# Results from T2K

A. Minamino (Kyoto)
on behalf of the T2K collaboration

Sep. 30, 2013

KEK-PH 2013 FALL @ KEK

# Neutrino Mixing

Flavor States

Note: $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

| "Atmospheric ν" | "Reactor/Acc. ν" | "Solar ν" | Majorana phases; |
|---|---|---|---|
| $\sin^2 2\theta_{23} > 0.95$ (90% C.L.) | $\sin^2 2\theta_{13} = 0.098 \pm 0.013$ | $\sin^2 2\theta_{12} = 0.857 \pm 0.024$ | Not yet observed |

- **$\theta_{13}$ is now precisely known**, and relatively large
- It may now be possible to put **constraints on $\delta_{CP}$** (Long-baseline experiments only: T2K & NOνA)
- However, **the large uncertainty on $\theta_{23}$** is now limiting the information that can be extracted from $\nu_e$ appearance measurements
- Precise measurements of **all the mixing angles** will be needed to maximize sensitivity to CP violation

## Oscillation Prob.

$$P_{\mu\to\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E^2}\right)$$

+ (subleading terms)

$$P_{\mu\to e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

+ (CPV term) + (matter term) + ...

# The T2K Collaboration

**Canada**
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

**France**
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

**Germany**
Aachen U.

**Italy**
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
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**Japan**
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Kobe U.
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Okayama U.
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**Poland**
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

**Russia**
INR

**~500 members, 59 Institutes, 11 countries**

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**United Kingdom**
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Lancaster U.
Oxford U.
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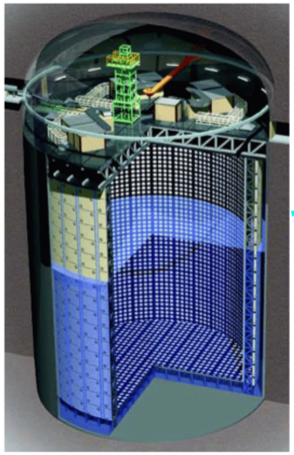
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

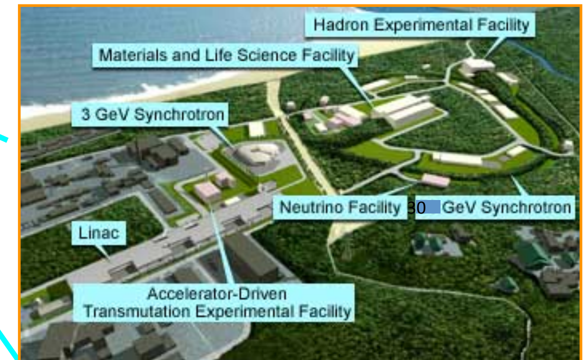
**USA**
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

# The T2K Experiment

Super-K Detector

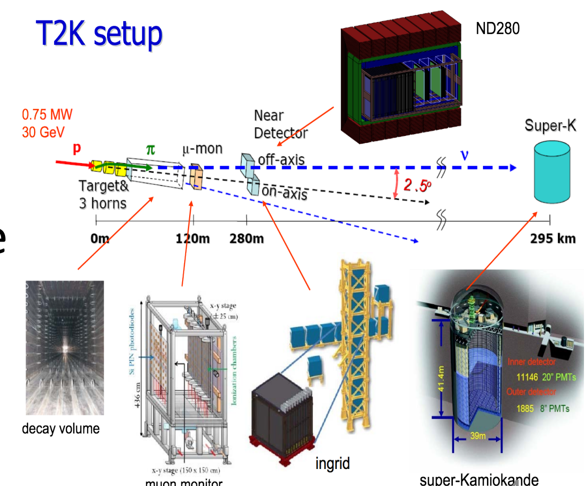



J-PARC Accelerator

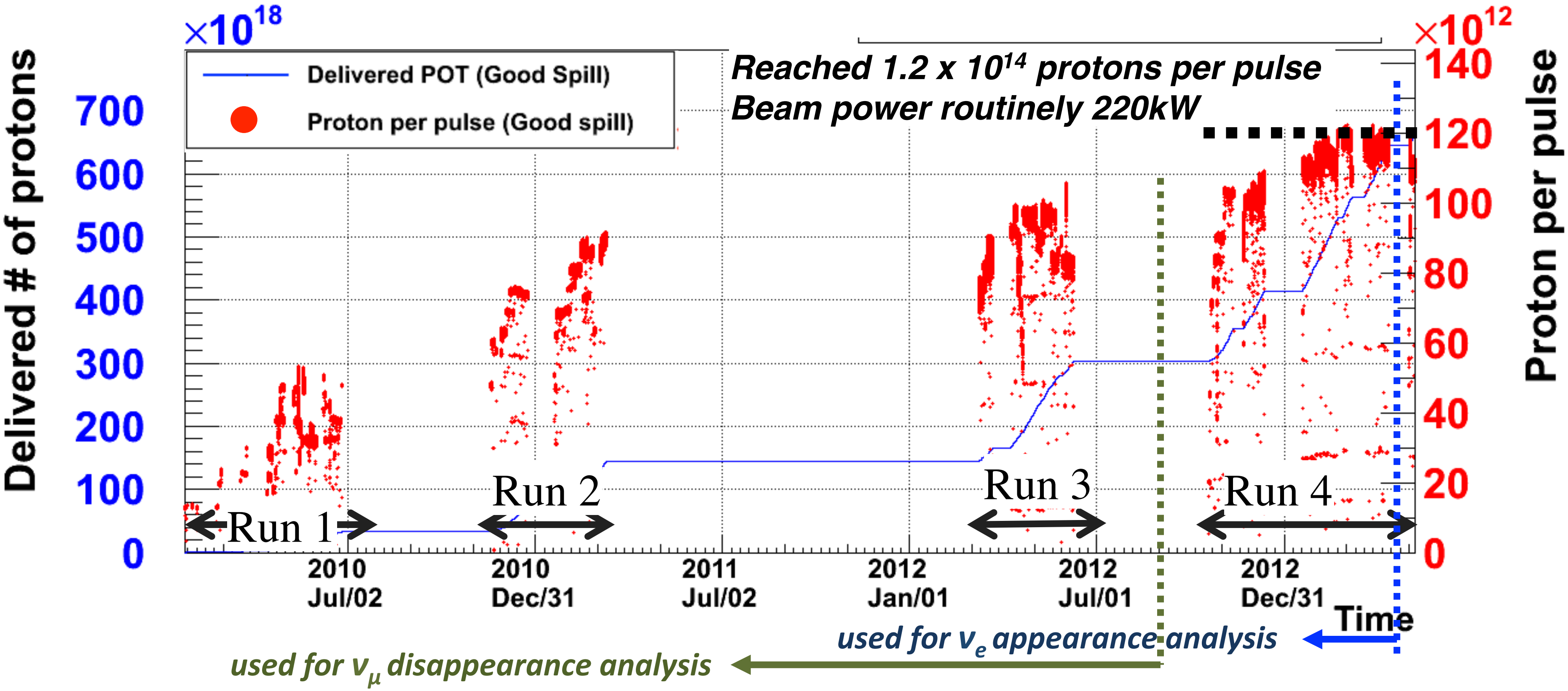



- The T2K experiment searches for neutrino oscillations in a **high purity $\nu_\mu$ beam**
- A near detector located 280 m downstream of the target measures the unoscillated neutrino spectrum
- The neutrinos travel 295 km to the Super-Kamiokande water Cherenkov detector
  - $\nu_e$ appearance (sensitive to $\theta_{13}$ & $\delta_{CP}$)
  - $\nu_\mu$ disappearance (sensitive to $\theta_{23}$ & $\Delta m^2_{32}$)

Near Detector

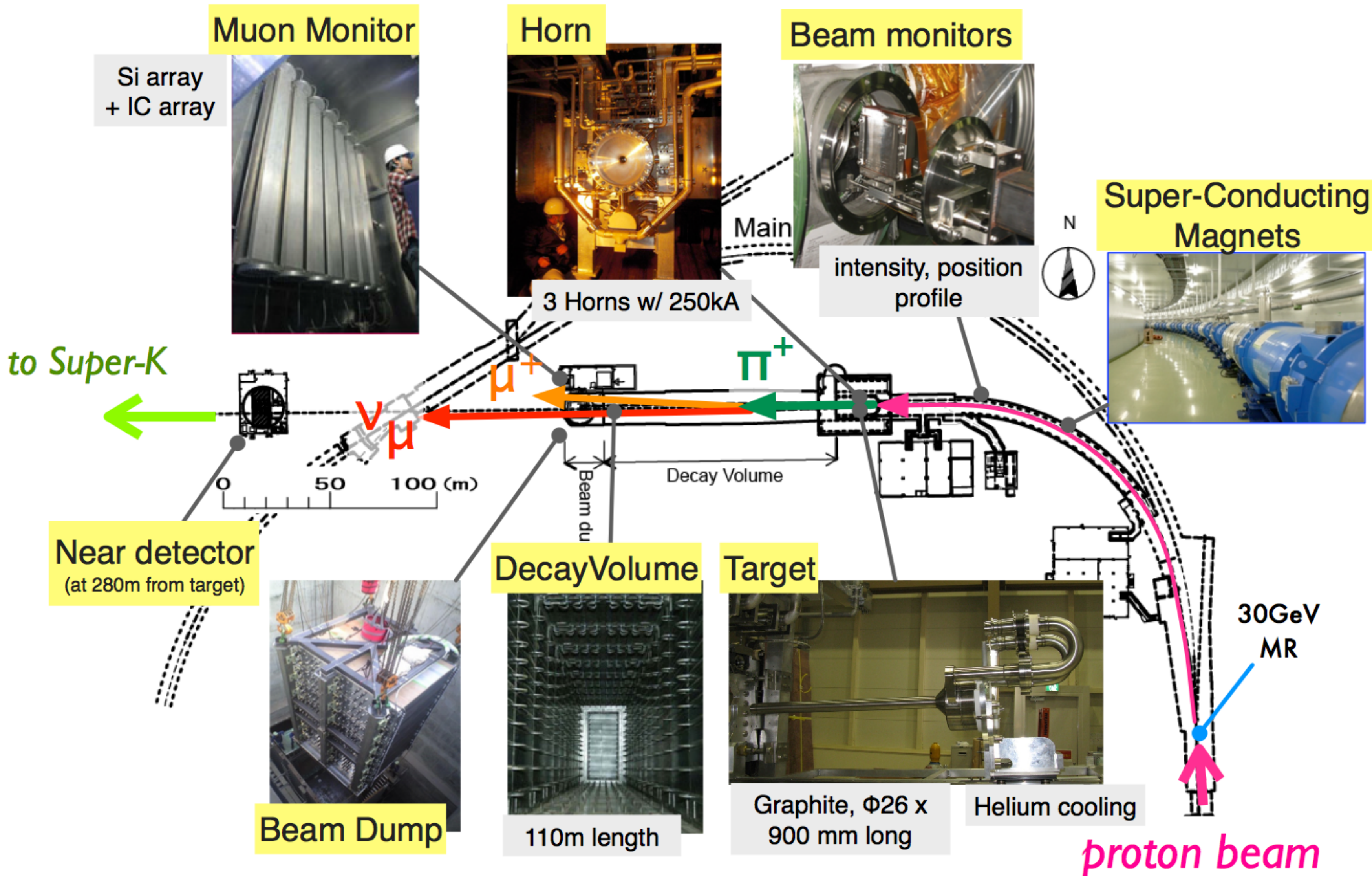


# Datasets



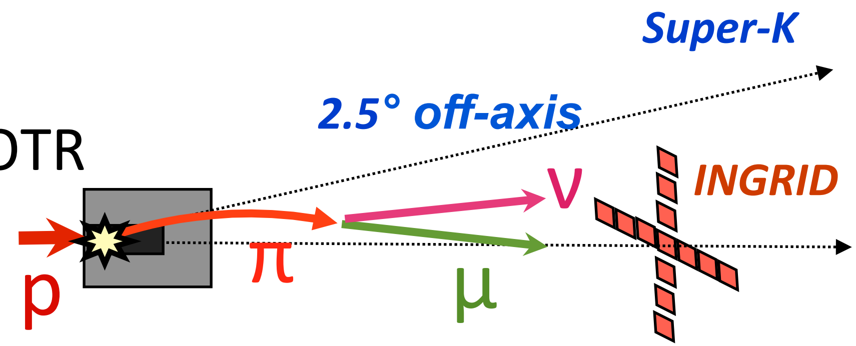

- Total delivered beam: $6.63\times10^{20}$ Protons on Target (POT)
- $\nu_\mu \rightarrow \nu_e$ analysis uses 96.3% of Run 1-4 data (through Apr 12, 2013)
- $\nu_\mu \rightarrow \nu_e$ analysis uses Run 1-3 data ($3.01\times10^{20}$ POT)

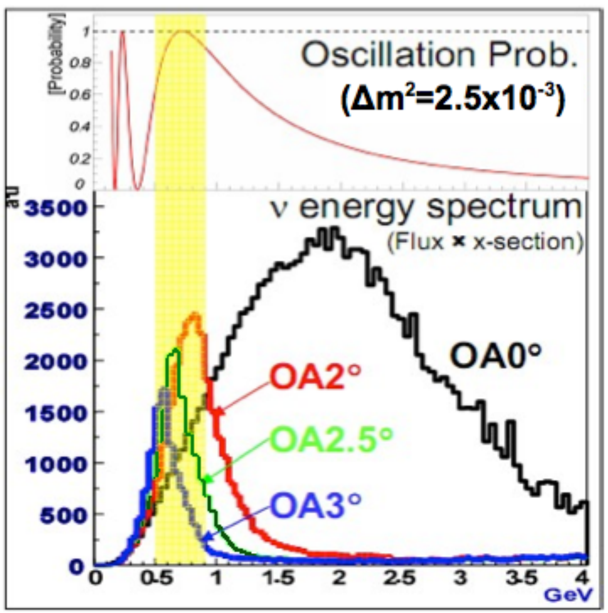
# T2K Beamline



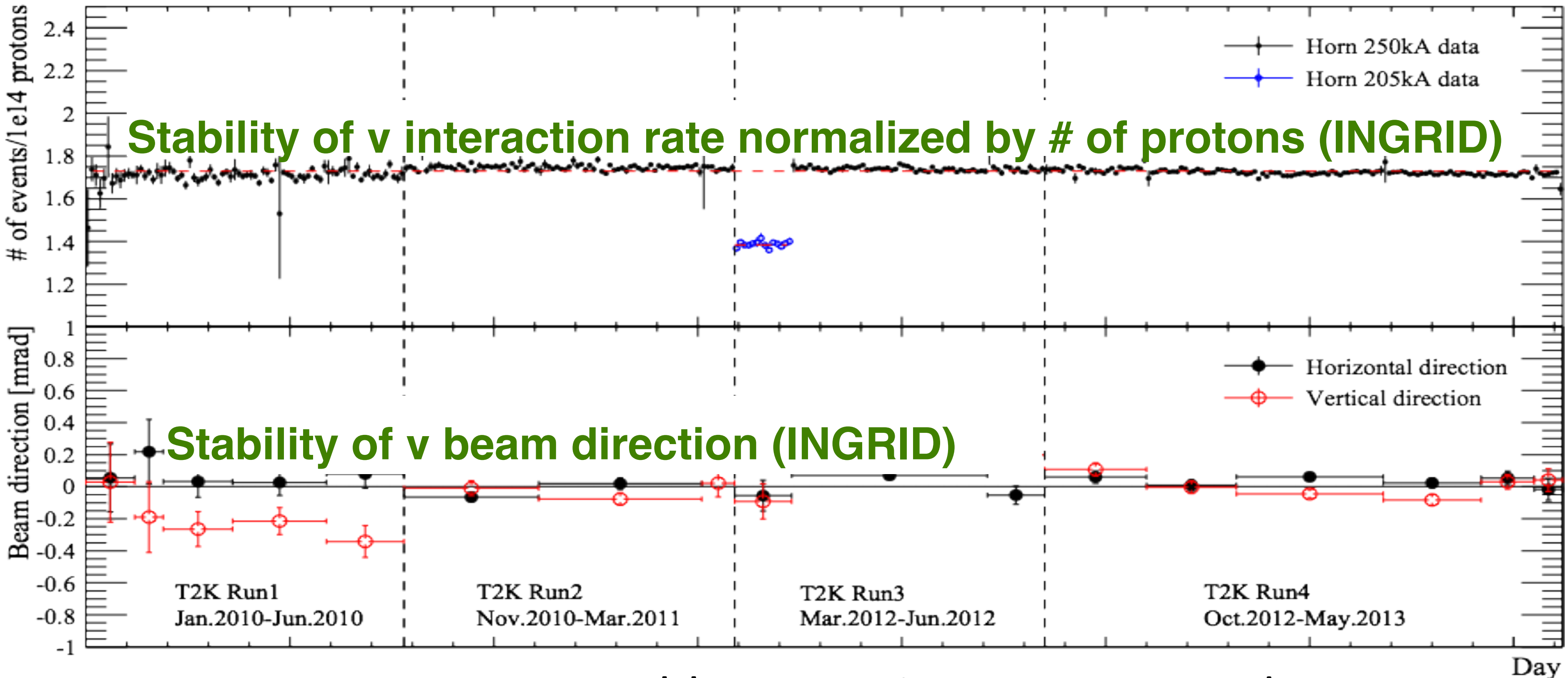
# Flux Prediction

- Proton beam monitoring
  - Profile on target from SEMs, OTR
  - Intensity from beam toroid
- Hadroproduction measurements, notably CERN-NA61 thin carbon target data
  - Replica T2K “thick” target ($1.9\lambda_0$) data in hand, and being analyzed
- Alignment of and current in horns
- The direction of the neutrino beam
  - 1 mrad change of ν beam direction results in ~16 MeV change of the peak neutrino energy in the observed rate



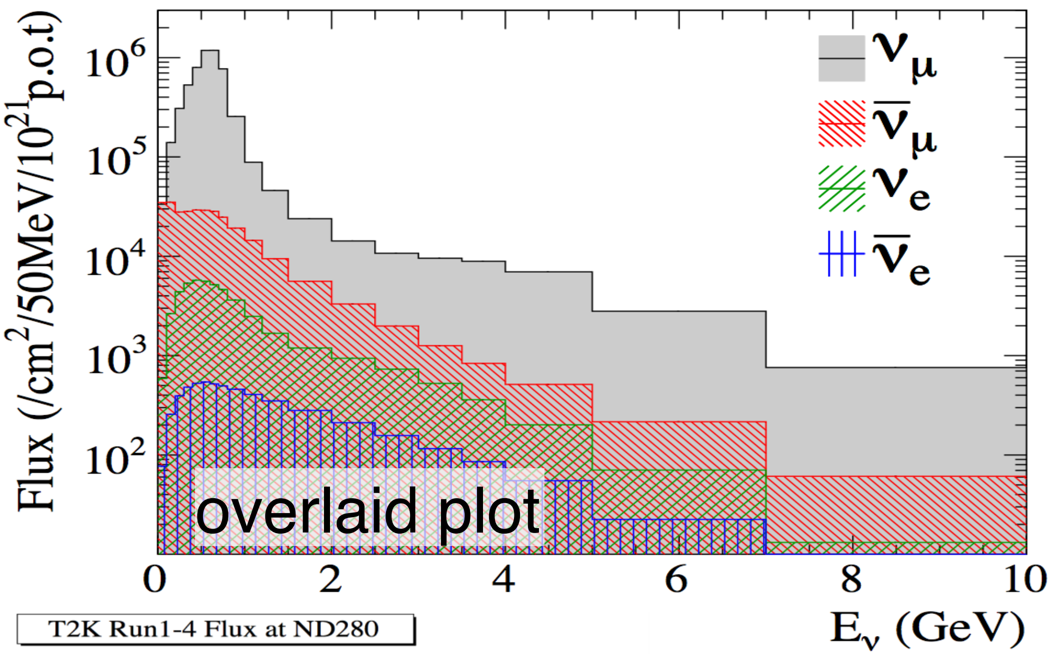
# Beam Stability

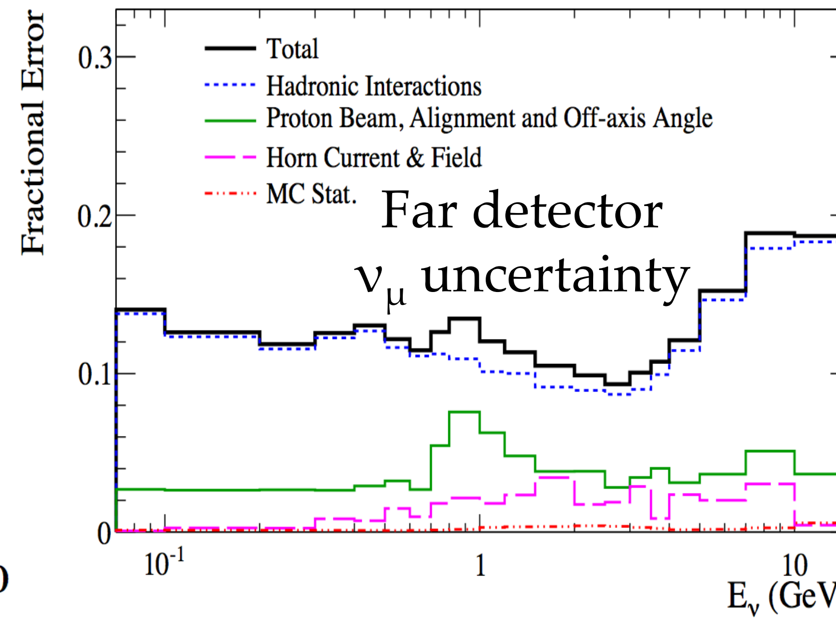



- Neutrino rate per POT stable to 0.7% over run period
- Recall: 1 mrad in beam direction is 16 MeV in peak $E_\nu$
- Dataset includes 0.21x $10^{20}$ p.o.t. with 250→205kA horn operation (13% flux reduction at peak) in Run3

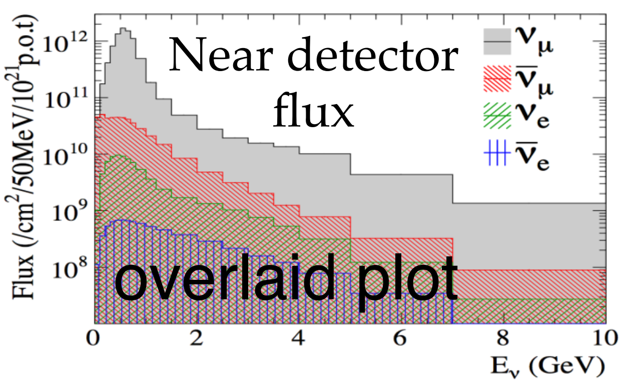
# Flux and Uncertainties

T2K Run1-4 Flux at Super-K



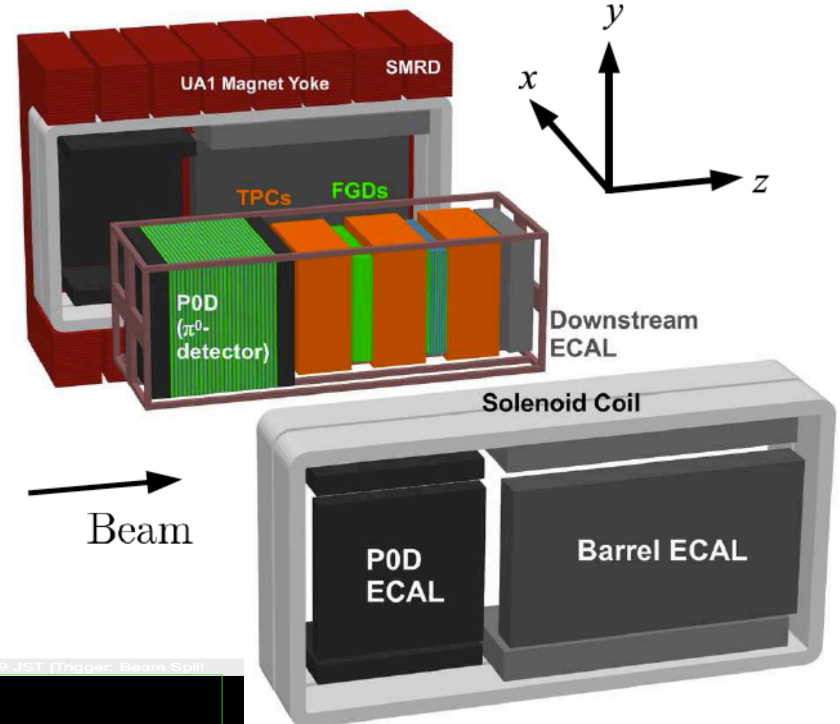

T2K Run1-4 Flux at ND280

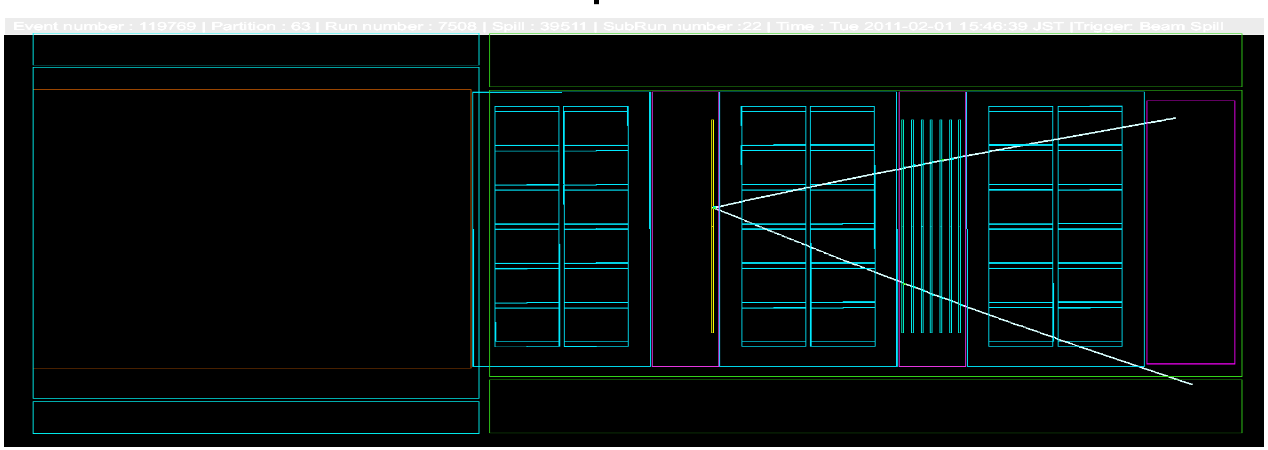



- A priori prediction of flux at Super-K has 10-15% uncertainties from 0.1 to 5 GeV
- Off-axis near (ND280) and Far (Super-K) fluxes are not identical, but highly correlated

# ND280: Off-axis Detectors

- Suite of tracking calorimeters and gas TPCs embedded in a 0.2T magnetic field
- Targets of both active polystyrene (CH) scintillator and passive water
- Muon, electron, proton and neutral and charged pion reconstruction capabilities



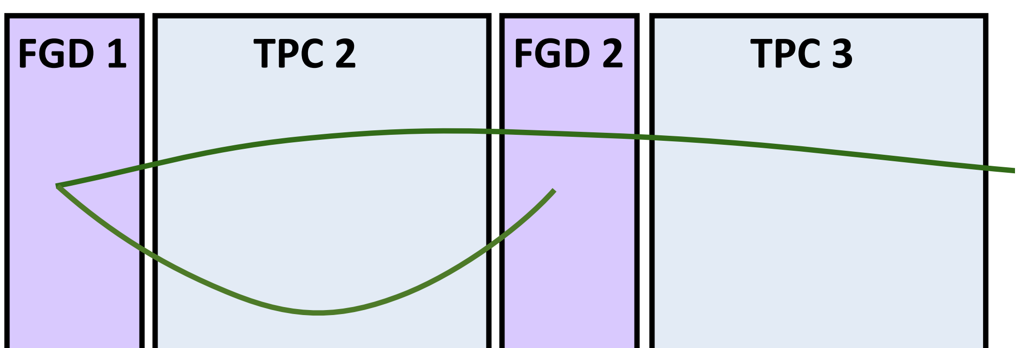



Charged-current single charged pion candidate

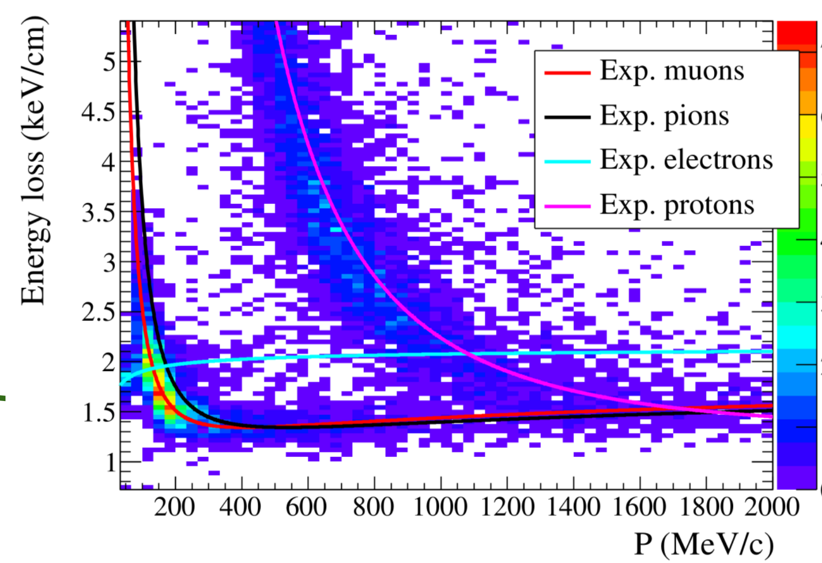
- Muon and pion identified by dE/dx in TPC gas
- Momentum from curvature in field

# Near Detector Samples for Oscillation Analyses

- Off-axis near detectors constrains flux and cross-sections.
- Exclusive samples based on # of final state charged pions
- Muon selection: highest momentum negative track in TPC from FGD1 (scintillator) target
- Pion selection depends on detector




- If pion tracked in TPC, ID by dE/dx in the TPC gas



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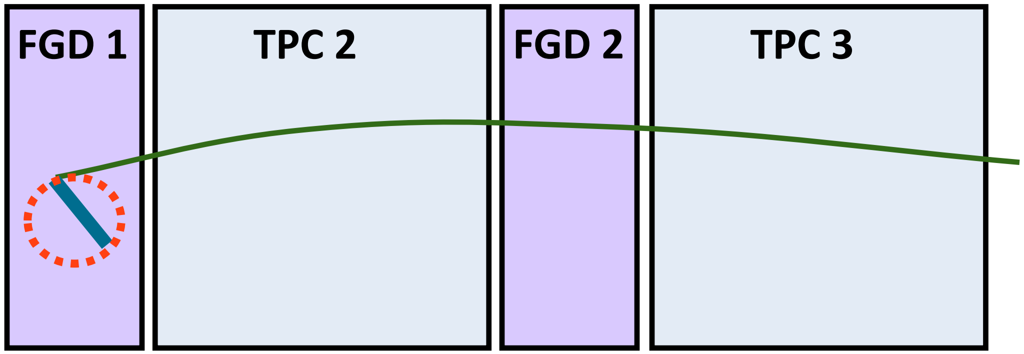


- FGD-contained pions identified by dE/dx
- Reconstruction less efficient than TPC
- Tag at most 1 FGD pion

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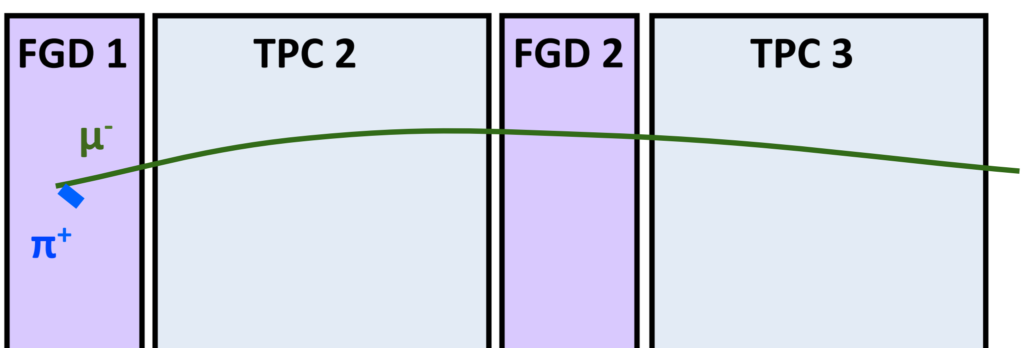
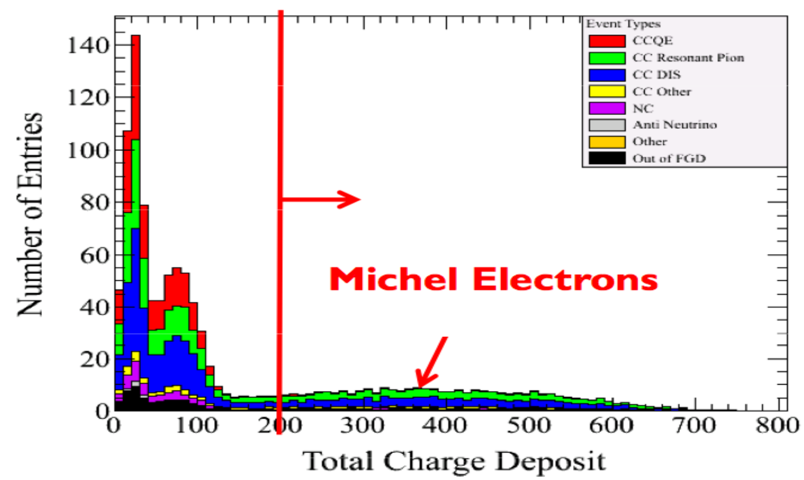


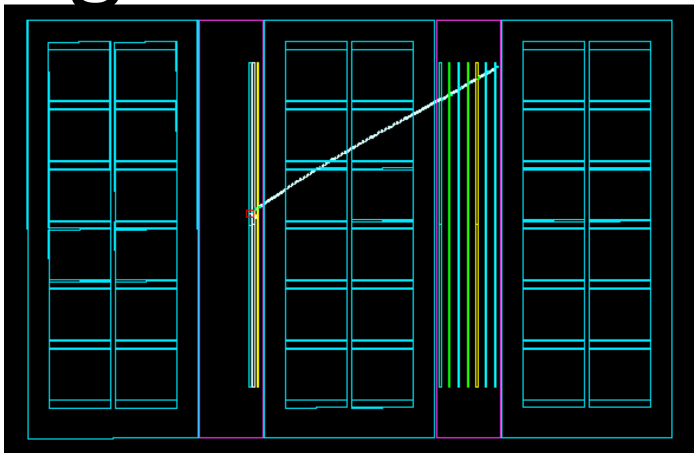

- Untracked pions may be tagged by Michel $e^-$



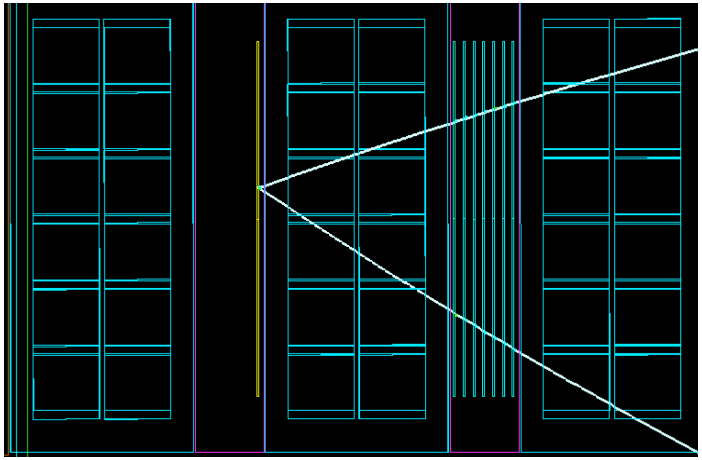
(delayed charge)

# ND280 Event Categories

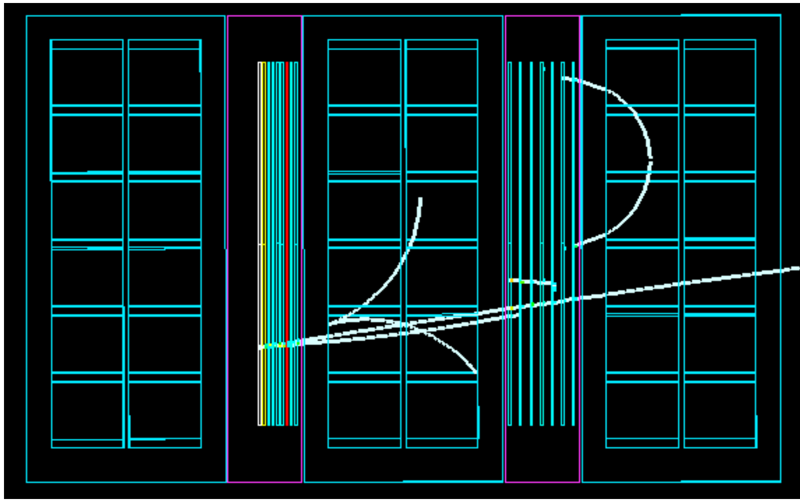
- Charged current (CC) with 0π



- CC $1\pi^+$

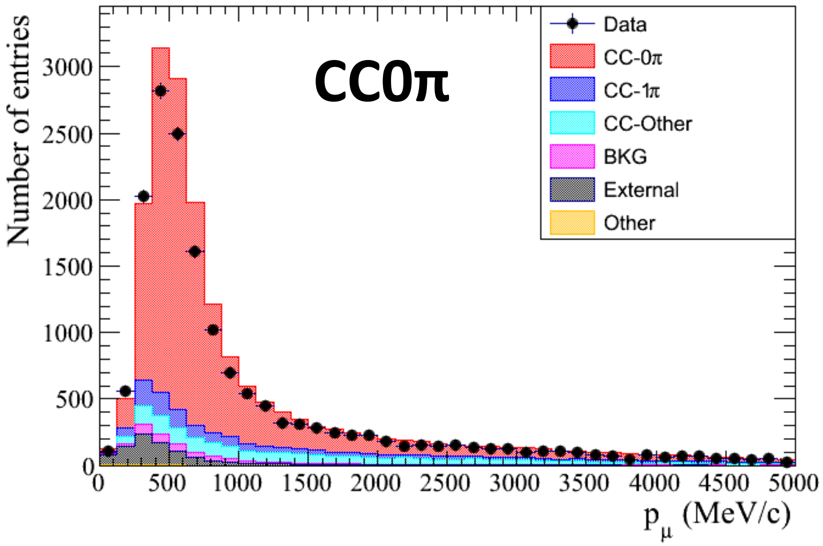


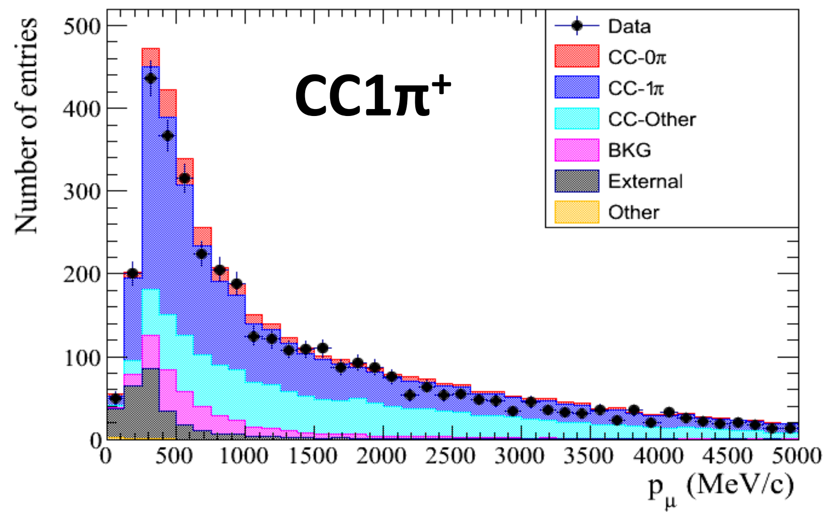
- CC Other ($\geq 1\pi^-$ or $\pi^0$ ,or $>1$ $\pi^+$)
  - $\pi^0$ candidates have identified electrons in the TPC

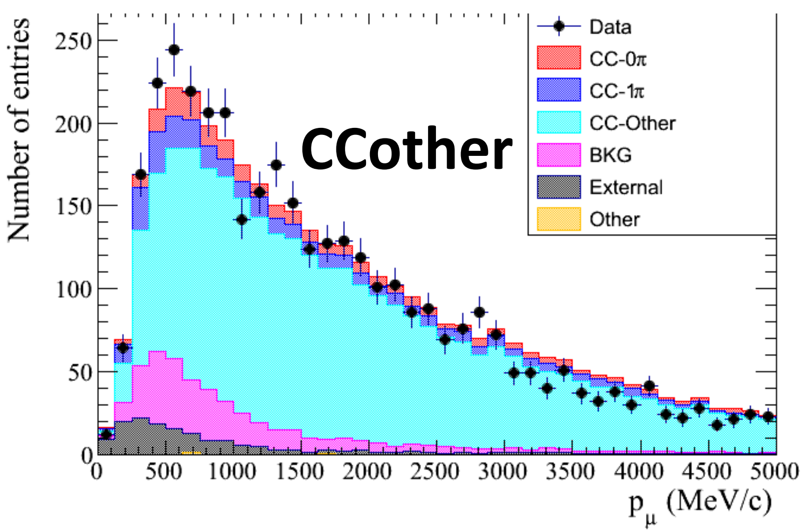


- Disappearance analysis joins CC $1\pi^+$ and CC other together

# Muon Momentum in ND280

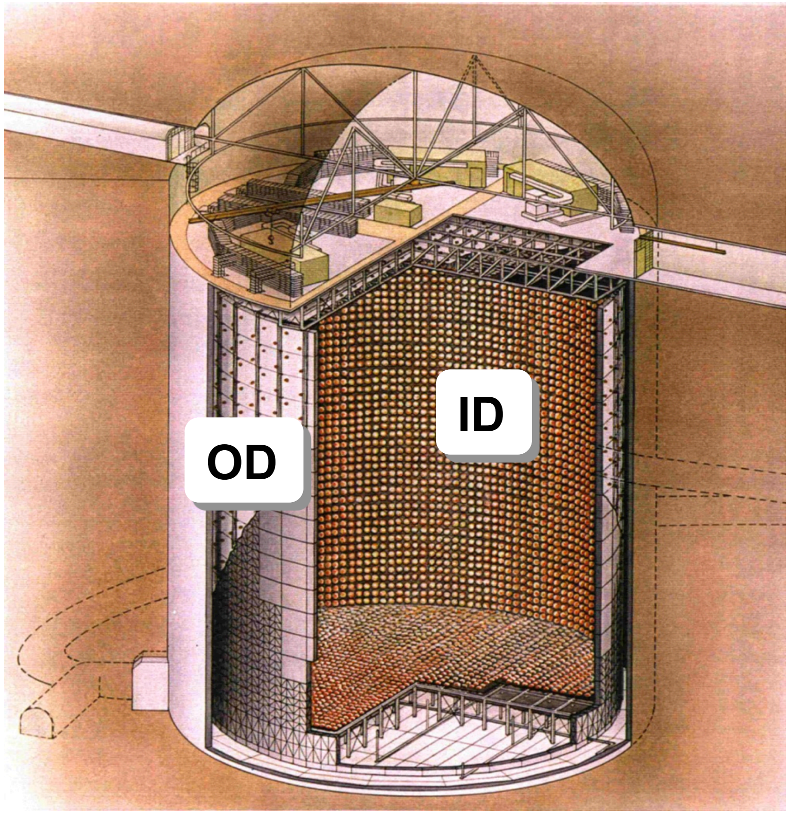


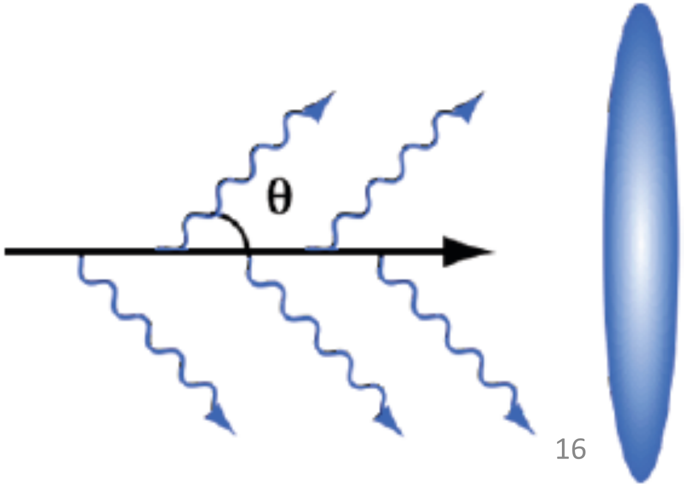

| True identification of interaction | CC0π sample | CC1π sample | CCother sample |
|---|---|---|---|
| CC0π | 72.6% | 6.4% | 5.8% |
| CC1π | 8.6% | 49.4% | 7.8% |
| CCother | 11.4% | 31% | 73.8% |
| Bkg(NC+anti-nu) | 2.3% | 6.8% | 8.7% |
| Out of FGD1 Fid Vol | 5.1% | 6.5% | 3.9% |

# Super-K (Far) Detector




- 50 kton (22.5 kton fiducial volume) water cerenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events
- Good reconstruction for T2K energy range

Cerenkov light produces a ring detected by the PMTs

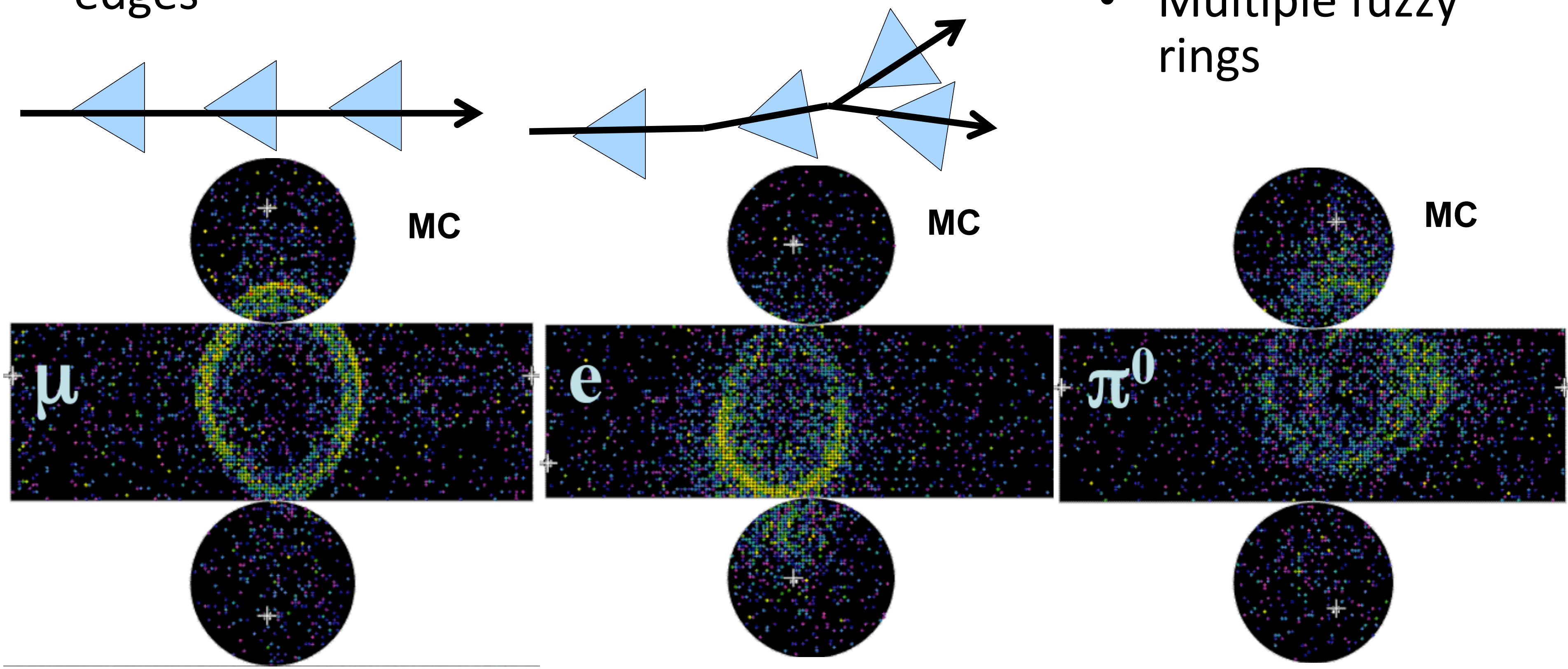


# Particle Identification at SK

- Muon scattering is minimal
- Rings with sharp edges

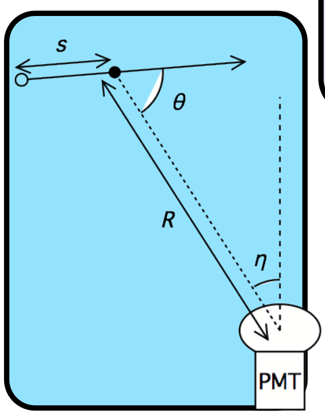
- Electromagnetic shower
- Rings are “fuzzy”

- $\gamma$ from $\pi^0$ decays shower and look like electrons
- Multiple fuzzy rings



# Improved Super-K Reconstruction Algorithm

- Each hit PMT gives charge and time information
- For a given event topology hypothesis, it is possible to produce a charge and time PDF for each PMT
  - Based on MiniBooNE likelihood model (NIM A608, 206 (2009))
- Event hypotheses are distinguished by best-fit likelihoods, e.g., electron vs muon or $\pi^0$




$$\mu^{\mathrm{dir}} = \Phi(p)\int ds\, g(s,\cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

Light Yield

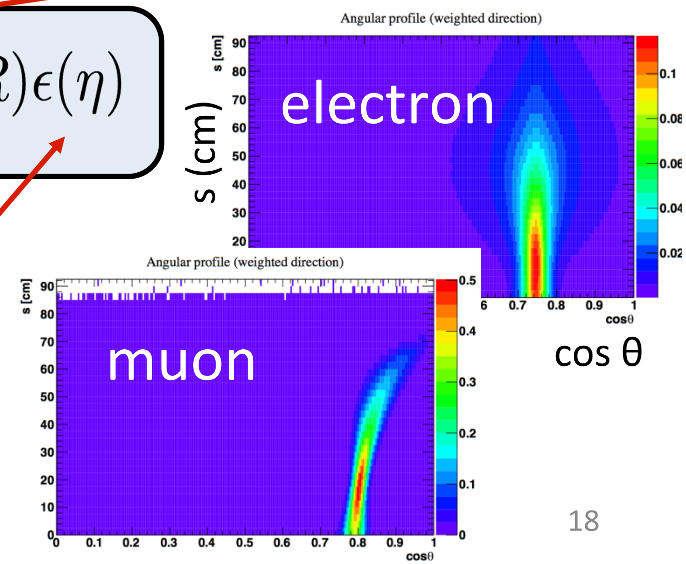
Integral over track length

Cerenkov light emission profile

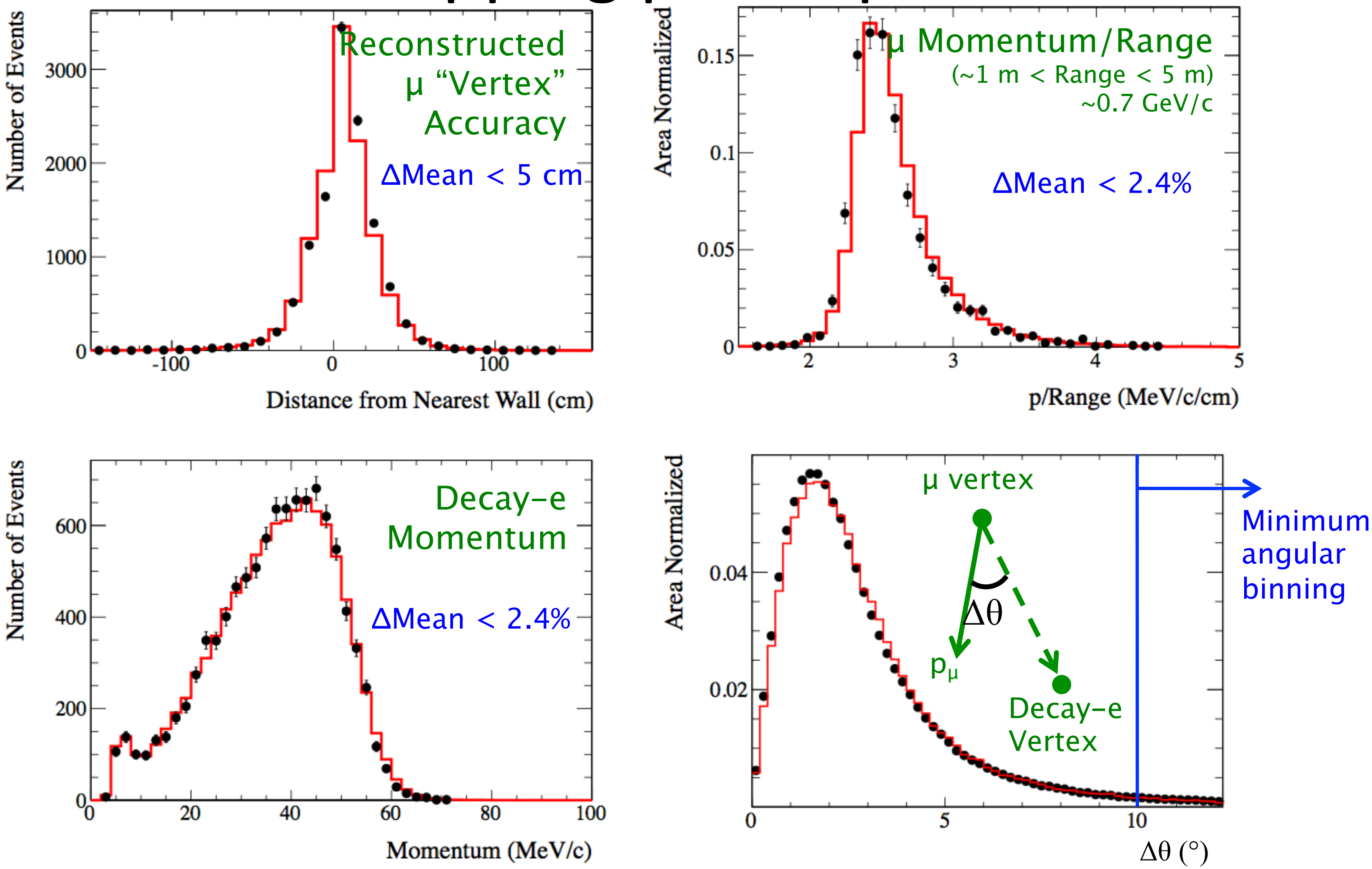
PMT solid angle

Water attenuation

PMT angular response



# Validation of new algorithm with Stopping μ in Super-Kamiokande

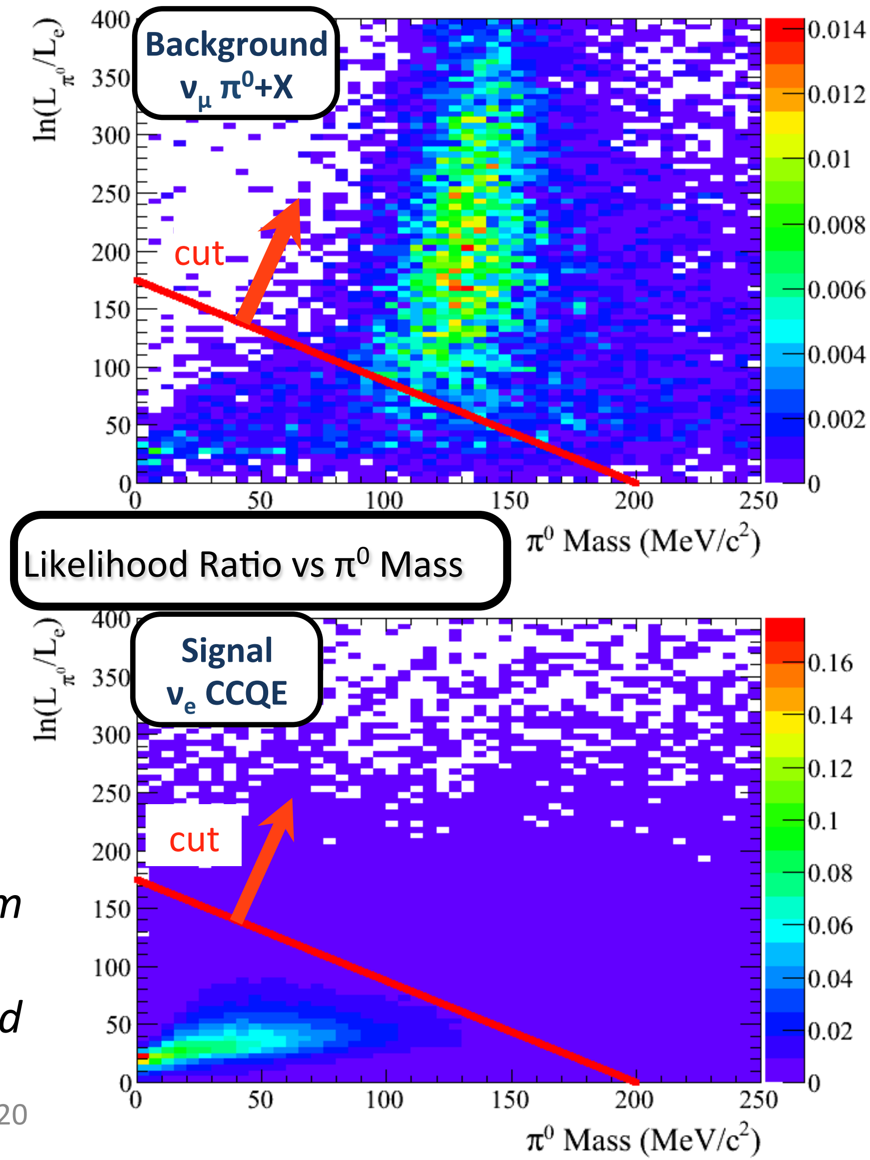



- Data/MC agreement within systematic uncertainties

# Enhanced $\pi^0$ Rejection

- New reconstruction algorithm can use mass of the $\pi^0$ hypothesis and best-fit likelihood ratio of $e^-$ and $\pi^0$

- Cut removes 70% more $\pi^0$ background than previous[§] method for a 2% added loss of signal efficiency

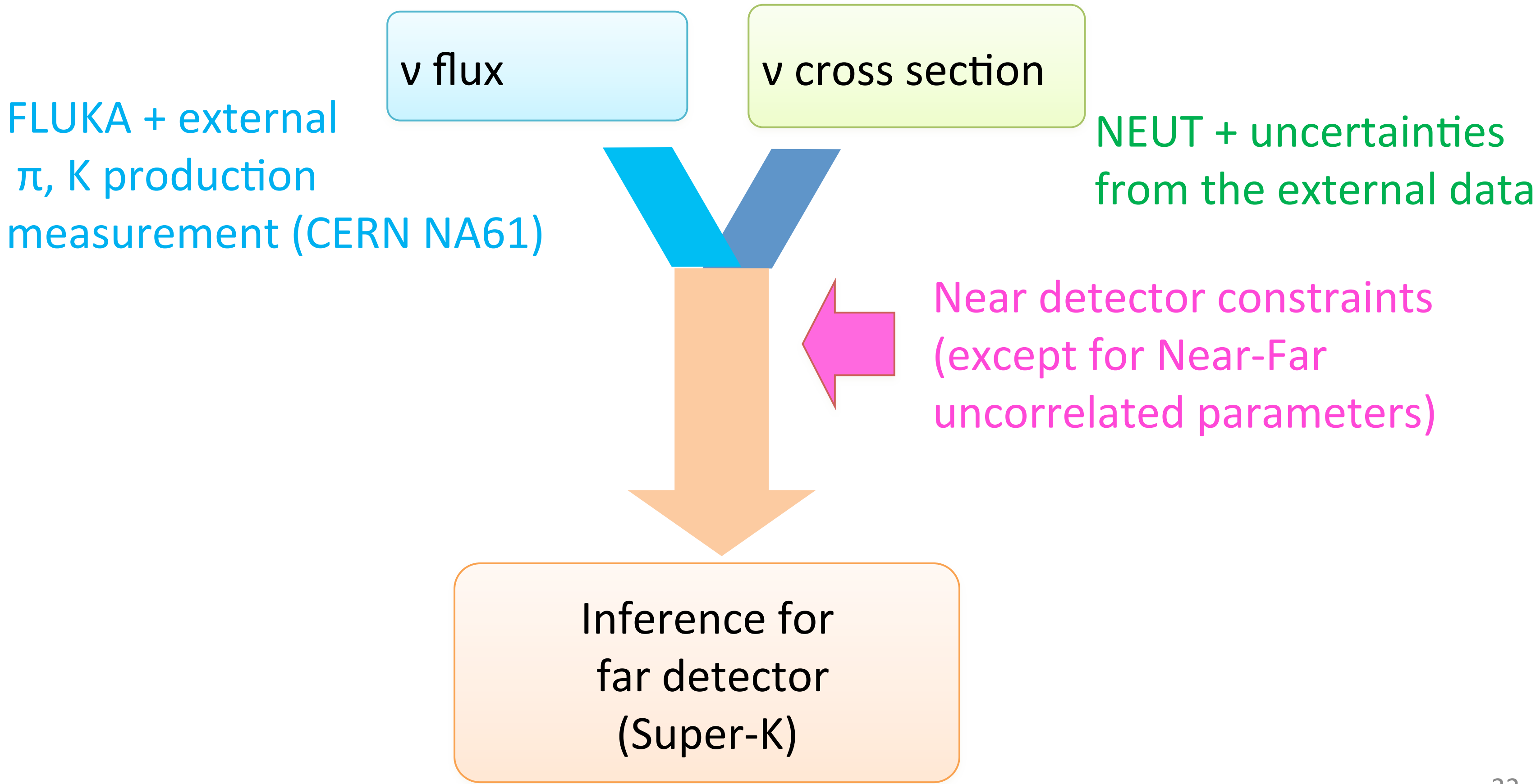



[§] *Previous approach (old reconstruction algorithm and old selection method) forced the reconstruction to find two rings and then formed a $\pi^0$ mass under the two-photon hypothesis*

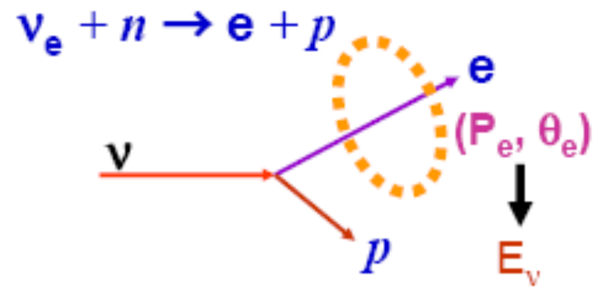
# NEUTRINO OSCILLATION ANALYSIS TECHNIQUE

# Inference for far detector

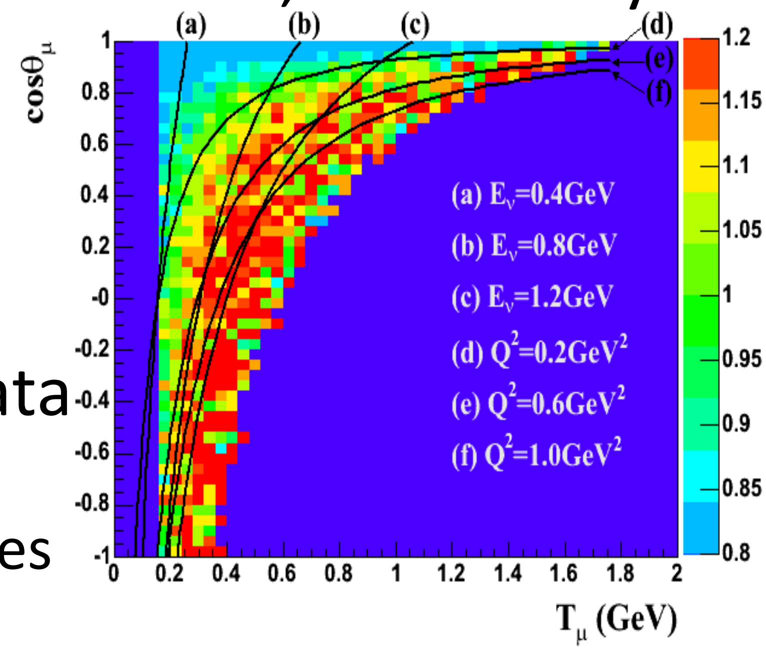
Our MC is based on the ν flux and cross section predictions from external data and models. We further constrain those predictions by the near detector measurement.



# Cross-section Model: CCQE




- Signal reaction for T2K energies
  - Elastic kinematics allow us to measure neutrino energy from muon
- T2K, like all practitioners in this business, is currently using a very simple model
  - Nucleon form factors from e$^-$ scattering and $\nu D_2$ scattering
  - Model of nucleus is Fermi gas
- Problem: doesn't agree with data
- Approach: add effective parameters ($M_A$, normalization) with uncertainties that span base model and data

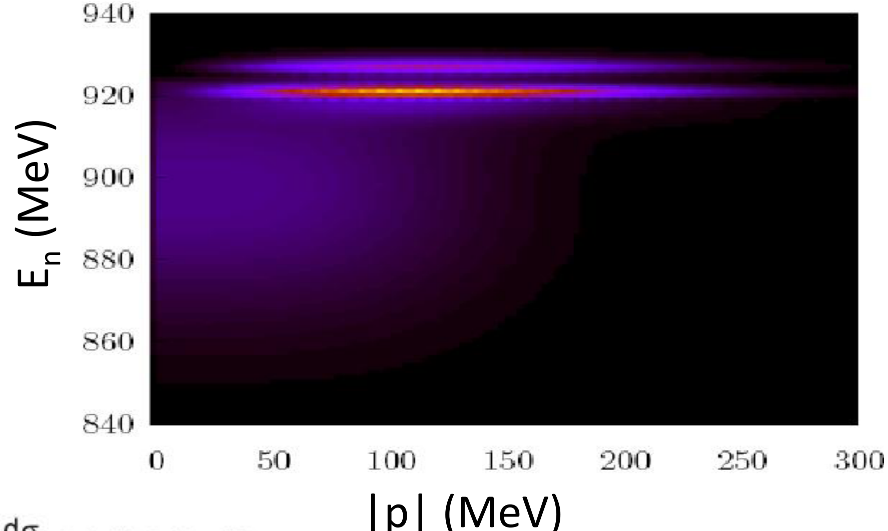


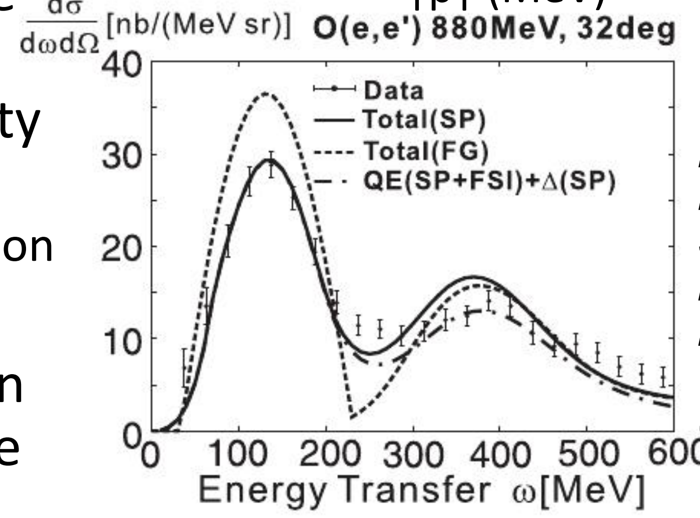

MiniBooNE (*Phys. Rev.* ***D81*** *092005, 2010)*

# Beyond Fermi Gas for CCQE

- There are also better nuclear models than a Fermi Gas
- Spectral function models define probability to remove a nucleon with a given momentum and energy state
- Small distortion to elastic kinematics
- Currently, we take the difference between this and a Fermi Gas model as a systematic uncertainty
  - Uses NuWro generator's implementation of spectral function
  - Significant in current analyses
- Will switch to spectral function in default models in the near future

*O. Benhar et al, Nucl.Phys. A579 (1994) 493-517*
*Ankowski and Sobczyk, Phys.Rev. C74 (2006) 054316*

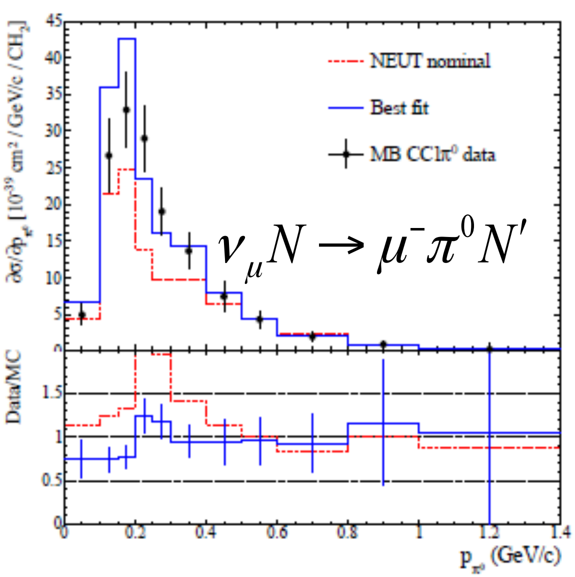


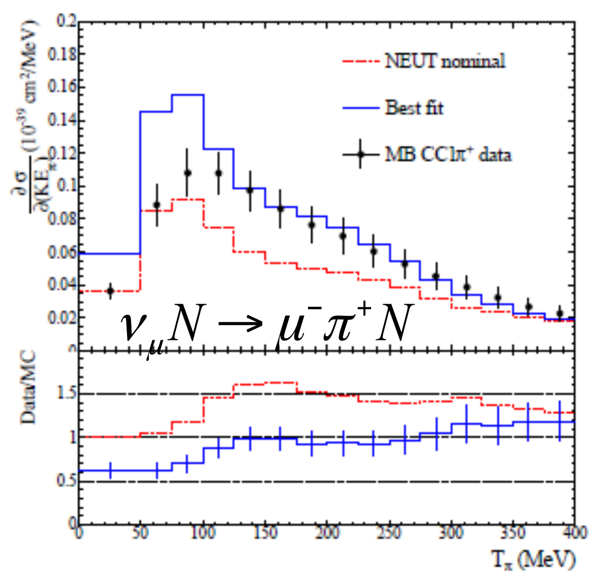



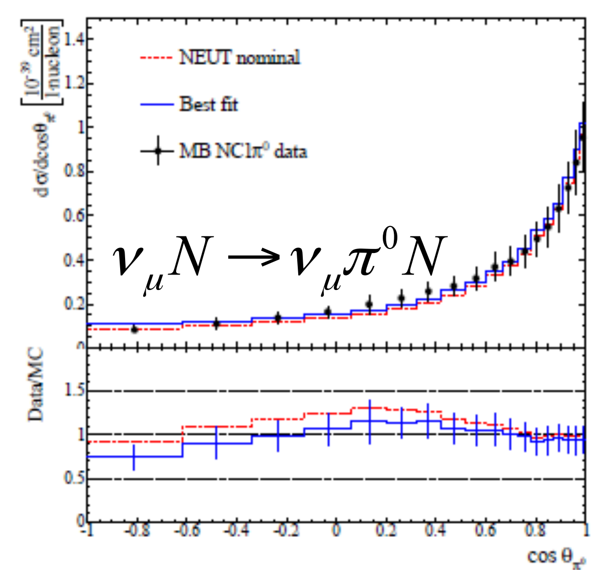

*Nakamura, Nasu, Sakuda and Benhar, Phys. Rev. C 76, 065208 (2007)*

# Cross-section: Pion Production

- Single pion data from MiniBooNE has been the core reference for T2K backgrounds
  - $\nu_\mu N \rightarrow \nu_\mu \pi^0 X$ as a background to $\nu_\mu \rightarrow \nu_e$ signal
  - $\nu_\mu N \rightarrow \mu^- \pi^+ X$ as a background to $\nu_\mu \rightarrow \nu_\mu$ (energy misreconstruction)
- Again, current models do not describe data well
- Again, systematic uncertainties assigned to this span reference model and data as effect parameters

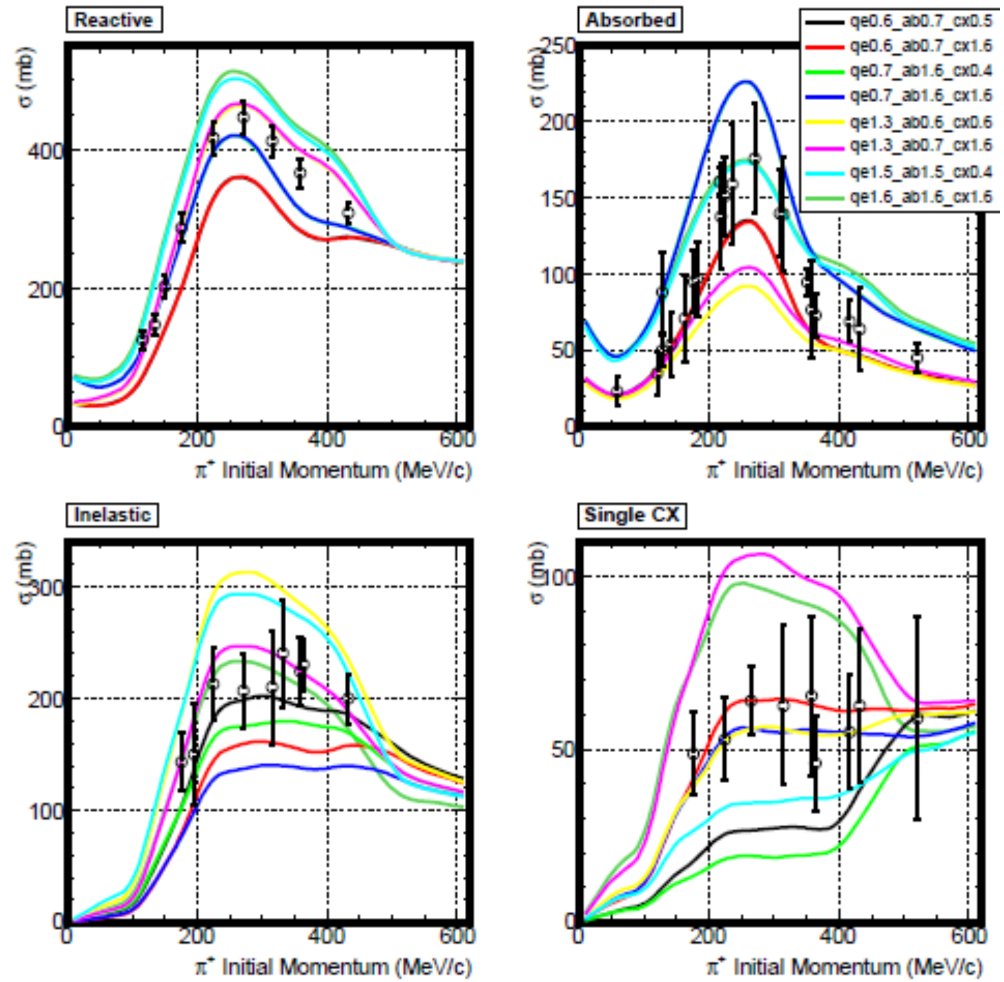


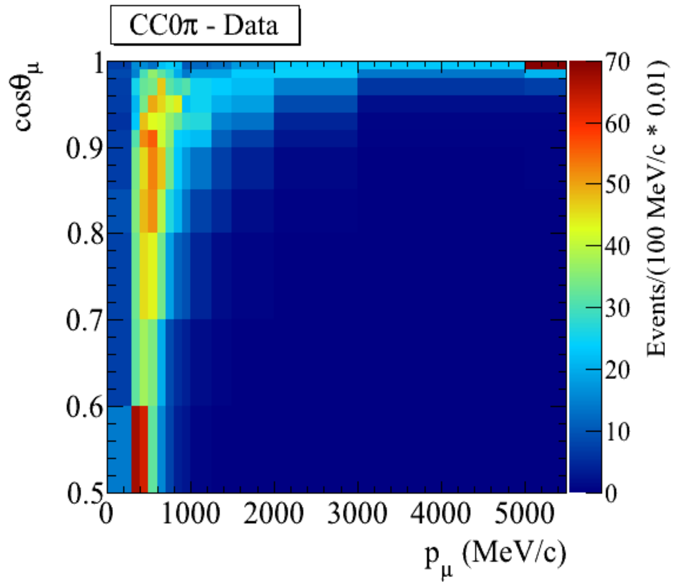



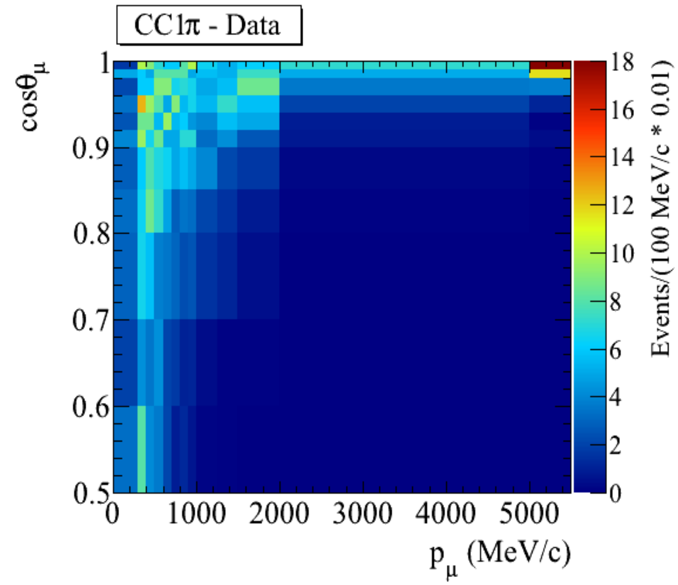
# Cross-section: Final State Interactions

- Interactions of final state hadrons in nucleus can cause migration from signal to background type events
- Constrain with external pion-nucleus scattering data in a cascade model
- Uncertainties assigned to span the pion-nucleus scattering data



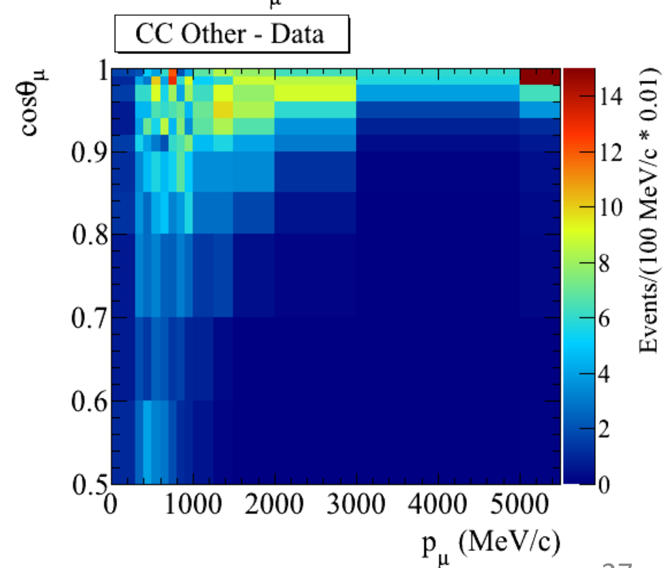
# ND280 Constraint Inputs



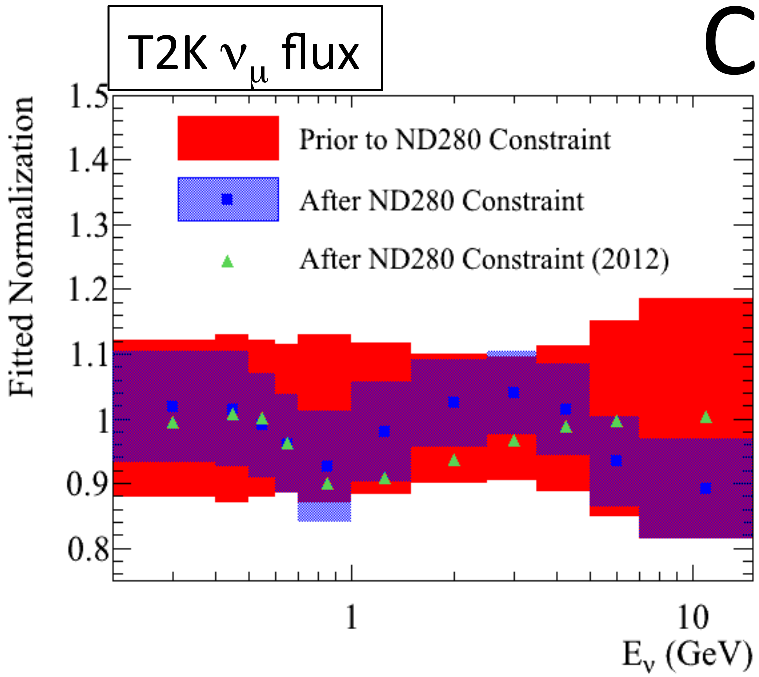




Data from T2K Runs 1-4, binned in muon momentum (p) and angle (cosθ)

| Selection | Number of Events |
|---|---|
| CC0π | 16912 |
| CC1π | 3936 |
| CC Other | 4062 |
| CC Inclusive | 24910 |



# Flux and Cross-Sections after ND280 Constraint




| Parameter | Prior to ND280 Constraint | After ND280 Constraint |
|---|---|---|
| $M_A^{QE}$ (GeV) | 1.21 ± 0.45 | 1.22 ± 0.07 |
| CCQE Norm.* | 1.00 ± 0.11 | 0.96 ± 0.08 |
| $M_A^{RES}$ (GeV) | 1.41 ± 0.22 | 0.96 ± 0.06 |
| CC1π Norm.** | 1.15 ± 0.32 | 1.22 ± 0.16 |

*For $E_\nu$<1.5 GeV **For $E_\nu$<2.5 GeV

- ND280 constraint reduces both flux and cross-section model uncertainties individually
  - Note in particular reductions on the "$M_A$" parameters which set $Q^2$ shape of these events
- Flux and cross-section parameters are anti-correlated after these fits because the constraint is a rate at ND280

# Inference for Far Detector after ND280 Constraint

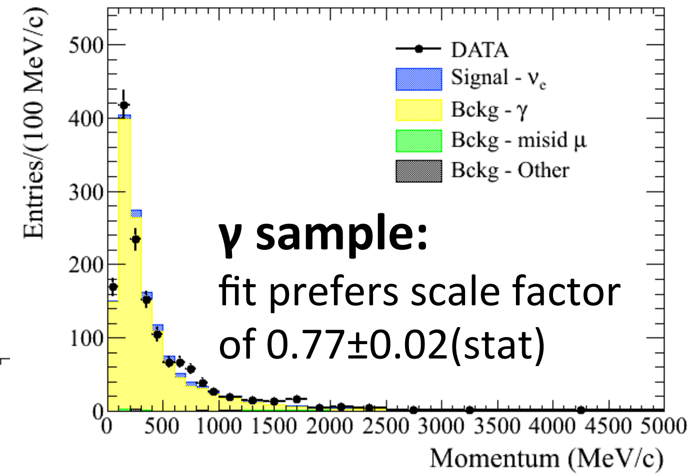
| | $\sin^2 2\theta_{13}=0.1$ | | $\sin^2 2\theta_{13}=0.0$ | |
|---|---|---|---|---|
| | $\nu_e$ Prediction (Events) | Error from Constrained Parameters | $\nu_e$ Prediction (Events) | Error from Constrained Parameters |
| No ND280 Constraint | 22.6 | 26.5% | 5.3 | 22.0% |
| ND280 Constraint (2012, Runs 1-3, disappearance) | 21.6 | 4.7%* | 5.1 | 6.1%* |
| ND280 Constraint (Runs 1-4, appearance) | 20.4 | 3.0% | 4.6 | 4.9% |

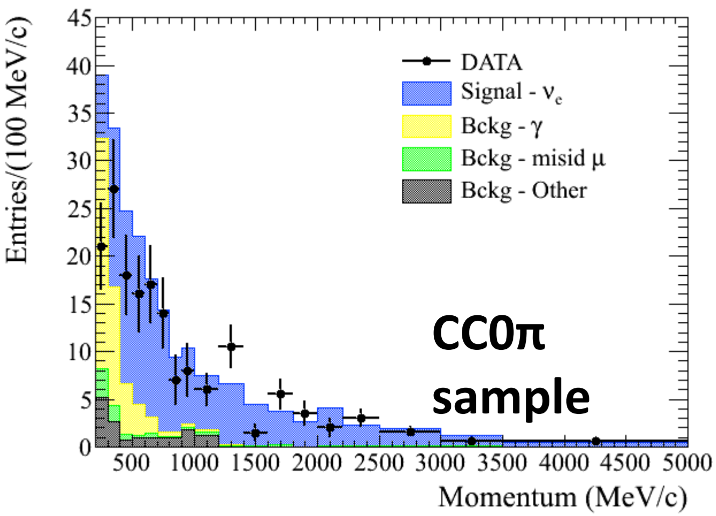
- Far detector uncertainties after ND280 constraint are smaller due to recent improvements (Run 1-3 → Runs 1-4)
  - Improved ND280 reconstruction and selections
  - Finer binning in p-θ

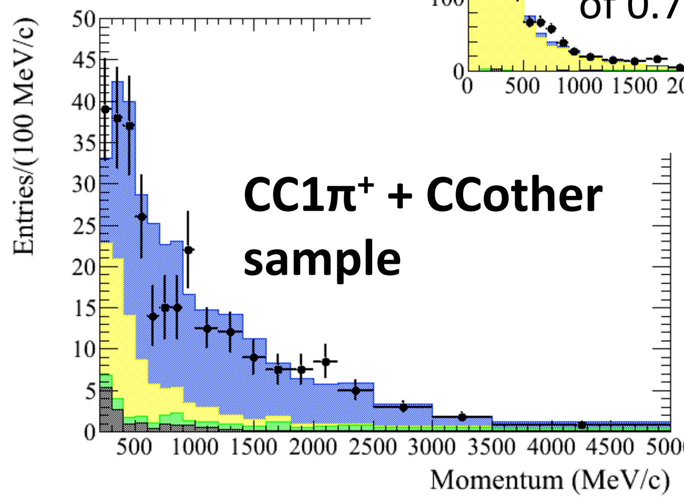
*Uncertainties reduced from previous T2K result due to new SK $\pi^0$ rejection algorithm

# ND280 $\nu_e$ Measurement

- Can check if pre-oscillation $\nu_e$ component of beam is correctly predicted in ND280
- Interactions in FGD and particle ID in TPC
- Major background: photons from $\pi^0$ decays
- Fit CC0π, CC1π+other and γ sideband



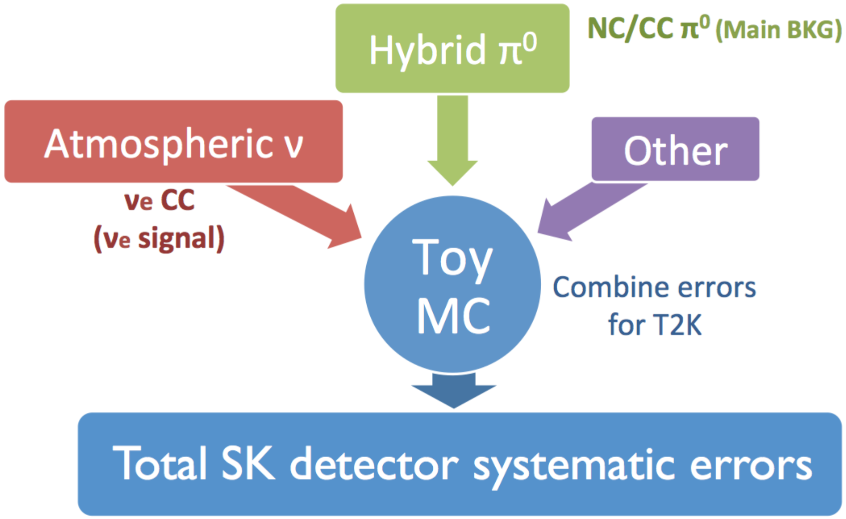




$$\frac{\text{measured } \nu_e \text{ flux}}{\text{predicted } \nu_e \text{ flux}} = 1.06 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$$

*Fine print: this analysis uses the results of the ND280 muon neutrino constraints*

# Far Detector Reconstruction Systematic Uncertainties




- Evaluation of Super-K detector systematic uncertainties uses control samples from the data
  - Atmospheric $\nu_e$
  - Hybrid $\pi^0$ (electron from $\nu_e$ CC and MC photon)
  - Cosmic ray muon samples
- Combine errors with Toy MC method

# Oscillation Likelihood Fits

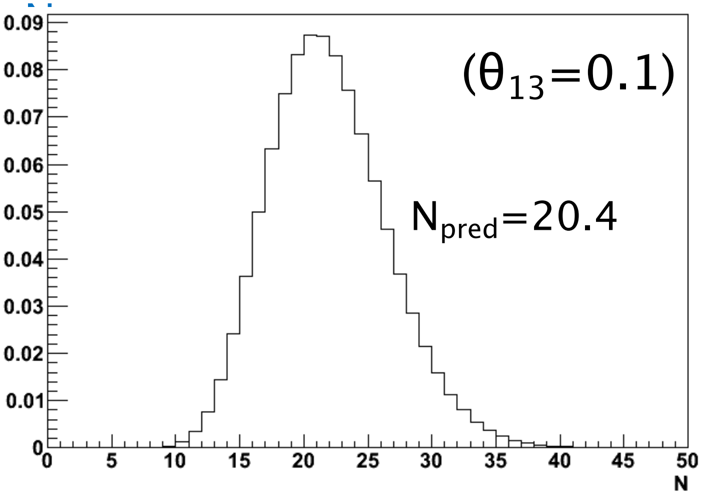
$$\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst}$$

Systematic parameter constraint term. Systematic parameters may be naturally floated in fits.

$$Poisson(N_{obs})_{\text{mean}=N_{\text{pred}}}$$

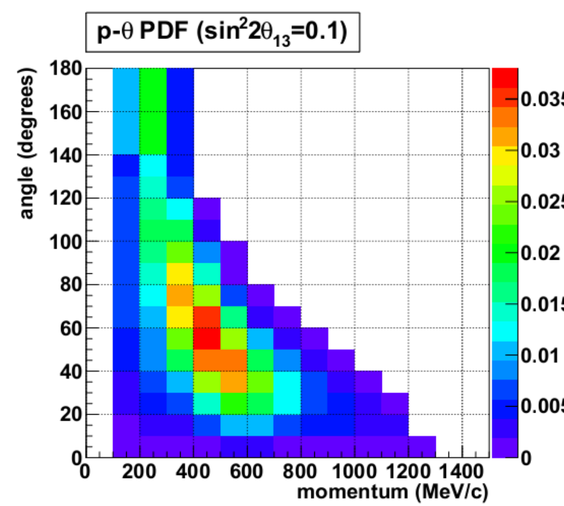
$$\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$$

$L_{norm}$ is the probability to have $N_{obs}$ when the predicted number of events is the Poisson distribution with mean =




$L_{shape}$ is the product of the probabilities that each event has ($p_i$, $\theta_i$).

φ: Predicted p–θ distribution (PDF) .



# $\nu_\mu \rightarrow \nu_\mu$ RESULTS

T2K collaboration, arXiV:1308.0465v1

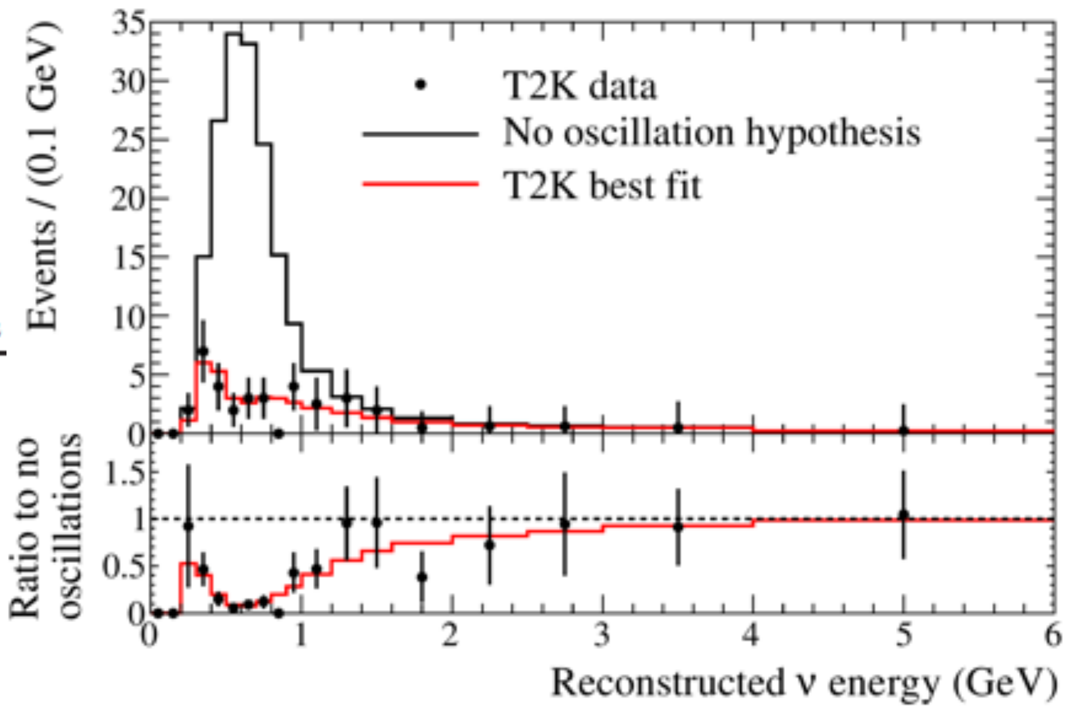
# Muon Spectrum

- Selected far detector $\nu_\mu$ CCQE candidates
  - Fully contained and fiducial single muon-like ring
  - $p_\mu$>200 MeV, no more than one decay $e^-$
  - 58 events in Run 1-3 data (3.01 x$10^{20}$ POT)

- Neutrino energy from elastic kinematics

$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

  - $E_b$ is mean binding energy



# Neutrino Oscillation Parameters

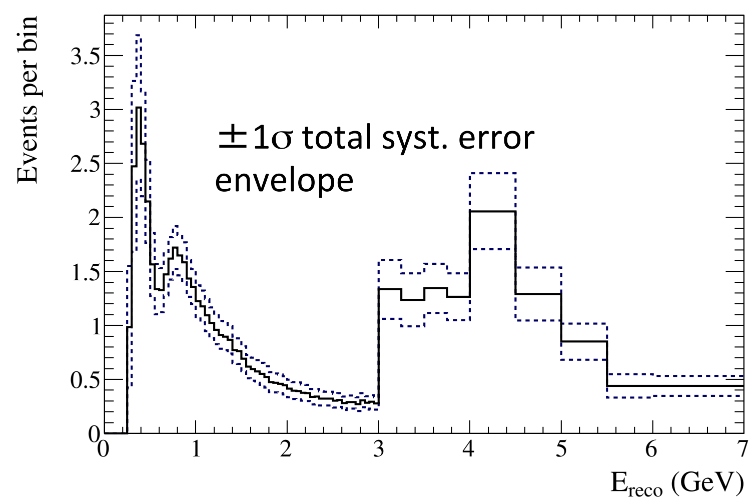
- Fit method
  - "$\sin^2 2\theta_{23}$ - $\Delta m_{32}^2$" space is scanned to find the best fit values which minimize the $\chi^2$.
  - 1st and the 2nd octants scanned separately
  - 3-flavor formulae used, but with some fixed parameters →

| Parameter | Value |
|---|---|
| $\Delta m_{21}^2$ | $7.50\times10^{-5}\mathrm{eV}^2$ |
| $\sin^2 2\theta_{12}$ | 0.857 |
| $\sin^2 2\theta_{13}$ | 0.098 |
| $\delta_{CP}$ | 0 |
| Mass hierarchy | Normal |
| Baseline length | 295 km |
| Earth density | 2.6 g/cm$^3$ |

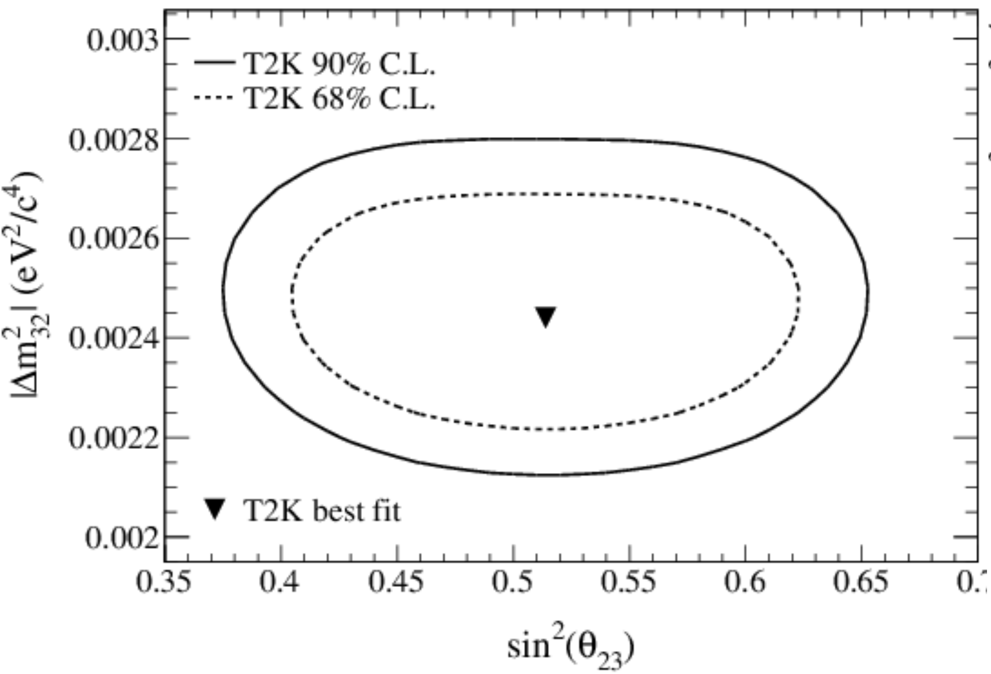
- Systematic uncertainties

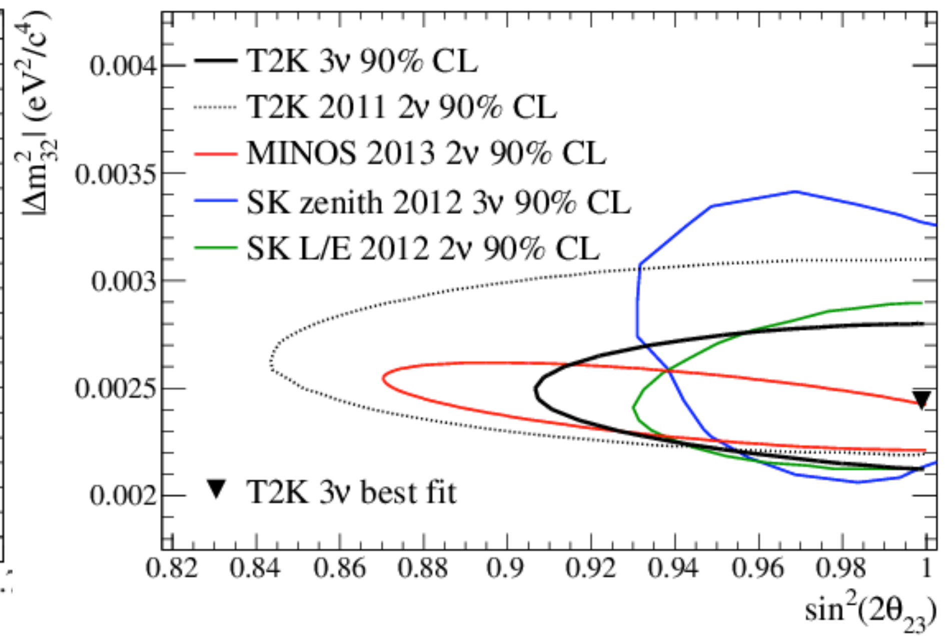
| Systematic uncertainty | before ND constraint | after ND constraint |
|---|---|---|
| Flux / $\nu$ x-sec. | 21.8 % | 4.2 % |
| Uncorrelated $\nu$ x-sec. | 6.3 % | |
| SK detector | 10.1 % | |
| FSI-SI | 3.5 % | |
| Total | 25.1 % | 13.1 % |

@ $(\sin^2 2\theta_{23}, \Delta m_{32}^2) = (1.00, 2.4\times10^{-3}\ \mathrm{eV}^2/c^4)$



# Results




Best fit w/ 68% C.L. error

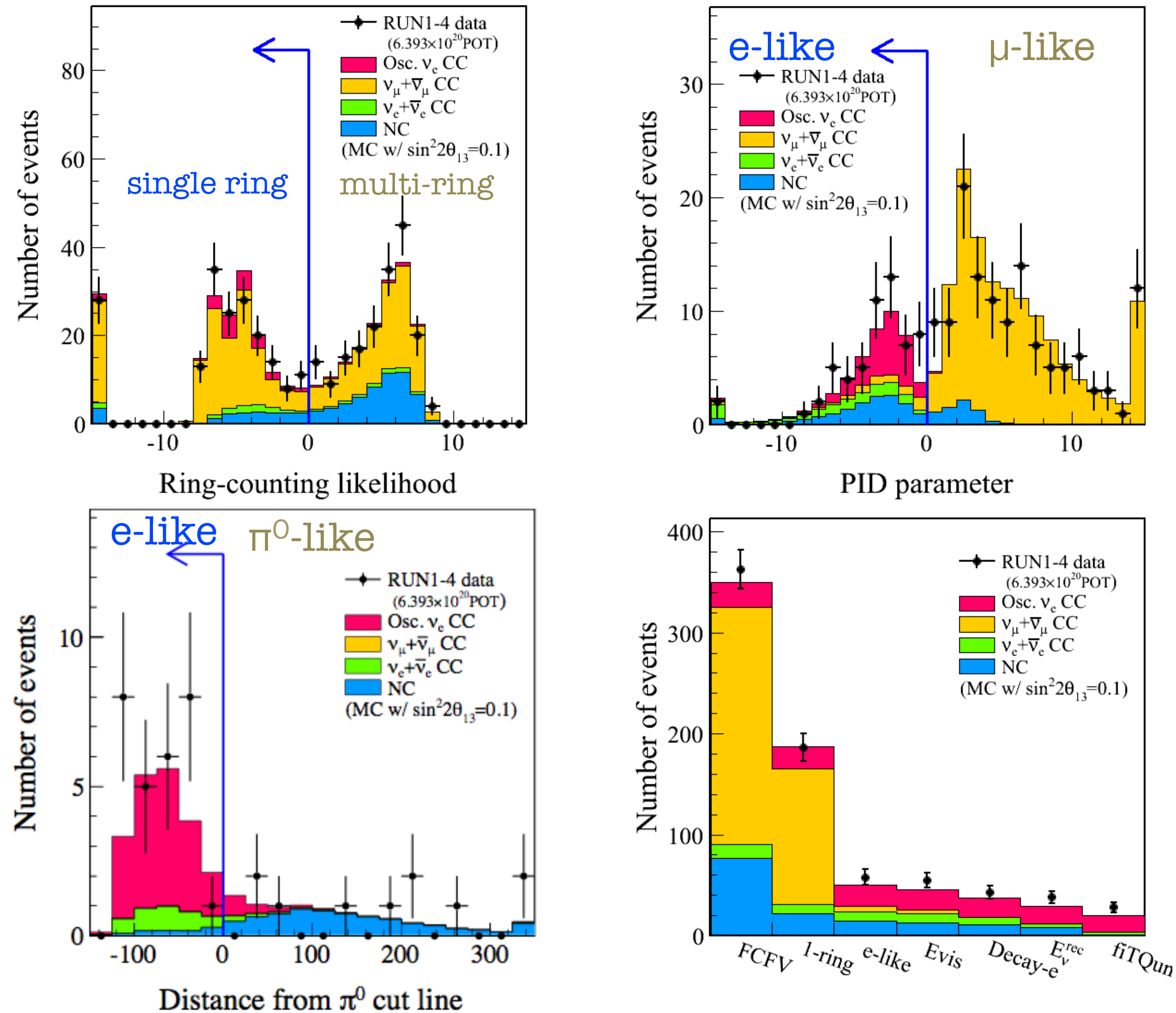
$$\sin^2\theta_{23} = 0.514 \pm 0.082, \quad \left|\Delta m^2_{32}\right| = 2.44^{+0.17}_{-0.15}\ \mathrm{eV}^2/\mathrm{c}^4$$

# $\nu_\mu \rightarrow \nu_e$ RESULTS

# T2K $\nu_e$ Event Selection

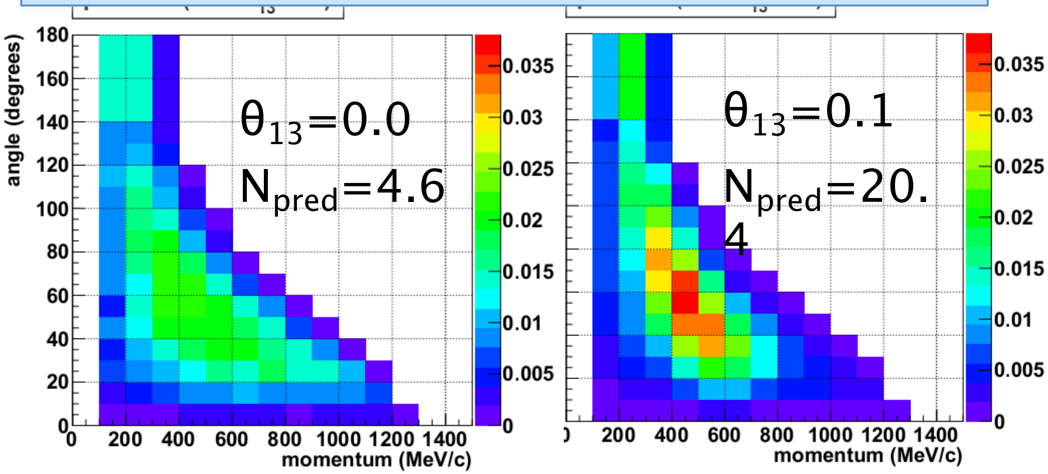
**$\nu_e$ Selection Cuts**

- \# veto hits < 16
- Fid. Vol. = 200 cm
- \# of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- new reconstruction algorithm $\pi^0$ cut
- 0 < $E_\nu$ < 1250 MeV



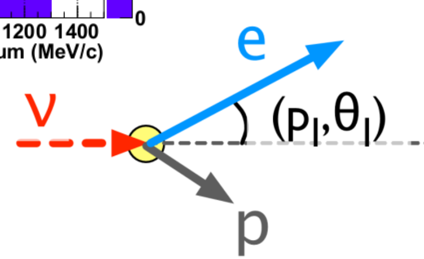
# Neutrino Oscillation Parameters

Electron momentum vs. angle distribution (MC)




Fixed ν oscillation parameters

| | |
|---|---|
| $\Delta m^2_{12}$ | $7.6 \times 10^{-5}$ eV$^2$ |
| $\Delta m^2_{32}$ | $2.4 \times 10^{-3}$ eV$^2$ |
| $\sin^2 2\theta_{23}$ | 1.0 |
| $\sin^2 2\theta_{12}$ | 0.8495 ← Was 0.8704 in 2012 analysis |
| $\delta_{CP}$ | 0 degree |




The analysis method is not changed from 2012 analysis.

- Scan over $\sin^2 2\theta_{13}$ space to find the maximum likelihood
- Fix the neutrino oscillation parameters other than $\sin^2 2\theta_{13}$.

# Infered number of events and systematic uncertainties

### Infered # of events w/ $6.4\times10^{20}$ POT

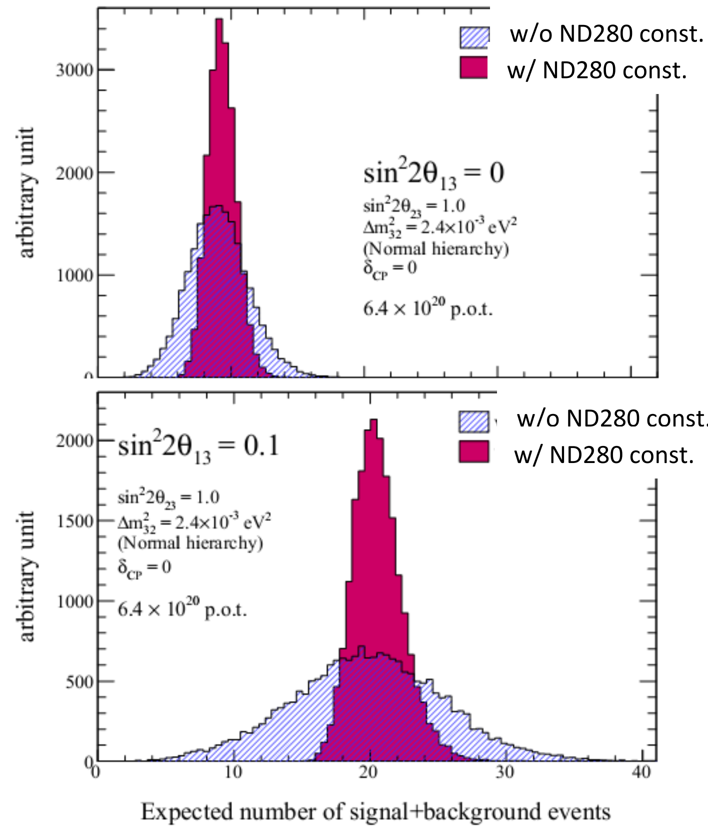
| Event category | $\sin^2 2\theta_{13}$=0.0 | $\sin^2 2\theta_{13}$=0.1 |
|---|---|---|
| $\nu_e$ signal | 0.38 | 16.42 |
| $\nu_e$ background | 3.17 | 2.93 |
| $\nu_\mu$ background (mainly NC$\pi^0$) | 0.89 | 0.89 |
| $\nu_\mu + \nu_e$ background | 0.20 | 0.19 |
| Total | 4.64 | 20.44 |
| Total (w/ 2012 flux & cross section parameters) | 5.15 | 21.77 |

Near detector constraint in 2013 inferes smaller number of events compared to 2012 anaysis.

### Systematic uncertainties

| Error source | $\sin^2 2\theta_{13}$=0.0 | $\sin^2 2\theta_{13}$=0.1 |
|---|---|---|
| Beam flux + $\nu$ int. in T2K fit | 4.9 % | 3.0 % |
| $\nu$ int. (from other exp.) | 6.7 % | 7.5 % |
| Far detector | 7.3 % | 3.5 % |
| Total | 11.1 % | 8.8 % |
| Total (2012) | 13.0 % | 9.9 % |

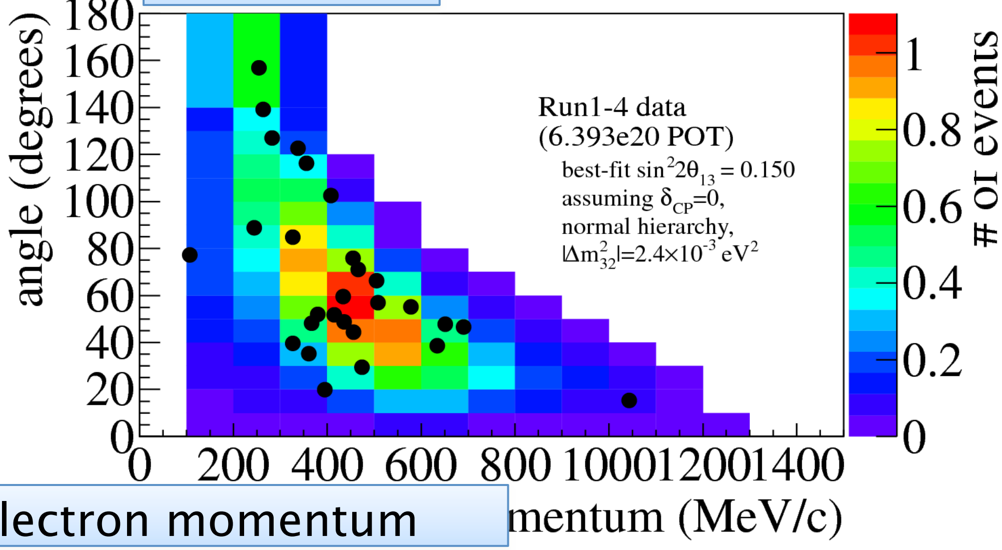
Distribution of infered number of events



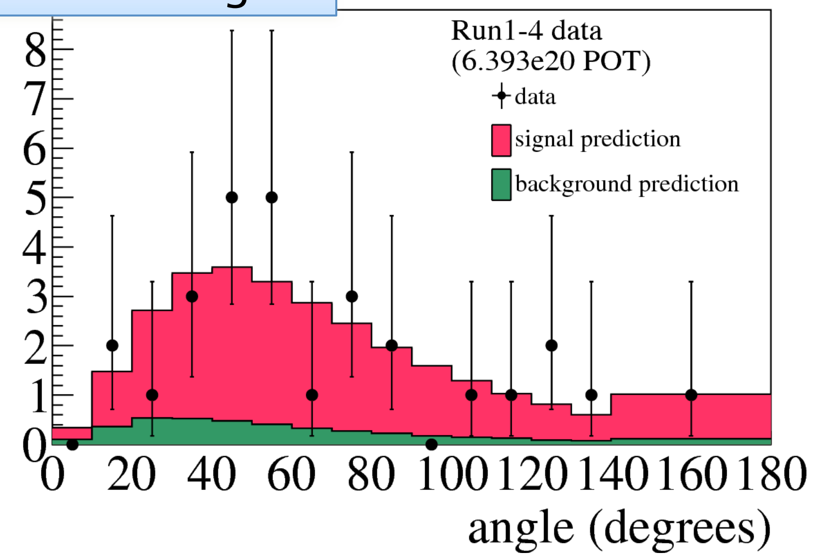

Errors are reduced from 2012 mainly due to near detector analysis improvement.

# Results

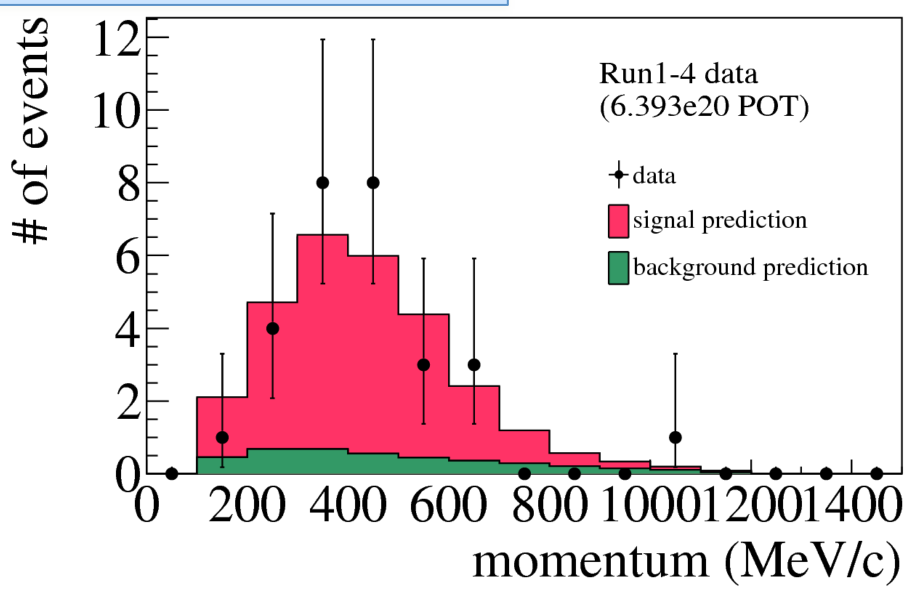
Electron p–θ




Electron angle




Electron momentum



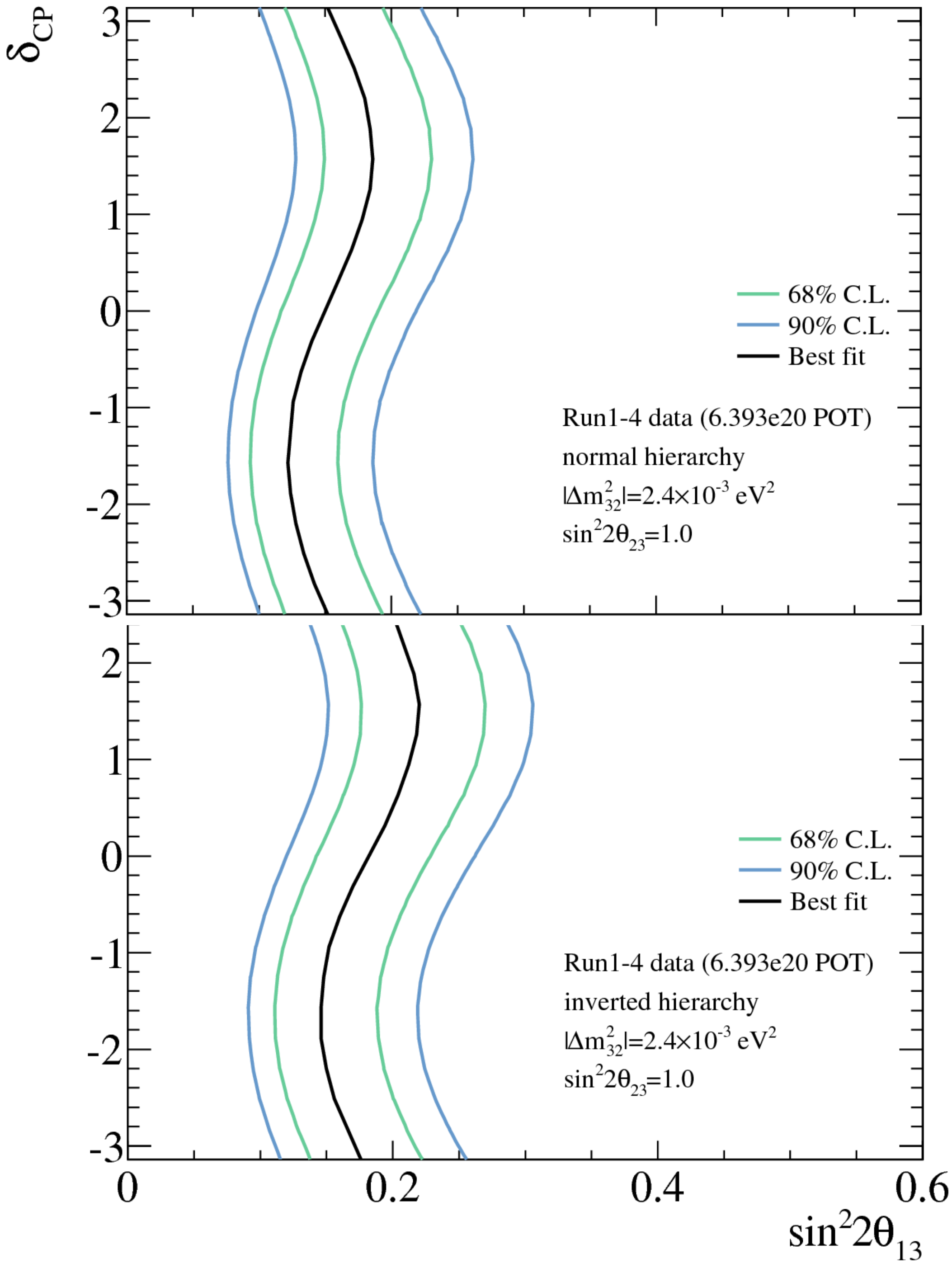

Assuming $\delta_{CP}=0$, normal hierarchy, $|\Delta m^2_{32}|=2.4\times10^{-3}$ eV$^2$, $\sin^2 2\theta_{23}=1$

Best fit w/ 68% C.L. error:

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

90% allowed region:

$$0.097 < \sin^2 2\theta_{13} < 0.218$$




# Results

Allowed region of $\sin^2 2\theta_{13}$ for each value of $\delta_{CP}$

Best fit w/ 68% C.L. error @ $\delta_{CP}=0$

**normal hierarchy:**

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

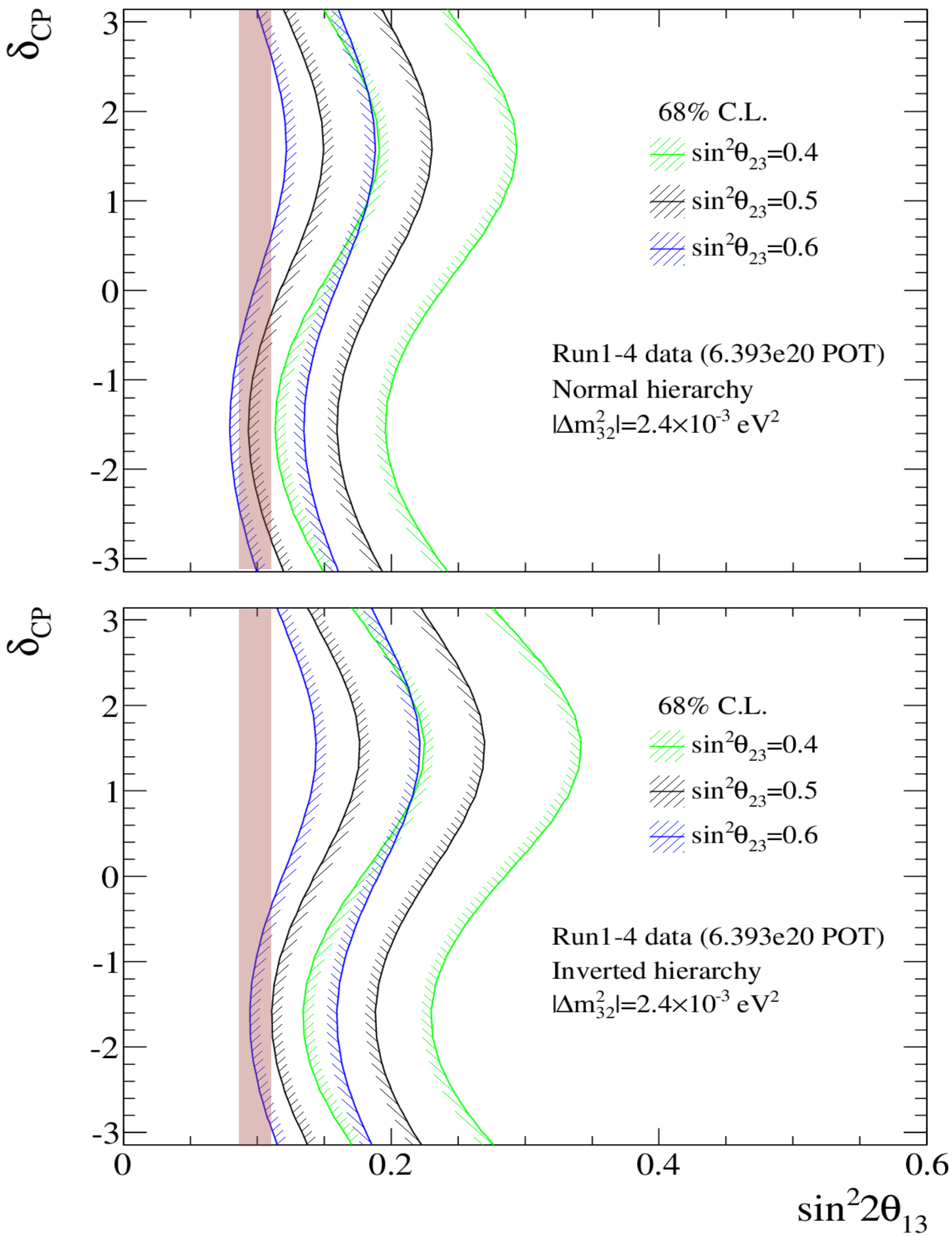
**inverted hierarchy:**

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

$\sqrt{(2\Delta \ln L)}$ significance of non-zero $\theta_{13}$ yields 7.5σ

NOTE: These are 1D contours for values of $\delta_{CP}$, not 2D contours in $\delta_{CP}$-$\theta_{13}$ space

# $\delta_{CP}$ vs. $\sin^2 2\theta_{13}$ for $\theta_{23} \neq \pi/4$




$\delta_{CP}$ vs. $\sin^2 2\theta_{13}$ contour depends significantly on the value of $\sin^2\theta_{23}$.

Pink band represents PDG2012 reactor average value of $\sin^2 2\theta_{13} = (0.098 \pm 0.013)$

NOTE: These are 1D contours for values of $\delta_{CP}$, not 2D contours in $\delta_{CP}$-$\theta_{13}$ space

# CONCLUSIONS AND FUTURE PROSPECTS

# T2K and J-PARC Run Plans

- T2K's neutrino oscillation analyses still statistics limited
  - So far, we have been able to steadily decrease systematics
- T2K will continue to run and benefit from planned J-PARC Main Ring (MR) power improvements
  - 220 kW operation in CY2013. Integrated 6.7E20 POT to date.
  - Linac upgrade to be completed with a year. Expect range of steady MR operation for neutrino between 200-400 kW
  - Planned MR upgrade (depends on funding). Up to 750 kW
  - Possible scenario:
    - Doubling the # of proton per bunch
    - Doubling repetition rate
- T2K beamline designed to easily switch from neutrino to anti-neutrino beams
  - T2K has made no firm plans for anti-neutrino running

# Conclusions

- We have measured non-zero $\theta_{13}$ with $7\sigma$ significance by observation of $\nu_\mu \rightarrow \nu_e$
- Also measurement of $\nu_\mu \rightarrow \nu_\mu$ which favors maximal mixing
  - A doubling of statistics soon with Run 4 data
- Accelerator based neutrino oscillation research at “atmospheric” baseline are now precision measurements