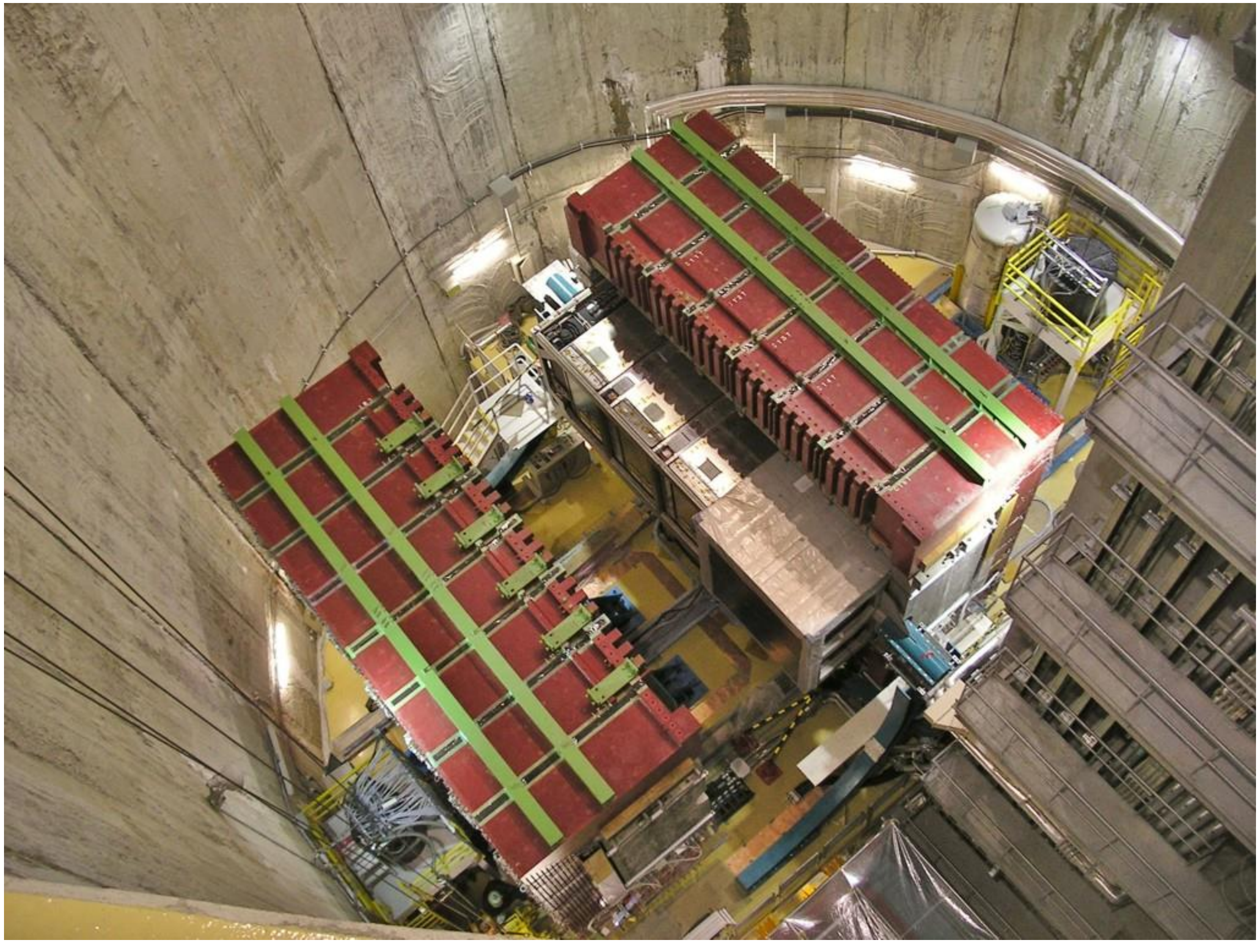


# Recent Results from the T2K Experiment

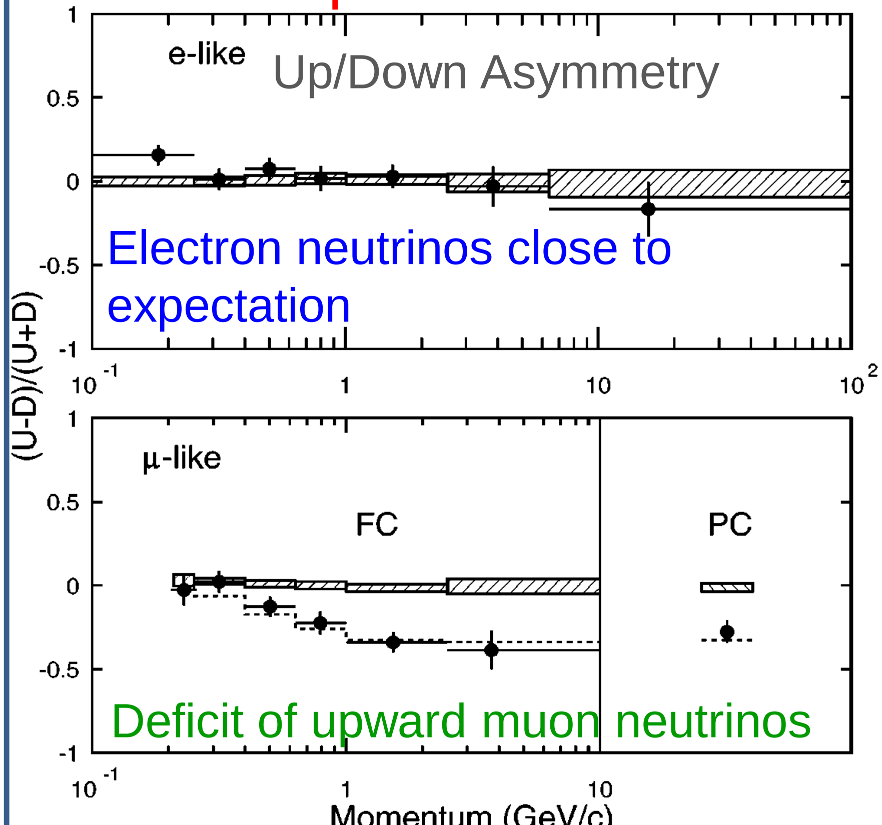
Jeremy P. Lopez
For the T2K Collaboration

HQL 2016
23 May 2016

University of Colorado Boulder

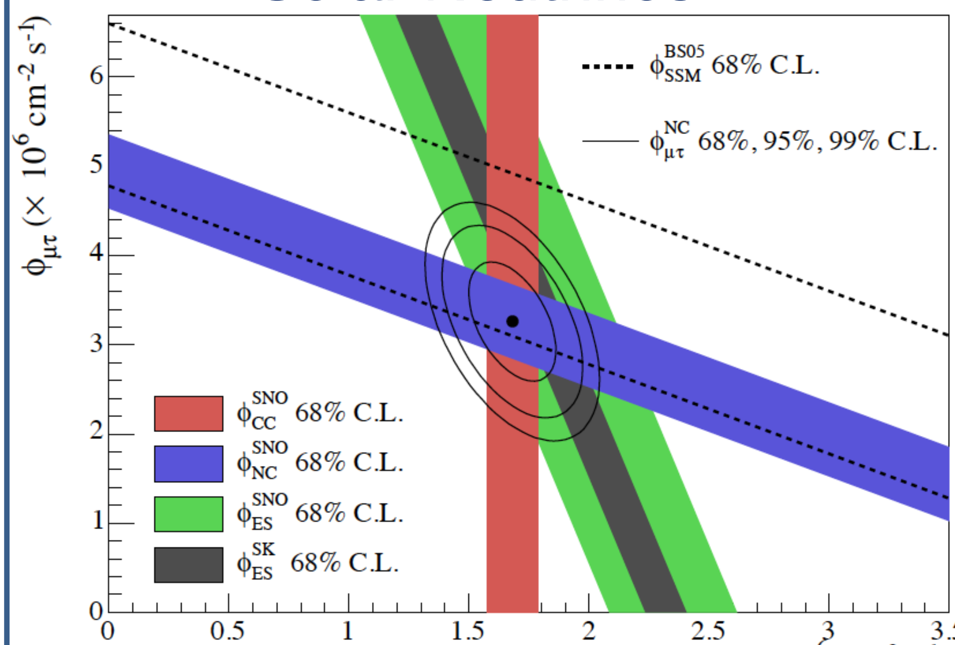
# Neutrino Oscillations

## Super-Kamiokande Atmospheric Neutrinos




Shaded Region: Model prediction
PRL 81 (1998) 1562-1567.

## SNO Solar Neutrinos




PRL 89 (2002) 011301.

$\nu_\mu$ and $\nu_\tau$ coming from the sun

Kajita (SK), McDonald (SNO): 2015 Nobel Prize

# Neutrino Oscillations

Three neutrinos

$$\text{Flavor states} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \text{Mass states}$$

Flavor and mass states not the same

PMNS Matrix (Unitary mixing matrix)

$$c_{ab} = \cos\theta_{ab}$$
$$s_{ab} = \sin\theta_{ab}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Survival probability (simplified two neutrino case)

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \frac{L\Delta m_{32}^2}{4E}$$

$$\Delta m_{32}^2 = m_3^2 - m_2^2$$

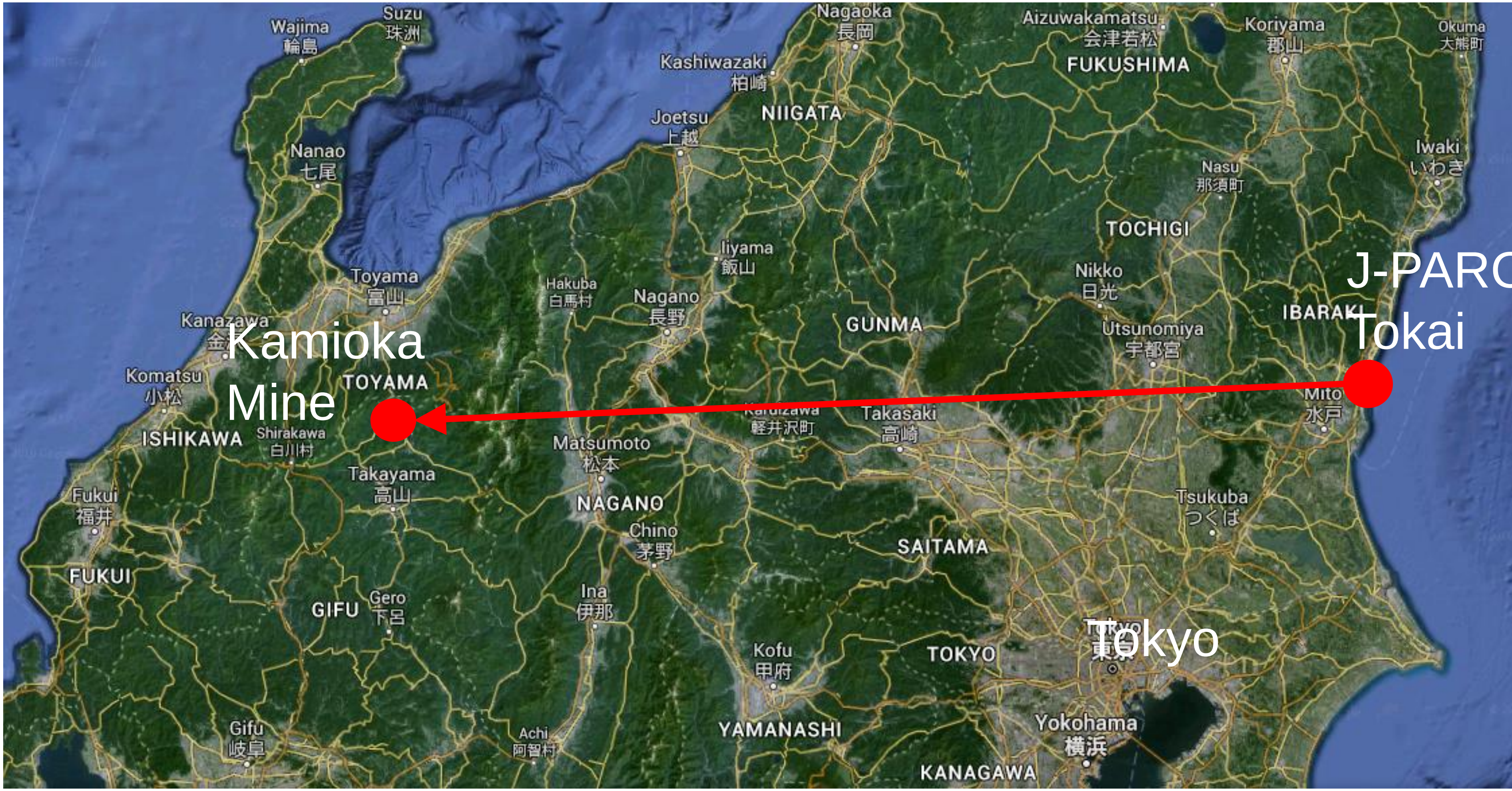
Three neutrino oscillations: 6 total parameters

# Neutrino Oscillation Parameters

| Parameter | Value | Experiment Types |
|---|---|---|
| $\Delta m^2_{12}$ | $(7.54 \pm 0.24) \times 10^{-5}$ eV$^2$ | Solar, Reactor |
| $\lvert\Delta m^2_{23}\rvert$ | $(2.43 \pm 0.06) \times 10^{-3}$ eV$^2$ | Atmospheric, Beam |
| $\sin^2\theta_{12}$ | 0.308±0.017 | Solar, Reactor |
| $\sin^2\theta_{23}$ | 0.437±0.030 | Atmospheric, Beam |
| $\sin^2\theta_{13}$ | 0.0234±0.0020 | Reactor, Beam |
| $\delta_{CP}$ | Unknown | |
| Mass Hierarchy | Unknown | |

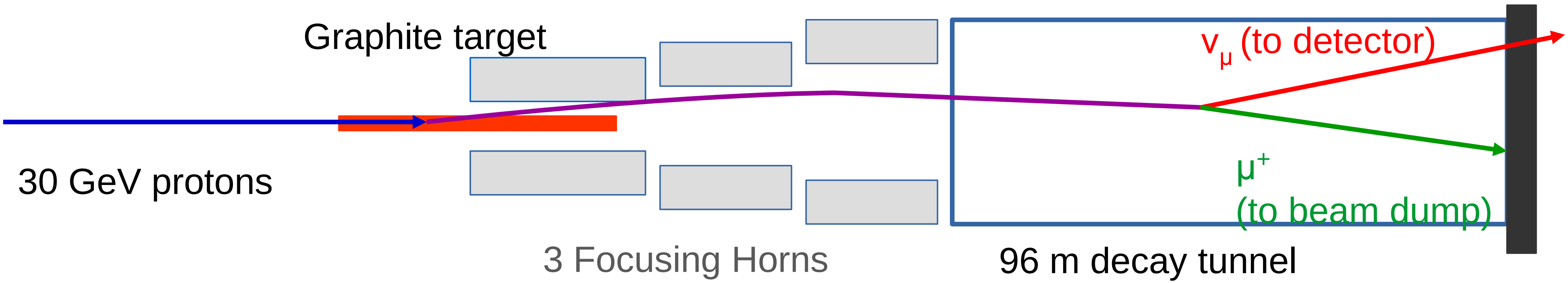
- $\delta_{CP}$: CP Violation (matter/antimatter asymmetry)
- Hierarchy: $+|\Delta m^2_{23}|$ or $-|\Delta m^2_{23}|$ (Determines ordering of mass states)

# The T2K Experiment

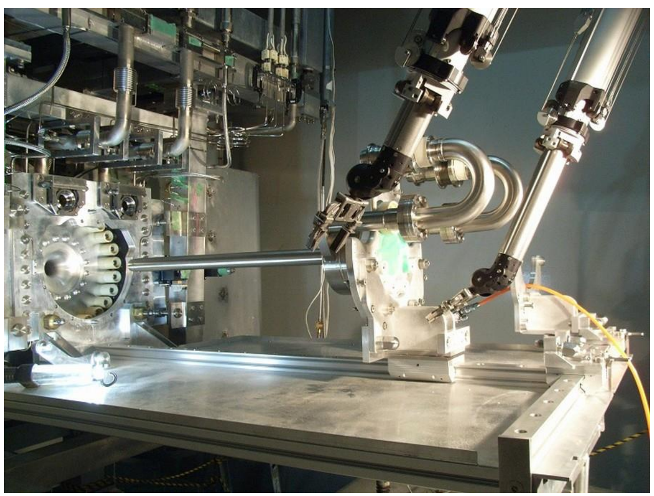



Off-axis beam from J-PARC to Kamioka
295-km baseline
600-MeV peak neutrino energy

# T2K Neutrino Beam




Primary beamline



Target & 1st Horn

Decay tunnel

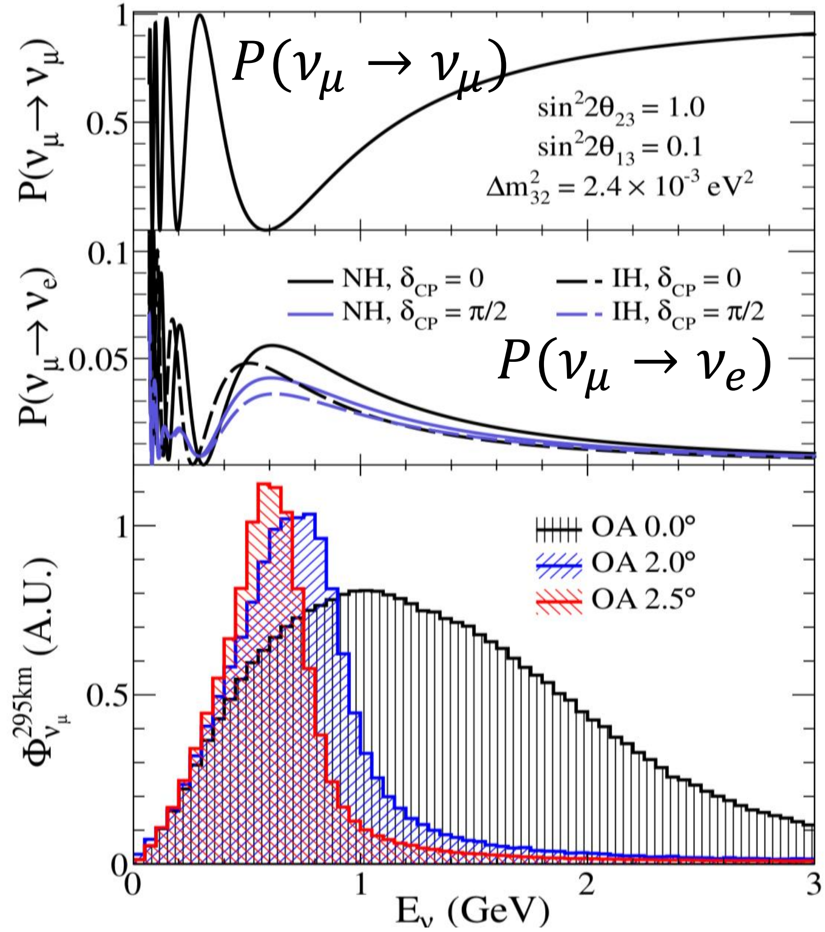
# Physics Goals

## Precision measurements of oscillations:

- $\nu_\mu$ disappearance
- $\nu_e$ appearance
  - First evidence for non-zero $\theta_{13}$!
- $\bar{\nu}_\mu$ disappearance
- $\bar{\nu}_e$ appearance

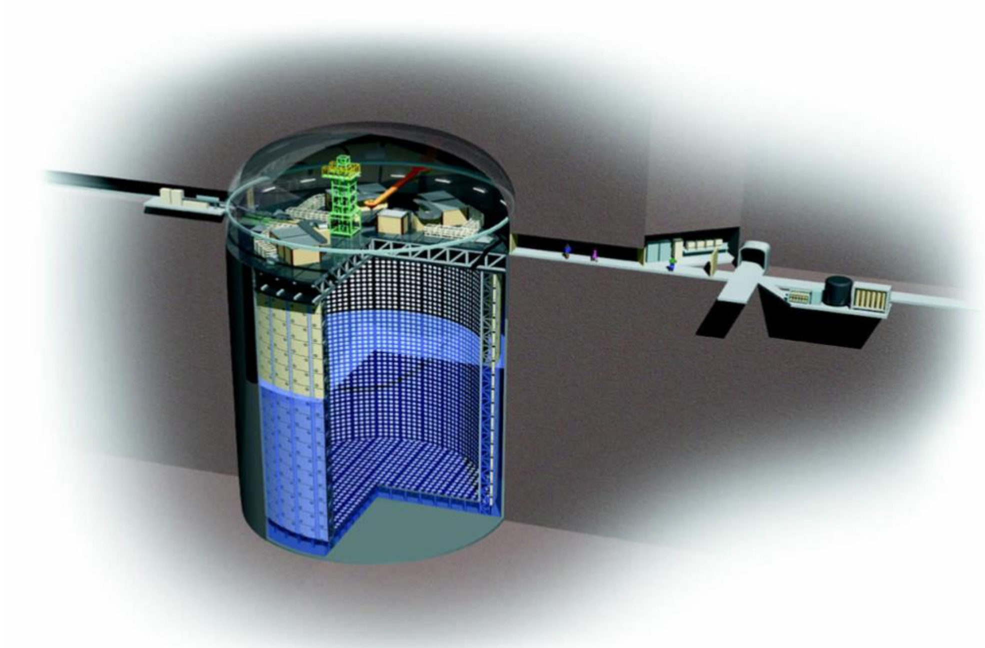
## Near detector physics

- Cross sections
- Short-baseline oscillations
- Lorentz violation
- More




2.5° off-axis beam tunes energy to oscillation maximum

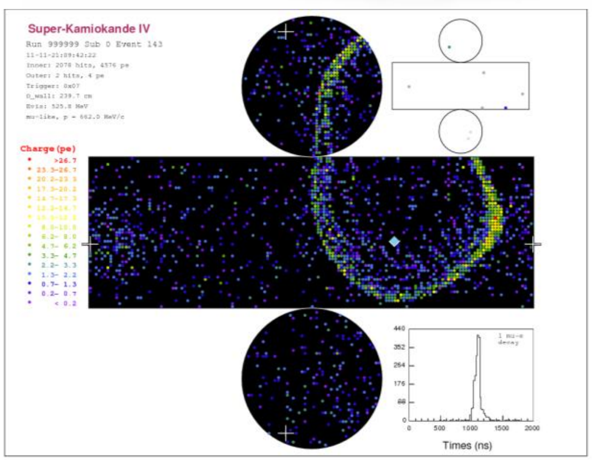
# Far Detector: Super-Kamiokande



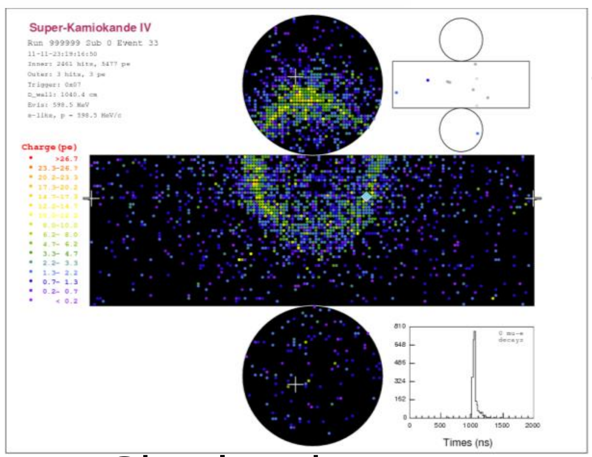
- 50-kton mass water Cherenkov detector
- Measures oscillated $\nu_\mu$ beam

Disappeareance: $\nu_\mu + A \rightarrow \mu^- + X$

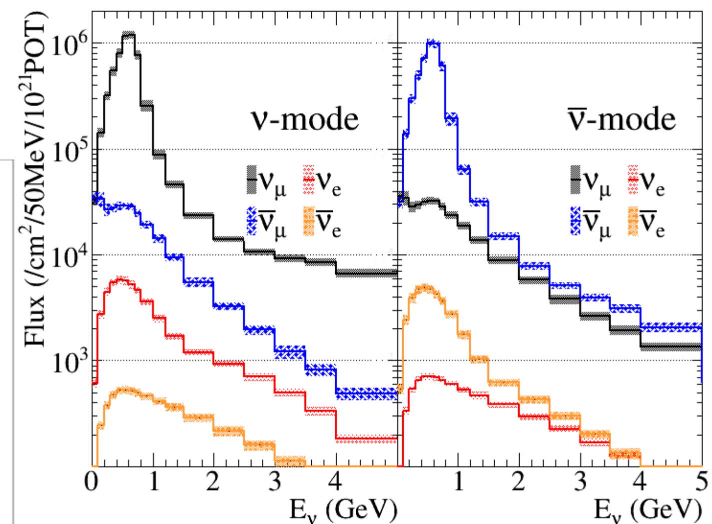
Appearance: $\nu_e + A \rightarrow e^- + X$




Simulated $\nu_\mu$ event

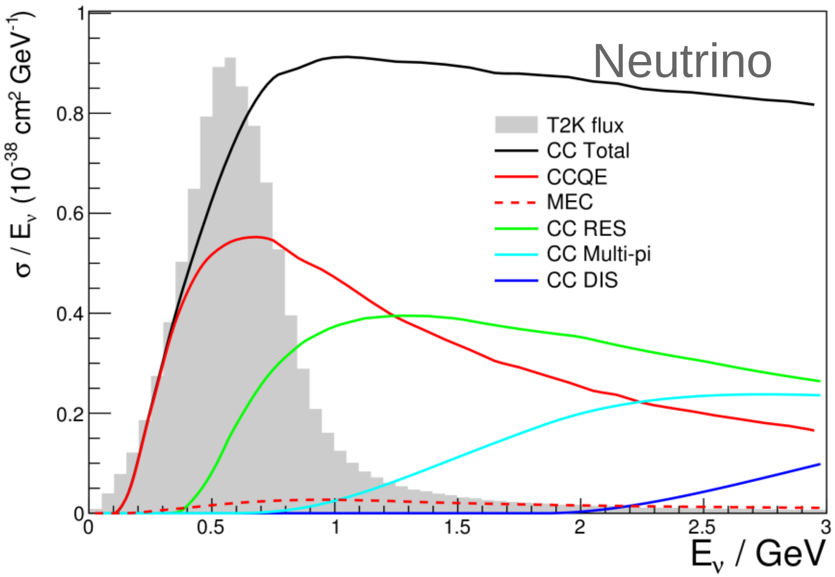


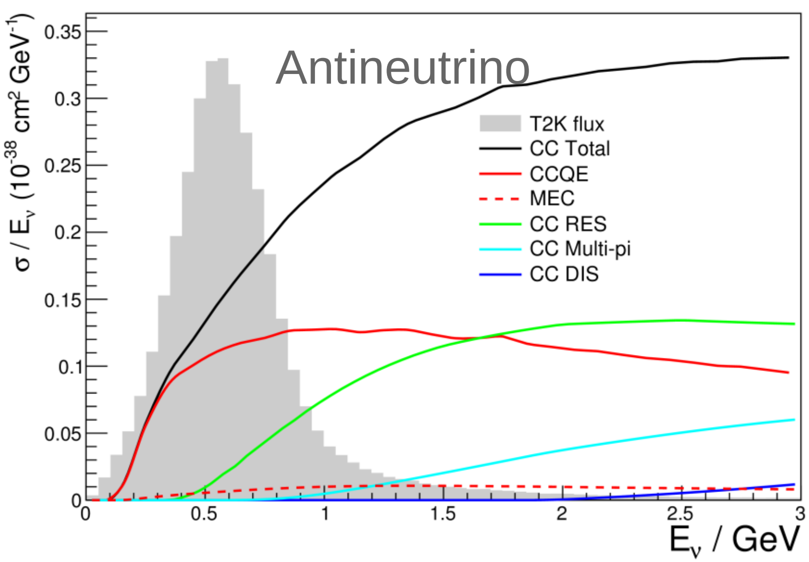

Simulated $\nu_e$ event

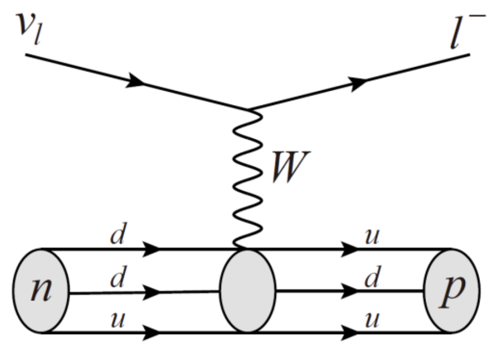



SK Flux Prediction

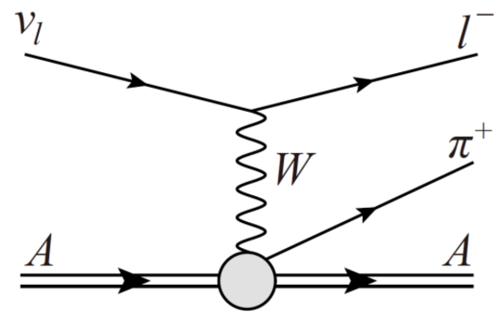
# T2K Charged-Current Interactions



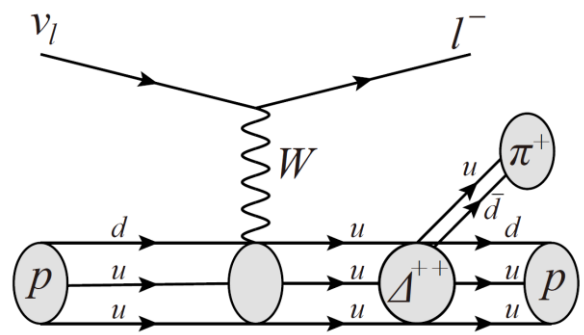



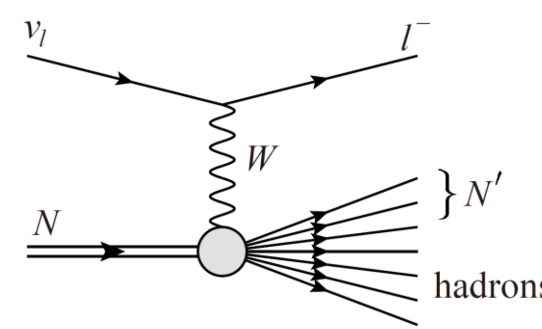

Quasielastic (CCQE)




Coherent Pion Prod.




Resonant Pion Prod.

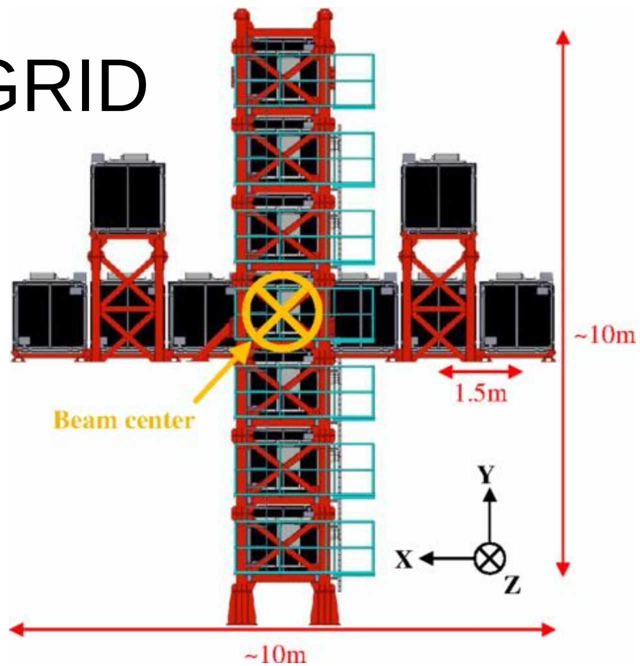



Deep Inelastic Scattering

- **Few existing measurements on water**
- **CCQE (i.e. no pions) is main signal channel**

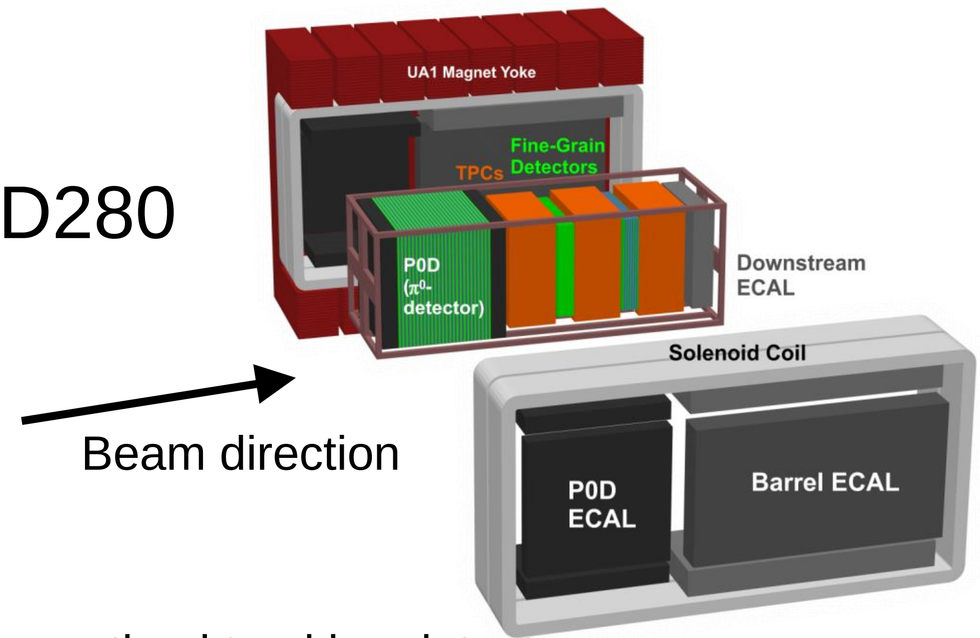
# Near Detectors

INGRID




Alternating scintillator & iron layers
Measure on-axis beam
Monitor beam profile

ND280



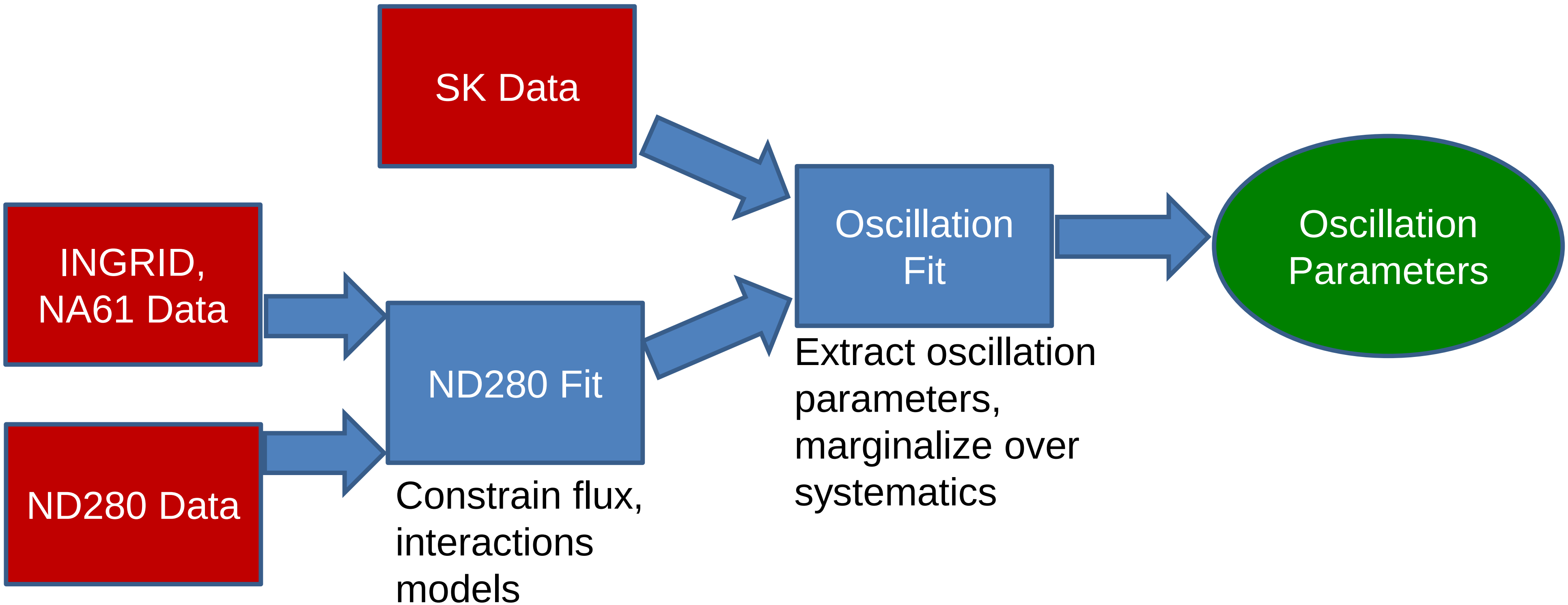

Magnetized tracking detector
Measure off-axis beam
Constrain SK flux/interaction model

Magnet + TPCs: Charge/Momentum reconstruction
FGD1: Scintillator target
FGD2: Scintillator & water target
P0D: Upstream scintillator & water targets
ECALs: Scintillator & lead

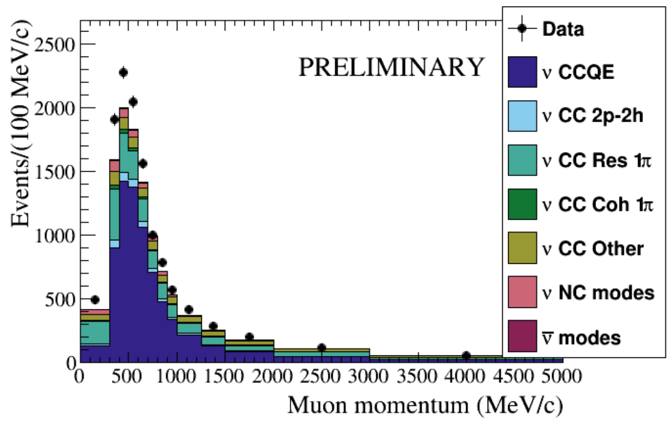
# T2K Oscillation Analysis

SK Selections:

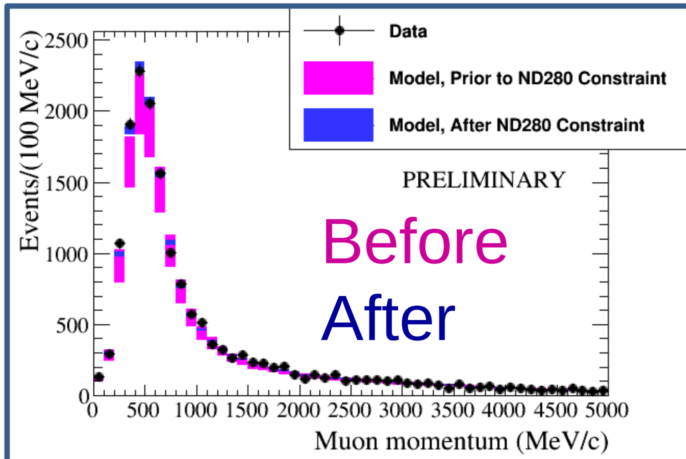
1) $\nu_\mu$ CC0π (CCQE-like) - Disappearance
2) $\nu_e$ CC0π - Appearance



# Near Detector Constraints




Select ND280 events by reconstructed topology




Fit cross section, flux, detector model to selected data samples

Example here:

$\nu$ beam,

$\nu_\mu$ CC0π (CCQE-like) sample

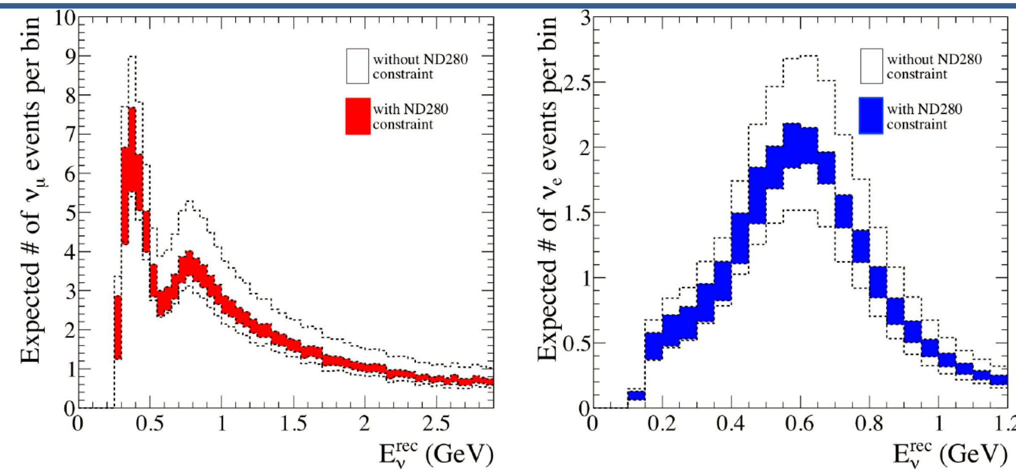
(p,cosθ) distribution

Other samples include:

$\nu_\mu$ CC1π (CC-Res-like) sample

$\nu_\mu$ CC-Other sample

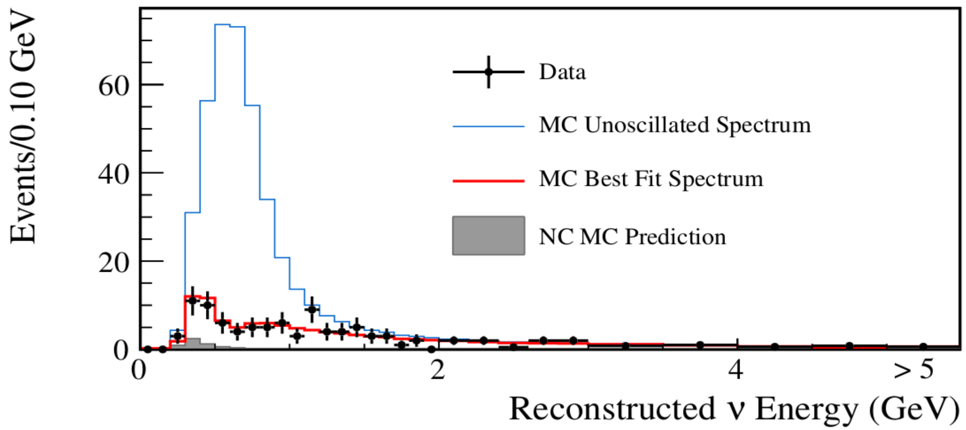
Reduce systematic uncertainties from ~25% to ~8%

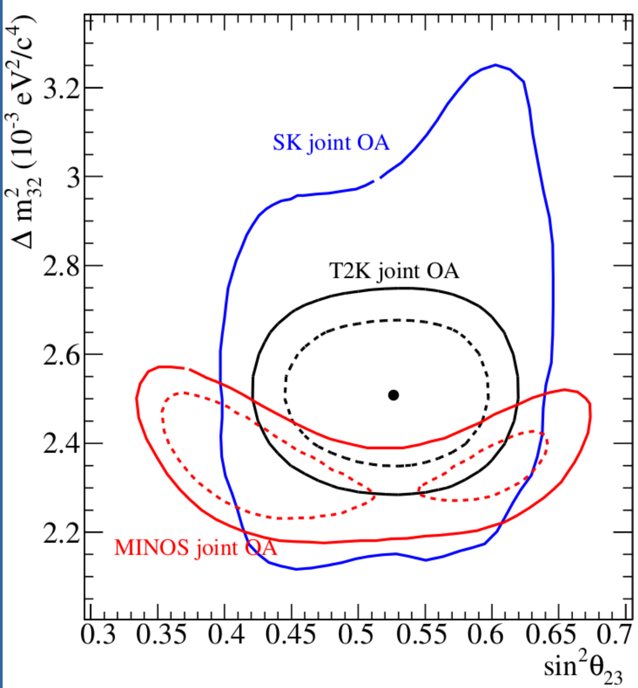



Apply fit (constrained) model to improve predicted SK spectra

# Neutrino Results

## Muon Neutrinos



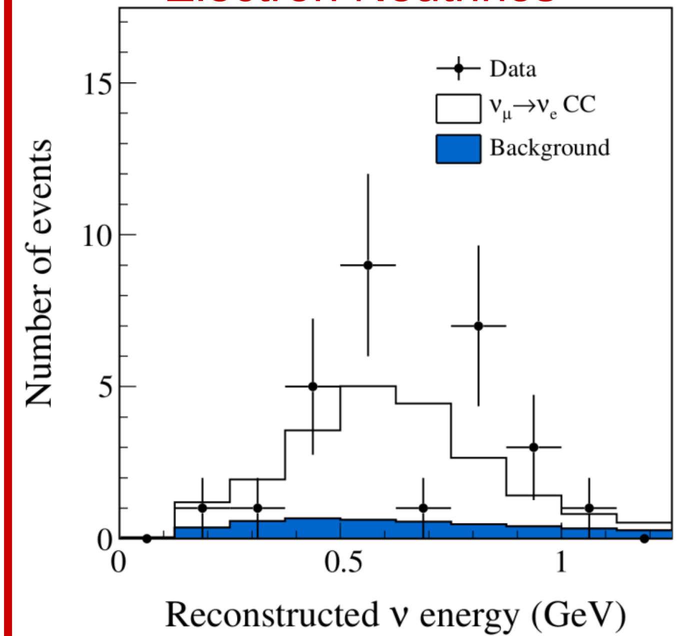



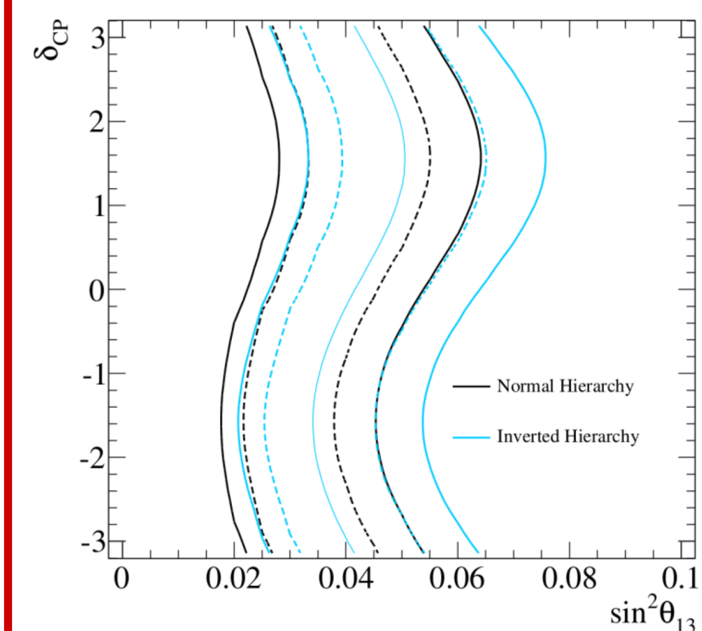

Early 2015
joint $\nu_\mu, \nu_e$
oscillation fit

Most precise
measurement
so far

Phys. Rev. D
91, 072010 (2015)

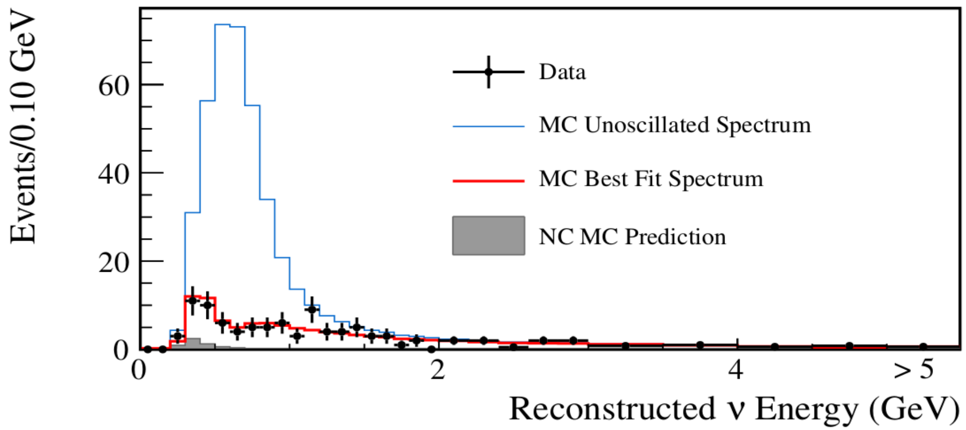
## Electron Neutrinos



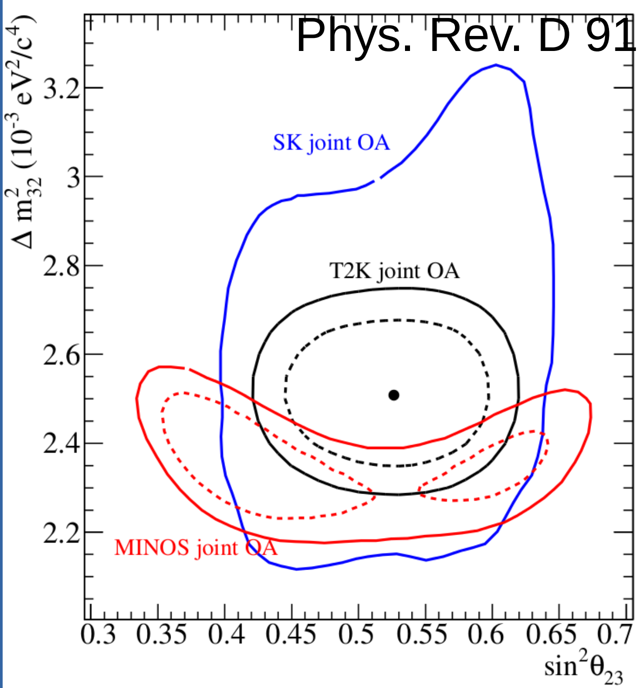



# Neutrino Results

## Muon Neutrinos



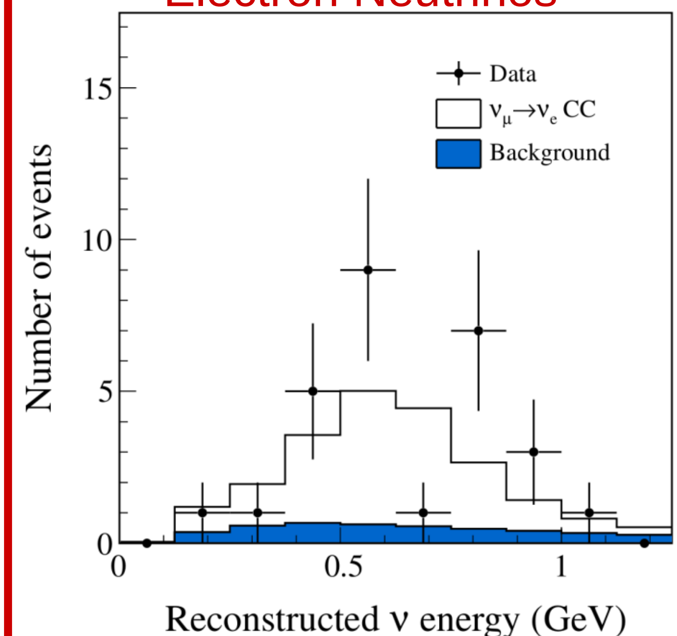

Phys. Rev. D 91, 072010 (2015)

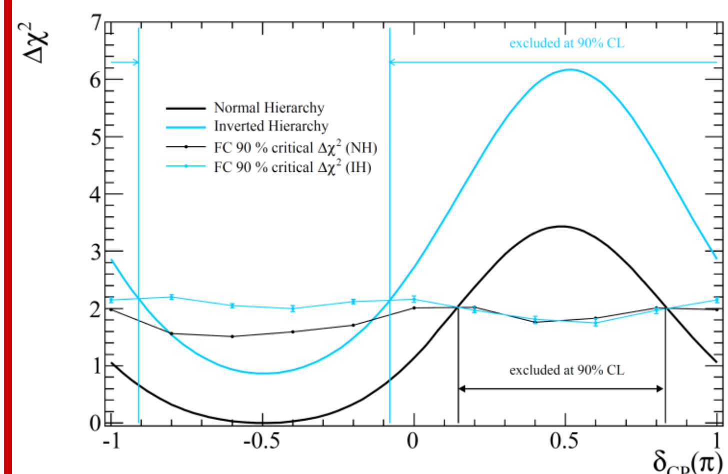



Early 2015 joint $\nu_\mu, \nu_e$ oscillation fit

Most precise measurement so far

## Electron Neutrinos




T2K+Reactor Fit

# CP Violation

Matter effect

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{L\Delta m^2_{32}}{4E}\left(1 + \frac{2a}{\Delta m^2_{31}}\sin 2\theta_{13}\right)$$
$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\boldsymbol{\sin\delta_{CP}}\sin^2\frac{L\Delta m^2_{32}}{4E}\sin\frac{L\Delta m^2_{21}}{4E}$$

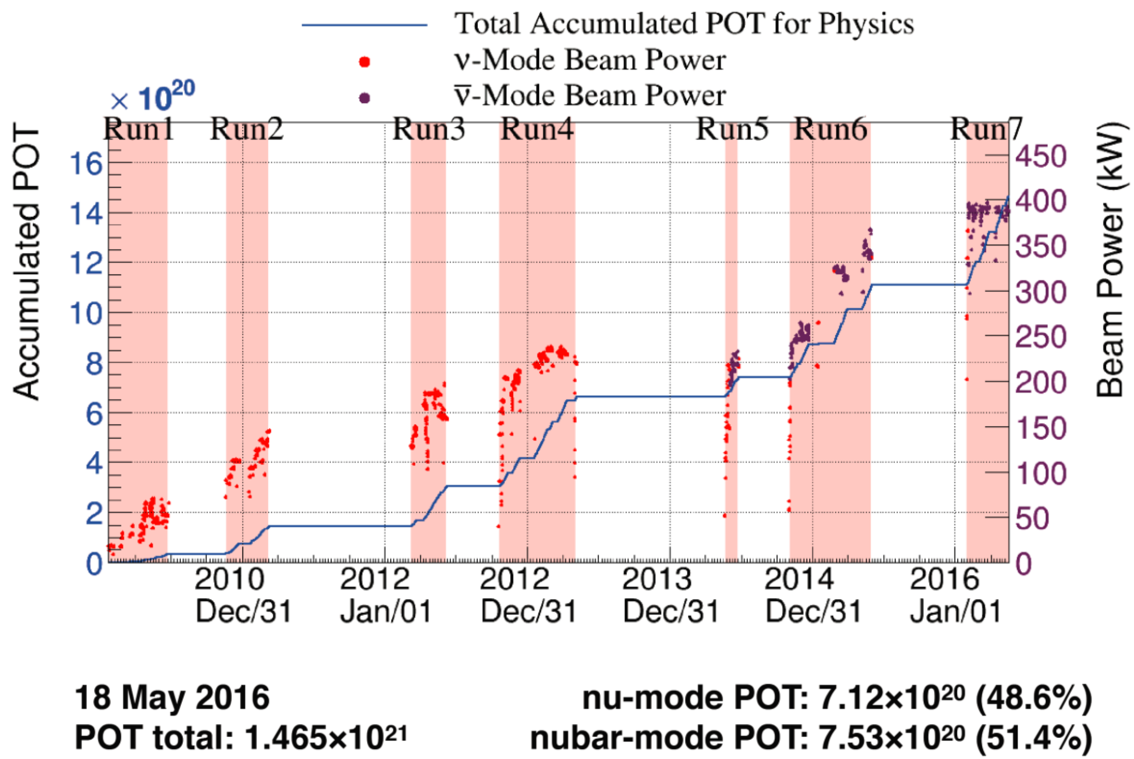
Ignoring matter effect:

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin\delta_{CP}$$

To measure CP violation, must compare $\nu$ and $\bar{\nu}$ oscillations

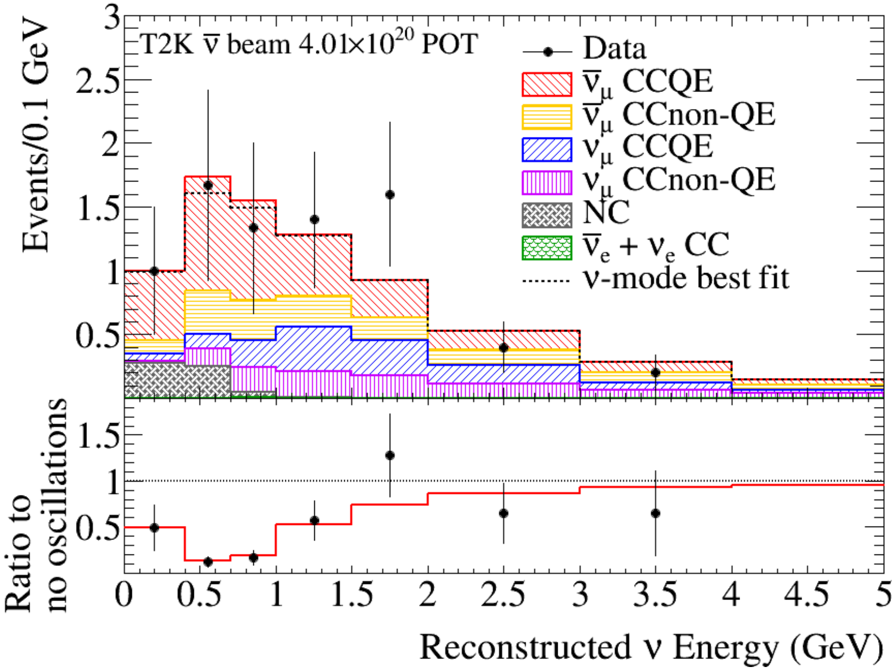
# Antineutrino Oscillations

- Running mostly in antineutrino mode since 2014
- First results released in 2015
- First publication in May 2016
- Current analysis uses:
- 0.43 x $10^{20}$ POT ND280 $\bar{\nu}$ data
- 5.82 x $10^{20}$ POT ND280 $\nu$ data
- 4.01 x $10^{20}$ POT SK data



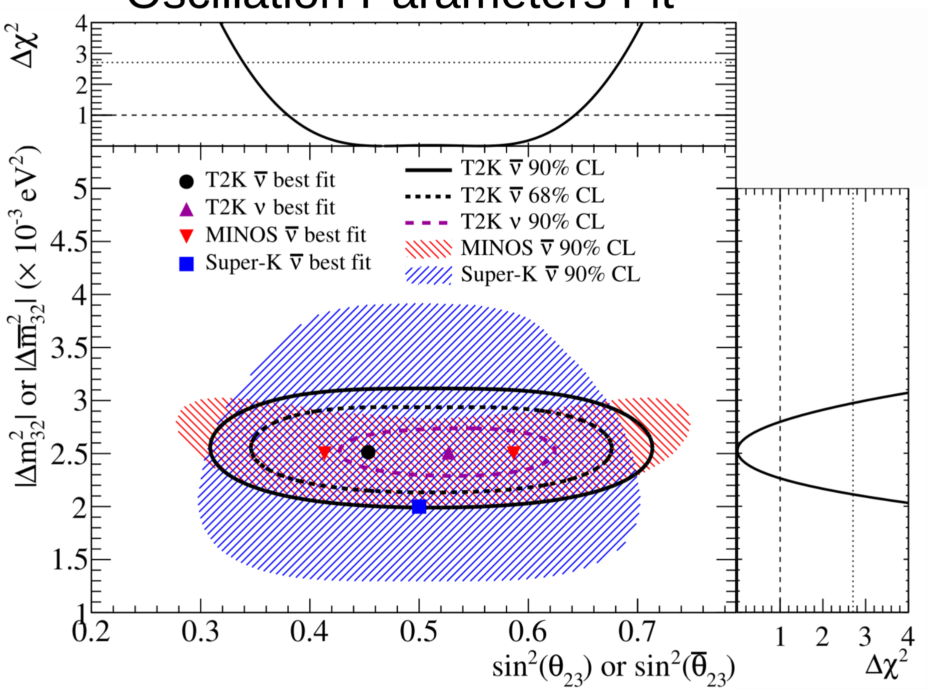
# $\bar{\nu}_\mu$ Disappearance

SK $\bar{\nu}_\mu$ Sample




Clear deficit of $\bar{\nu}_\mu$ compared to no oscillations

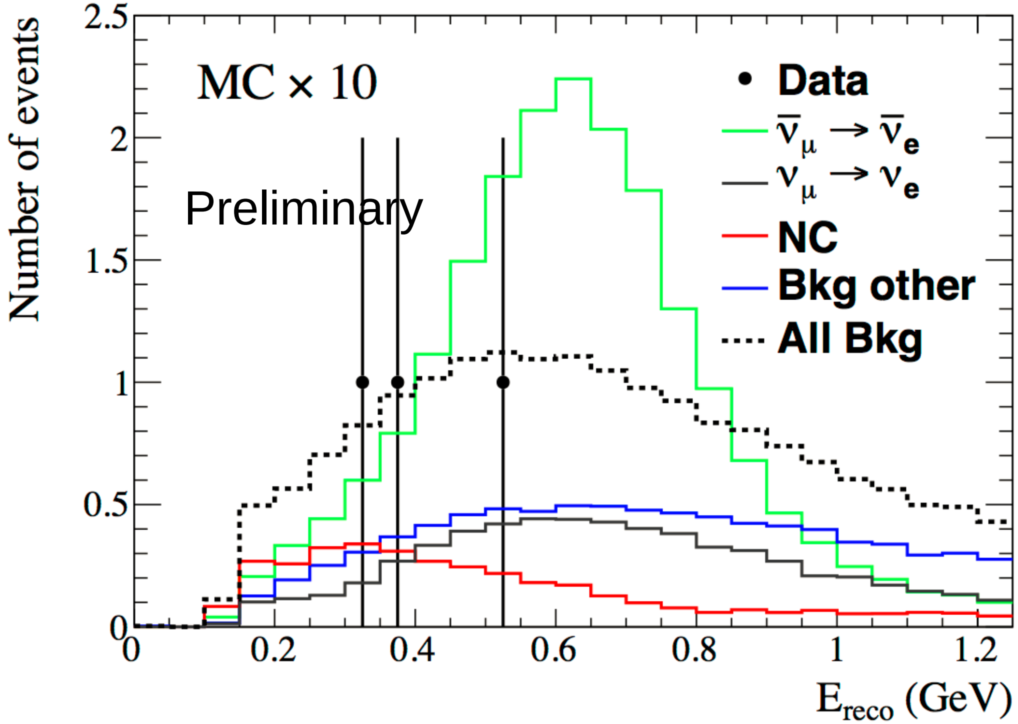
Oscillation Parameters Fit




PRL, 116, 181801 (2016)

- Most precise measurement so far
- $\bar{\nu}_\mu$ consistent with $\nu_\mu$ parameters

# $\bar{\nu}_e$ Appearance




| | $\delta_{CP} = -\pi/2$ | $\delta_{CP} = 0$ | $\delta_{CP} = +\pi/2$ |
|---|---|---|---|
| Sig $\bar{\nu}_\mu \to \bar{\nu}_e$ | 1.961 | 2.636 | 3.288 |
| Bkg $\nu_\mu \to \nu_e$ | 0.592 | 0.505 | 0.389 |
| Bkg NC | 0.349 | 0.349 | 0.349 |
| Bkg other | 0.826 | 0.826 | 0.826 |
| Total | 3.729 | 4.315 | 4.851 |

- 3 candidate $\bar{\nu}_e$ appearance events
- Low statistics, still consistent with expected background
- Need more data

Compared to this result:
Have >10x ND280 data used
Have ~2x SK data

# Cross Section Measurements

Flux-averaged
Cross Section

Data | Expected Background

$$\sigma \sim \frac{N - B}{\varepsilon \Phi N_{targets}}$$

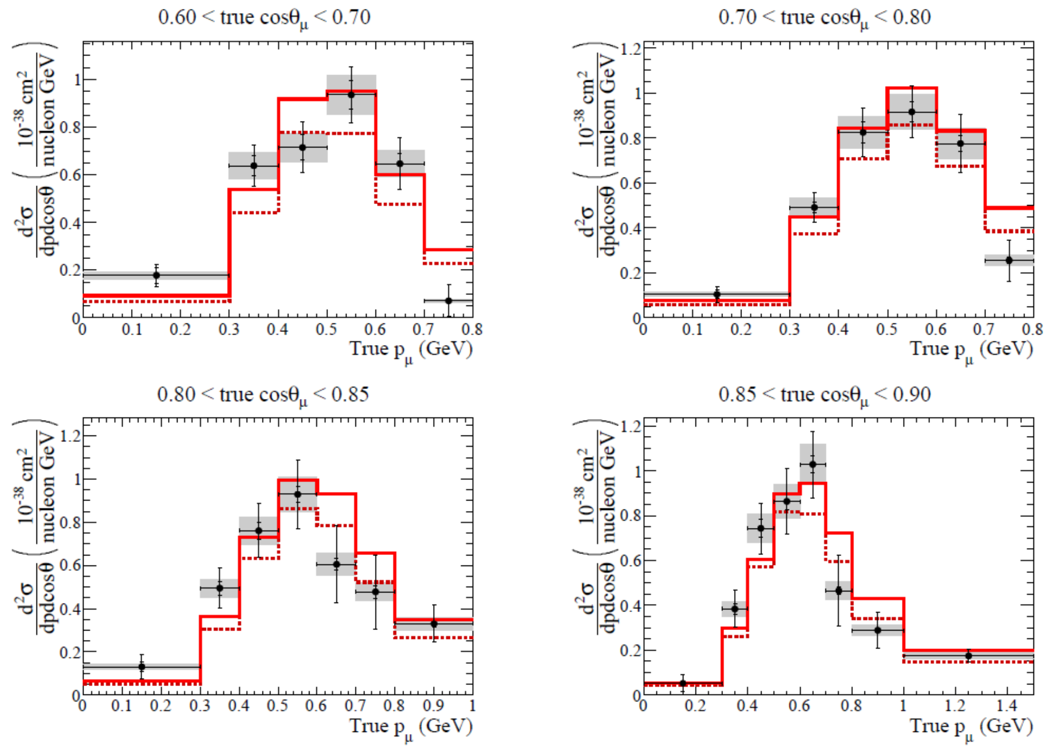
Efficiency | Flux

- Neutrino-nucleus interactions are complicated
- Test & constrain neutrino interaction models
- Reduce uncertainties in oscillation measurements
- ND280 and INGRID Cross Sections:
  - Interactions on several materials (scintillator, water, iron, etc)
  - Interactions with different final state topologies

# Charged-Current with 0 $\pi$ on Scintillator

Method 1:

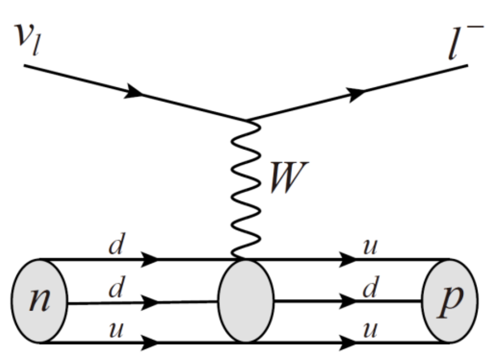
- Select muon using dE/dx
- 0 or 1 protons found (defined by dE/dx) with no other tracks
- Perform binned likelihood fit




Method 2:

- Select muon using dE/dx
- Look for events with 0 pion candidate tracks
- Extract cross section using Bayesian unfolding

Cross section for several muon angle bins
Red solid: Martini et al. prediction
Red dashed: Nieves et al. prediction




Systematics dominated by flux uncertainty (8.5%)

arXiv:1602.03652

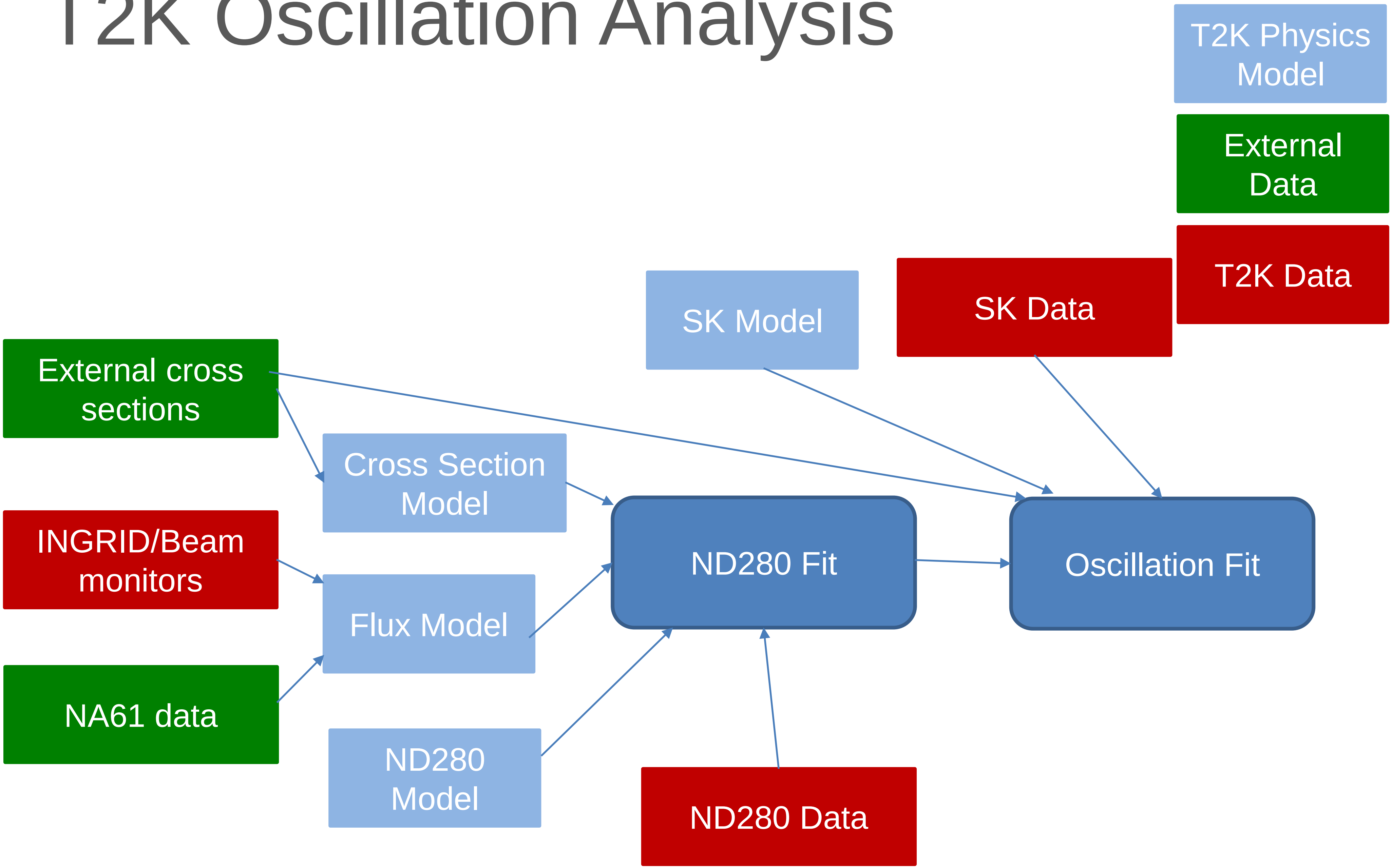
# Future Outlook and Conclusions

- T2K uses an off-axis neutrino beam to study long-baseline neutrino oscillations
- Already producing leading antineutrino measurements with first $\bar{\nu}$ results, new result with ~2x data later this year
- Many neutrino interactions results being released too
- Continuing to take data to improve existing results
- Many new results to come (water cross sections, antineutrino interactions, …)

# Thank You

# Backups

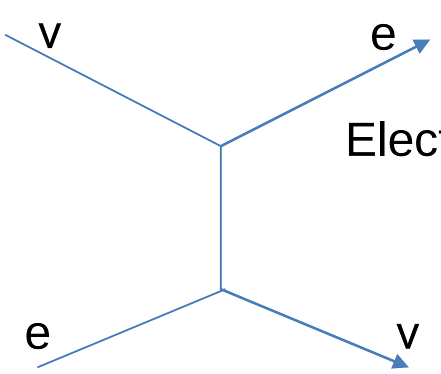
# T2K Oscillation Analysis



# MSW (Matter) Effect

$\nu_e$ CC interactions in matter add an additional potential energy:

$$H\begin{pmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{pmatrix} \to \frac{1}{2E}U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger\begin{pmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{pmatrix} + \begin{pmatrix}\sqrt{2}G_F n_e & 0 & 0\\0 & 0 & 0\\0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{pmatrix}$$




Electrons in matter

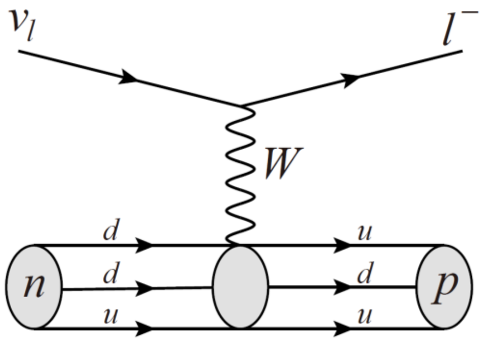
Extra mass term:
Changes mixing angles
Changes effective mass splitting

# More on Interactions

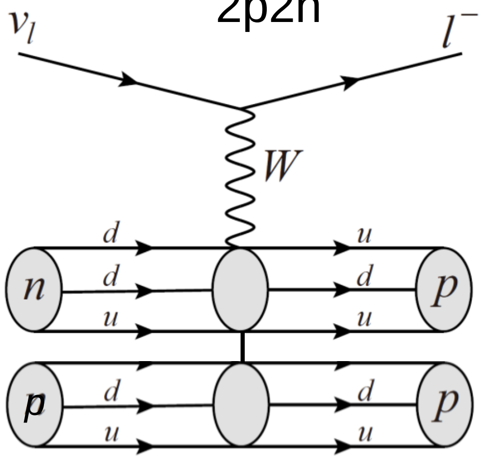
- Interactions in target nuclei are important
- Need to understand SK event topologies rather than fundamental interaction types

## CC0π Topology

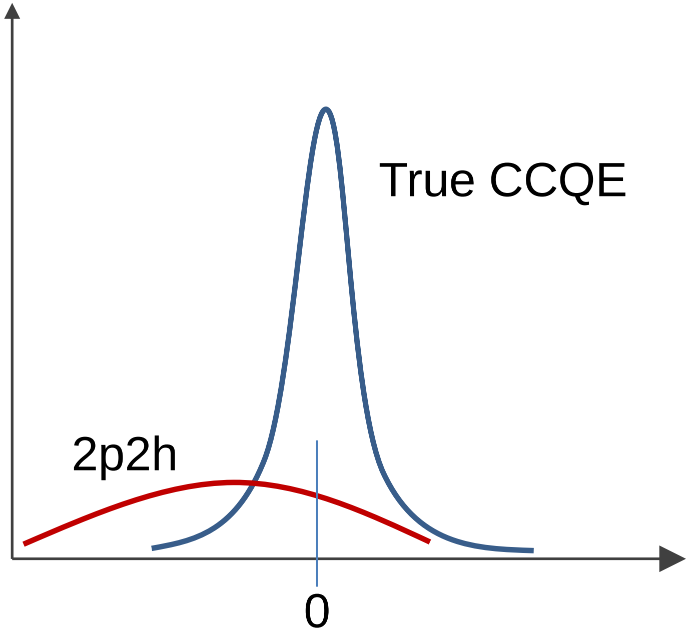
CCQE
Simplest interaction




Multinucleon effects
2p2h

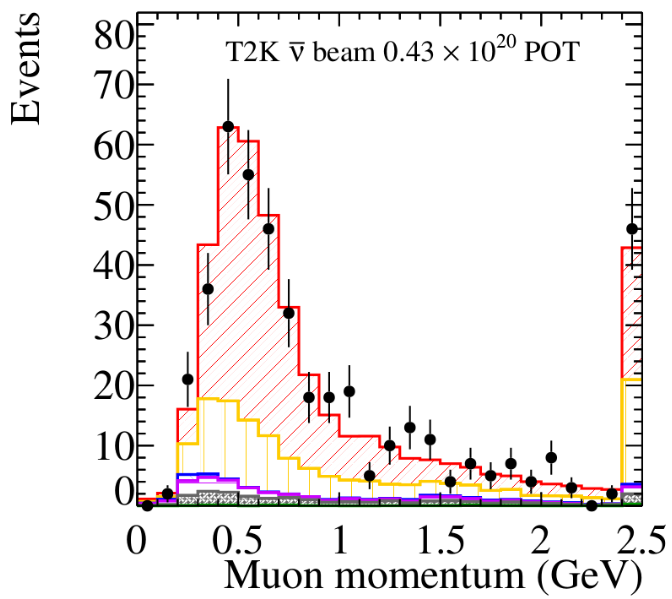



Others include:
CC Res. w/ pion absorption in nucleus, …



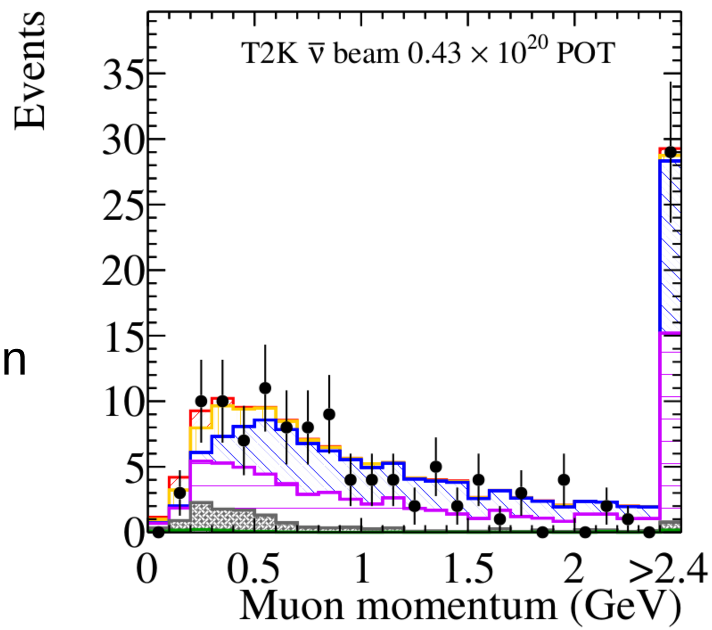

Other topologies will affect event reconstruction

# Antineutrino ND280 Samples

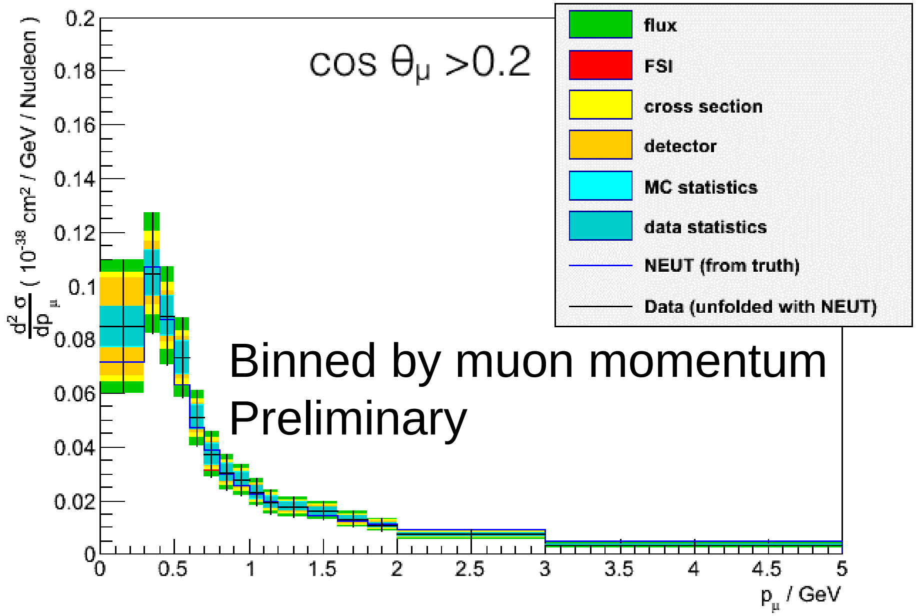


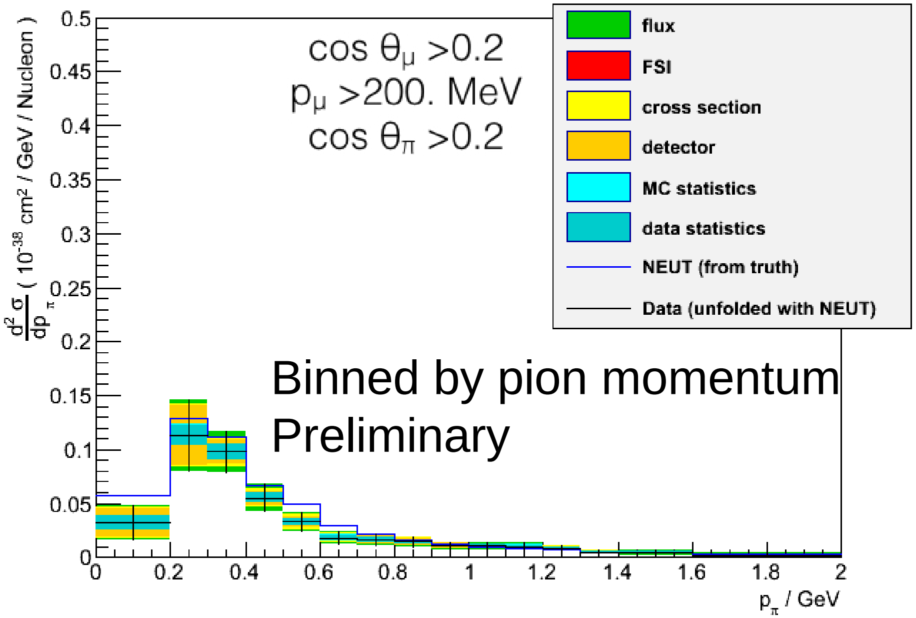

- $\bar{\nu}_\mu$ CC 1 track sample
- Mostly contains CCQE
- Simpler sample definition than in $\nu_\mu$ analysis

- $\nu_\mu$ CC 1 track
- Intrinsic wrong sign background (nu in antinu beam) much larger in antinu beam

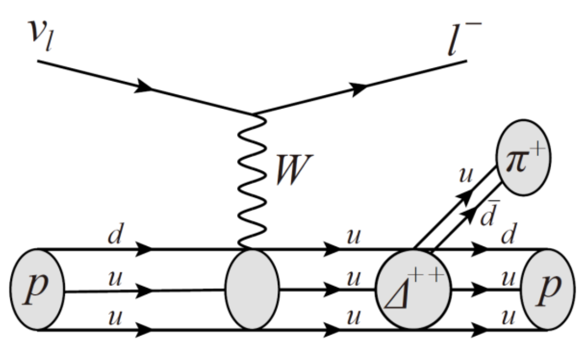


# Charged-Current with 1 $\pi^+$ on Scintillator



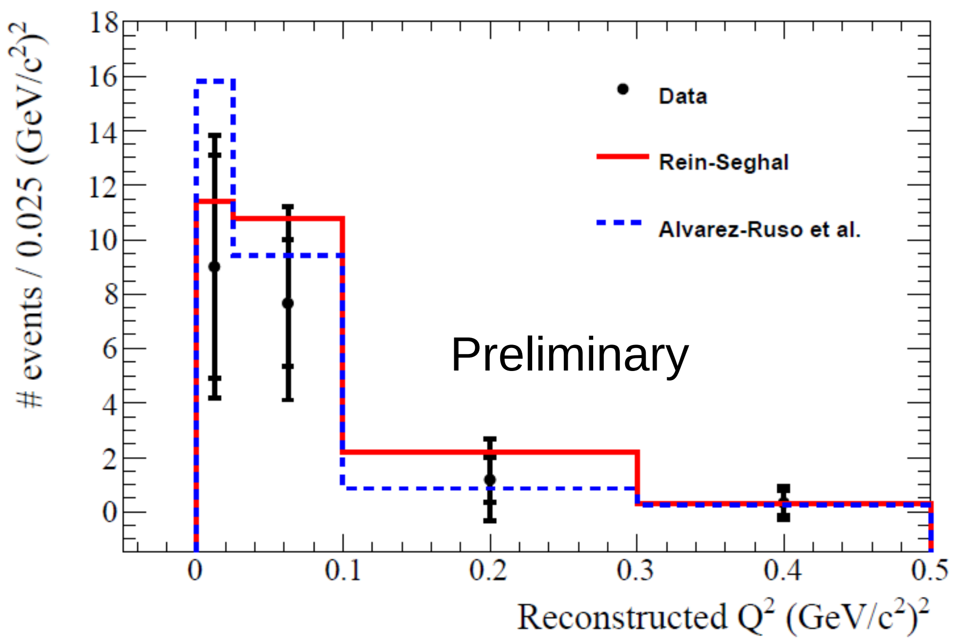




- Select muon from TPC dE/dx
- Select pion from dE/dx and/or muon decay tagging
- Veto $\pi^0$ using calorimeters
- Using iterative Bayesian unfolding to extract result
- Muon distributions show good agreement
- Discrepancy between NEUT MC and measured pion distributions



# Charged-Current Coherent Pion Production on Scintillator

- First measurement at energy below 1.5 GeV
- Select muon by dE/dx
- Select pion candidate with MIP dE/dx
- Low vertex activity
- Large uncertainties from background & vertex activity models




arXiv:1604.04406

Coherent production:
Nucleus stays in ground state
Little momentum is transferred