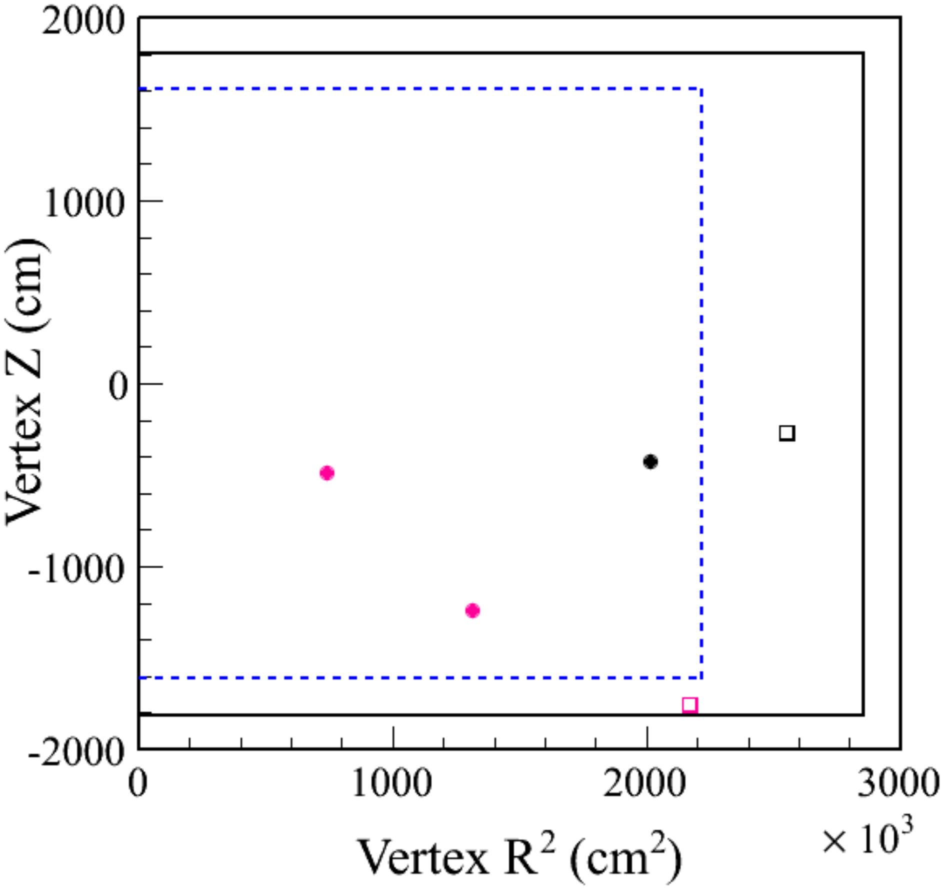




dT0 distribution of all the FC events (zoomed into the spill on-timing window) observed during Run1-5 (orange) and Run6 (green). The eight dotted vertical lines represent the 581 nsec-interval bunch center positions fitted to the observed FC event times albeit with their spacing preserved. The two histograms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

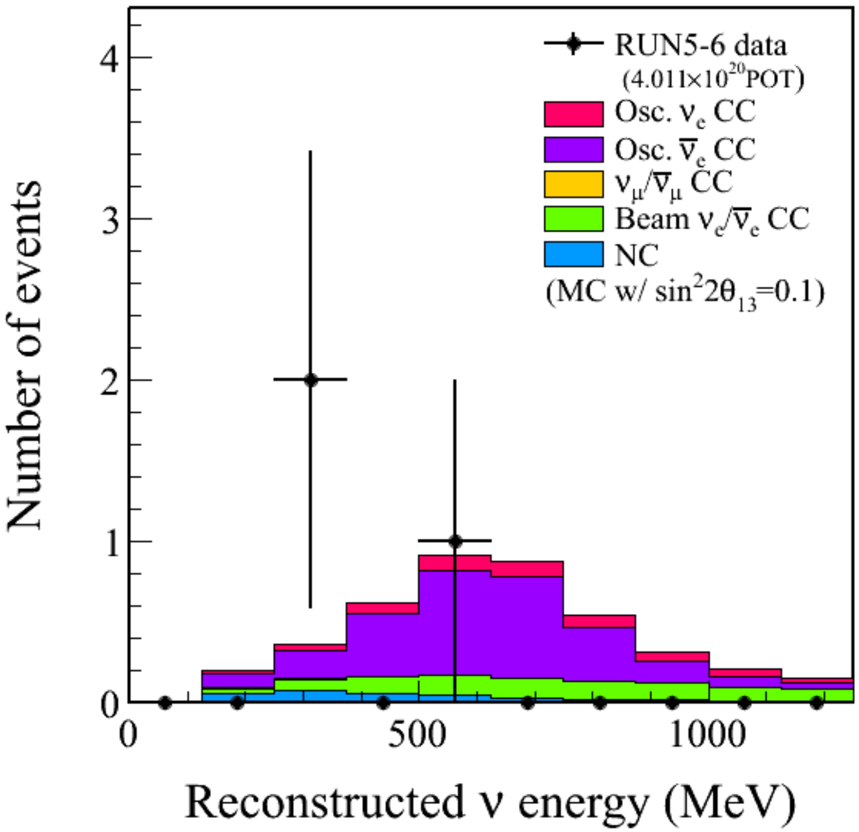
Antielectron neutrino candidates distributions

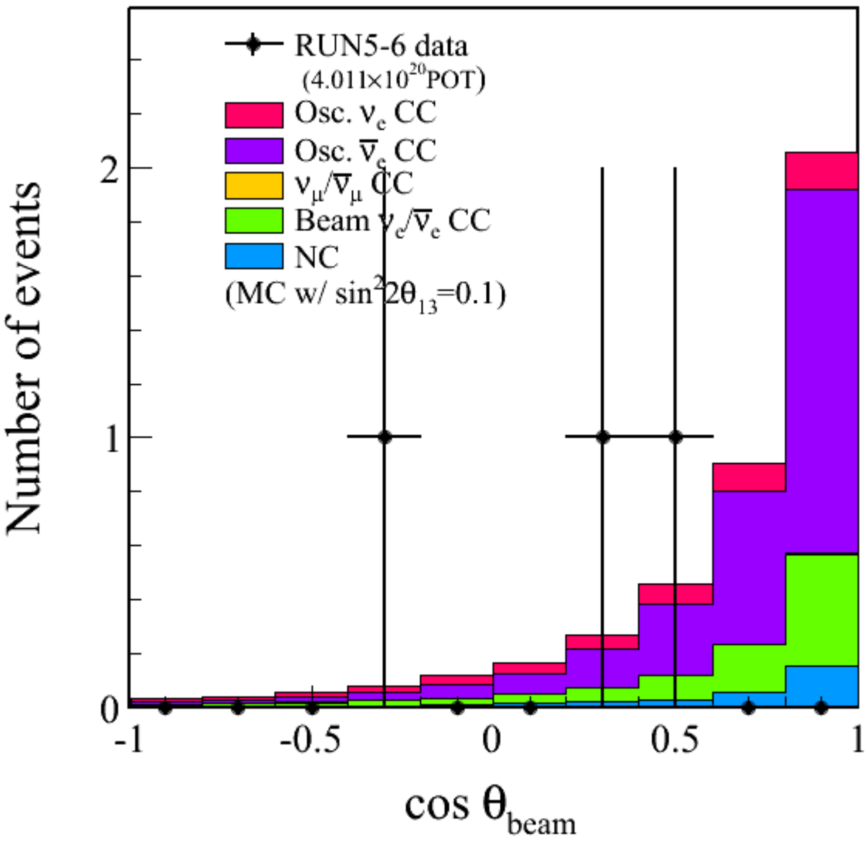




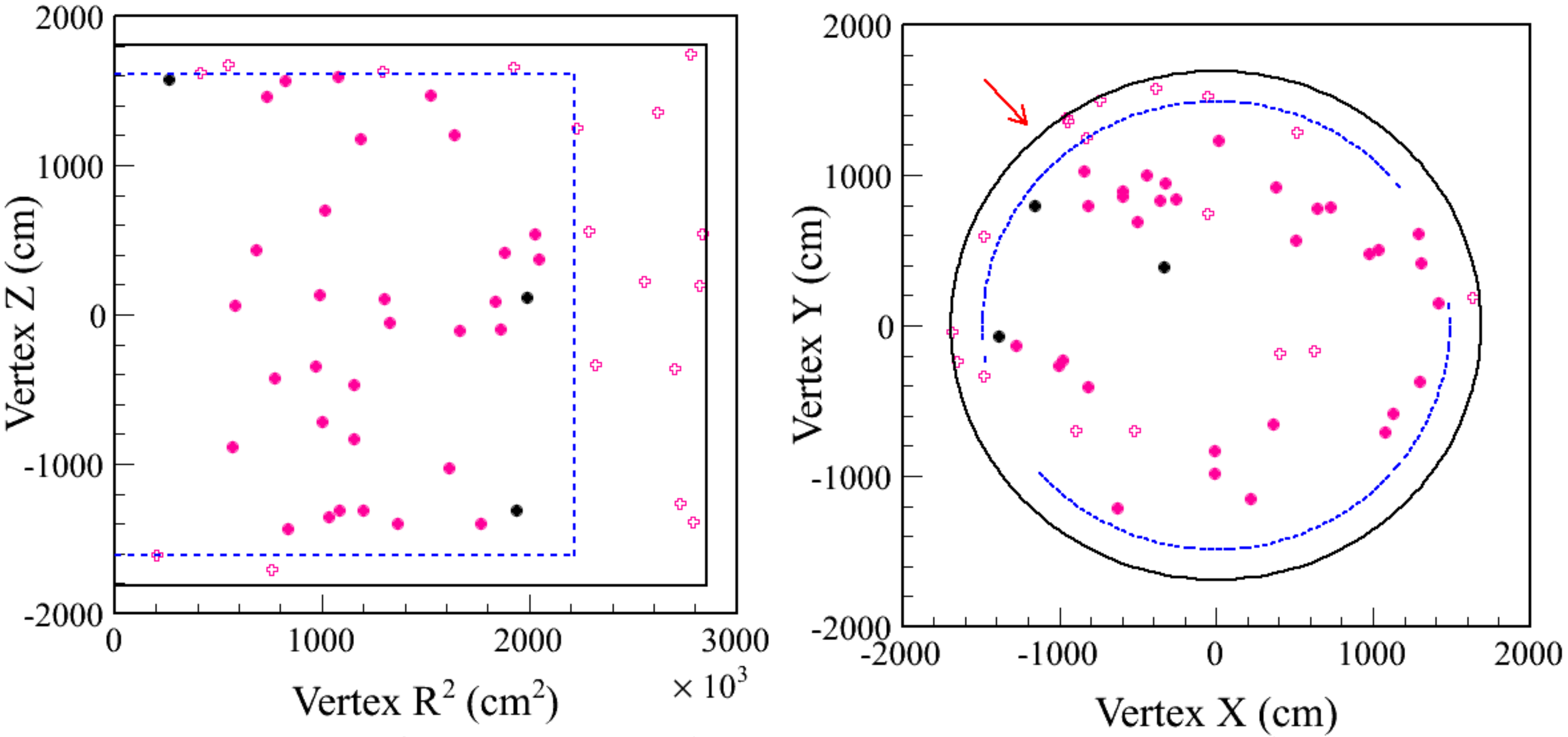
Two-dimensional R^2-Z distribution of the reconstructed vertex position of the anti-nue candidate events. Dashed blue line indicates the fiducial volume boundary. Black markers are events observed during RUN5, and pink markers are events from RUN6. Hollow crosses represent events passing the anti-numu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

Antielectron neutrino candidates distributions



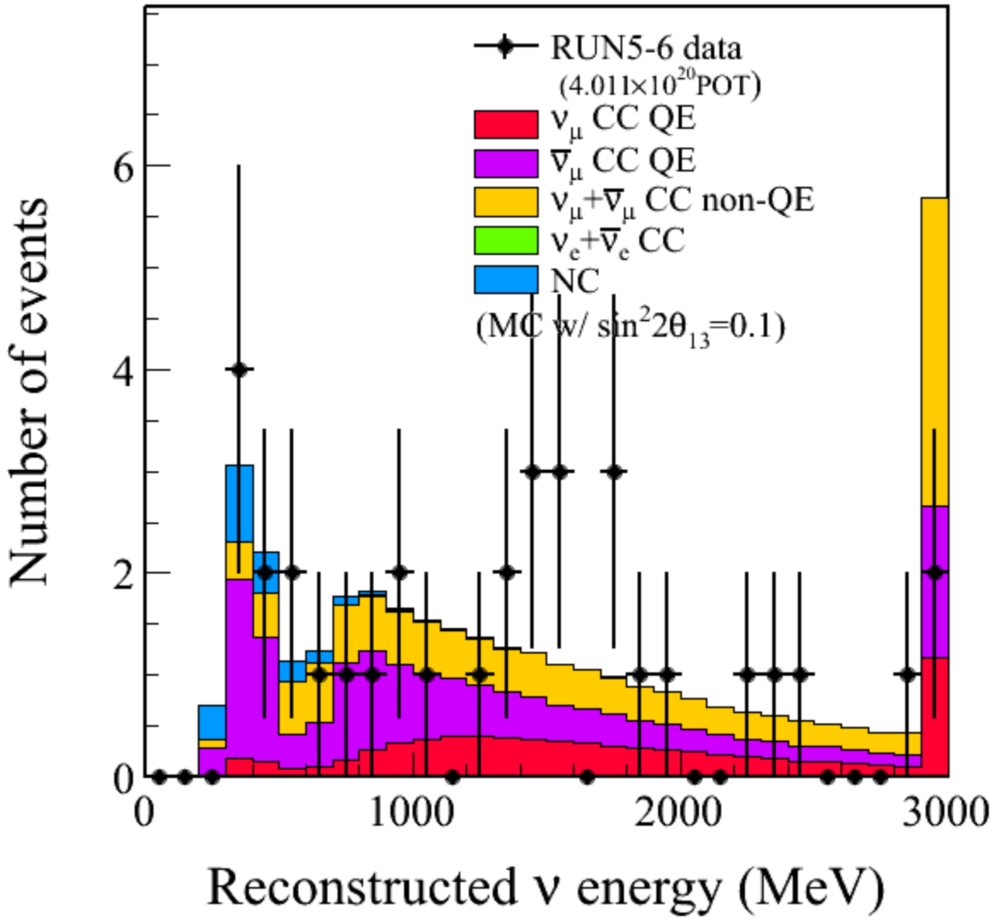


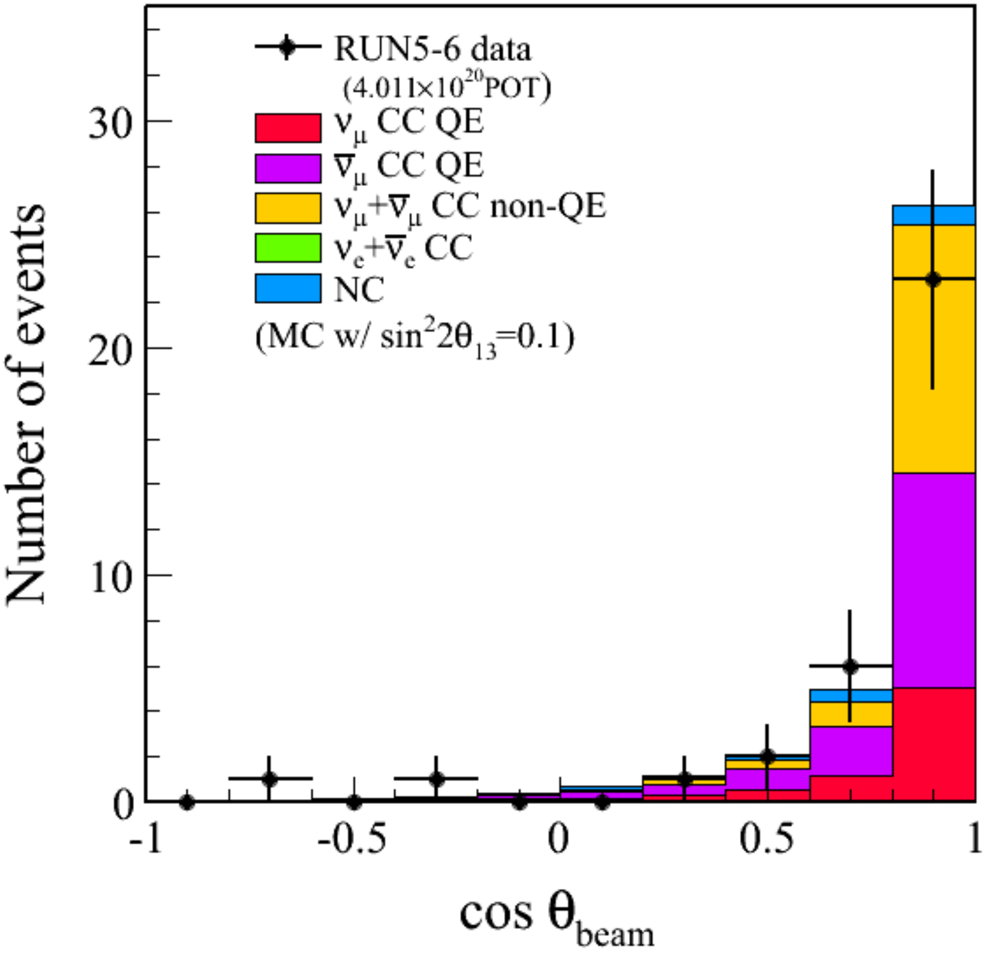
Antimuon neutrino candidates distributions



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

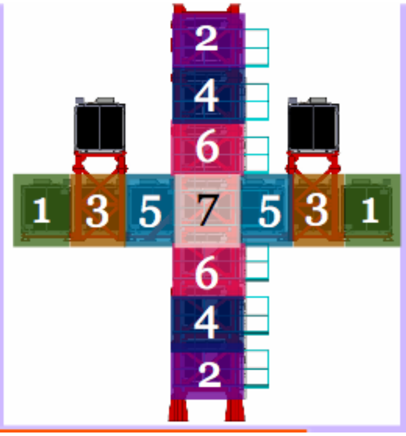




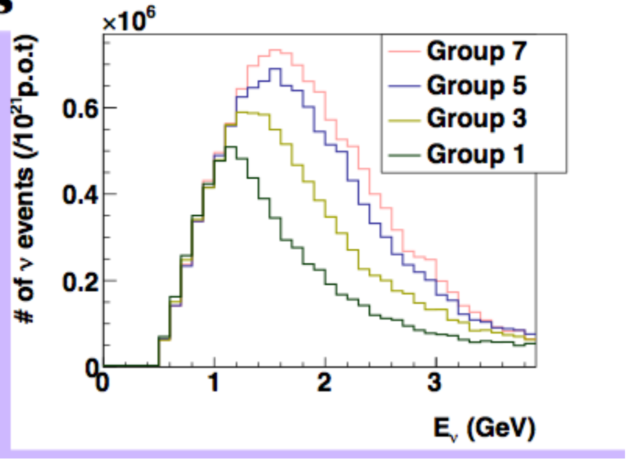
T2K on-axis CC inclusive on Fe

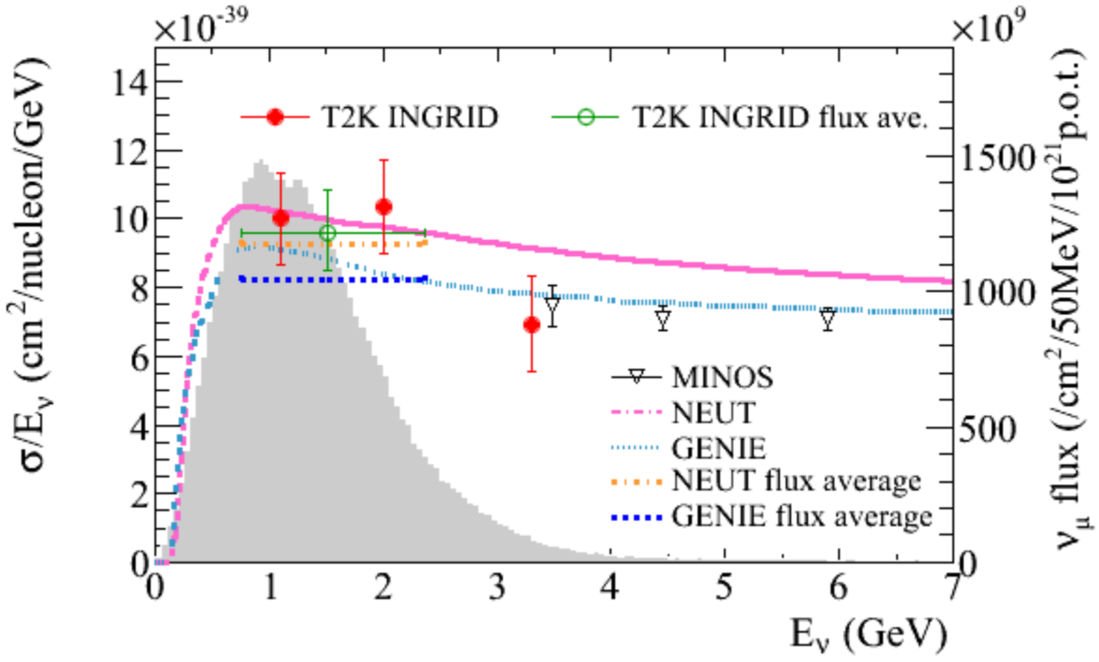
1. Utilize # of event at different modules
   - Different energy spectra at different modules because of different off-axis angles (θ_{OA}=0-0.9°)
2. Group two modules to minimize effects from the variation of the neutrino beam direction
   - 14 modules → 7 groups

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

Use of near detectors on T2K

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

		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%

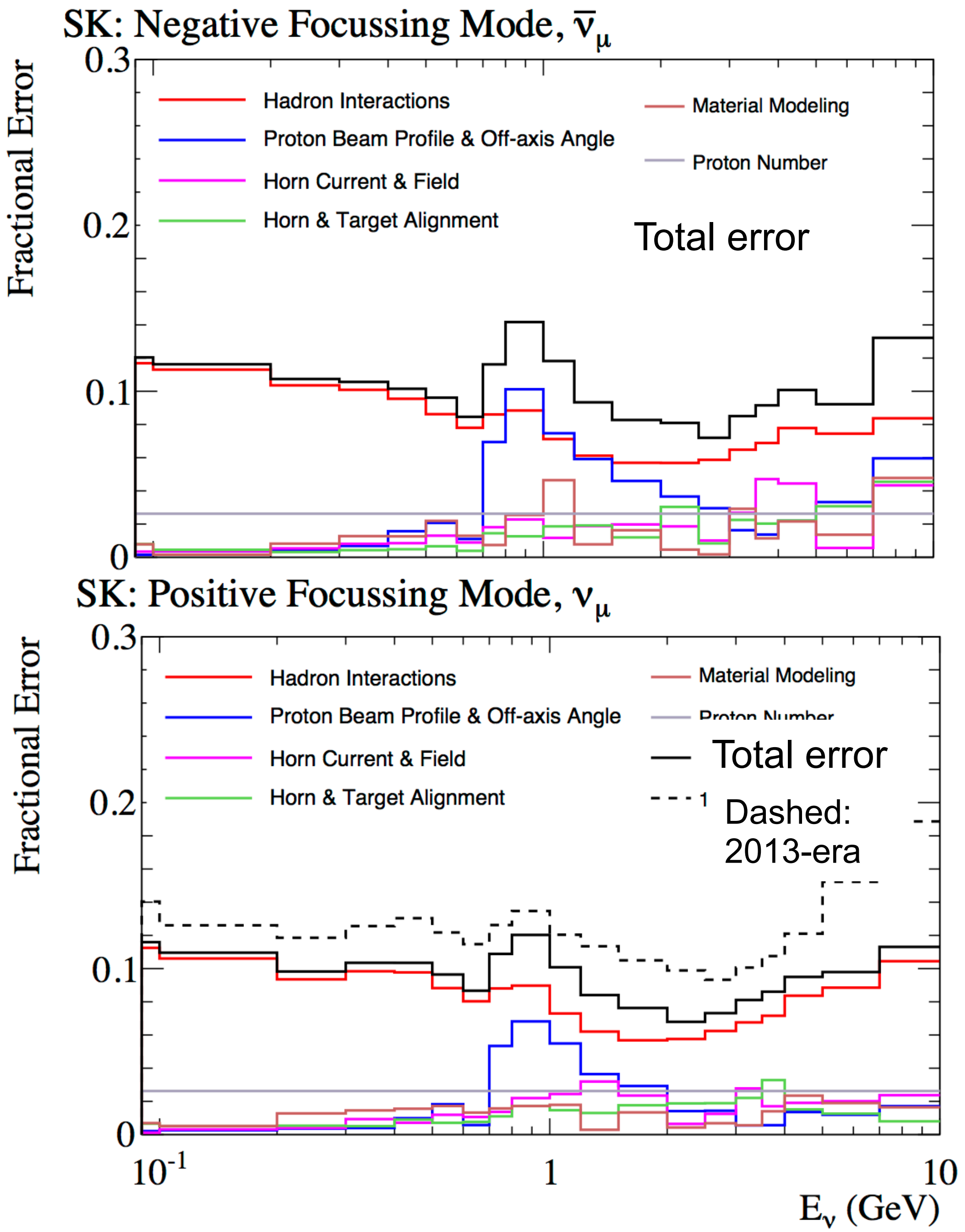
Fractional error on number-of-event prediction

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

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

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

Flux uncertainties

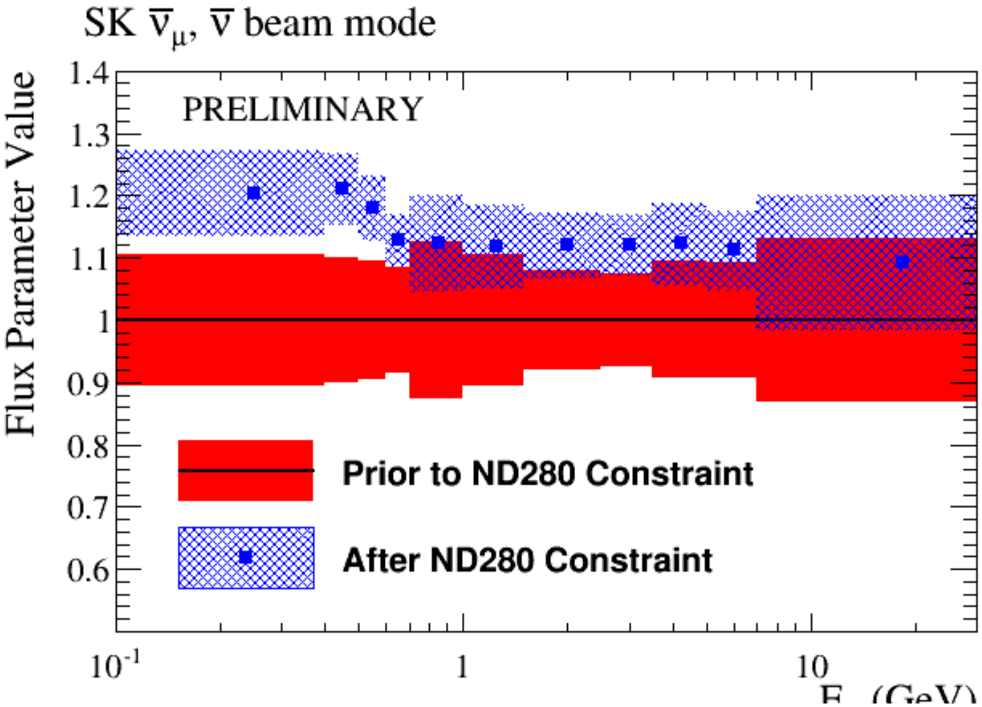


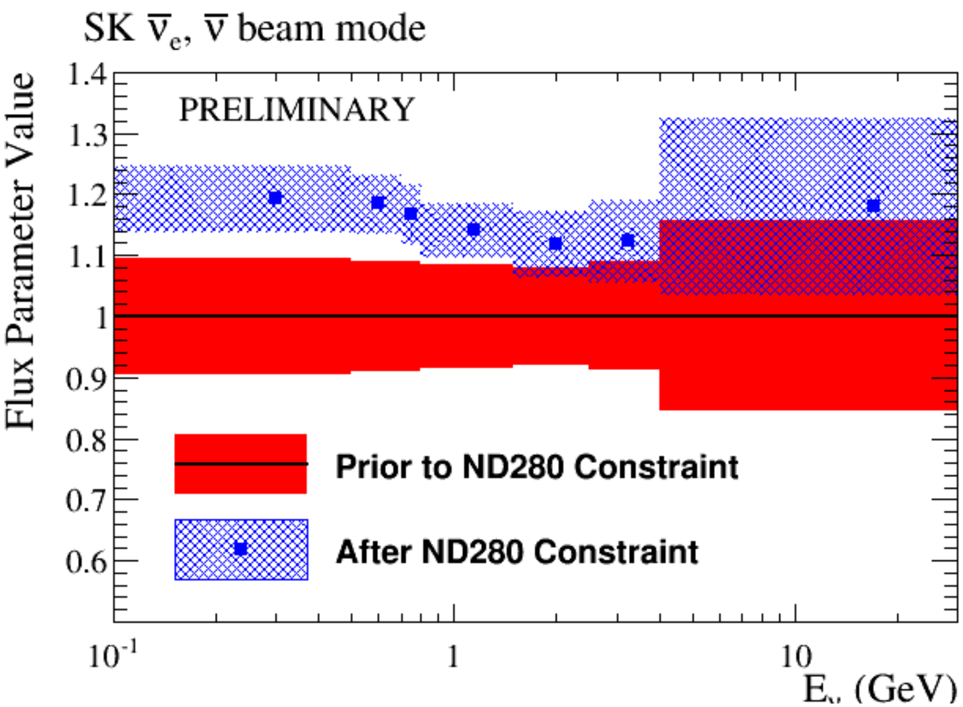
Total error

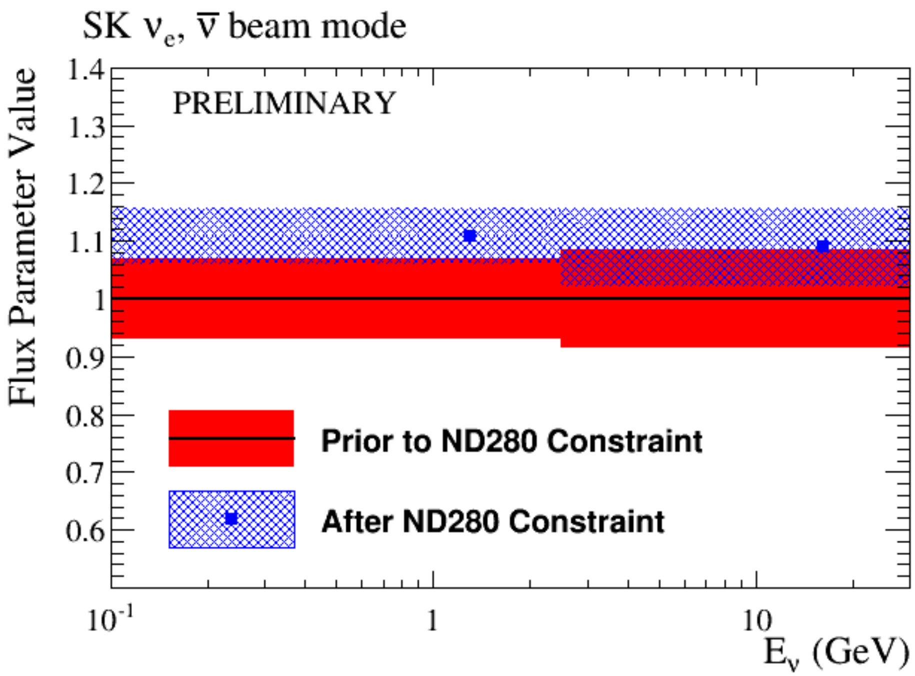
Total error

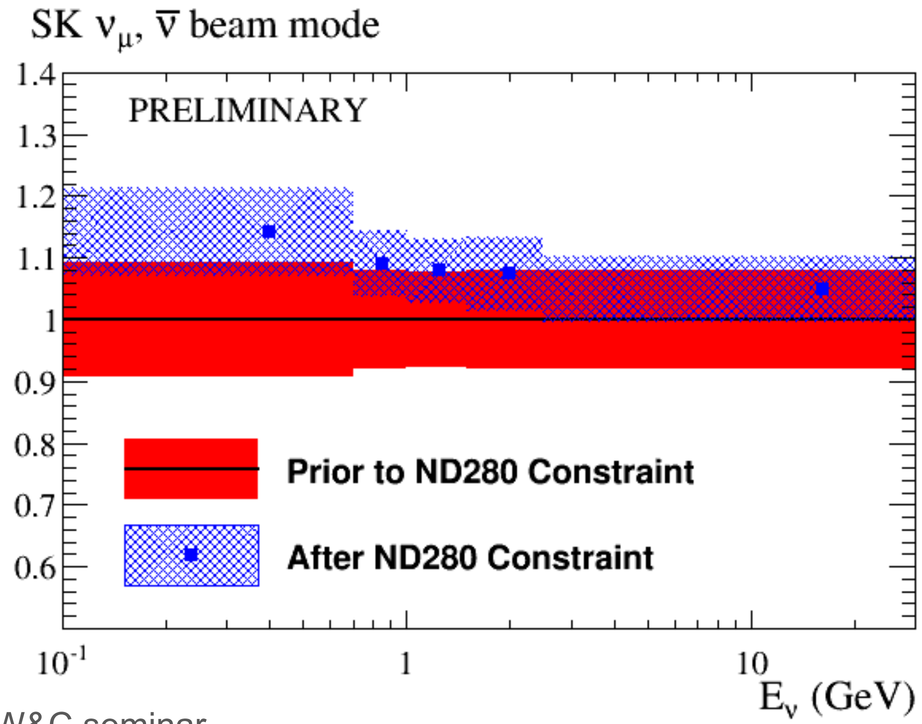
Dashed: 2013-era

Flux tuning from near detector fit

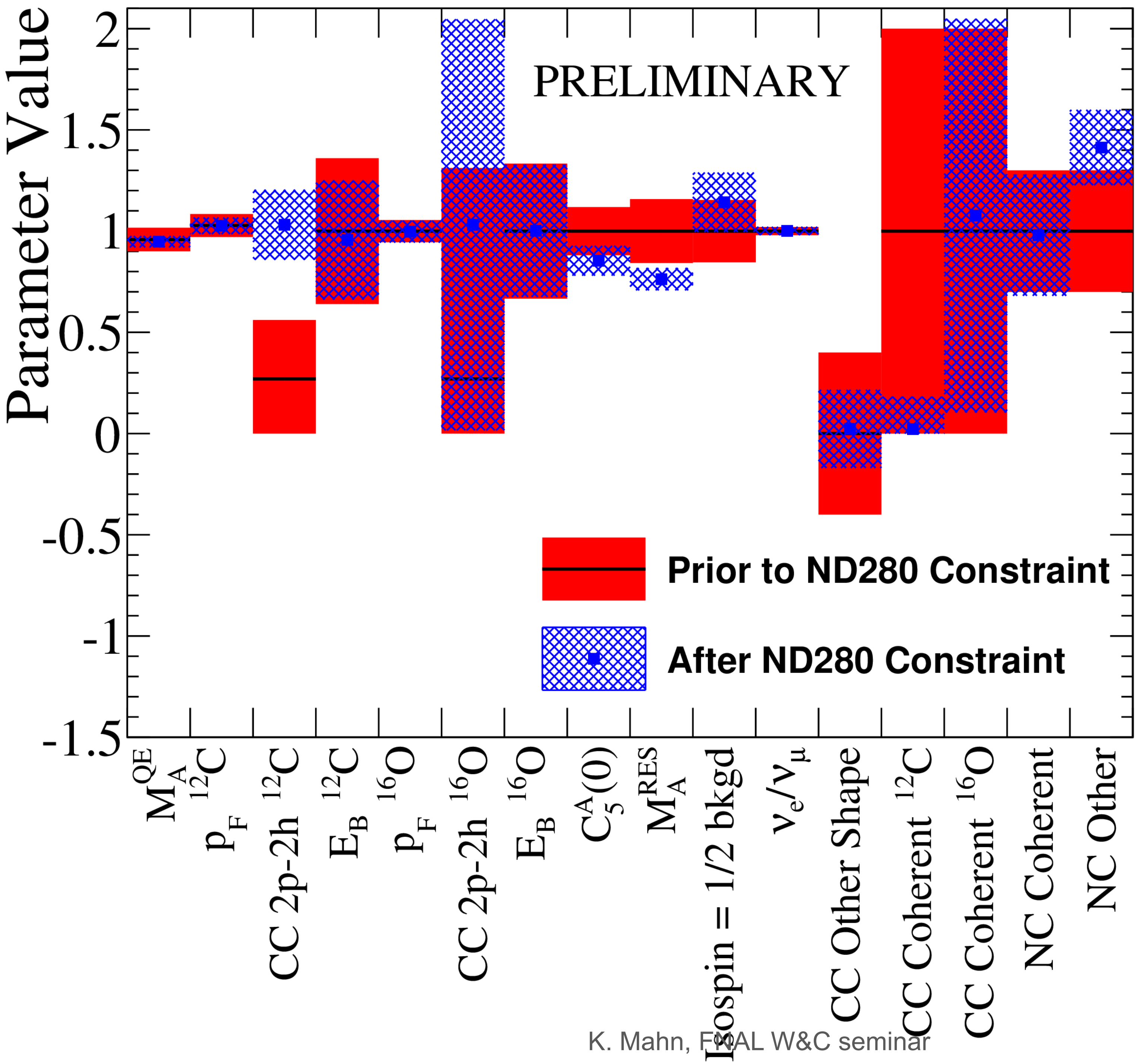




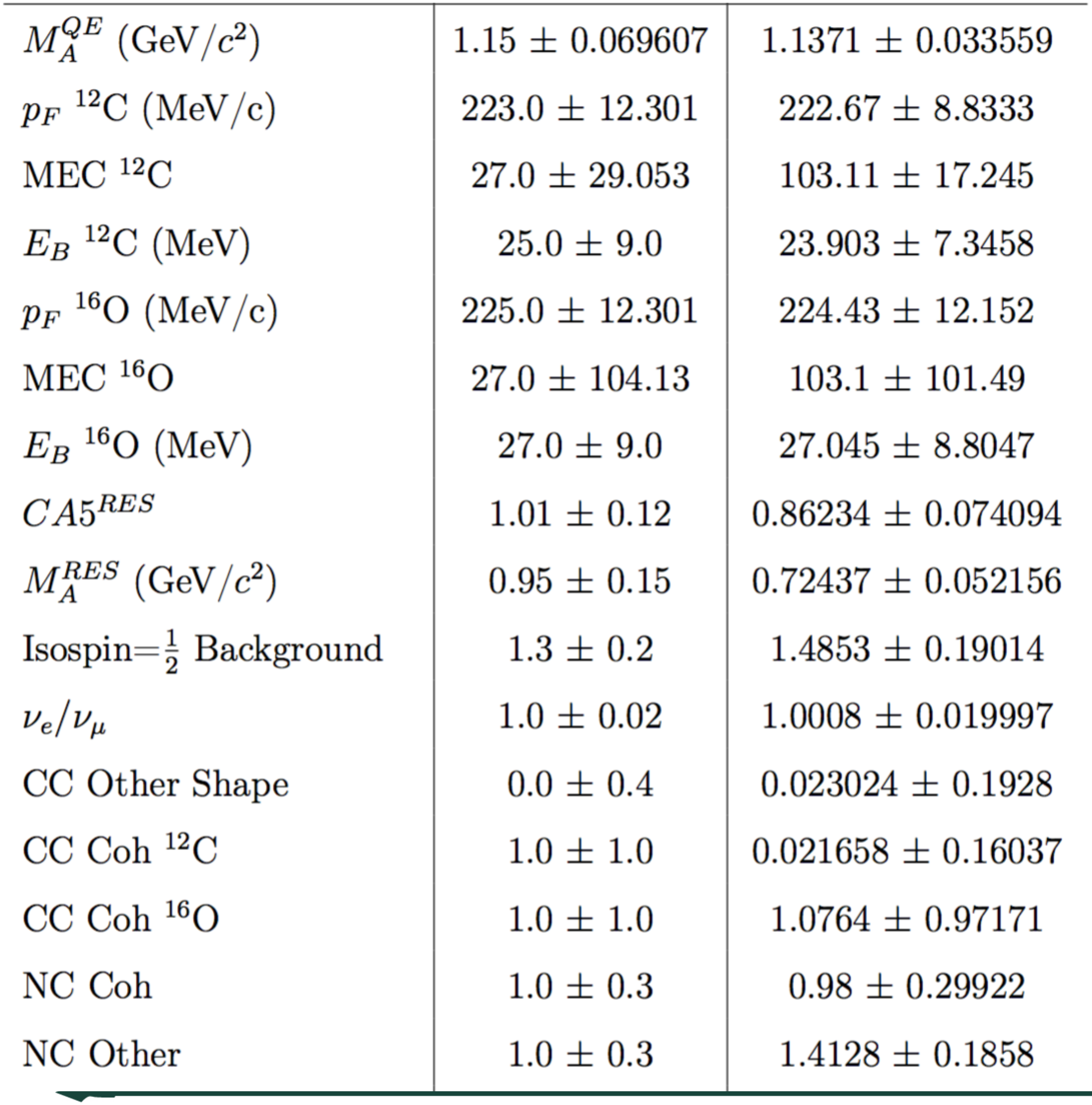




Cross section tuning from near detector fit

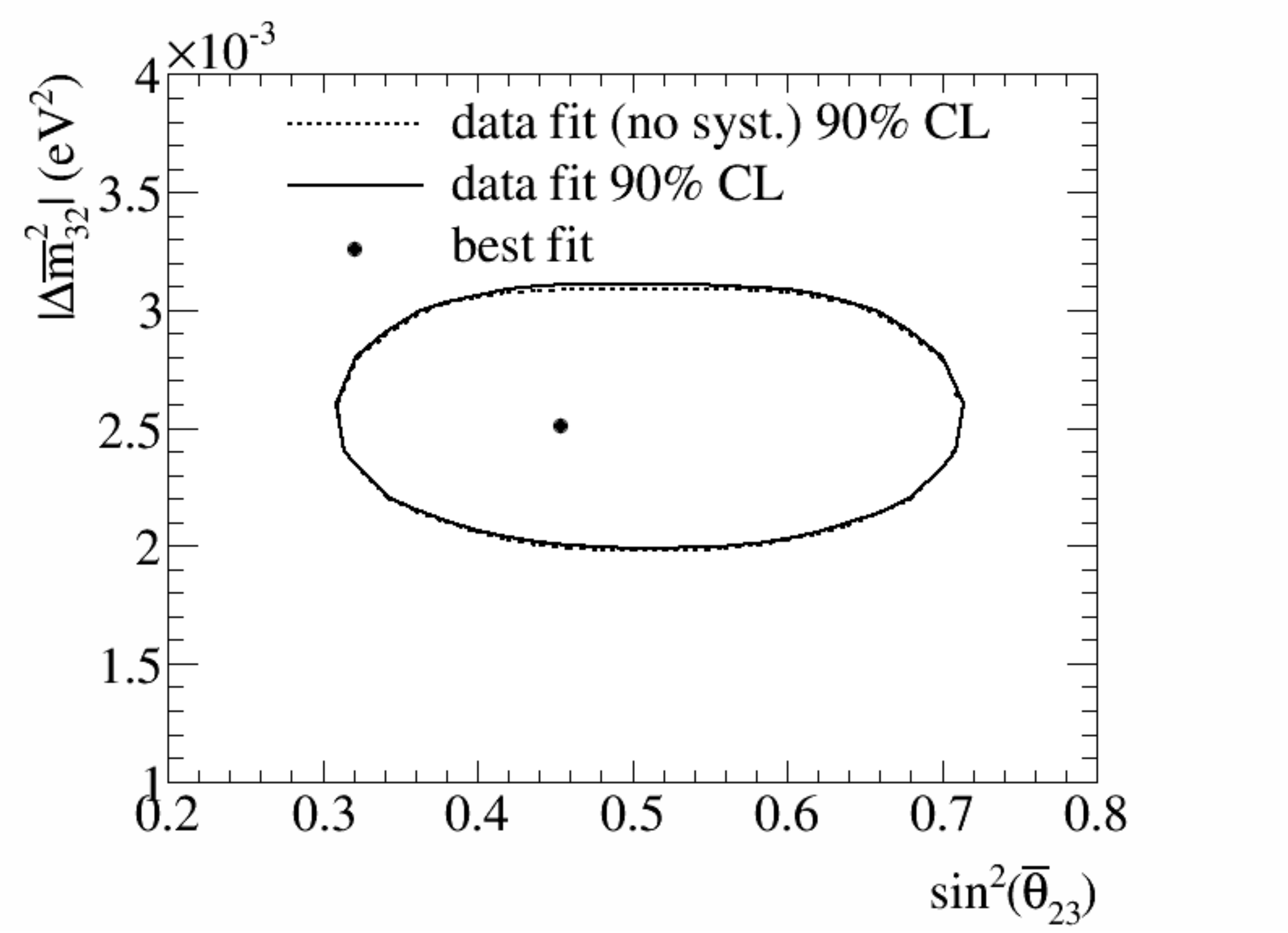


Cross section tuning from near detector fit



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

Impact of systematic uncertainty



Our antineutrino measurements are statistics limited

- Analysis with and without systematics included barely changes the contours