Recent Results from T2K

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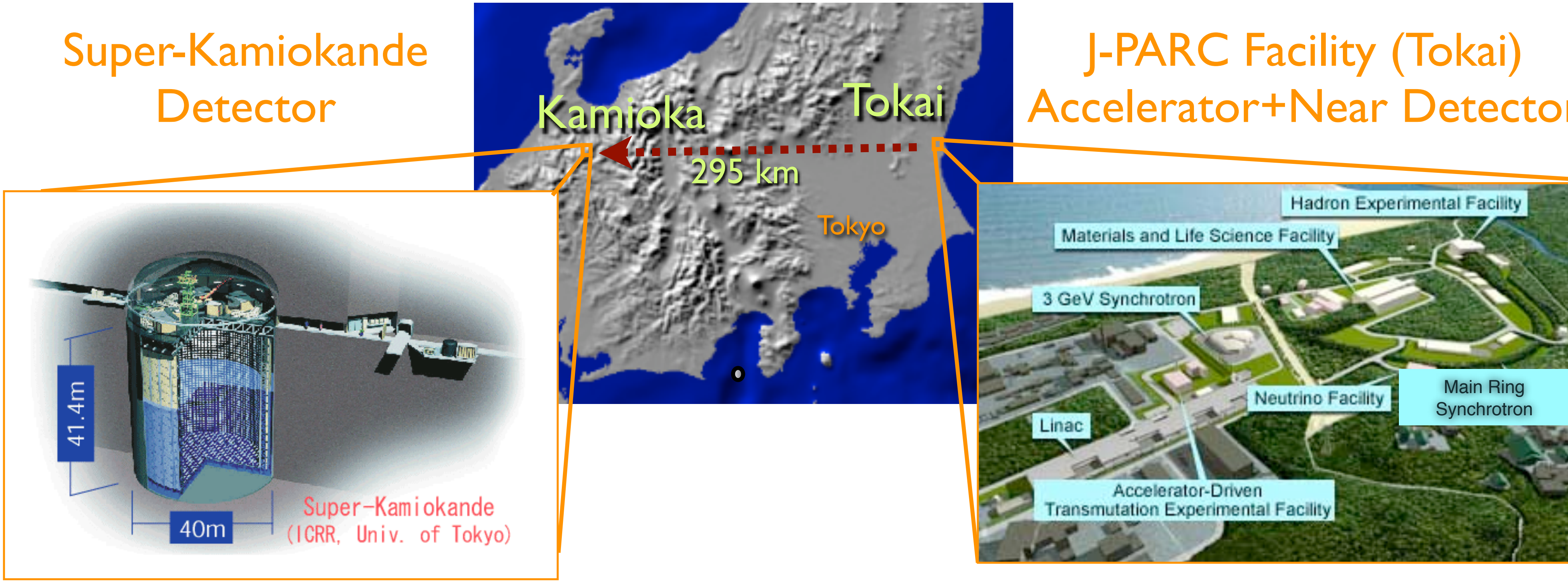
Neutrino Flux Workshop, University of Pittsburgh, Dec 6–8,2012

Outline

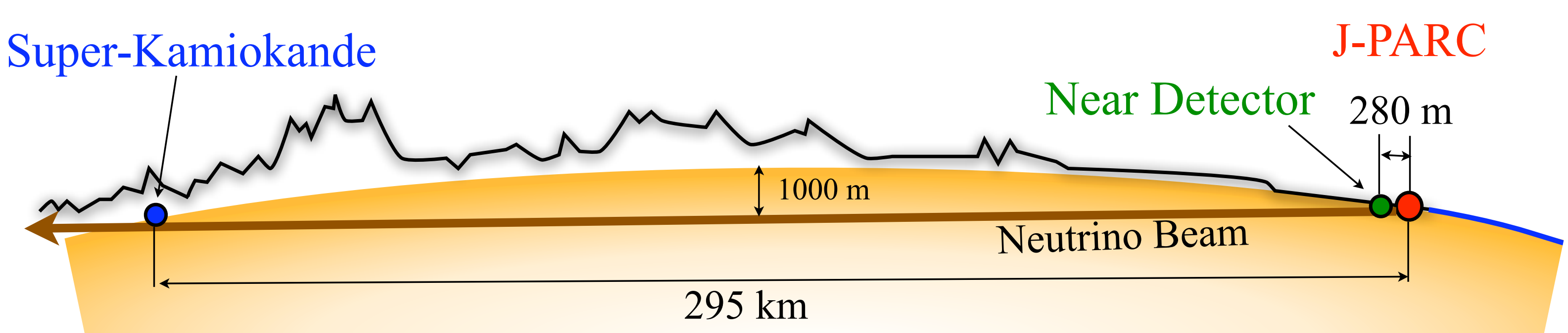
- T2K Beamline and Detectors
- Uncertainties from prior measurements
- Constraints from Near Detector
- ν_e Appearance Results

T2K Beam

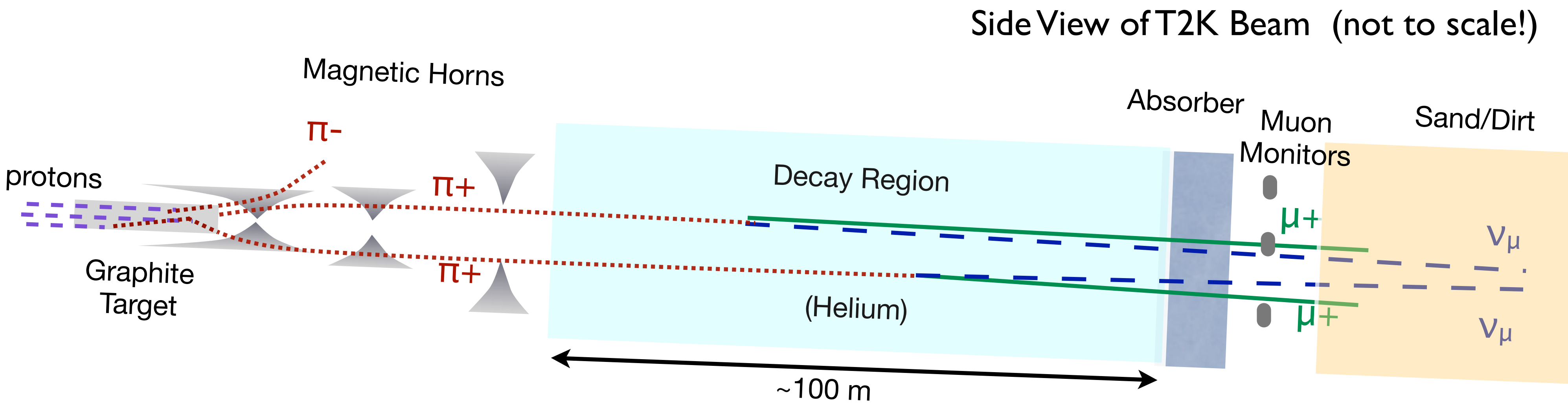
T2K: Tokai-to-Kamioka



- Long-baseline neutrino experiment with detectors at near and far locations
- Neutrino beam travels 295 km across Japan



J-PARC Accelerator Chain

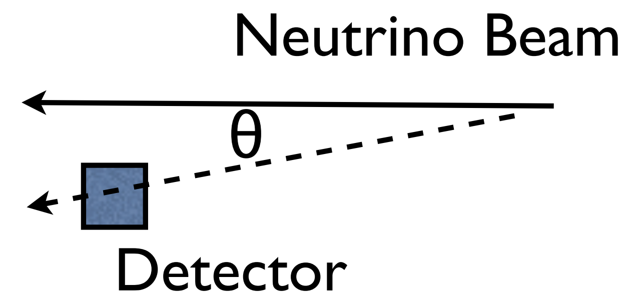


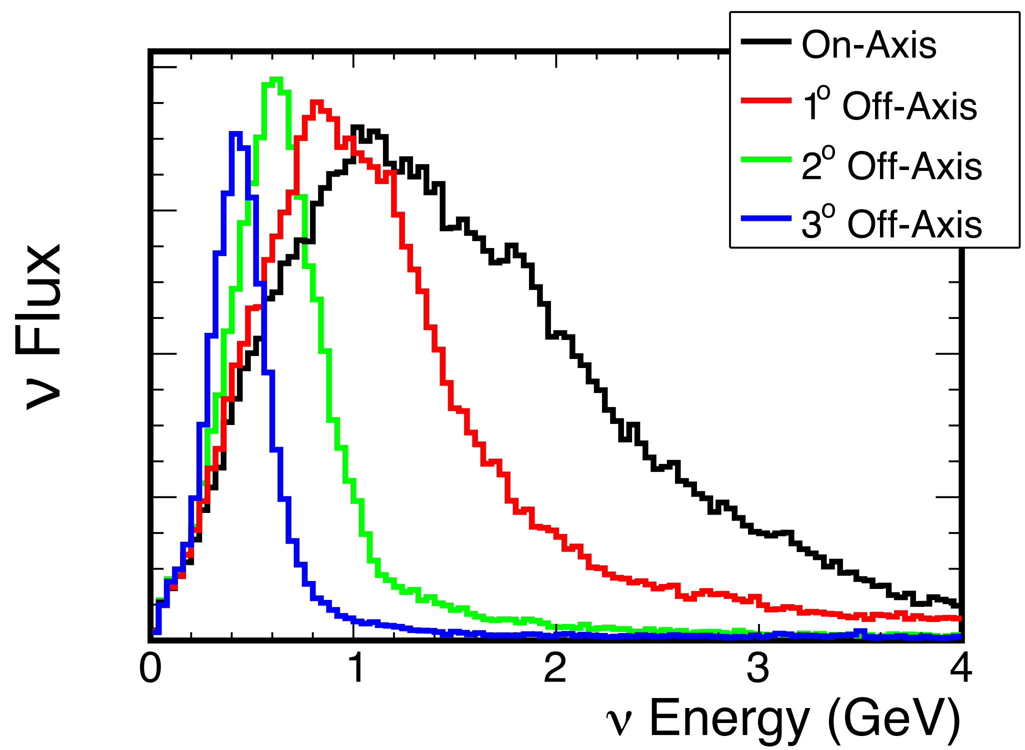
- 30 GeV protons strike graphite target, producing πs and Ks
- 3 magnetic horns to focus π^+ and K^+ into the desired direction
- Beam is ~95% ν_μ, 4% $\bar{\nu}_\mu$, 1% ν_e

"Off-Axis" Beam

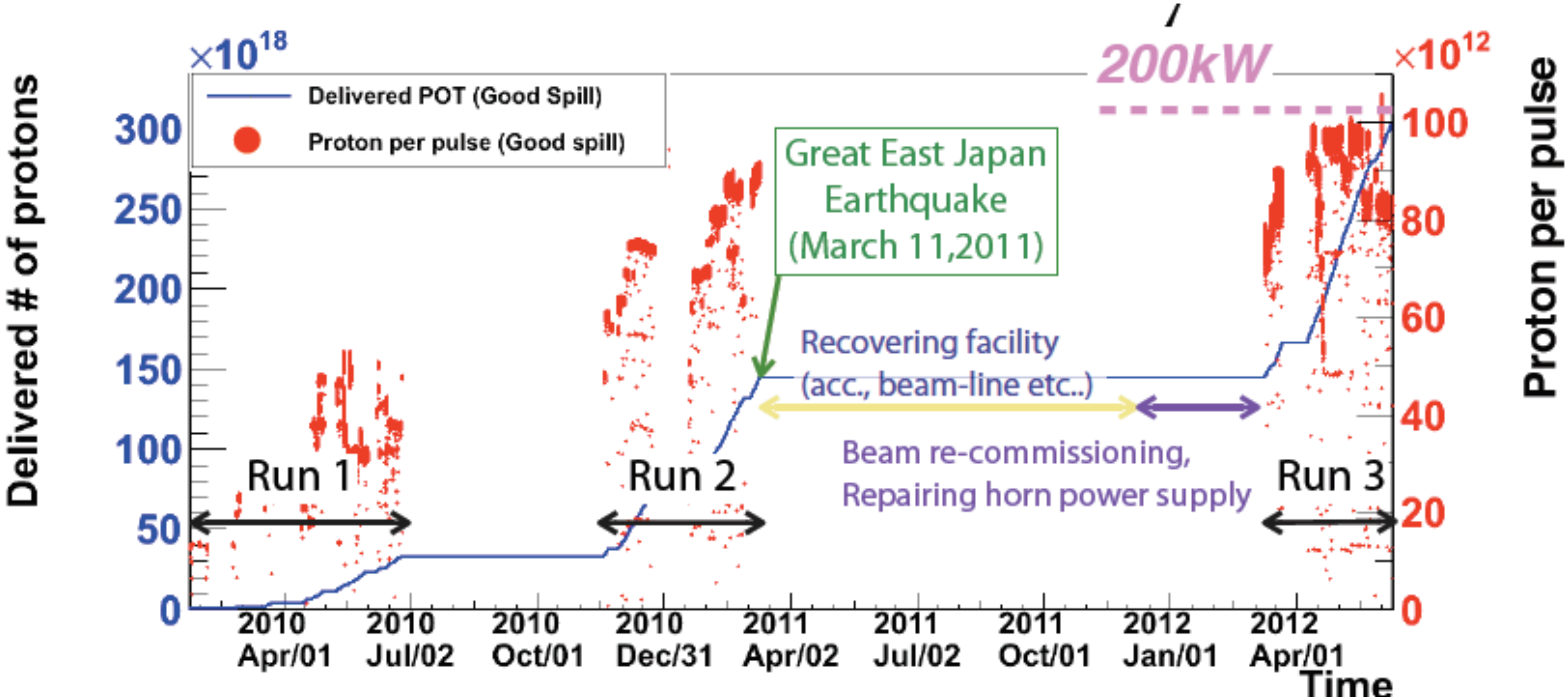
- Both T2K detectors are 2.5° off ν beam axis
- Smaller ν flux, but more low energy flux, and νs are in a very narrow energy range

- Oscillations depend on L/E so narrow E range is preferable
- Reduces background from high-energy NC π^0 interactions





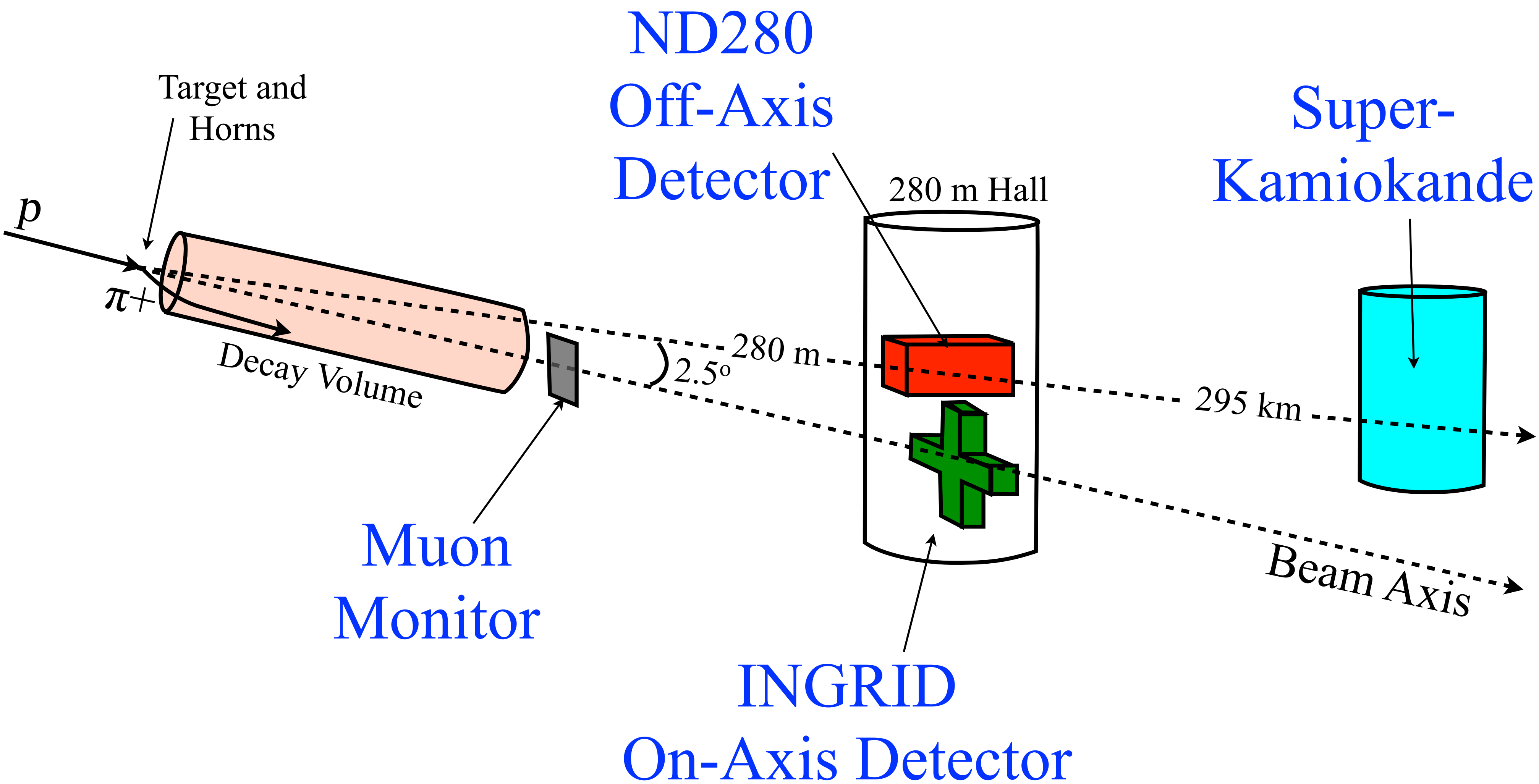
T2K Run Periods



- Run 2 ended by March 2011 earthquake
- **Run 3** began Jan 2012
- Total protons on target 3.01×10^{20} protons
- Preliminary ν_e results here are for **Run 1, 2, 3**
- **Run 4** began in Oct 2012

T2K Detectors

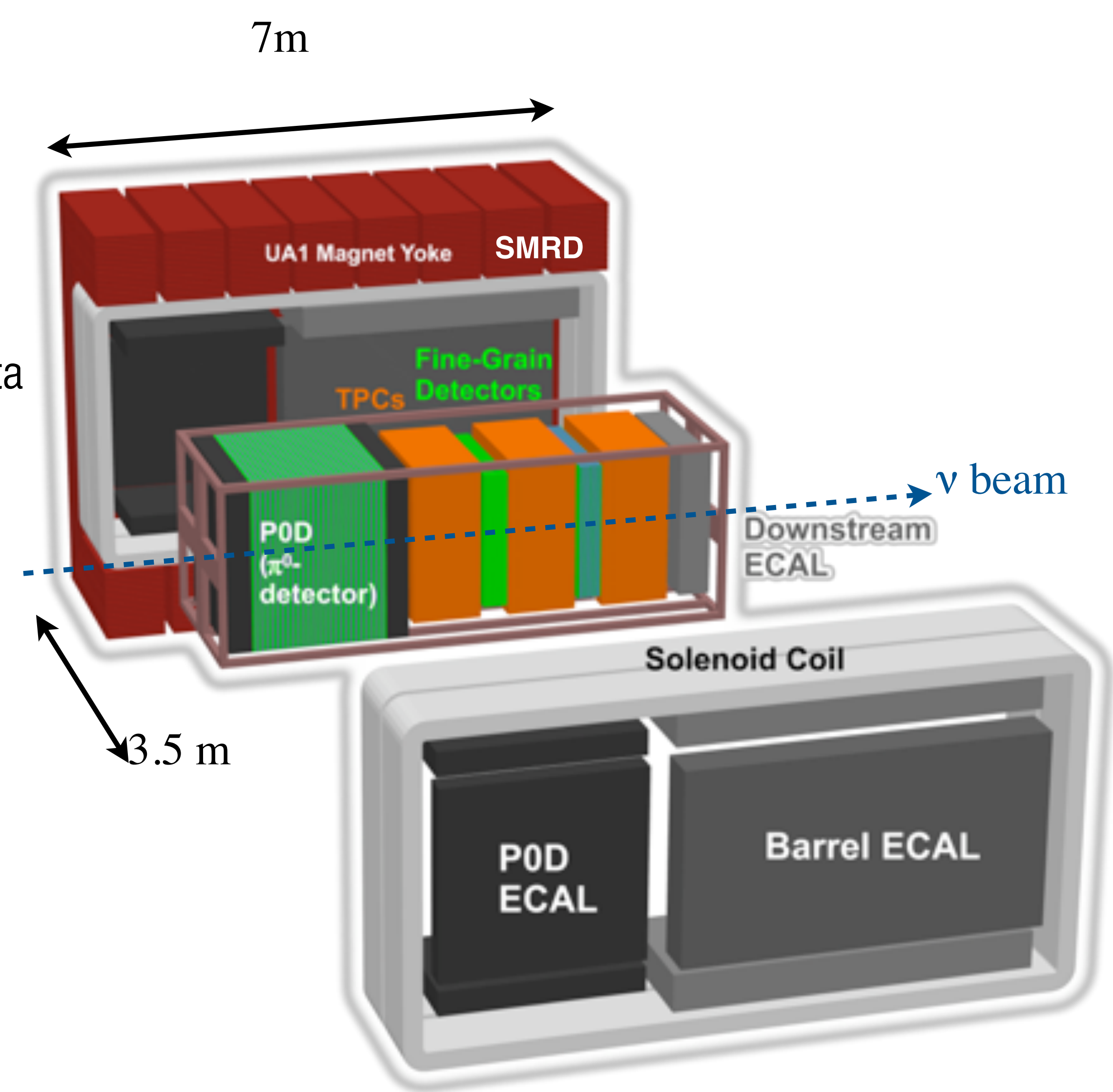
T2K Detectors



Not to scale!

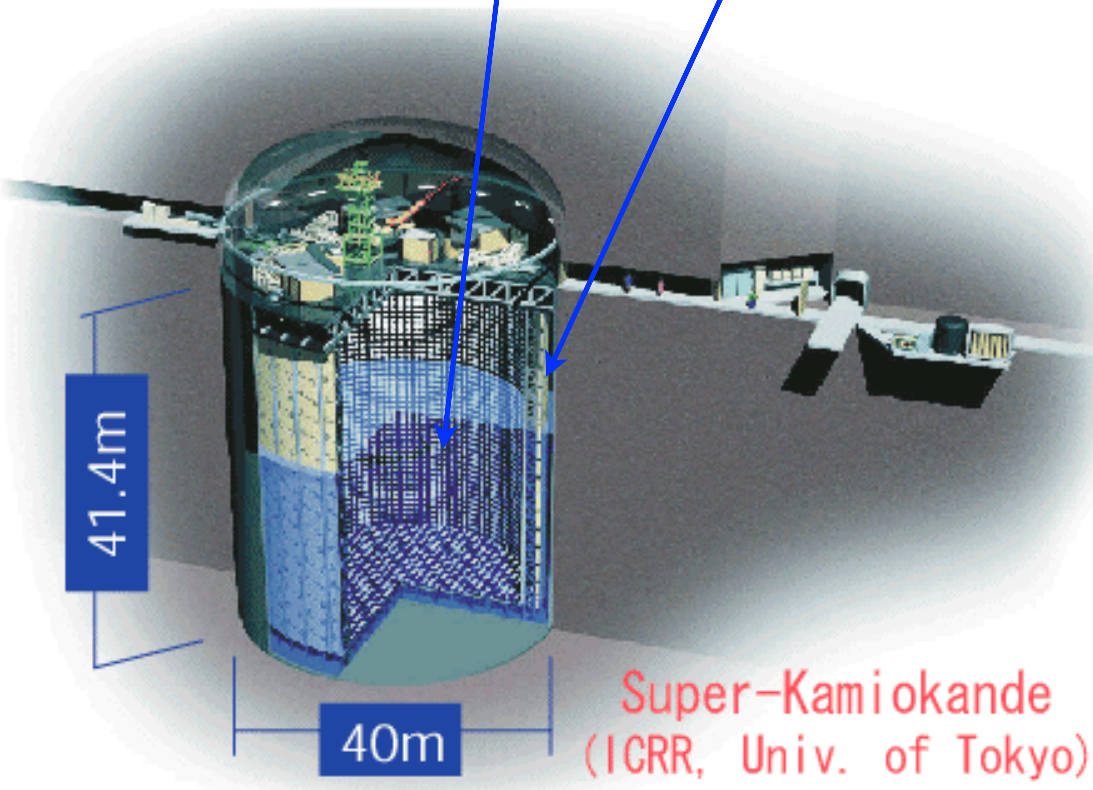
ND280: Off-Axis Near Detector

- Inside the 0.2 T UA-1 magnet
- ~ 10,000 ν interactions per day
- Tracker
  - Fine-grained scintillator tracker + 3 TPCs
  - Distinguishes particles due to dE/dx
  - Uses track curvature to determine momenta
- Pi-Zero Detector
  - Optimized to measure π^0 production
- ECAL
  - Catches γ's that have not interacted elsewhere in the detector
- Side Muon Range Detector
  - Measures momenta of lateral muons
  - Muon trigger for calibration purposes
- Scintillator bars read out by MPPCs inside magnet

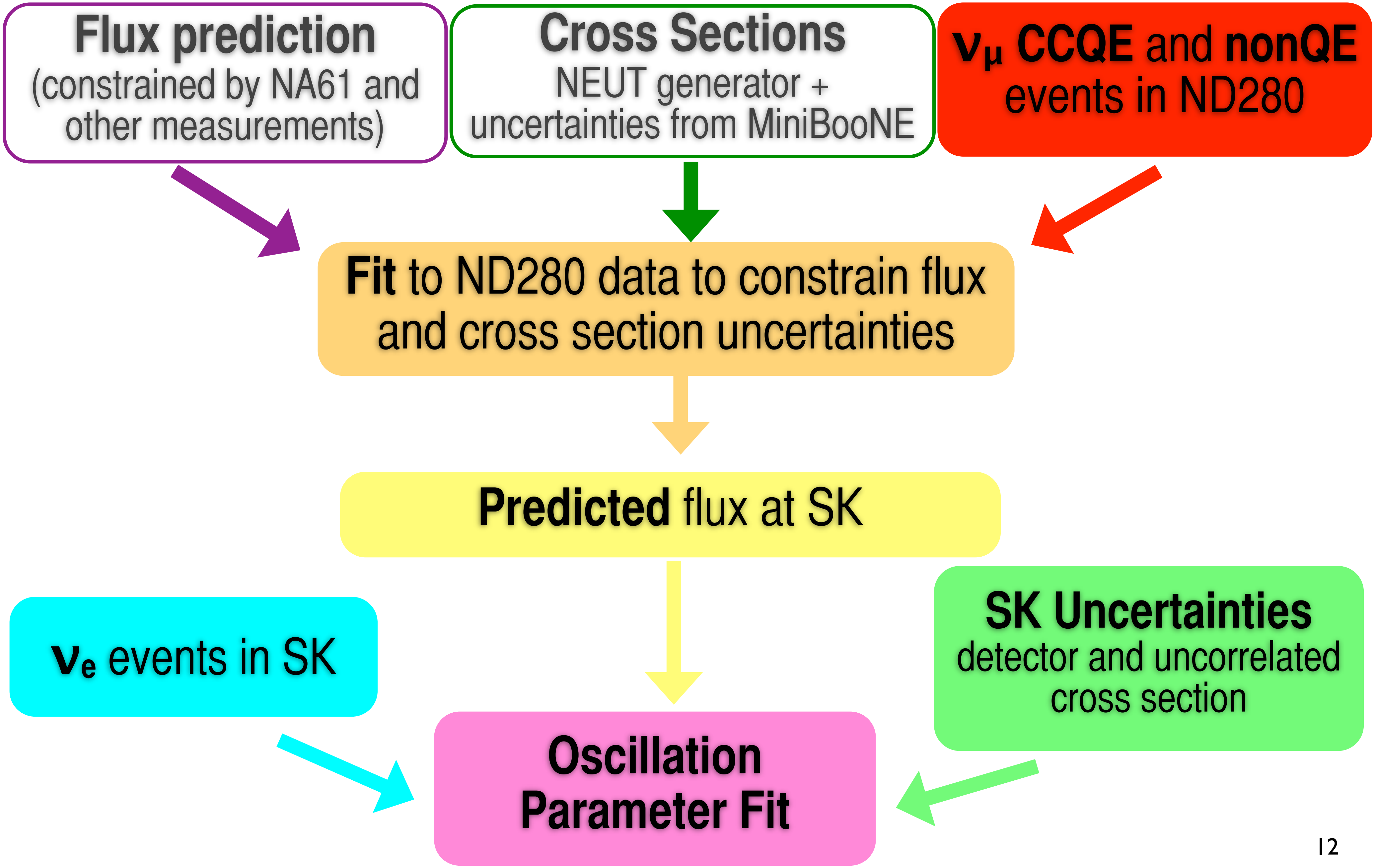


Super-Kamiokande: Far Detector

- Began data taking in 1996
- Large volume water Cerenkov detector
- 50 kton of pure H_2O (22.5 kton fiducial volume)
- 11,000 phototubes
- Outer layer with 1885 phototubes to reject external events
- Expect a handful of events per day at full beam power.



2012 Oscillation Analysis Method



Prior Constraints from External Measurements

Cross Section Data

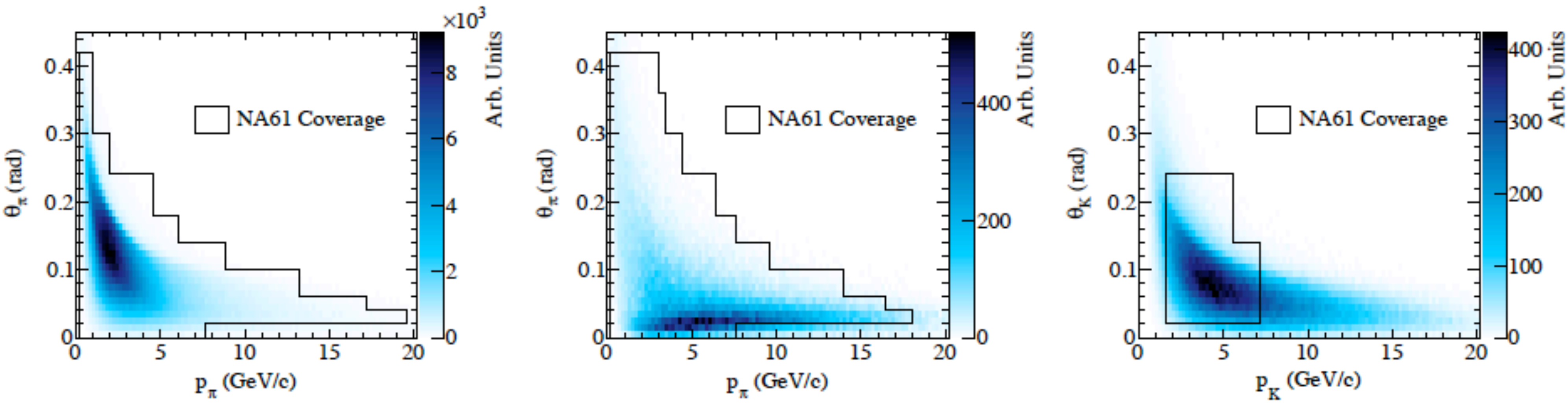
- Cross sections modeled using Neut (and Genie), neutrino-nucleon scattering with a Fermi-gas nuclear model, and final state interactions
- Fits are performed to external neutrino scattering data
  - At present only using **MiniBooNE**
  - Data sets used CCQE, CC π^0, CC π^+, NC π^0
  - K2K, SciBooNE used a cross checks
- Final state interactions constrained by $\pi^+ - {}^{12}C$ scattering data

Neutrino Flux Constraints

- Flux predictions and uncertainties for T2K (arXiv:1211.0469) have recently been accepted for publication in Phys Rev D
- Neutrino flux simulation based on FLUKA2008 for target, and Geant3 outside the target. GCALOR used for hadronic interactions.
- Hadron production and interactions are **re-weighted by external data**.

External Flux Data

- Primarily uses **NA61 data** (See Alexis' talk), which used same proton energy and has good acceptance for phase space relevant for T2K.
  - Pions: Phys. Rev. C 84, 034604 (2011).
  - Kaons: Phys.Rev. C 85, 035210 (2012).



(a) π^+ (b) π^- (c) K^+

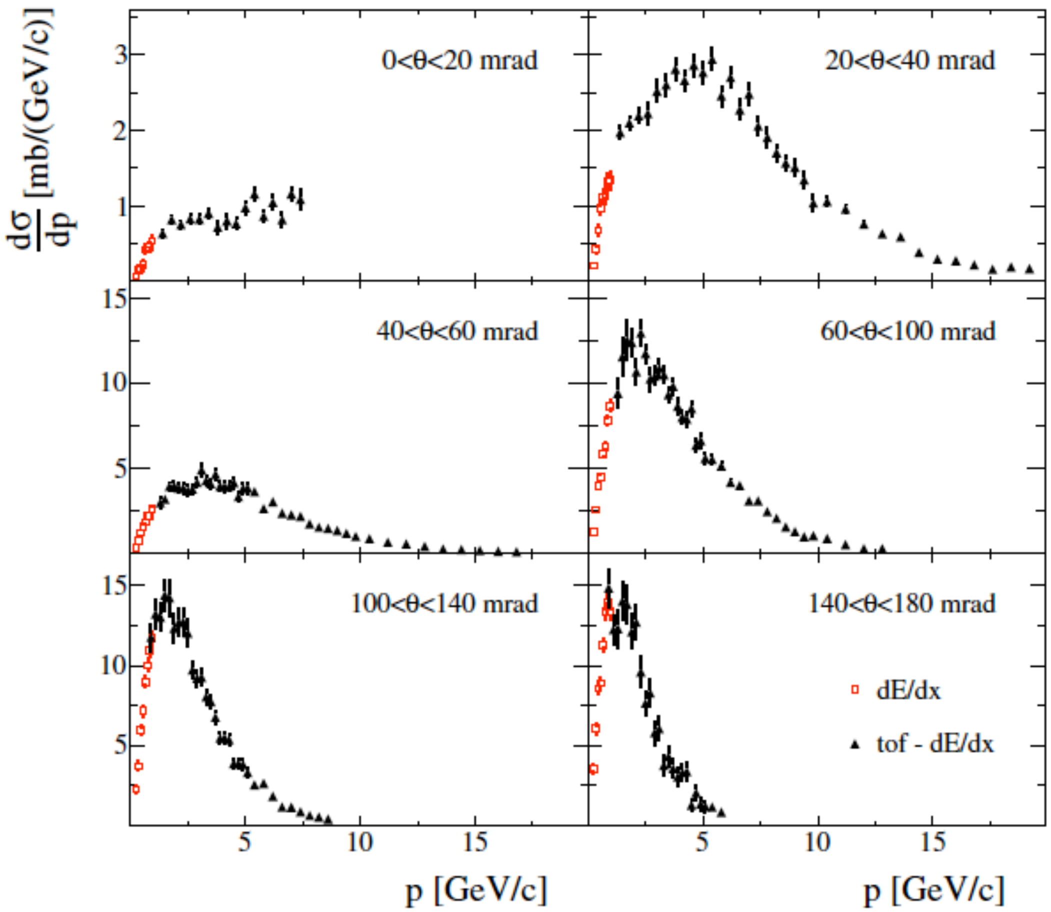
- Data from Eichten and Allaby is used for kaons outside of NA61 phase space
  - T. Eichten et al., Nucl. Phys. B 44 (1972). J. V. Allaby et al., Tech. Rep. 70–12 (CERN,1970).

NA61 π Data

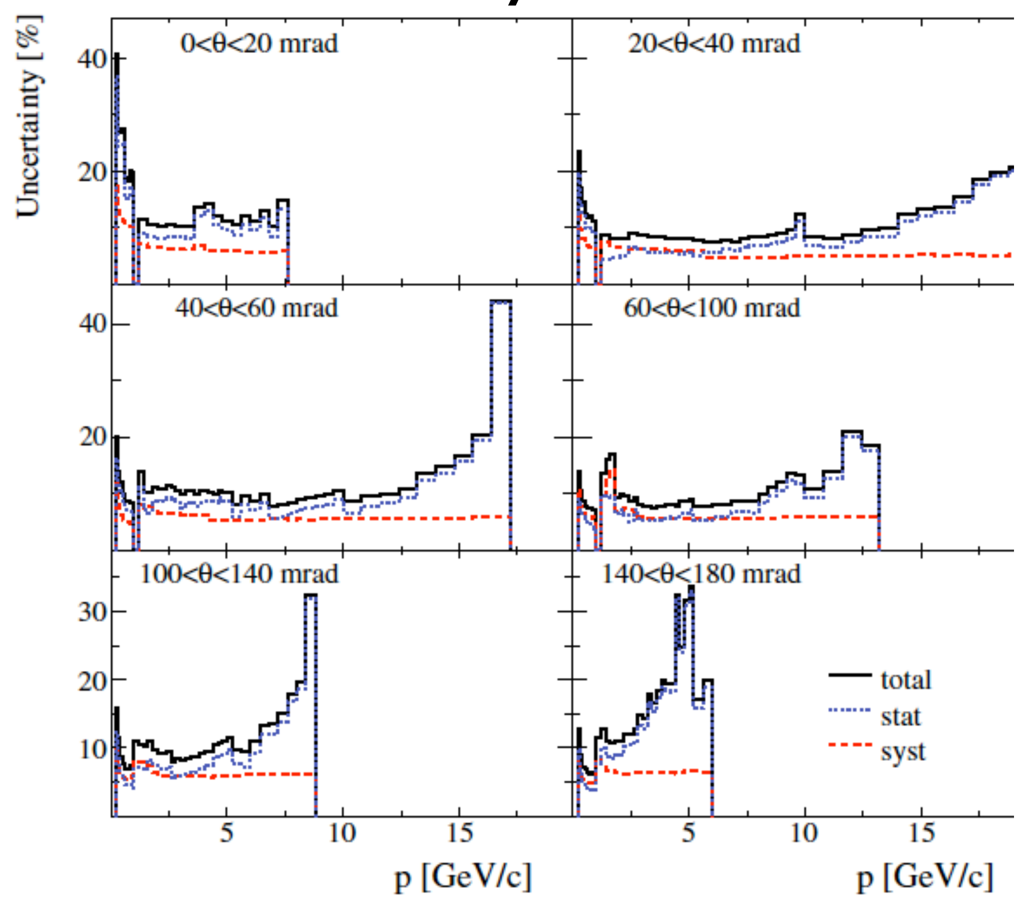
Phys. Rev. C 84, 034604 (2011)

- Uncertainties typically ~10%

π^+ data

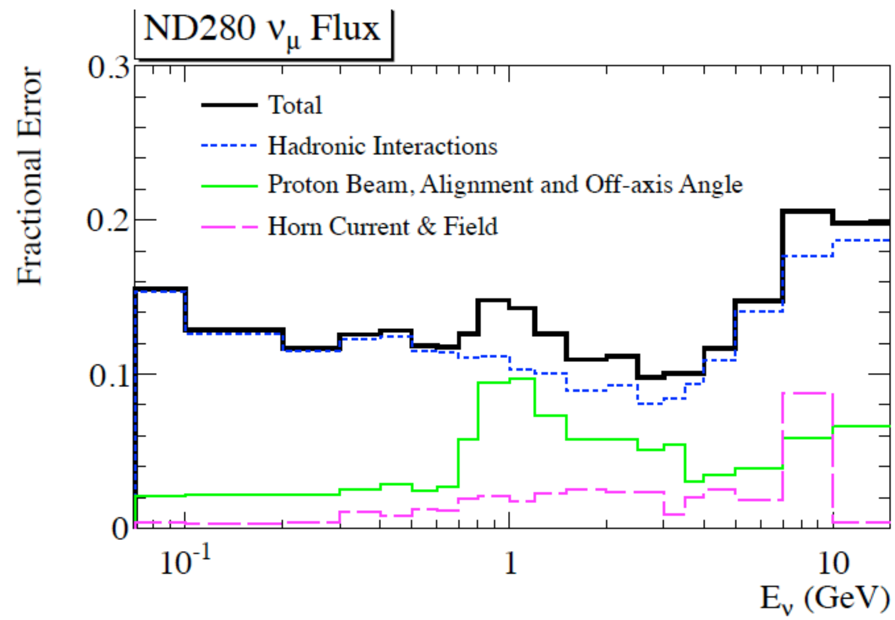


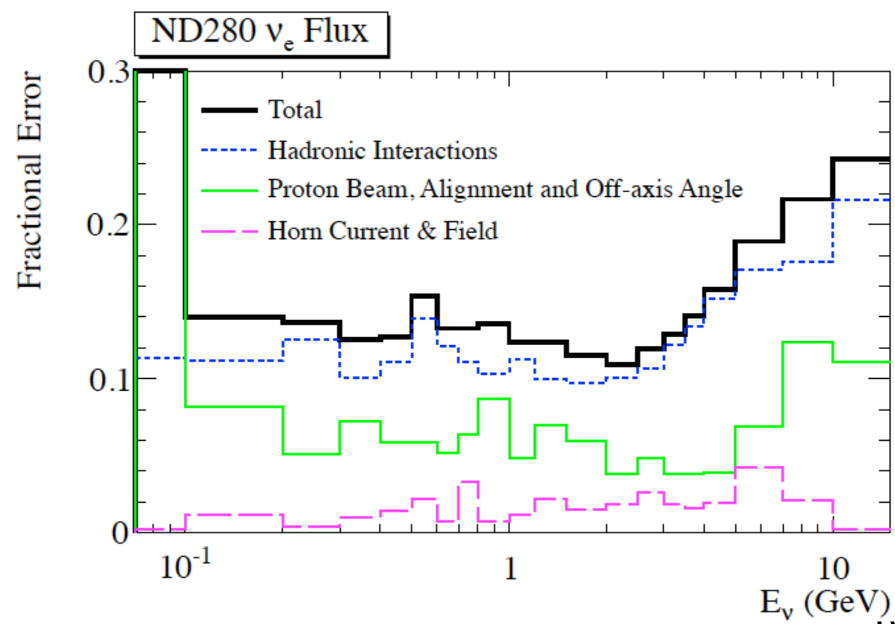
π^+ uncertainty



Flux Uncertainties

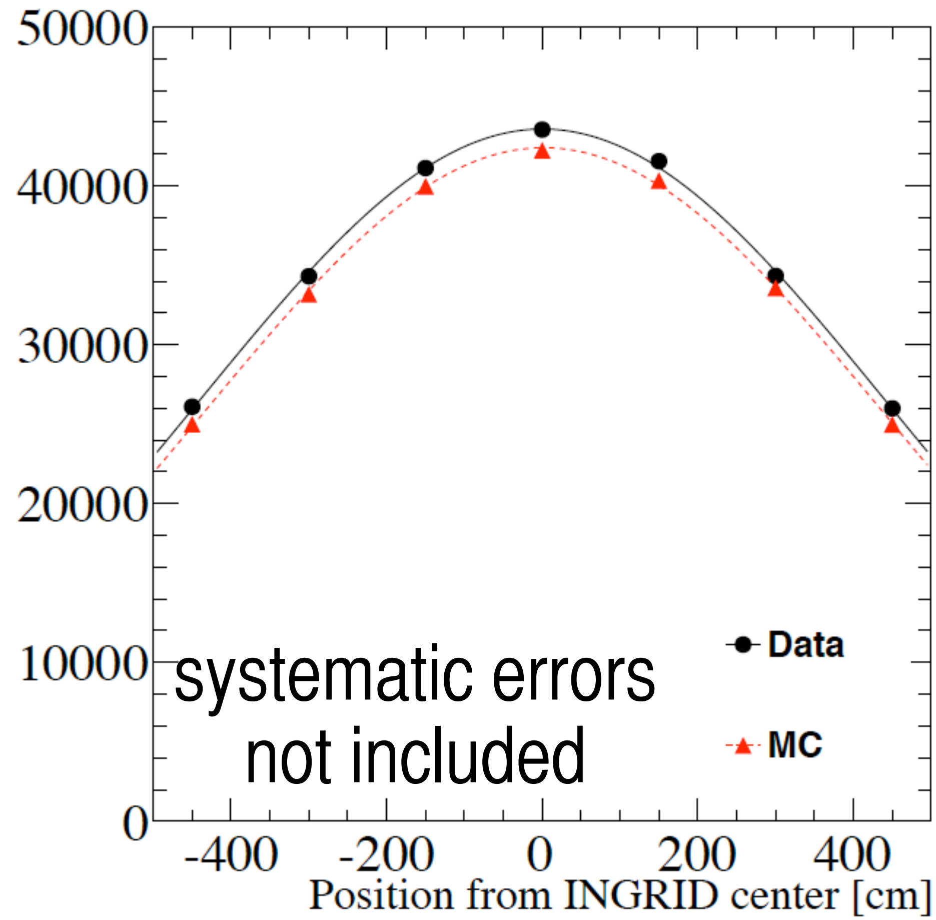
- Uncertainties in hadron production include:
  - data uncertainties
  - momentum scaling uncertainties
  - phase space not covered by data
- Additional uncertainties on flux include:
  - beam direction
  - alignment
  - horn current and magnetic field uncertainties.





Cross-check with INGRID

- INGRID measures on axis rate, position, and profile of neutrino beam, 280m from target
- All is in good agreement with flux predictions



	Data	Prediction
Rate [events/POT]	1.59×10^{-14}	1.53×10^{-14}
Horizontal center [mrad]	$0.009 \pm 0.052(\text{stat.}) \pm 0.336(\text{syst.})$	0.064
Vertical center [mrad]	$-0.314 \pm 0.055(\text{stat.}) \pm 0.373(\text{syst.})$	-0.477

Constraints from Near Detector

Method

- ND280 data in 40 bins of muon momentum, and angle for CCQE-like and nonQE-like samples

$$L_{ND280}^{ratio} = \frac{\pi(\vec{b})\pi(\vec{d})\pi(\vec{d}) \prod_i [N_i^p(\vec{b},\vec{x},\vec{d})]^{N_i^d} e^{-N_i^p(\vec{b},\vec{x},\vec{d})}/N_i^d!}{\pi(\vec{b}_{nom})\pi(\vec{x}_{nom})\pi(\vec{d}_{nom}) \prod_i [N_i^d]^{N_i^d} e^{-N_i^d}/N_i^d!}$$

- **Binned maximum likelihood fit** to maximize ratio given above
  - b's are beam flux parameters
  - x's are cross section parameters
  - d's are uncertainties on detector acceptance, efficiency and reco
  - N_i^d and N_i^p are the data and predicted events in bin i

- Prior probability distributions (π's) are given by expressions like

$$\pi(\vec{b}) = \frac{1}{(2\pi)^{k/2}|V_b|^{1/2}} e^{-\frac{1}{2}\Delta\vec{b}(V_b^{-1})\Delta\vec{b}^T}$$

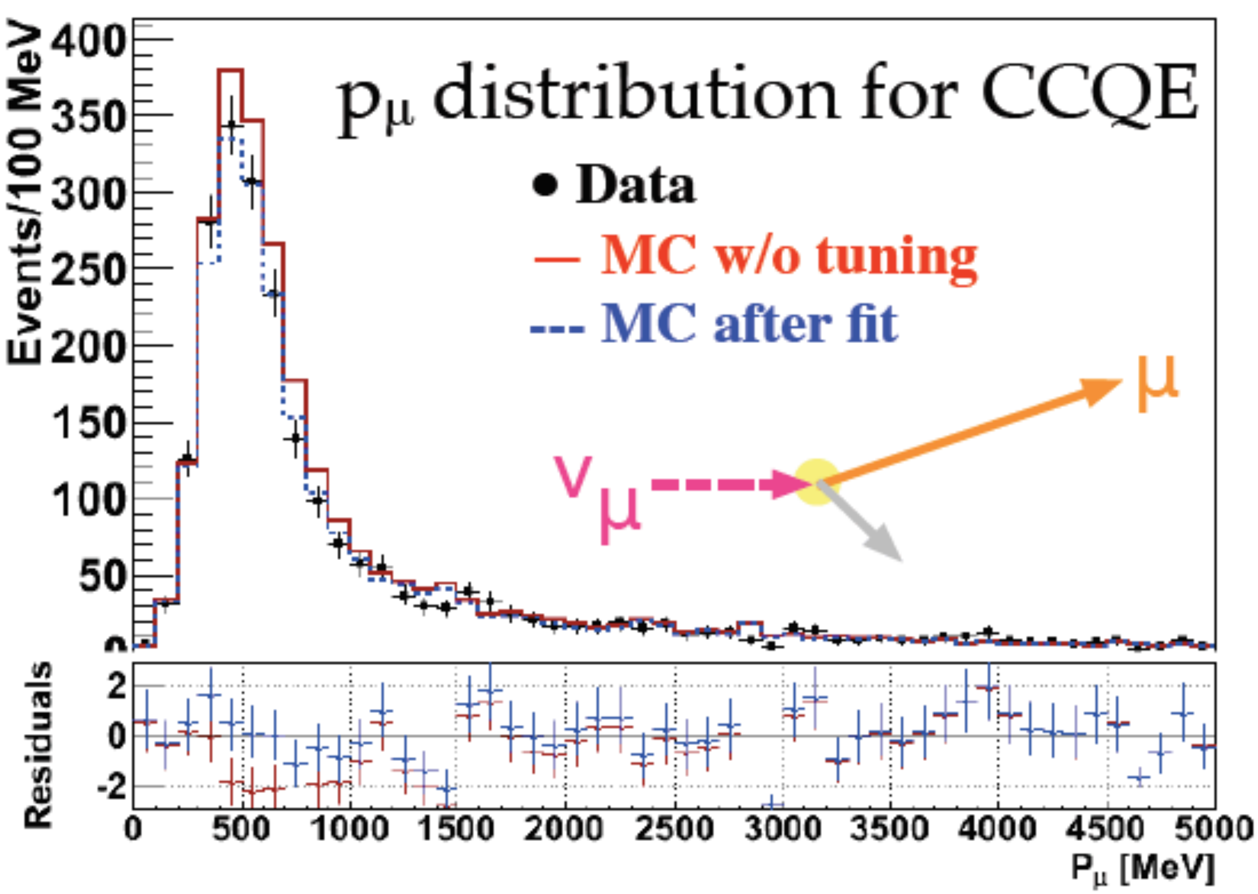
  - V_b is covariance matrices that describe the uncertainties and correlations on the beam flux parameters

Fit Parameters

- Cross section parameters:
  - Parameters that affect the Q^2 distribution are modified by reweighting by the ratio in a bin of p_μ, $\cos\theta_\mu$, E_ν of the new cross section divided by the nominal one
  - Parameters include model parameters like M_A^{QE}, M_A^{Res}, Fermi momentum, and normalizations (sometimes E dependent) for processes like CCQE, CC1π, and NC1π^0

- For neutrino flux, parameters are true neutrino flux in 22 bins
  - 11 bins for ν_μ and 7 for ν_e flux
  - 2 bins each for anti-ν_μ and anti-ν_e

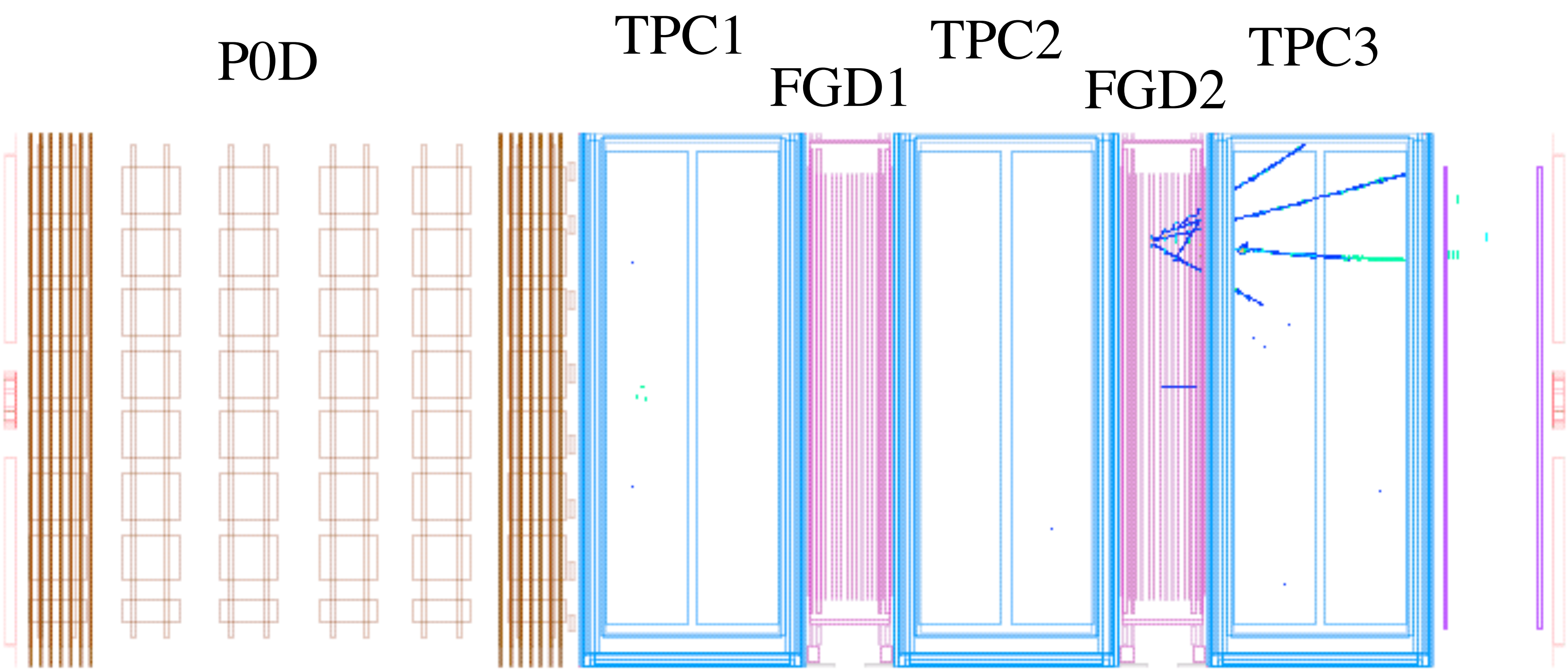
ν_μ CC Events in ND280



- Selection
  - Vertex in FGD fiducial volume
  - At least one negative muon-like track in the TPC
  - No track in upstream TPC
  - CCQE: only 1 track matched between FGD and TPC, no Michel electrons

Example Event Display

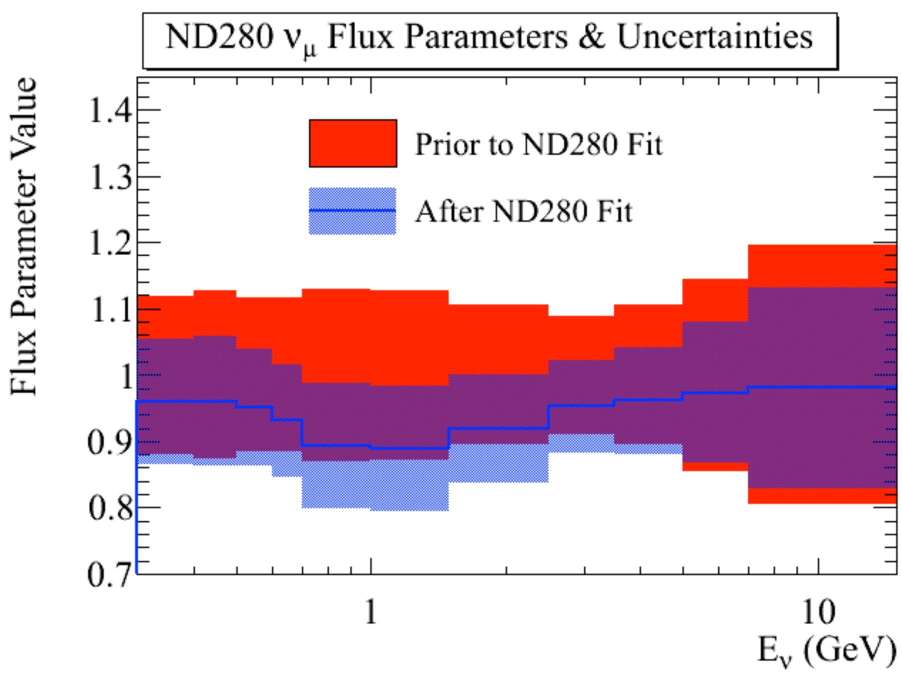
Event number : 21012 | Partition : 63 | Run number : 3026 | Spill : 55510 | SubRun number :7 | Time : Sun 2010-02-28 14:12:51 JST |Trigger: Beam Spill

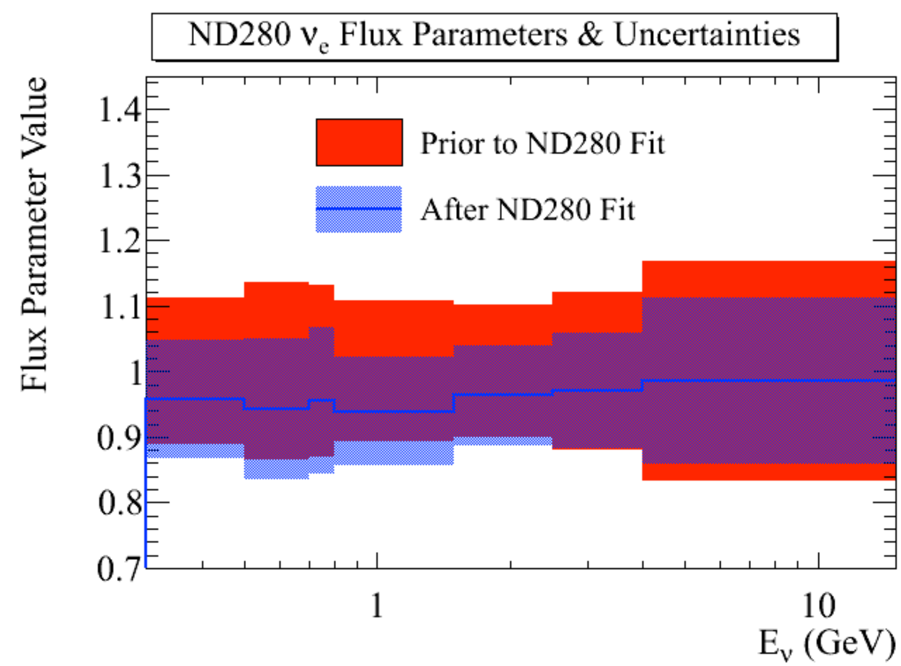


Fit to Near Detector Data

- Fit to near detector data used to constrain flux and cross-section uncertainties.

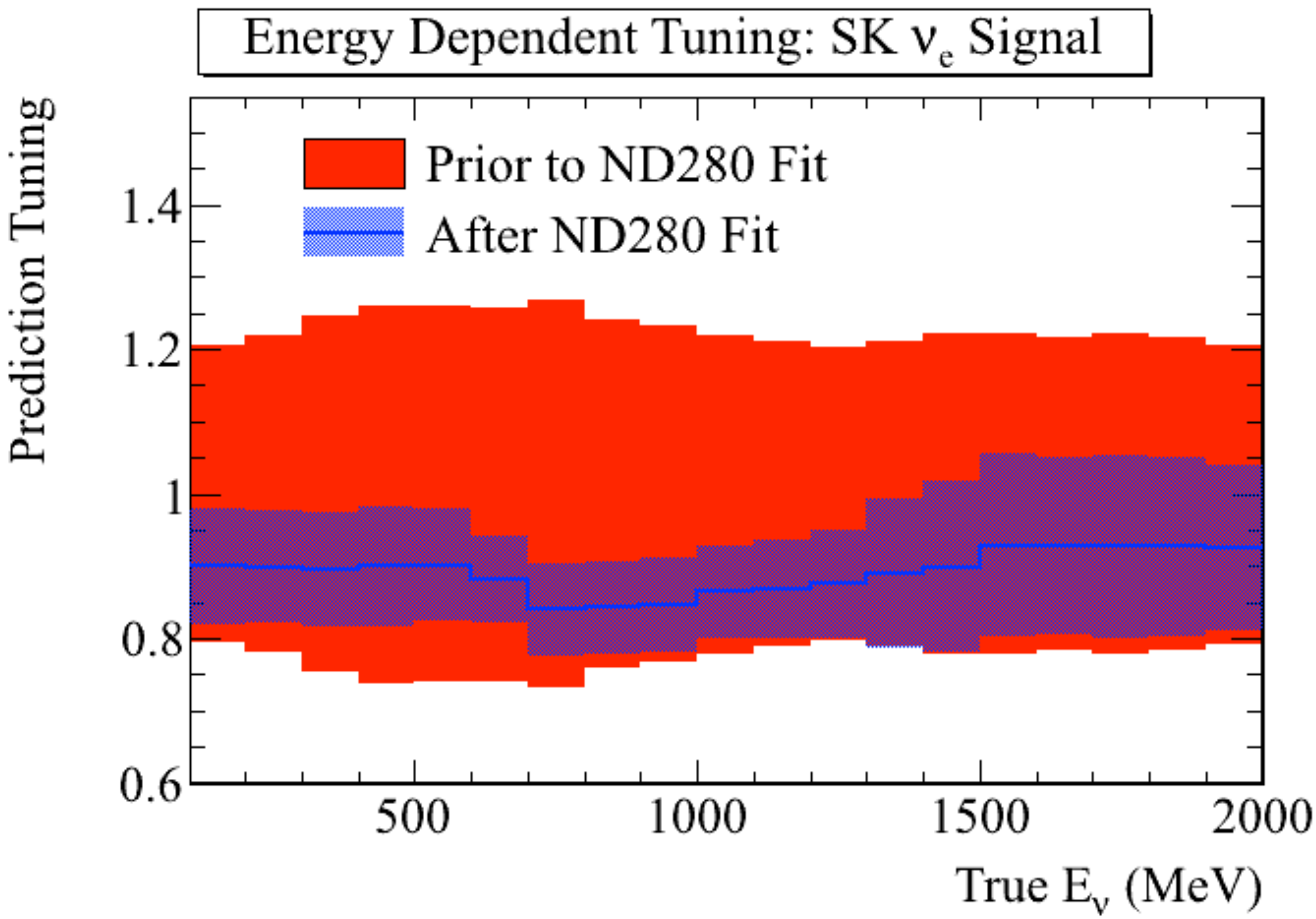
Parameter	Prior value	Prior error	**Post-fit value**	**Post-fit error**
M_A^{QE}	1.21	0.45	1.33	0.20
M_A^{Res}	1.16	0.11	1.154	0.096
CCQE norm (0<E<1.5 Gev)	1.0	0.11	0.955	0.085
CC1π norm (0<E<2.5 GeV)	1.63	0.40	1.605	0.294





Flux Uncertainties at SK

- These uncertainties are then propagated to flux at SK
- Only the errors constrained by the ND280 fit are shown here



ν_e Appearance results in T2K

$\nu_\mu \rightarrow \nu_e$

Run 1+2: Phys.Rev.Lett.107:041801,(2011)

Run 1, 2, 3: Preliminary results shown at ICHEP, Paper in preparation

ν_e Event Selection

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- Sample of fully contained e-like events
- Selection cuts

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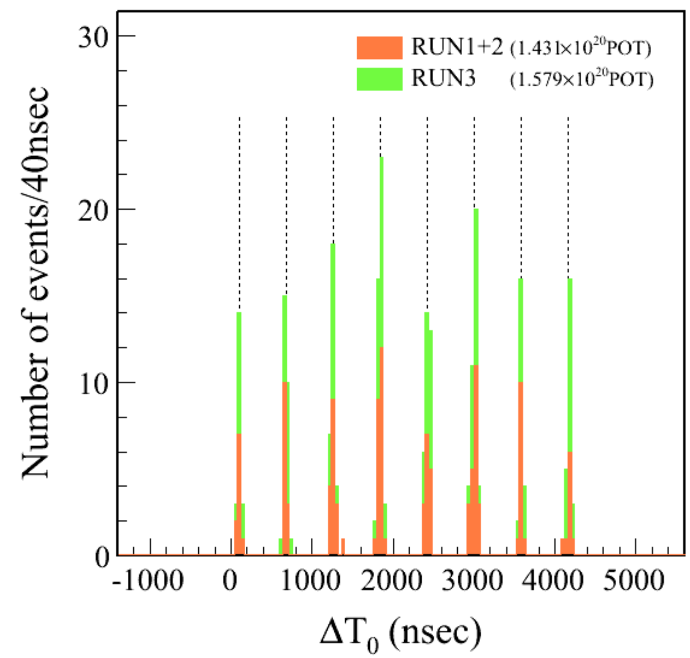
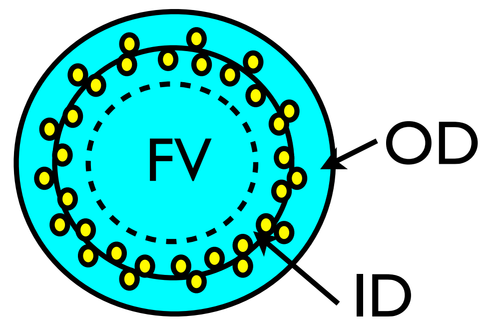
    1. Coincident with beam time



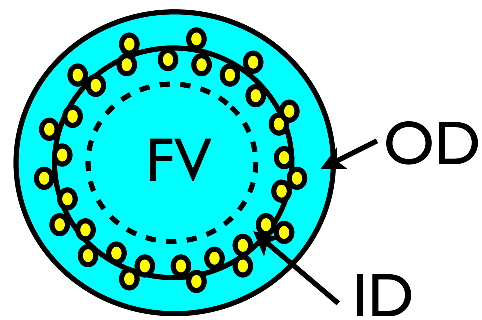
ν_e Event Selection

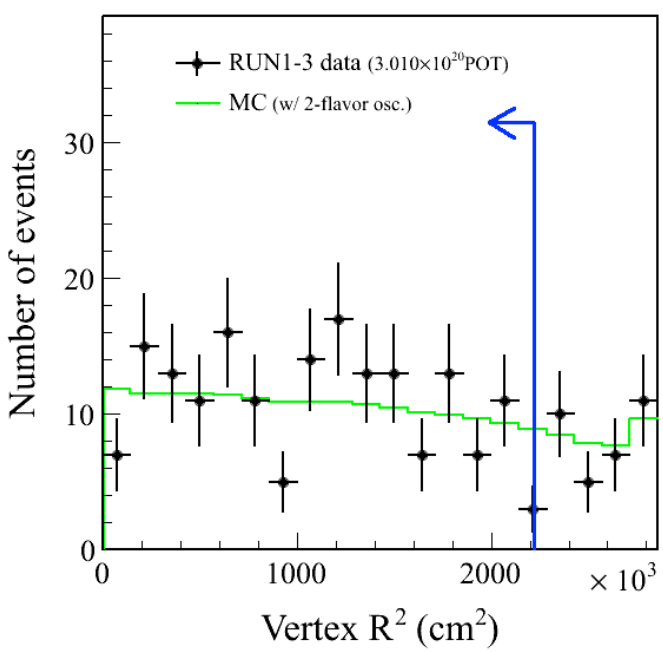
- Sample of fully contained e-like events
- Selection cuts
    1. Coincident with beam time
    2. <16 hits in outer detector

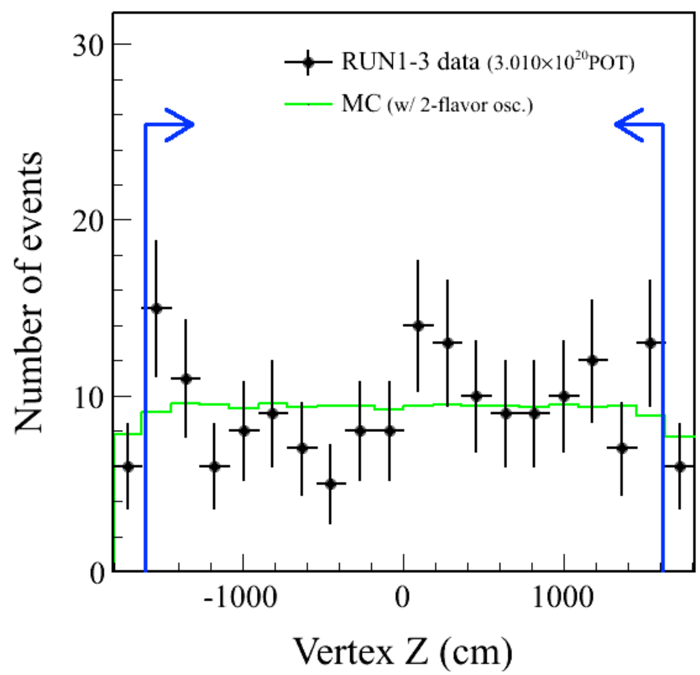


ν_e Event Selection

- Sample of fully contained e-like events
- Selection cuts
  1. Coincident with beam time
  2. <16 hits in outer detector
  3. vertex>200 cm from inner detector walls







ν_e Event Selection (cont.)

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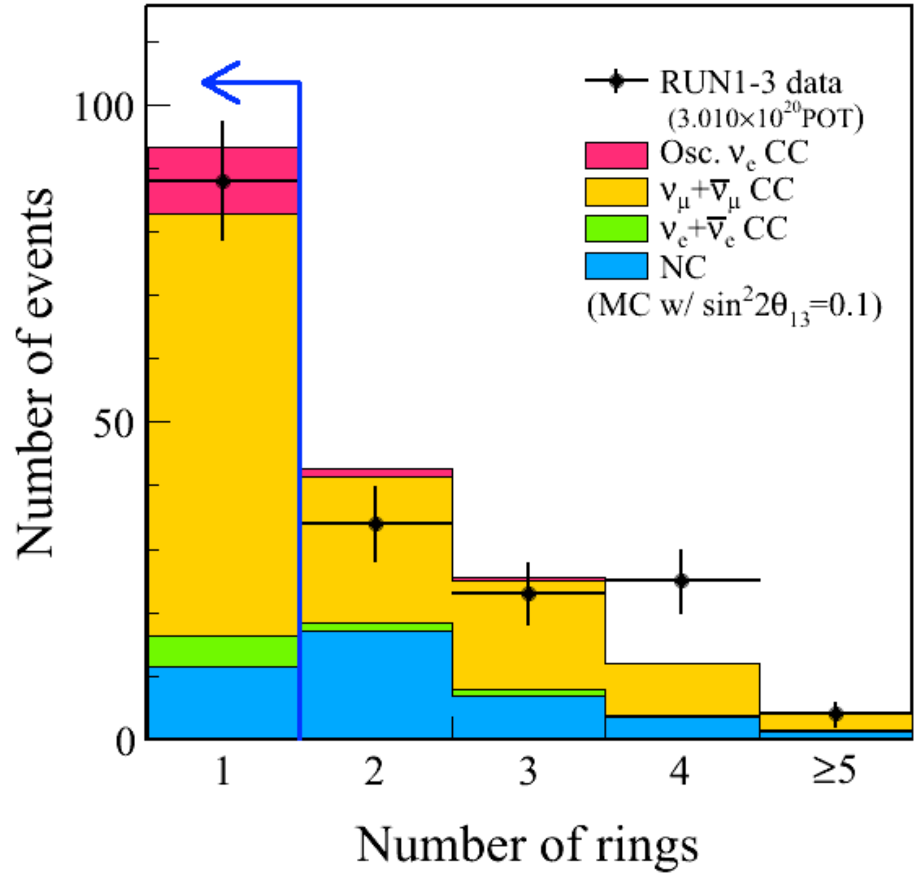
- Selection cuts (cont.)

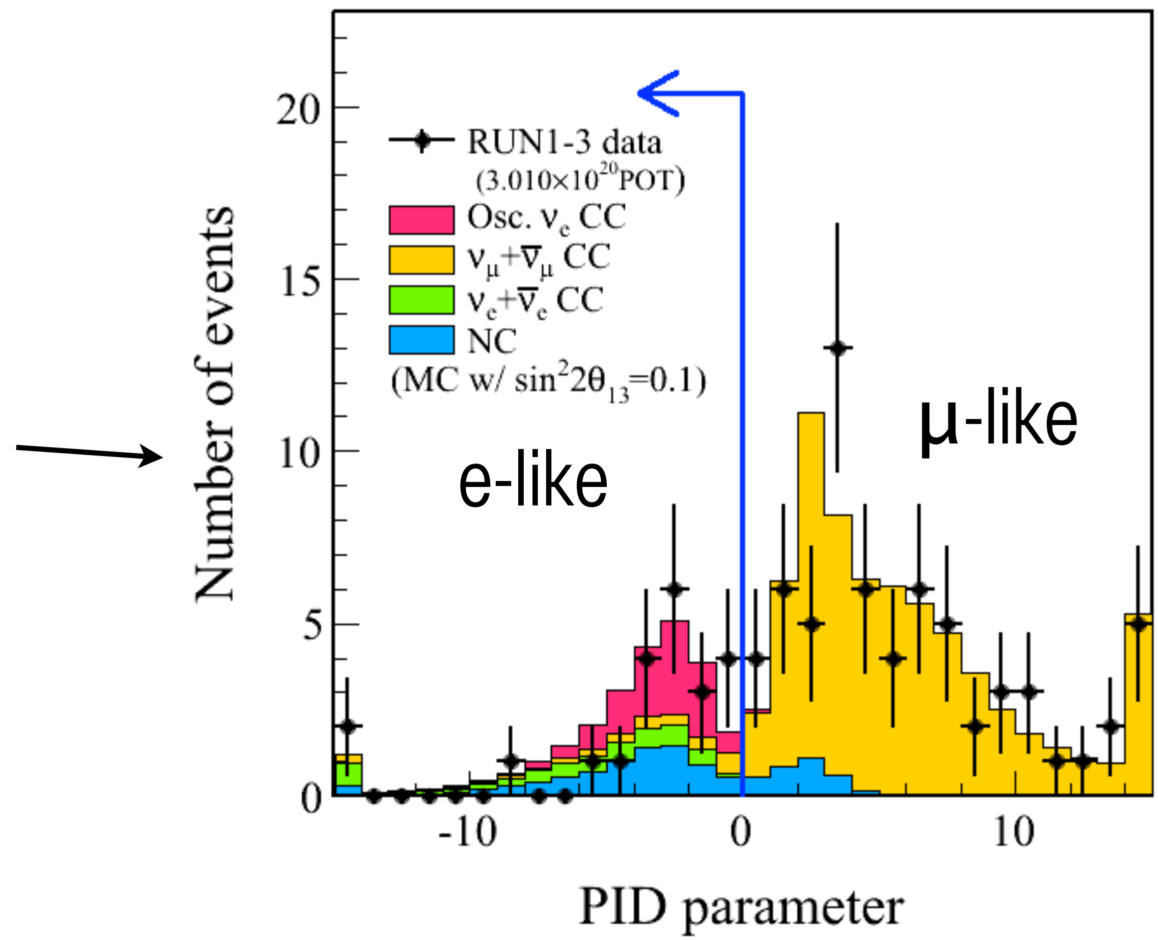
ν_e Event Selection (cont.)

- Selection cuts (cont.)
  4. Single ring



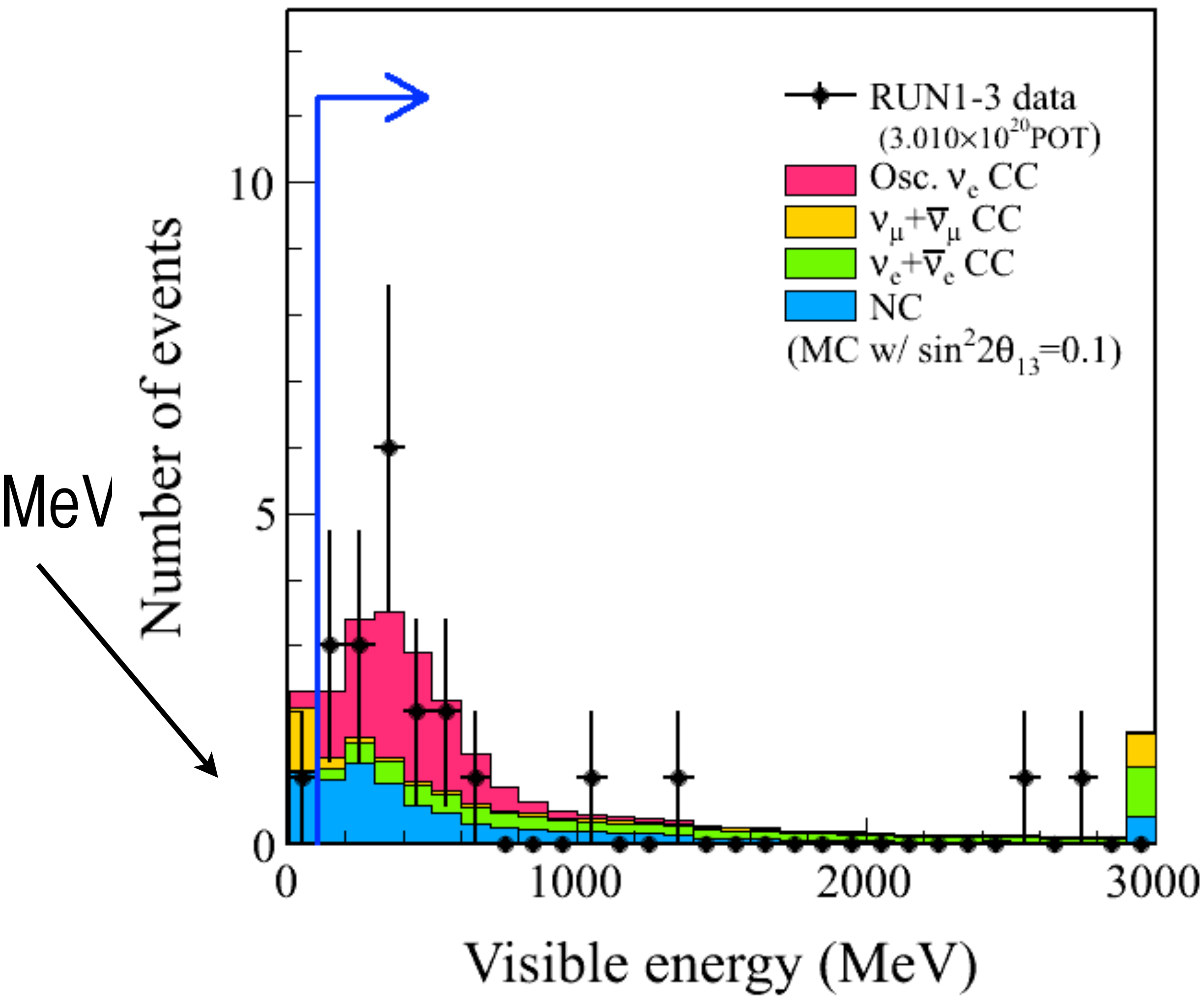
ν_e Event Selection (cont.)

- Selection cuts (cont.)
  4. Single ring
  5. Ring is electron-like



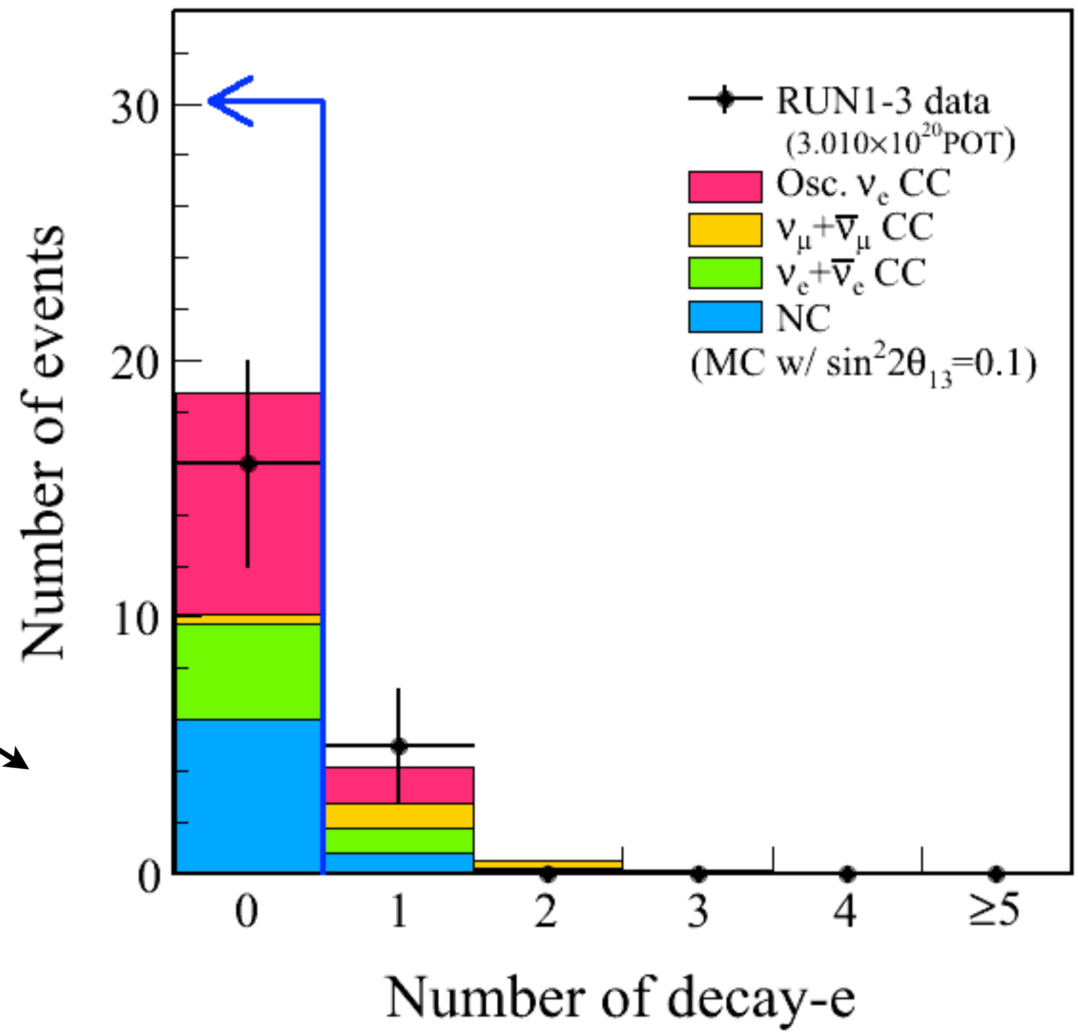
ν_e Event Selection (cont.)

- Selection cuts (cont.)
  4. Single ring
  5. Ring is electron-like
  6. visible energy > 100 MeV



ν_e Event Selection (cont.)

- Selection cuts (cont.)
  4. Single ring
  5. Ring is electron-like
  6. visible energy > 100 MeV
  7. No decay electron observed



ν_e Event Selection (cont.)

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- Selection cuts (cont.)

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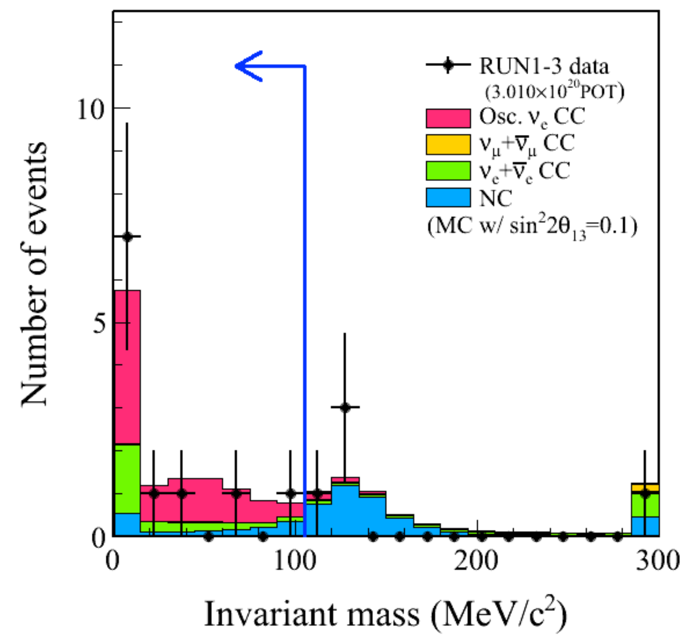
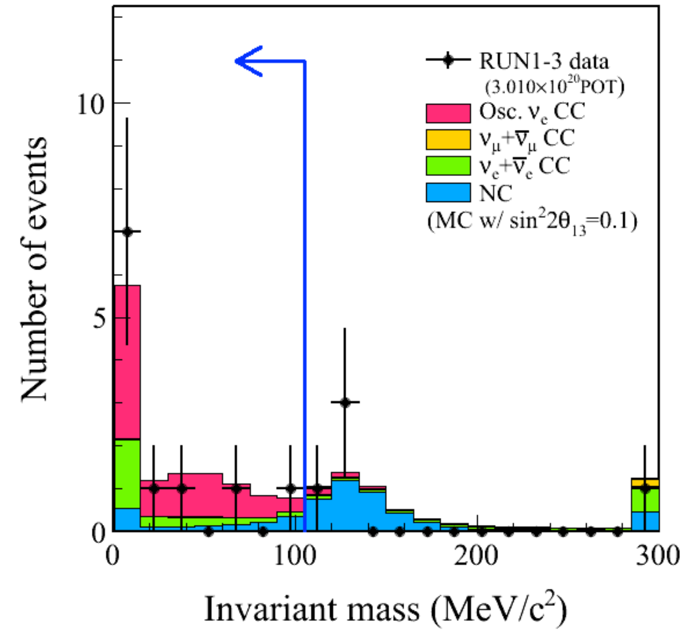
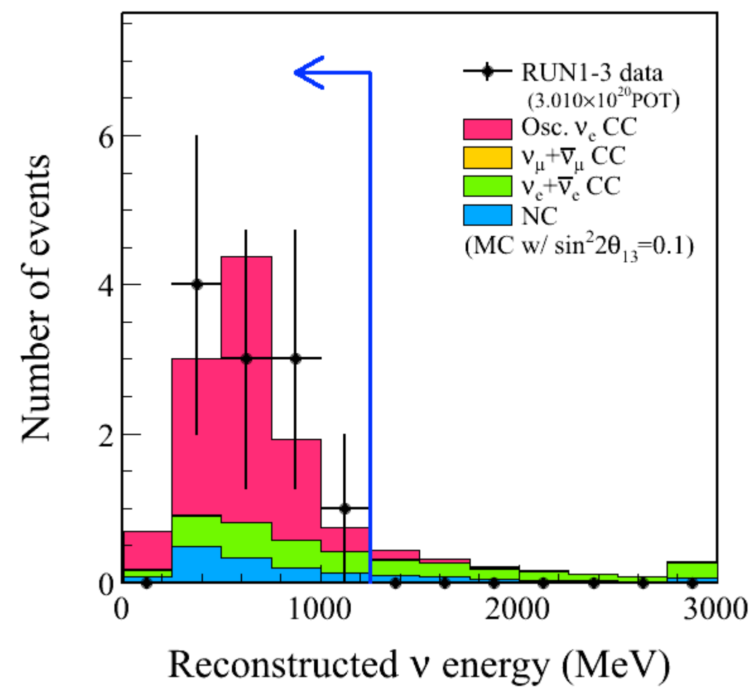
- Selection cuts (cont.)
  8. Reconstructed invariant mass for π^0 is < 105 MeV/c^2



ν_e Event Selection (cont.)

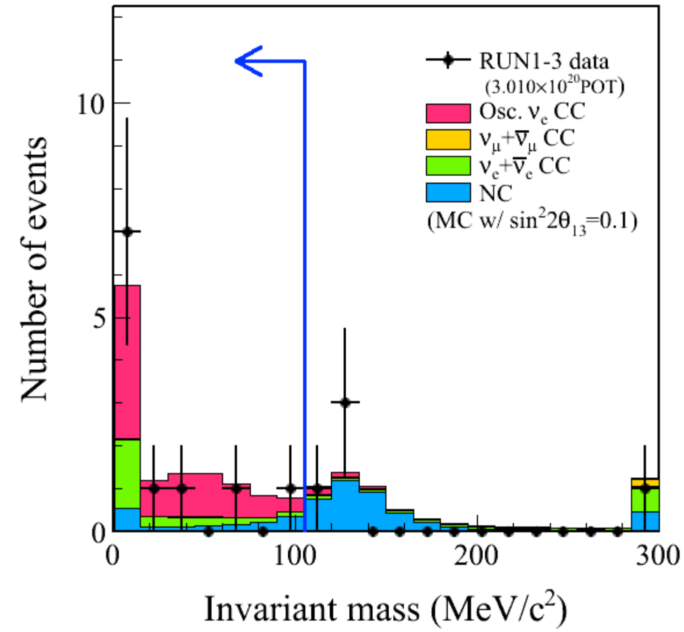
- Selection cuts (cont.)
  8. Reconstructed invariant mass for π^0 is < 105 MeV/c^2
  9. Reconstructed ν energy is < 1250 MeV

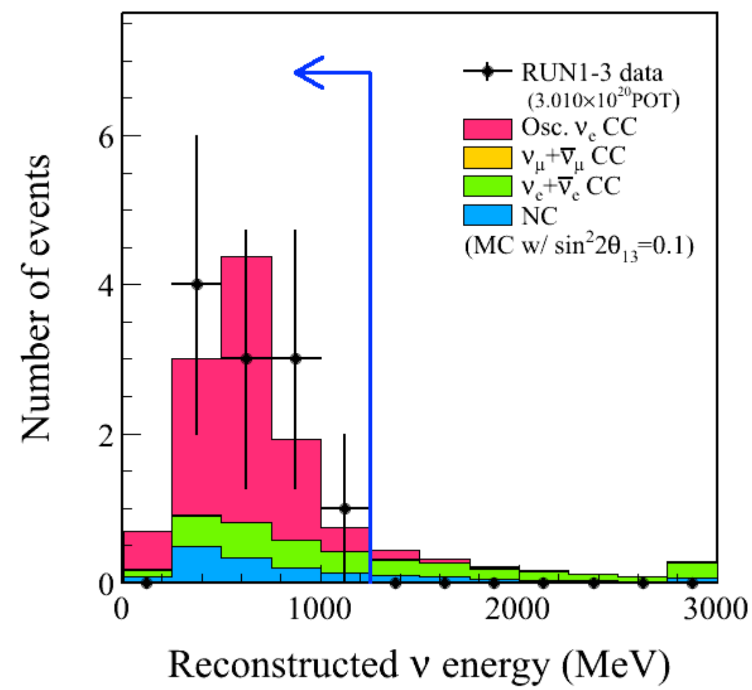




ν_e Event Selection (cont.)

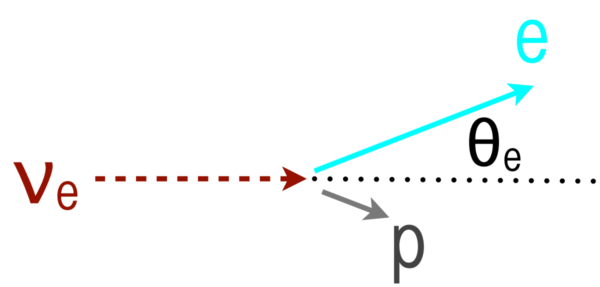
- Selection cuts (cont.)
  8. Reconstructed invariant mass for π^0 is < 105 MeV/c^2
  9. Reconstructed ν energy is < 1250 MeV



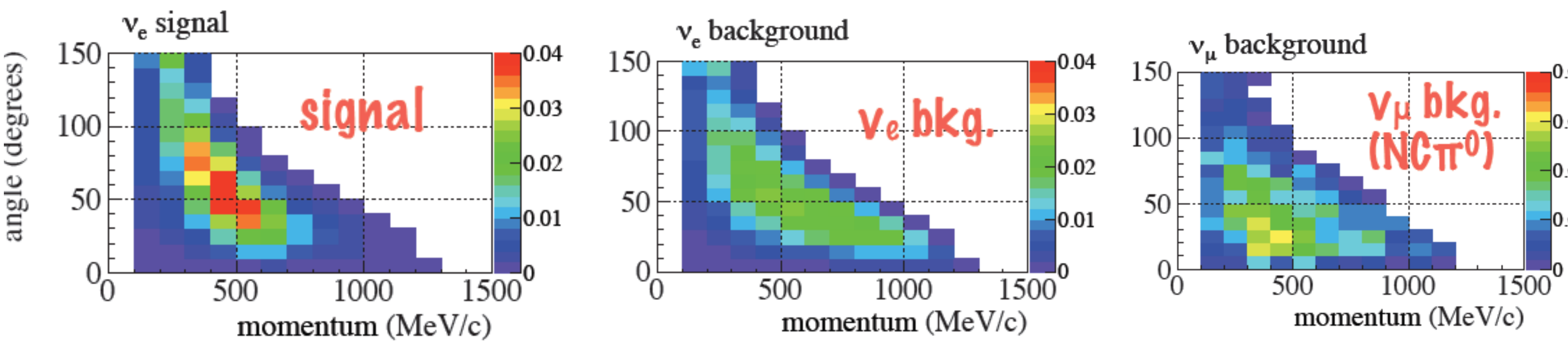


- **11 events observed**
- Predicted number of events:
  - **3.2** ($\sin^2 2\theta_{13}$=0.0)
  - **10.7** ($\sin^2 2\theta_{13}$=0.1)

Fit for Oscillation Parameters

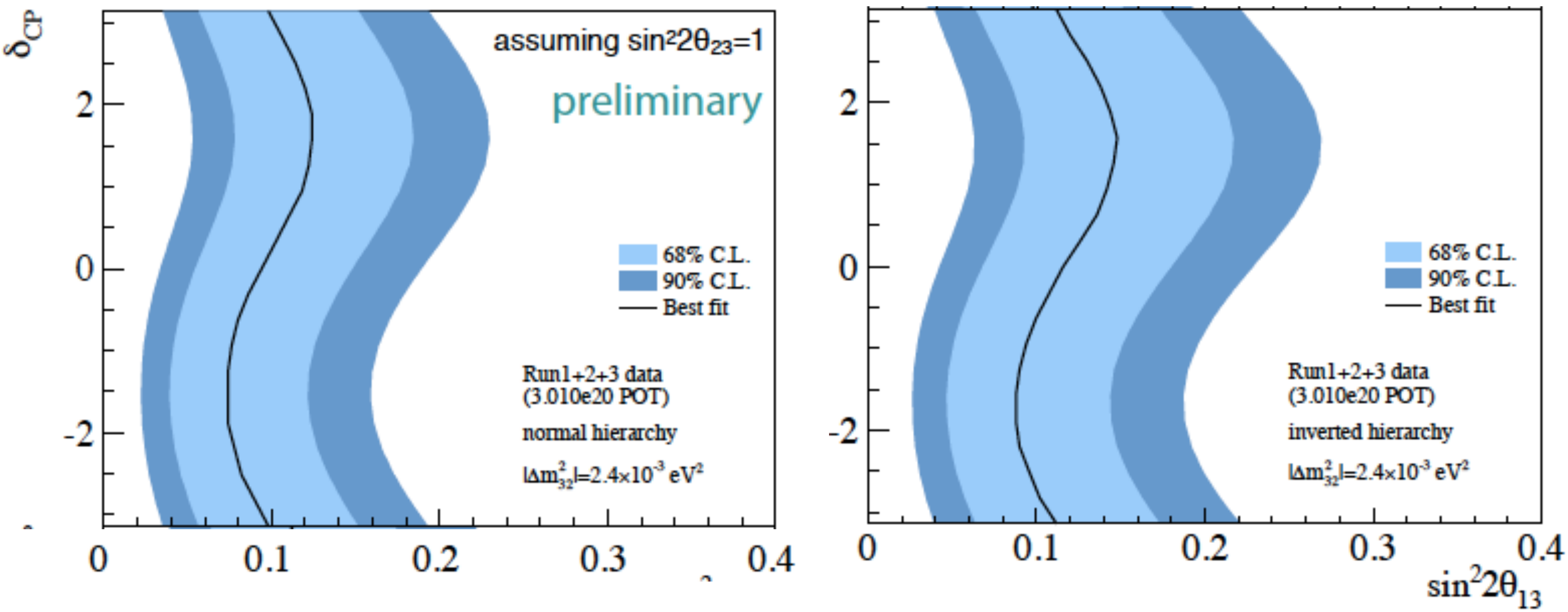


- Data is fit to the event rate in bins of electron momentum and angle.



- Independently checked with fits to energy spectrum, and total number of events only.

Allowed Parameters



- Preliminary results shown at ICHEP 2012
- $\sin^2 2\theta_{13}=0.0$ is **excluded** at the **3.2σ level**
- For $|\Delta m_{23}^2|$ fixed at 2.4×10^{-3} eV^2, best fit ($\delta_{cp}=0$) $\sin^2 2\theta_{13}=0.094$(normal); $=0.116$(inverted)
- Good agreement with best fit from recent reactor results

Future Plans for T2K

- Results on ν_e appearance and ν_μ disappearance for full Run 1,2,3 dataset with 3.01×10^{20} protons on target are being prepared for publication this fall
- Many neutrino cross section measurements are being performed in the near detector.

- Plan to collect ~20 times more data, Linac will be upgraded in 2013
- Goals:
  - Total of 8×10^{20} protons by end of 2013
  - Total of 1.2×10^{20} protons by end of 2014
  - Total of 1.8×10^{21} protons by end of 2015
- Run 4 data taking has just begun.