14th International Workshop on Neutrino Factories, Super Beams and Beta Beams

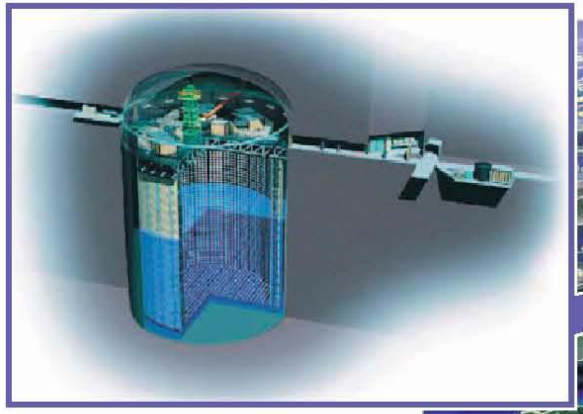
Results from T2K

Clark McGrew
For the T2K Collaboration

- The T2K Experiment
- Recent Results
  - Electron Neutrino Appearance
  - Muon Neutrino Disappearance
- Summary and Future Directions

The T2K Experiment

(Tokai-to-Kamioka)



Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

- Neutrino Oscillation Physics
  - Discovery of electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$)
    - Measure θ_{13}, δ_{CP}

2011 ν_e result: PRL 107, 041801, 2011: non appearance probability: 0.7%

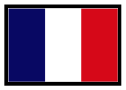
  - Precision measurement of muon neutrino disappearance
    - Measure θ_{23}, Δm^2_{13}

2011 ν_μ results: PRD 85, 031103(R), 2012

The T2K Collaboration

Canada

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



France

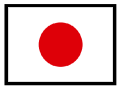
CEA Saclay
IPN Lyon
LLR E. Poly
LPNHE Paris

Germany

Aachen U.

Italy

INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma



Japan

ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu
Osaka City U.
U. Tokyo

Poland

IFJ PAN, Cracow
U Silesia, Katowice
NCBJ, Warsaw
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia

INR

S Korea

Chonnam N. U.
Dongshin U.
Seoul N. U.

Spain

IFIC, Valencia
IFAE, Barcelona

Switzerland

ETH Zurich
U. Bern
U. Geneva

UK

Imperial C. L
Lancaster U
U. Liverpool
Oxford U.
Queen Mary U. L
U. Sheffield
STFC/RAL
STFC/Daresbury
U. Warwick

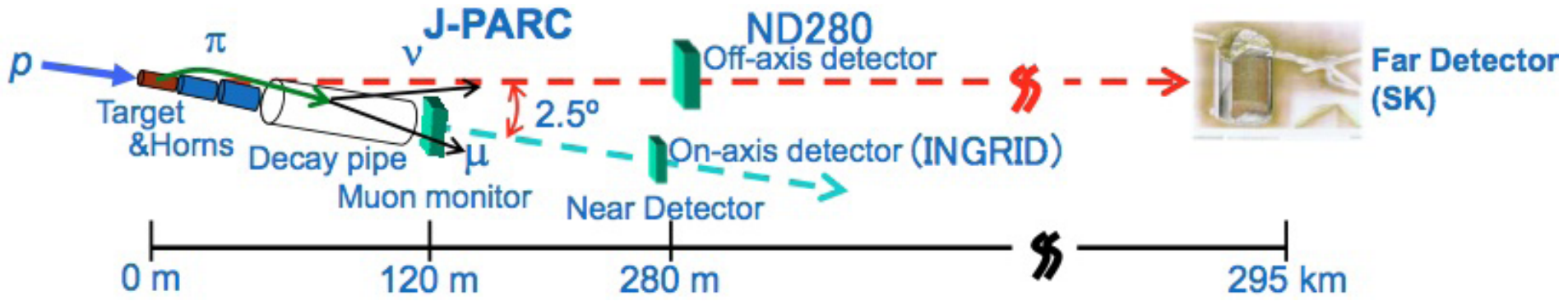
USA

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

Host Institutions — KEK, ICRR

12	Countries
59	Institutions
~500	Members

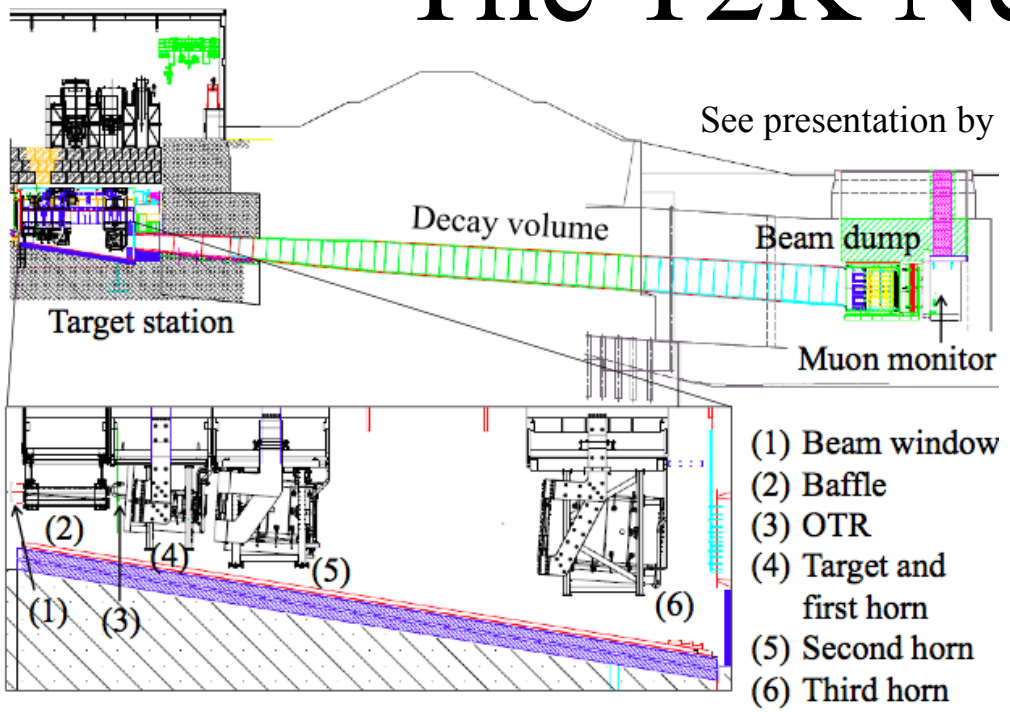
T2K Overview



- High Power Accelerator
  - 30 GeV proton beam on 90 cm graphite target
  - Pion production measured by CERN NA61
- Intense and High Quality Neutrino Beam
  - Three magnetic horns focus positively charged hadrons
- Secondary Beam Monitoring
  - Muon monitors behind beam dump: muon intensity and direction
- High Resolution Near Detector at 280 m
  - INGRID on-axis: ν beam direction and intensity
  - ND280 off-axis: cross sections, ν beam spectrum, flux and flavor
- Far Detector at 295 km @ 2.5 degree off-axis
  - Super-Kamiokande: measure ν flux, spectrum and flavor

Measurements are combined in a joint fit to constrain the ν fluxes and cross sections

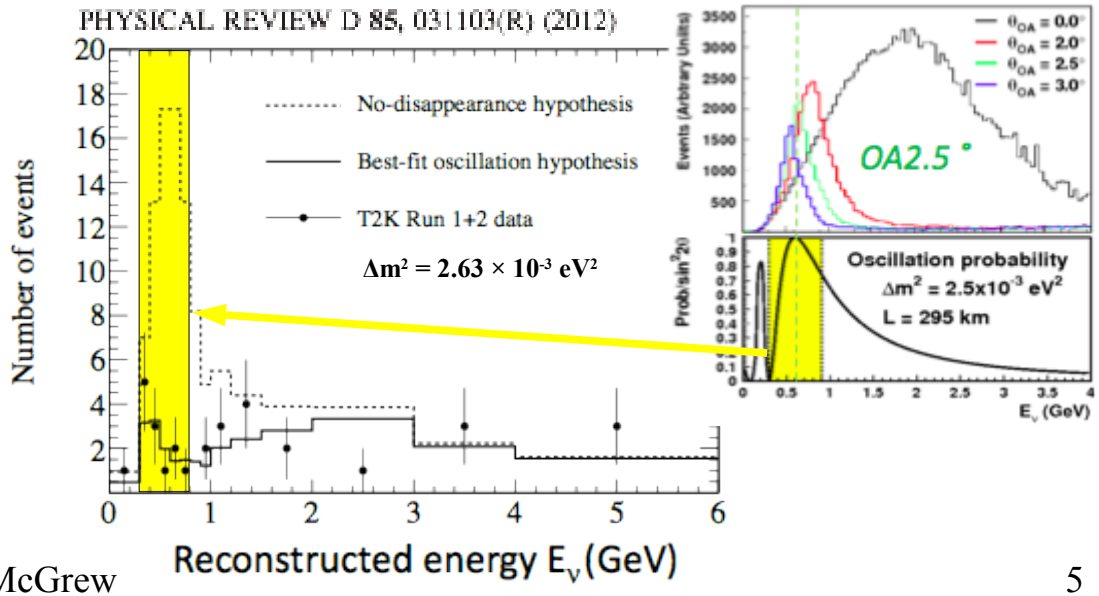
The T2K Neutrino Beam



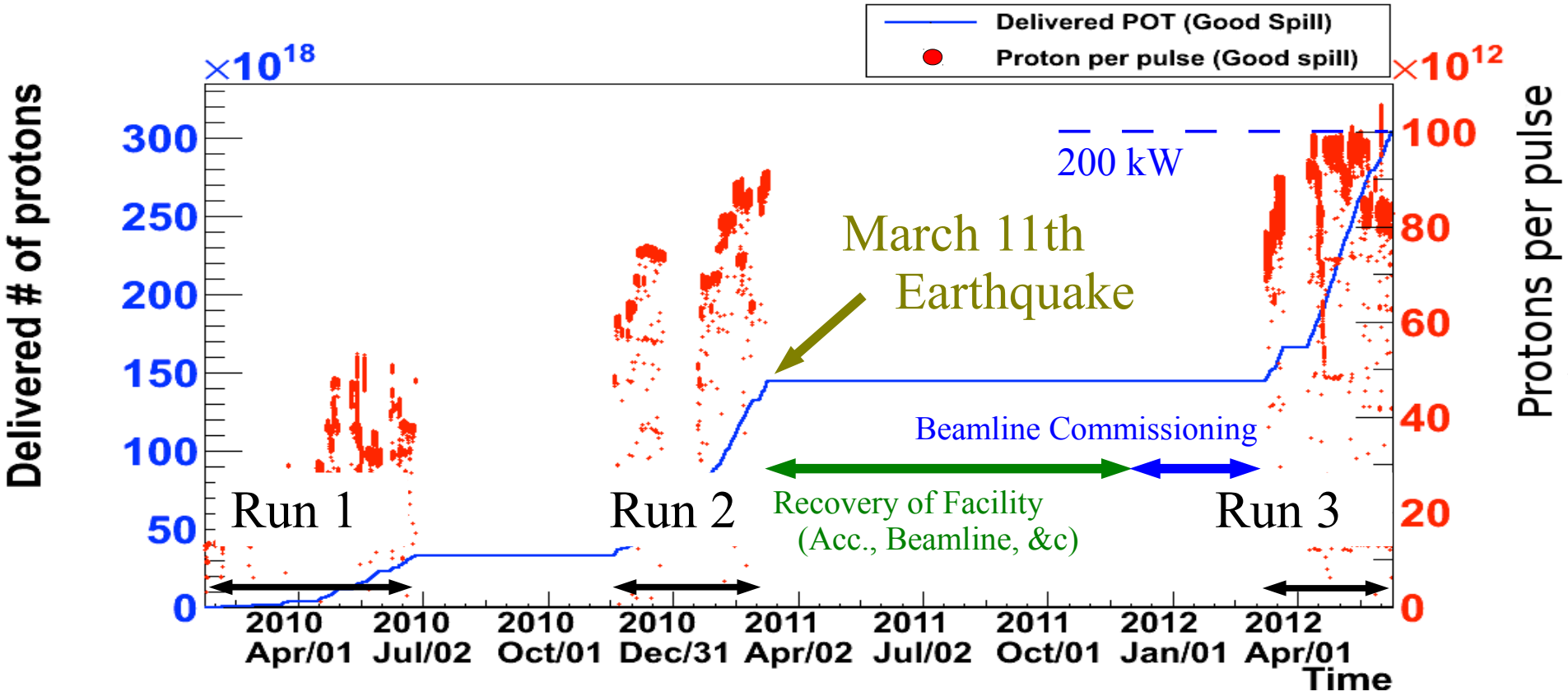
See presentation by T. Ishida (The JPARC ν Beam)

- 2.5 Degree Off-Axis Beam
  - Low energy narrow band beam
    - Peak energy is ~ 600 MeV
      - Tuned to oscillation maximum
      - Shifts by 25 MeV/mrad
  - Reduced background from high energy tail

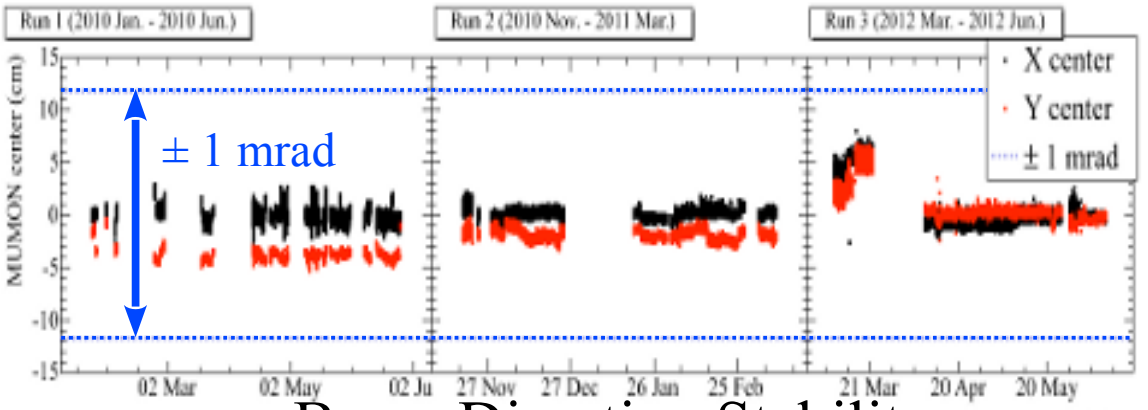
- Intense, High Quality ν Beam
  - Up to 1×10^{14} 30 GeV protons extracted every 2.5 to 3 sec
  - Secondary particles focused by three horns
  - ν_μ mostly from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e from μ and K decays
    - 109 m decay volume
    - Small intrinsic ν_e fraction (~1%)



Beam Performance



- Total : 3.01×10^{20} POT
  - Run 1: 0.32×10^{20} POT
  - Run 2: 1.11×10^{20} POT
  - Run 3: 1.58×10^{20} POT
- Peak Intensity is above 200 kW



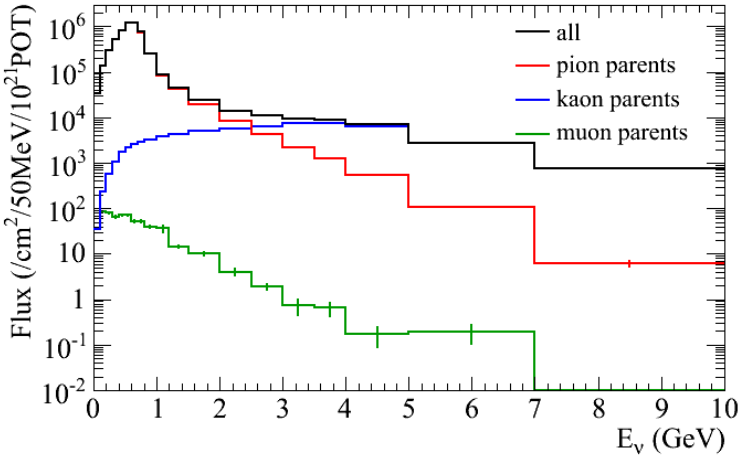
Beam Direction Stability

Neutrino Flux Prediction

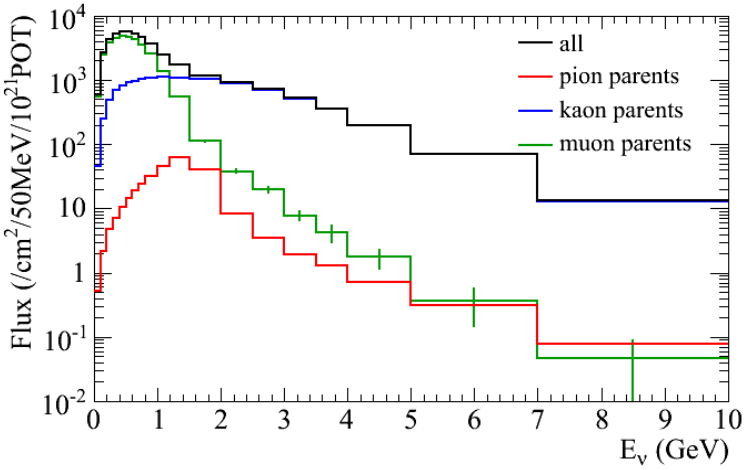
(using CERN NA61 results)

arxiv:hep-ex/1112.0150, 2011
PR C84: 0344603, 2011
PR C85 035210, 2012

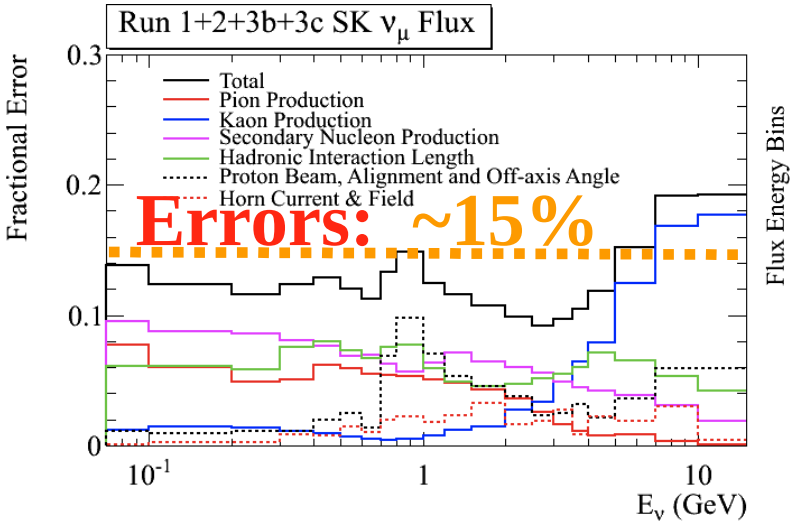
See presentation by S. Murphy (T2K Flux Uncertainties)

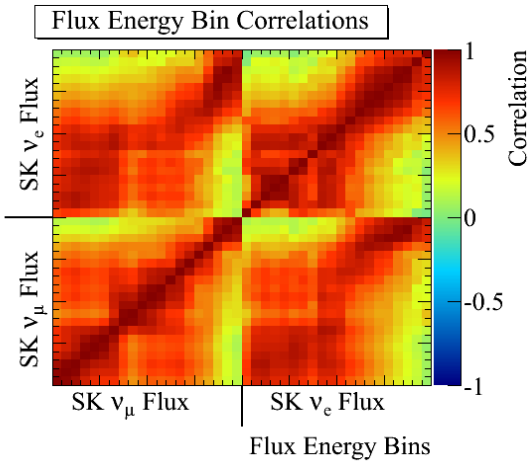


- Hadron production from CERN NA61
  - Both pion and kaon
- Energy dependent errors for ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$
  - Full correlations for ND280 and SK
  - covariance used in flux and cross section fit

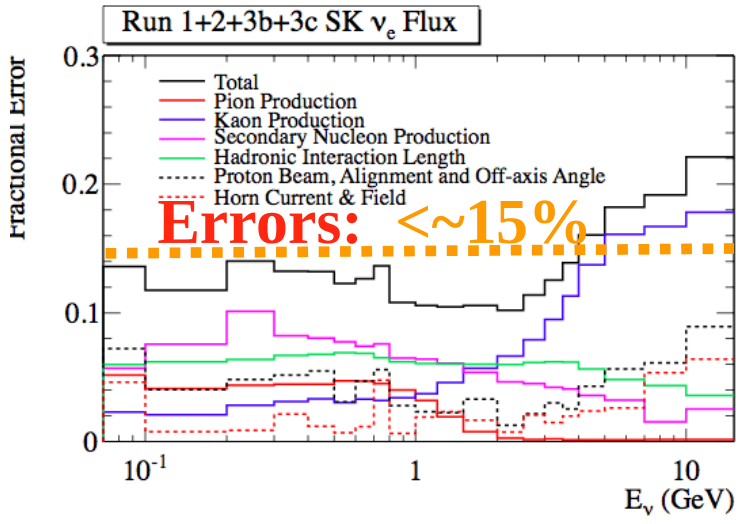


ν_μ Flux and Uncertainty





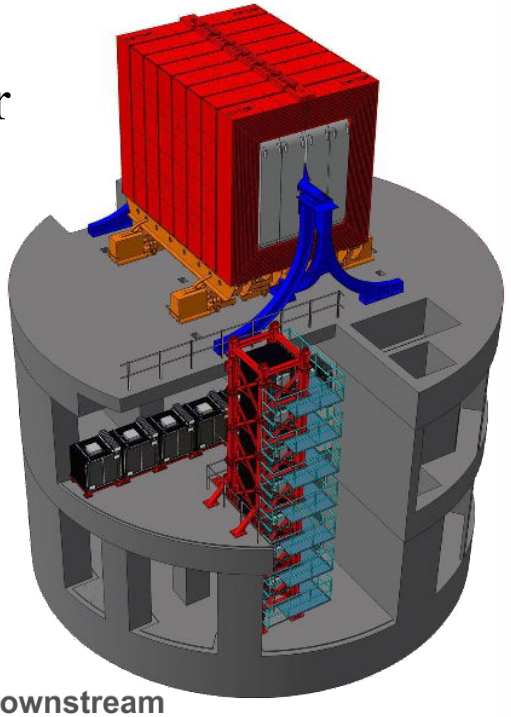
ν_e Flux and Uncertainty

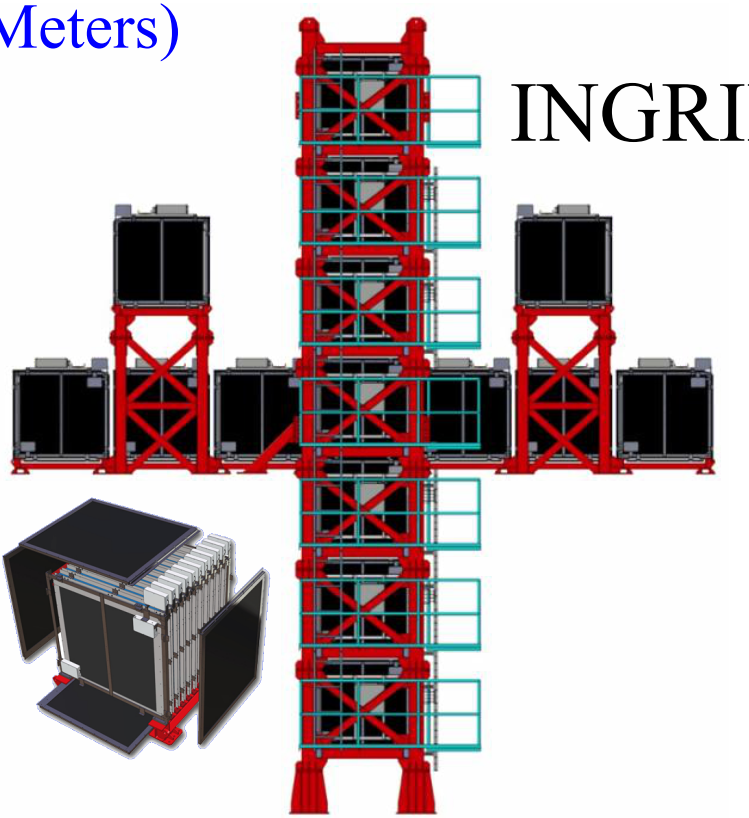


The ND280 Detectors

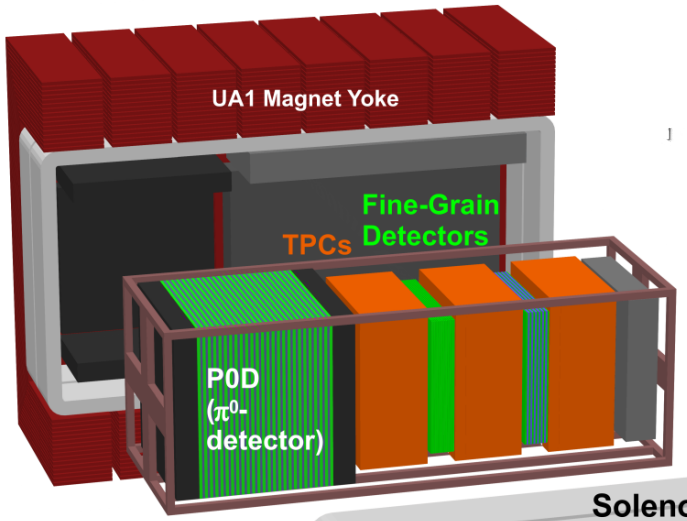
(Near Detectors @ 280 Meters)

- On-Axis: INGRID
  - Neutrino Beam Monitor
    - Direction
    - Rate

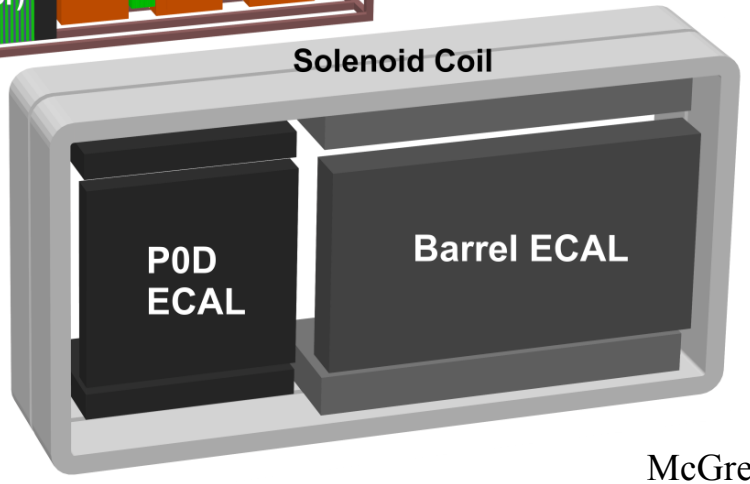




INGRID



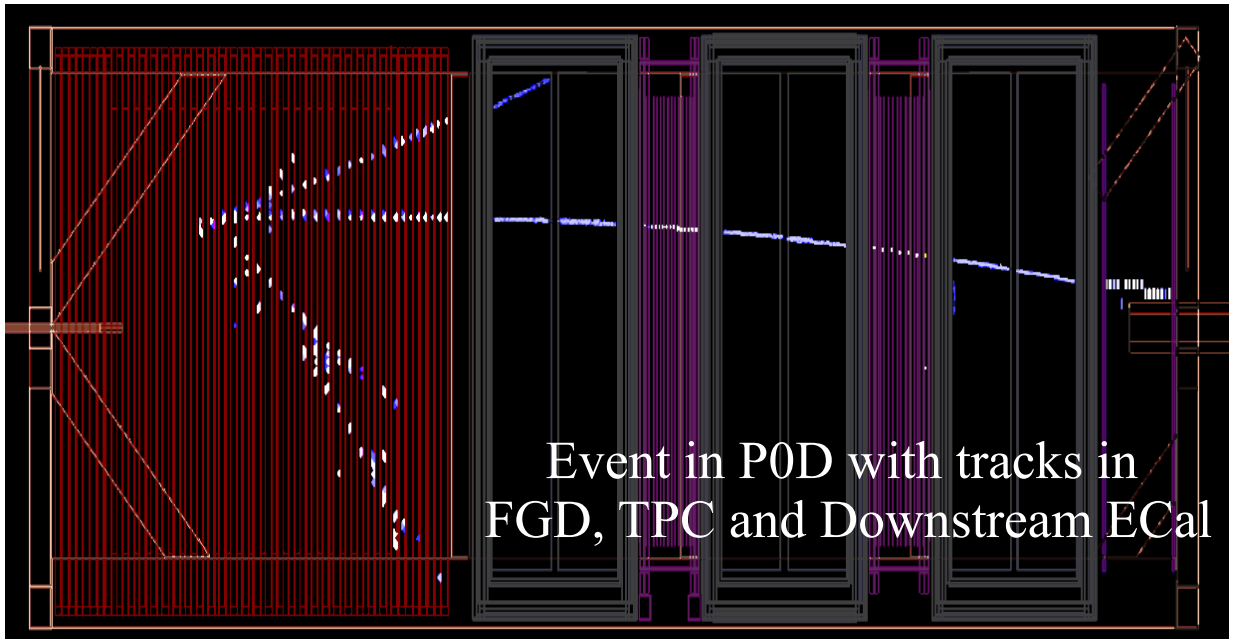
Downstream ECAL



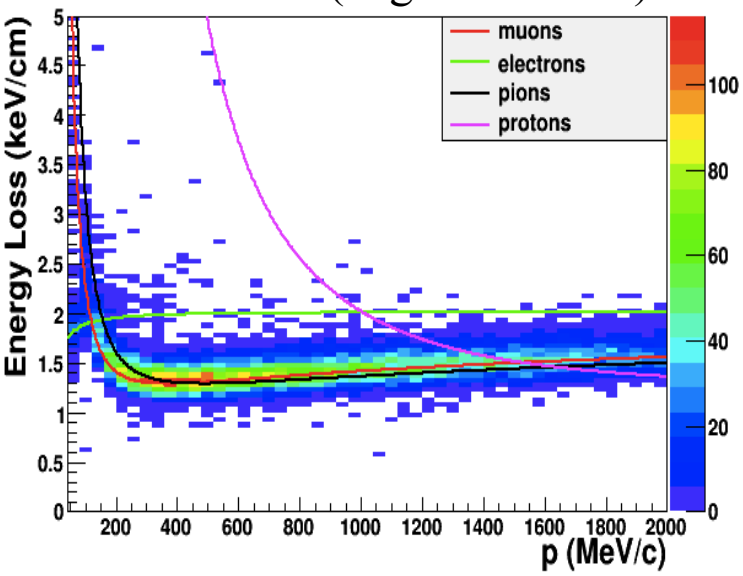
ND280

- Off-Axis: ND280 @ 2.5 deg
  - Off-axis flux normalization
  - Neutrino cross sections
  - In UA1/NOMAD magnet (0.2 T)
    - Target+Particle Tracking
    - π^o detection
    - EM calorimetry
    - Side muon range detection

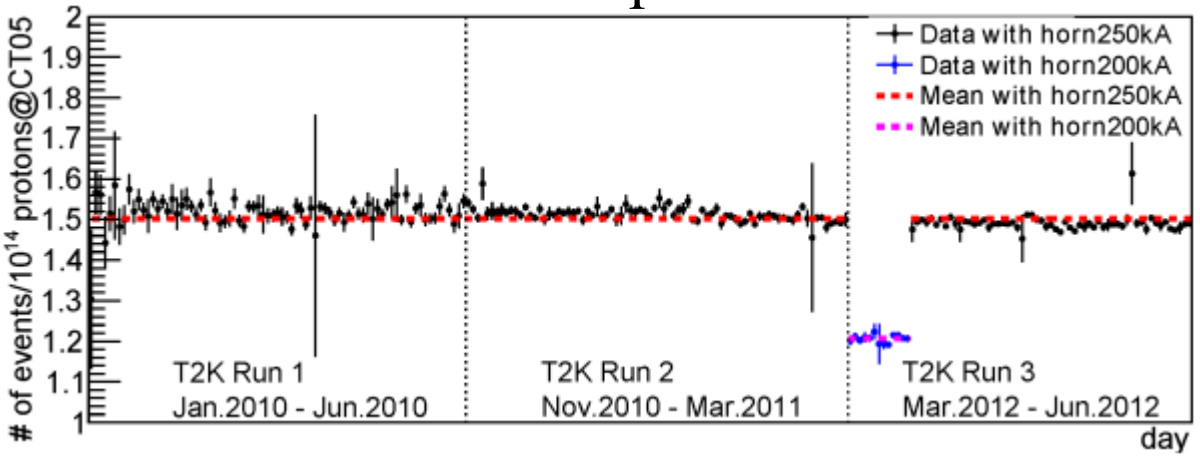
ND280 Performance



TPC dE/dX (negative tracks)

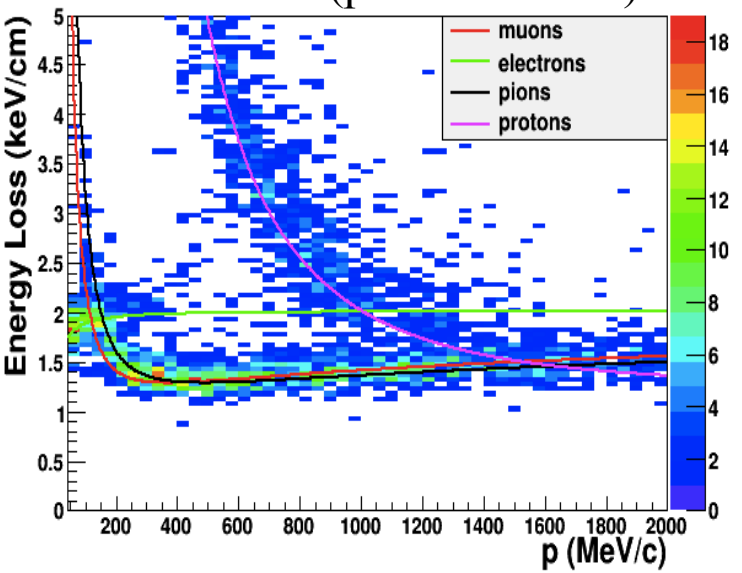


INGRID Event Rate per P.O.T



No pileup correction applied

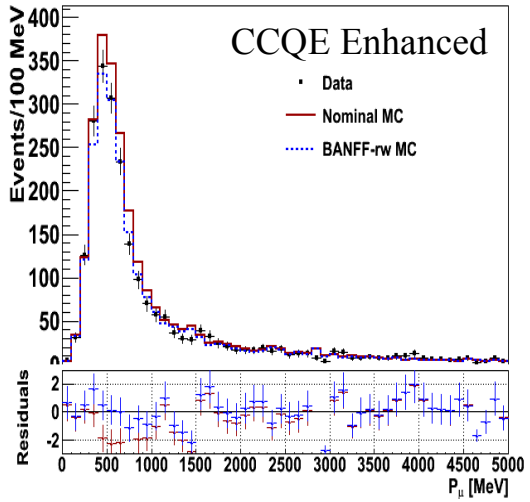
TPC dE/dX (positive tracks)

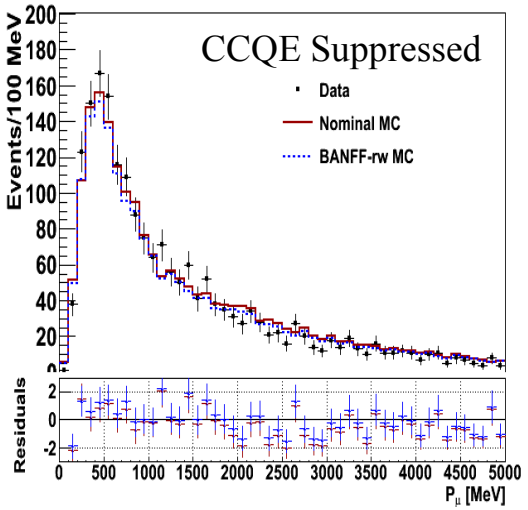


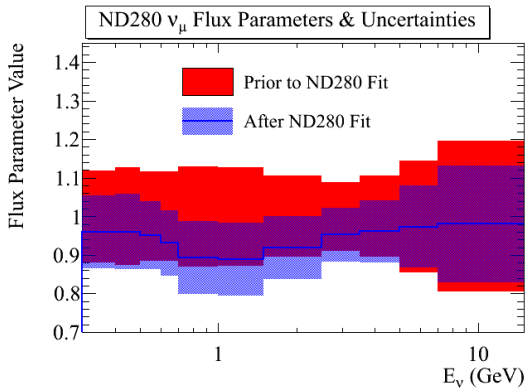
ND280 ν_μ Measurements and Fit

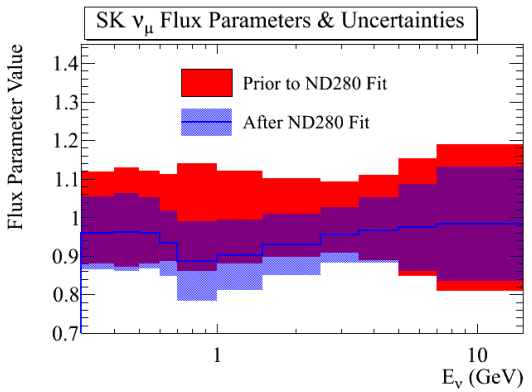
(Run 1 & 2 w/ 1.08×10^{20} POT)

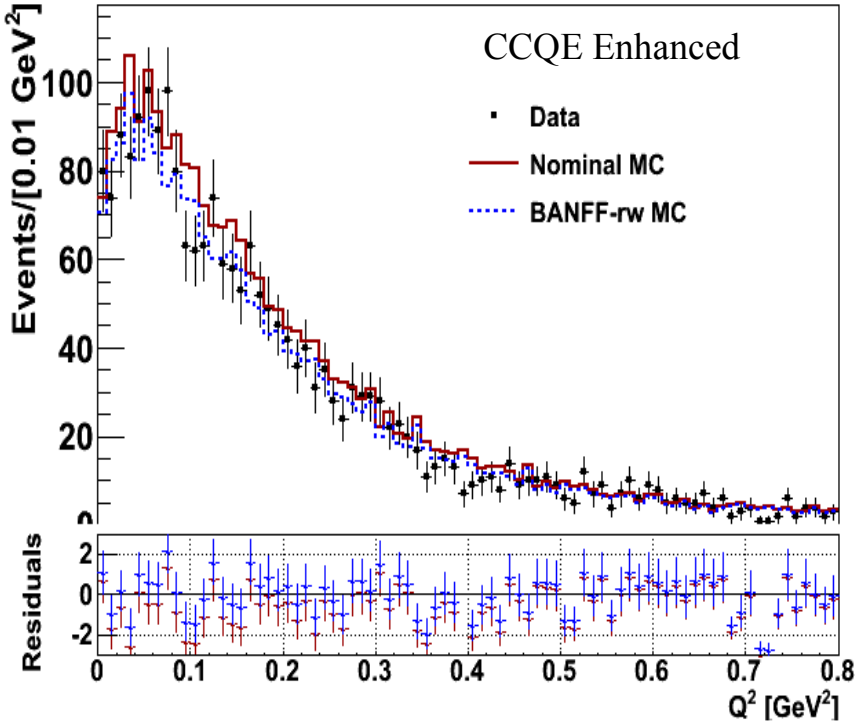
- Number of events in P_μ vs θ_μ used in fit to constrain flux and cross section
  - Use external data for prior constraint of cross sections









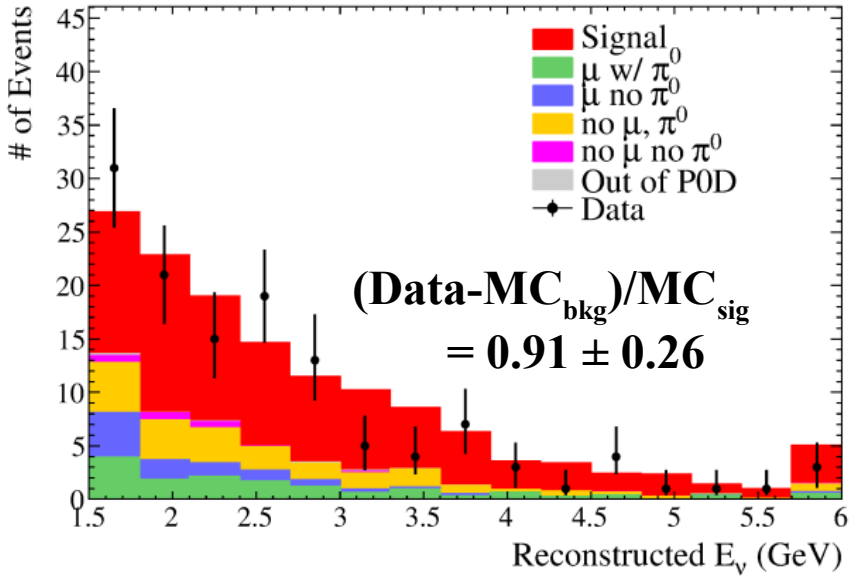


- Basic Selection
  - Negative track in FV
  - Veto events with upstream TPC
  - Muon ID uses TPC
- CCQE selection:
  - 40% efficiency w/ 72% purity
  - 1 FGD+TPC Track
  - No decay electron signal in FGD

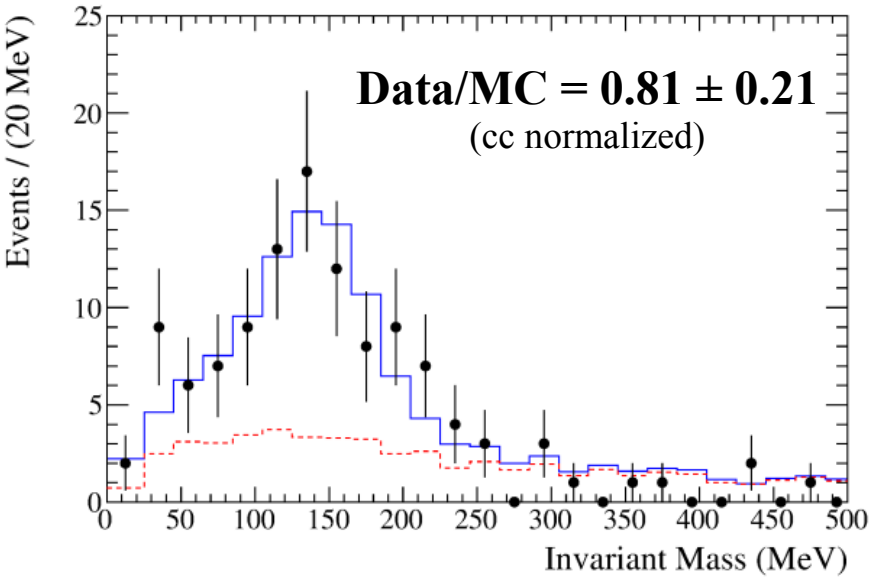
See presentation by K. Mahn (ND280 Constraints)
See presentation by P. Rodrigues (NEUT MC Tuning)

ND280 ν_e and NC π^o Rates

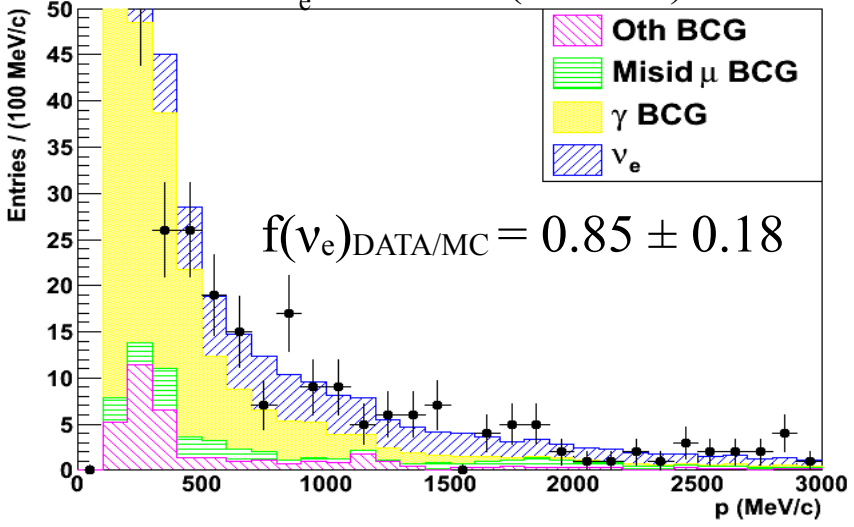
High energy ν_e event rate (PØD)



Neutral current π^o event rate (PØD)



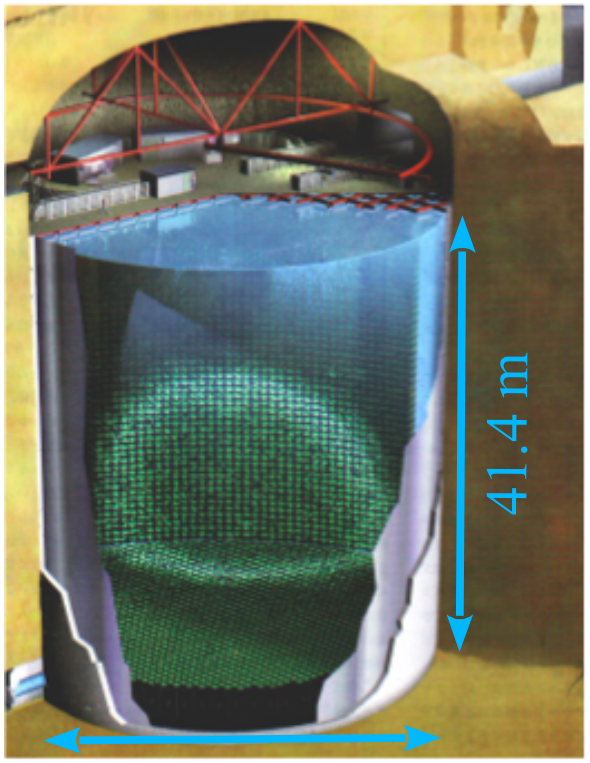
Enhanced ν_e selection (Tracker)



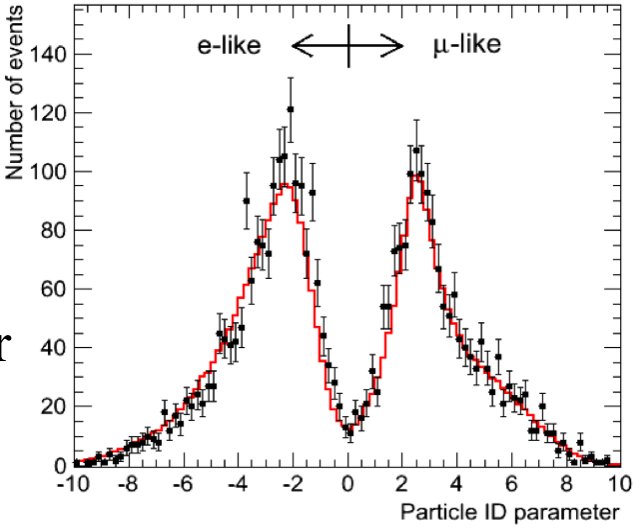
- Dominant T2K ν_e backgrounds are measured in the ND280
  - Intrinsic Beam ν_e
  - Neutral Current π^0
- Rates are consistent with MC prediction

See presentation by G. Christodoulou (T2K Cross Section Measurements)

The T2K Far Detector: Super-Kamiokande

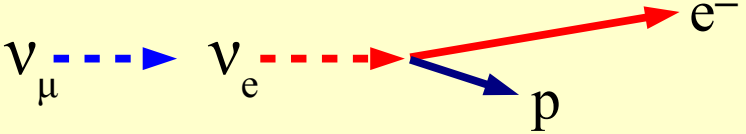


- 50 kt Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
  - Typically 61% ν_e signal eff. w/ 95% π^o rejection
    - 32 kt inner volume (22.5 kt fiducial)
    - 2 m outer volume to identify entering particles
- Probability to mis-id muon as electron is ~ 1%
- Dead-time free DAQ
  - All triggers in ±0.5 ms of neutrino arrival time recorded
- GPS time recorded in real-time for every spill



Signal: Single-ring e-like

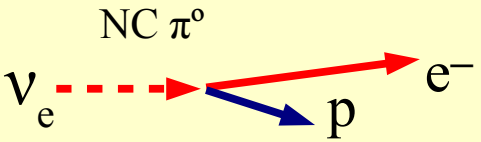
assumed to be CCQE

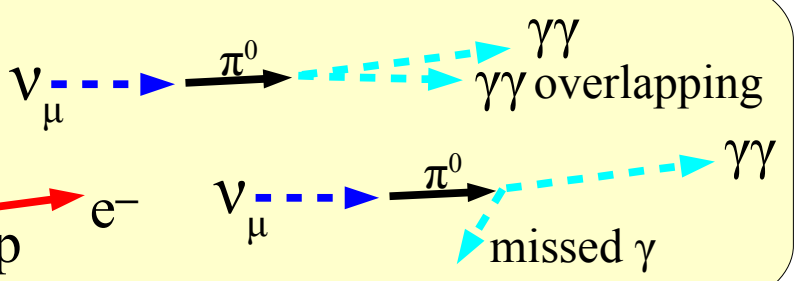


Background

intrinsic ν_e

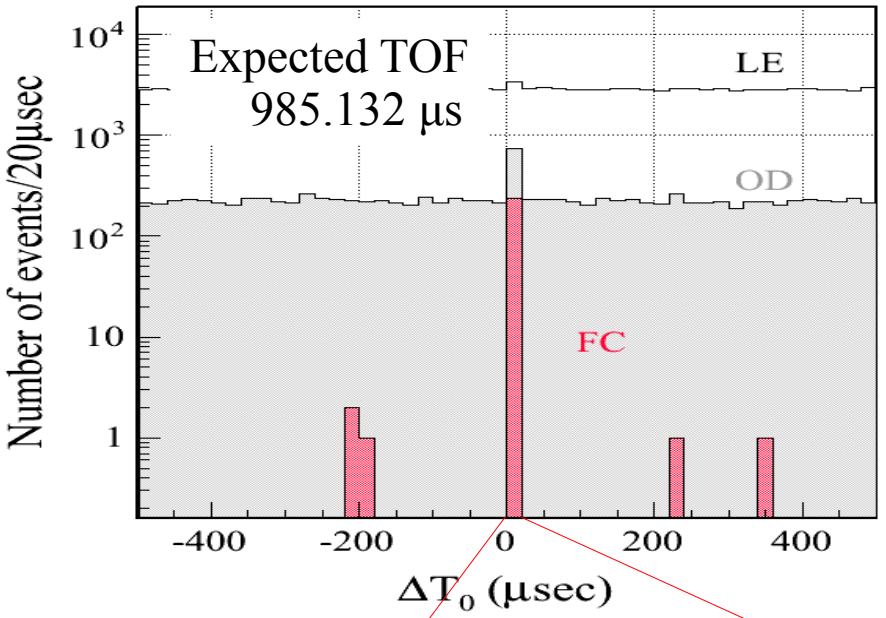
NC π^o

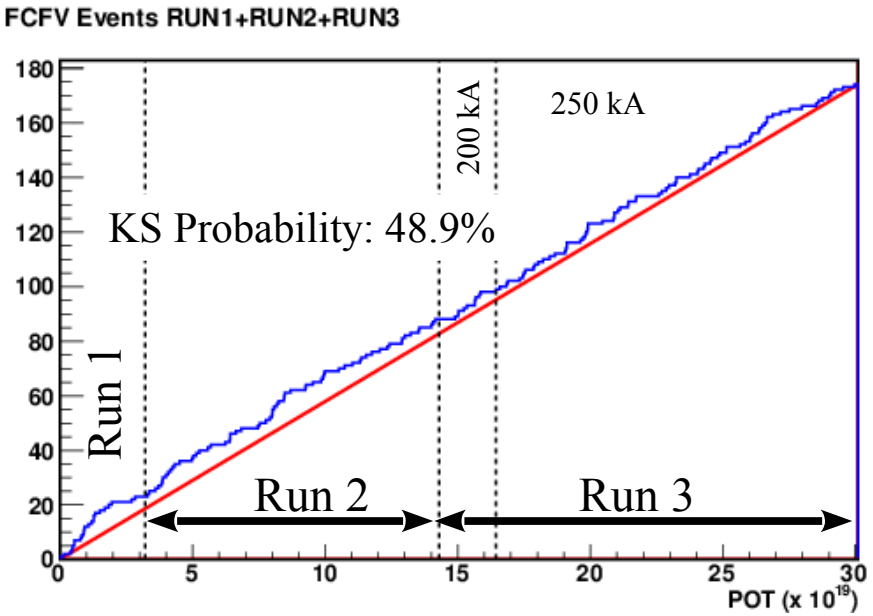


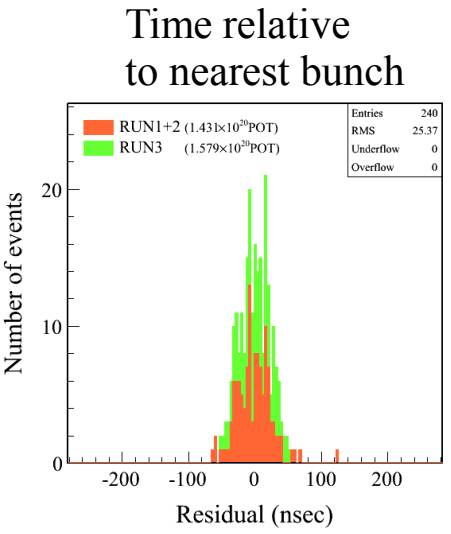


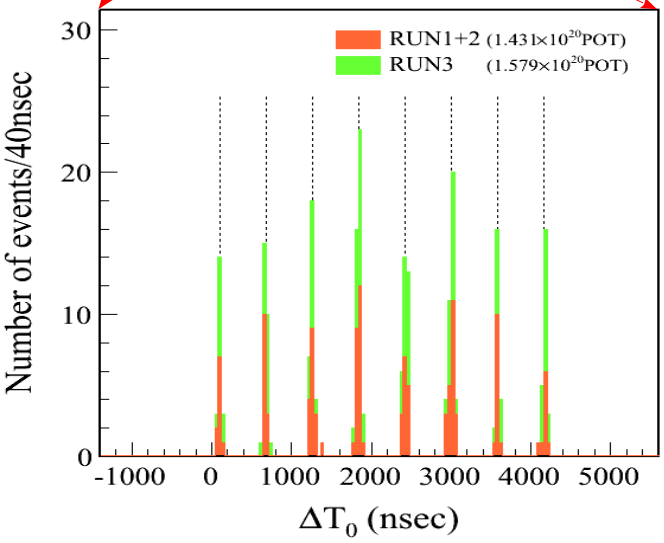
Far Detector Event Selection

- T2K beam timing
  - Within ± 500 μs of expected arrival time
- Fully Contained (FC)
  - No signal in outer detector
- Vertex in fiducial volume
  - > 2 m from wall



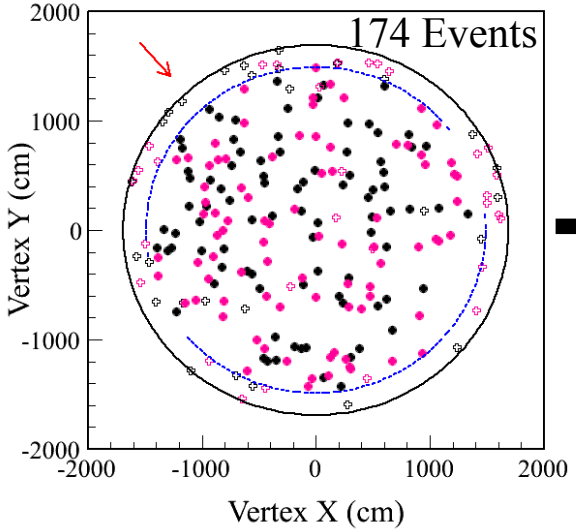




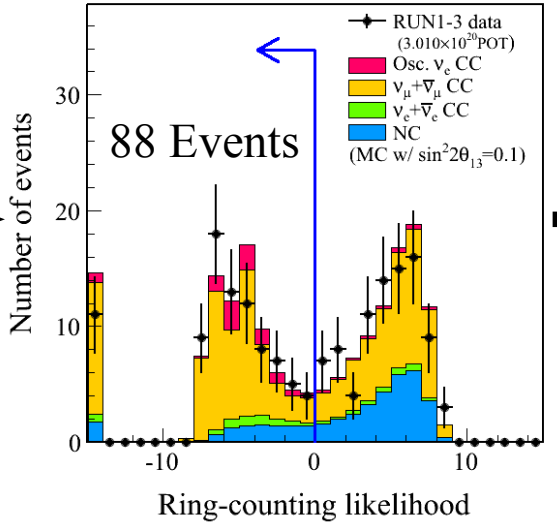


Far Detector Basic ν_e Selection

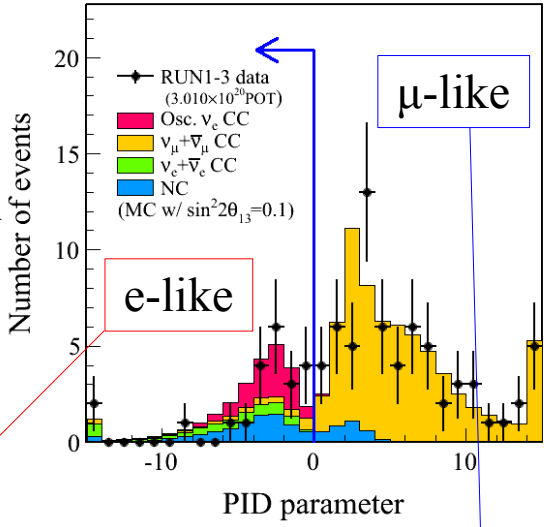
Fully Contained and in Fiducial Volume



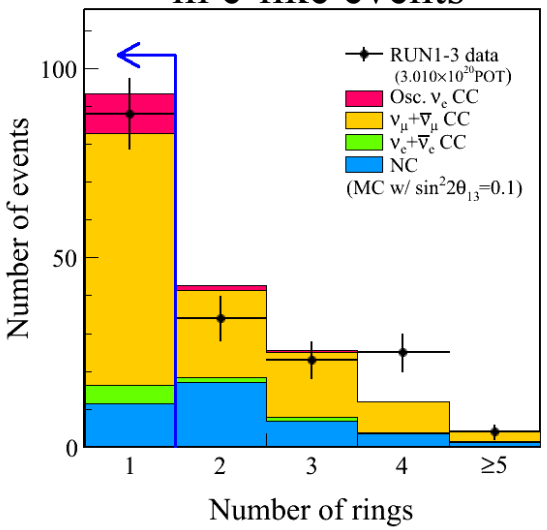
Ring Counting: Single Ring



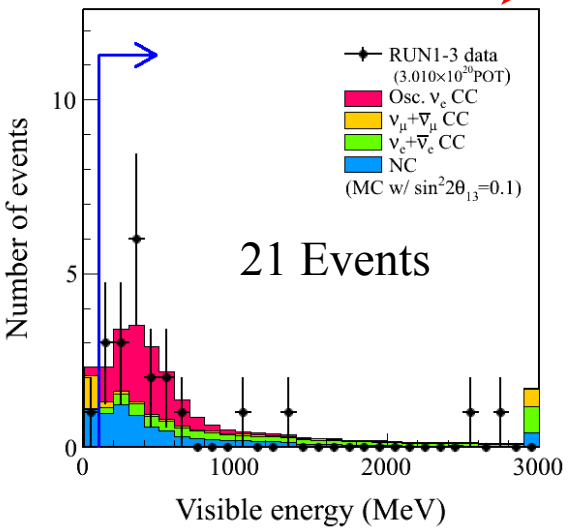
Particle Id: Electron-Like



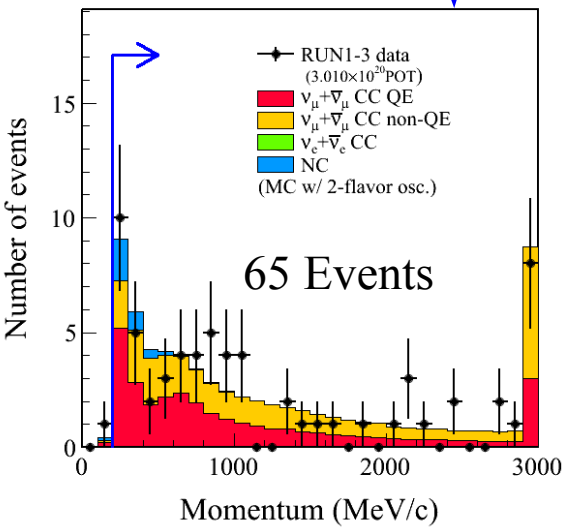
Number of Rings in e-like events



Electron Candidates



Muon Candidates

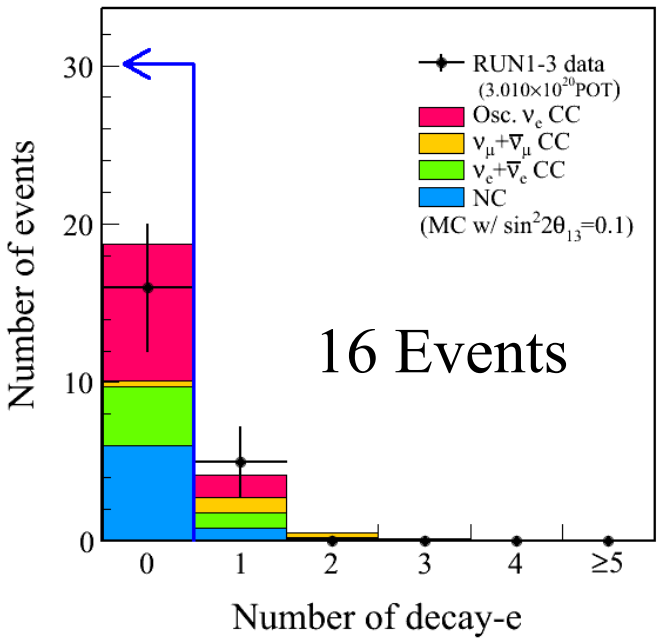


Summary of Far Detector Events

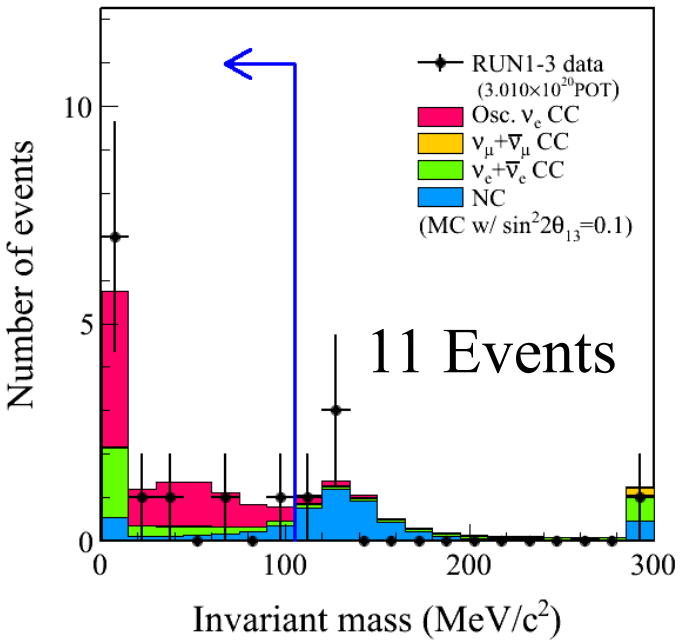
RUN1+2+3 3.010×10^{20} POT	Data	MC Expectations			BG (12μs window)
		$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0$	No osc.	
FC	240	231.6	216.4	465.8	0.039
FCFV	174	163.4	152.7	322.0	0.0048
Single-ring	88	85.6	76.5	222.7	
μ-like (p_μ>200MeV/c)	66 (65)	61.8 (61.4)	61.8 (61.4)	201.4 (200.1)	
e-like (p_e>100MeV/c)	22 (21)	23.8 (21.7)	14.7 (12.8)	21.4 (14.8)	
Multi-ring	86	77.8	76.2	99.2	

Far Detector Final ν_e Selection

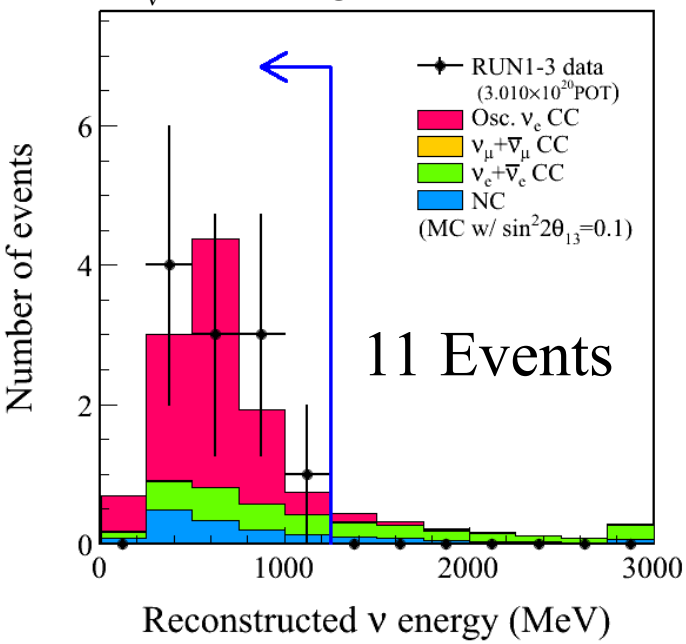
No Muon Decay Signals



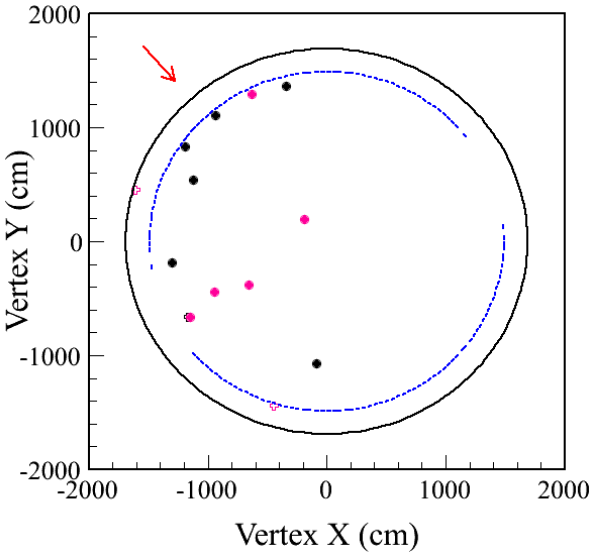
Invariant mass assuming $\gamma\gamma$



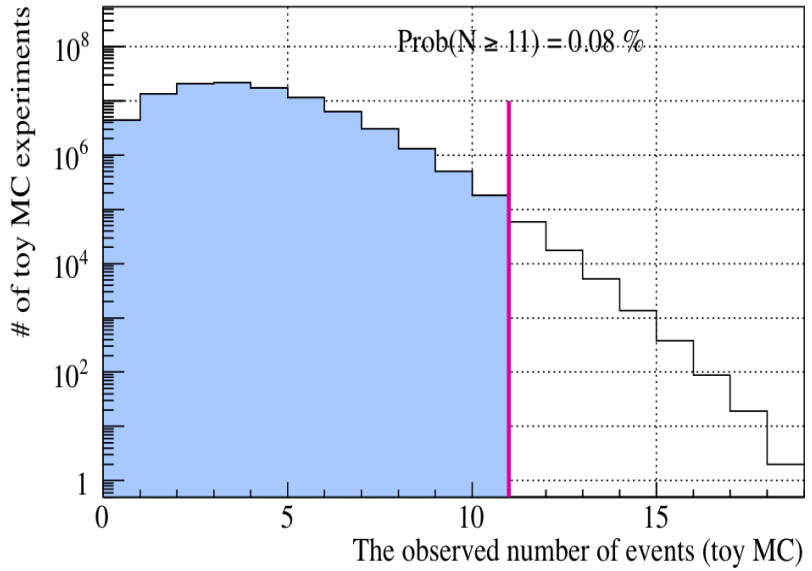
E_ν assuming CCQE

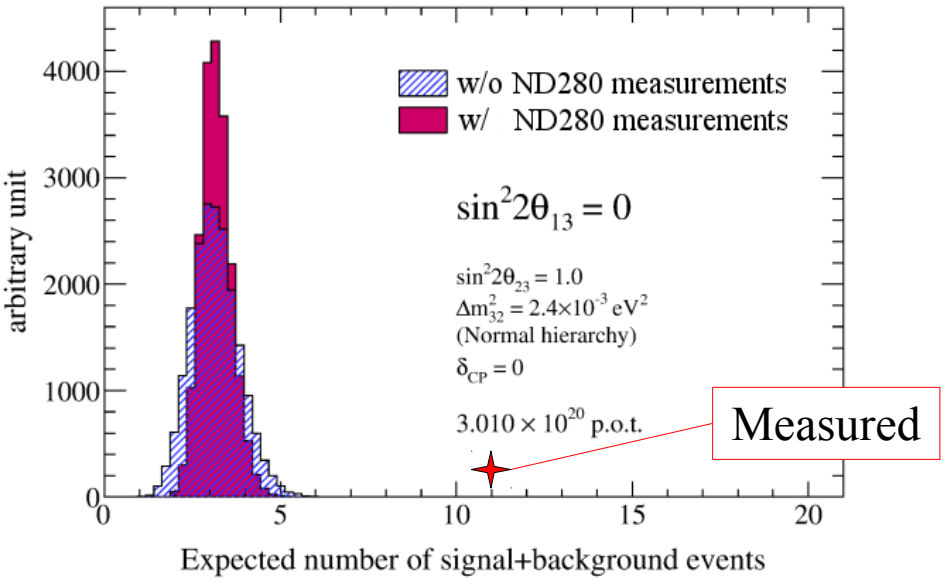


Event Category	**$\sin^2 2\theta_{13} = 0$**	**$\sin^2 2\theta_{13} = 0.1$**
Total	**3.22 ± 0.43**	**10.71 ± 1.10**
ν_e Signal	0.18	7.79
Intrinsic ν_e Background	1.67	1.56
ν_μ Background (mostly π^o)	1.12	1.12
$\bar{\nu}_e + \bar{\nu}_\mu$ Background	0.16	0.16



Evidence for Electron Neutrino Appearance



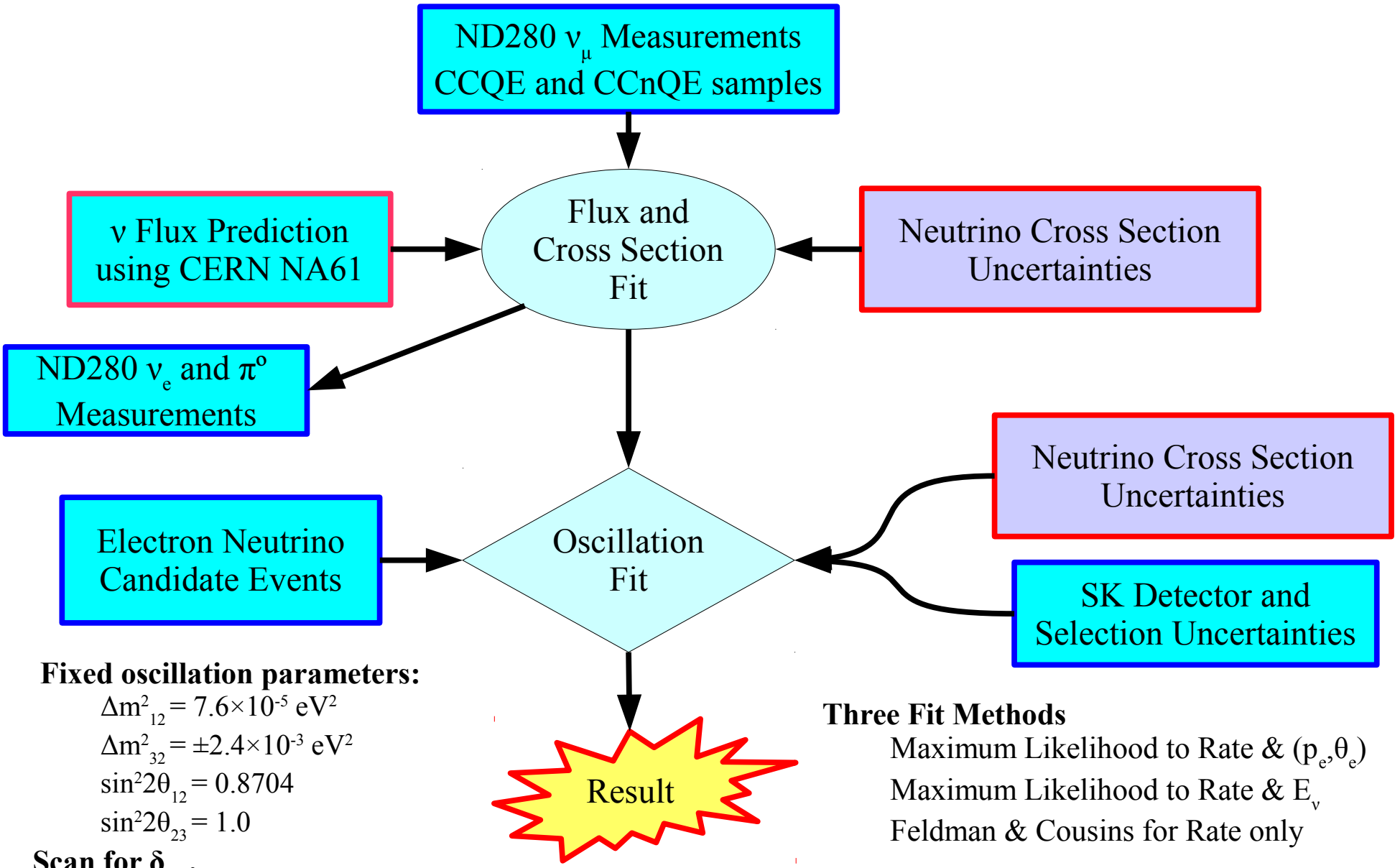


Error Source	Pred. Uncertainty
Beam Flux & ν Int.	8.7%
External X-Sec Meas.	5.9%
Final State Interactions	3.1%
Far Detector Systematics	7.1%
Total	**13.4%**
Previous Analysis (2011)	23%

	POT	Events
Run 1+2	1.431×10^{20}	6
Run 3	1.579×10^{20}	5
Run 1+2+3	3.010×10^{20}	11

Observed: **11 events**
Predicted: **3.22 ± 0.43 @ 3.01×10^{20} POT**
Probability: **0.08% (i.e. 3.2 σ)**

The ν_e Oscillation Analysis



Fixed oscillation parameters:

$\Delta m^2_{12} = 7.6\times10^{-5}$ eV^2

$\Delta m^2_{32} = \pm2.4\times10^{-3}$ eV^2

$\sin^2 2\theta_{12} = 0.8704$

$\sin^2 2\theta_{23} = 1.0$

Scan for δ_{CP}.

Three Fit Methods

Maximum Likelihood to Rate & (p_e,θ_e)

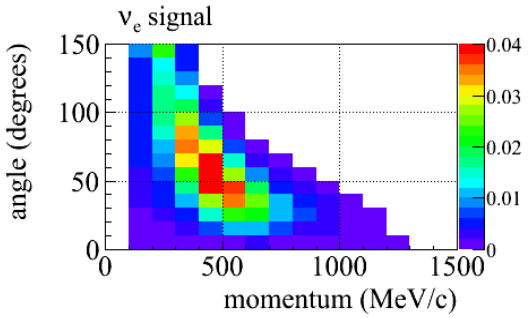
Maximum Likelihood to Rate & E_ν

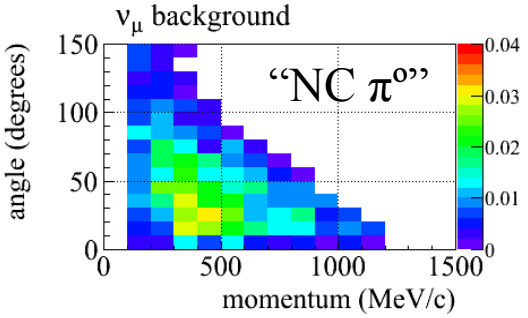
Feldman & Cousins for Rate only

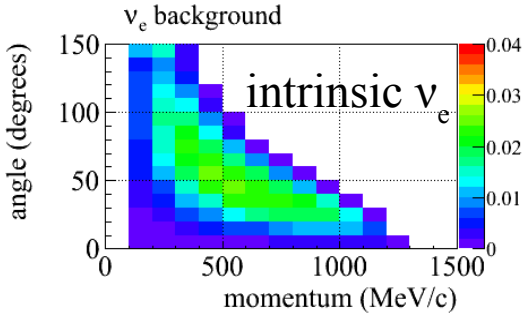
Determining Oscillation Parameters

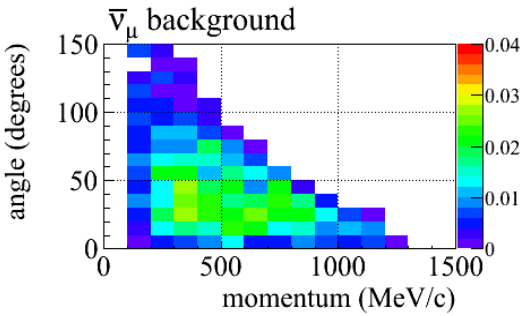
$$L\left(N_{obs}, \vec{x}; o, f\right) = L_{norm}\left(N_{obs}; o, f\right) \times L_{shape}\left(\vec{x}; o, f\right) \times L_{sys}\left(f\right)$$

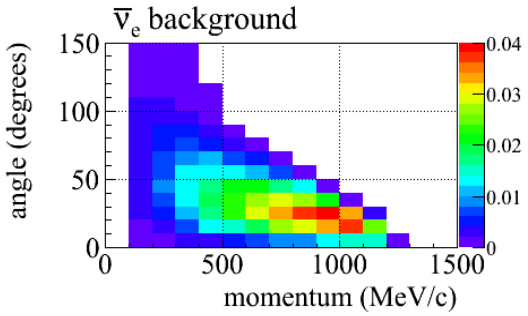
Oscillation Parameters | **Number of Candidates** | **Measured ($\vec{p}_l$, θ_l)** | **Constraints from ND280 and systematic params.**





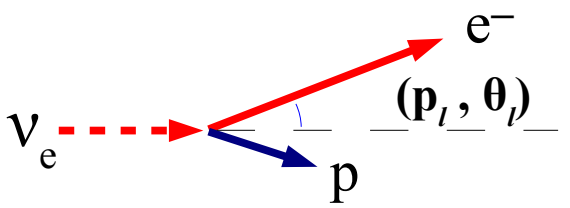






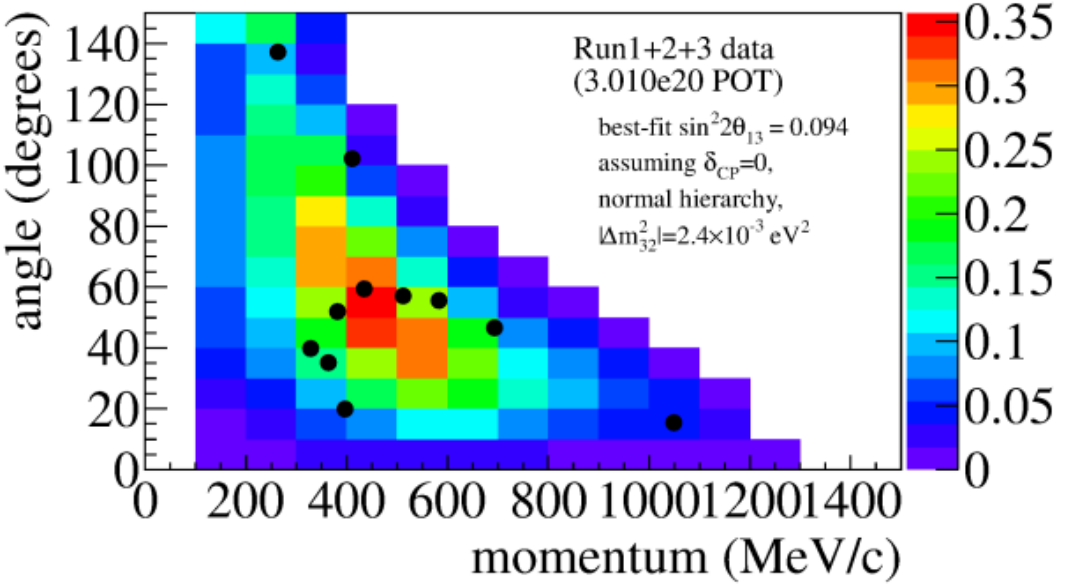
Differences in electron momentum and angle distributions allow signal and background separation

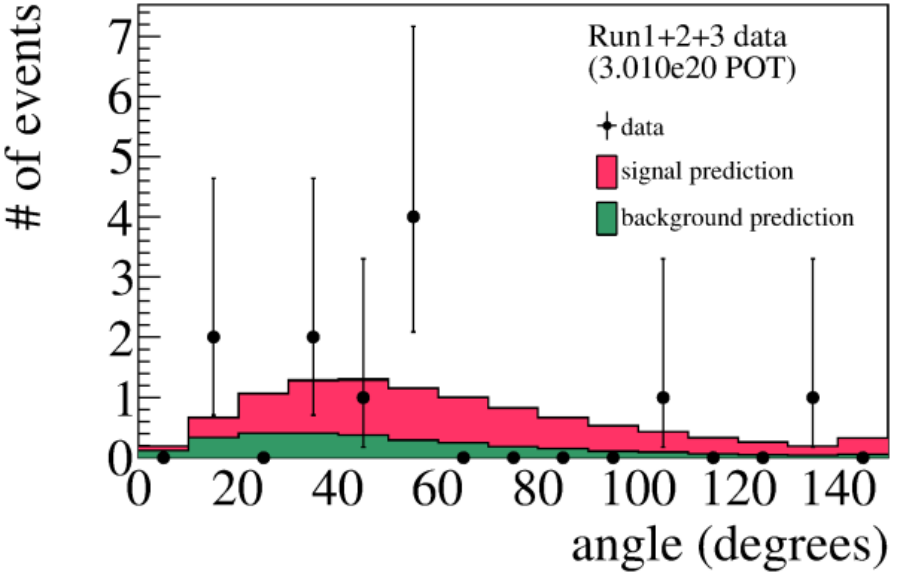
The other two fit methods give consistent results

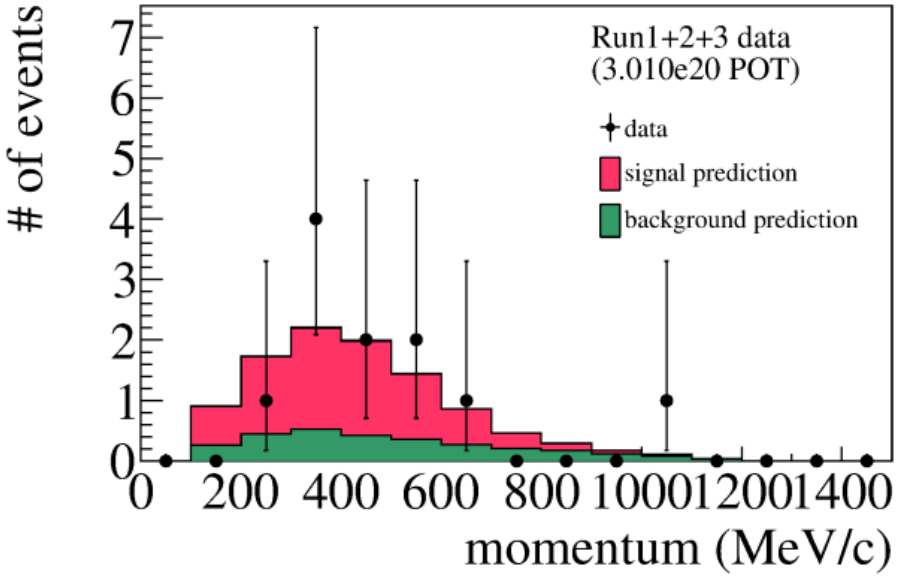


- Extended likelihood fit
  - Number of observed events
    - 11 ν_e candidates
  - Lepton Momentum
  - Lepton Angle
- Includes constraint terms
  - ND280 fit
  - Independent SK systematics

Oscillation Analysis Results (Normal Hierarchy)







Normal Hierarchy
with $\delta_{cp} = 0$

$|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2

$\sin^2 2\theta_{32} = 1$

Best Fit: $\sin^2 2\theta_{13} = 0.094$

68% C.L. $0.054 < \sin^2 2\theta_{13} < 0.147$

90% C.L. $0.033 < \sin^2 2\theta_{13} < 0.188$

θ_{13} vs δ_{CP}

Fixed oscillation parameters:

$\Delta m^2_{12} = 7.6\times10^{-5}$ eV^2

$\Delta m^2_{32} = \pm2.4\times10^{-3}$ eV^2

$\sin^2 2\theta_{12} = 0.8704$

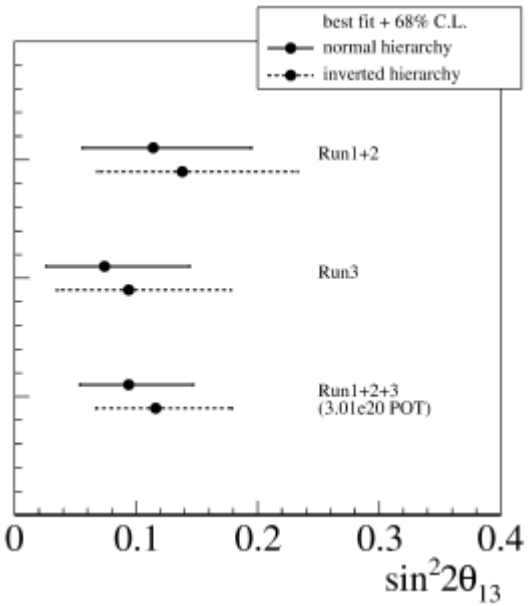
$\sin^2 2\theta_{23} = 1.0$

δ_{CP} is scanned

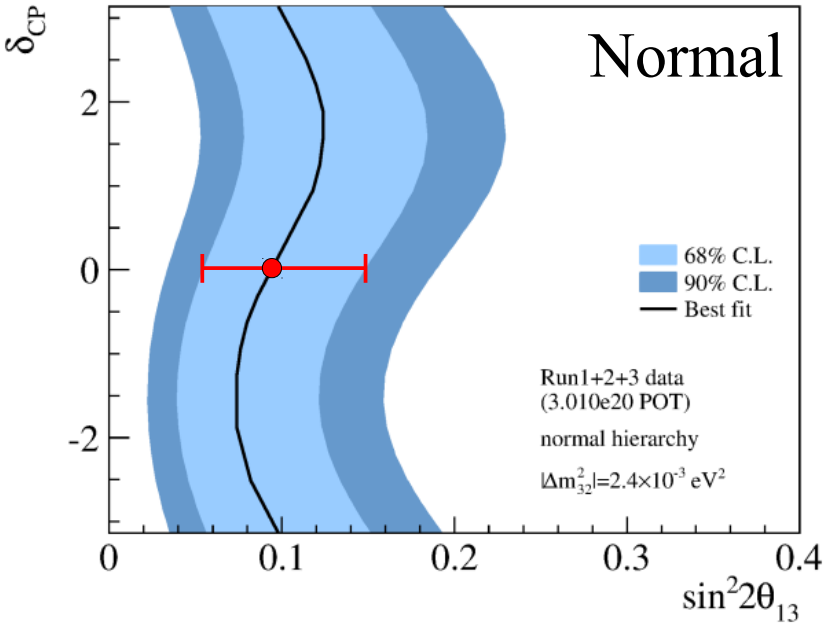
Normal $\quad \sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$

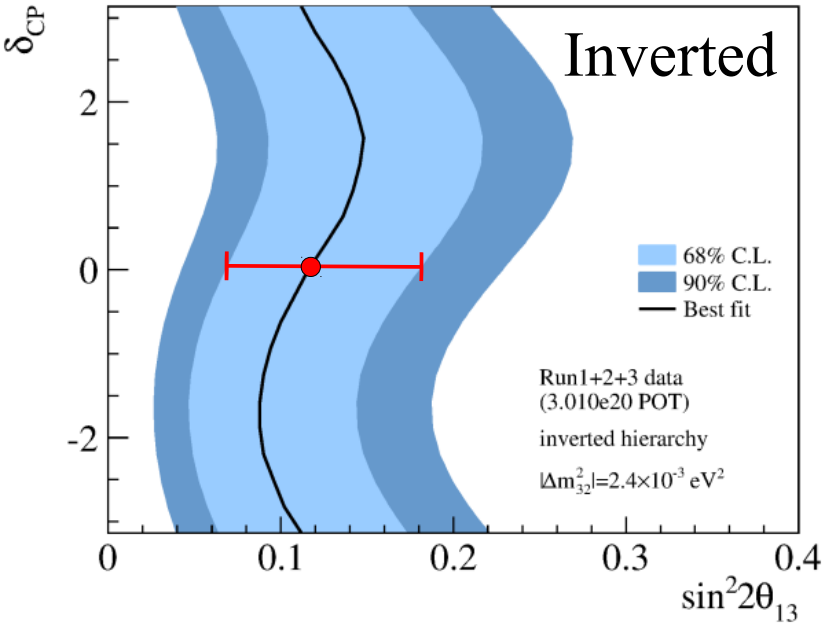
Inverted $\quad \sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$

@ $\delta_{CP} = 0$



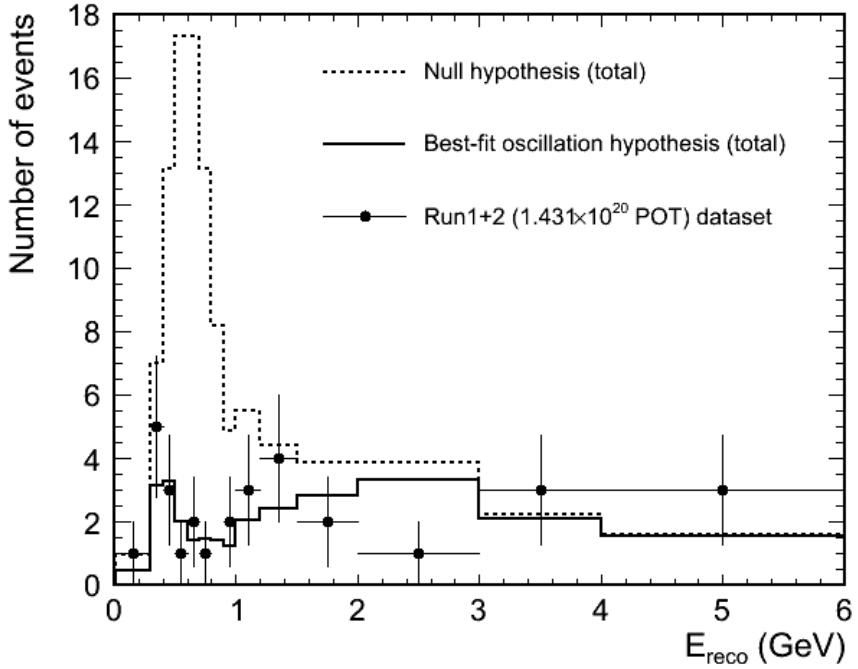
Run 1+2 & Run 3 measurements are consistent

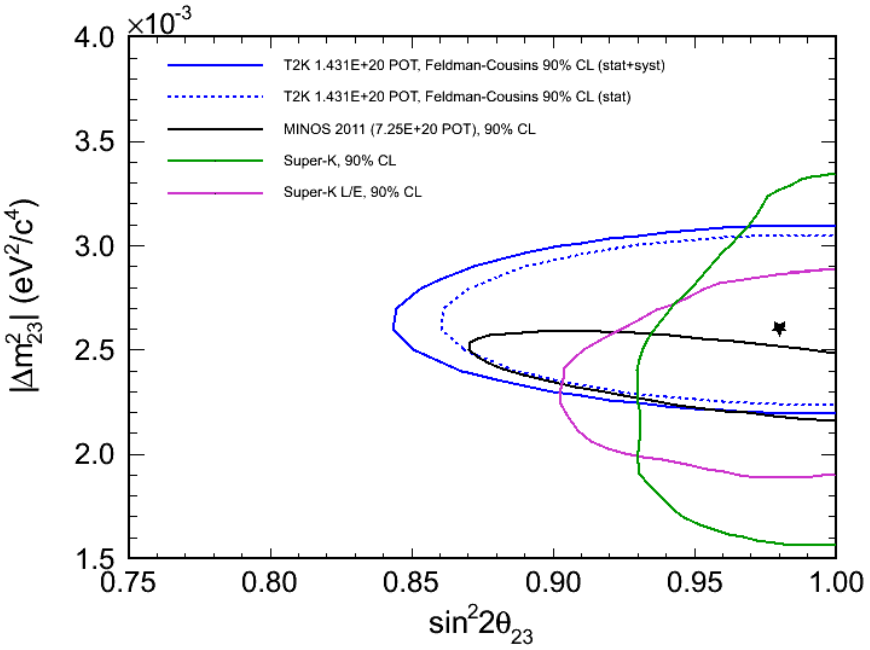




ν_μ Disappearance Analysis

- Run 1+2 muon neutrino disappearance analysis
  - Exposure is 1.43×10^{20} POT (~2% of propose T2K exposure)
  - First off-axis measurement of muon neutrino disappearance [PRD85, 031103(R) (2012)]
- Statistics Limited
  - Large suppression at peak neutrino energy
- Best Fit
  - $\sin^2 2\theta_{23} = 0.98$
  - $\Delta m_{32}^2 = 2.65 \times 10^{-3}$ eV^2





Summary

- The current T2K exposure is 3.01×10^{20} POT
  - About 4% of the proposed T2K exposure
- We have found evidence for electron neutrino appearance
  - 11 electron neutrino candidates observed
    - P-Value is 0.0008 (equivalent to 3.2 σ)
    - Confirms Run 1+2 data [PRL 107, 041801, 2011]
      - 6 events with 1.5±0.3 expected for 1.43×10^{20} POT
      - P-Value is 0.007 (equivalent to 2.5 σ)
  - Opens the possibility to measure CP violation in the lepton sector
- An updated muon disappearance measurement is coming soon.
- New high power runs are planned
  - 8×10^{20} POT (2013) → 12×10^{20} POT (2014) → 18×10^{20} POT (2015)
  - New runs begin in mid-October.