# Recent Results from T2K and Introduction to the νPRISM Detector Concept

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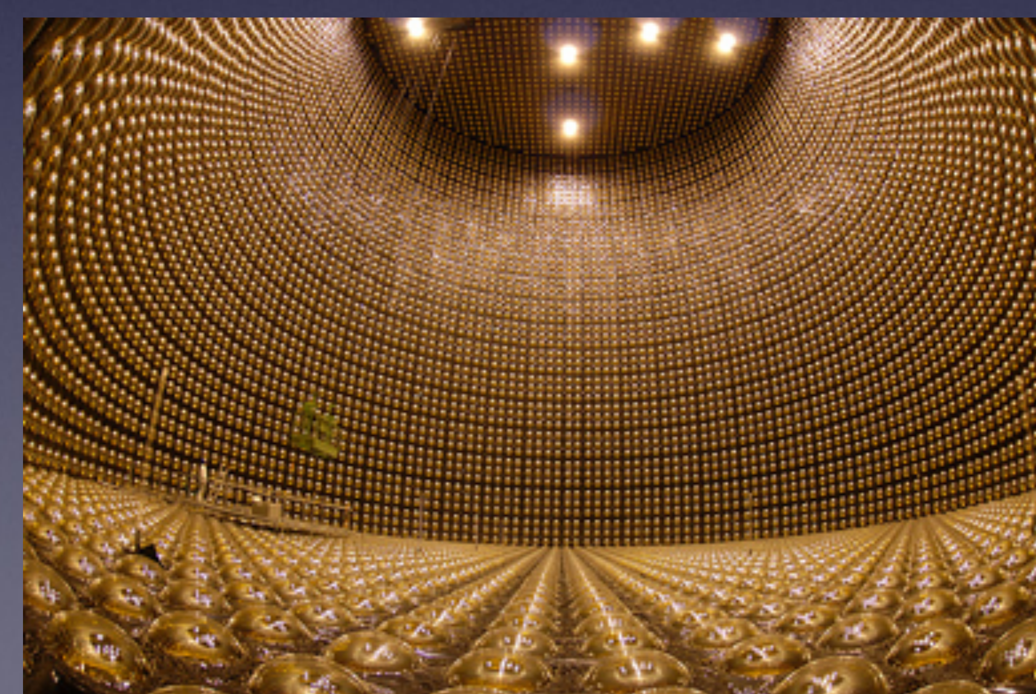


# Introduction to Neutrino Oscillations

Oscillations arise due to mixing between the flavor and mass eigenstates:

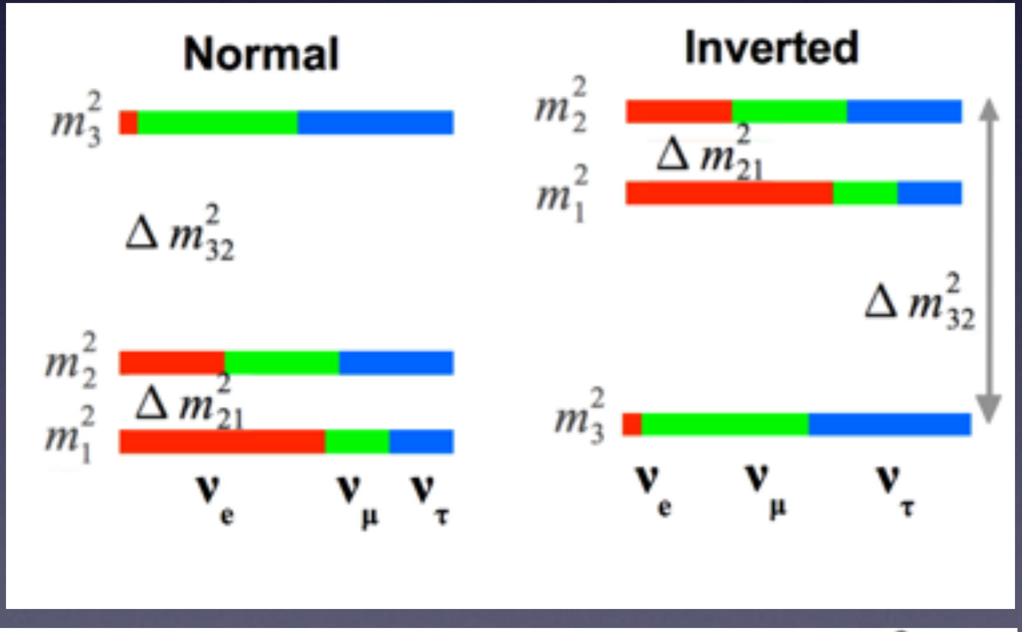
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\times\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\theta_{23}\approx 45^\circ$ $\theta_{13}\approx 9^\circ$ $\theta_{12}\approx 34^\circ$

$\delta_{CP}=?$

Depend on the mixing angles, complex phase and mass splittings

Currently two possible hierarchies of the mass states are allowed by the data




Oscillation probability depends on neutrino energy (E) and distance (L)

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

# CP Violation in Neutrino Mixing

CP violation is possible in oscillations of one neutrino flavor to another

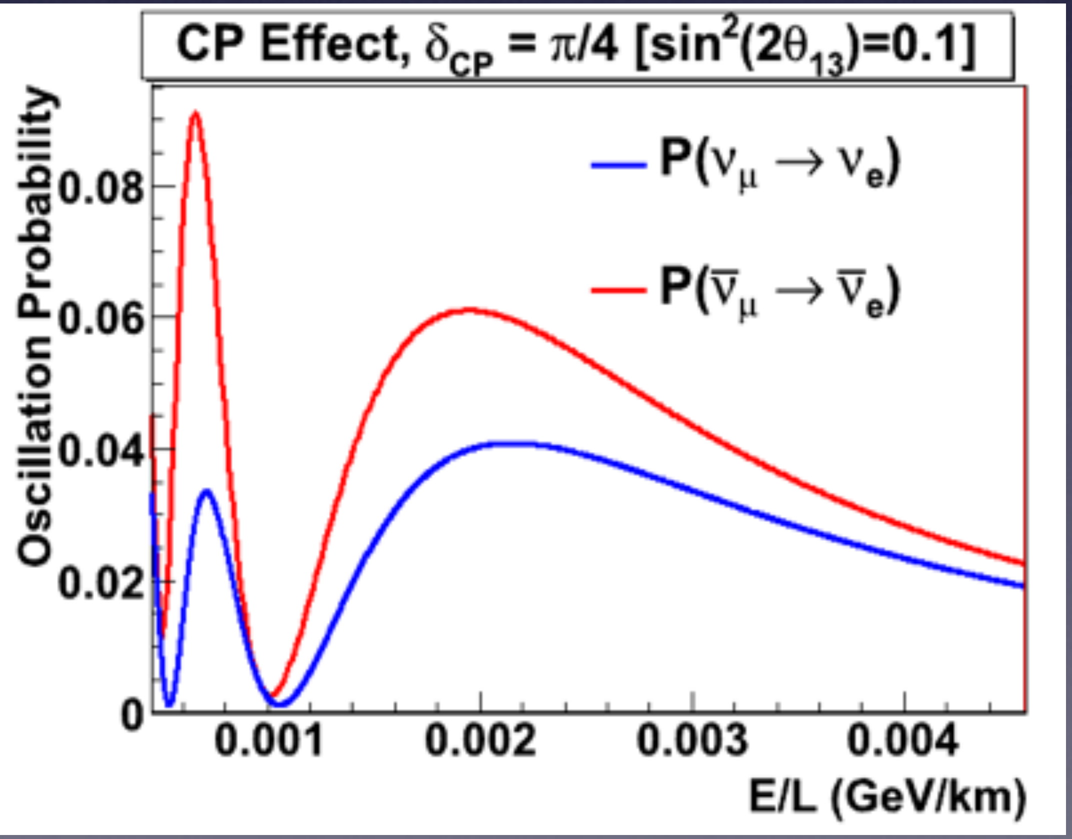
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{31}^2 L}{4E}$$
$$-\ \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m_{21}^2 L}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{31}^2 L}{4E}\sin\delta_{CP}$$
$$+\ (\text{CP even term, solar term, matter effect term}), \qquad (1)$$

The sign of this term changes for antineutrinos

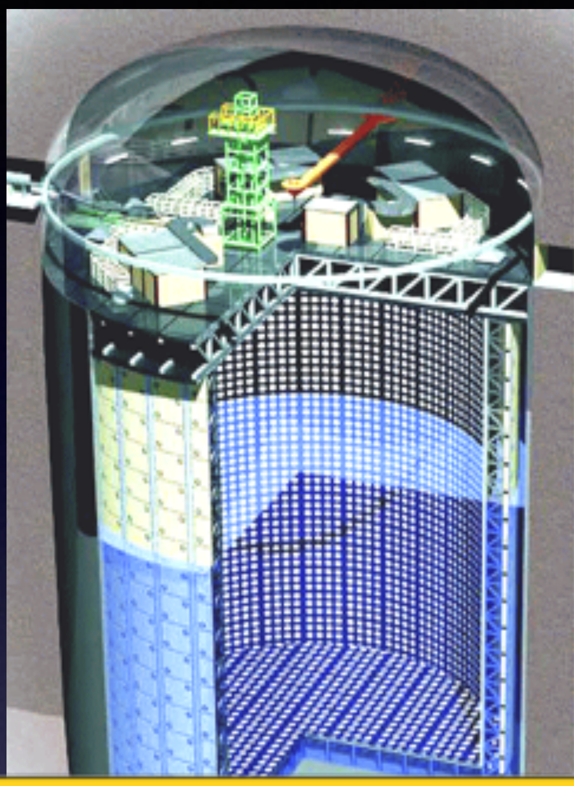
Need all three mixing angles to be non-zero.

CP violating term introduces an asymmetry between neutrino and antineutrino oscillations that can be measured:

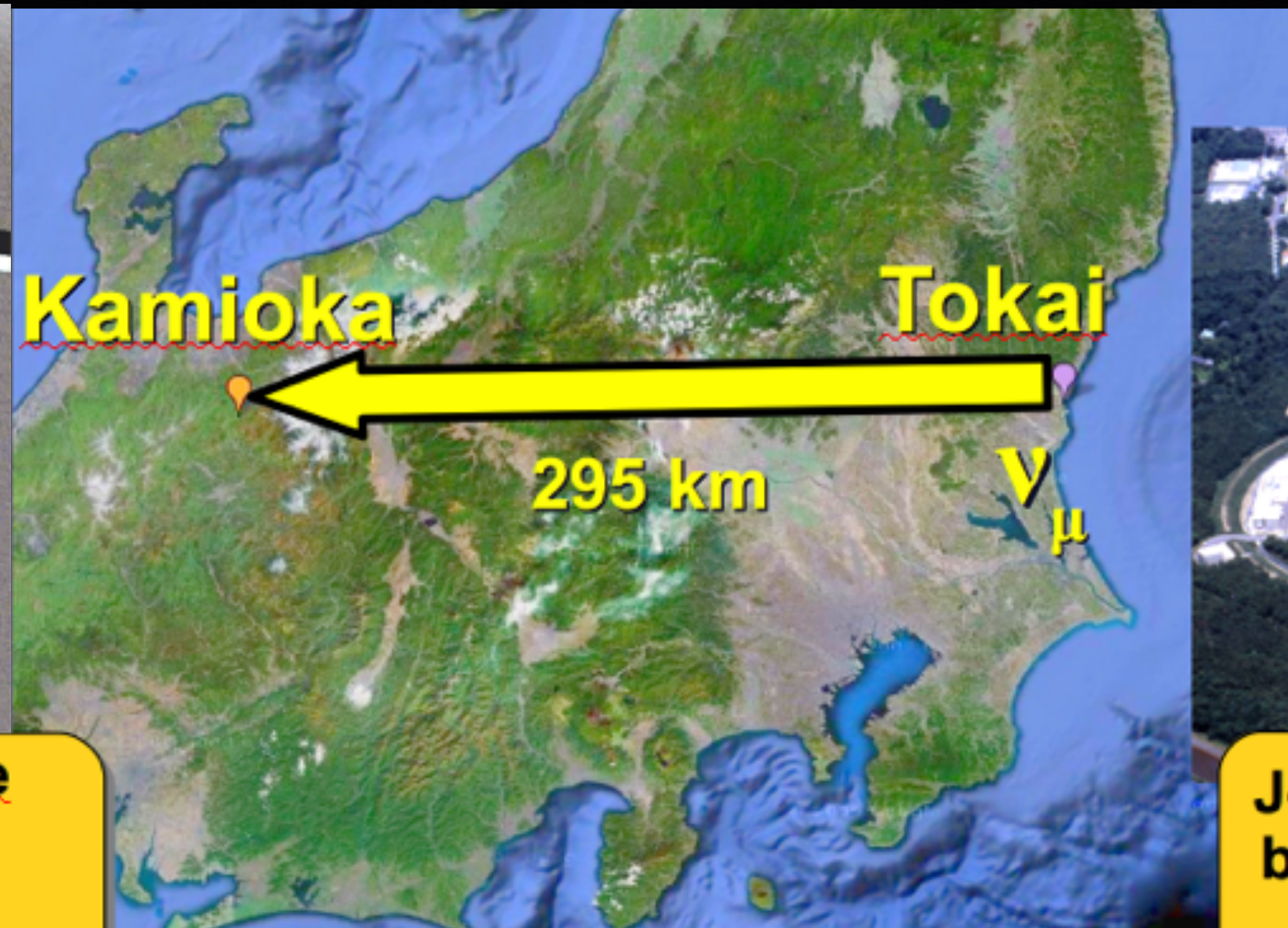
$$A_{CP} \equiv \frac{P-\overline{P}}{P+\overline{P}} \approx \frac{\Delta m_{12}^2 L}{E}\cdot\frac{\sin 2\theta_{12}}{\sin\theta_{13}}\cdot\sin\delta$$



# The T2K Experiment



Super-Kamiokande
22.5 kton (fiducial)
water cherenkov
detector at 295 km




J-PARC: 30 GeV proton beam, design power of 750 kW

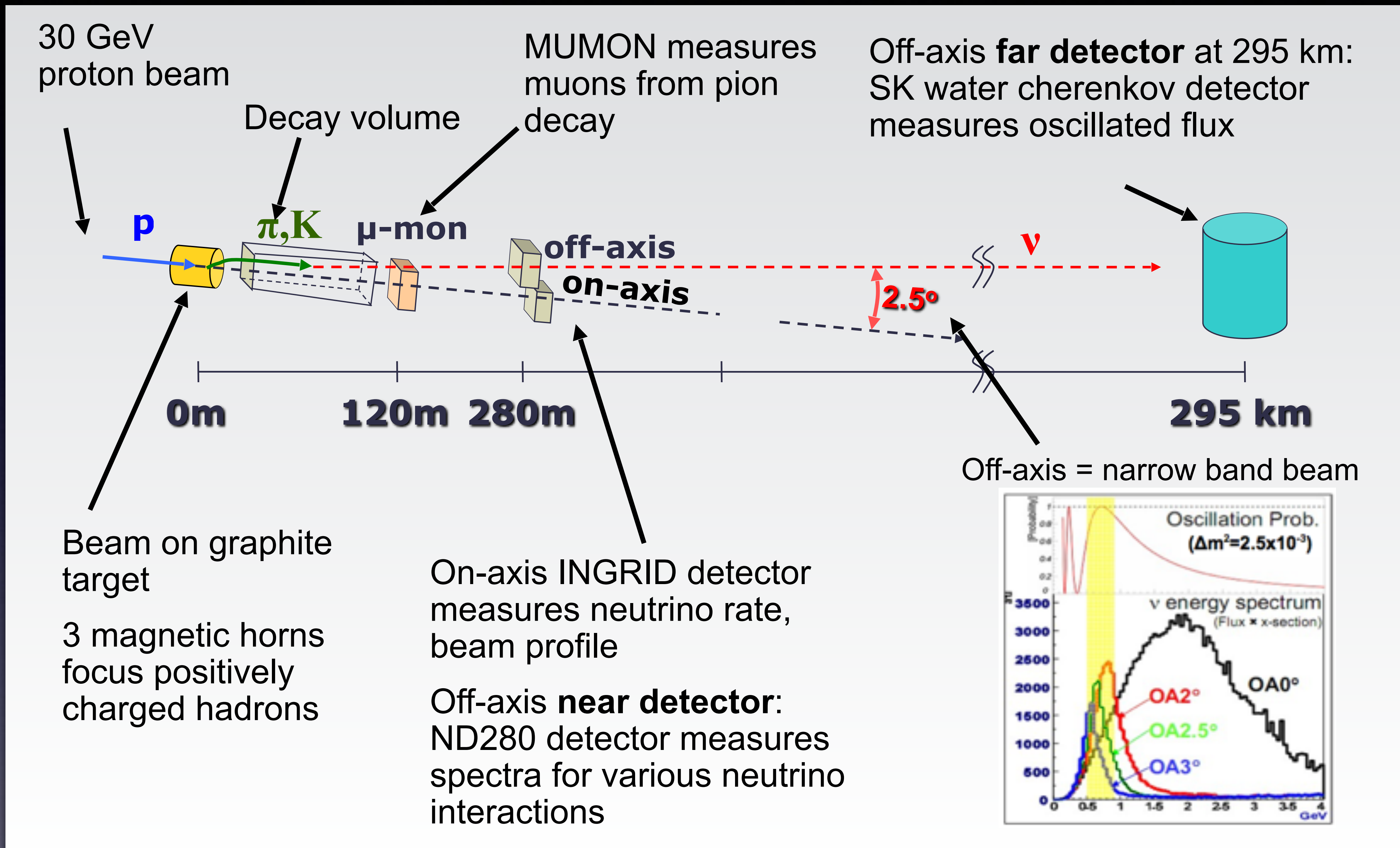
Measure the $\nu_\mu$ survival

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{32}^2 L}{4E_\nu}$$

Measure the $\nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E_\nu}$$

# Experiment Overview

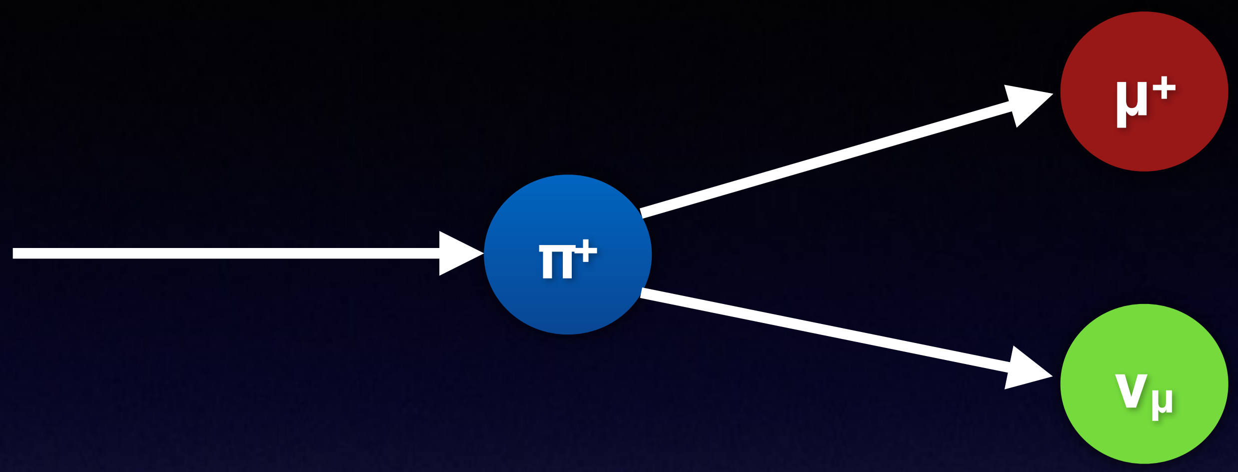



Oscillations -> we observe at SK a deficit of the original neutrino flavor in the beam ($\nu_\mu$) and an excess of the flavor to which they are oscillating ($\nu_e$)

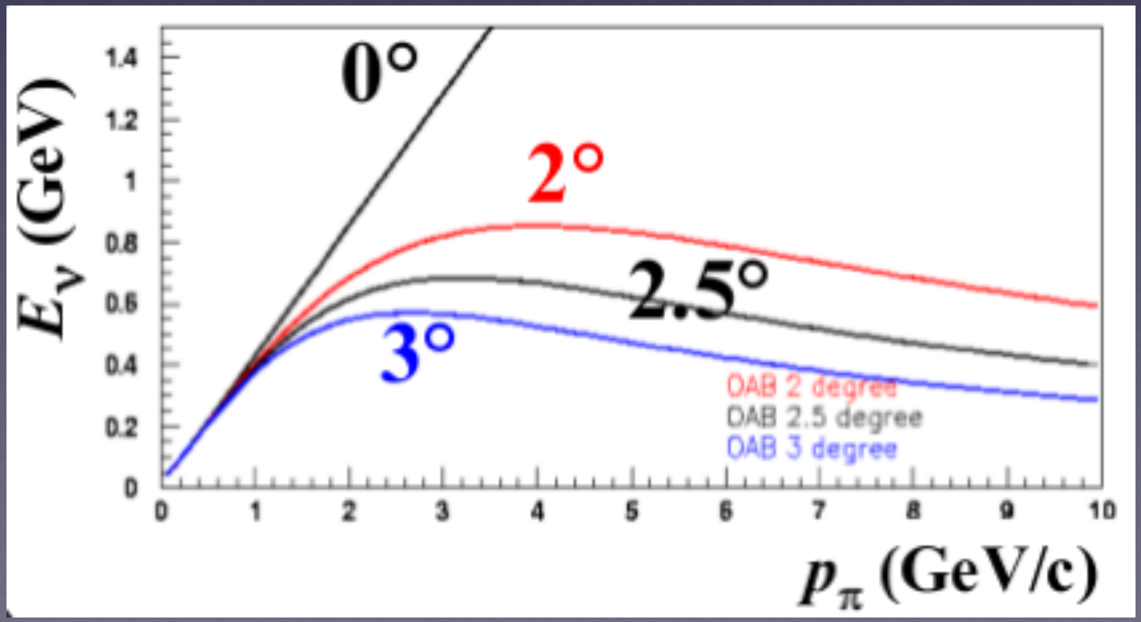
# Off-axis Effect

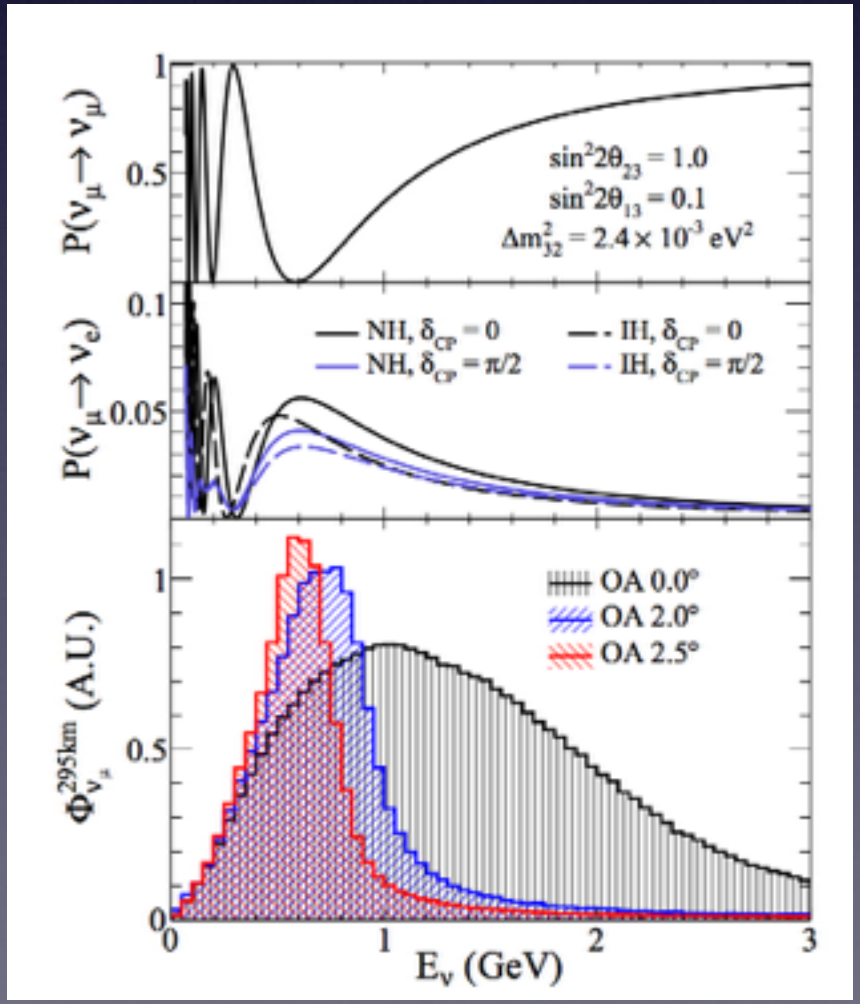
Most neutrinos in beam are $\nu_\mu$ from 2 body pion decays

2 body decay kinematics: neutrino energy dependence on pion momentum is weak at angles away from pion direction

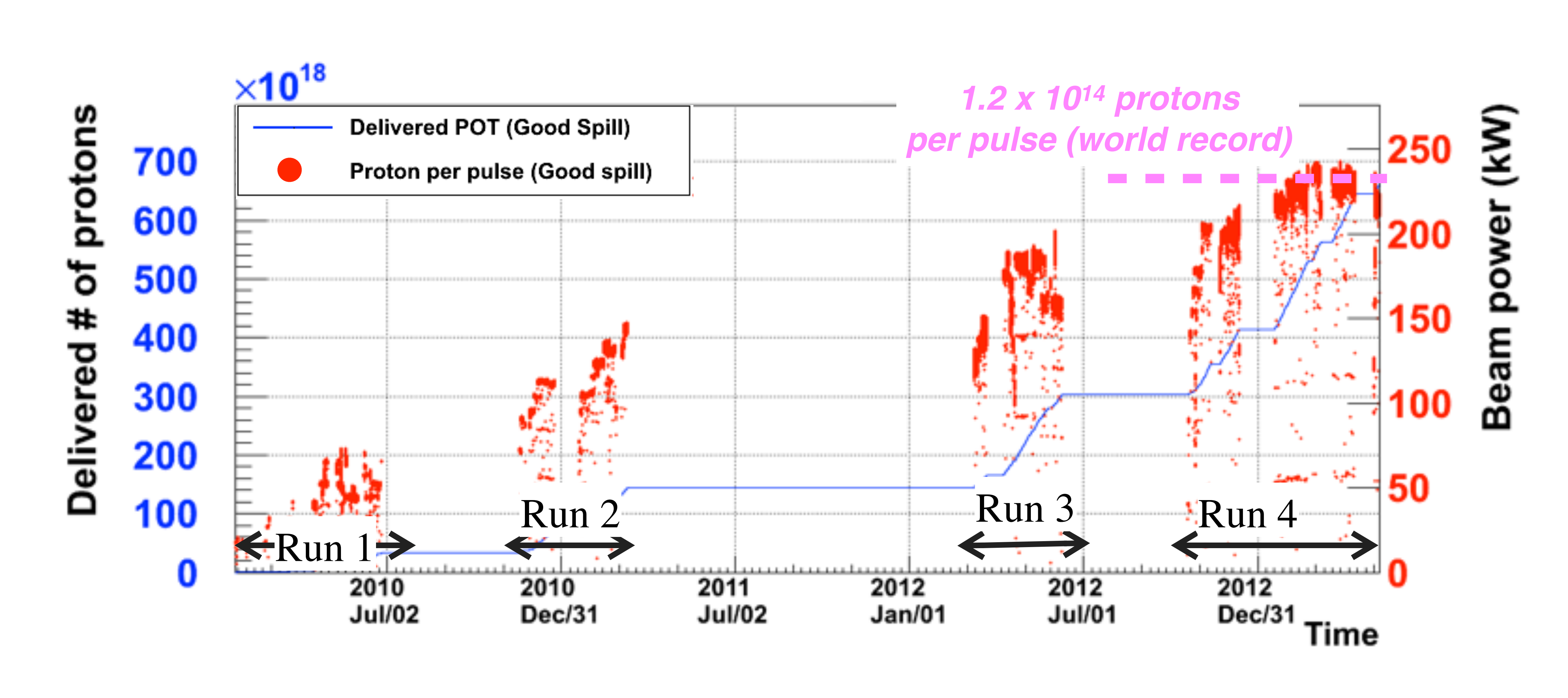



Detector at “off-axis” angle sees a narrow band beam



# Data Collected

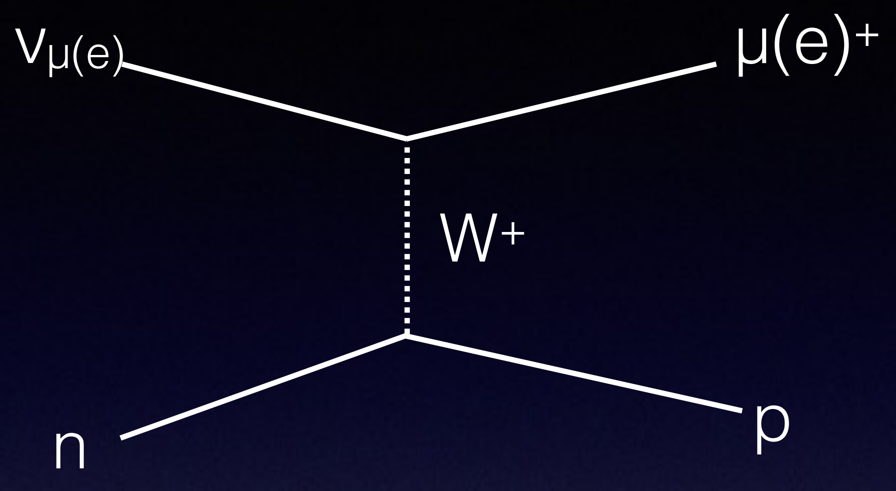



We collected 6.63 x $10^{20}$ protons on target (p.o.t.) so far

**Data for analysis = 6.57 x $10^{20}$ p.o.t.  (full data set up to now)**

About 8% of the p.o.t. for which T2K has been approved

# Detecting Neutrinos at SK



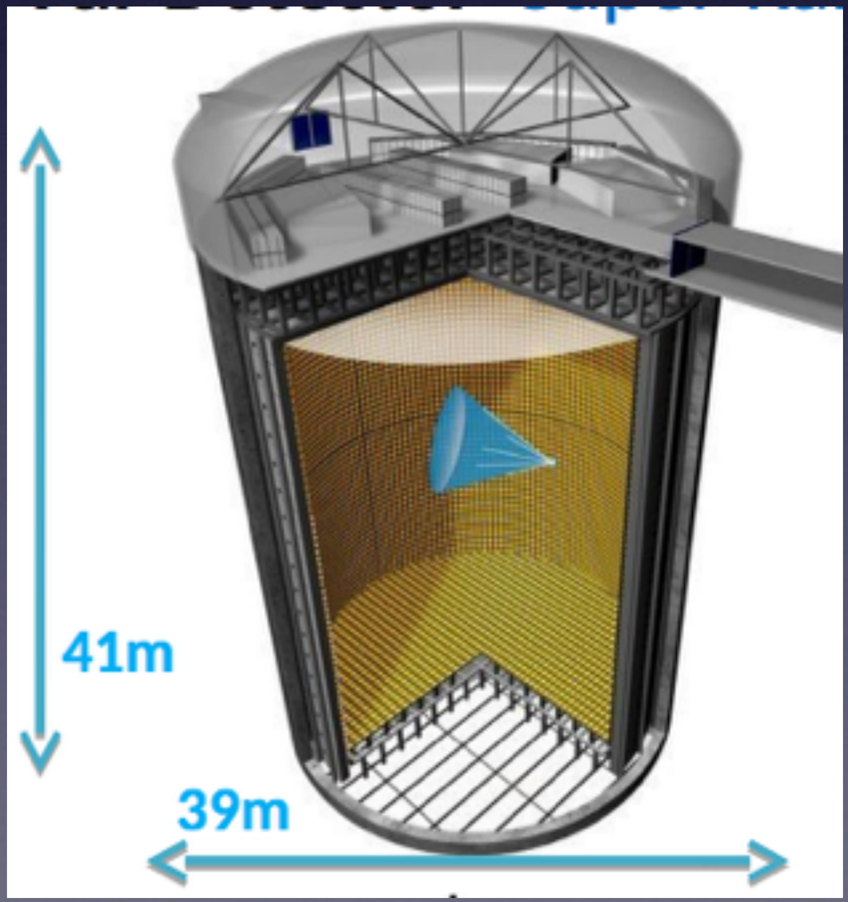

Detector neutrino interactions in the 22.5 kton SK fiducial volume

The signal channel is the charged current quasi-elastic (CCQE) scattering off of a single bound neutron

The proton in the final state is typically below cherenkov threshold, not visible

Final state muon or electron produces a cherenkov ring imaged by the SK PMTs

Select events with a single muon-like or electron-like ring



# Particle ID at SK

**Electrons**

Electrons shower

Fuzzy ring edges

**Muons**

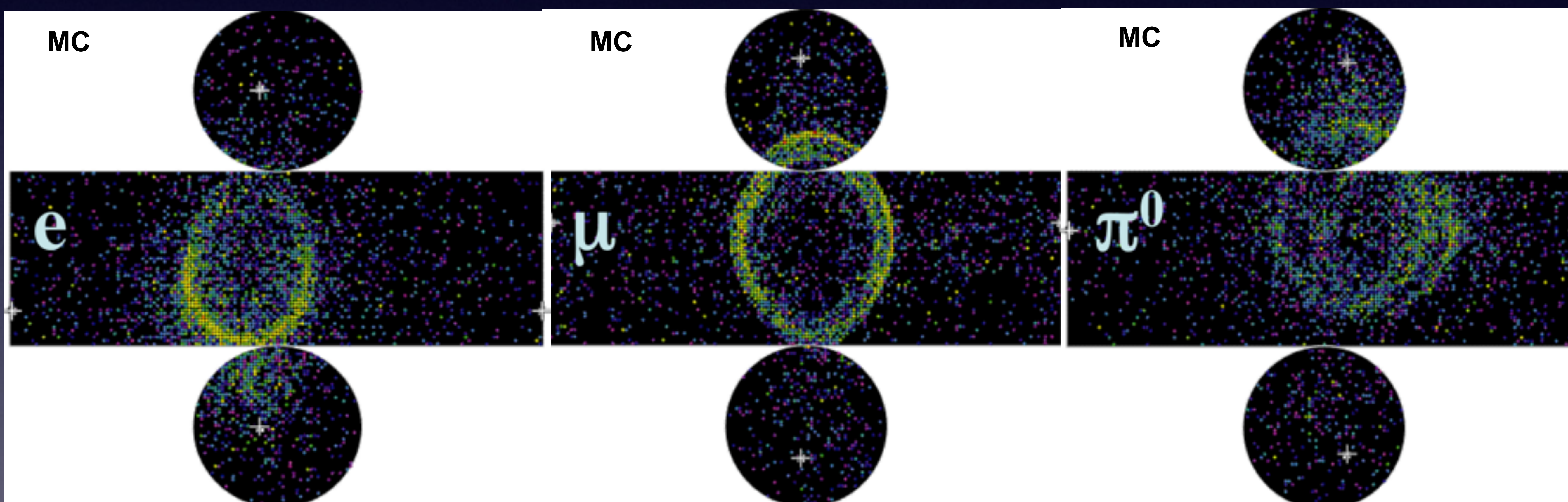
Muon follows a straighter trajectory

Ring with sharper edges

**Neutral Pions**

γs from $\pi^0$ decays shower and look like electrons

Differentiate by finding second ring

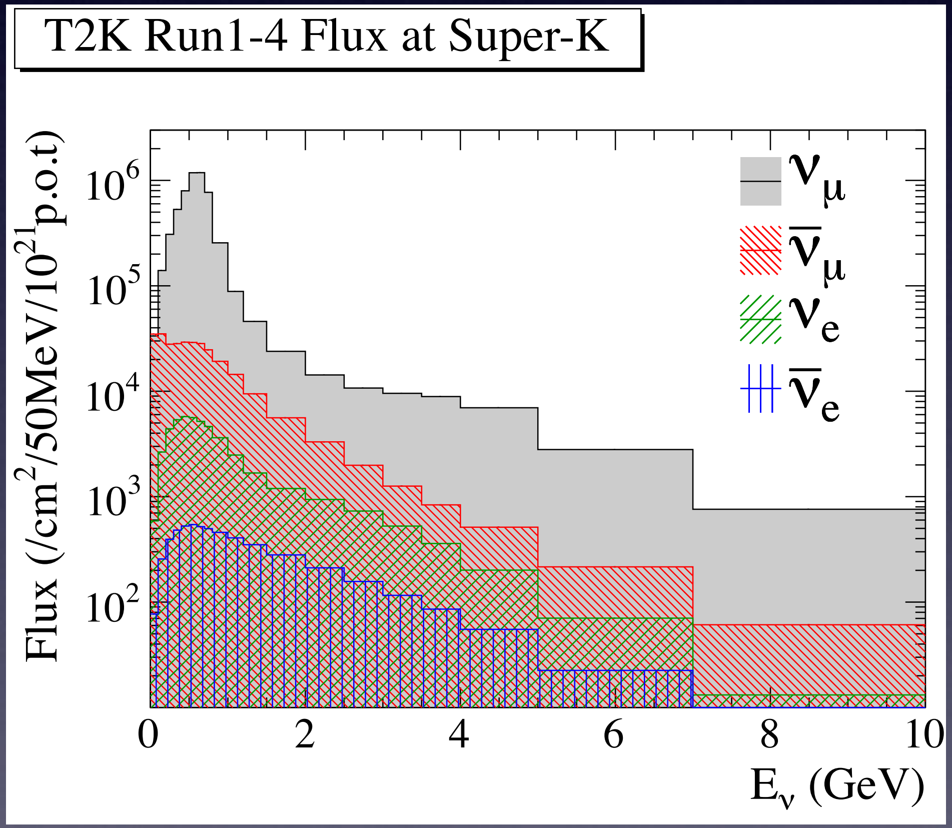


# Neutrino Flux and Cross-Section Models

To test an oscillation hypothesis, need to know the expected rate of interactions at SK

Need to model the neutrino flux and interactions

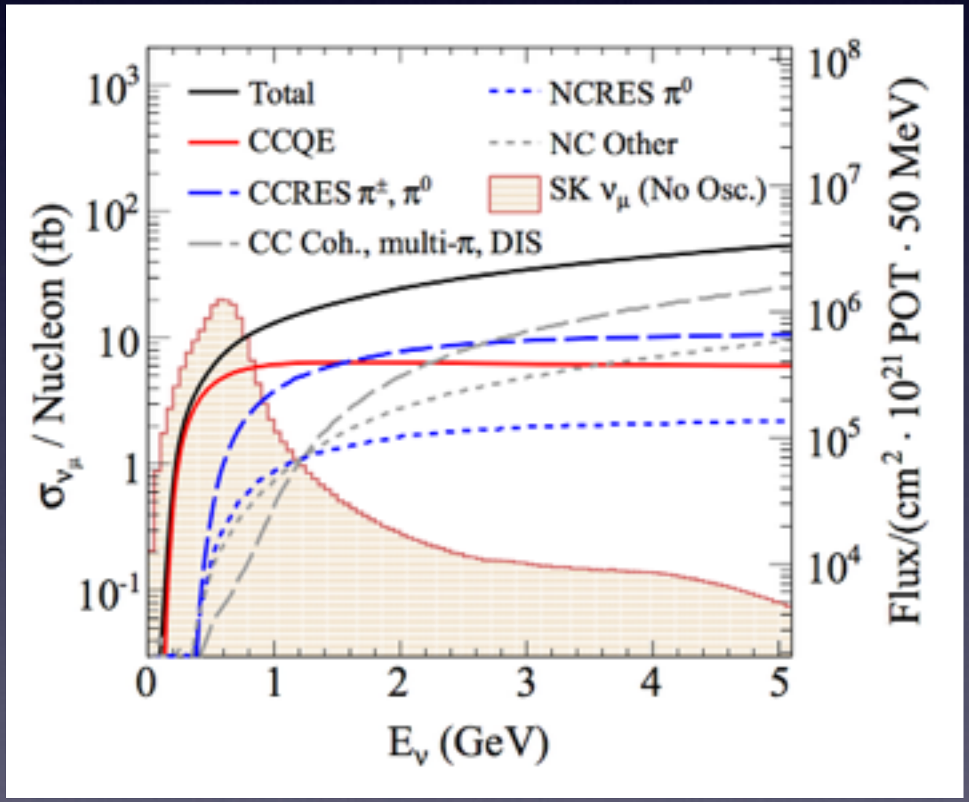
## Flux:




From simulation of the T2K beam line

Tuned with hadron production data from the NA61/SHINE experiment

## Interaction Cross-Sections:

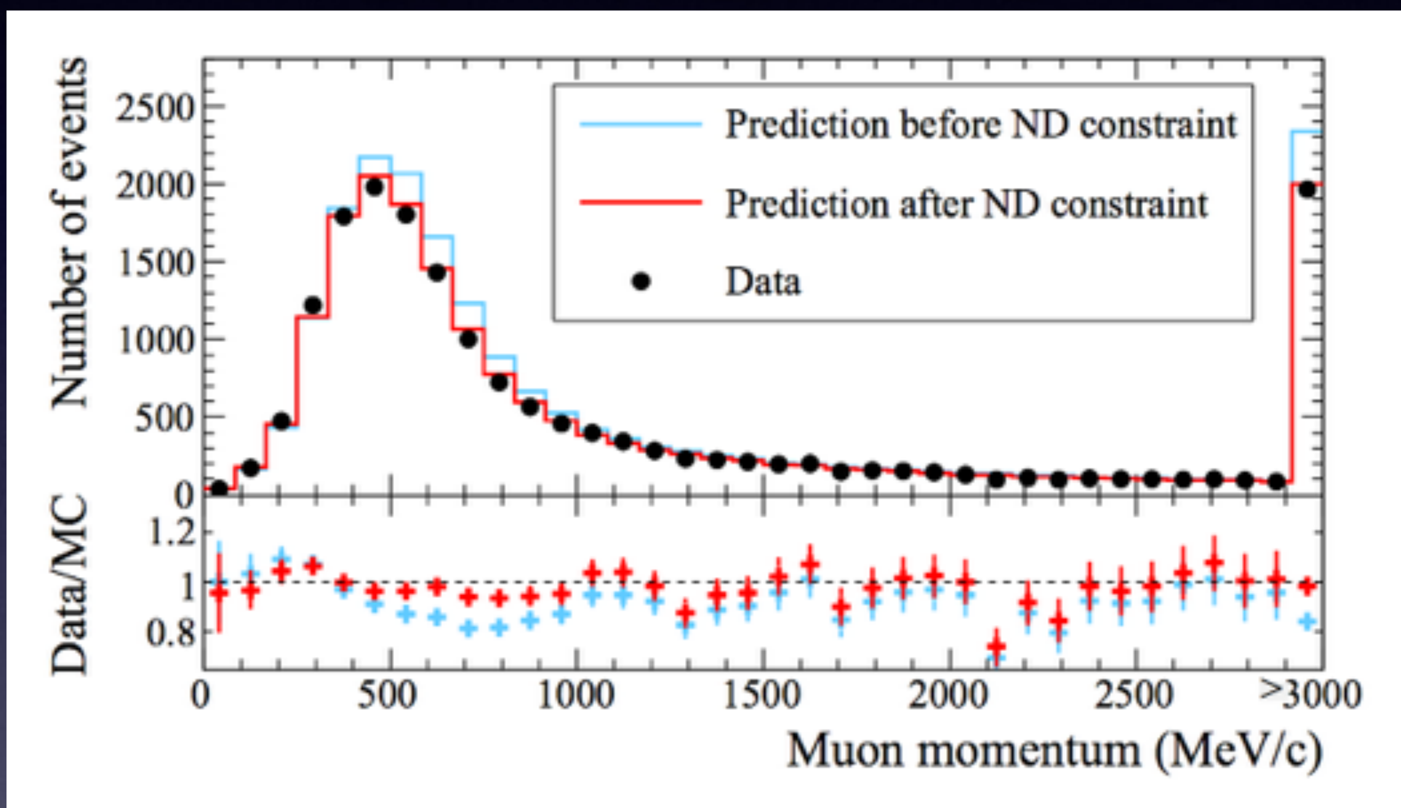



NEUT interaction generator

Tuned with data from external experiments such as MiniBooNE, K2K

# Using ND280 (Near Detector) Data

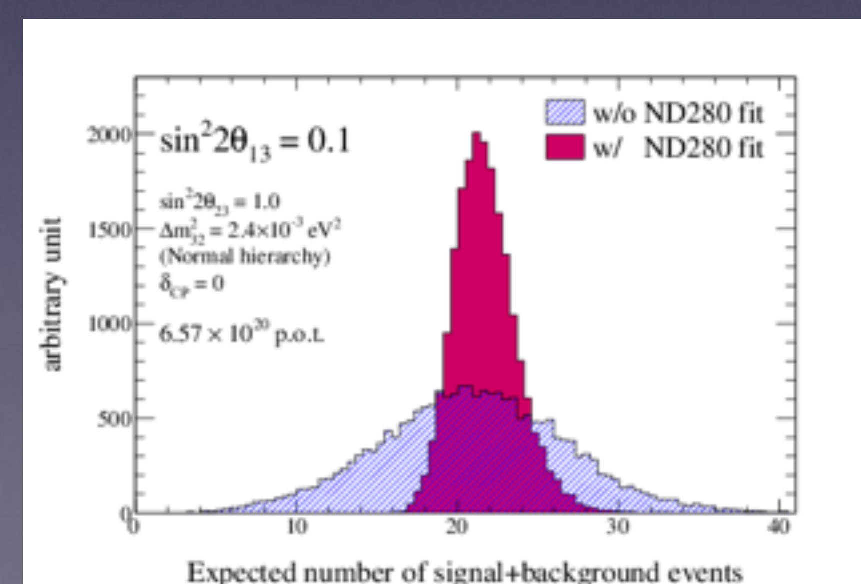
We constrain nuisance parameters in our flux and cross section models by fitting samples of $\nu_\mu$ charged current candidate events in ND280




Significantly improves the agreement between the model and ND280 data

Shrinks uncertainties on the flux and interaction models

Systematic uncertainty on the predicted number of $\nu_e$ candidate events at SK is reduced from 28% to 9%



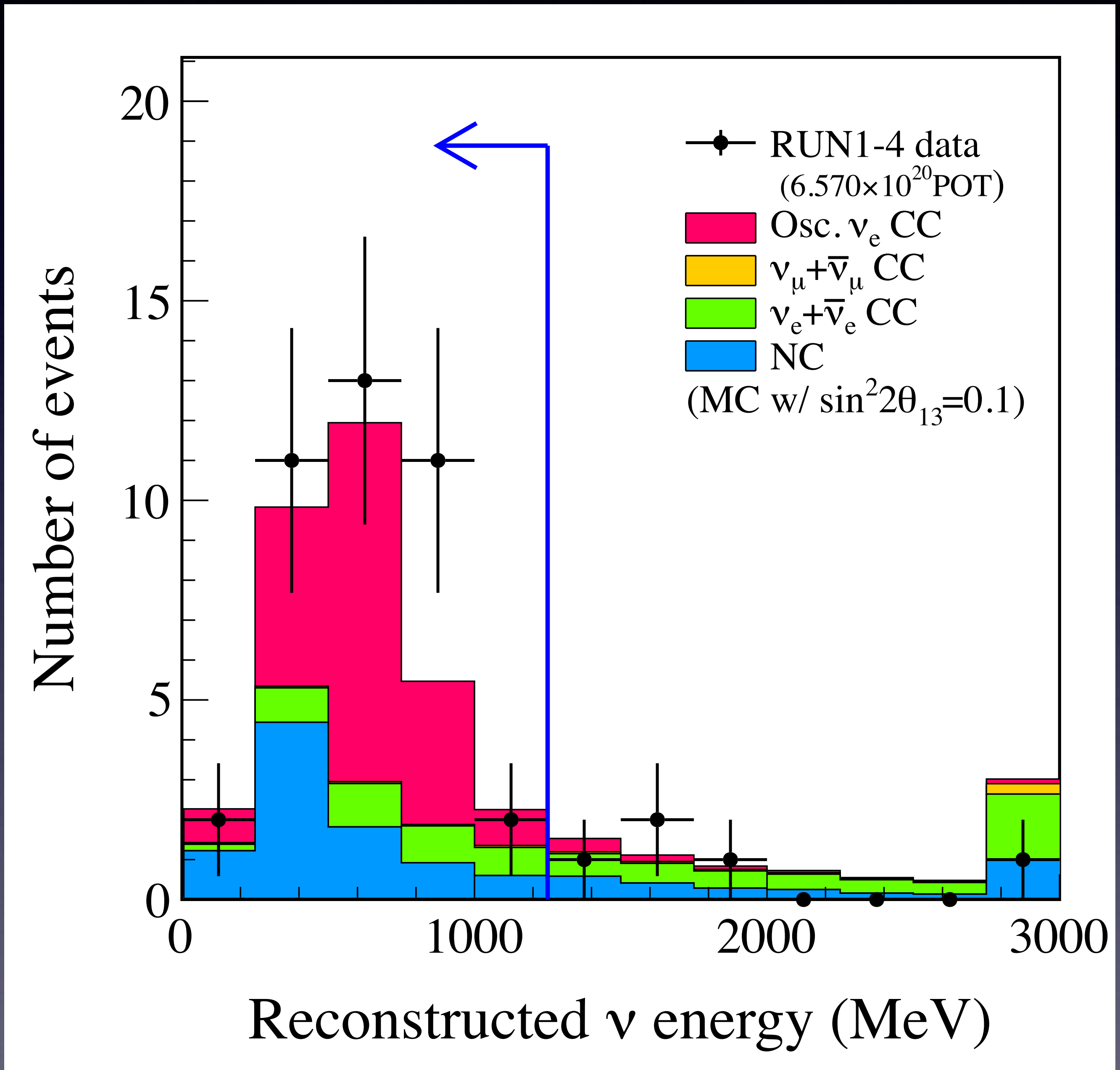
# The $\nu_e$ Appearance Measurement

T2K observes 28 single electron ring candidate events

Expect 4.92±0.55 (syst.) if $\theta_{13}=0$

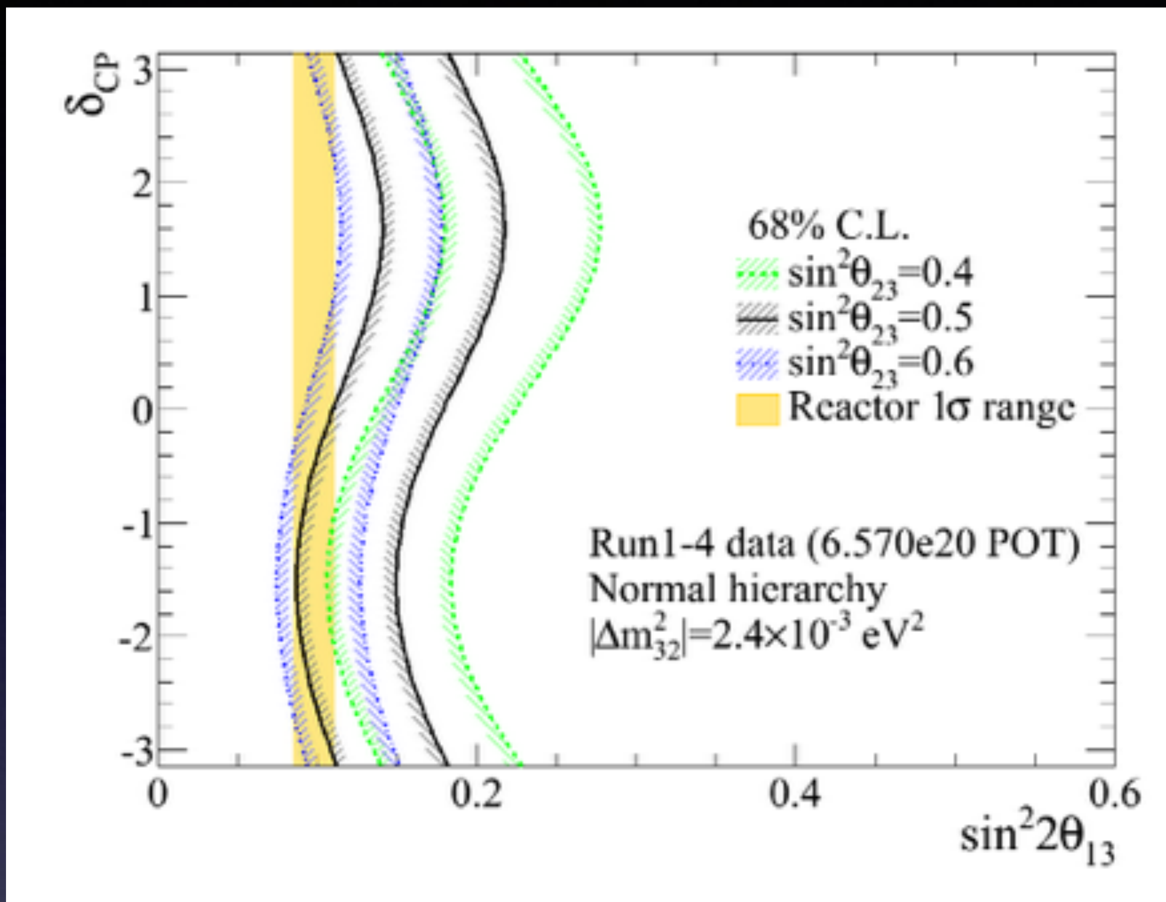
This constitute a 7.3σ significance for $\theta_{13}\neq0$

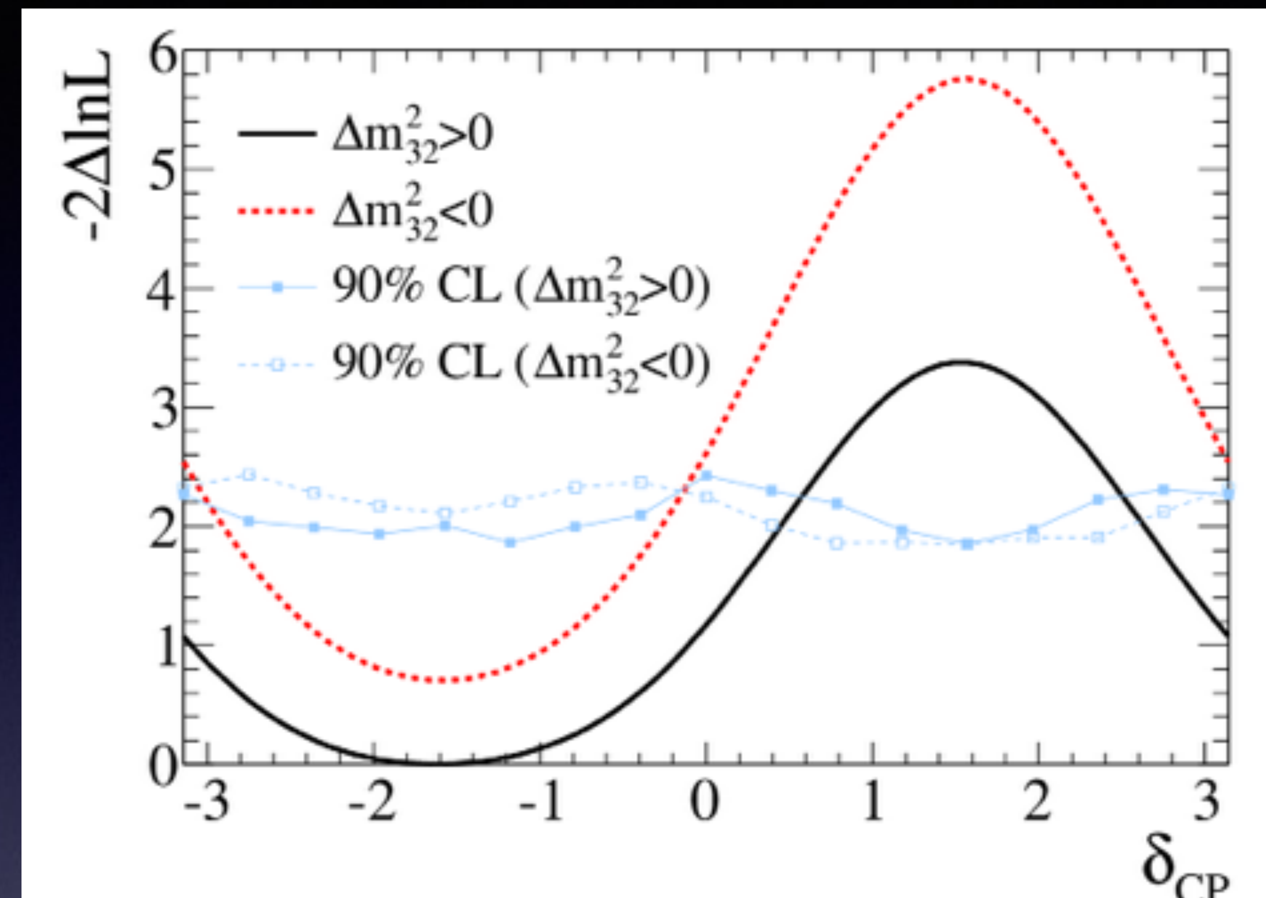
Observation of $\nu_\mu \rightarrow \nu_e$ oscillations




**Phys.Rev.Lett. 112 (2014) 061802**

# Constraint on $\delta_{CP}$




For a given $\theta_{23}$ and $\delta_{CP}$, we have allowed regions for $\sin^2 2\theta_{13}$

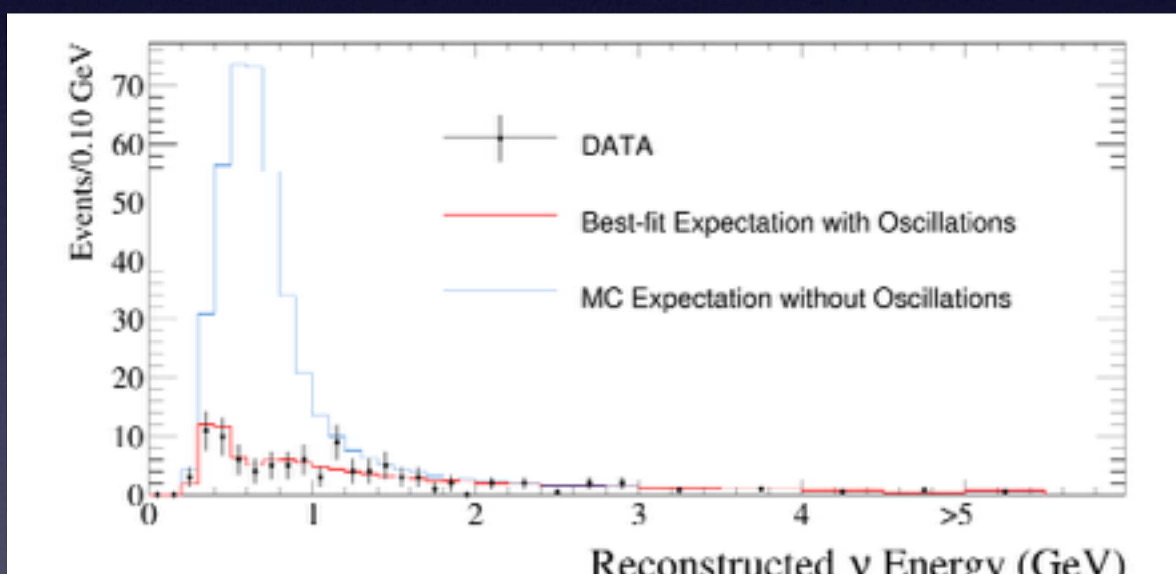
Since reactor constraint on $\sin^2 2\theta_{13}$ is strong, can constrain $\delta_{CP}$

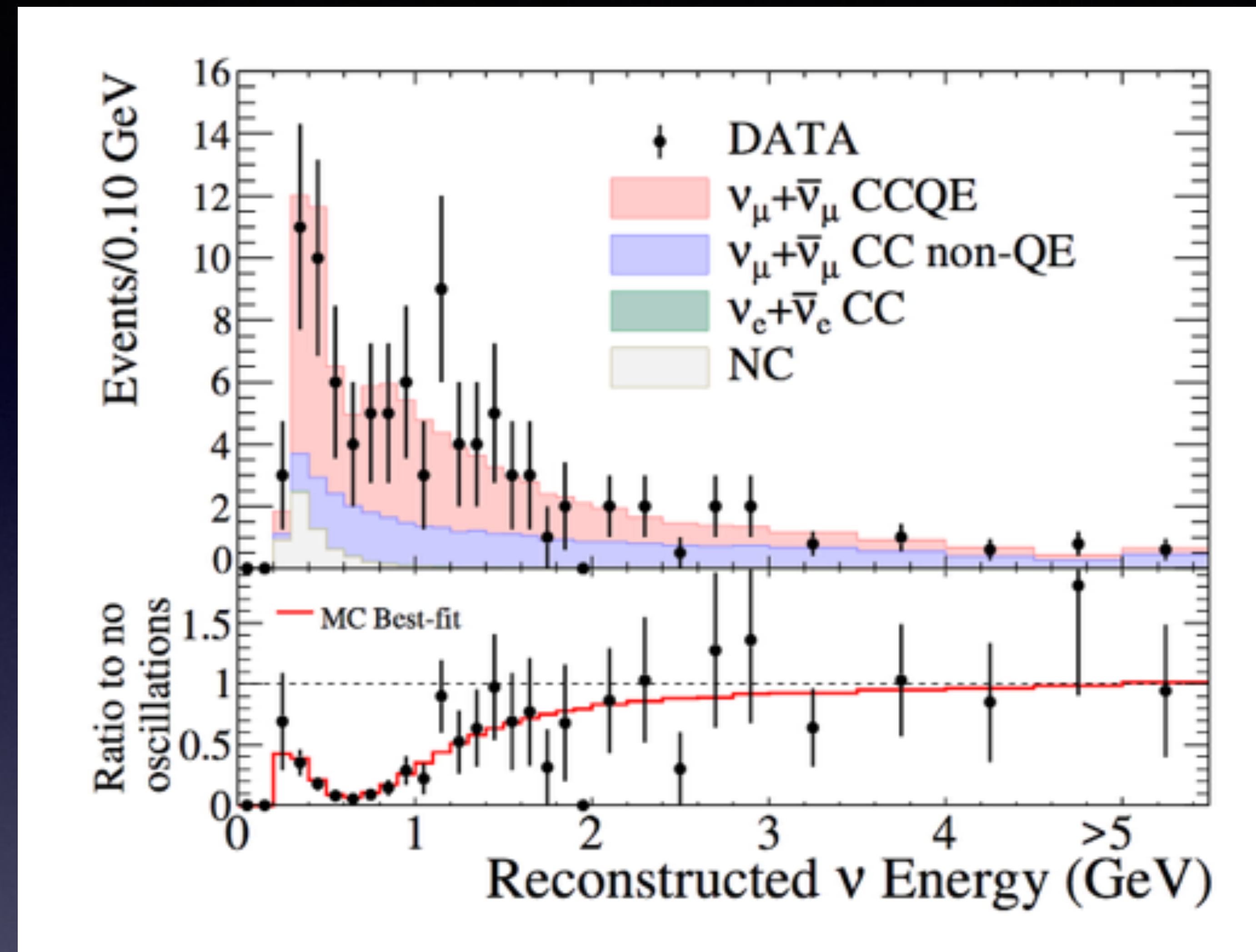
Data prefer a large CP violation effect

# The $\nu_\mu$ Disappearance Measurement

T2K observes 120 single muon ring candidate events

Expect 446.0±22.5 (syst.) if no oscillations




The data deficit is consistent with the pattern expected with oscillations

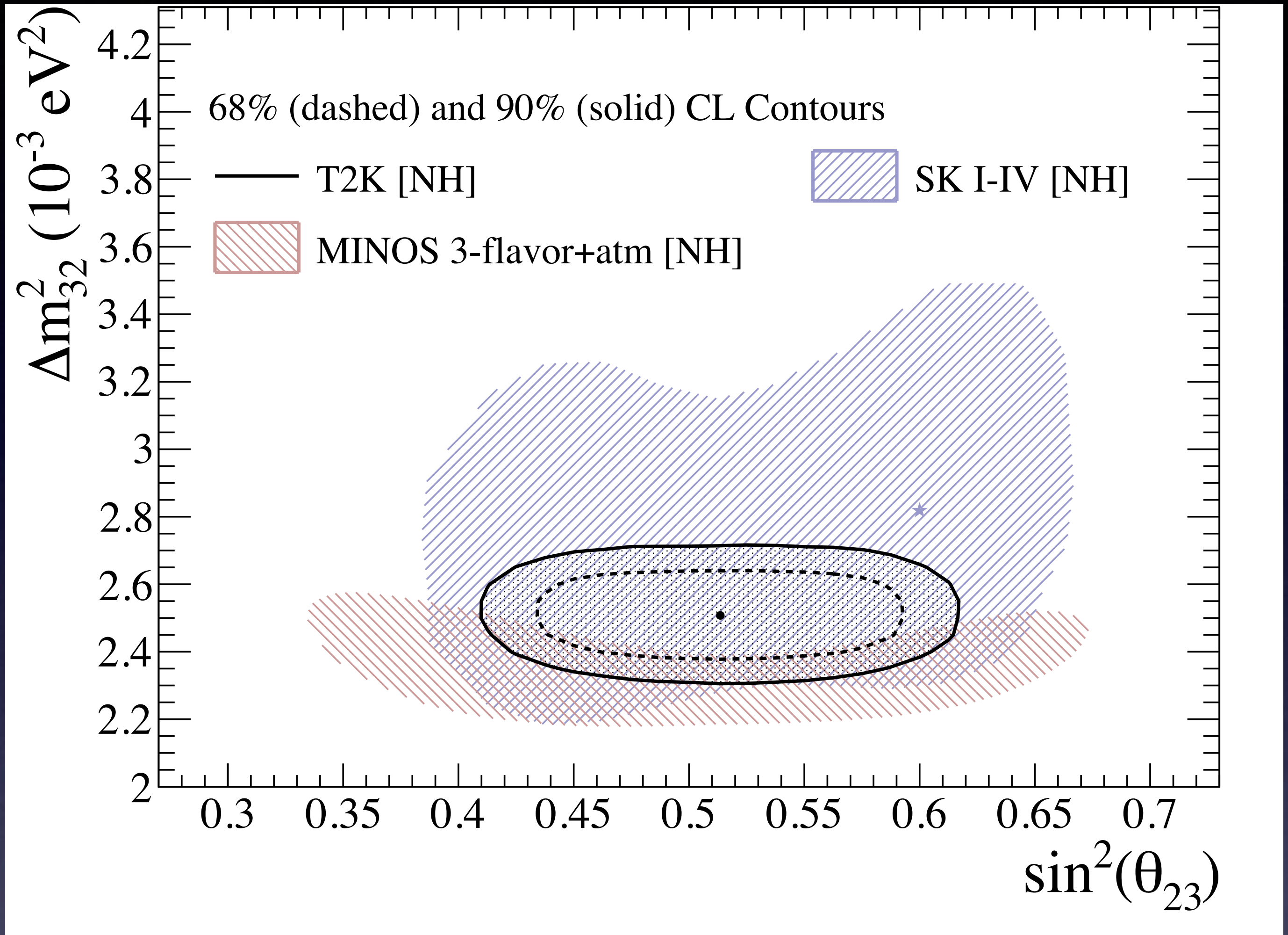
The data are fit to the oscillation hypothesis. Estimates of $\theta_{23}$ and $\Delta m^2_{32}$ are extracted

# Measured Oscillation Parameters

T2K data prefer maximal disappearance while MINOS and SK prefer non-maximal

Still have a consistent picture with T2K, MINOS and SK

T2K has world's strongest constraint on $\theta_{23}$




$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056} (0.511 \pm 0.055) \text{ for NH(IH)}$$

$$\text{NH:} \Delta m_{32} = 2.51 \pm 0.10 \times 10^{-3} \text{ eV}^2$$

$$\text{IH:} \Delta m_{13} = 2.48 \pm 0.10 \times 10^{-3} \text{ eV}^2$$

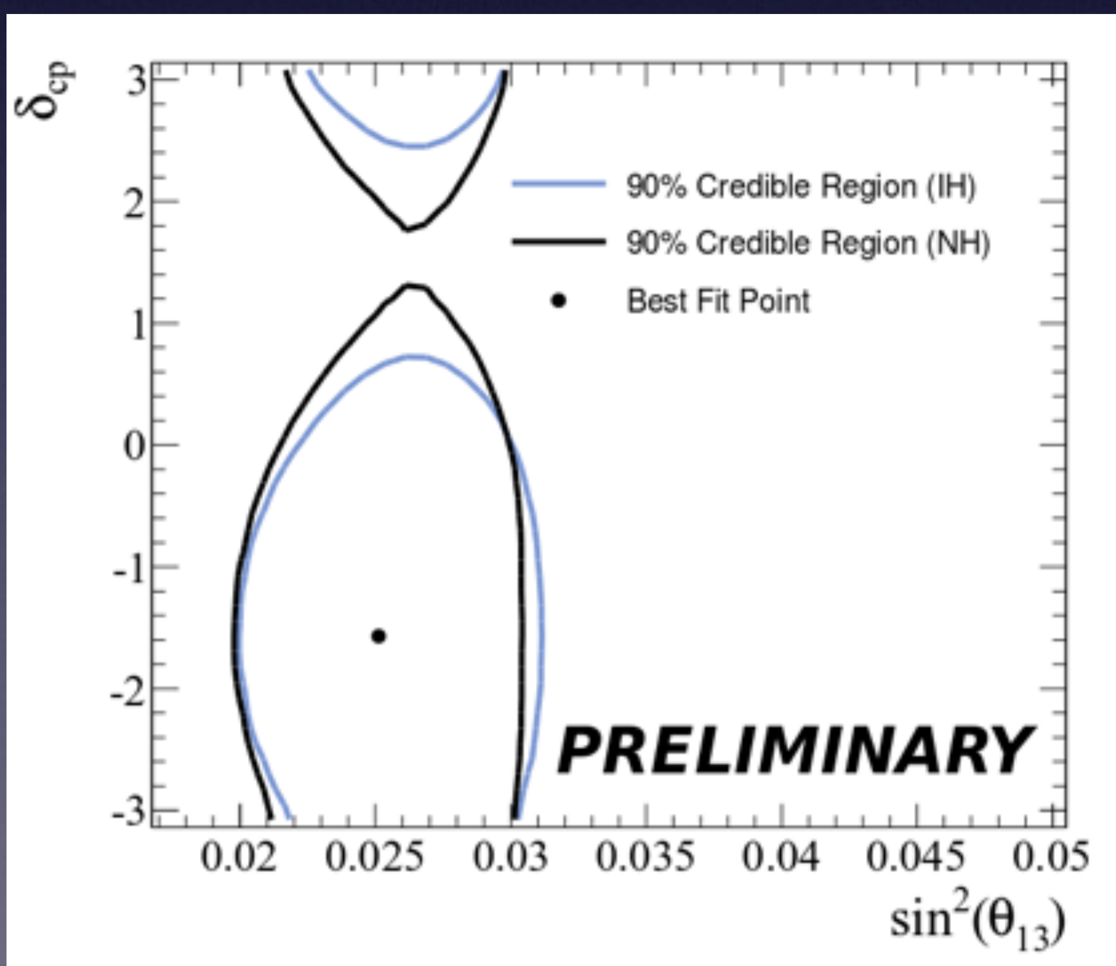
**Accepted to PRL arXiv:1403.1532**

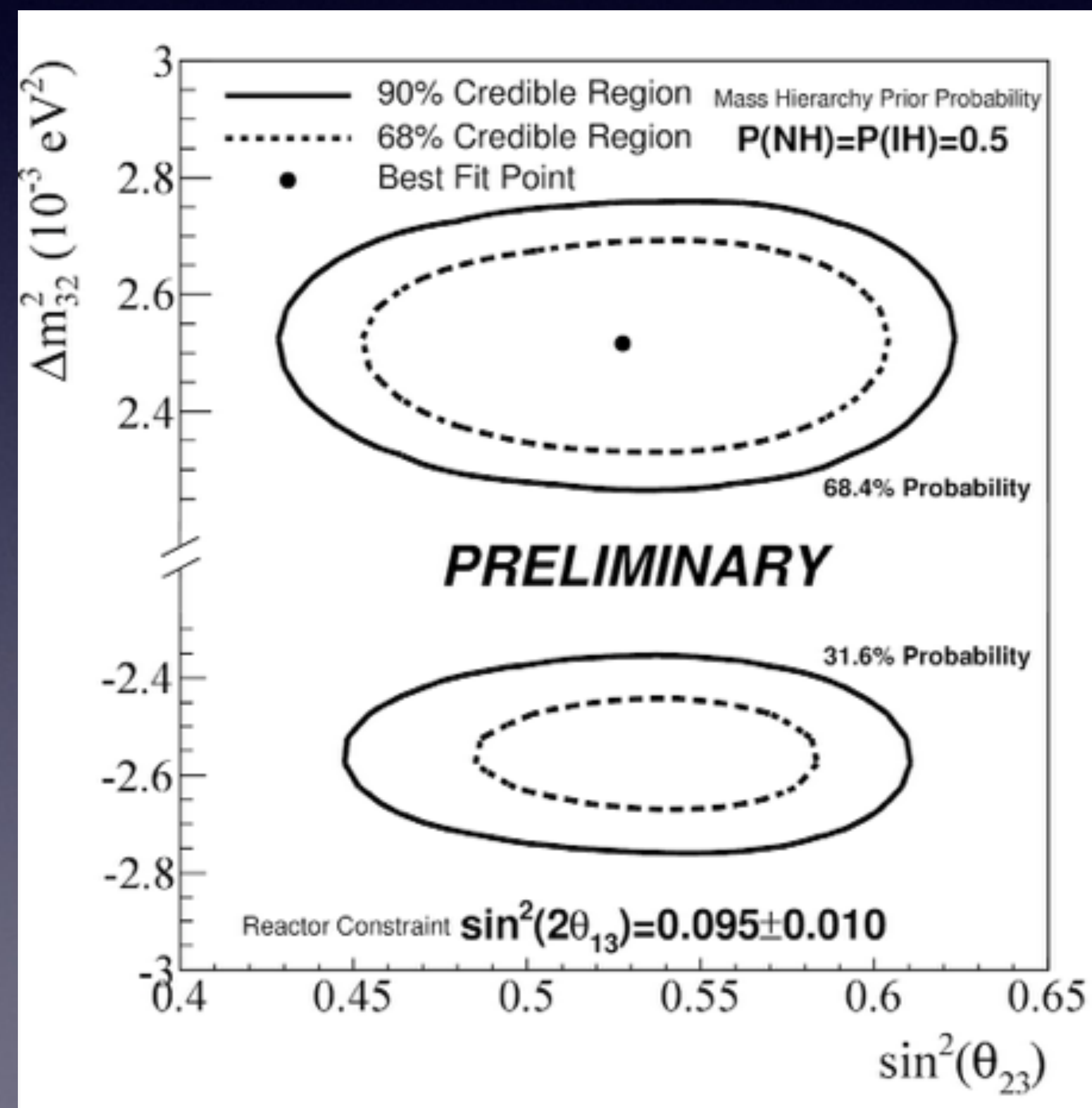
# Joint $\nu_\mu$ and $\nu_e$ Analysis

Ideally, T2K should fit both the $\nu_\mu$ and $\nu_e$ candidate samples and simultaneous constrain all of the oscillation parameters

We are doing this with both a frequentist analysis and a Bayesian analysis that uses Markov Chains

From the Bayesian analysis:



# A Subtle Importance in Neutrino Interaction Modeling

**What we measure:**

The lepton 4 momentum in events with only a visible lepton candidate

Often work with the reconstructed neutrino energy assuming scattering on a single bound nucleon at rest

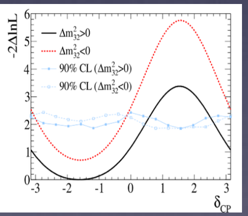
$$E_{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

**The oscillations depend on:**

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{32}^2 L}{4 E_\nu}$$

Oscillations depend on the neutrino energy, which we don't measure directly

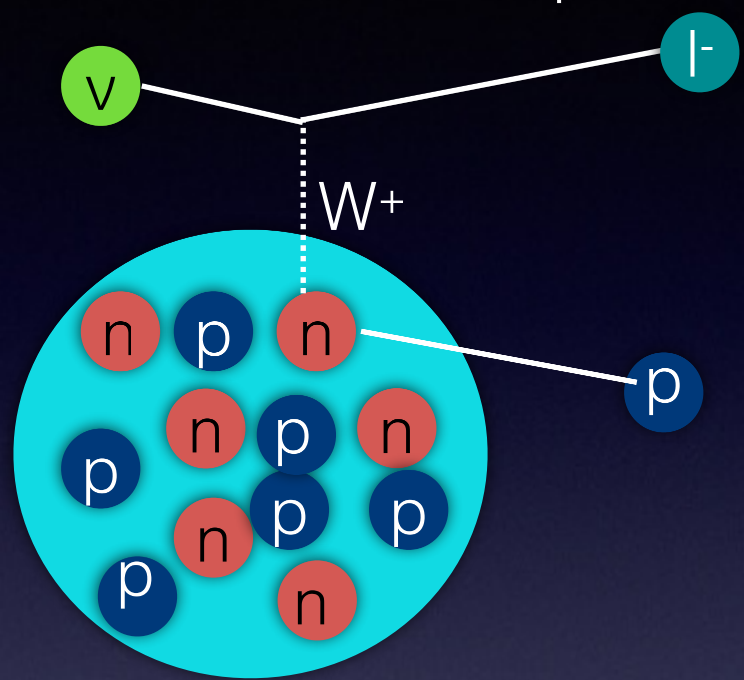
Interaction Model



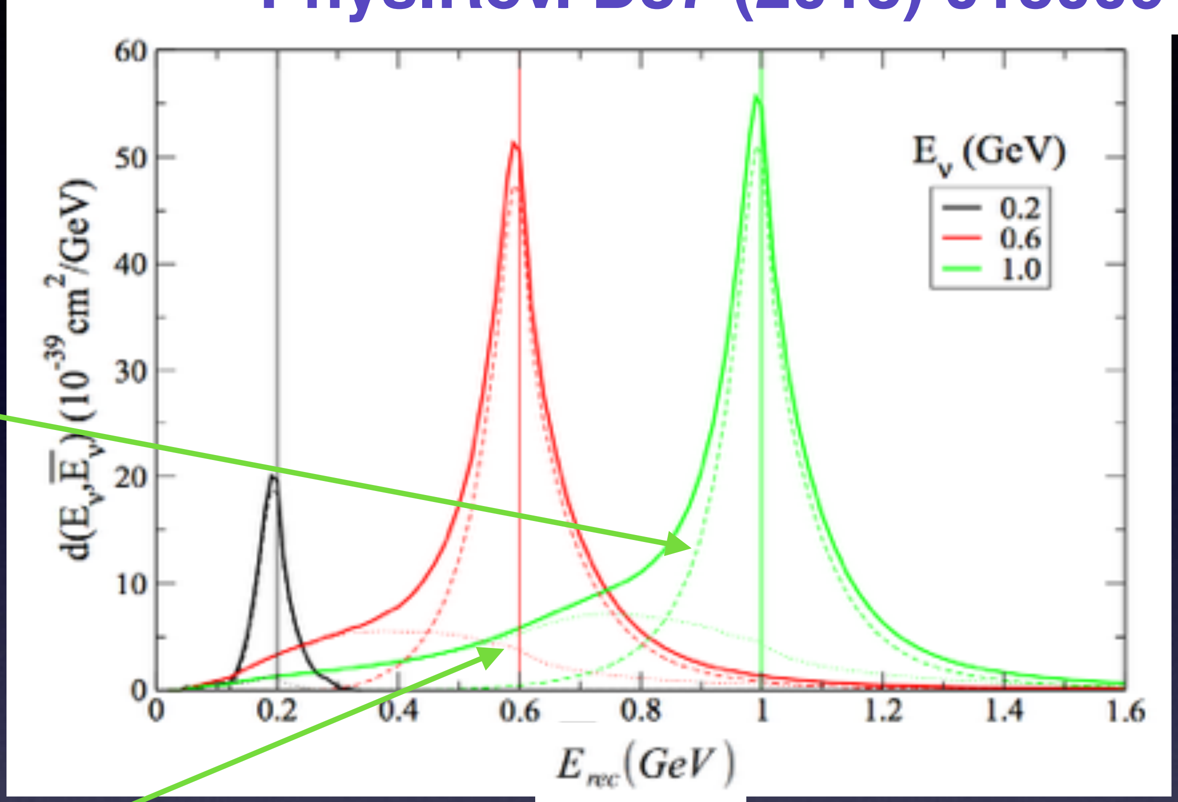

To test an oscillation hypothesis against the data, we rely on the interaction model to relate the measured quantities and neutrino energy

# Lepton Kinematic Modeling Challenges

Quasi-elastic scatter on single nucleon in nuclear potential



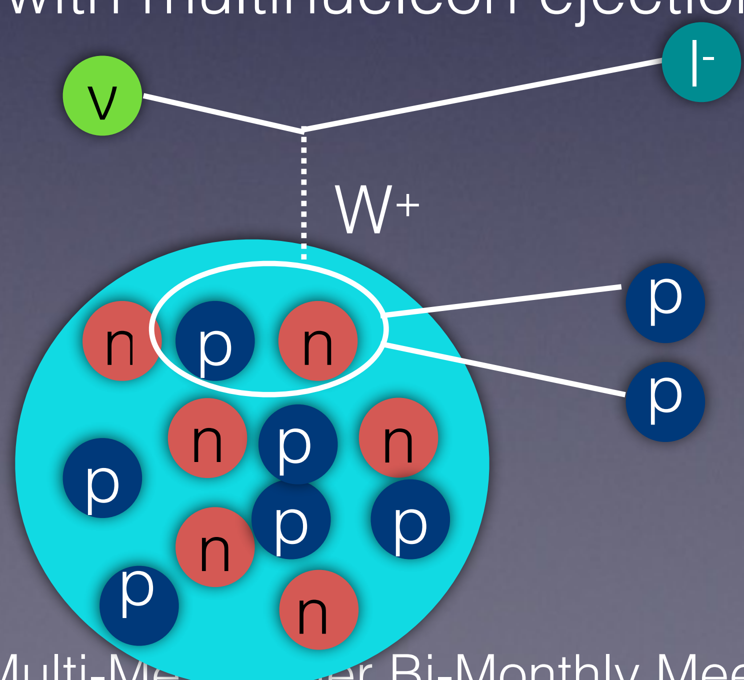

Martini et. al.
Phys.Rev. D87 (2013) 013009




Fill the "peak" region

Fill the "tail" region

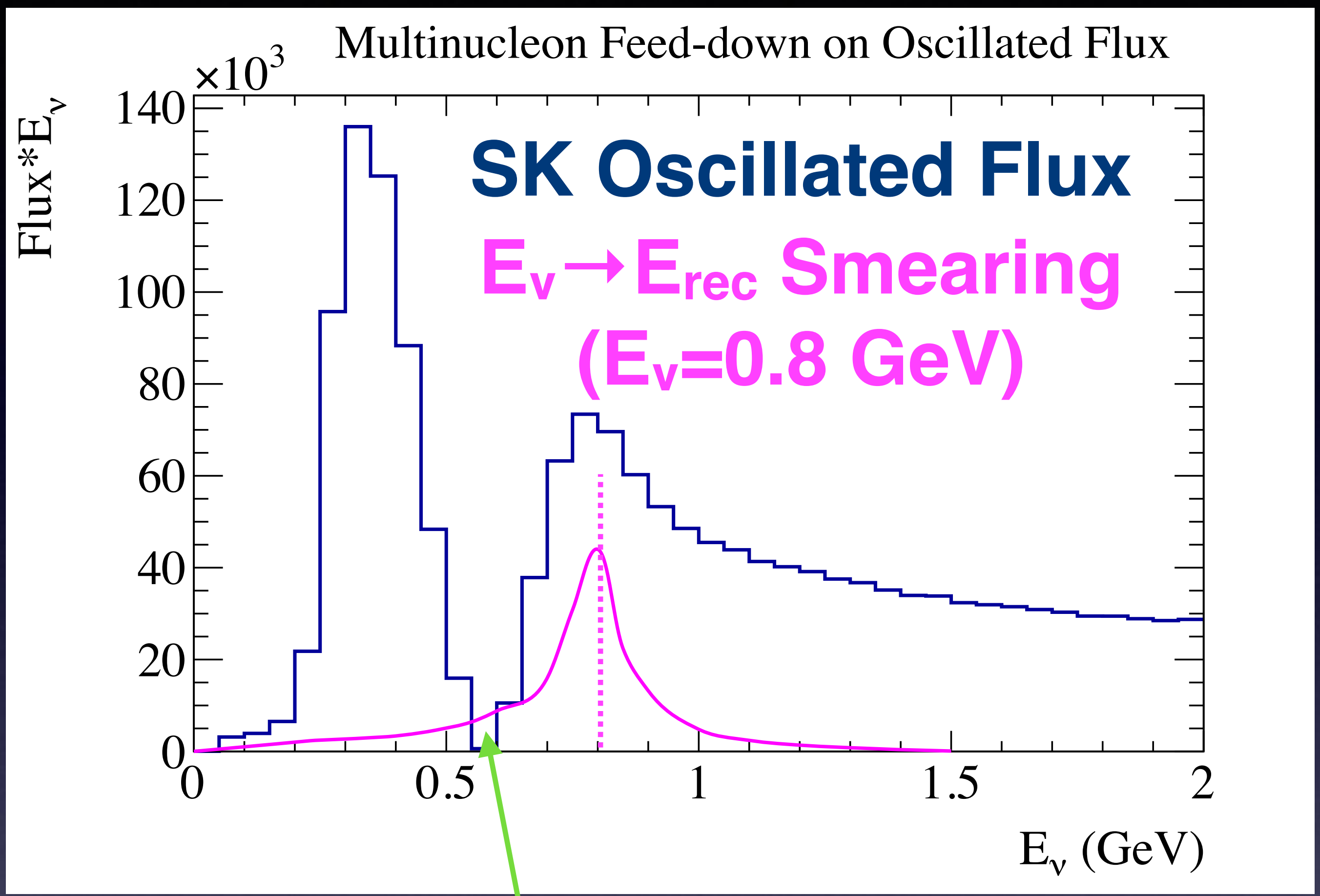
Scatter on correlated nucleon pair with multinucleon ejection

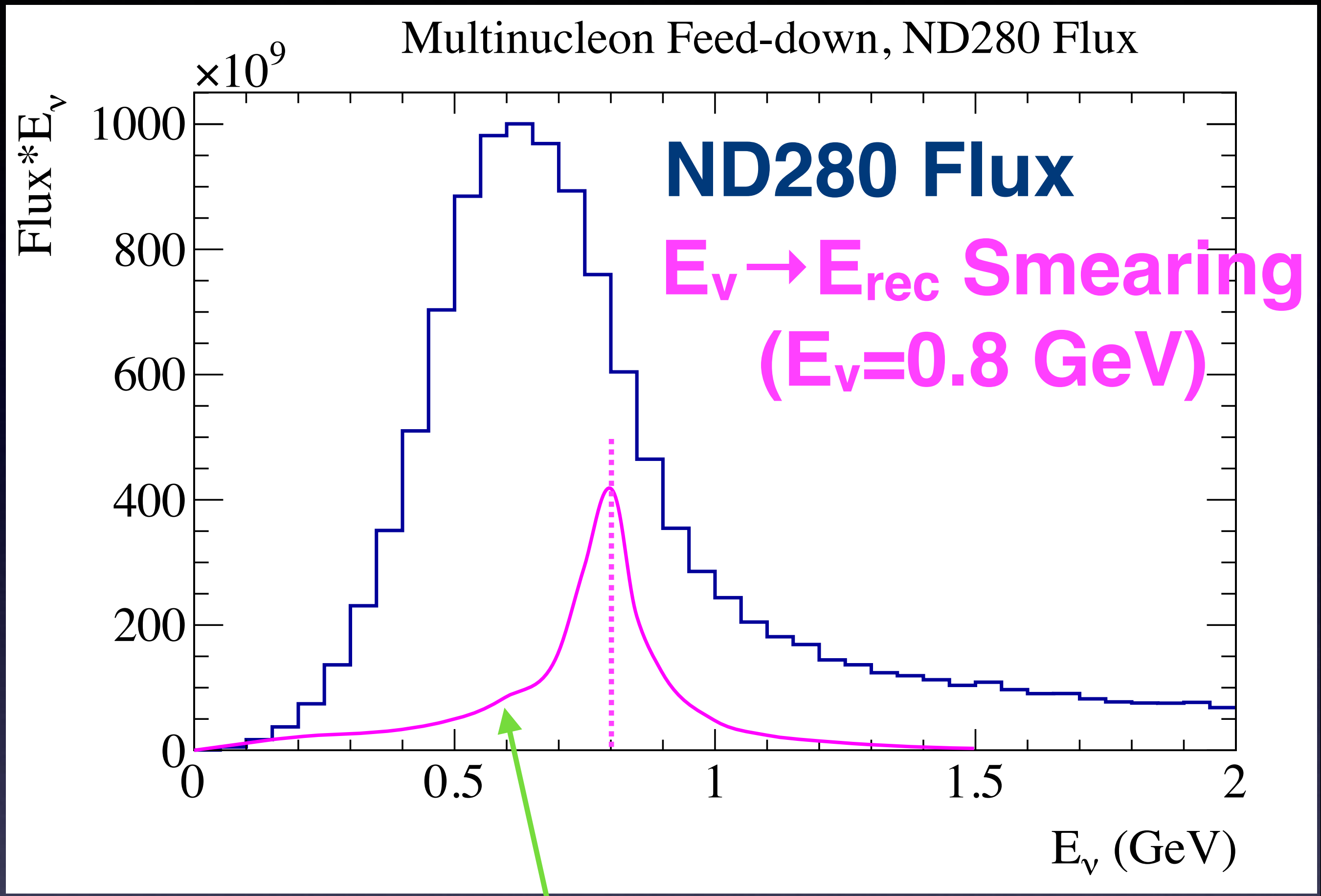



In a water cherenkov detector, it is typically not possible to differentiate these categories of events

The multinucleon part of the cross section has not been measured and predictions vary significantly between models

# Multinucleon Feed-down




The feed-down from multinucleon events and other nuclear effects can fill in the region of maximum oscillation

Choice of model can have a strong effect on the measured value of $\theta_{23}$

Difficult to measure this feed-down in ND280 since QE events from the flux peak fill the same phase space

The modeling of these nuclear effects is **under-constrained** by current near detector data

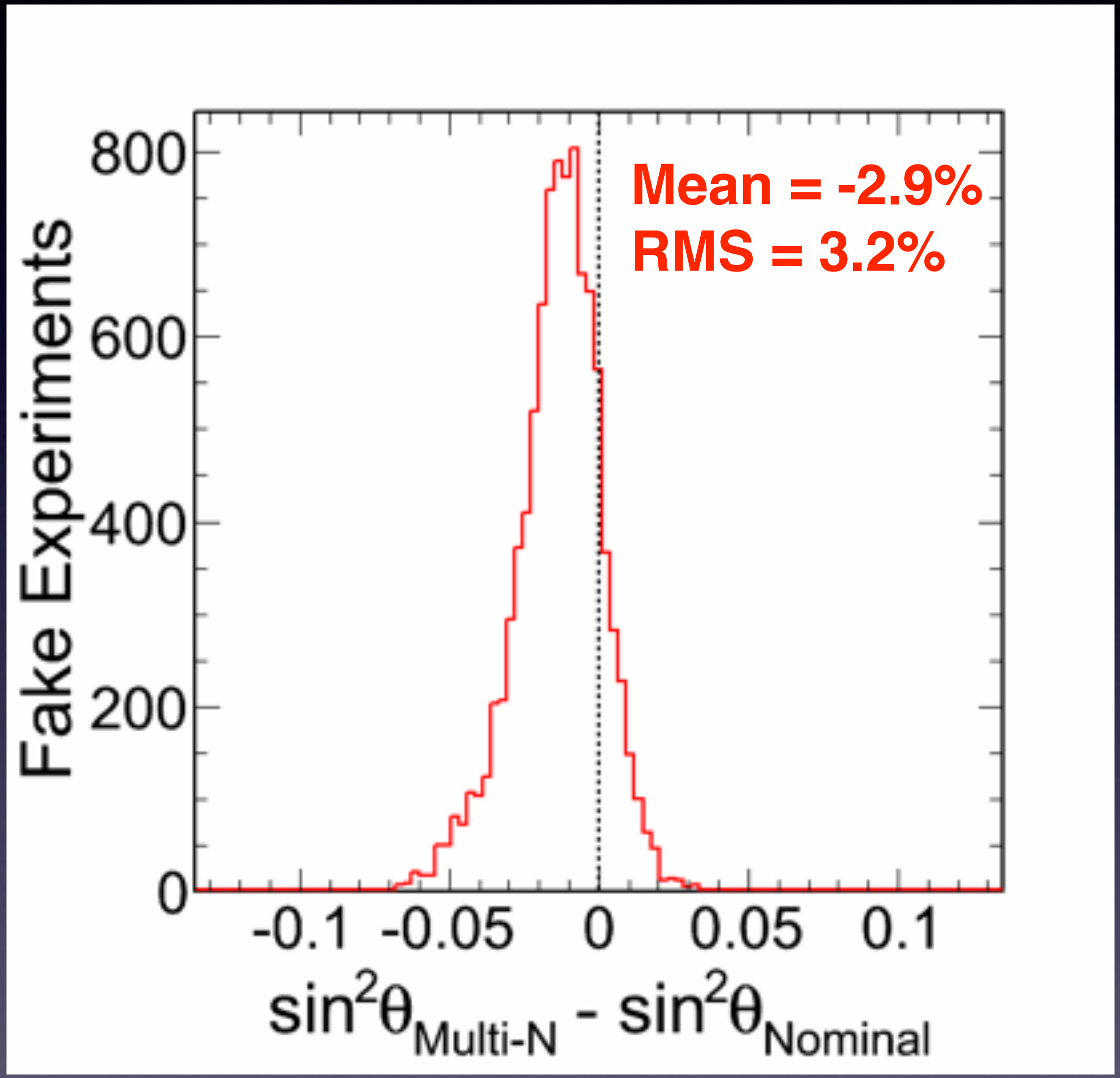
# Potential Effect in T2K Analysis

T2K performs studies on toy data to estimate the effect of mis-modeling the multinucleon part of the cross section

Potential average bias of 3% and a toy-to-toy variation of 3% on the measured $\theta_{23}$

While the T2K measurement is still statistics limited (10% uncertainty on $\sin^2\theta_{23}$), these model uncertainties are among the largest systematic errors

Currently no data to directly constrain these effects.  Relying on model comparisons.

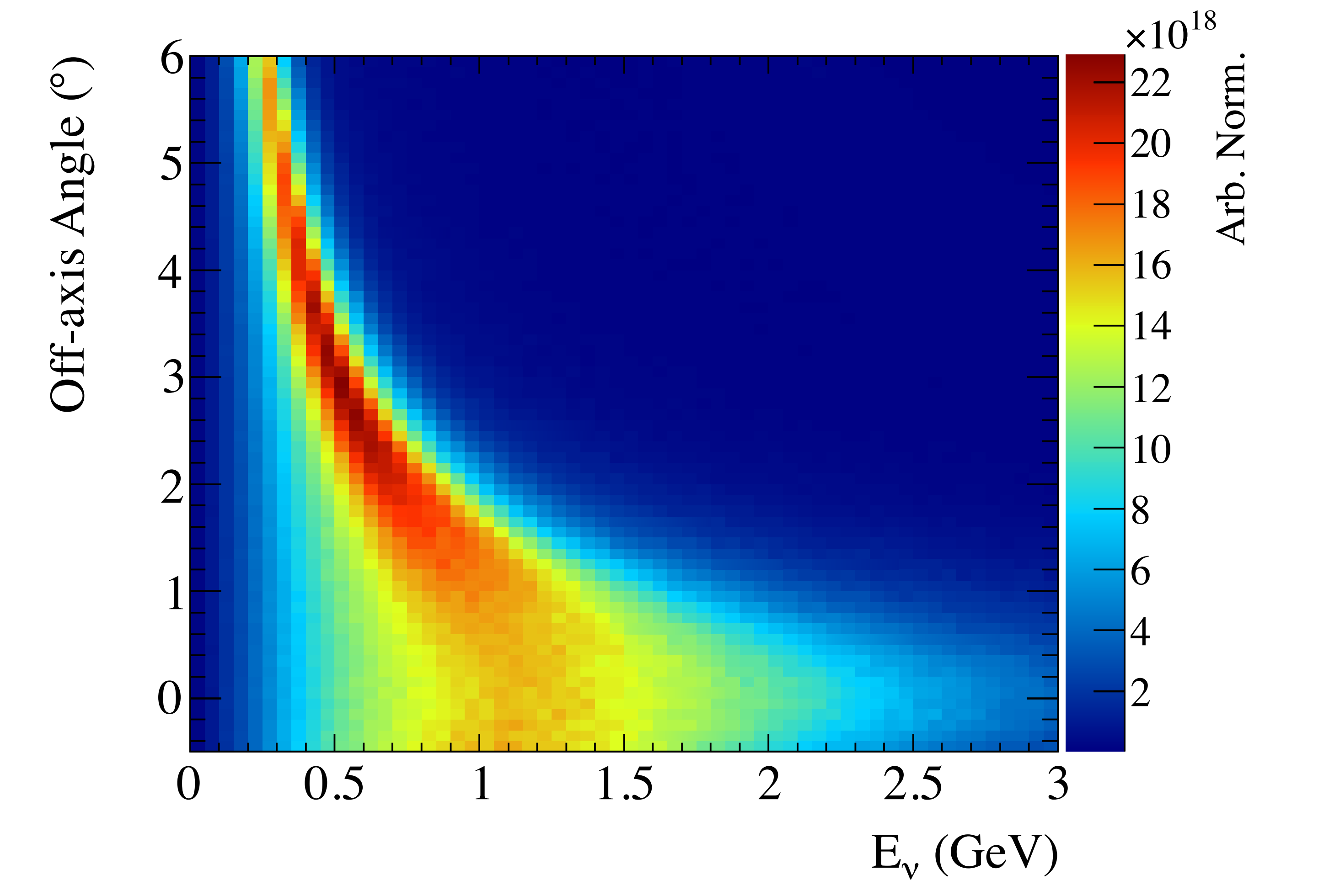


# How to Tackle This Problem

Life would be much easier if we could produce a mono-energetic beam of neutrinos at ~1 GeV → Could directly measure the "smearing" function

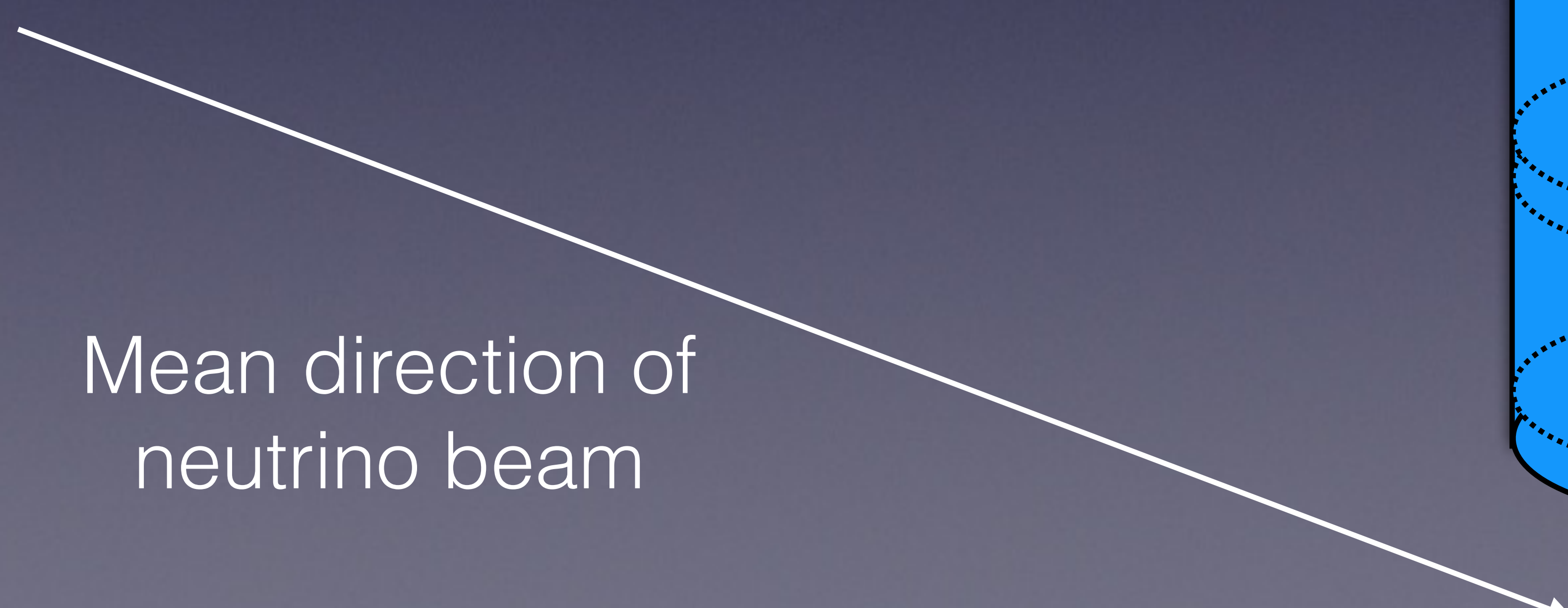
We can do the next best thing and take advantage of the off-axis effect

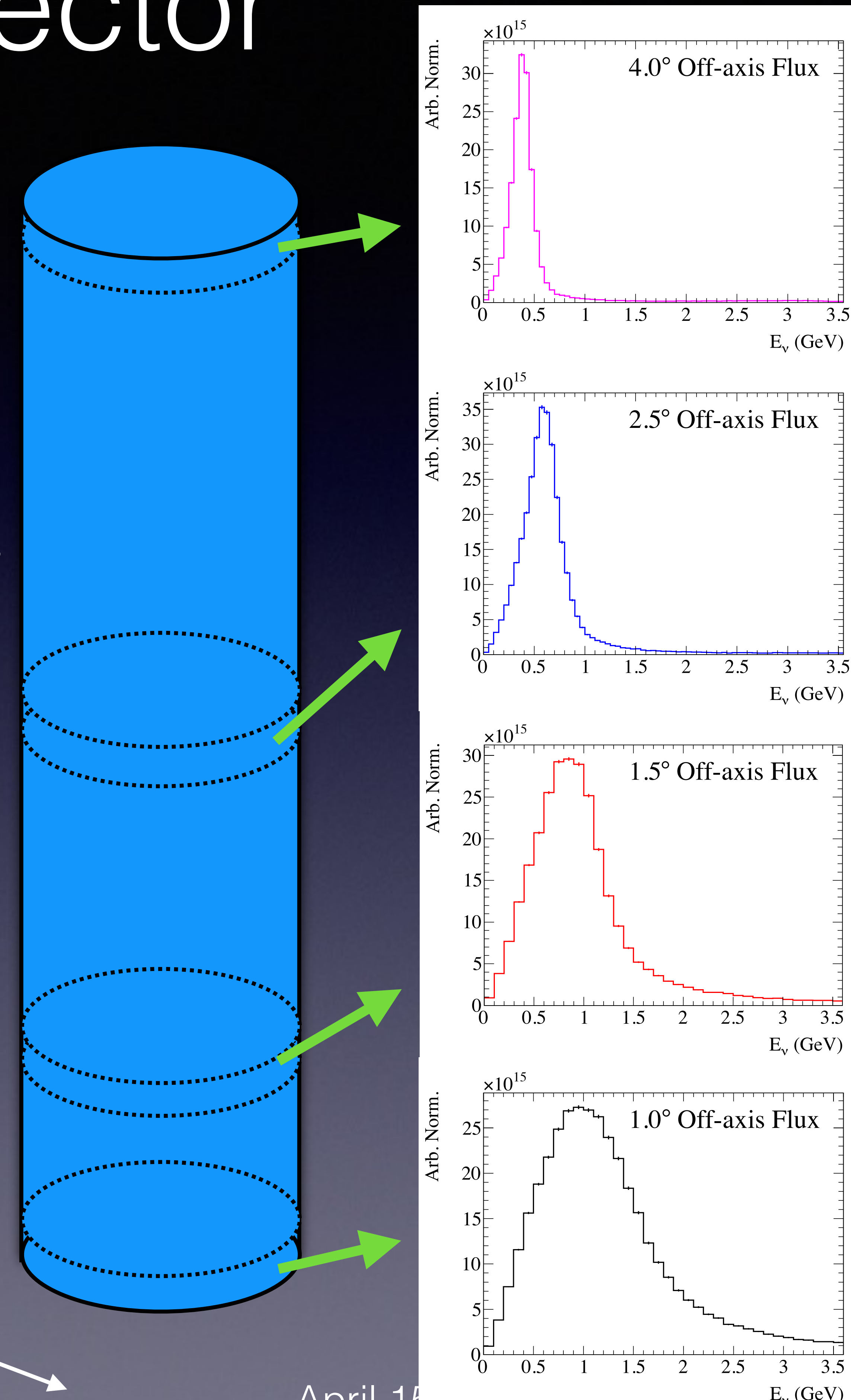
Varying the off-axis angle gives us spectra peaked at different energy → Use this extra information to over-constrain the problem



# The νPRISM Detector

- Idea to build a ~50 m tall WC detector ~1 km downstream of the J-PARC neutrino beam
- Covers off-axis angles of 1.0-4.0°
- Events in the detector are associated with a different neutrino spectrum, depending on where the interaction takes place
- Studies of the physics potential in both the T2K and HK collaborations



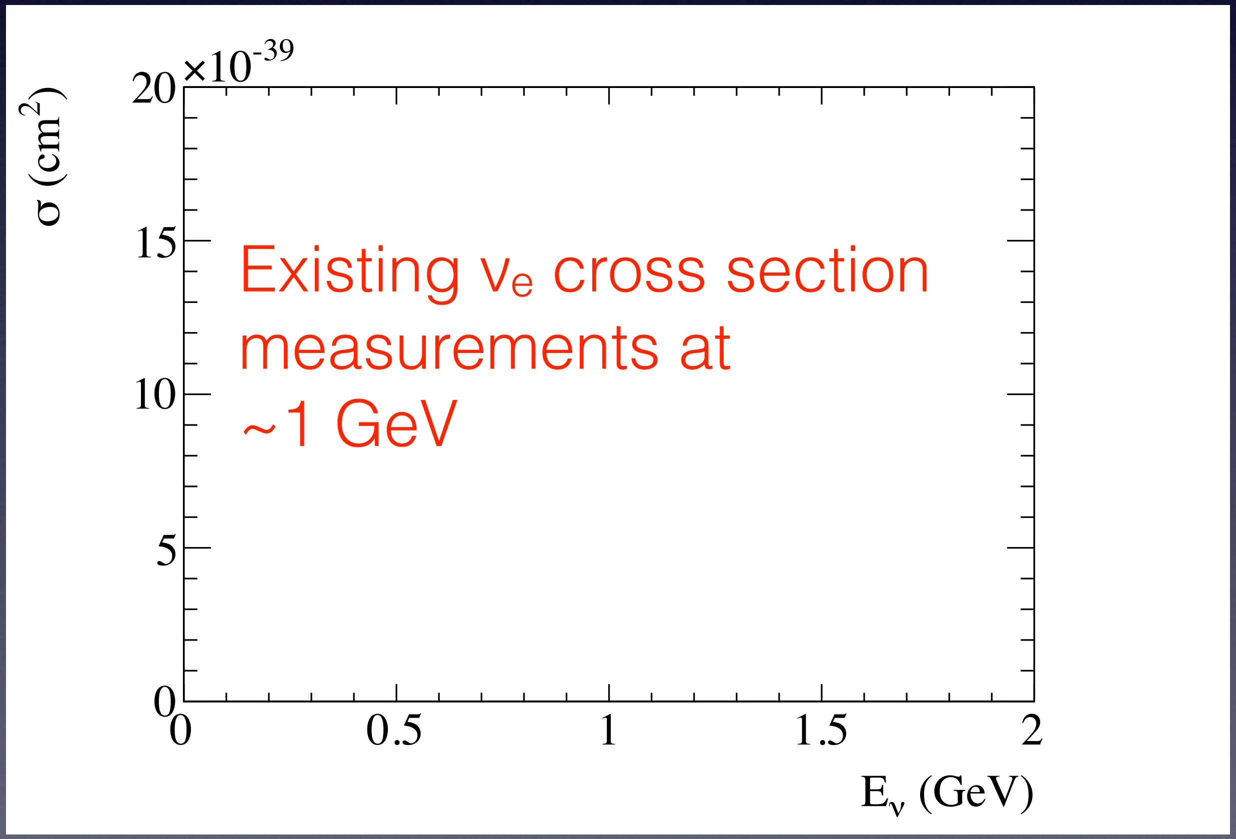
# More on νPRISM Measurements

- Measurements are made on the same nuclei as SK → complete correlation of nuclear effects
- Can measure the energy dependence of neutral current interactions
- Water cherenkov technology can separate well muons, electrons and $\pi^0$
  - Samples of $\nu_e$ interactions in νPRISM can be used to:

Measure the $\nu_e$ cross section

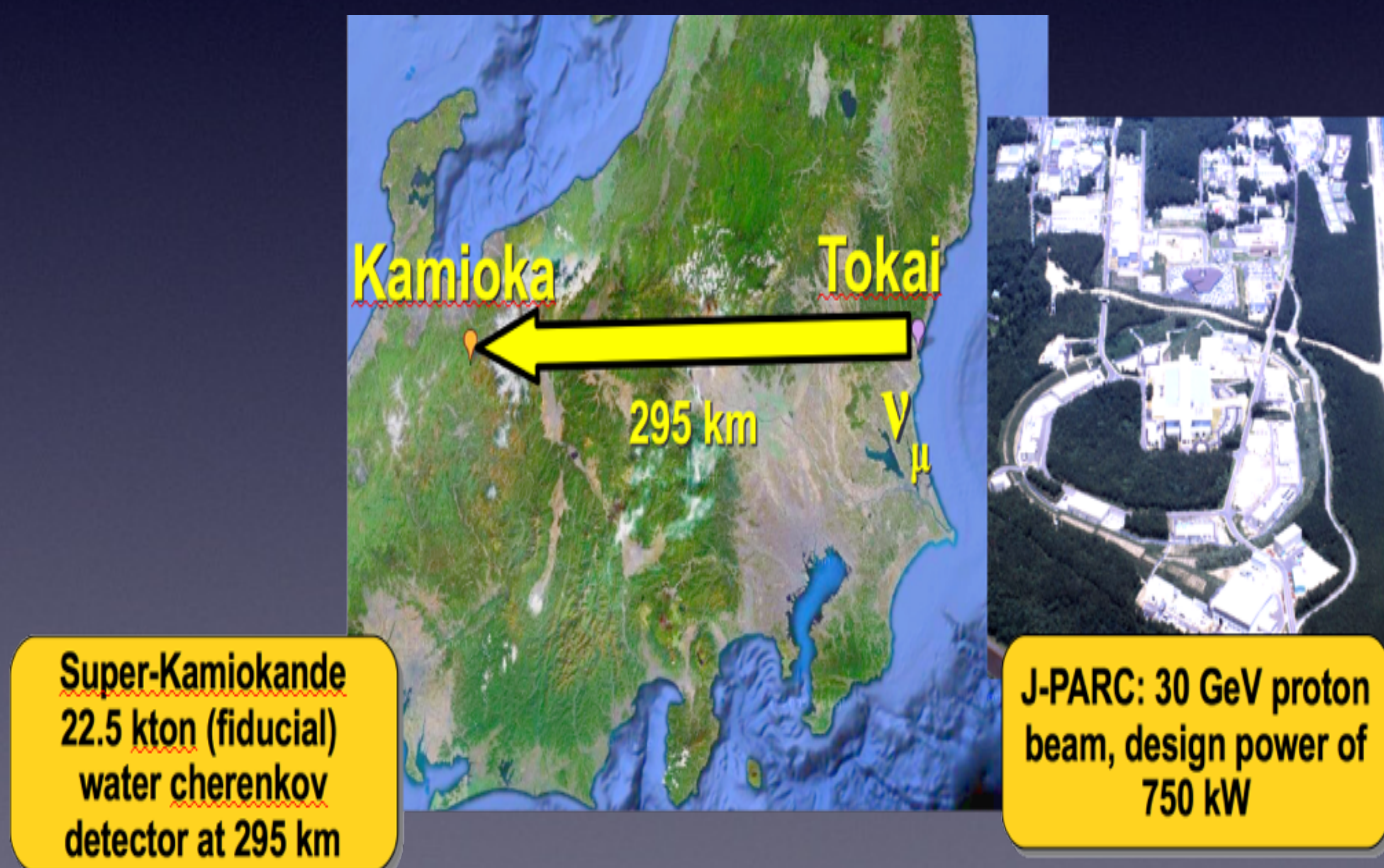
Currently rely completely on the models that are tuned to $\nu_\mu$ data

Important for the $\nu_e$ appearance oscillation measurement since the signal are $\nu_e$ interacting at SK



# Sterile Oscillations at νPRISM

- MiniBooNE and LSND see excesses of $\nu_e$ candidates at short baselines
- May be due to short baseline oscillations involving sterile neutrinos
- νPRISM is a new way to study this effect by keeping the baseline fixed and varying the neutrino energy spectrum



# Summary and the Future

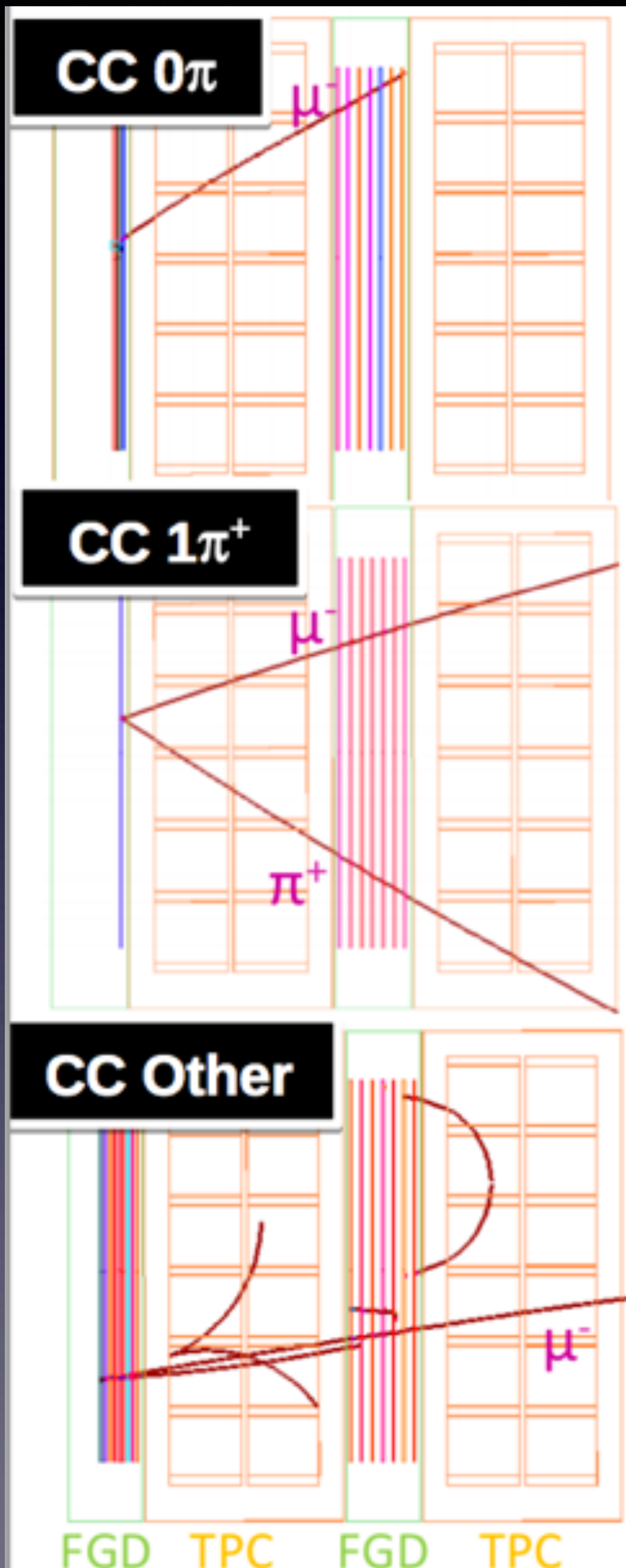
- T2K has analyzed our full data set, about 8% of the expected final T2K data
- **Discovery of $\nu_\mu \rightarrow \nu_e$ oscillations**, **starting to constrain $\delta_{CP}$**, **world best measurement of $\theta_{23}$**!
- Many interesting results I didn't have time for including neutrino interaction cross-section measurements at ND280 and SK
- T2K will soon be moving into regime where systematic errors are of similar size as statistical errors
  - Thinking about new approaches to reducing systematic errors
  - The **νPRISM** detector is one approach that is being studied
- Plan to start a data taking running this May
- Plan to take our first data with an antineutrino beam this year. Important step towards measuring $\delta_{CP}$

# Extra Slides

# Systematic Errors ($\nu_\mu$)

| Systematic Uncertainty | Before ND280 Fit RMS/Mean $N_{SK}$ (%) | After ND280 Fit RMS/Mean $N_{SK}$ (%) |
|---|---|---|
| **ND280 Constrained Flux and Xsecs** | 21.6 | 2.7 |
| **SK Only Xsecs** | 5.9 | 4.9 |
| **Combined SK Detector and Hadronic Interactions** | 6.3 | 5.6 |
| SK Detector Uncertainties | 5.3 | 4.8 |
| Hadronic Interactions in Oxygen and Water | 3.4 | 3.0 |
| **$\sin^2\theta_{12}$, $\Delta m^2_{12}$, $\sin^2\theta_{13}$, $\delta_{CP}$** | 0.2 | 0.2 |
| **Total** | 23.4 | 8.1 |

# ND280 Data




Select data originating in the first FGD

CC events identified by presence of muon candidate

Break into subsamples with:

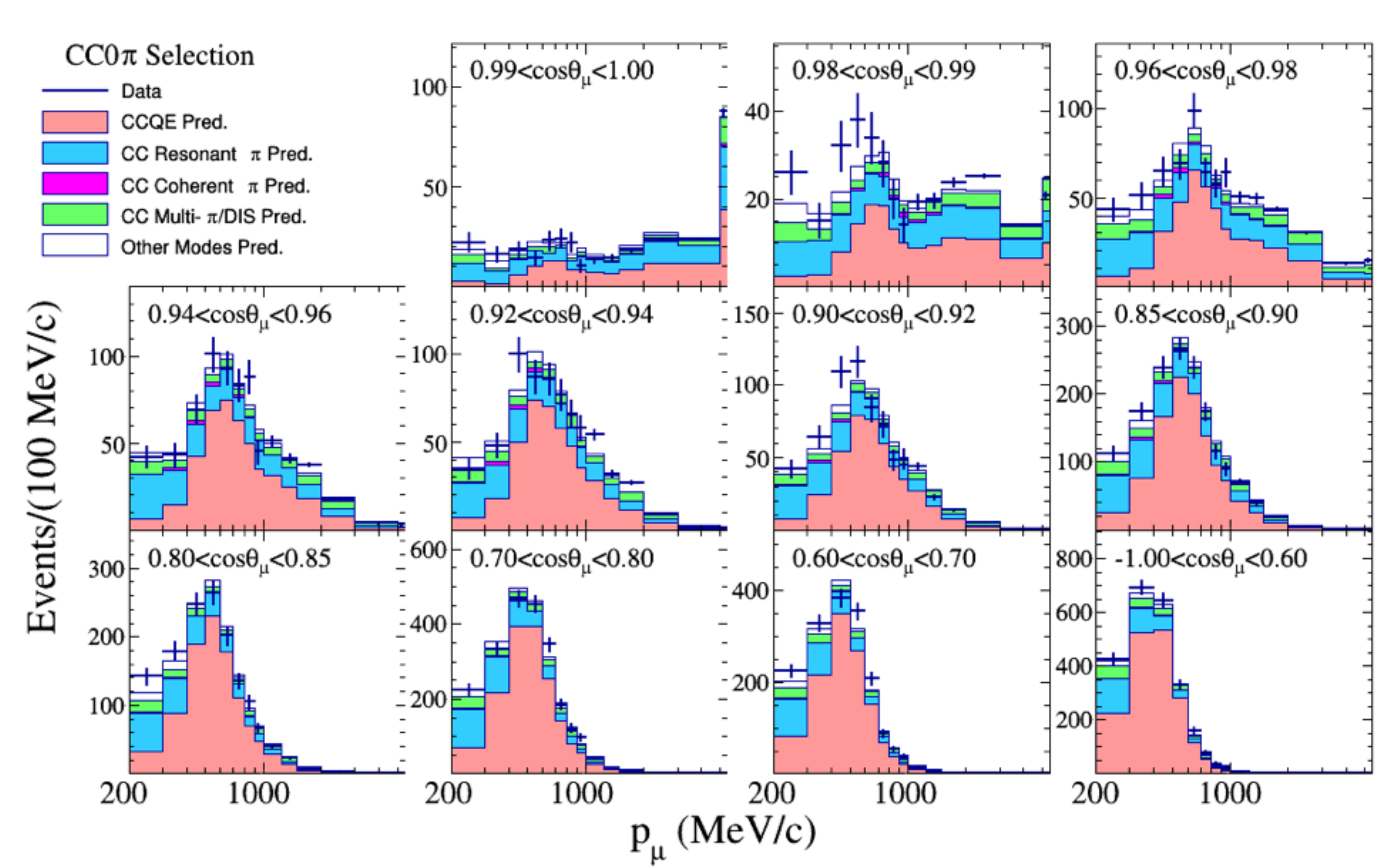
1. No pion in the final state
2. 1 $\pi^+$ in the final state
3. Multiple pions, photons or $\pi^-$ in the final state

**Number of Events**

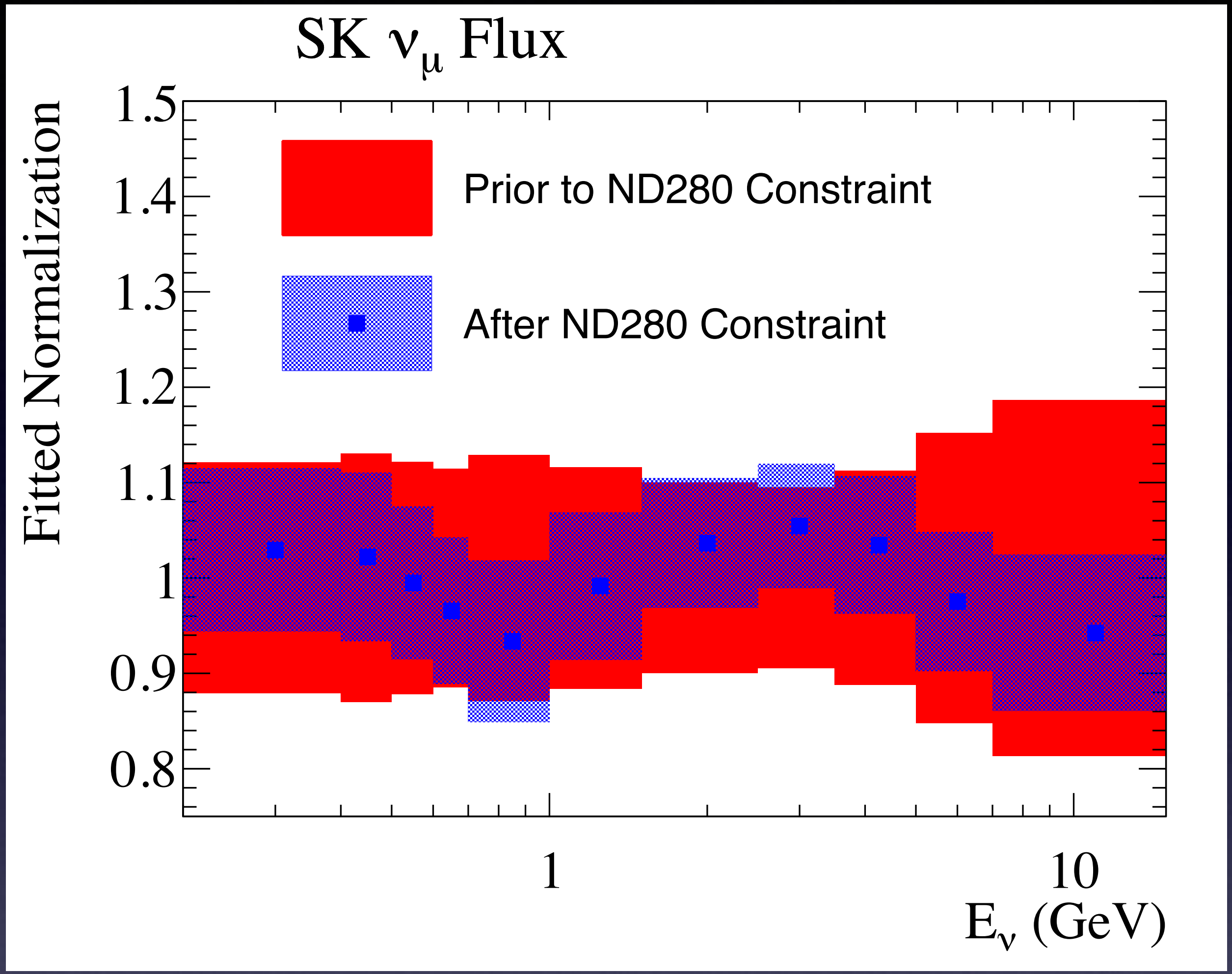
| Selection | Data | MC (before ND280 constraint) | MC (after ND280 constraint) |
|---|---|---|---|
| CC0π | 17369 | 19980 | 17352 |
| CC1π | 4047 | 4953 | 4110 |
| CC Other | 4173 | 4545 | 4119 |
| CC Inclusive | 25589 | 29477 | 25581 |

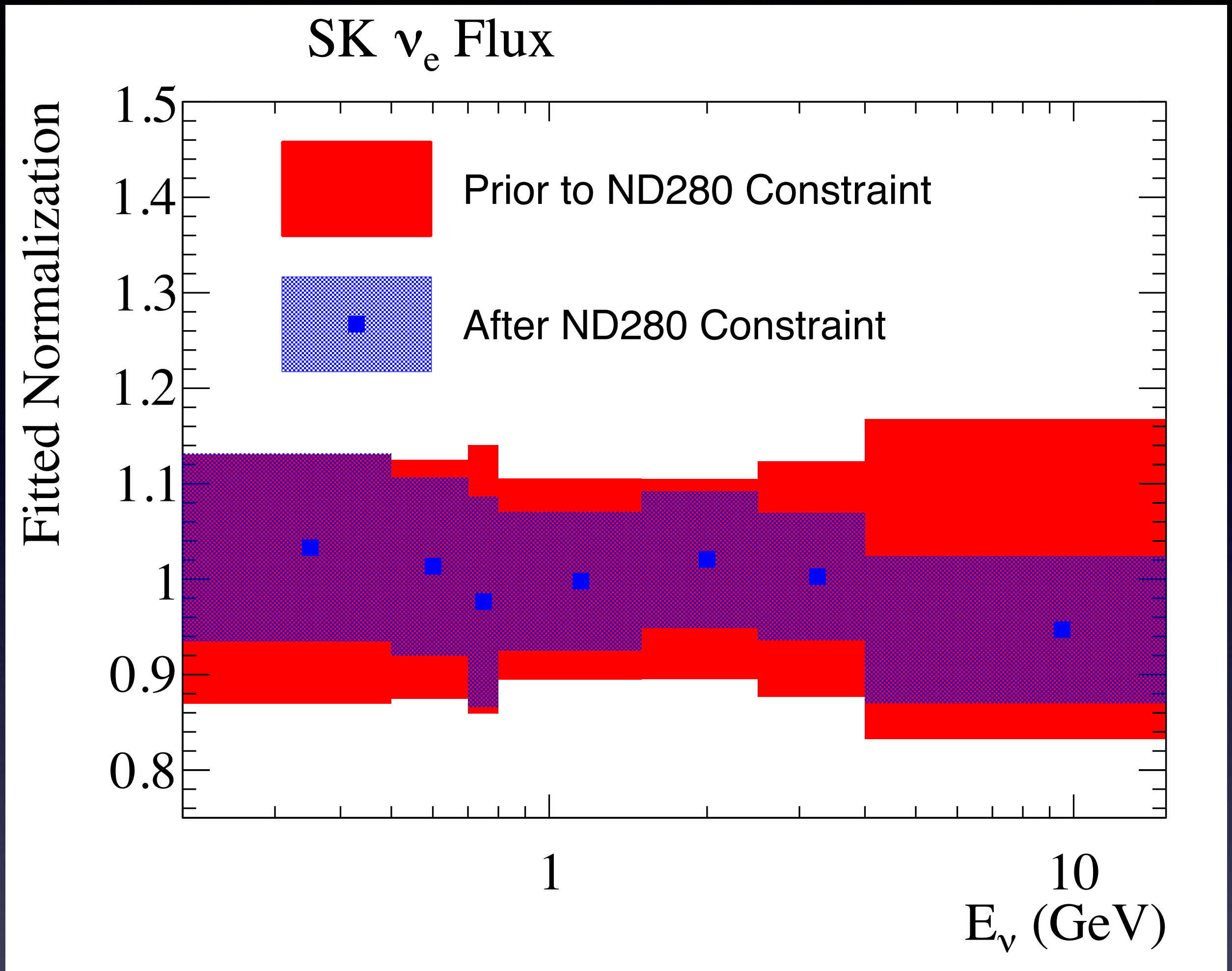
| Interaction | CC-0π | CC-1π | CC Other |
|---|---|---|---|
| CCQE | 63.5% | 5.3% | 3.9% |
| Resonant p | 20.2% | 39.5% | 14.3% |
| DIS | 7.5% | 31.3% | 67.8% |
| Coherent p | 1.4% | 10.6% | 1.4% |
| Other | 7.4% | 13.3% | 12.6% |

# ND280 Fit Results



# Flux Uncertainty Reduction



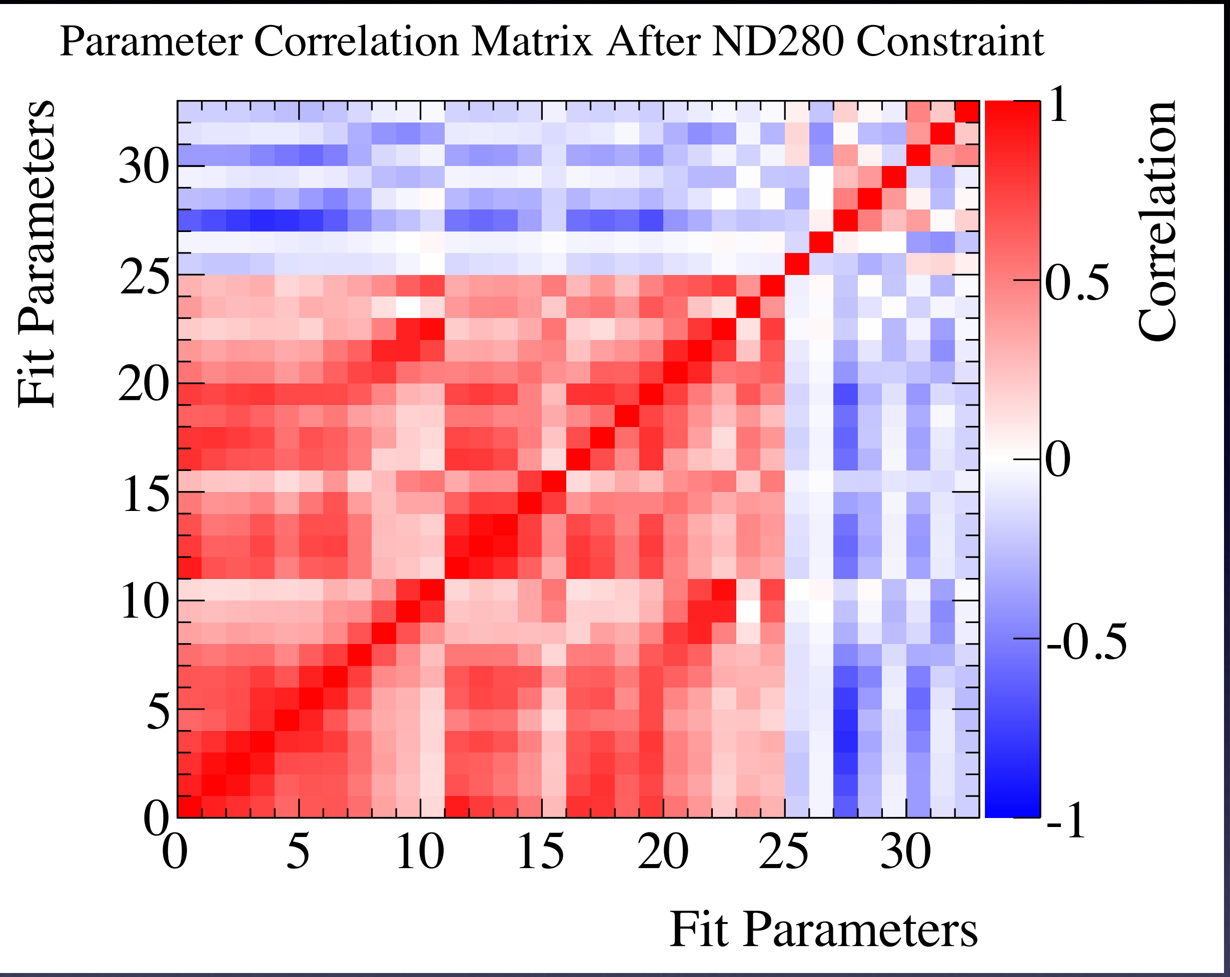




ND280 constraint tunes the flux prediction as a function of the neutrino energy

Reduces the uncertainty on the flux prediction

# Cross-section Uncertainty Reduction

| Parameter | Prior to ND280 Constraint | After ND280 Constraint |
|---|---|---|
| $M_A^{QE}$ (GeV) | 1.21 ± 0.45 | 1.240 ± 0.072 |
| $M_A^{RES}$ (GeV) | 1.41 ± 0.22 | 0.965 ± 0.068 |
| CCQE Norm. $E_\nu$<1.5 GeV | 1.00 ± 0.11 | 0.966 ± 0.076 |
| CCQE Norm. 1.5<$E_\nu$<3.5 GeV | 1.00 ± 0.30 | 0.93 ± 0.10 |
| CCQE Norm. $E_\nu$>3.5 GeV | 1.00 ± 0.30 | 0.85 ± 0.11 |
| CC1π Norm. $E_\nu$<2.5 GeV | 1.15 ± 0.32 | 1.26 ± 0.16 |
| CC1π Norm. $E_\nu$>2.5 GeV | 1.00 ± 0.40 | 1.12 ± 0.17 |
| NC1$\pi^0$ Norm. | 0.96 ± 0.33 | 1.14 ± 0.25 |




Interaction cross-section model parameters are tuned and their uncertainties are reduced

After the fit to the ND280 data, the flux parameters (0-24) and the cross-section parameters (25-32) pick up correlations since the data only constrains the modeling of the event rate

# One Way to Use νPRISM Data

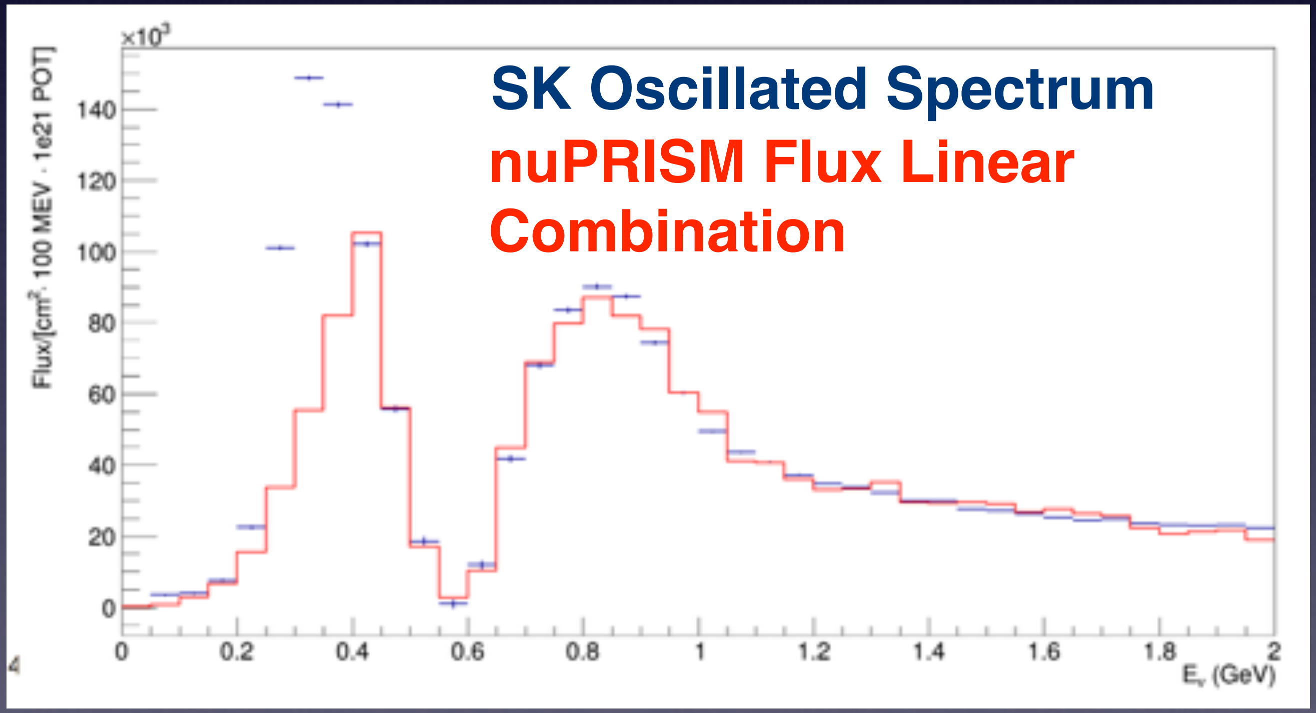
Each off-axis slice of nuPRISM corresponds to a different neutrino energy spectrum

Can expand an arbitrary spectrum as a linear combination of nuPRISM spectra

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

Oscillated SK Flux — Linear combination of nuPRISM fluxes

Can reproduce the oscillated flux rater well except at low energy




Can use the same $C_i$ weights to derive the expected SK observed distribution from the observed nuPRISM distribution

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

# νPRISM Event Rates

TABLE XVII. The event rates and purities for single muon-like ring and single electron-like ring selections for $3.9\times10^{21}$ ($11.7\times10^{21}$) POT in the νPRISM detector with the beam operating in neutrino (antineutrino) mode.

| | 1 Ring $\mu$ | | 1 Ring e | |
|---|---|---|---|---|
| Off-axis Angle (°) | Candidates | CC $\nu_\mu(\bar{\nu}_\mu)$ Purity | Candidates | CC $\nu_e(\bar{\nu}_e)$ Purity |
| 1.0-2.0 | $3.42\times10^6(3.06\times10^6)$ | 97.5%(84.7%) | $2.56\times10^4(2.95\times10^4)$ | 45.8%(27.1%) |
| 2.0-3.0 | $1.76\times10^6(1.65\times10^6)$ | 97.7%(81.8%) | $1.36\times10^4(1.66\times10^4)$ | 67.2%(38.0%) |
| 3.0-4.0 | $7.85\times10^5(8.02\times10^5)$ | 97.2%(76.2%) | $7.91\times10^3(1.09\times10^4)$ | 74.9%(40.1%) |

Efficiencies are based on SK photo-coverage and PMT granularity

Expect improvement in 1 Ring e purities with finer PMT granularity