Recent Neutrino Oscillation Results From the T2K Experiment

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on behalf of the T2K collaboration

Outline

- Neutrino Oscillations and T2K
- T2K experimental setup
- Analysis methodology
- 2013 Results
  - $\nu_\mu \rightarrow \nu_\mu$ Disappearence, $\sin^2 2\theta_{23}$
  - $\nu_\mu \rightarrow \nu_e$ Appearence, $\sin^2 2\theta_{13}$
- Summary and Future

Neutrino Oscillation

If neutrinos have mass then... $|\nu_l\rangle = \sum_i U_{li}|\nu_i\rangle$ ... where ...

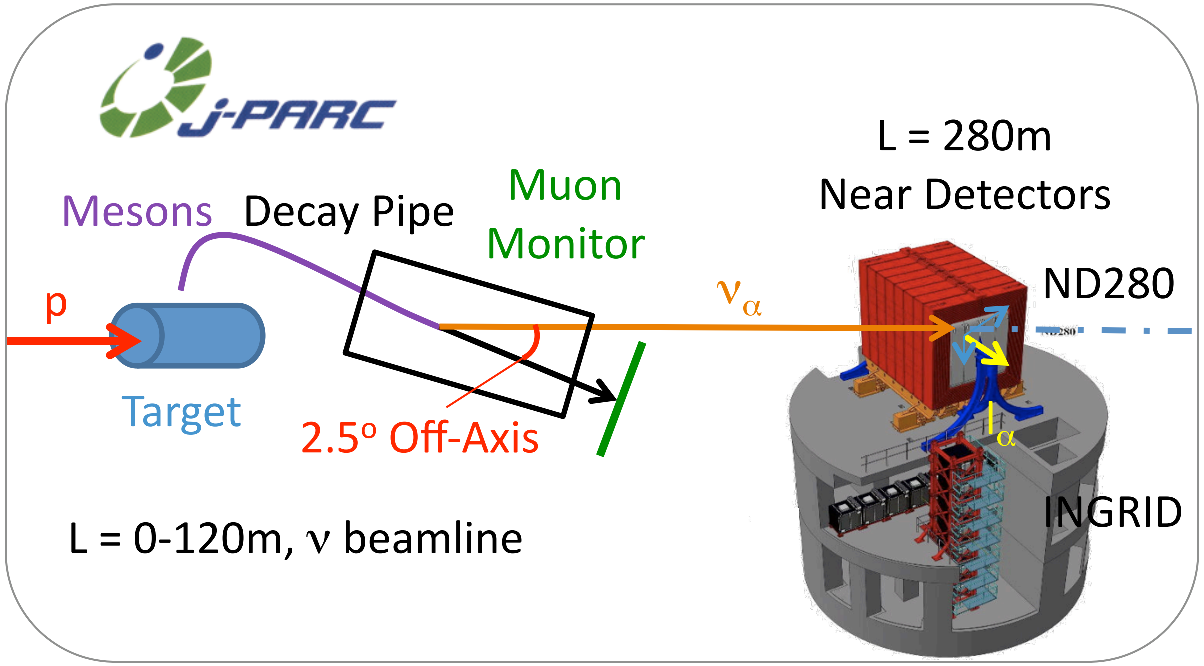
$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

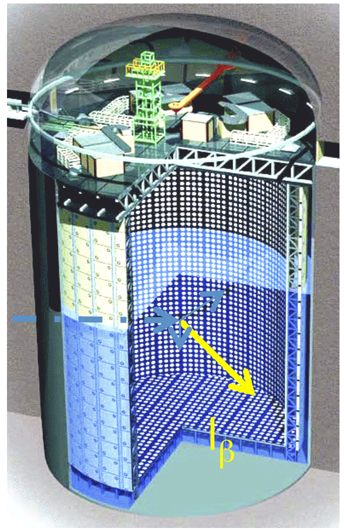
Atmospheric Interference Solar

Oscillation probability evolution from flavour α to β is dependent on mass difference squared Δm^2_{ij} (eV/c^2), energy of the neutrino, E (GeV), and distance it travels, L (km).

$$P_{\alpha \to \beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha i}U^*_{\beta i}\right)\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j} \Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha i}U^*_{\beta i}\right)\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

T2K L = 295 km





L = 295km Far Detector
Super-KamiokaNDE

Disappearance: $$P_{\mu\to\mu} \sim 1-\left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right)$$
$$+\ (\text{matter term})$$

Appearance: $$P_{\mu\to e} \sim \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$
$$+\ (\text{solar term}) + (\text{CP interference term}) + (\text{matter term})$$

Leading order

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
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

~500 members, 59 Institutes, 11 countries

Spain
IFAE, Barcelona
IFIC, Valencia

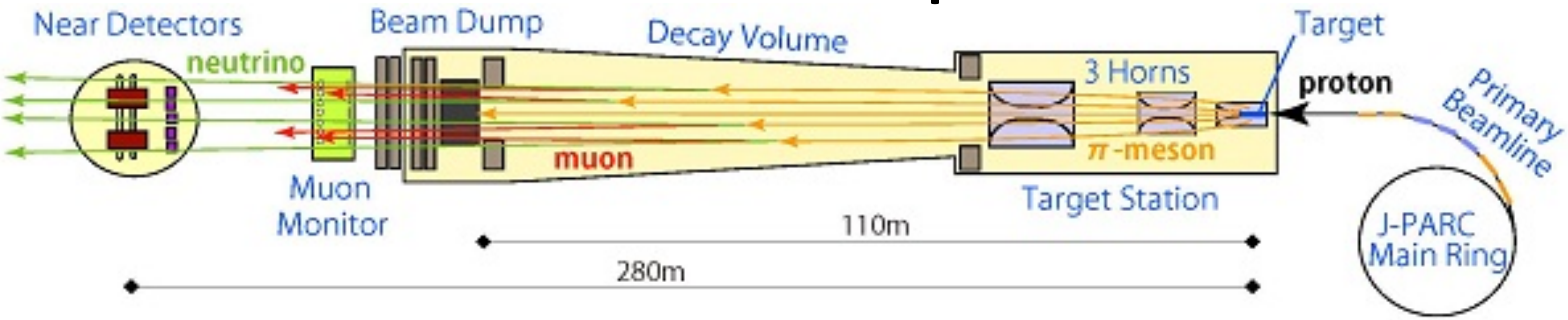
Switzerland
ETH Zurich
U. Bern
U. Geneva

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

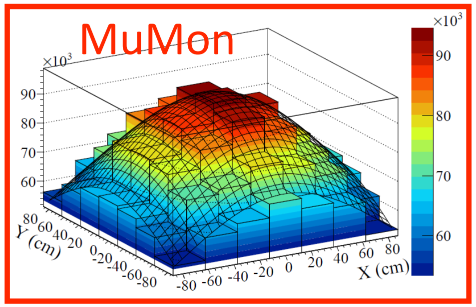
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

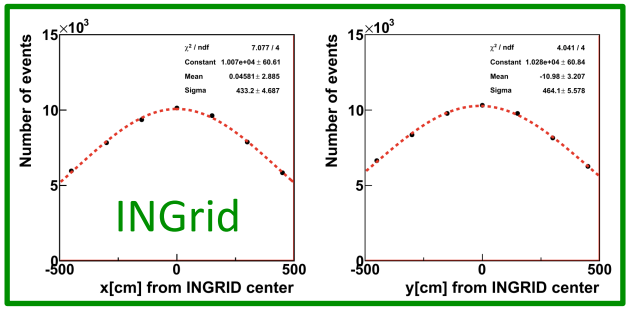
Experimental Setup

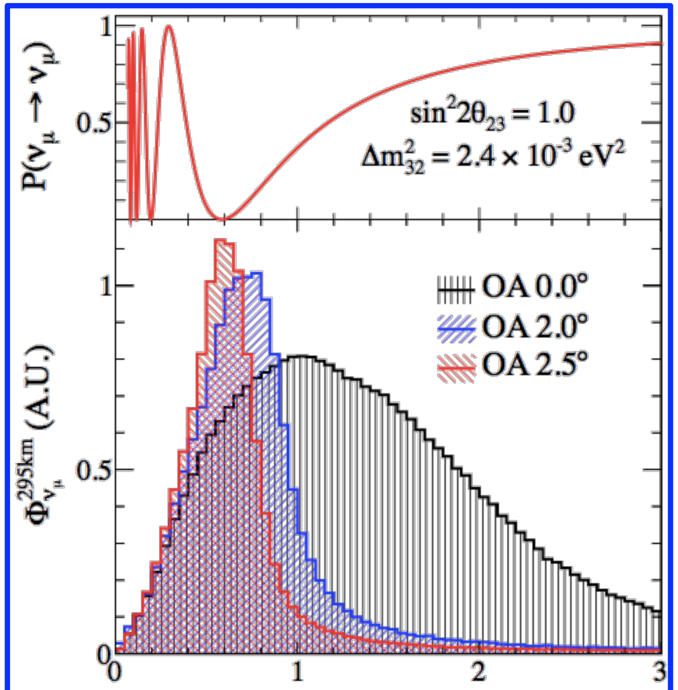
Japan Proton Accelerator Research Complex ν-Beamline



- 250 kA Focussing horns & 110m He filled decay volume
- Series of beam monitors, MuMon muon monitor and INGrid near detector monitors beam centre
- 2.5° off-axis configuration
  - Reduces peak energy to oscillation maximum
  - Reduces spread of energies around peak.

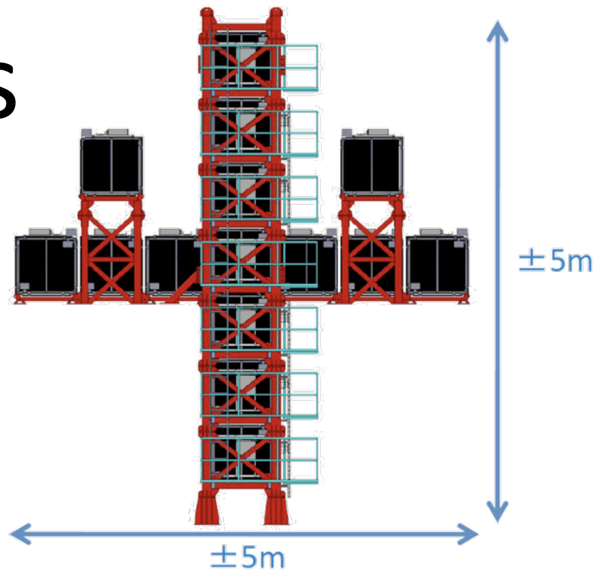






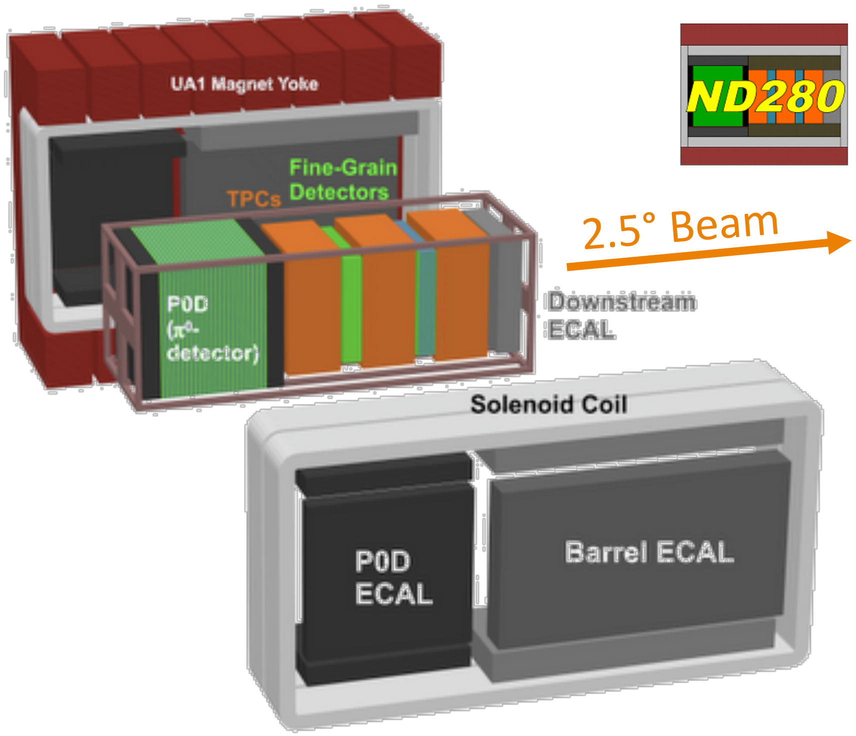
arxiv.org/1211.0469

Near Detectors



INGRID: Interactive Neutrino Grid

- 280m from target centred on beam axis
- 16x iron/scintillator tracking calorimeters
- 1x all-scintillator proton module
- monitors beam centre, profile and CC^{inc} rate



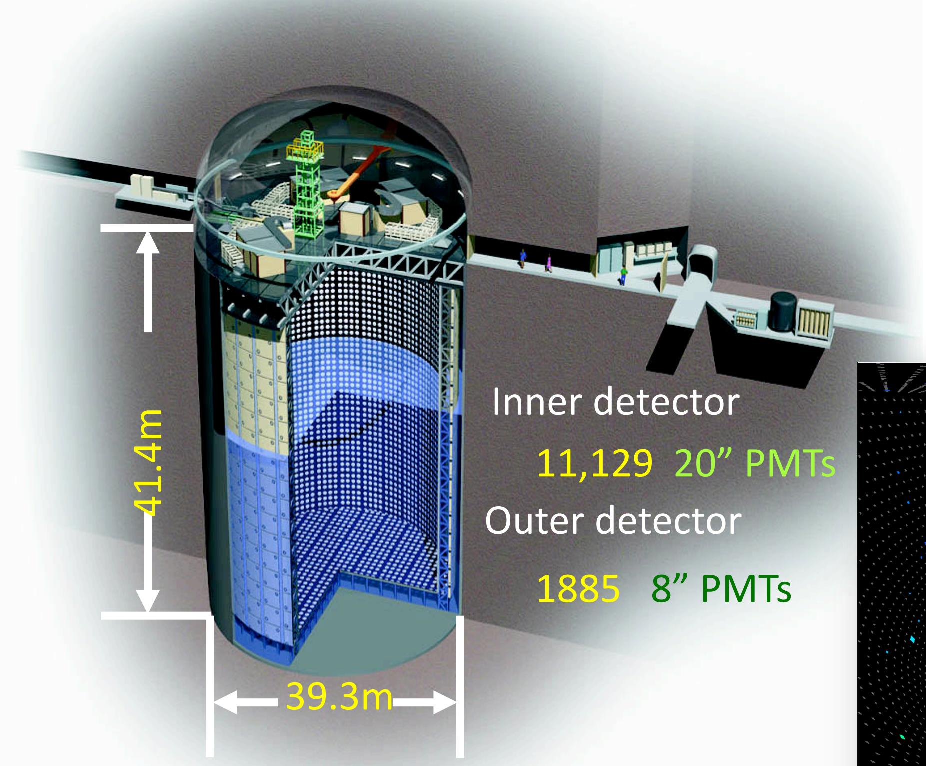
ND280: Near Detector @ 280m

Used in ND280 analysis presented later

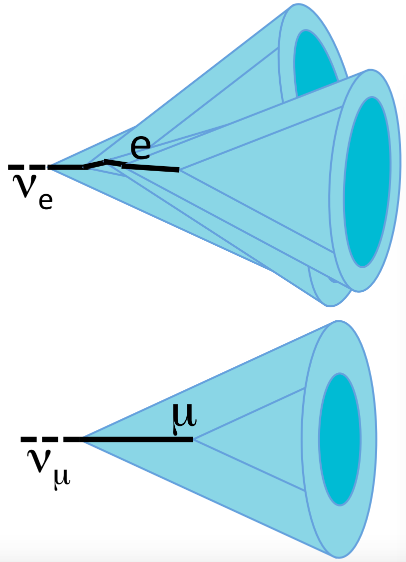
- 280m from target 2.5° from beam axis
- Upstream π^0 detector (**P0D**)
- 2x 0.8ton **F**ine **G**rained scintillation **D**etectors (**FGD**) with C and H_20 target
- 3x **T**ime **P**rojection **C**hambers (**TPC**) for accurate dE/dx based PID
- Hermetic lead/scintillator **E**lectromagnetic **Cal**orimeters (**ECAL**)
- Side Muon Range Detector scintillator magnet yoke
- 0.2T refurbished UA1/NOMAD magnet

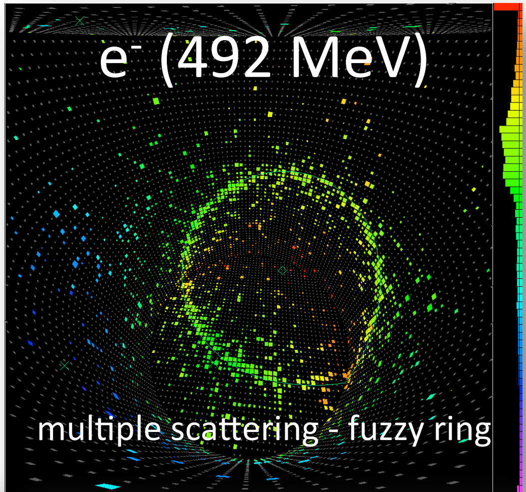
T2K Far Detector: Super-Kamiokande

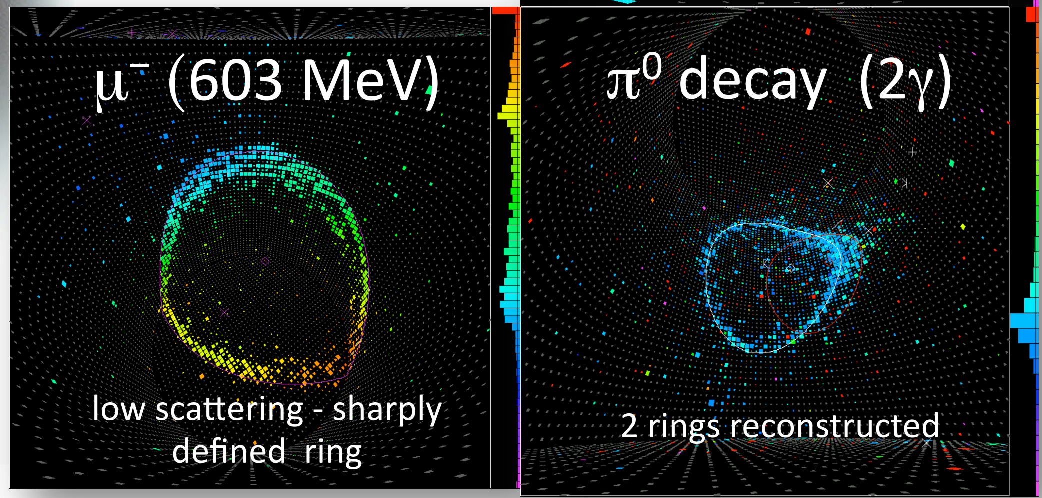
- 50 kton (22.5 kton fiducial) water Cerenkov detector
- Good reconstruction for T2K energy range



- Particle Identification (PID) based on shape of Cerenkov rings





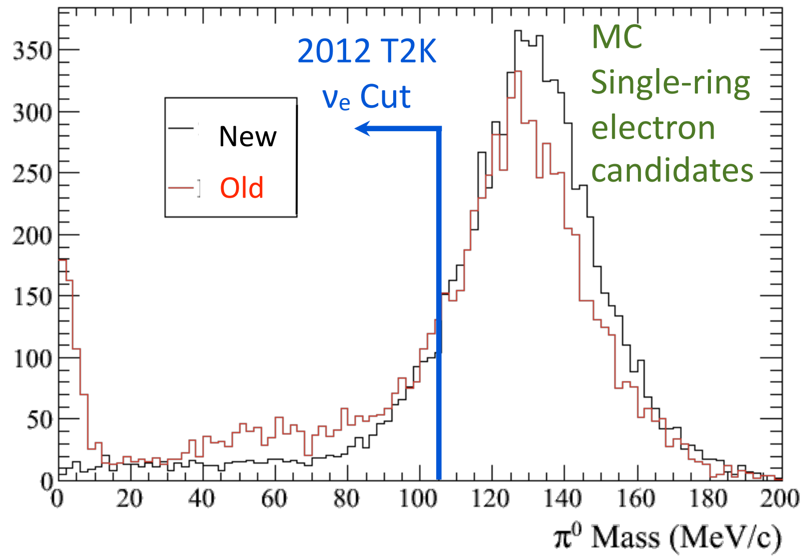


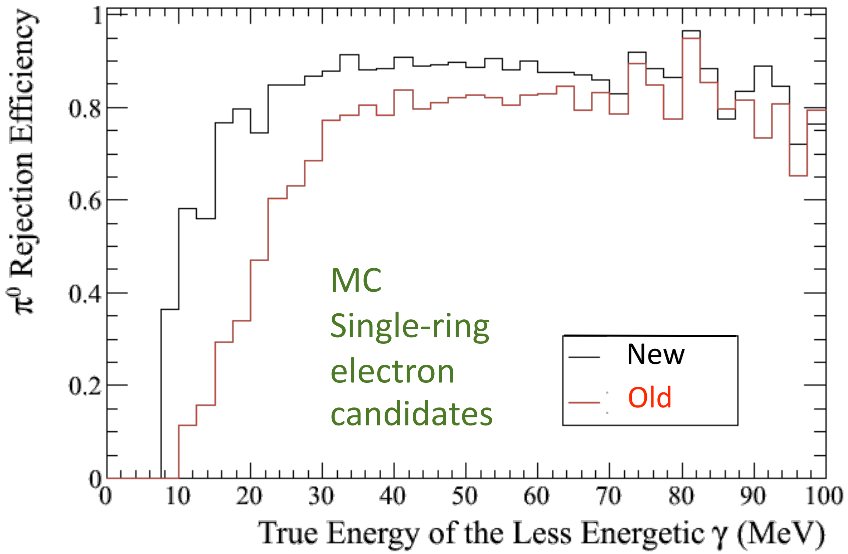
Event displays show Monte Carlo

A new Cherenkov Detector Reconstruction Package

- Based on MiniBooNE Likelihood Model [NIM A608, 206 (2009)]
- For given event hypothesis generate charge and time PDF
- Event hypothesis then distinguished by best fit likelihoods.
- New method uses mass of the π^0 hypothesis and best-fit likelihood ratio of e^- and π^0
- Cut removes 70% more π^0 background than previous§ method for a 2% added loss of signal efficiency

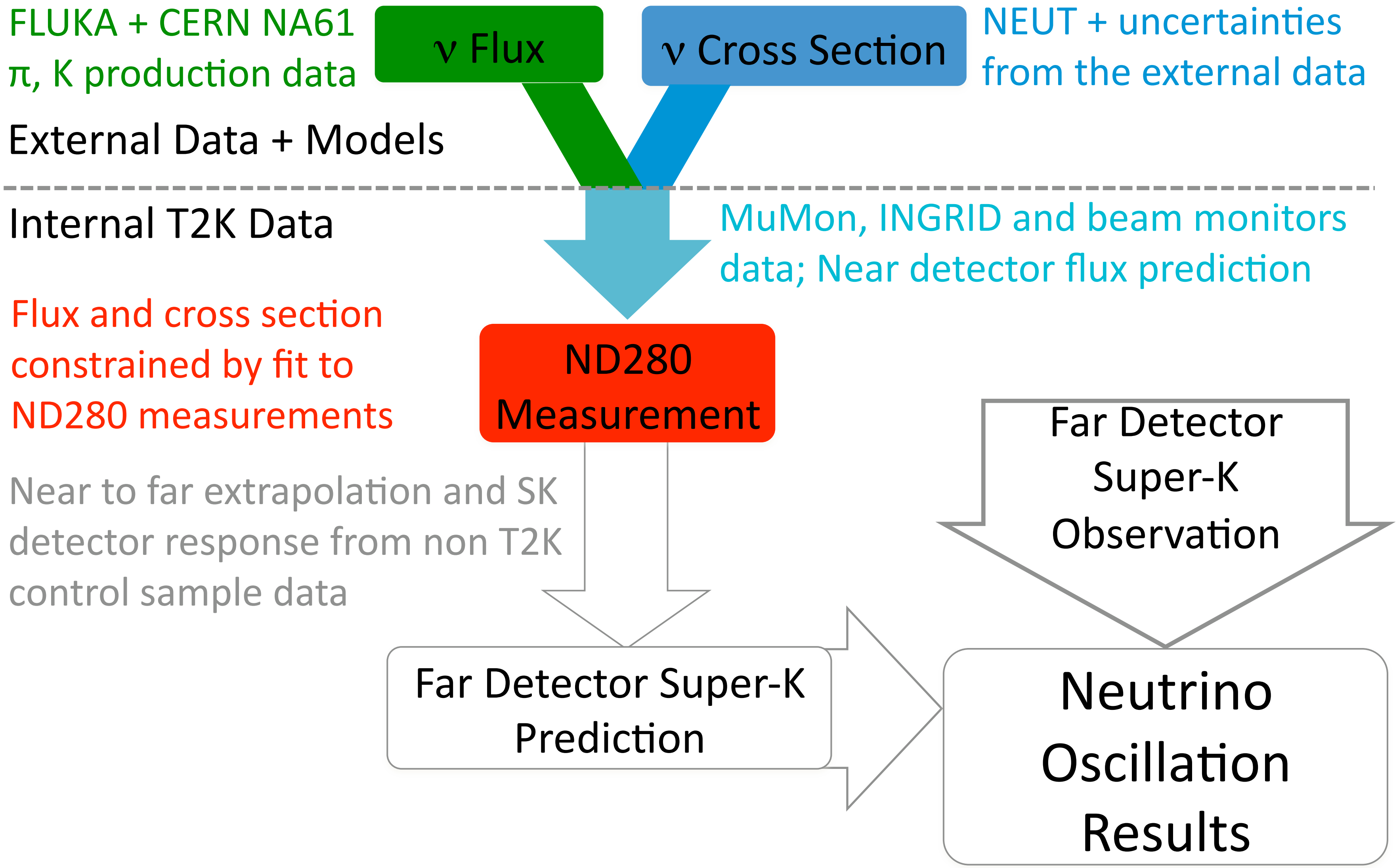
§ *Previous approach forced the reconstruction to find two rings and then formed a π^0 mass under the two-photon hypothesis*



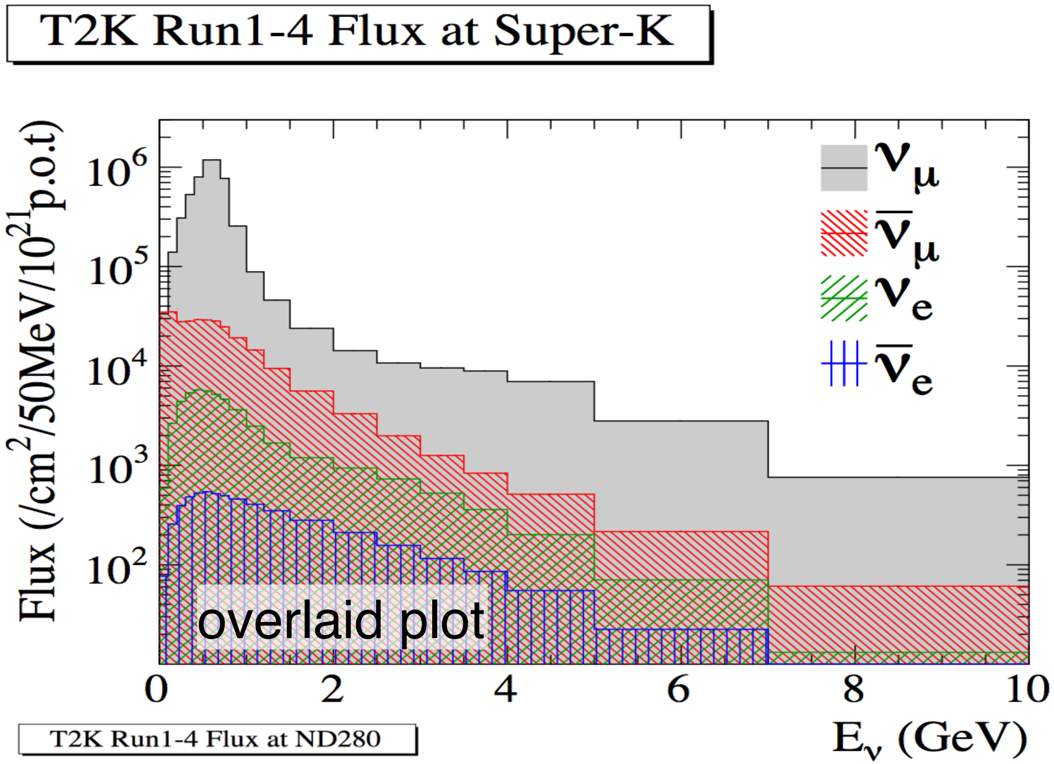


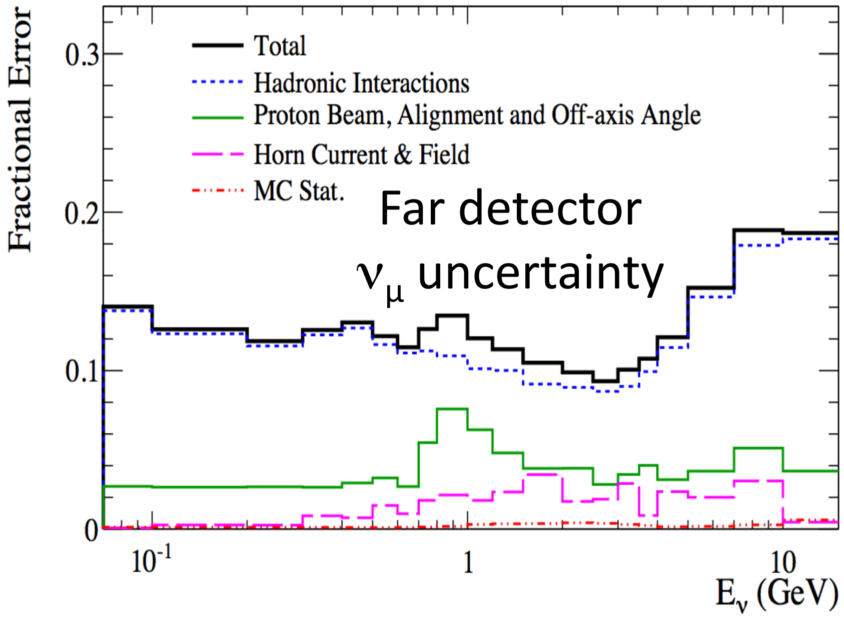
Analysis Method

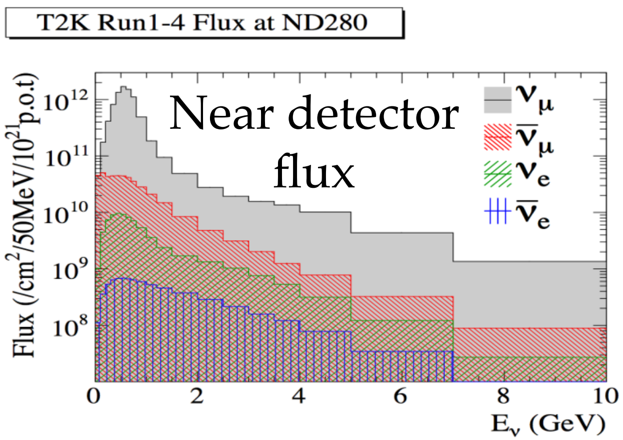
T2K Neutrino Oscillation Analysis Flow



Flux and Uncertainties





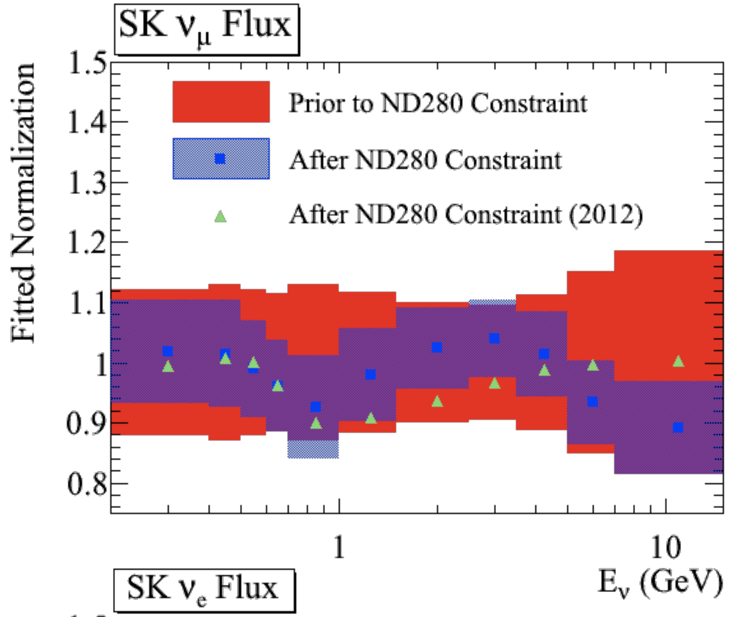


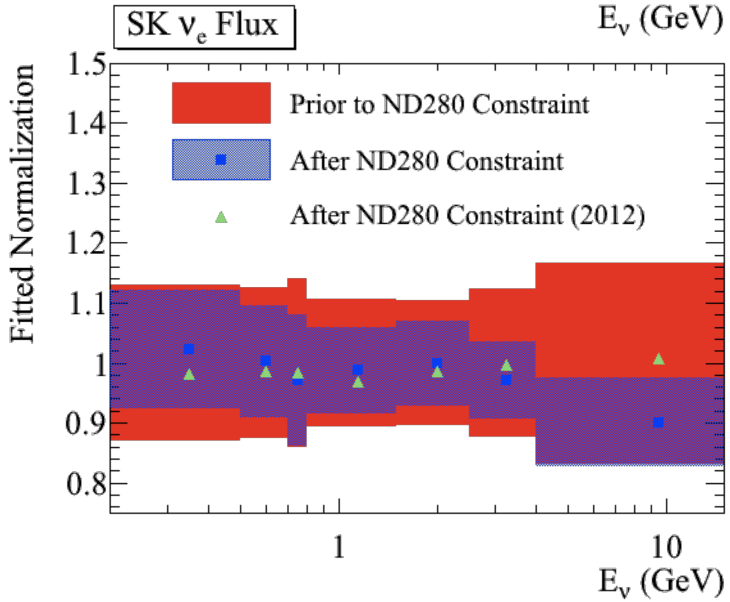
- A priori prediction of flux at Super-K has 10-15% uncertainties from 0.1 to 5 GeV
- Off-axis near (ND280) and Far (Super-K) fluxes are not identical, but highly correlated

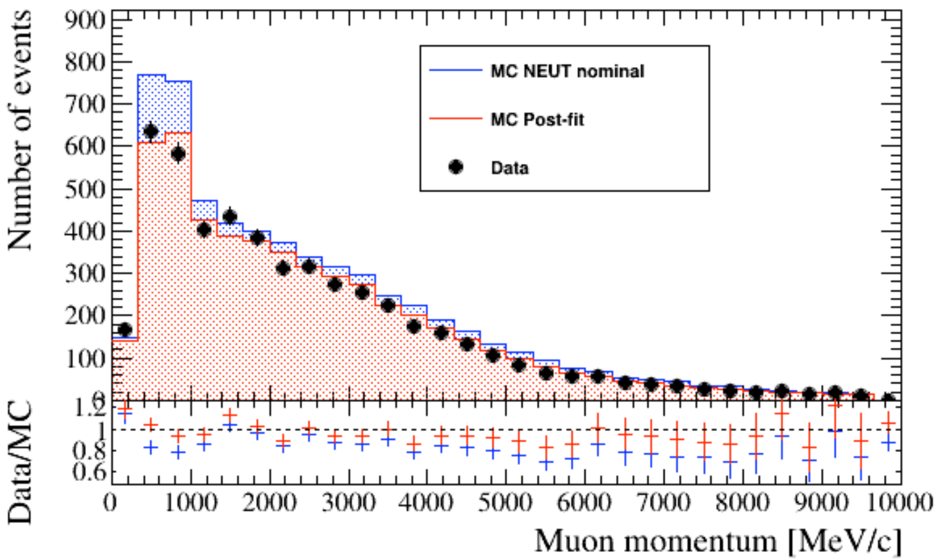
ND280 Flux Constraint

Far Detector ν_μ and ν_e flux predictions constrained by 2013 ND280 analysis

- Right: central values and error bands for normalization parameters before and after the near detector constraint – different from 2012
- Below: μ-momentum for CCQE (CC-0π) events in the ND280 before and after ND280 analysis







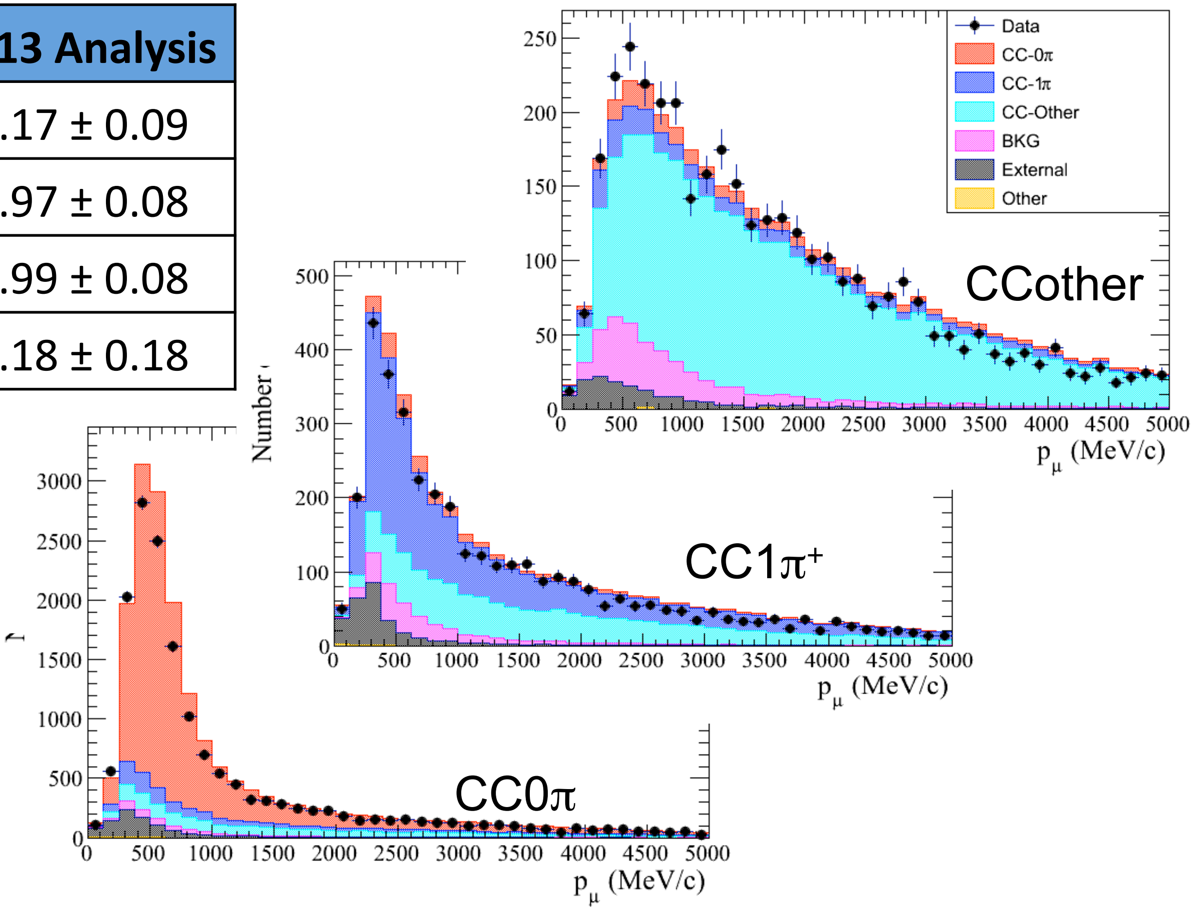
ND280 Cross Section Constraint

2012 Single CC^{inc} ν_μ selection → 2013 three CC subsamples

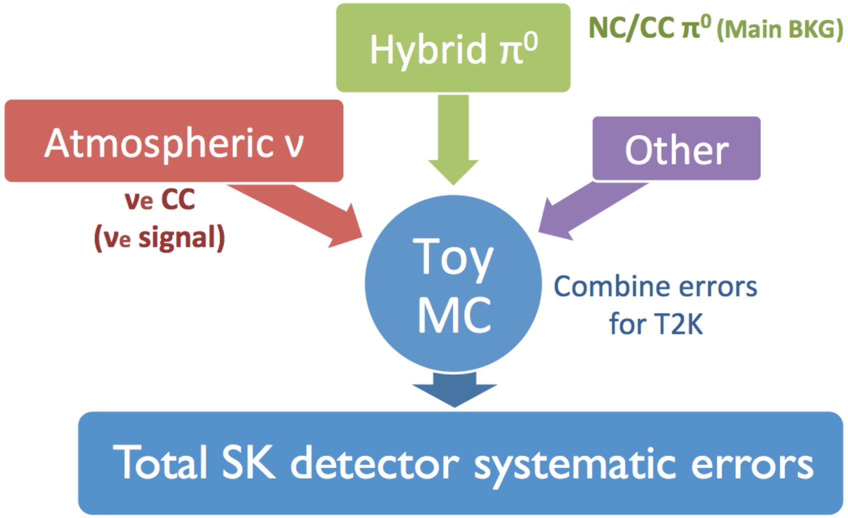
- Improves data/MC agreement - Improves parameter errors

Parameter	2012 Analysis	2013 Analysis
M_A^{QE} (GeV)	1.33 ± 0.20	1.17 ± 0.09
M_A^{RES} (GeV)	1.15 ± 0.10	0.97 ± 0.08
CCQE Norm.	0.96 ± 0.09	0.99 ± 0.08
CC1π Norm.	1.63 ± 0.29	1.18 ± 0.18

Sample	efficiency	purity
CC 0π	50.1%	72.6%
CC $1\pi^+$	29.5%	49.4%
CCOther	35.2%	73.8%



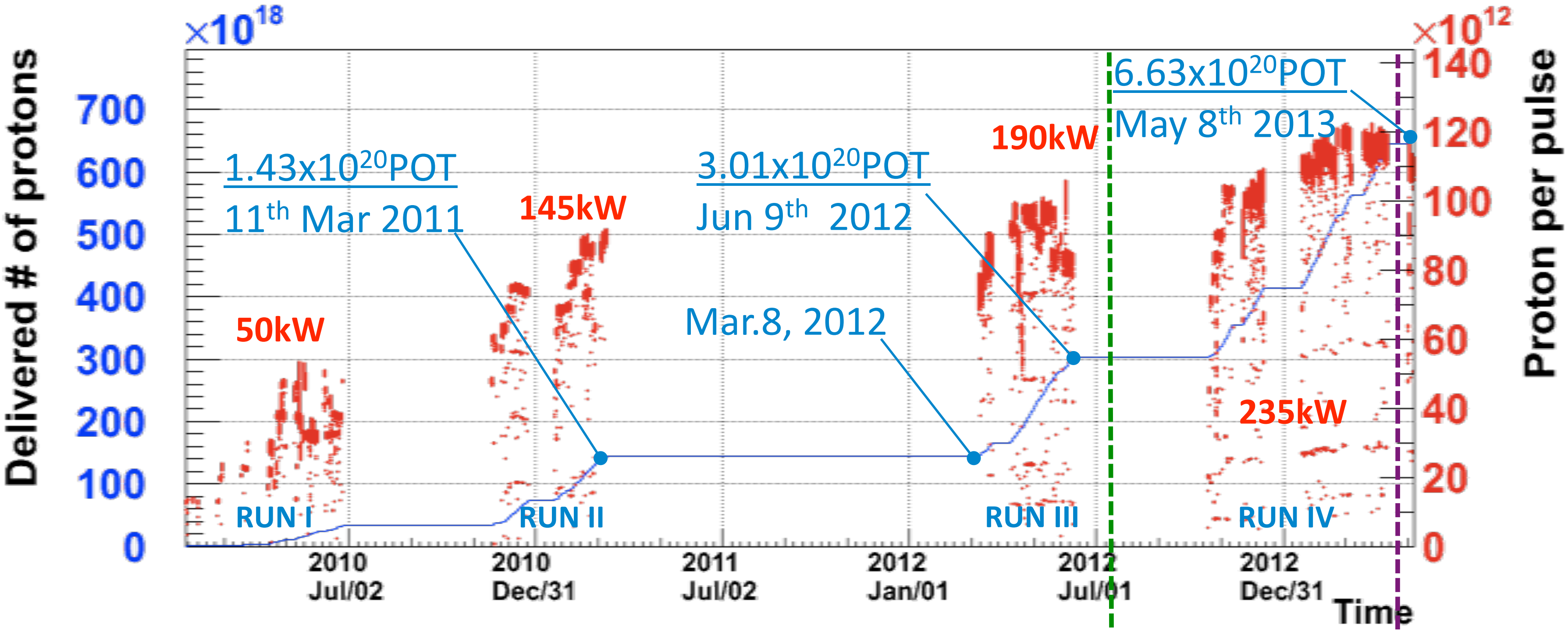
Super-K Far Detector Errors



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

Latest Results

Data Sets Used



- $\nu_\mu \rightarrow \nu_\mu$ analysis: Run 1-3 data (3.01×10^{20} POT)
- $\nu_\mu \rightarrow \nu_e$ analysis: 96.3% Run 1-4 data (up to April 12th 2013)

- <1mrad (~16MeV [2%]) beam stability for total period
- Achieved 1.2×10^{14} protons per pulse (WR)
- Stable 220kW running
- 8% of design goal POT so far

Neutrino Oscillation Parameter Likelihood Fits

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

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

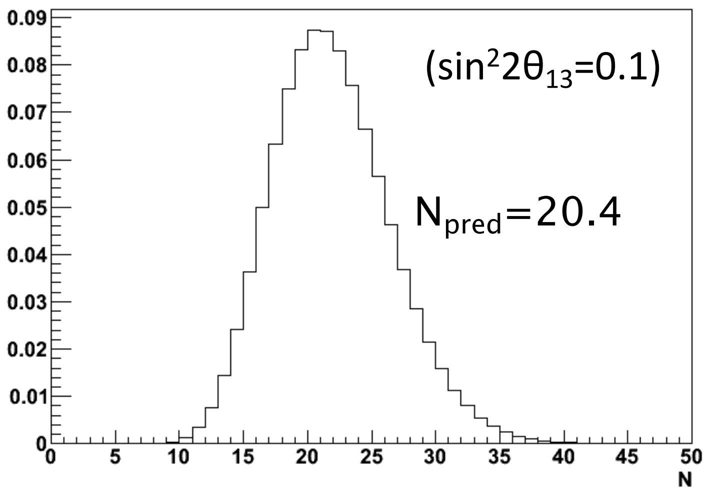
L_{norm} is the probability to have N_{obs} when the predicted number of events is the Poisson distribution with mean = N_{pred}.

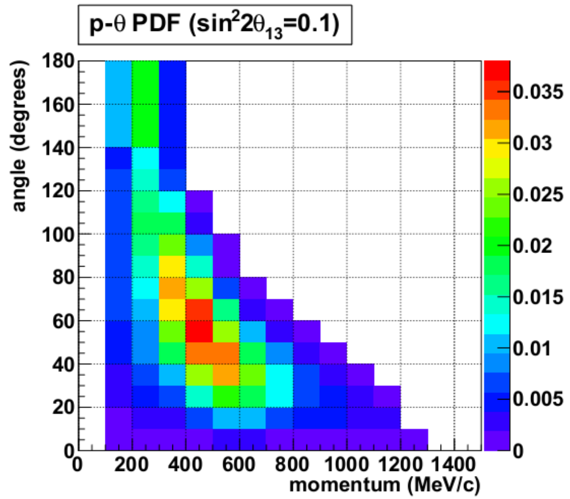
$$\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$$

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

ϕ: Predicted p-θ distribution (PDF) .

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



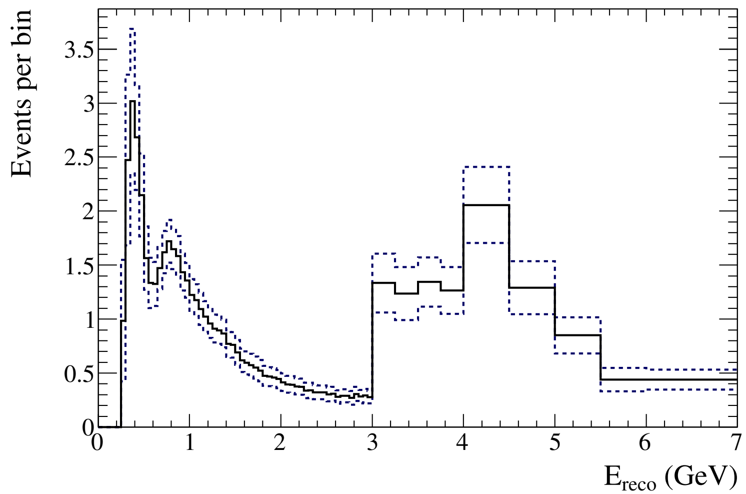


$\nu_\mu \rightarrow \nu_\mu$ Analysis

Fit method

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

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



Systematic uncertainties

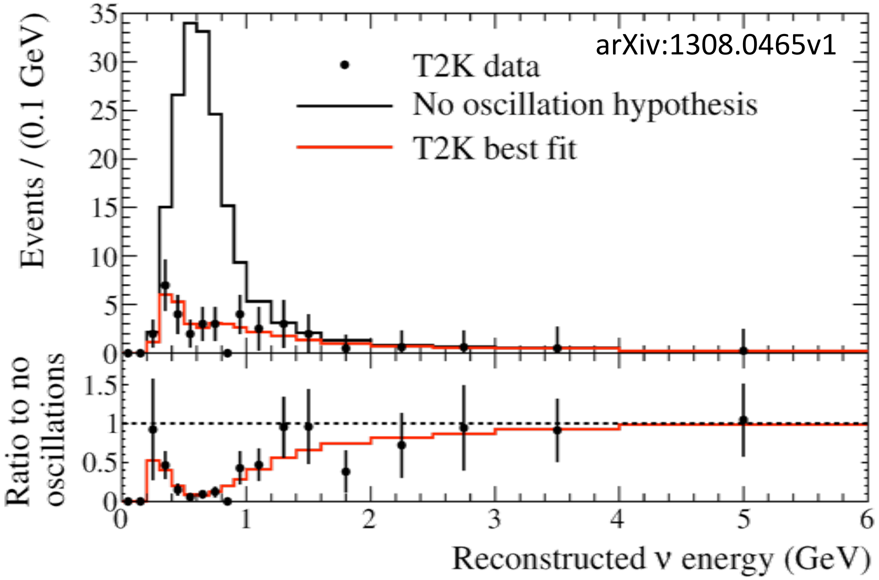
Systematic uncertainty	before	after
	ND constraint	
Flux / ν x-sec.	21.8 %	4.2 %
Uncorrelated ν x-sec.	6.3 %	
SK detector	10.1 %	
FSI-SI	3.5 %	
Total	25.1 %	13.1 %

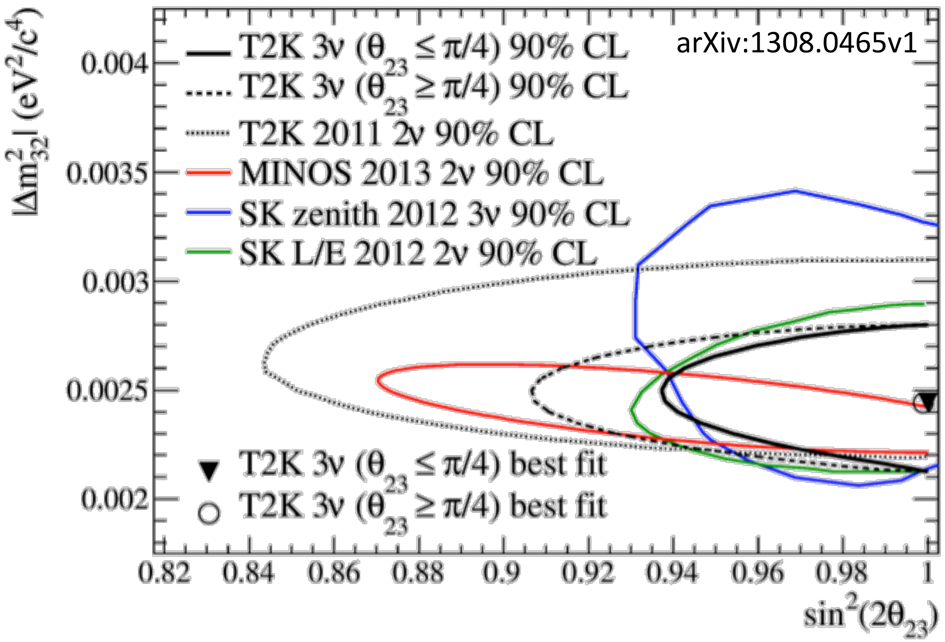
$\nu_\mu \rightarrow \nu_\mu$ 2013 Result

Analysis	2012	2013	
N_{exp} w/ No Osc.	104	204.75 ± 16.75^{sys}	
N_{Obs}	31	58	
θ_{23} Octant	$\theta_{23}<\pi/4$	$\theta_{23}<\pi/4$	$\theta_{23}>\pi/4$
$\sin^2 2\theta_{23}$	0.98	**1.000**	**0.999**
$\lvert\Delta m^2_{32}\rvert$ (eV^2)	2.65×10^{-3}	**2.44×10^{-3}**	**2.44×10^{-3}**

T2K has a world leading sensitivity to $\sin^2 2\theta_{23}$!

- Octant choice effects shape of confidence contour
- Future results presented as $\sin^2\theta_{23}$ opposed to $\sin^2 2\theta_{23}$

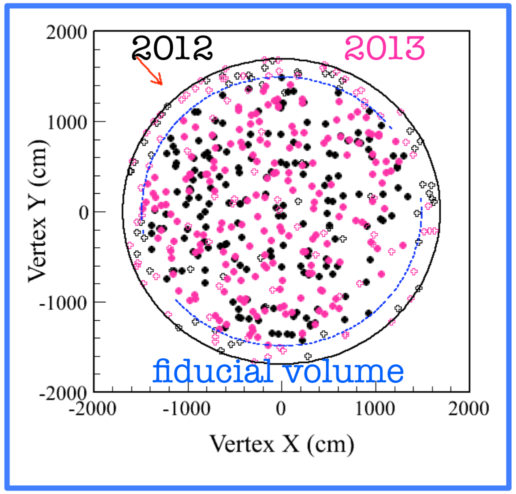


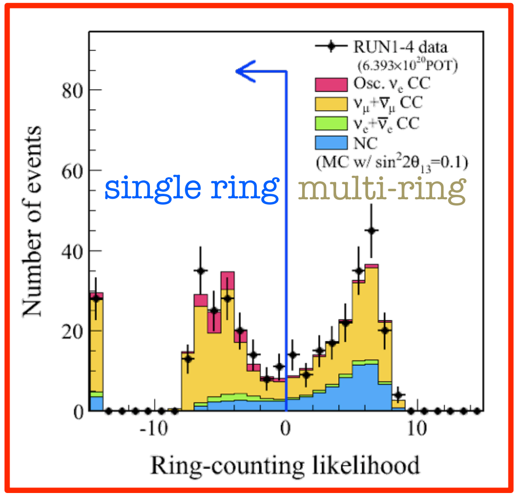


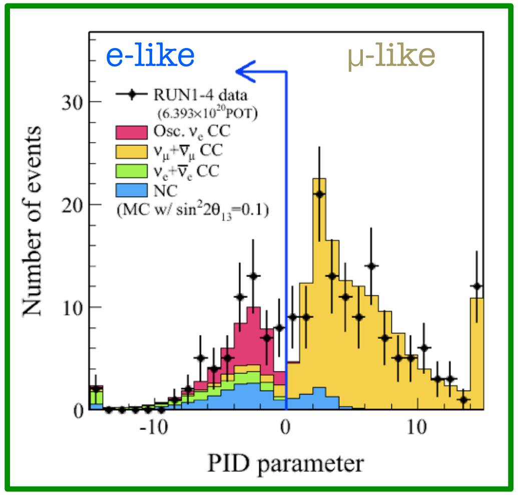
$\nu_\mu \rightarrow \nu_e$ 2013 Event Selection

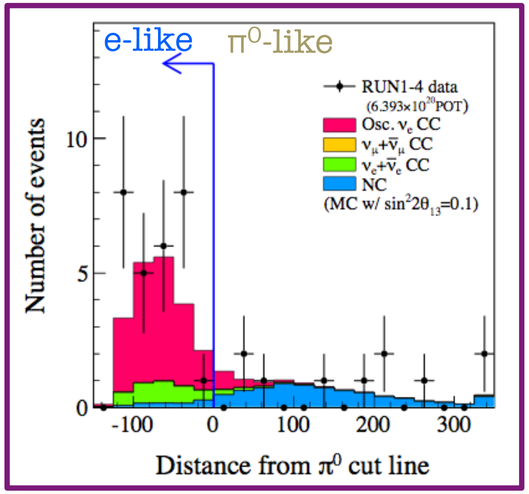
Event selection:

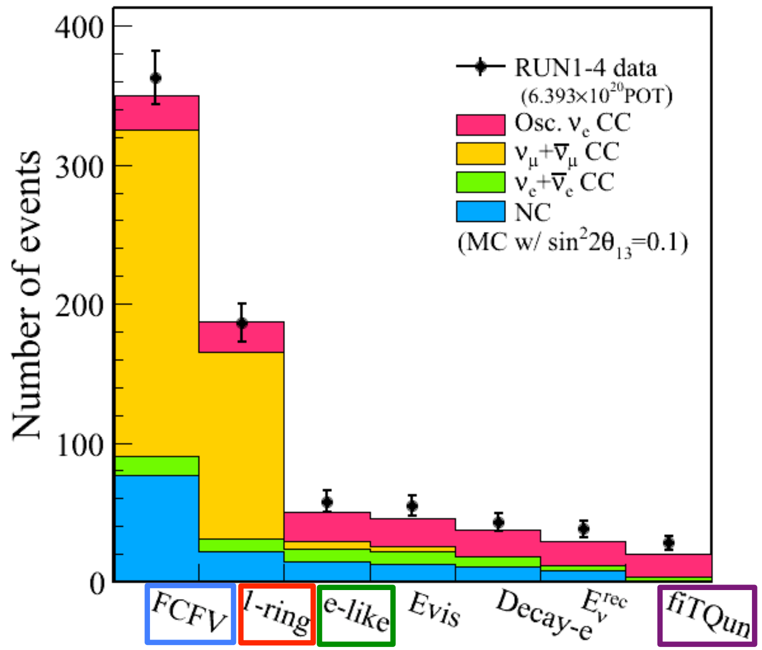
- Fully contained in fiducial volume
- Only one reconstructed rings
- Ring is electron like
- Visible energy > 100MeV
- No Michel Electrons
- Reconstructed energy < 1.25 GeV
- (2013)2D π^0 invariant mass : fiTQun likelihood cut











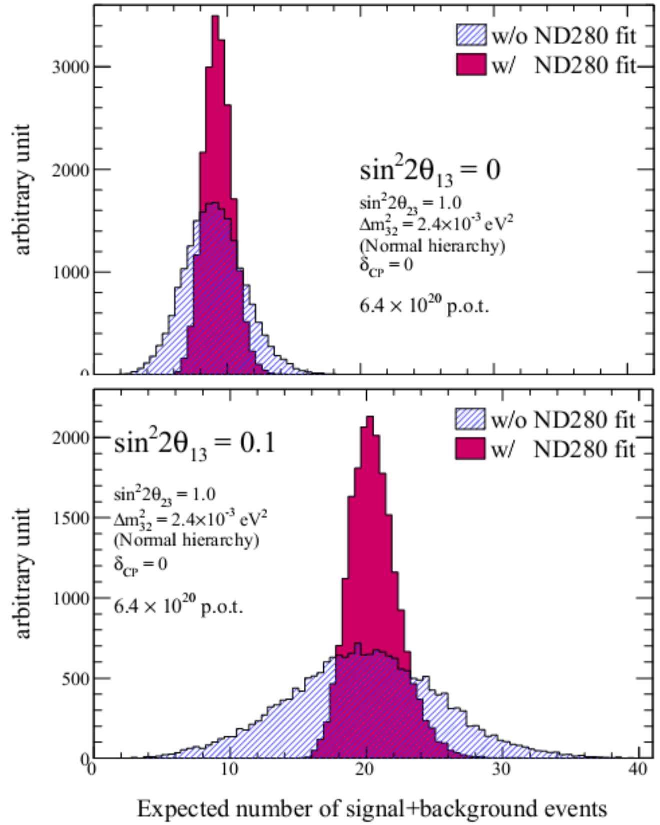
$\nu_\mu \rightarrow \nu_e$ 2013 Predicted Number of Events

Predicted # of events w/ 6.393×10^{20} POT

Event Category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
ν_e signal	0.38	16.42
ν_e background	3.17	2.93
ν_μ background (mainly NCπ^0)	0.89	0.89
$\nu_\mu + \nu_e$ background	0.20	0.19
Total (2013)	4.64	20.44
Total (2012)	5.15	21.77

Systematic Uncertainties

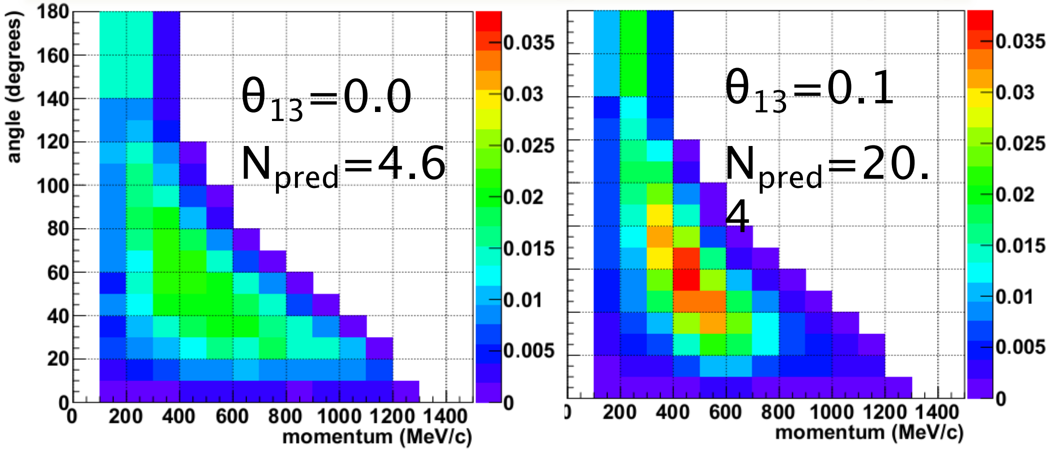
Error Source	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux + ν int. T2K fit	4.9 %	3.0 %
ν int. (other exp.)	6.7 %	7.5 %
Far detector	7.3 %	3.5 %
Total (2013)	11.1 %	8.8 %
Total (2012)	13.0 %	9.9 %



Reduction in errors 2012-2013 mainly due to near detector analysis improvement.

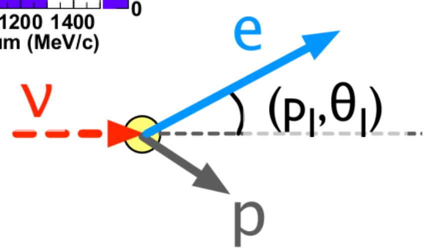
$\nu_\mu \rightarrow \nu_e$ 2013 Predicted Number of Events

Electron momentum vs. angle distribution (MC)



Fixed neutrino oscillation parameters

Δm^2_{12}	7.6×10^{-5} eV^2
Δm^2_{32}	2.4×10^{-3} eV^2
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{12}$	0.8495 ← Was 0.8704 in 2012 analysis
δ_{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 neutrino oscillation parameters other than $\sin^2 2\theta_{13}$.

$\nu_\mu \rightarrow \nu_e$ 2013 Analysis Results

Observed 28 Events

- Norm only 5.5σ excl of $\sin^2 2\theta_{13} = 0$

Δm^2_{12}	7.6×10^{-5} eV^2
Δm^2_{32}	2.4×10^{-3} eV^2
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{12}$	0.8495 ← Was 0.8704 in 2012 analysis
δ_{CP}	0 degree

- p-θ shape fit yields

Best fit w/ 68% C.L. errors

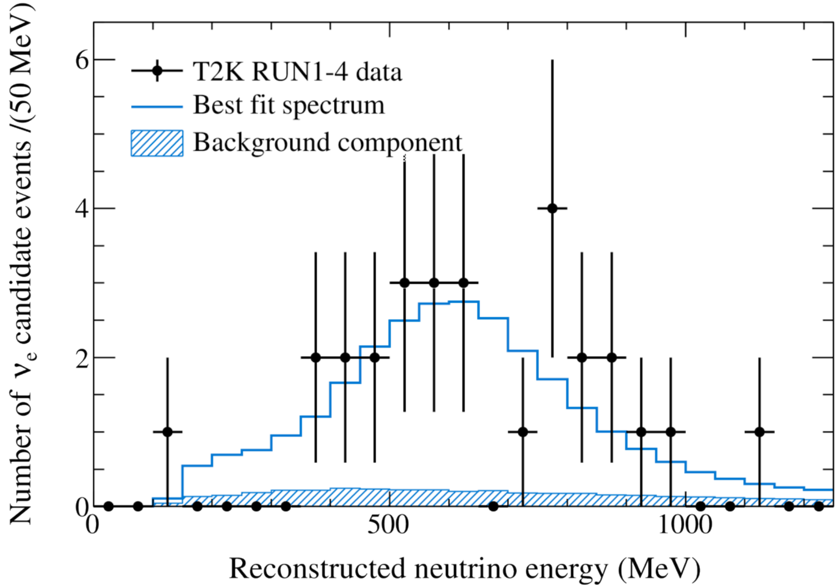
normal hierarchy:

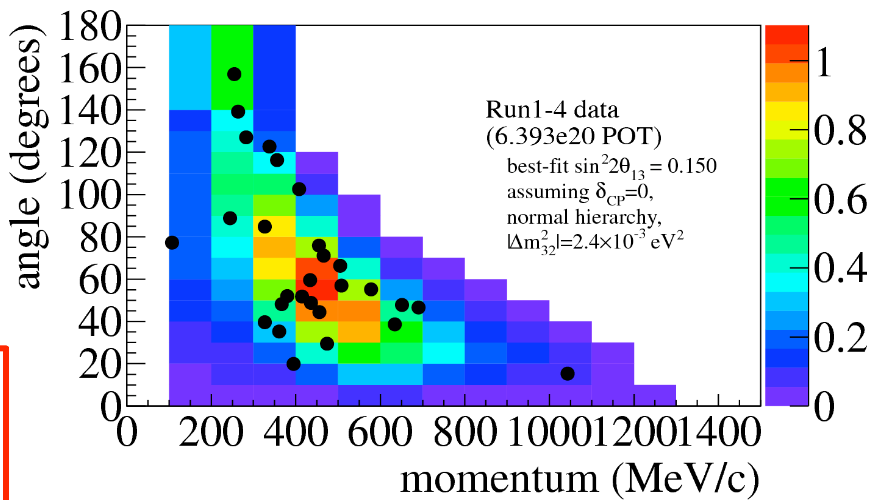
$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

inverted hierarchy:

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

$\sqrt{(2\Delta \ln L)}$ excl. $\sin^2 2\theta_{13} = 0$ at 7.5σ





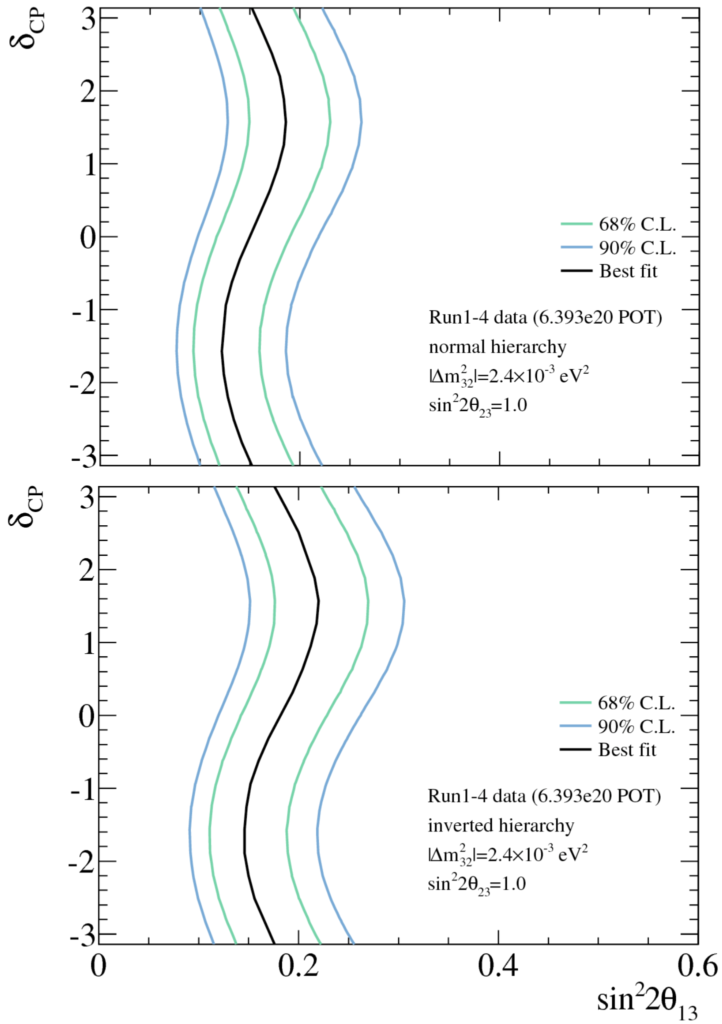
NB: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space

δ_{CP}

$$P_{\mu\to e} \sim \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

+ (solar term) + (CP interference term) + (matter term)

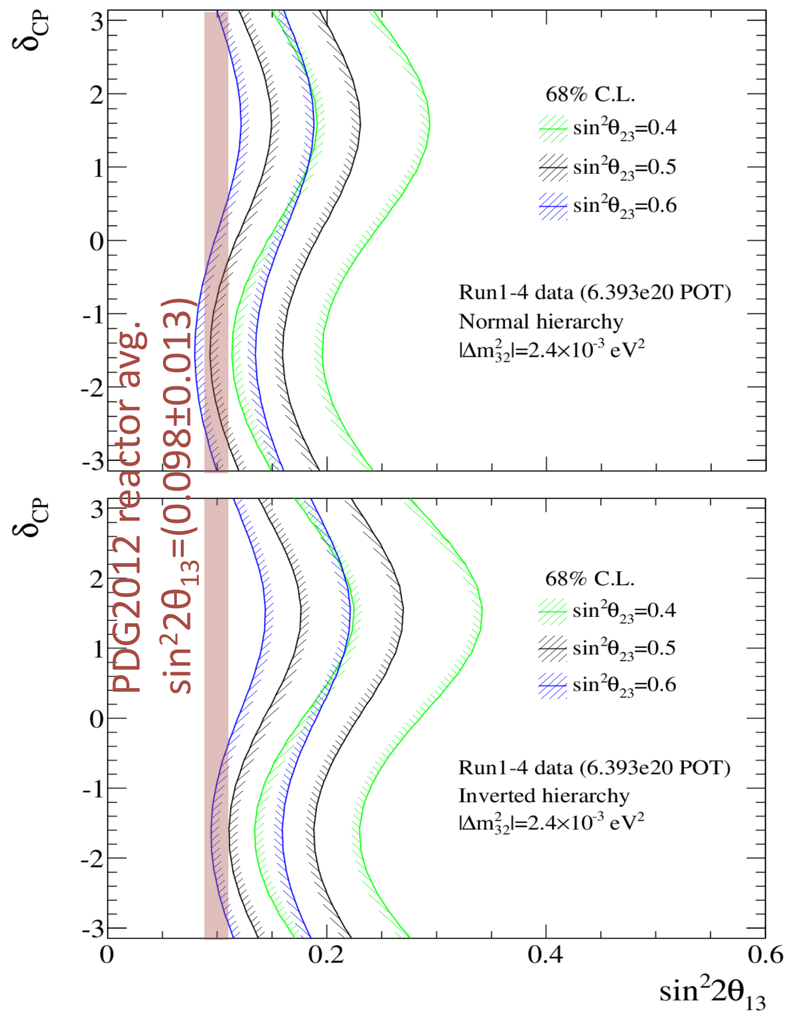
$\sin^2 2\theta_{23} = 1.0$



$\sin^2\theta_{23} = 0.4, 0.5, 0.6$

Normal Hierarchy

Inverted Hierarchy



Summary

- Improvements in 2013 analyses
  - significant improvement on parameter errors from near detector constraints
  - 70% reduction of π^0 background with new far detector reconstruction algorithm.
- Achieved steady operation of JPARC beam at 220 kW
  - 6.39×10^{20} POT accumulated by April 12th
- World leading sensitivity to $\sin^2 2\theta_{23}$ around maximal
  - via observation of the $\nu_\mu \rightarrow \nu_\mu$ disappearance channel
  - 58 ν_μ observed vs unoscillated expectation of 204.75
  - Contours for both octants of $\sin^2 2\theta_{23}$ are provided
  - Future Will provide results in $\sin^2\theta_{23}$
- $\sin^2 2\theta_{13}=0$ is excluded with a significance of **<u>7.5σ</u>** ($\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$)
  - From observation of the $\nu_\mu \rightarrow \nu_e$ appearance channel.
  - First evidence (>5σ) of neutrino flavour change

Future

The future of T2K looks exciting:

- Only 8% of design POT on tape
- New far detector reconstruction to be fully implemented.
- Analysis improvements and increased stats will reduce systematics.
- Important to improve precision of $\sin\theta_{23}$ en-route to understanding δ_{CP} – T2K current world leader.

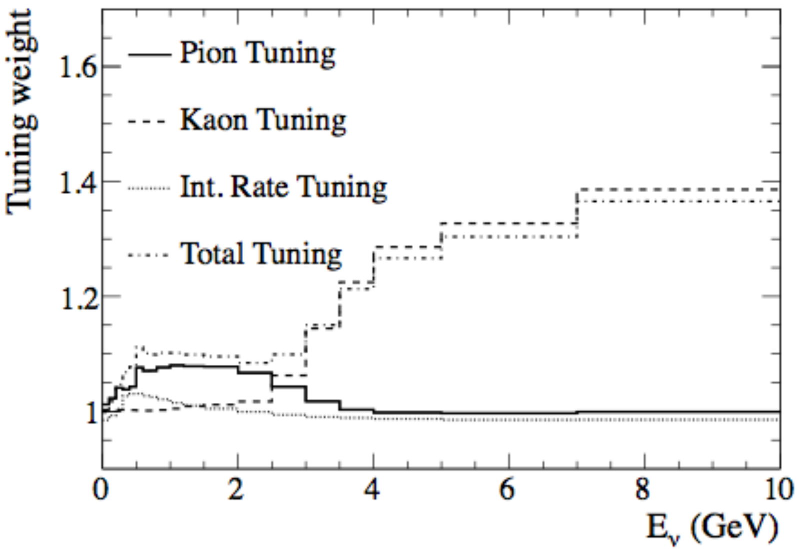
Back-ups

External Data and Models

ν Flux

Hadroproduction simulated with FLUKA2008.3d, weighted so that interactions match external data [Phys. Rev. D 87, 012001 (2013)] from

- NA61/SHINE (CERN) [Phys. Rev. C 84, 034604 (2011)] & [Phys. Rev. C 85, 035210 (2012)]
- T. Eichten *et al.* [Nucl. Phys. B 44 (1972)]
- J. V. Allaby *et al.* [Tech. Rep. 70-12 (CERN,1970)]



ν Cross Sections

ν interactions modeled with NEUT and weighted with fits to external data

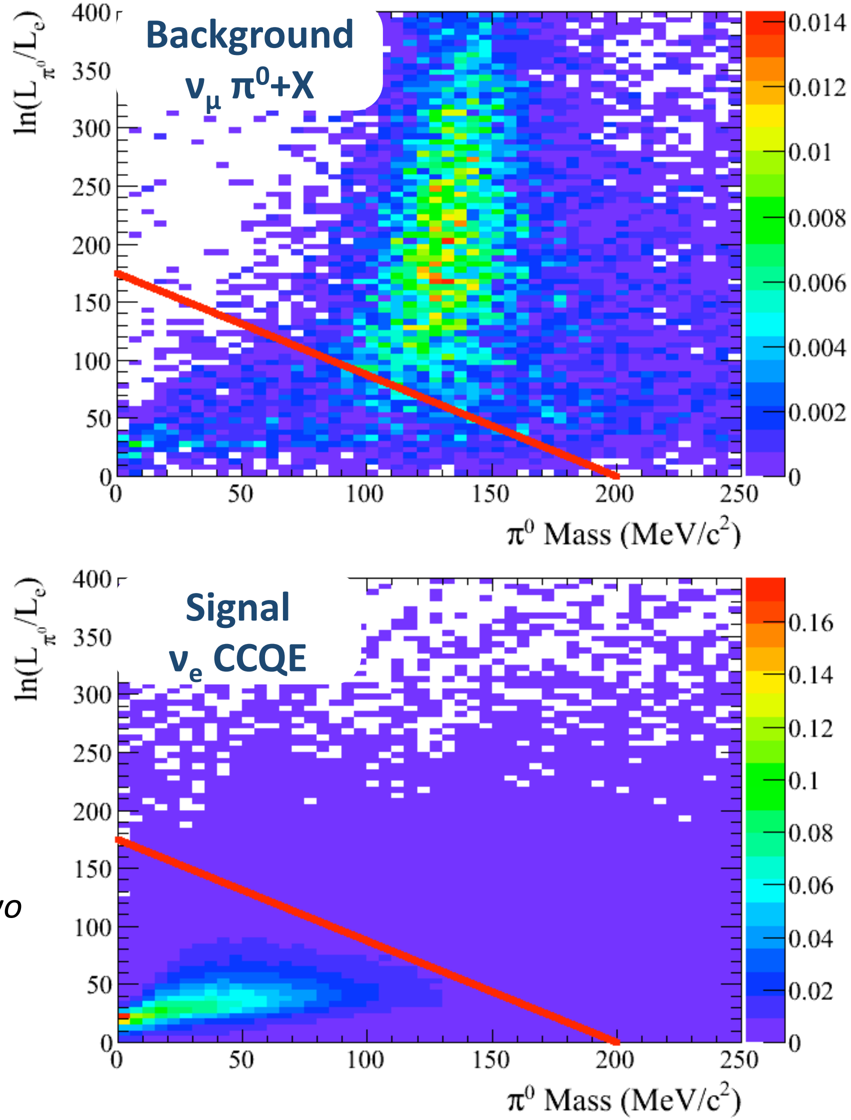
Effective parameters M_A^{QE}, M_A^{Res} and normalisations are fit to data (E.g. MiniBooNE [*Phys. Rev.* ***D81*** *092005, 2010*]) weight CCQE and π production cross sections respectively, and provide uncertainties.

Final state interactions constraints and uncertainties from pion-nuclei scattering data

More in Kikawa-san's talk…

fiTQun: A new Cherenkov Detector Reconstruction Package

- Based on MiniBooNE Likelihood Model [NIM A608, 206 (2009)]
- For given event hypothesis generate charge and time PDF
- Event hypothesis then distinguished by best fit likelihoods.
- fiTQun uses mass of the π^0 hypothesis and best-fit likelihood ratio of e^- and π^0
- Cut removes 70% more π^0 background than previous§ method for a 2% added loss of signal efficiency



§ Previous approach (P0LFit) forced the reconstruction to find two rings and then formed a π^0 mass under the two-photon hypothesis

Future Sensitivity

$\nu_\mu \rightarrow \nu_e$ Oscilation

Precise measurement of $\sin^2 2\theta_{13}$ enhances the T2K sensitivity to δ_{CP} and the θ_{23} octant:

(ν_μ disappearance measures $\sin^2 2\theta_{23}$ and cannot distinguish the octant alone)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \quad \to \text{Leading, matter effect}$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \quad \to \text{CP conserving}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin_{31} \sin\Phi_{21} \quad \to \text{CP violating}$$

$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21} \quad \to \text{Solar}$$

$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E} \cos\Phi_{32} \sin\Phi_{31} \quad \to \text{Matter effect}$$

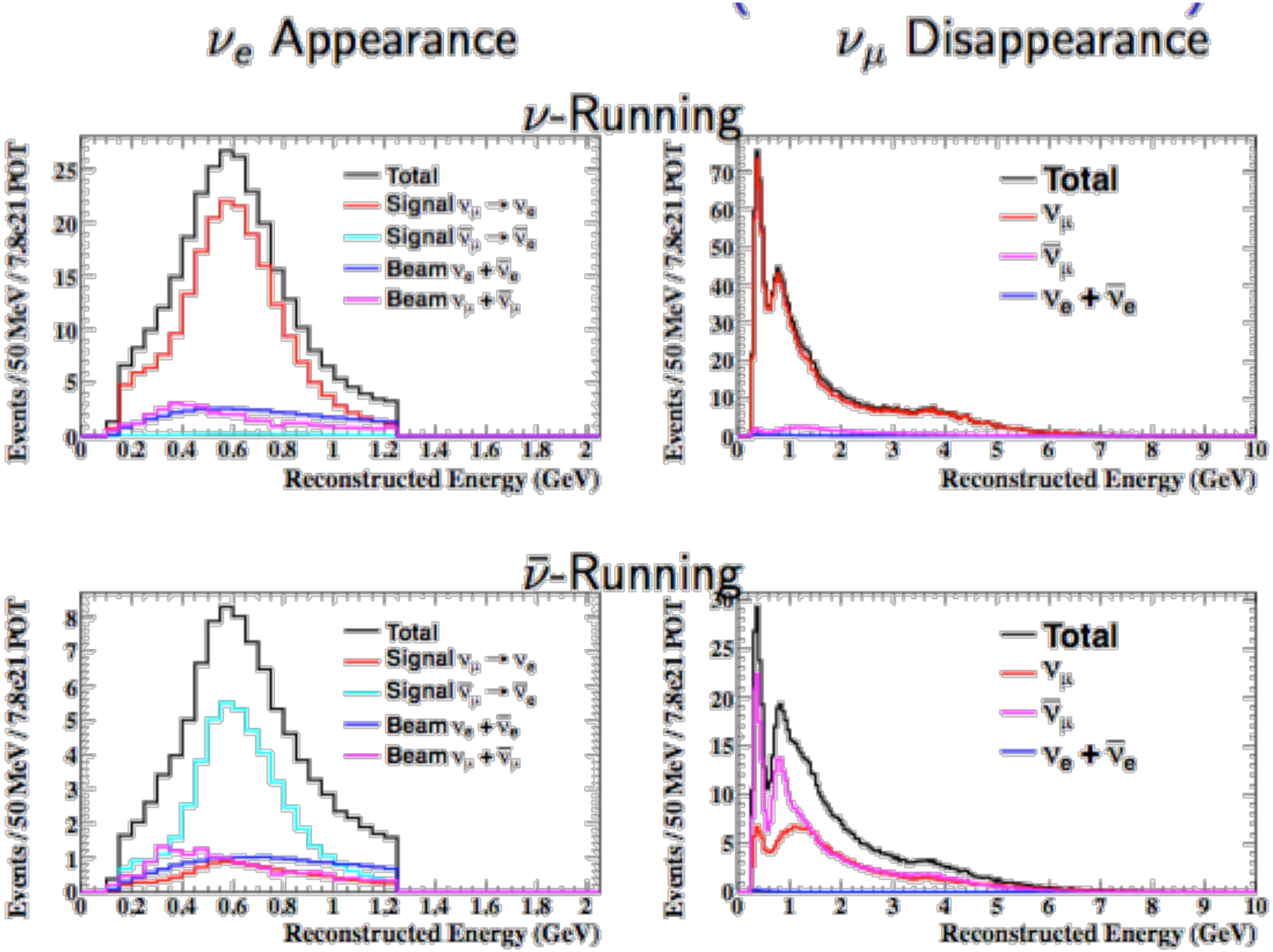
$(C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij},\ \Phi_{ij} = \Delta m_{ij}^2 L/4E)$

- δ_{CP} completely unknown
- MH completely unknown
- $\theta_{12} = 33.6° \pm 1.0°$
- $\theta_{23} = 45° \pm 6°$ (90% C.L.) – is θ_{23} maximal?
- $\theta_{13} = 9.1° \pm 0.6°$ – from reactor

T2K Future Sensitivity Study

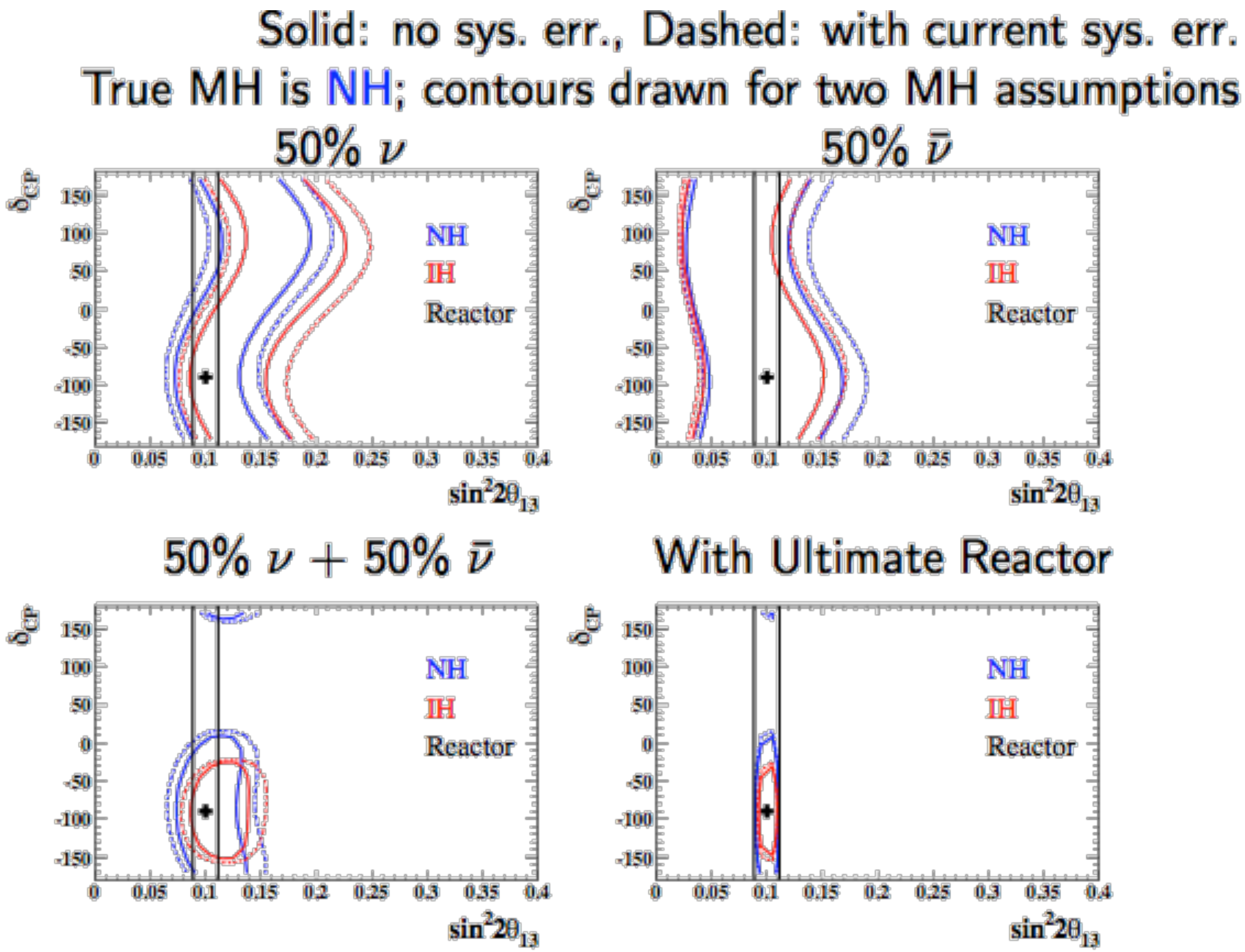
- T2K combined 3 flavor appearance + disappearance fits
  - At full T2K statistics – 7.8×10^{21} POT
  - Simultaneously fit MC SK reconstructed energy spectra for ν_e, ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$
  - Maximum likelihood fit
  - Uncertainties on $\sin^2 2\theta_{13}$, δ_{CP}, $\sin^2\theta_{23}$, and Δm^2_{32} are considered
  - Nominal assumption: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$, normal MH
- Current T2K systematic errors used
  - $\sim$10% for ν_e, $\sim$13% for ν_μ
  - $\bar{\nu}$ errors estimated as equal to ν errors with an additional 10% normalization uncertainty
- With and without a reactor constraint based on the expected ultimate precision of Daya Bay + RENO + Double Chooz on $\sin^2 2\theta_{13}$ $(= 0.1 \pm 0.005)$

Reconstructed E_{ν} @SK Full T2K Stats (7.8 x10^{21} POT)



Ultimate T2K 90% C.L.

True δ_{CP}= -90^o, $\sin^2 2\theta_{13}$ = 0.1

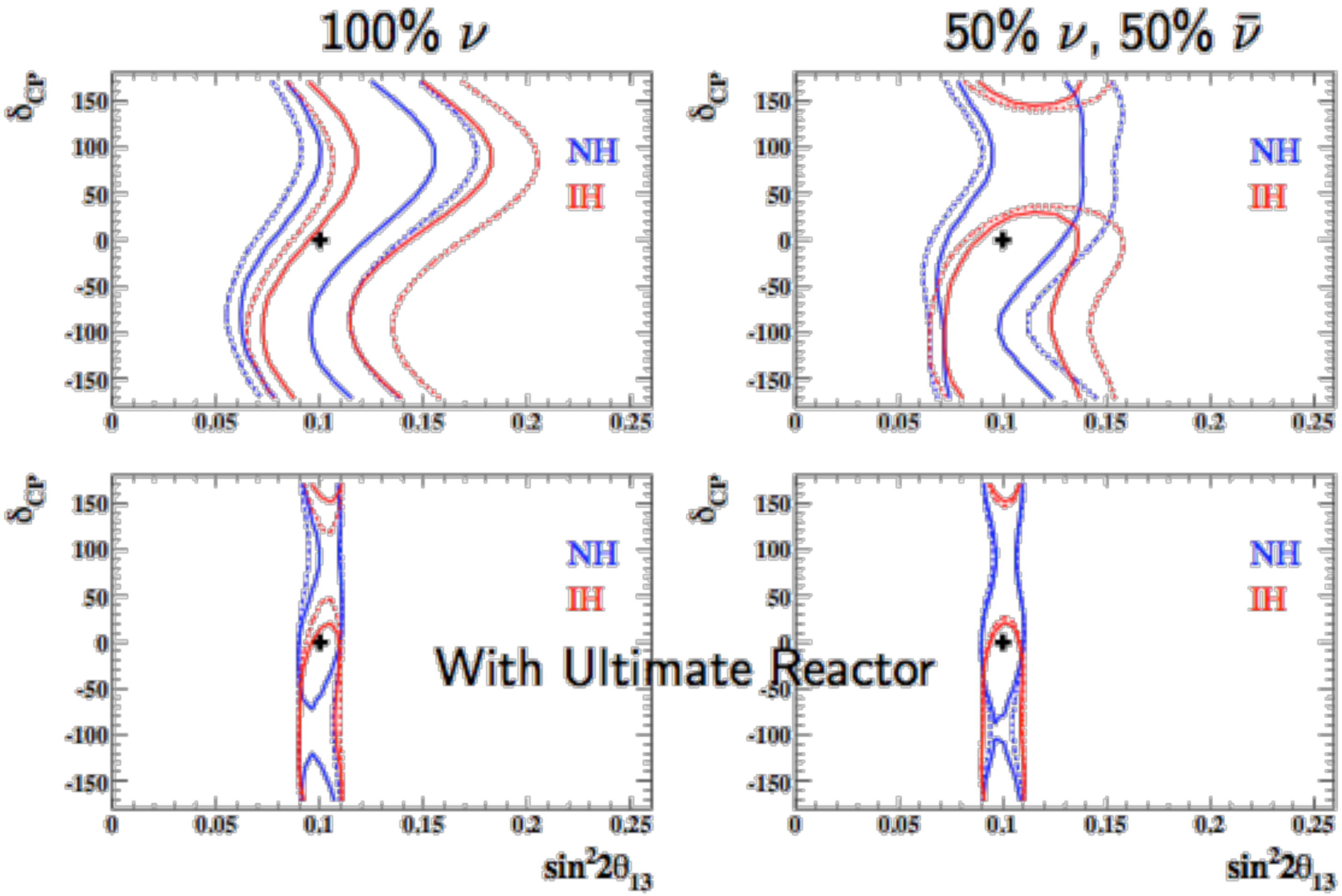


Ultimate T2K 90% C.L.

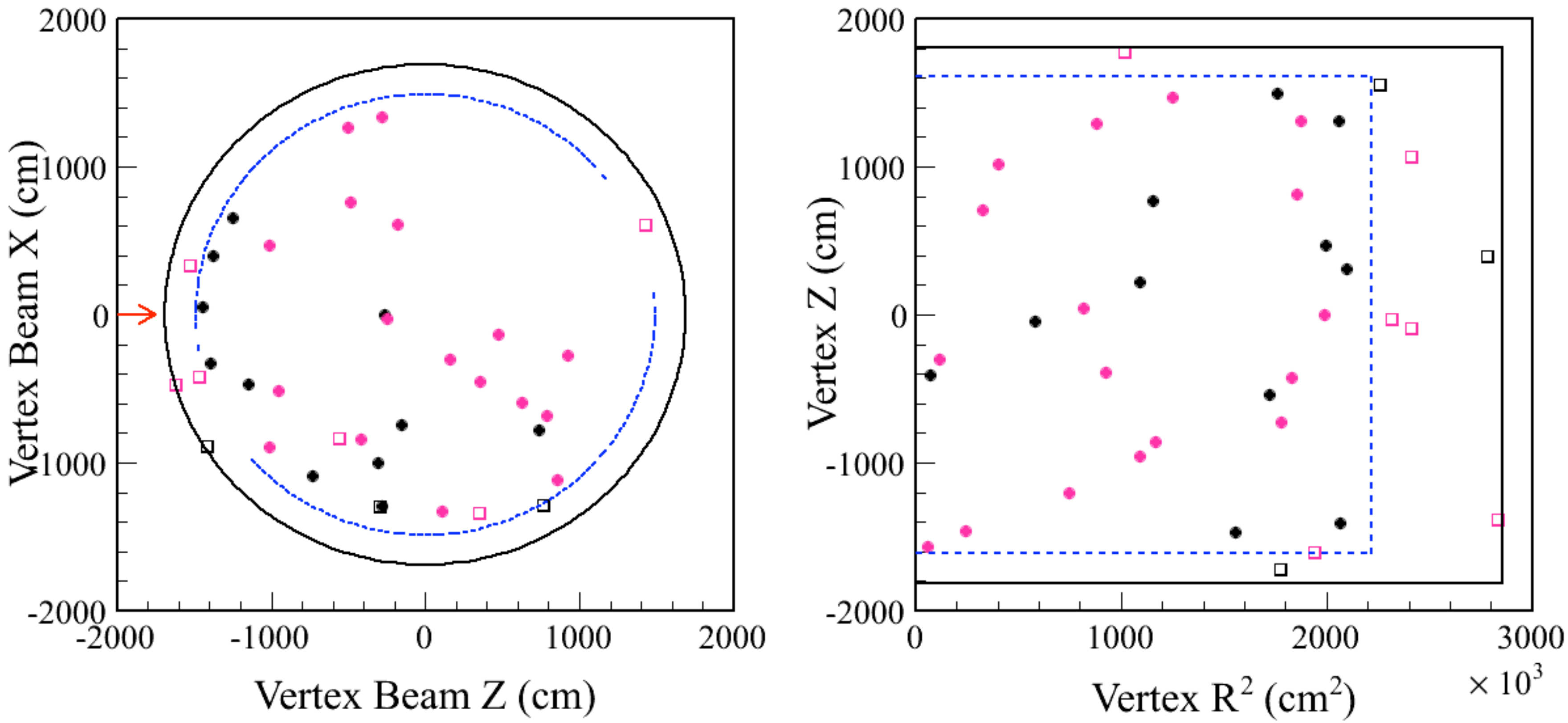
True $\delta_{CP} = 0^o$, $\sin^2 2\theta_{13} = 0.1$

Solid: no sys. err., Dashed: with current sys. err.

True MH is NH; contours drawn for two MH assumptions



Super-K ν_e Candidate Vertex Distributions



Info from JPARC

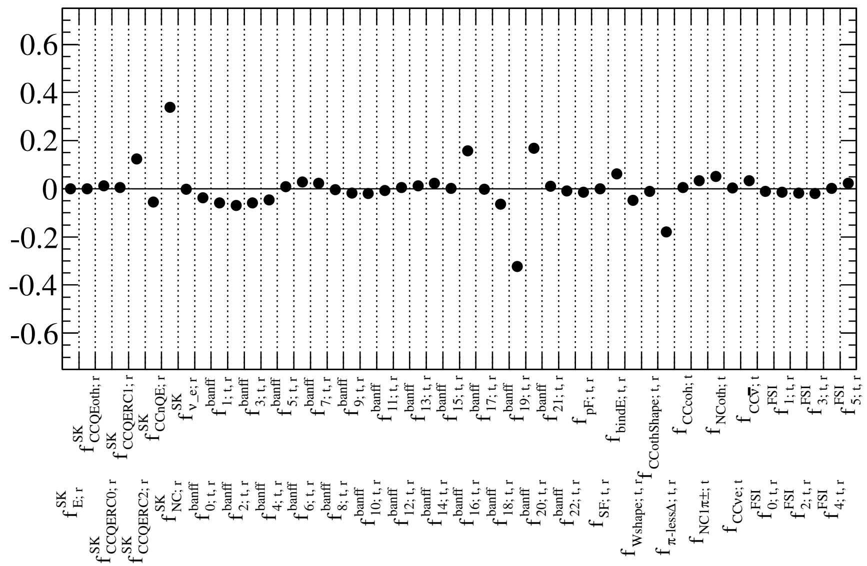
List of all publicized information in English July 26 : Message from Director Ikeda of the J-PARC center
http://j-parc.jp/en/topics/20130726director_message.html
July 8 : J-PARC News - June 2013 (Issue #98)
http://j-parc.jp/en/news/2013/J-PARC_News-e1306.html
June 27 : A delay in suspending the operation of the accelerator complex and a delay in turning off the ventilation fans at the Hadron Experimental Facility (HD Facility)
http://j-parc.jp/en/topics/HDAccident20130627.pdf
June 21 : Results of the individual does measurements from the radioactive material leak at the HD Facility
http://j-parc.jp/en/topics/HDAccident20130621.pdf
June 21 : Postponement of the 2nd International Symposium of Science at J-PARC (J-PARC 2013)
http://j-parc.jp/en/topics/20130621director_message.html
June 18 : 2nd Accelerator Facility Accident Report to Nuclear Regulation Authority - Full Version -
http://j-parc.jp/en/topics/20130618Accident_Report.html
June 18 : Submission of the 2nd report on the radioactive material leak at the HD Facility of J-PARC
http://j-parc.jp/en/topics/HDAccident20130618_02.pdf
June 18 : On the establishment of an External Expert Panel to review the leak accident of radioactive material at the J-PARC HD Facility
http://j-parc.jp/en/topics/HDAccident20130618_01.pdf
June 13 : J-PARC News Special Issue
http://j-parc.jp/en/news/2013/J-PARC_News-e_Special-Issue1305.html
June 10 : Notification of Cancelation of Assigned Beamtime to the End of July 2013 due to the Accident at HD Facility
http://j-parc.jp/en/topics/20130610director_message.html
May 31 : Submission of the 1st report on the radioactive material leak at the HD Facility of J-PARC (Accelerator Facility Accident Report) - full version-
http://j-parc.jp/en/topics/HDAccident20130531.pdf
May 31 : A summary of the accident at HD Facility on May 23 2013 (based on the Japanese documents publicized at the J-PARC website on May 25 and May 29)
http://j-parc.jp/en/topics/summary20130531.pdf
May 30 : Extension of the 2013B call for proposals deadline
http://j-parc.jp/researcher/MatLife/en/news/20130530.html
May 29 : Message from Director of J-PARC Center
http://j-parc.jp/en/topics/20130529director_message.html
May 27 : Message from the Director of J-PARC Center to Users
http://j-parc.jp/en/topics/20130527director_message.html
May 25 : Accident of J-PARC Hadron Experimental Facility
http://j-parc.jp/en/topics/20130525presse.html

MUON NEUTRINO DISAPPEARANCE ANALYSIS

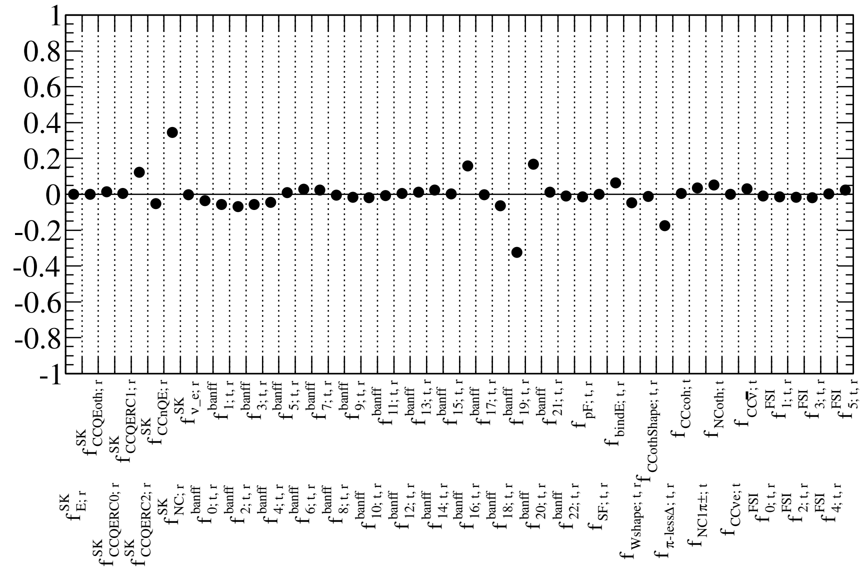
ν_μ disappearance results using $3.01{\times}10^{21}$ POT

Pulls of 48 systematic errors @ best fit points

1st octant



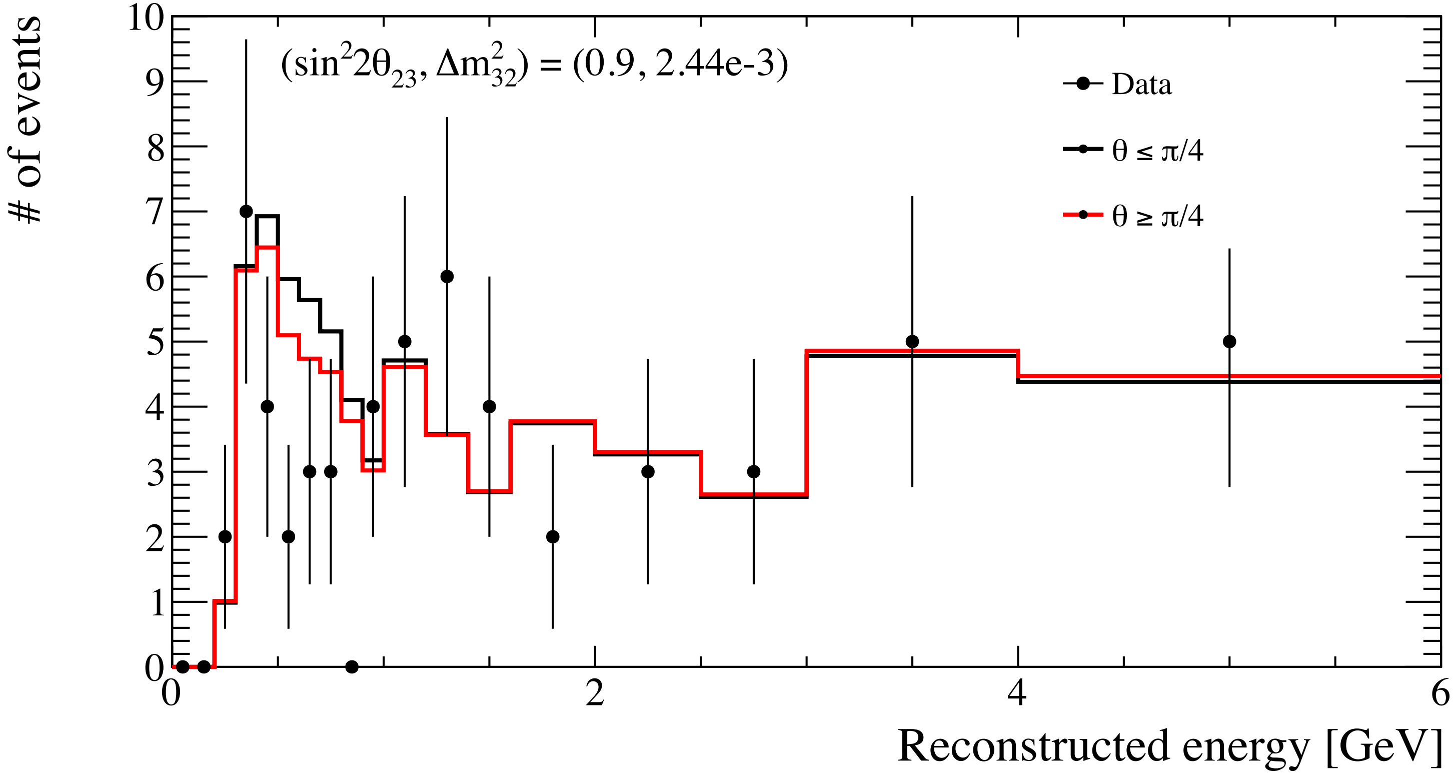
2nd octant



$$\text{pull} = \frac{f_{\text{best fit}} - f_{\text{nominal}}}{\sigma_{\text{best fit}}}$$

ν_μ disappearance results using 3.01×10^{21} POT

Fit spectra @ $(\sin^2 2\theta_{23}, \Delta m_{32}{}^2) = (0.9, 2.44\text{e-}3)$



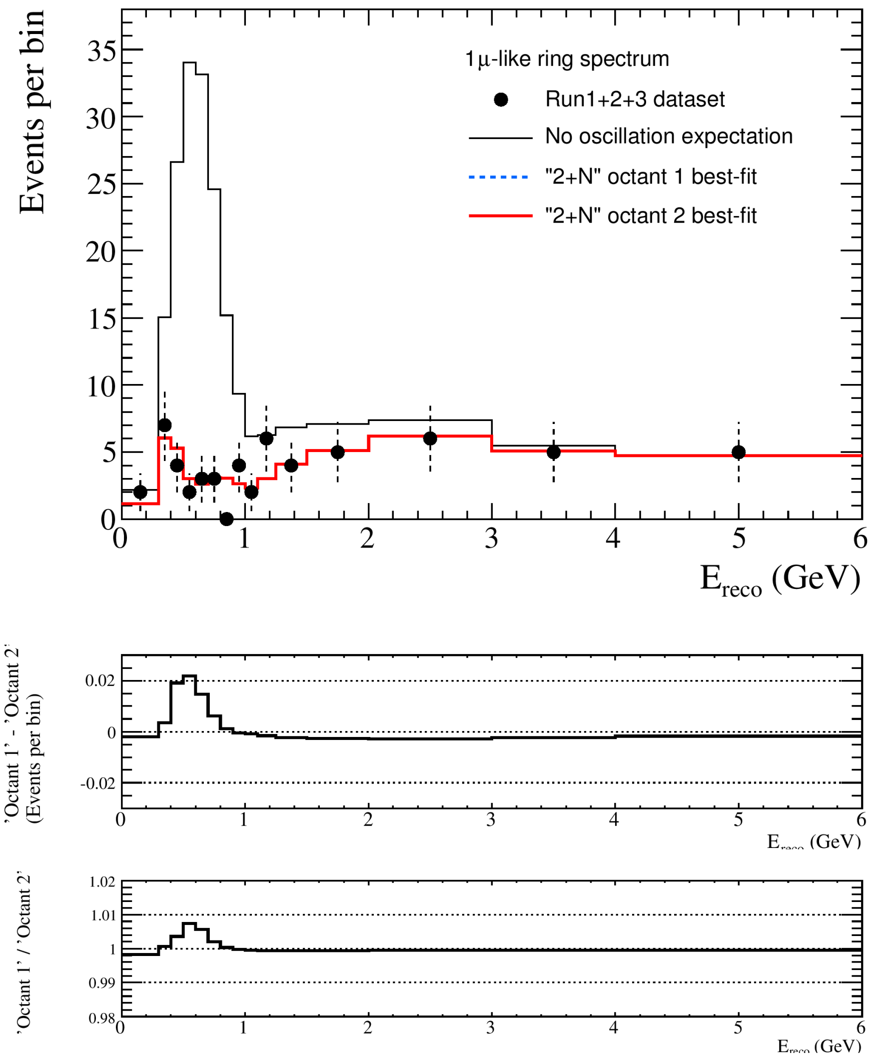
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}}\right)\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$

Leading

Next-to-leading

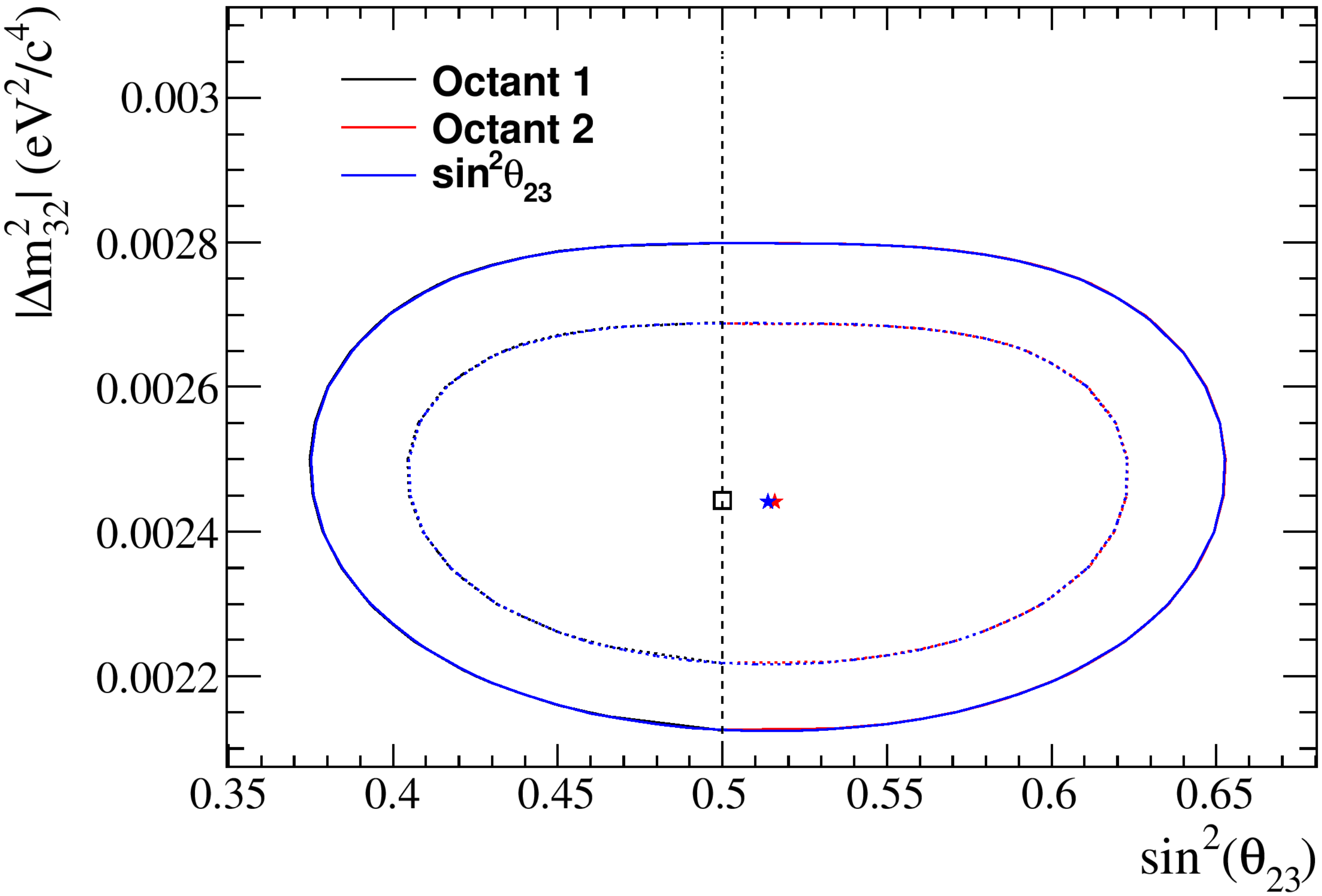
ν_μ disappearance results using 3.01×10^{21} POT

Comparison of best fit spectra between $1^{st}/2^{nd}$ octants

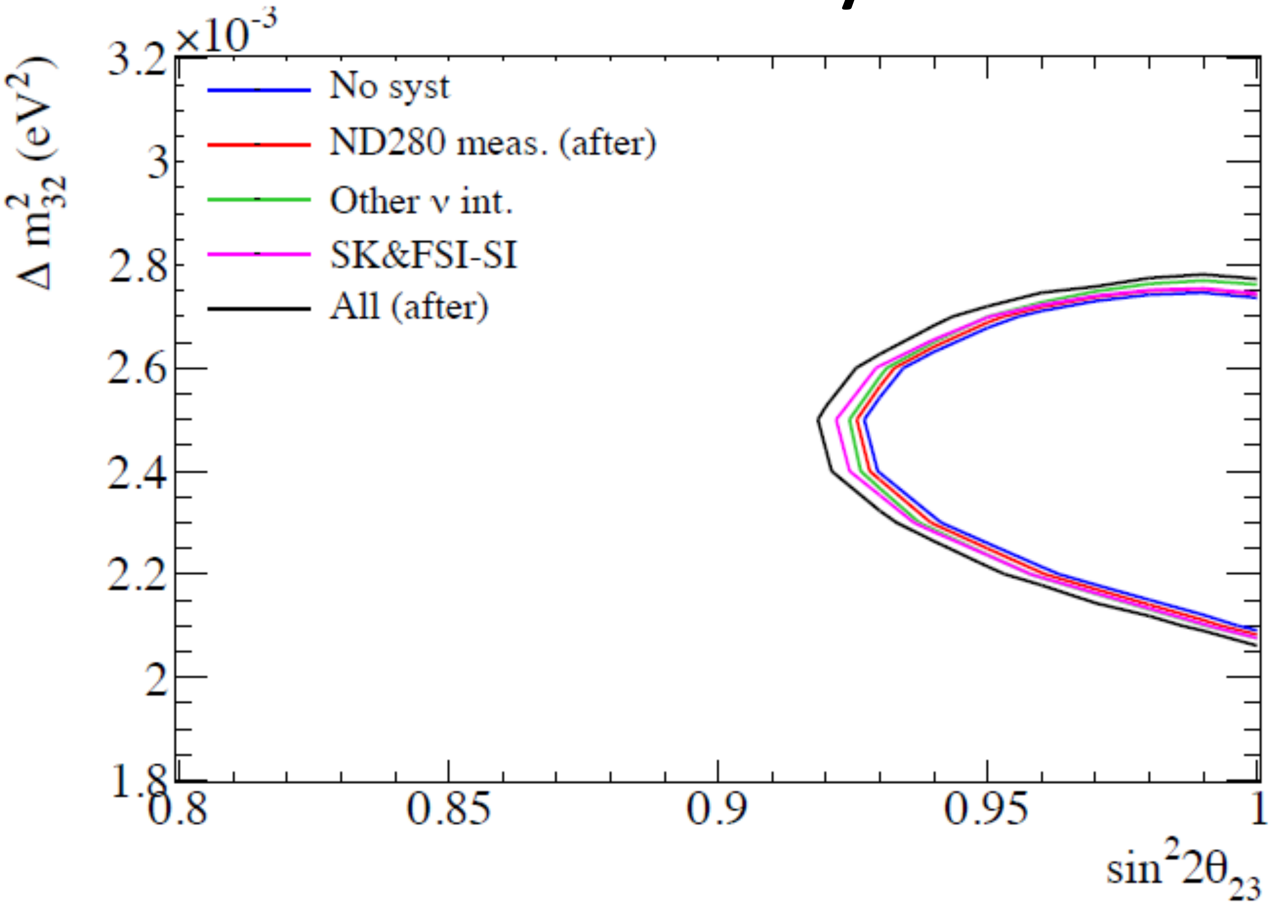


ν_μ disappearance results using 3.01×10^{21} POT

"$\sin^2 2\theta_{23}$ fit result" is consistent with "$\sin^2\theta_{23}$ fit result".



Effect of Systematics on Disappearance Sensitivity



- 1st Octant expected 90% CL contours for true $(\sin^2 2\theta_{13}, \Delta m^2_{23}) = (1.0, 2.4\times10^{-3})$
- Effect of individual categories of systematic uncertainties and the total systematic uncertainty

Enumeration of Disappearance Systematic Uncertainties

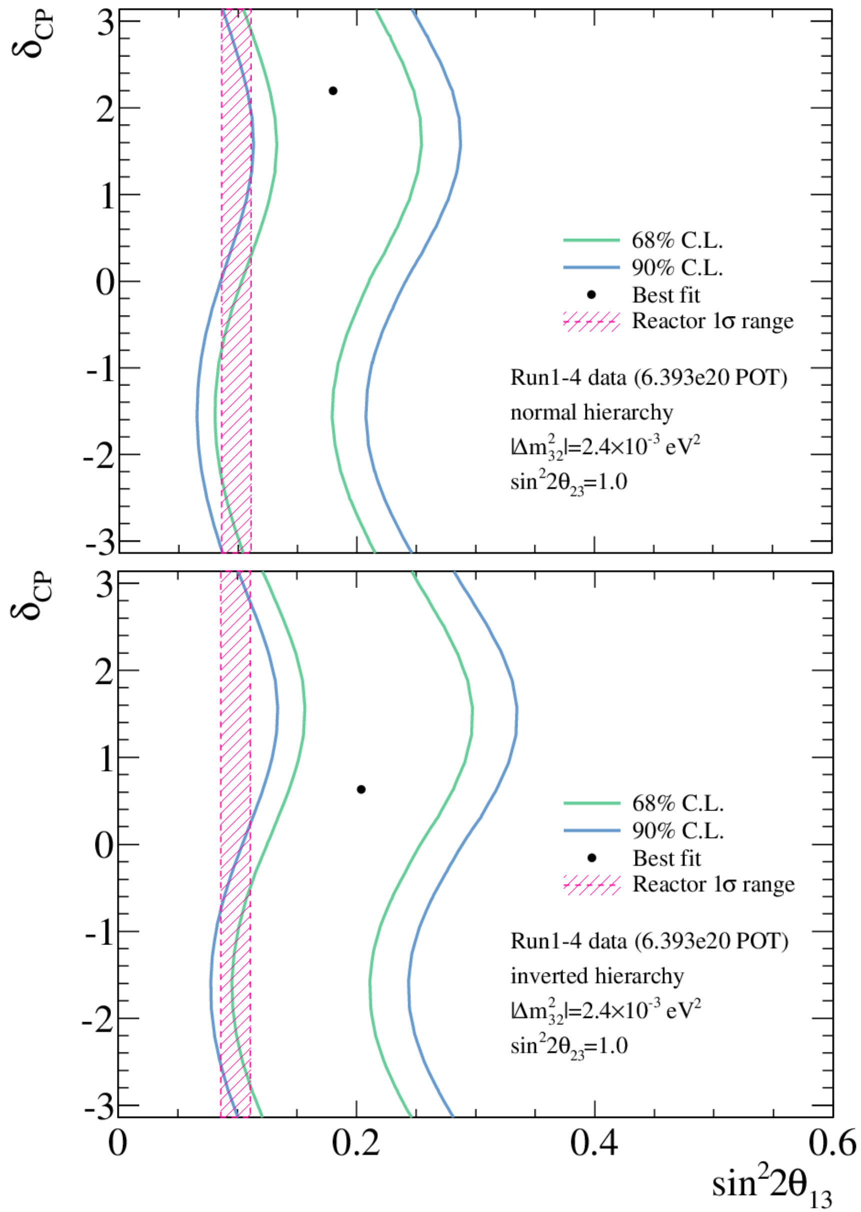
Systematic uncertainty	$(\sin^2 2\theta_{23}, \Delta m^2_{32}) = (1.0, 2.4 \times 10^{-3})$ Before ND280 fit	After ND280 fit
Beam flux	±10.5	±7.1
M_A^{QE}	+13.8/-16.9	+6.3/-7.0
M_A^{RES}	+7.6/-7.4	+4.4/-4.3
CCQE norm (E^{true} <1.5 GeV)	±4.5	±3.5
CCQE norm (E^{true}=1.5~3.5 GeV)	±4.3	±3.0
CCQE norm (E^{true} >3.5 GeV)	±1.4	±1.0
CC1π norm (E^{true} <3.5 GeV)	±4.4	±2.9
CC1π norm (E^{true} >3.5 GeV)	±4.8	±3.3

Systematic uncertainty	$(\sin^2 2\theta_{23}, \Delta m^2_{32})$ Before ND280 fit
CC other shape	±0.8
Spectral function	-0.7/+0.7
E_b	0.0/+0.2
p_F	+0.1/0.0
CCCoh norm	±0.9
NC1πC norm	±0.9
NCOth norm	±0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	(no changed)
W-shape	±0.4
Pi-less delta decay	±6.2
$\sigma_{\bar{\nu}}/\sigma_{\nu}$	±2.4
SK eff. & FSI-SI for $\nu_\mu, \bar{\nu}_\mu$ CCQE (E^{rec} <0.4 GeV)	±0.2
SK eff. & FSI-SI for $\nu_\mu, \bar{\nu}_\mu$ CCQE (E^{rec}=0.4~1.1 GeV)	±1.0
SK eff. & FSI-SI for $\nu_\mu, \bar{\nu}_\mu$ CCQE (E^{rec} >1.1 GeV)	±2.4
SK eff. & FSI-SI for $\nu_\mu, \bar{\nu}_\mu$ CCnonQE	±7.8
SK eff. & FSI-SI for ν_e CC	±0.2
SK eff. & FSI-SI for All NC	+6.4/-5.8
SK energy scale	(not changed)

- Fractional change (in %) of the number of candidate events under a change to each systematic parameter by 1 error size of before or after ND280 constraint at true $(\sin^2 2\theta_{13}, \Delta m^2_{23})=(1.0, 2.4\text{x}10^{-3})$

ELECTRON NEUTRINO APPEARANCE ANALYSIS

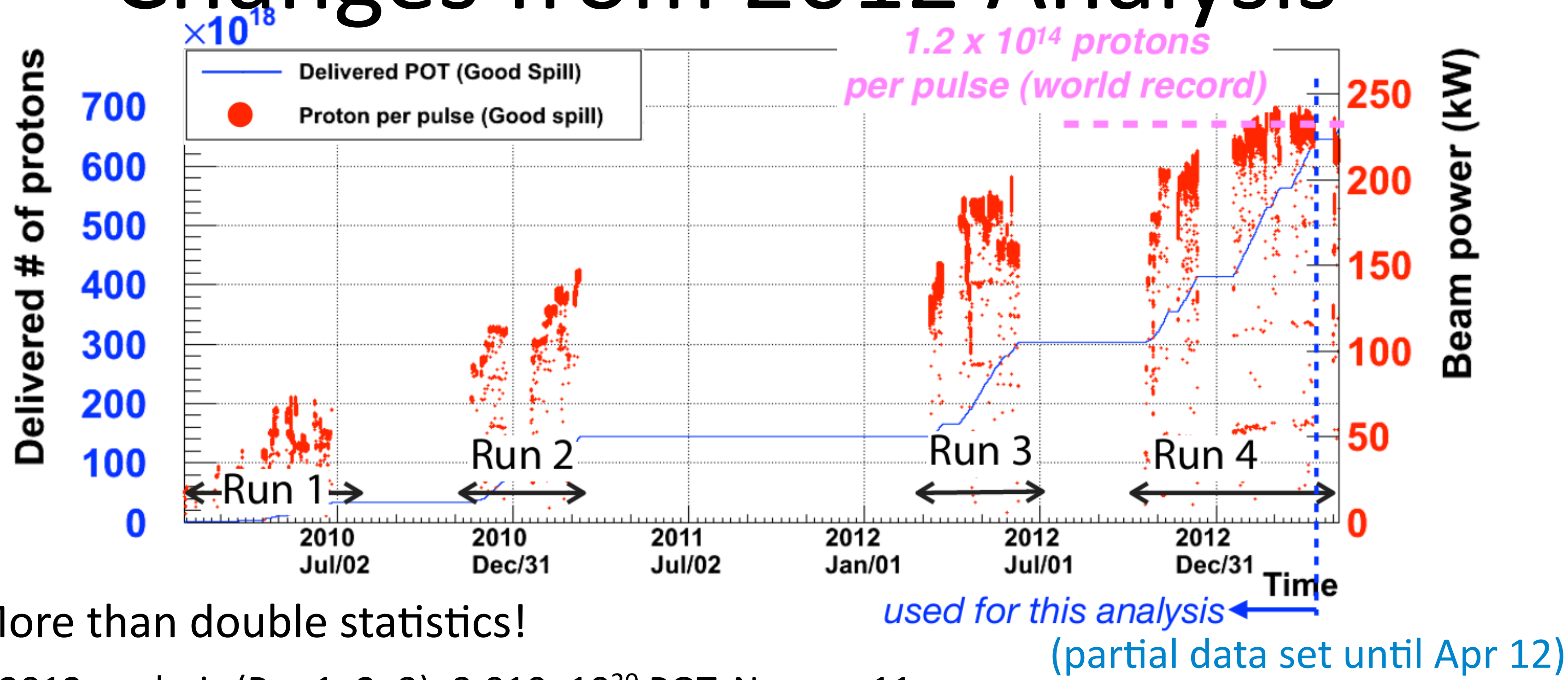
2D Contour of δ_{CP} vs. $\sin^2 2\theta_{13}$ with reactor result



In these plots, the contours are calculated in 2D space.

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

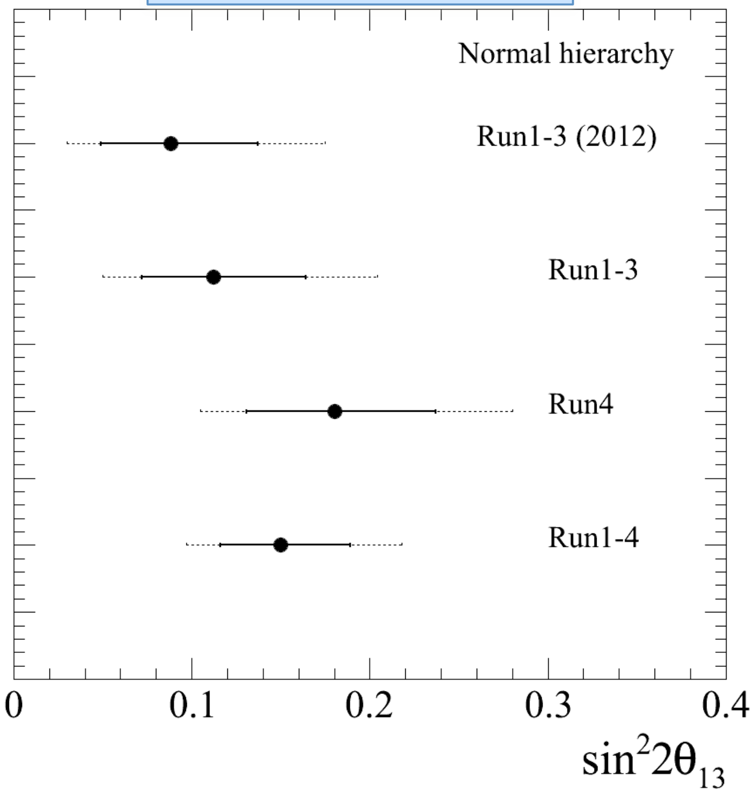
Changes from 2012 Analysis



- More than double statistics!
  - 2012 analysis (Run1+2+3): 3.010×10^{20} POT, $N_{events} = 11$
  - 2013 analysis (Run1+2+3+4(~Apr 12)): 6.393×10^{20} POT, $N_{events} = 11+17 = 28$
- The background rejection cut is improved by using a new SK reconstruction algorithm. BG events reduced from 6.4 to 4.6!
- Near detector measurement is improved by having new event categories which can further constraint the neutrino beam flux and cross section systematic errors.

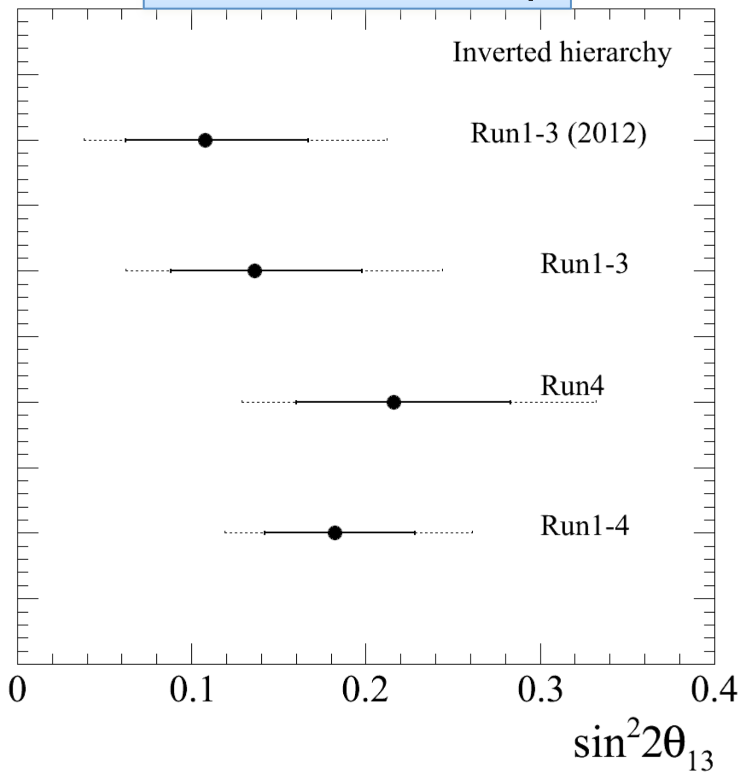
Current and Previous Results

Normal hierarchy



—68% C.L.
---90% C.L.

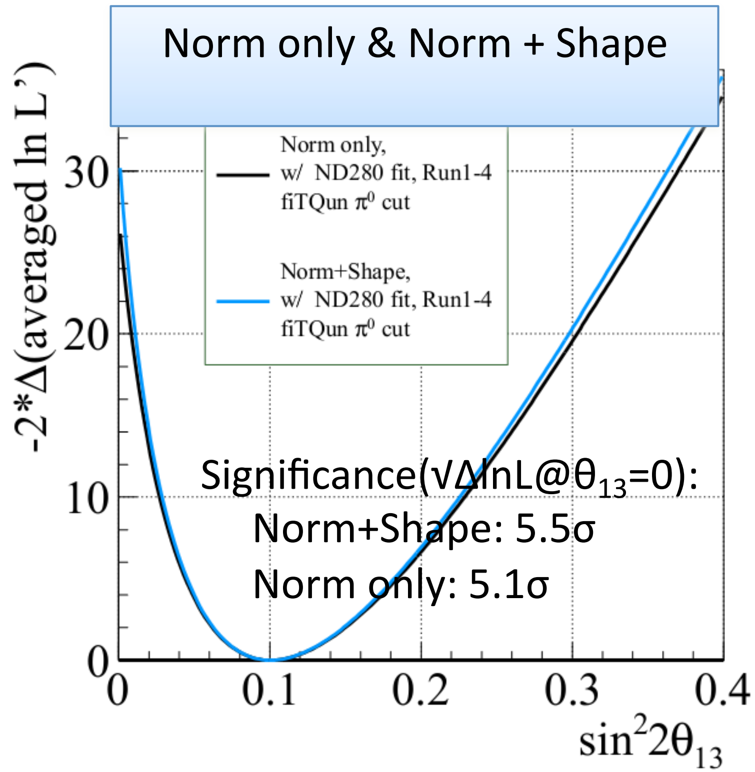
Inverted hierarchy



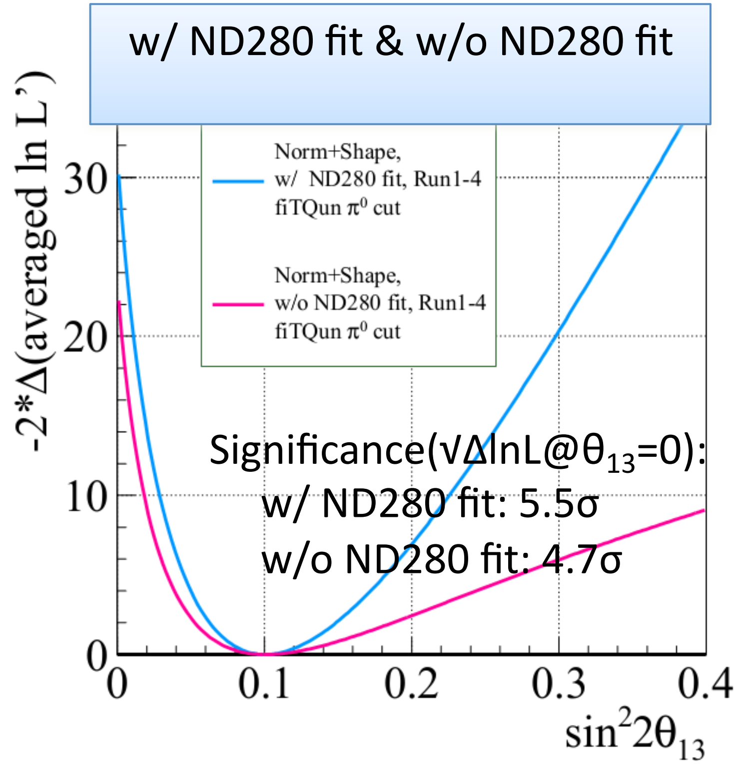
- Run 4 best fit value is higher than the others.
- Run1-3 (2012) looks different from Run1-3, because:
  - N_{pred} decreased by using new Super-K reconstruction, while N_{obs} did not change.
  - N_{pred} decreased with Run 1-4 near detector fit.

Sensitivity checks

We fit the toy MC experiments (true $\sin^2 2\theta_{13}=0.1$) to check the sensitivity.
The averaged lnL curves ↓ are generated by averaging 4000 toy experiments.



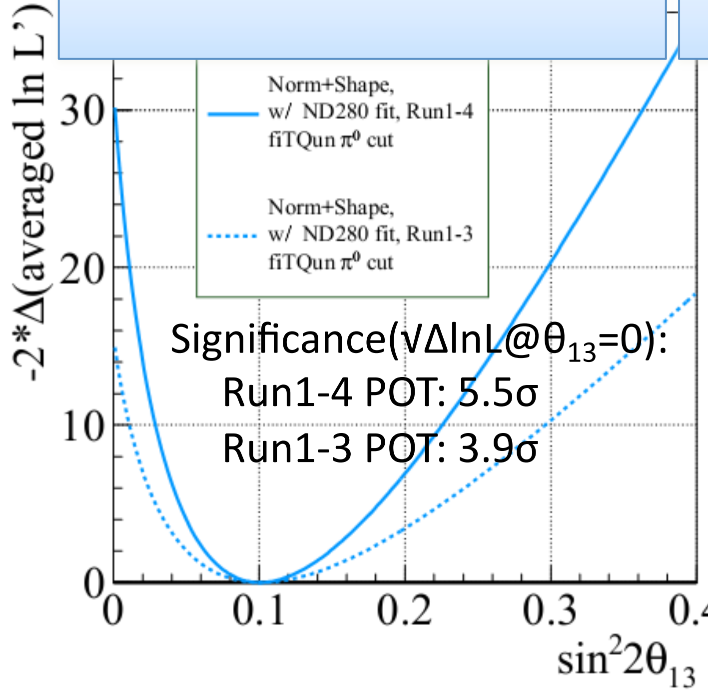
Effect of using shape information is not significant but important.



ND280 fit makes relatively large improvement.

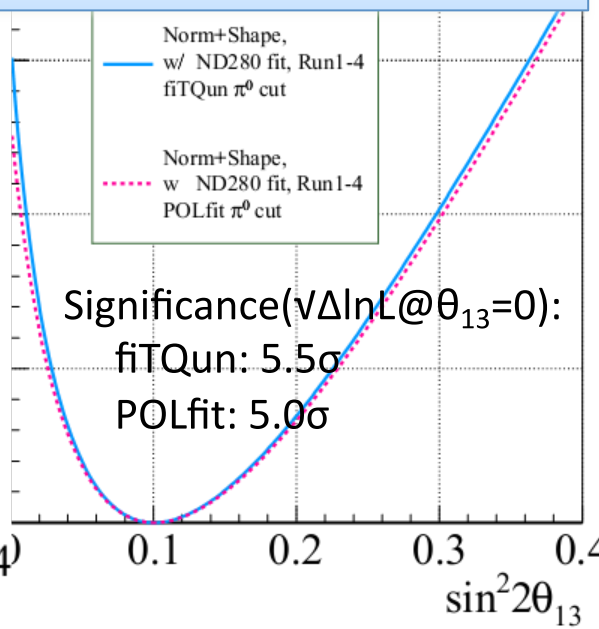
Sensitivity checks

Run1-4 POT & Run1-3 POT



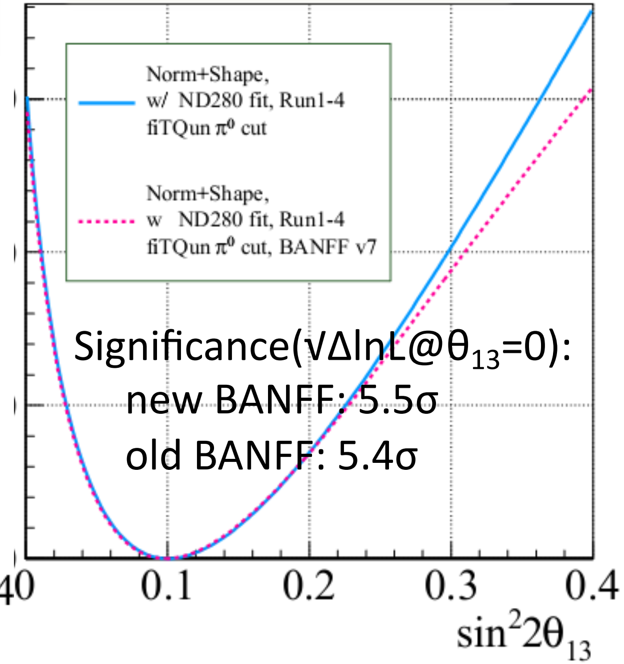
Significance becomes much larger by adding Run4.

fiTQun π^0 cut & POLfit π^0 cut



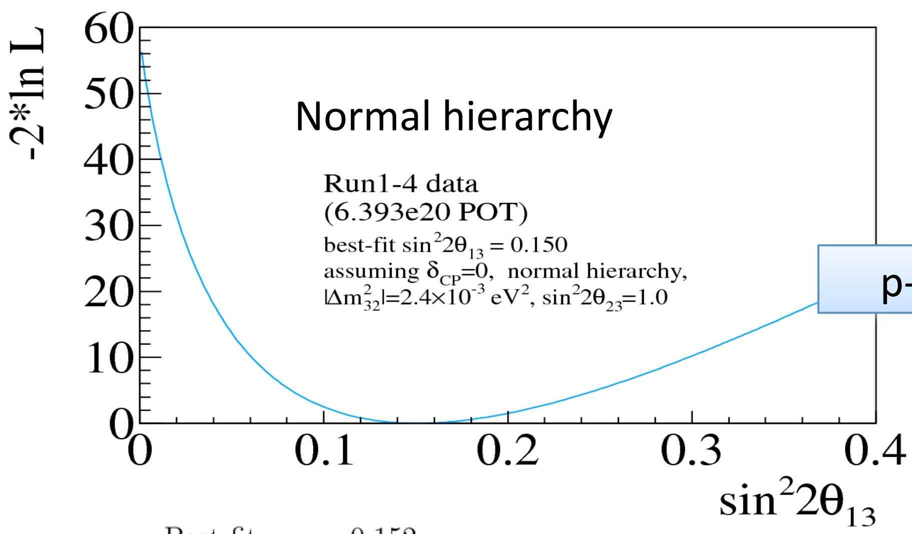
Effect of using fiTQun is not significantly large but important.

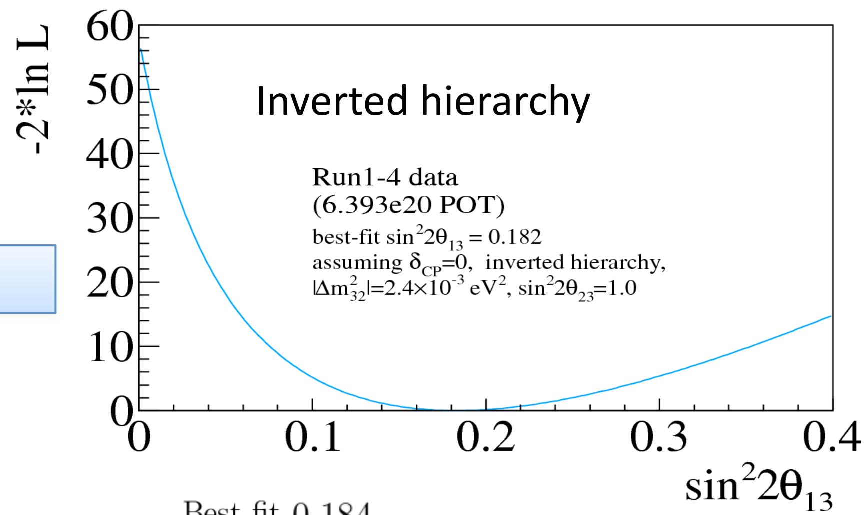
old & new BANFF



Significance is not much different for toy MC, because the N_{exp} become smaller with new BANFF while the errors are improved.

Likelihood curves for Run1-4 data fit

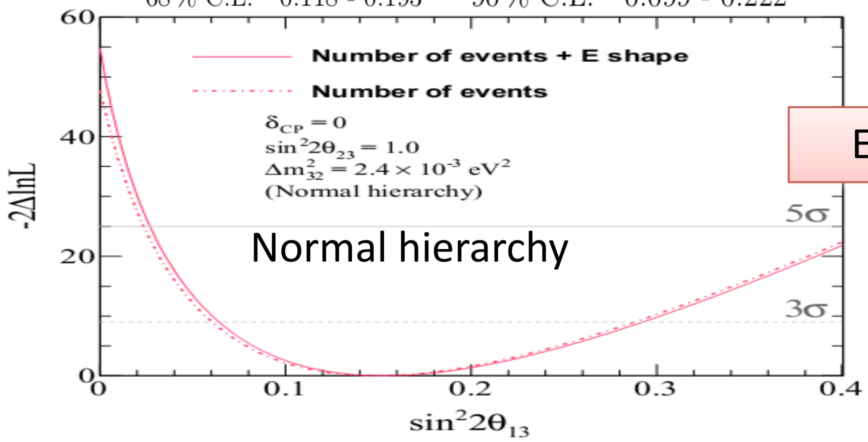




p-θ

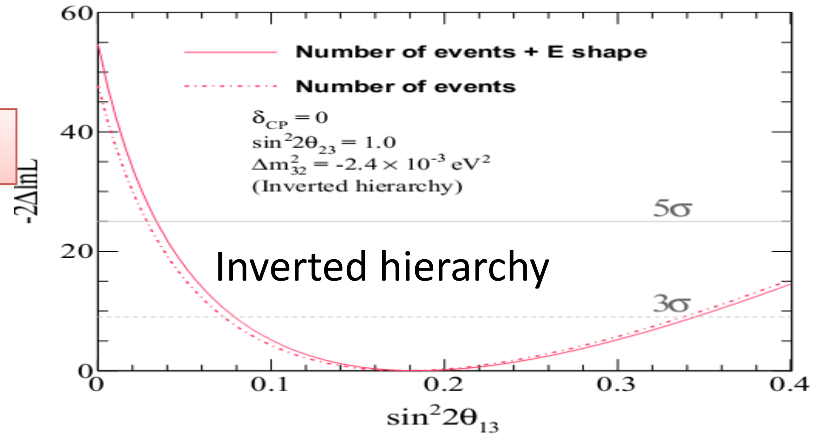
Best fit 0.152

68 % C.L. 0.118 - 0.193 90 % C.L. 0.099 - 0.222



Best fit 0.184

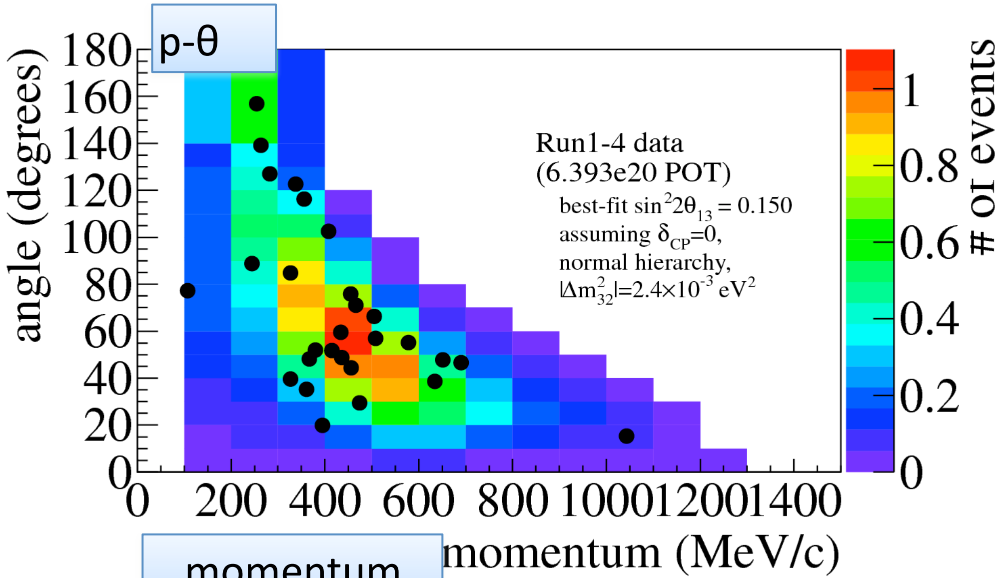
68 % C.L. 0.143 - 0.230 90 % C.L. 0.120 - 0.264

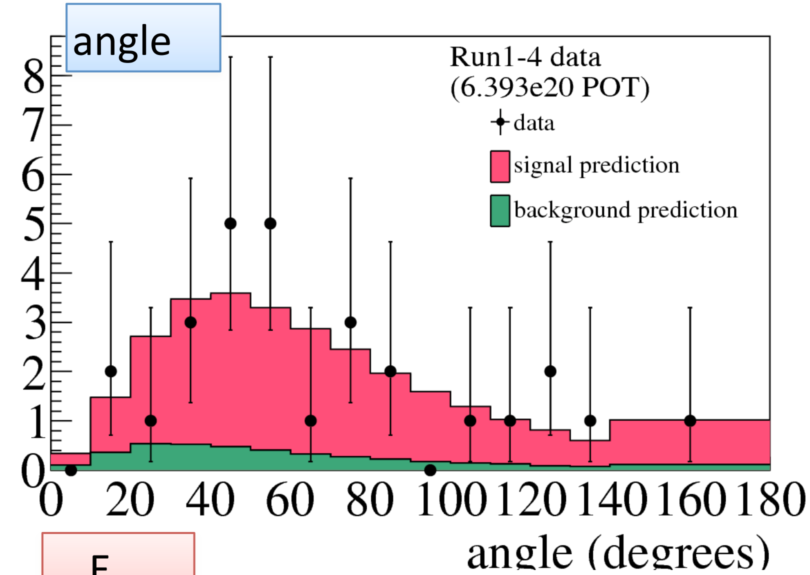


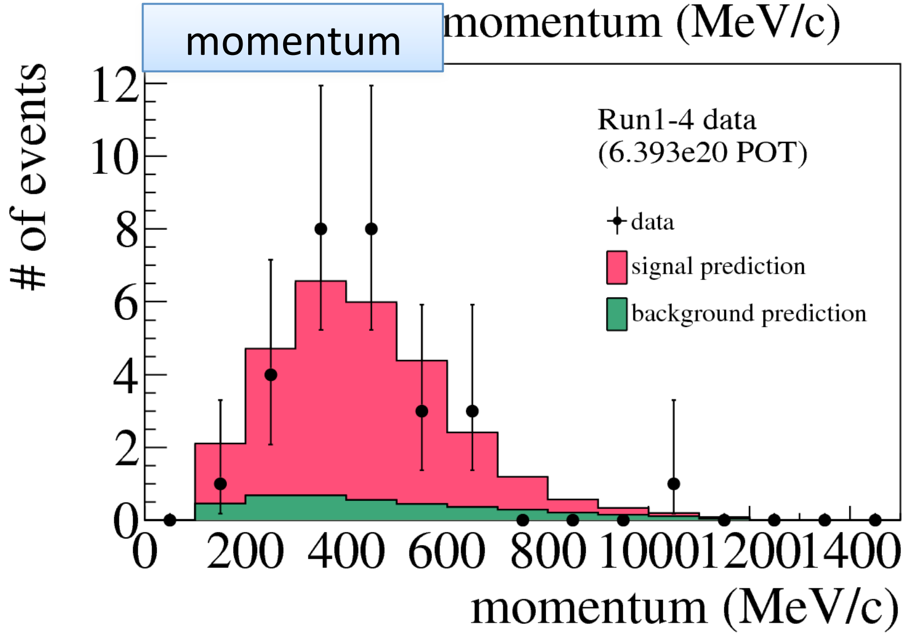
E_{rec}

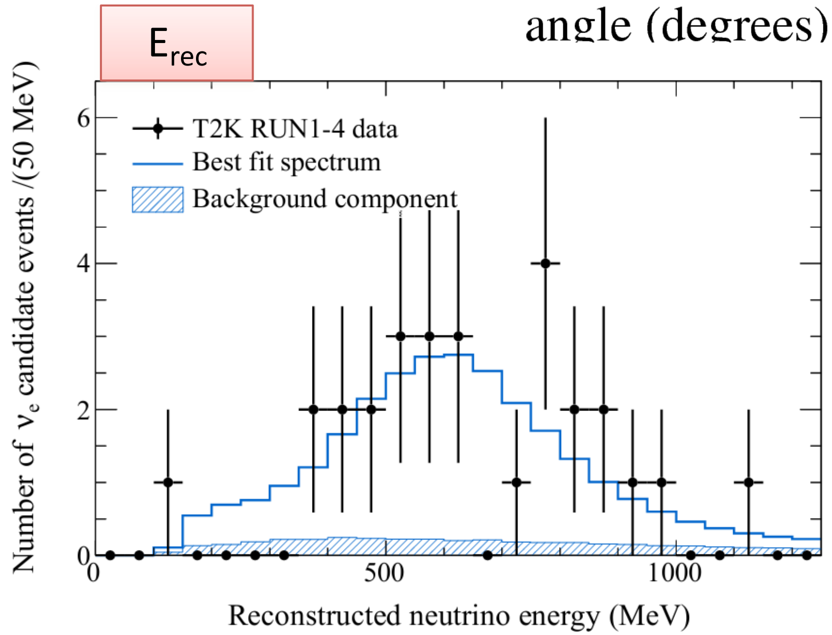
(summary table will be shown later.)

Best fit distributions (Run1-4, normal hierarchy)

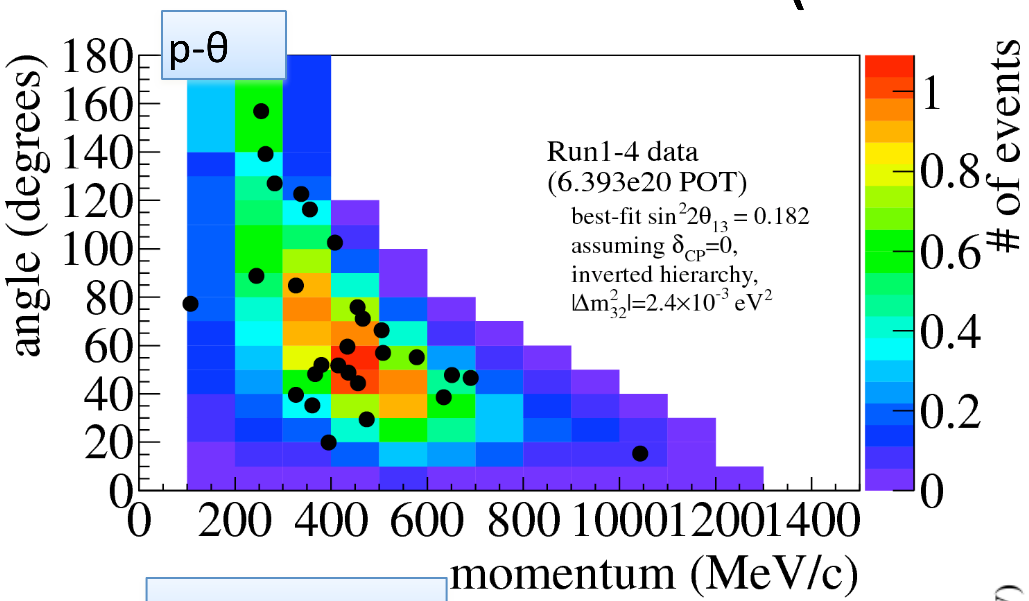


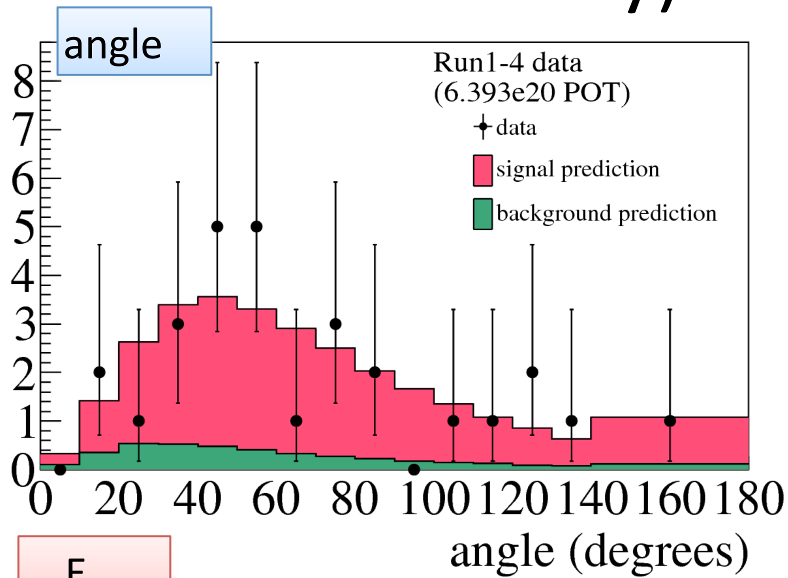


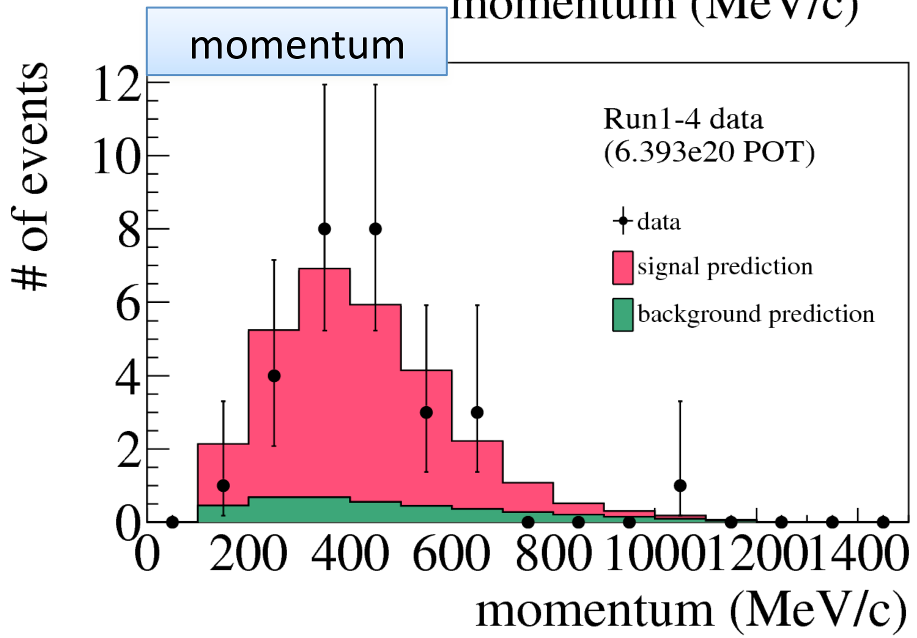


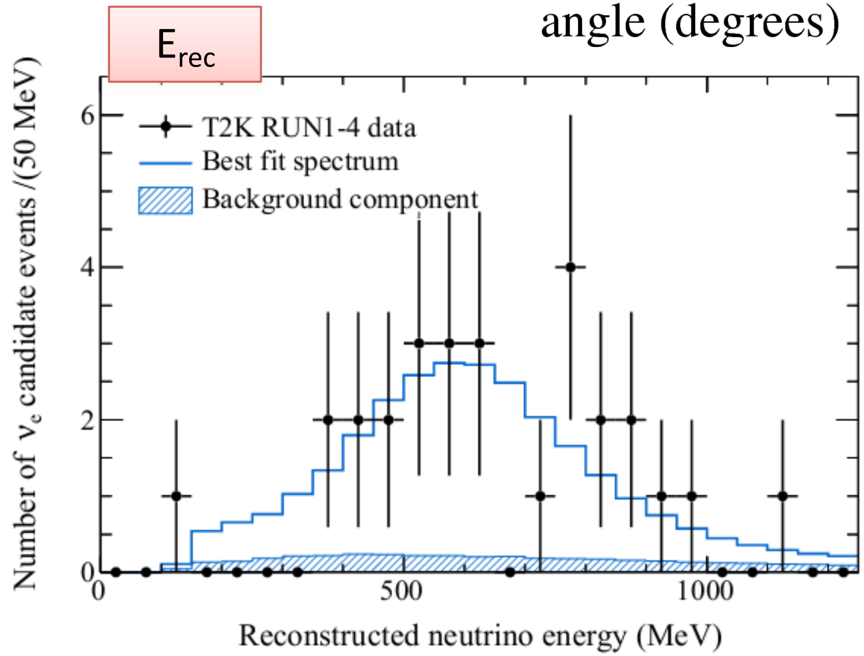


Best fit distributions (Run1-4, inverted hierarchy)









Fit summary table

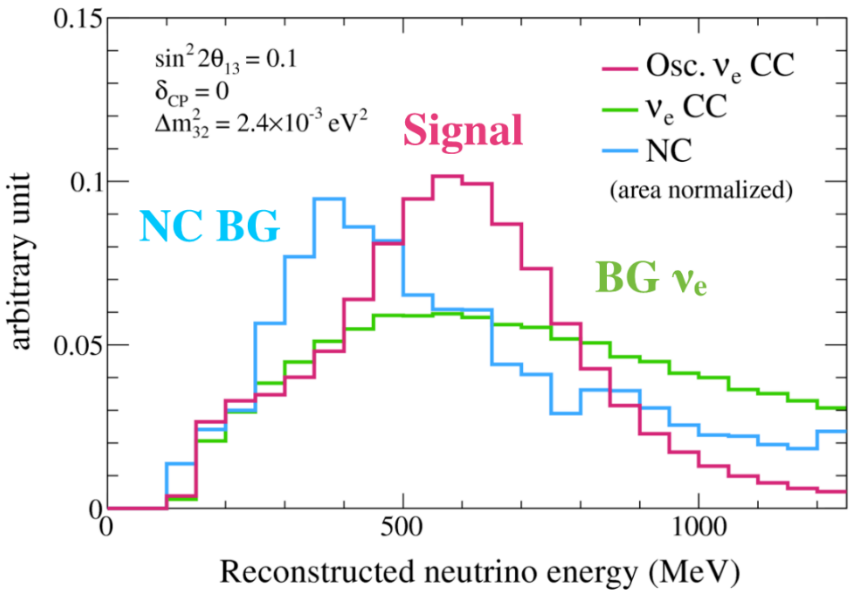
	Run1-4 (p-θ)	Run1-4 (E_{rec})	Run4 only	Run1-3 (2013 analysis)	Run1-3 (2012 analysis)
POT	6.39e20	6.39e20	3.38e20	3.01e20	3.01e20
Observed number of events	28	28	17	11	11
<u>Normal hierarchy</u> Best fit 90% C.L. 68% C.L.	0.150 0.097 – 0.218 0.116 – 0.189	0.152 0.099 – 0.222 0.118 – 0.193	0.180 0.105 – 0.280 0.131 – 0.237	0.112 0.050 – 0.204 0.072 – 0.164	0.088 0.030 – 0.175 0.049 – 0.137
<u>Inverted hierarchy</u> Best fit 90% C.L. 68% C.L.	0.182 0.119 – 0.261 0.142 – 0.228	0.184 0.120 – 0.264 0.143 – 0.230	0.216 0.129 – 0.332 0.160 – 0.283	0.136 0.062 – 0.244 0.088 – 0.198	0.108 0.038 – 0.212 0.062 – 0.167

Oscillation analysis method 2

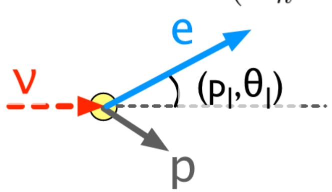
Method 2: Rate + reconstructed E_ν shape (1D)

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

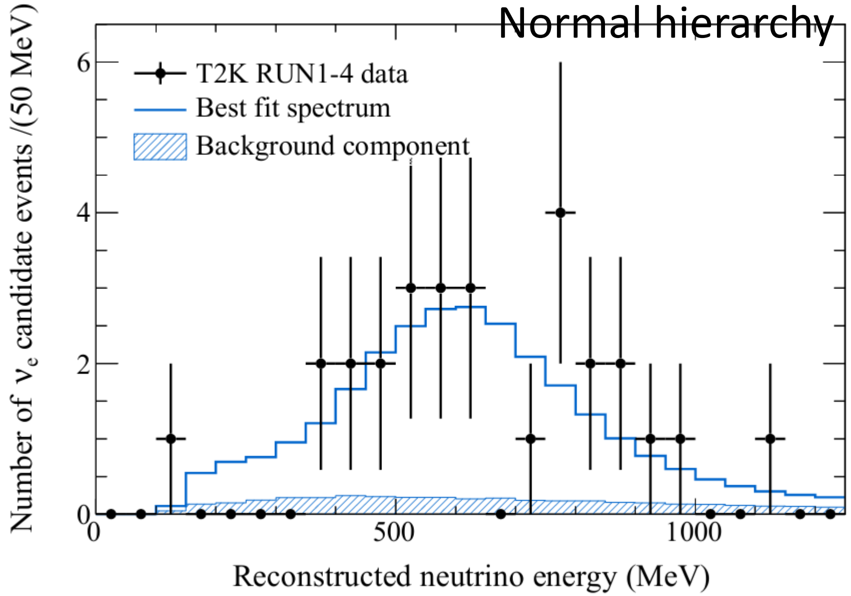
Fit data to the reconstructed energy distribution



$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$



Fit result



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

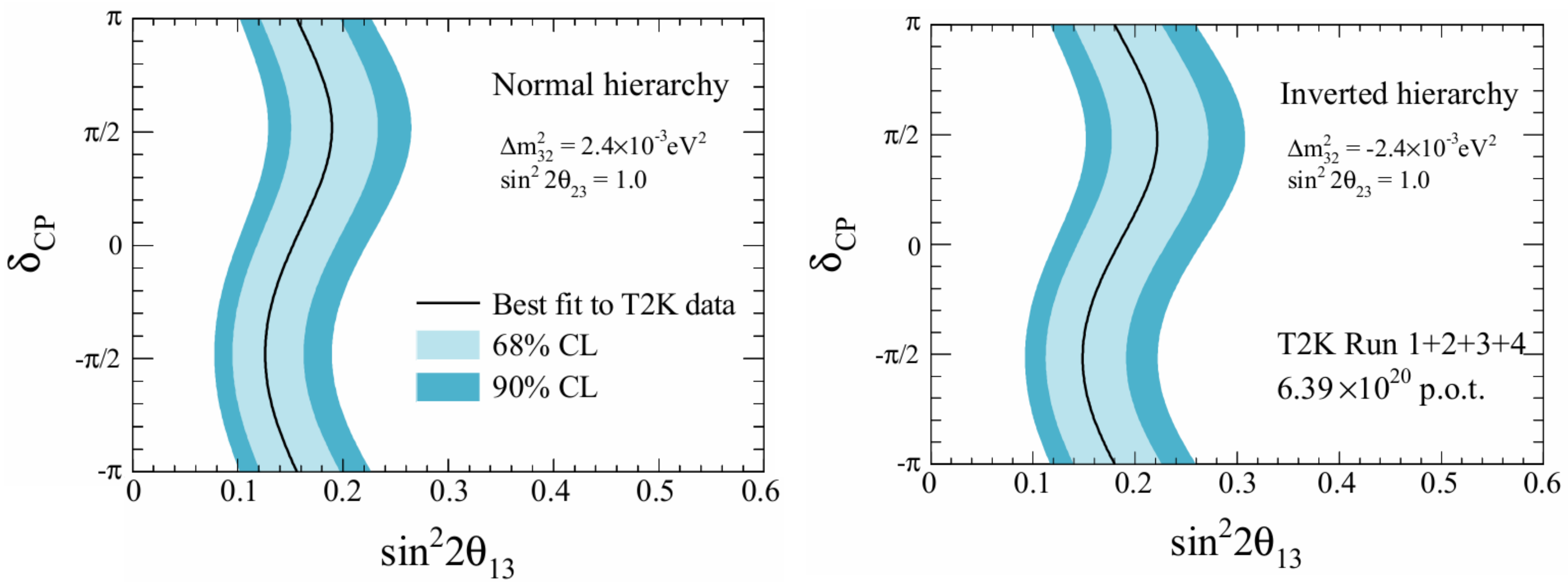
$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034}$$

Oscillation analysis method 2

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

Method 2: Rate + reconstructed E_ν shape (1D)

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



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

normal hierarchy:

$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034}$$

inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.184^{+0.046}_{-0.041}$$