Oscillation Results from T2K

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on behalf of the T2K Collaboration

Cornell LEPP Journal Club
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What We Hope to Learn

- Neutrino mass is the one discovery we have in hand of "beyond standard model" physics
- We still have fundamental questions about the nature of this new physics
  - How are these masses are generated?
  - How does that mechanism relate to standard model physics?
  - What implications does it have for the early universe?
- Study of neutrino masses and mixings is our only known window into this new physics

T2K's Signatures

- Neutrino oscillation at the "atmospheric" baseline (T2K and NOvA) probes this new physics in several interesting ways
  - Sensitive to structure of the mixing matrix, the neutrino mass spectrum and to CP violation in oscillations

- T2K studies both muon neutrino disappearance and muon to electron neutrino flavor conversion

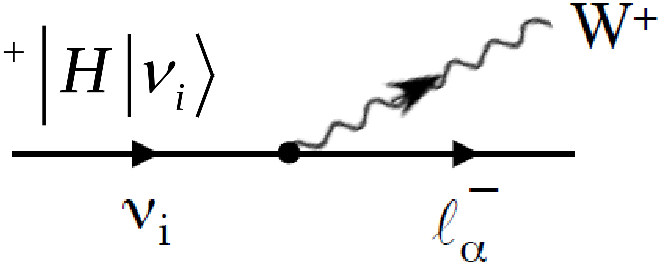
$$\overset{(-)}{\nu}_{\mu} \not\to \overset{(-)}{\nu}_{\mu} \qquad \overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}$$

Neutrino Masses, Mixings and Oscillations

Notation & figure courtesy B. Kayser

- PMNS mixing matrix, $U_{\alpha i}$

$$U_{\alpha i} \sim \langle \ell_\alpha^- W^+ | H | \nu_i \rangle$$



"atmospheric" "solar"

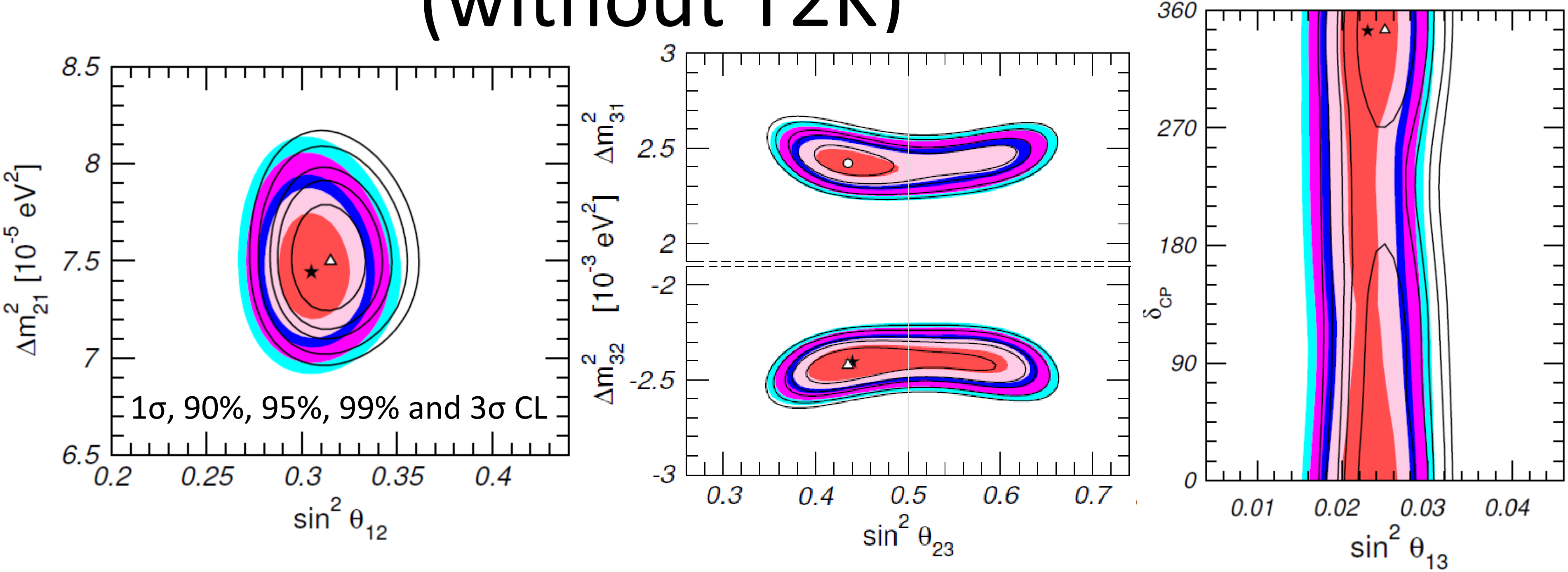
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

- Vacuum oscillation in terms of $U_{\alpha i}$, masses and L/E:

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta\right) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2\left(\Delta m_{ij}^2 \frac{L}{E}\right)$$
$$\overset{(-)}{+} 2\sum_{i>j} \Im\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2\left(\Delta m_{ij}^2 \frac{L}{E}\right)$$

How we know what we know (without T2K)

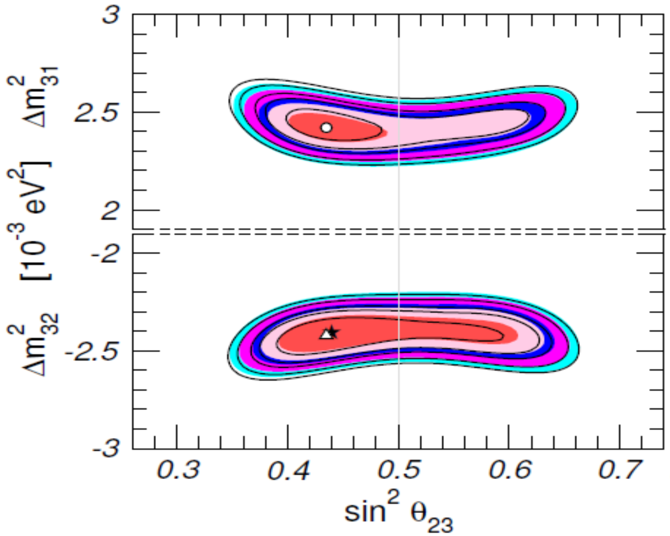


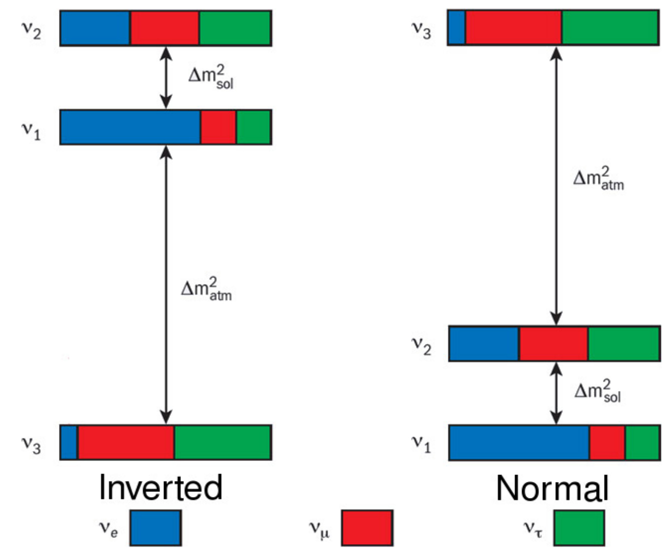
Nu-Fit, M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, arXiV:1209.3023

- Δm^2_{21} and θ_{12} from solar (SNO, Super-K, Borexino, radiochemical) and from long-baseline reactor data(KAMLAND)
- Δm^2_{32} and θ_{23} from atmospheric (Super-K) and accelerator (MINOS)
- θ_{13} (mostly) from reactor experiments (Daya Bay, RENO, Double CHOOZ)
- δ is essentially unconstrained by current measurements

Interesting "Degeneracies" of the 2-3 Sector

- $\sin^2 2\theta_{23}$ is nearly maximal and θ_{23} can be either larger or smaller than $\pi/4$ radians
  - Leading effect in atmospheric and accelerator ν_μ disappearance experiments goes as $\sin^2 2\theta_{23}$
  - Invariant under $\theta_{23} \rightarrow (\pi/2)-\theta_{23}$
- Sign of Δm^2_{32} is not known
  - Can be determined from matter effects, as is our knowledge that $\Delta m^2_{21} > 0$ from solar neutrinos





Oscillation Probabilities at T2K

- Sub-leading terms and matter effects becoming important at precisions of T2K measurements. "Disappearance" parameters affect "appearance" parameters and vice versa
- In particular, large θ_{13} makes sub-leading effects very important. Two flavor fits are no longer a good approximation.

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{32} \cdot L}{4E} + (\text{solar term})$$

$$+ (\text{interference or "CP" terms}) + (\text{matter term})$$

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

$$+ (\text{matter term})$$

Leading

Differentiates 1st/2nd octants of θ_{23}

THE T2K EXPERIMENT

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

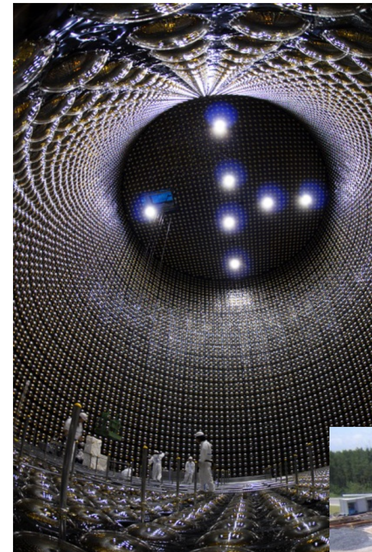
Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

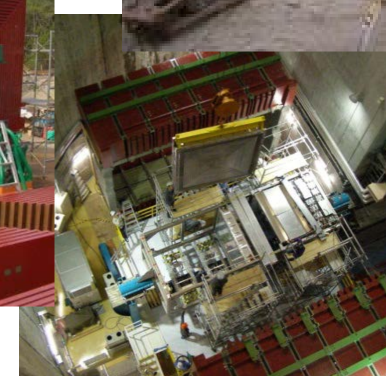
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

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

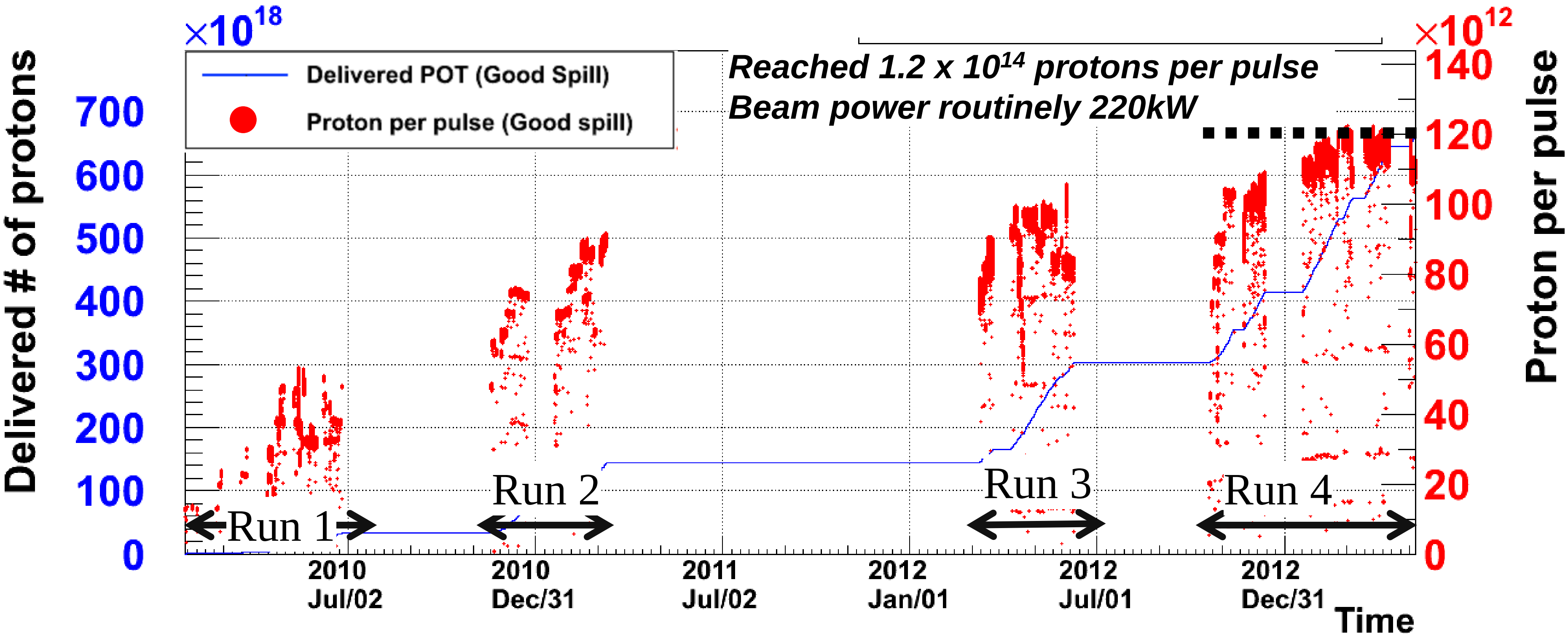
Brief History of T2K



- 1996 Super-Kamiokande detector begins operation
- 1999 Ko Nishikawa and Yoji Totsuka formulate $\nu_\mu \rightarrow \nu_e$ experiment at J-PARC
- 2000-2004 Letter of Intent; Detailed design; Formation of international collaboration
- 2004 Five year construction plan for T2K approved by Japanese government
- April 2009 Commissioning of beamline
- January 2010 First neutrino events for neutrino oscillation studies
- March 2011 Great East Japan earthquake
- June 2011 T2K announces 2.5σ "indication" of $\nu_\mu \rightarrow \nu_e$
- March 2012 T2K resumes data taking after earthquake recovery

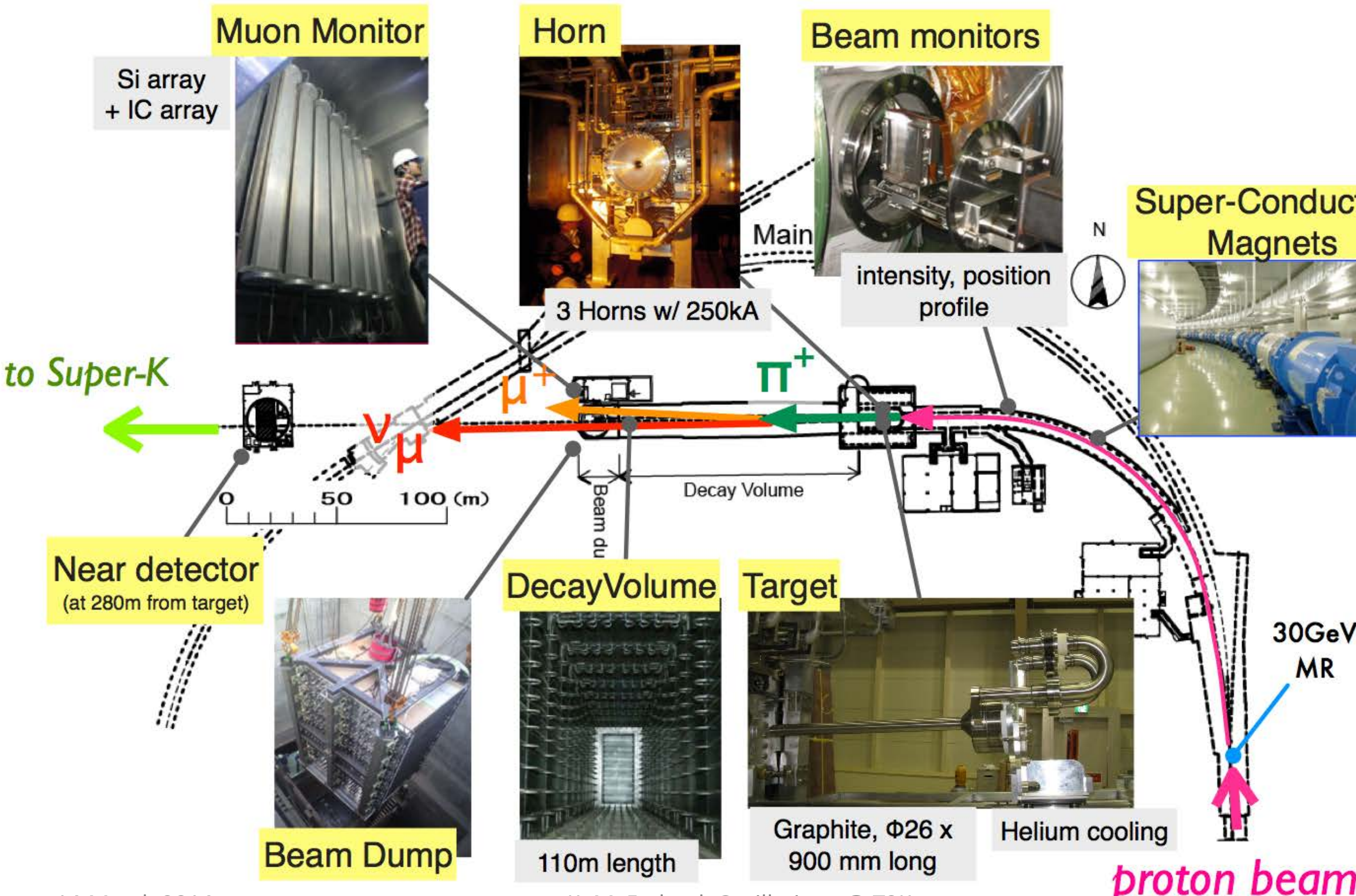


Datasets



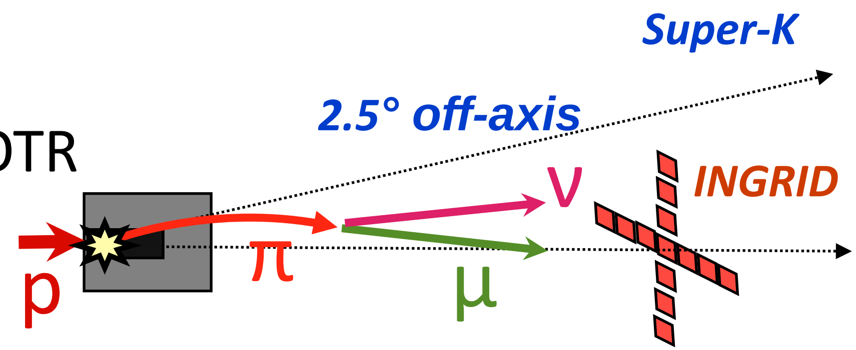
- Total delivered beam: 6.63×10^{20} Protons on Target (POT)
- Next beam to T2K in early summer 2014

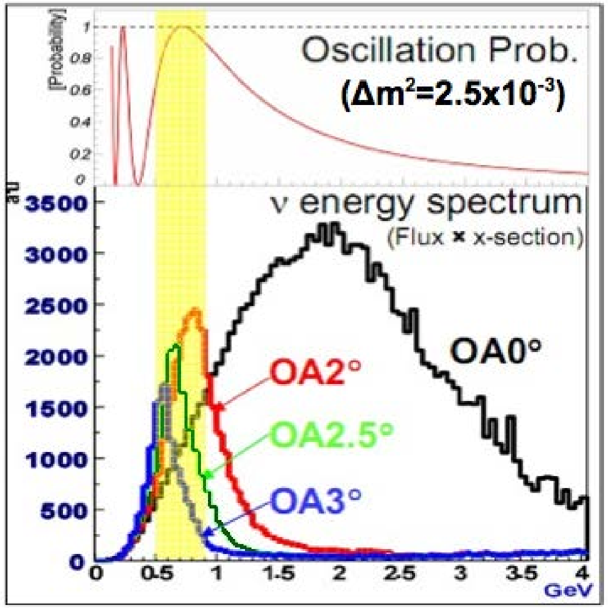
T2K Beamline



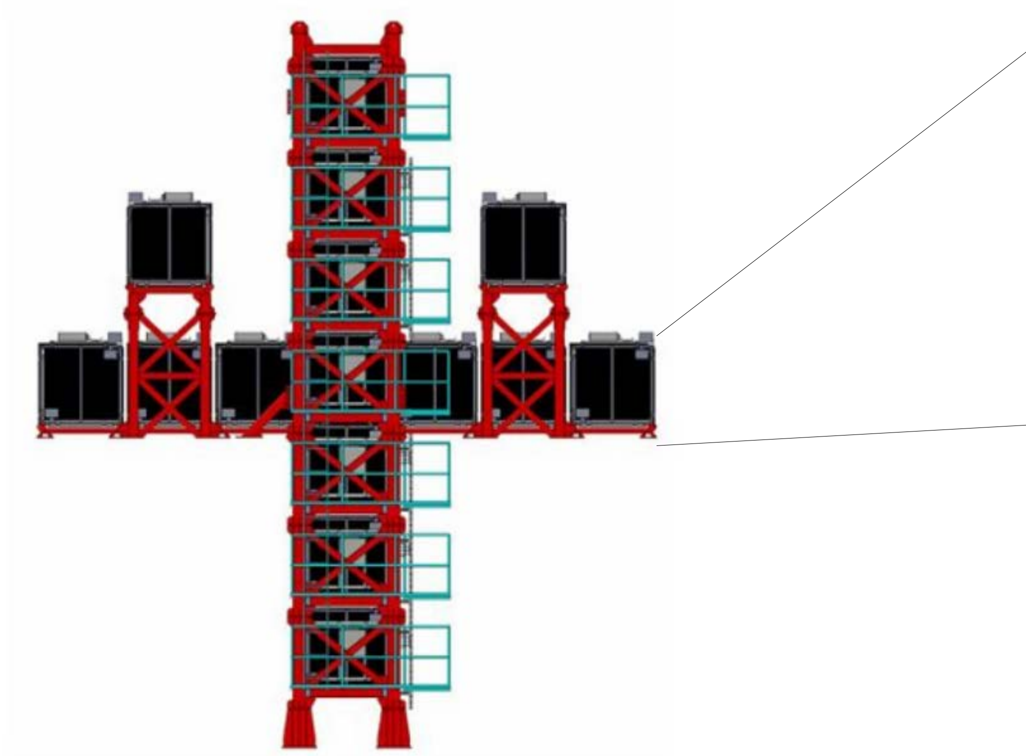
Ingredients of Flux Prediction

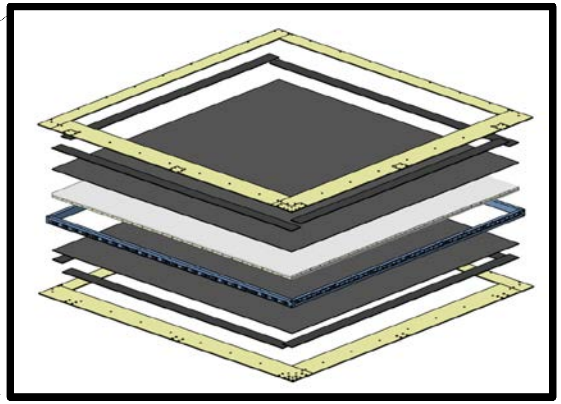
- Proton beam monitoring
  - Profile on target from SEMs, OTR
  - Intensity from beam toroid
- Hadroproduction measurements, notably CERN-NA61 thin carbon target data
  - Replica T2K "thick" target ($1.9\lambda_0$) data in hand, and being analyzed
- Alignment of and current in horns
- The direction of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

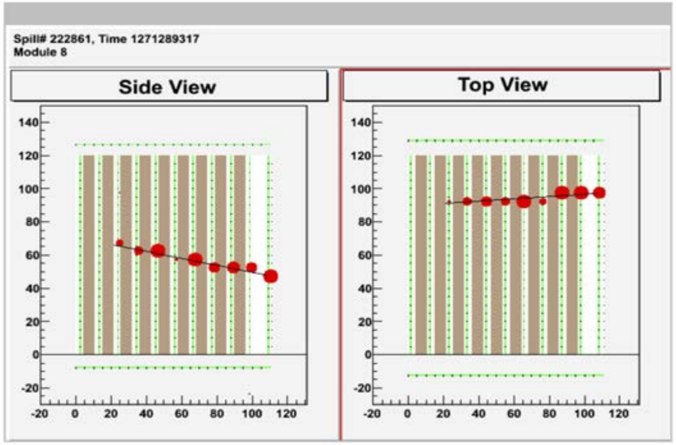




ND280: On-axis (INGRID)

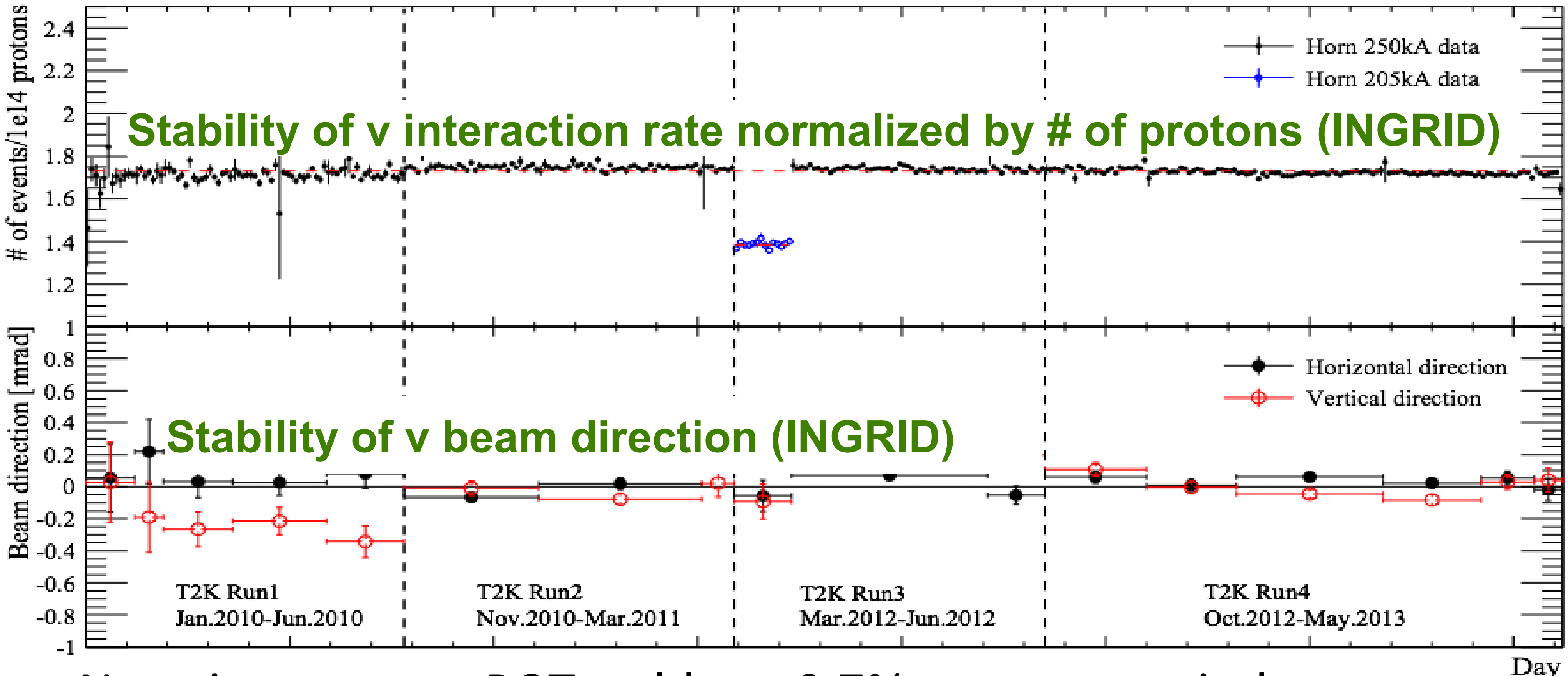






- 16 modules (14 in cross configuration)
- Iron and scintillator layers
- Measures neutrino beam profile and rate
- Counts muons as a function of angle

Beam Stability

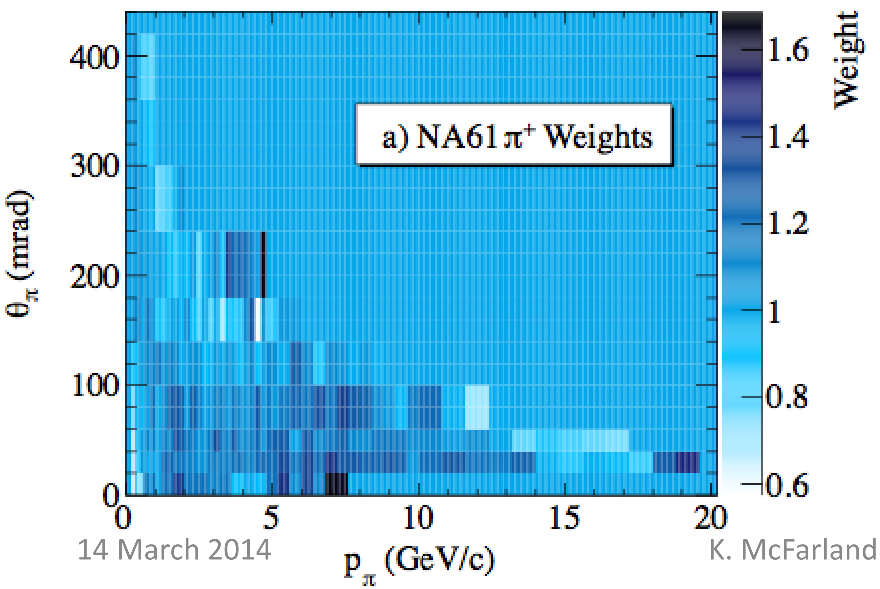


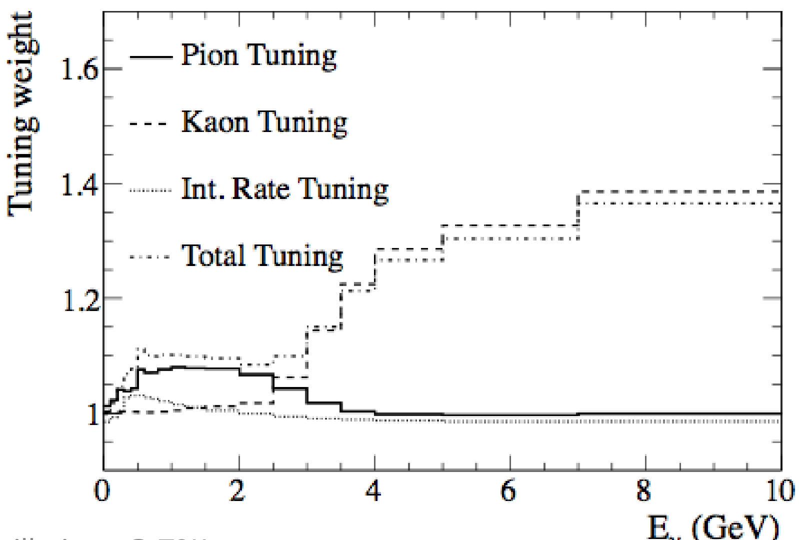
- Neutrino rate per POT stable to 0.7% over run period
- Recall: 1 mrad in beam direction is 16 MeV in peak E_ν
- Dataset includes 0.21x 10^{20} p.o.t. with 250→205kA horn operation (13% flux reduction at peak) in Run3

External Data and Flux

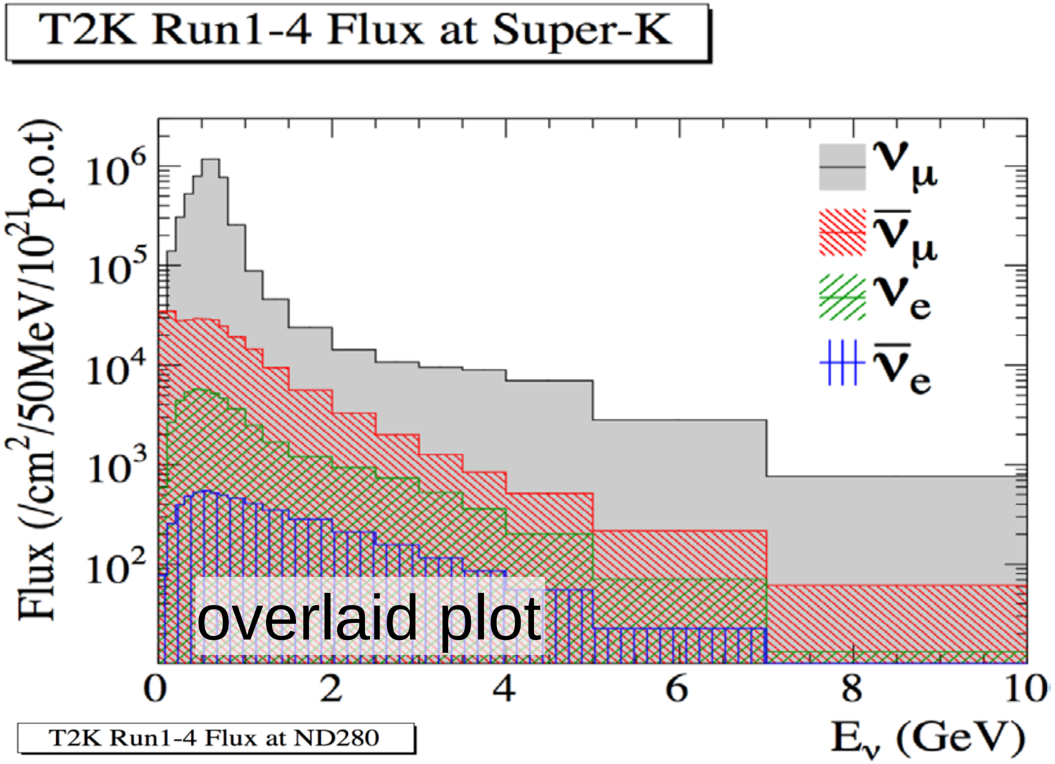
- Hadroproduction simulated with FLUKA2008.3d, weighted so that interactions match external data **[1]**
  – NA61/SHINE (CERN) **[2][3]**, Eitchen *et al.* **[4]**, and Allaby *et al.* **[5]**

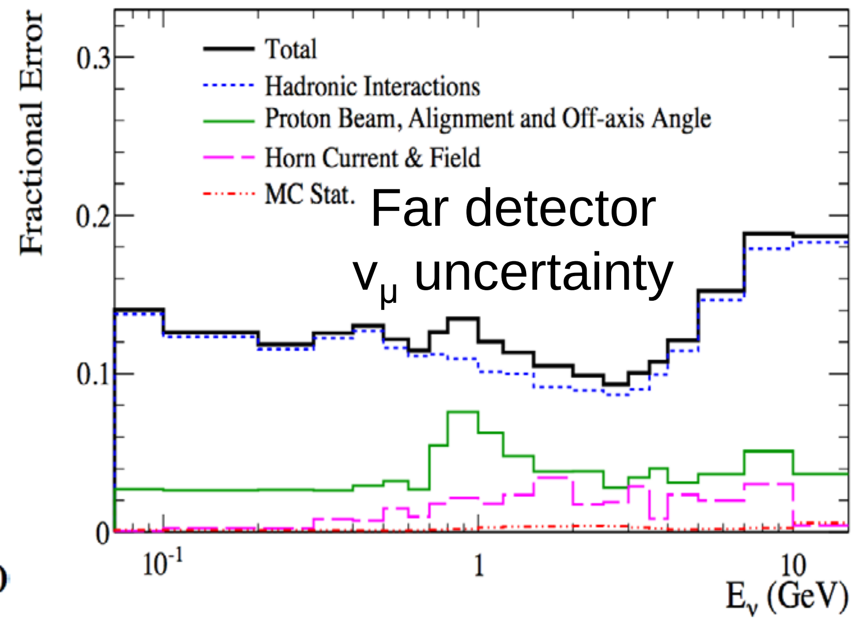
[1] K. Abe et al. (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).
[2] N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
[3] N. Abgrall *et al*. (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
[4] T. Eichten *et al.*, Nucl. Phys. B 44 (1972)
[5] J. V. Allaby *et al.*, Tech. Rep. 70-12 (CERN,1970)

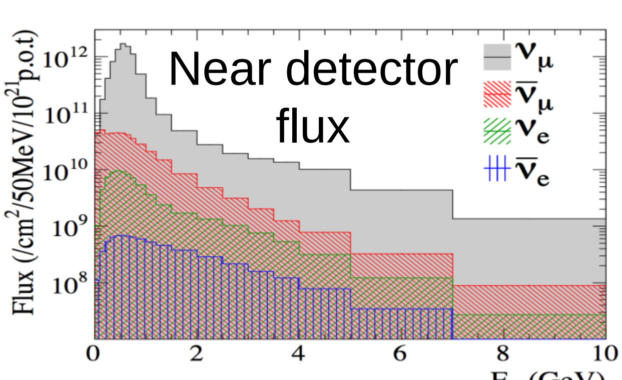




Flux and Uncertainties



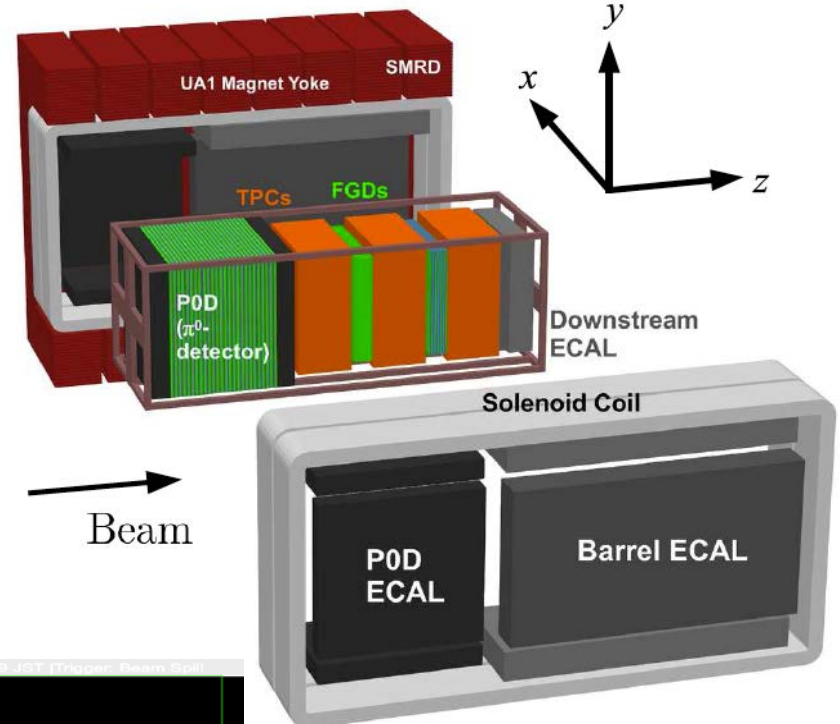


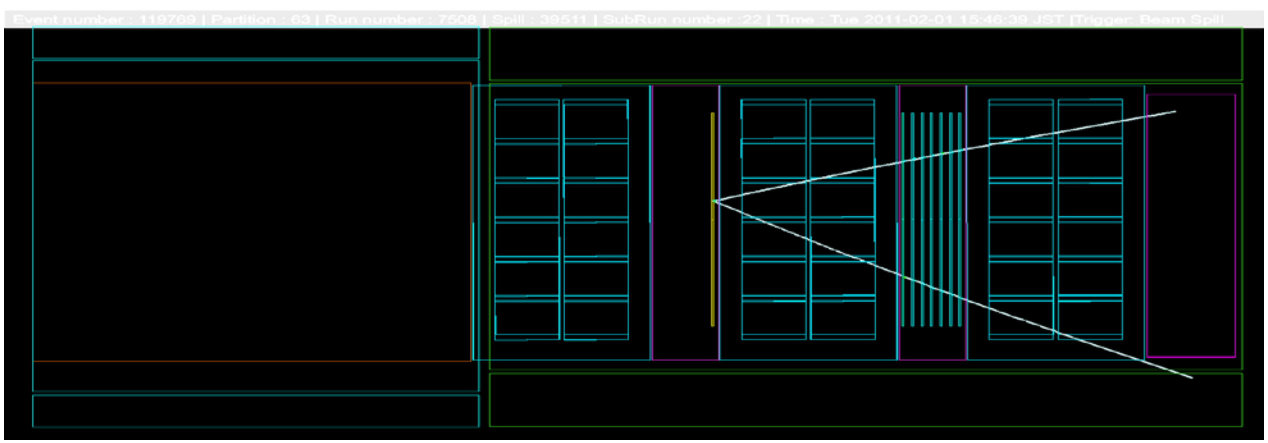


- A priori prediction of flux at Super-K has 10-15% uncertainties from 0.1 to 5 GeV
- Off-axis near (ND280) and Far (Super-K) fluxes are not identical, but highly correlated

ND280: 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



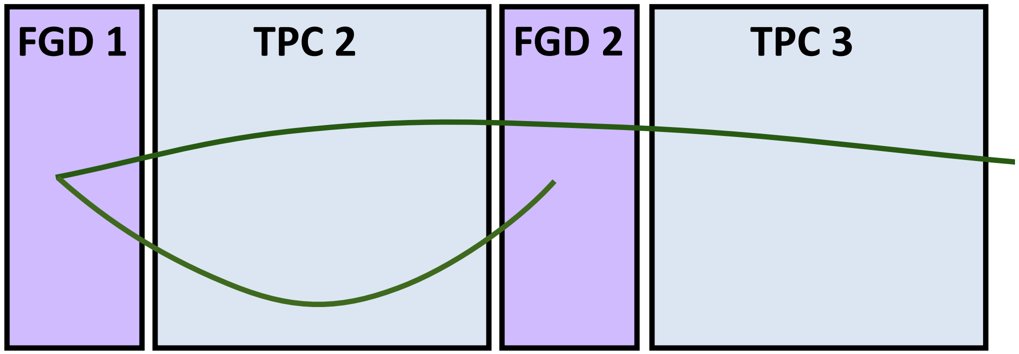


Charged-current single charged pion candidate

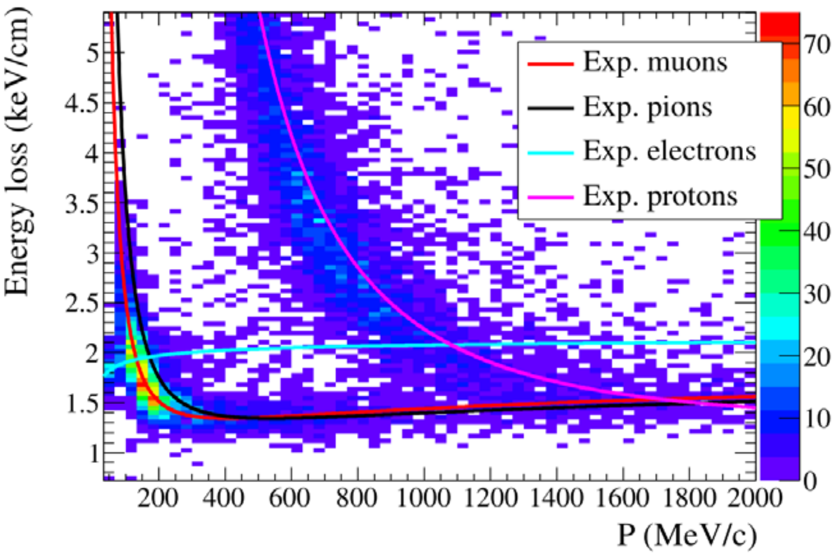
- Muon and pion identified by dE/dx in TPC gas
- Momentum from curvature in field

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

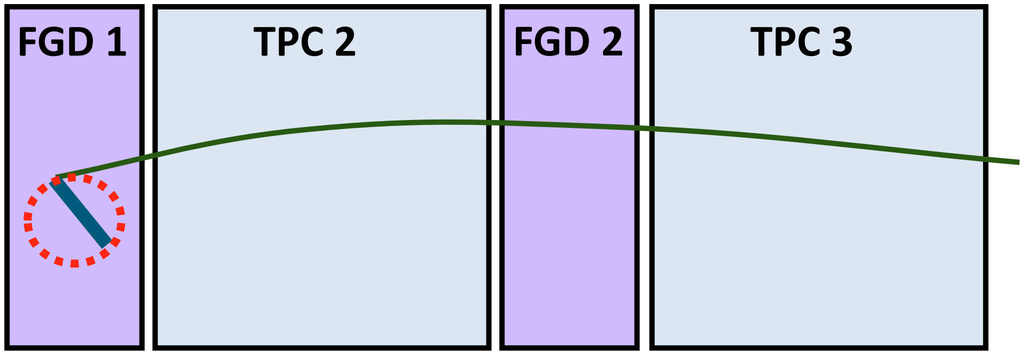


- If pion tracked in TPC, ID by dE/dx in the TPC gas



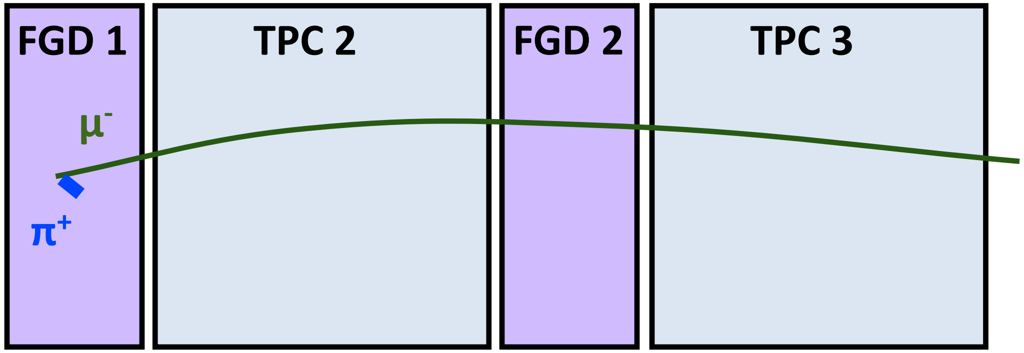
Near Detector Samples for Oscillation Analyses

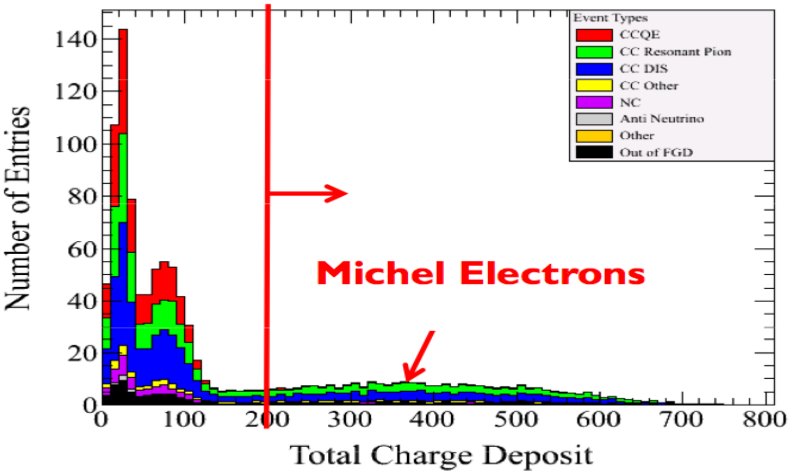
- Off-axis near detectors constrains flux and cross-sections.
- Exclusive samples based on # of final state charged pions
- Muon selection: highest momentum negative track in TPC from FGD1 (scintillator) target
- Pion selection depends on detector
- FGD-contained pions identified by dE/dx
- Reconstruction less efficient than TPC
- Tag at most 1 FGD pion



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
- Untracked pions may be tagged by Michel e^-

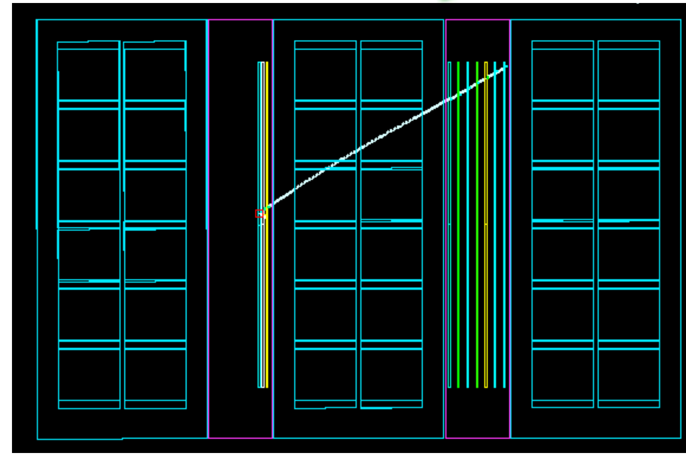




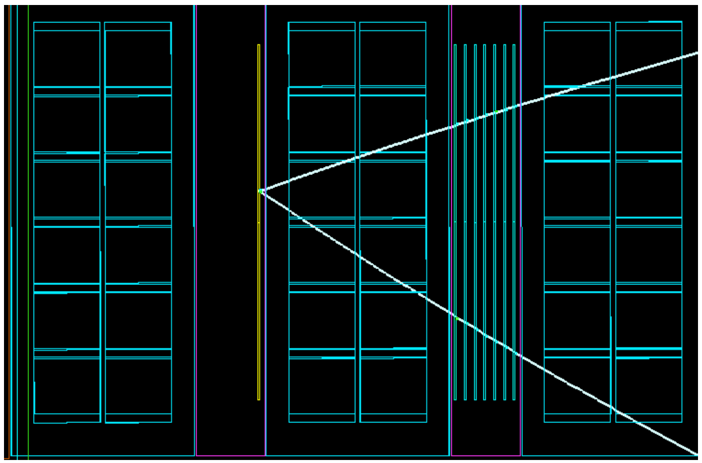
(delayed charge)

ND280 Event Categories

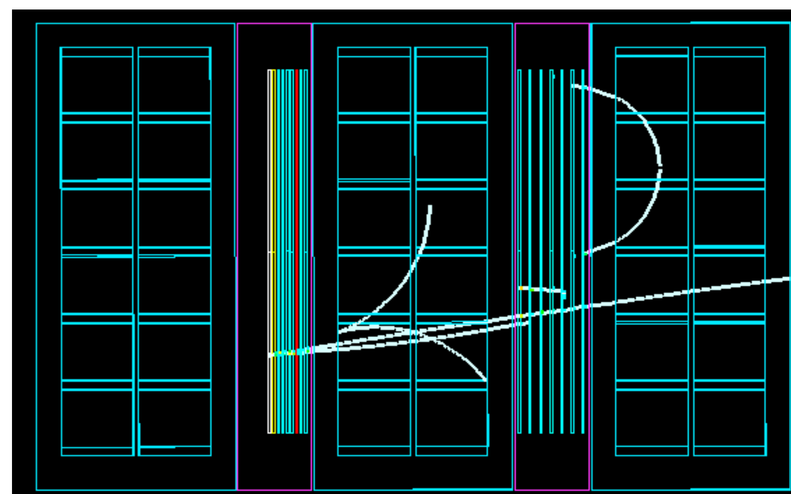
- Charged current (CC) with 0π



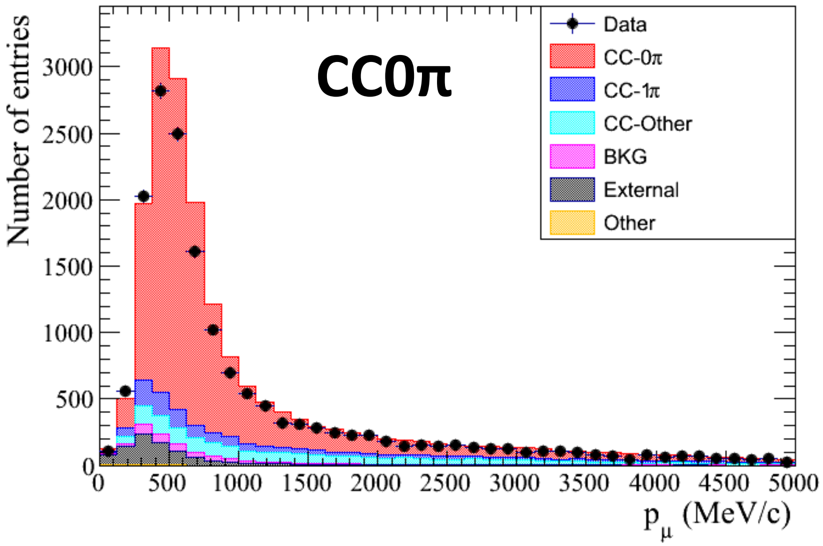
- CC 1π^+

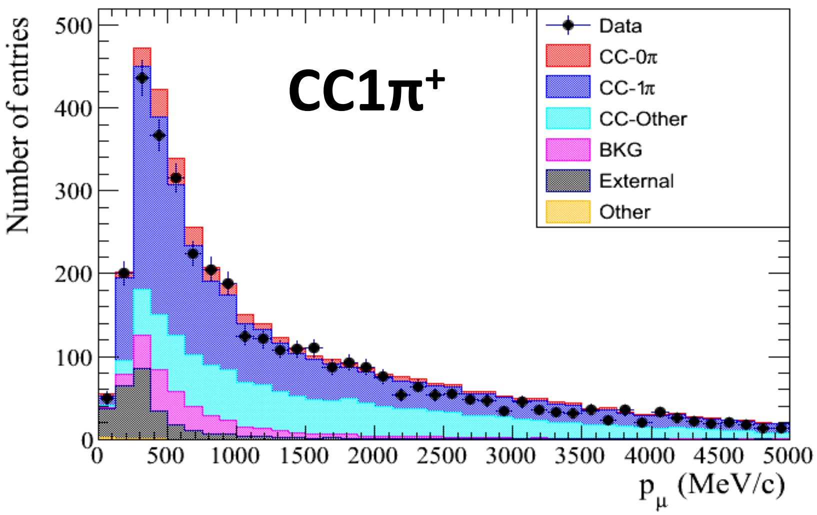


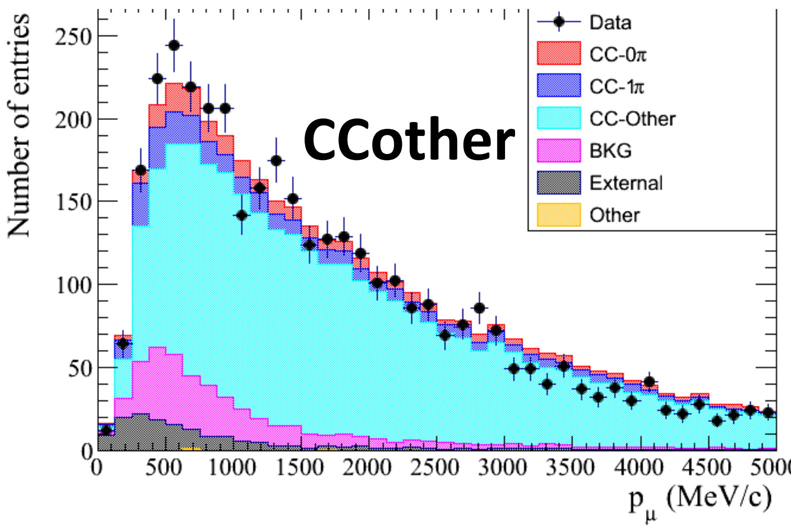
- CC Other (≥1π^- or π^0 ,or >1 π^+)
  - π^0 candidates have identified electrons in the TPC
- Disappearance analysis joins CC 1π^+ and CC other together



Muon Momentum in ND280

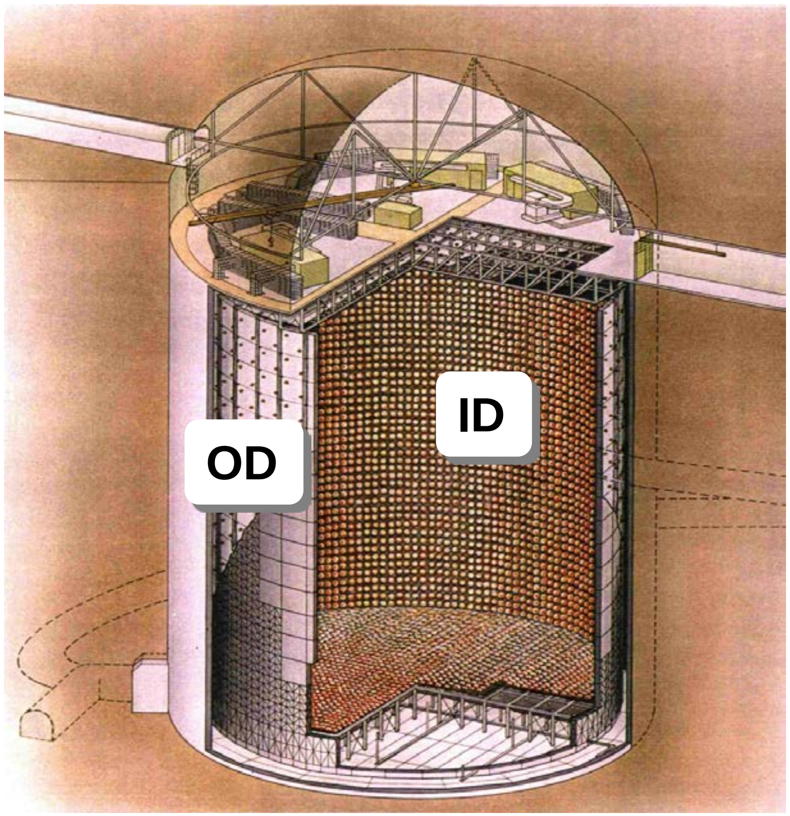






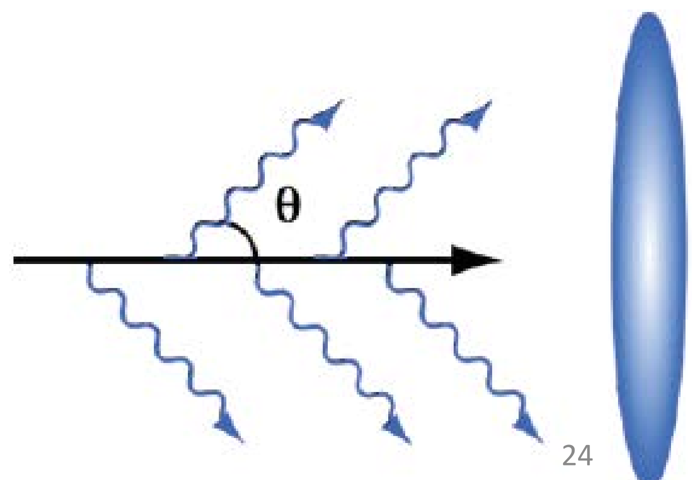
True identification of interaction	CC0π sample	CC1π sample	CCother sample
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out of FGD1 Fid Vol	5.1%	6.5%	3.9%

Super-K (Far) Detector



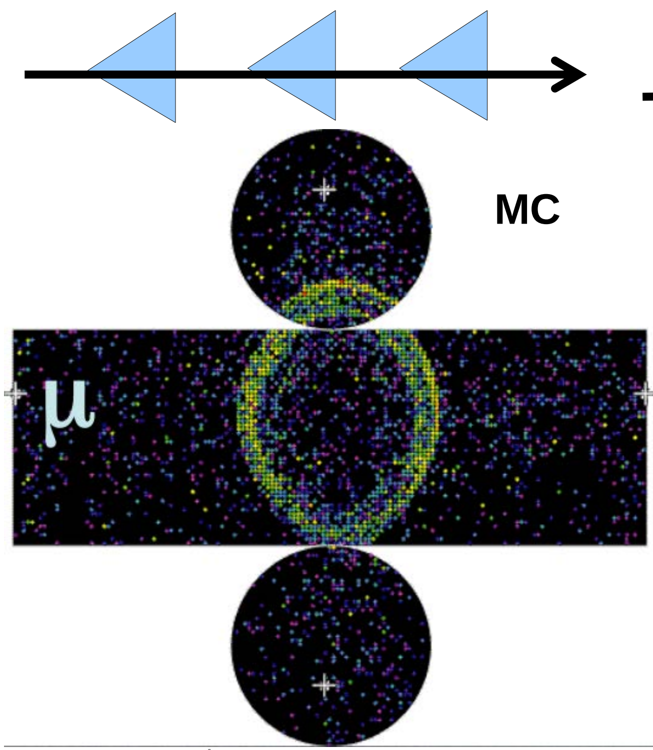
- 50 kton (22.5 kton fiducial volume) water cerenkov detector
- ~11,000 20'' PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8'' PMT for outer detector (OD): veto cosmics, radioactivity, exiting events
- Good reconstruction for T2K energy range

Cerenkov light produces a ring detected by the PMTs

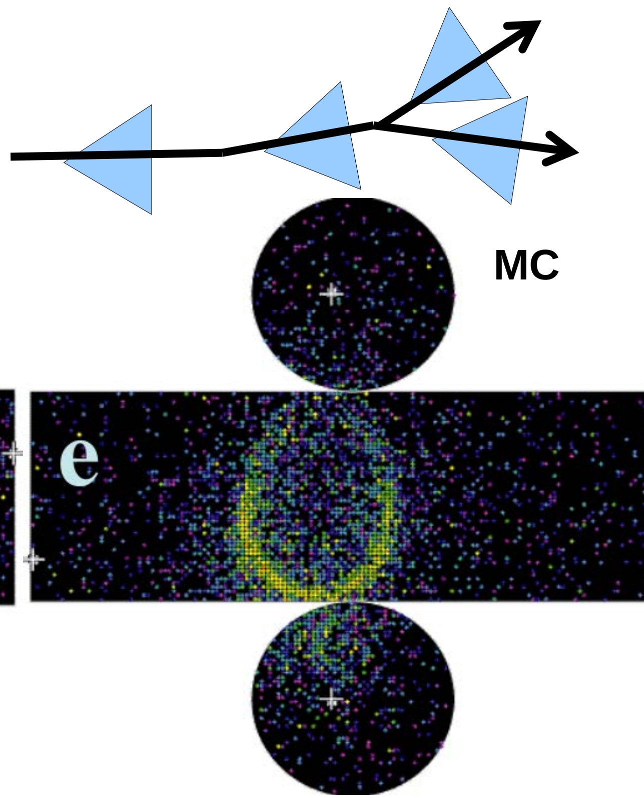


Particle Identification at SK

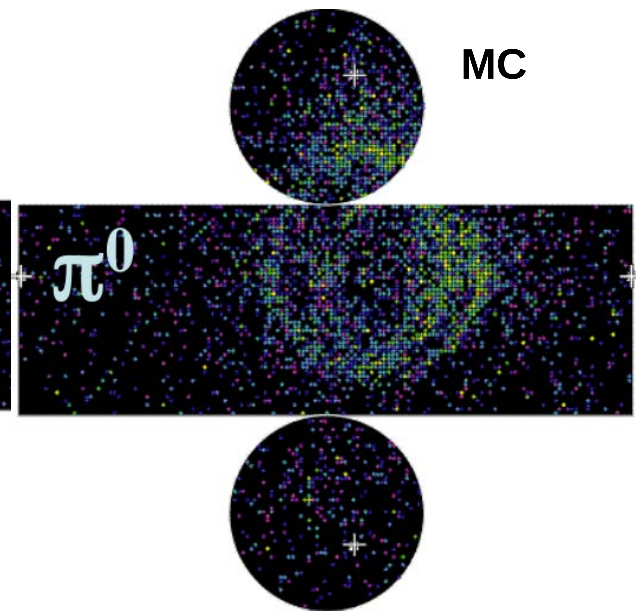
- Muon scattering is minimal
- Rings with sharp edges



- Electromagnetic shower
- Rings are “fuzzy”

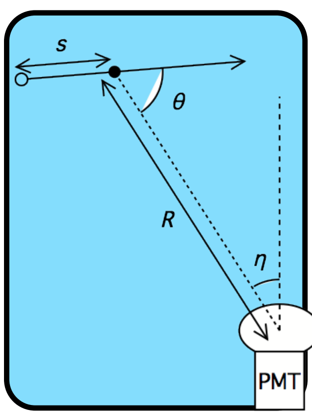


- γ from π^0 decays shower and look like electrons
- Multiple fuzzy rings



fiTQun: 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 π^0



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

Light Yield

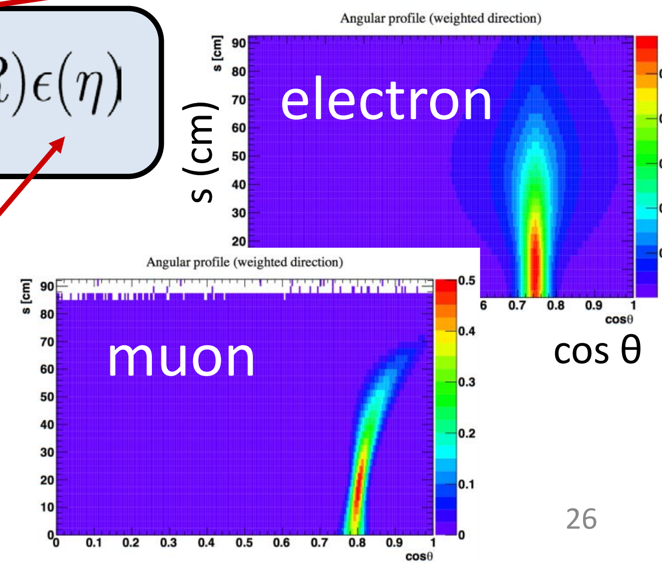
Integral over track length

PMT solid angle

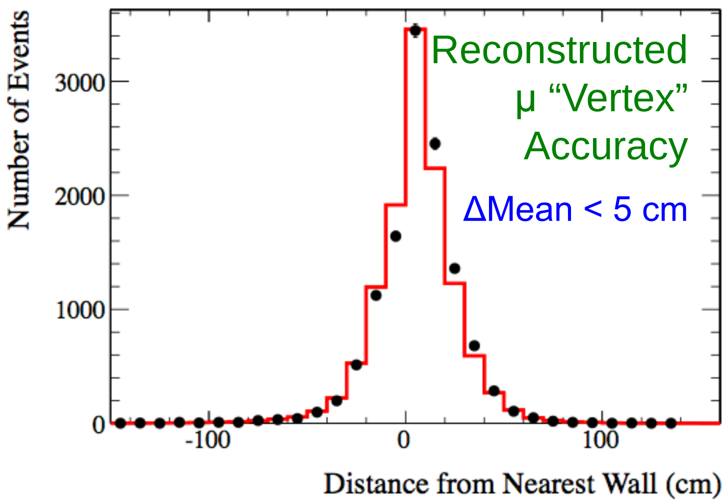
Water attenuation

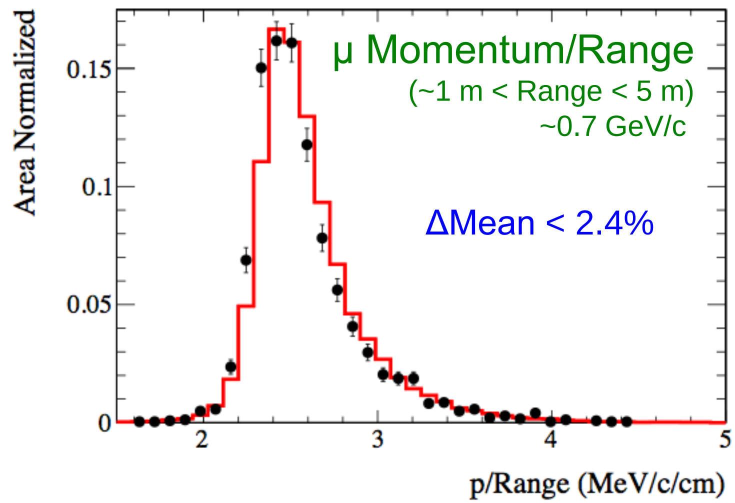
PMT angular response

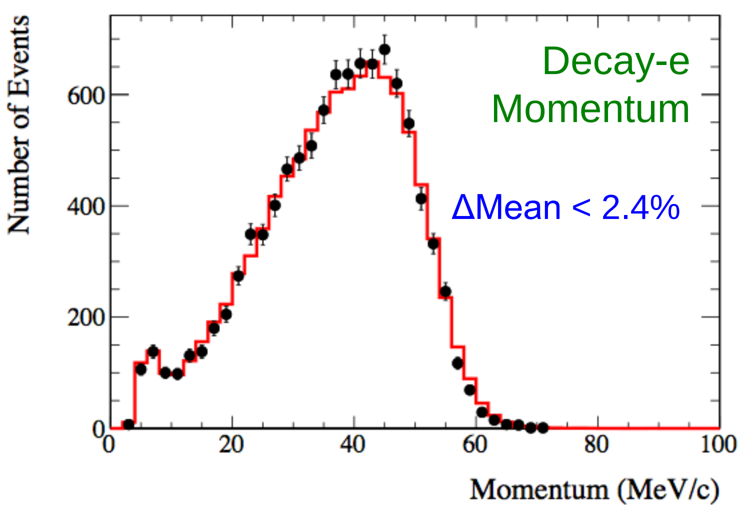
Cerenkov light emission profile

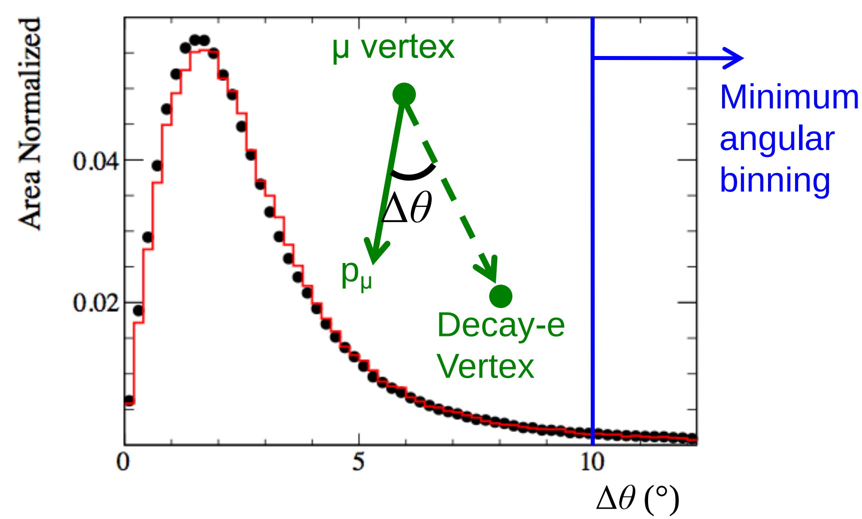


Validation with Stopping μ in Super-Kamiokande





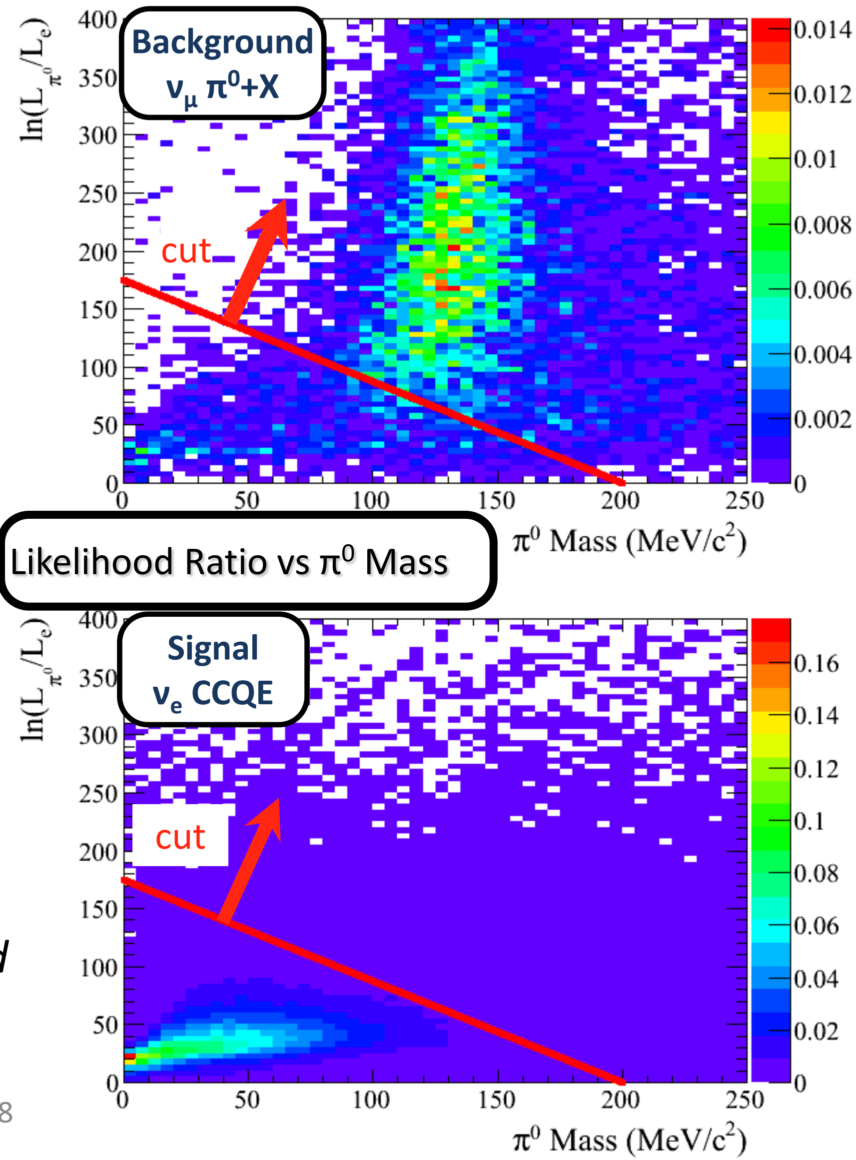




- Data/MC agreement within systematic uncertainties

Enhanced π^0 Rejection

- fiTQun can use 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

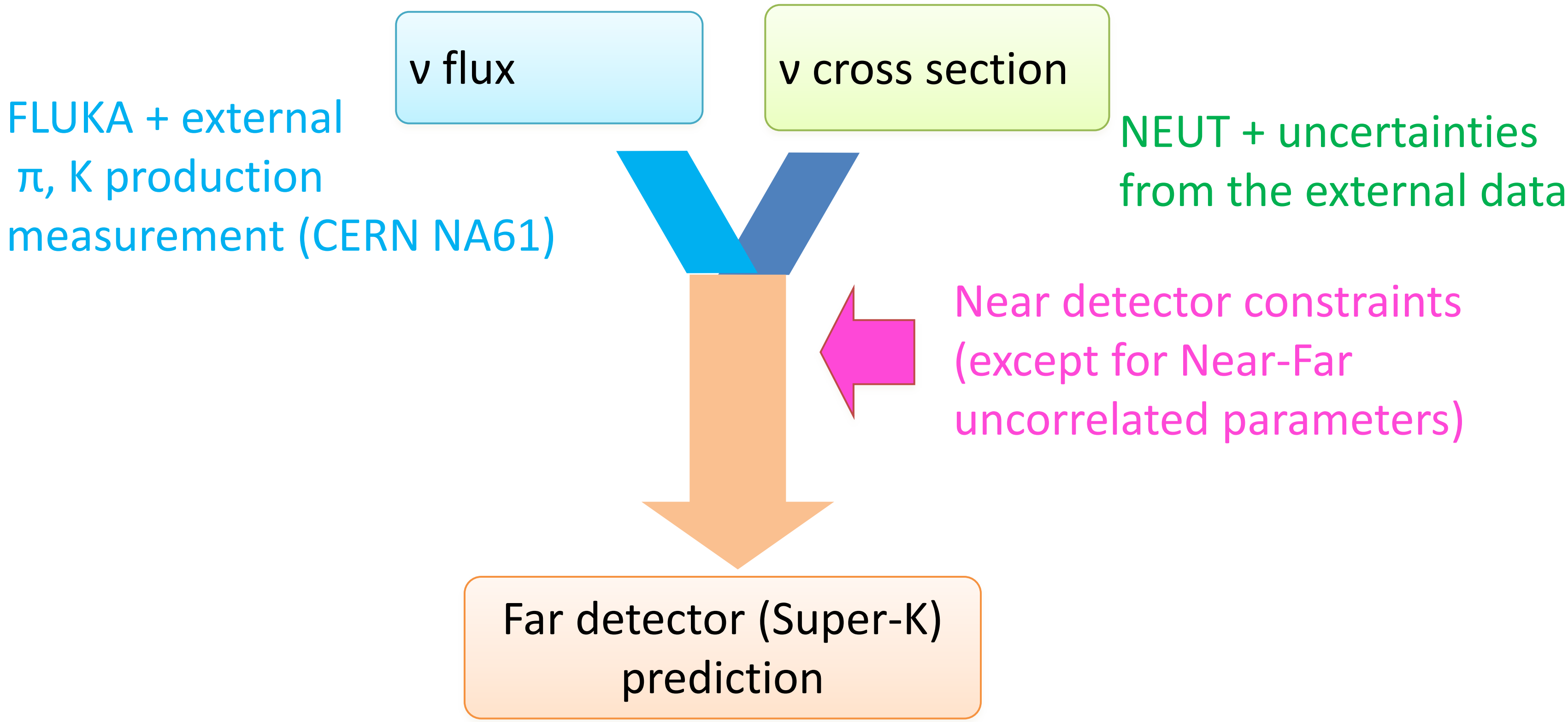


§ *Previous approach (POLFit) forced the reconstruction to find two rings and then formed a π^0 mass under the two-photon hypothesis*

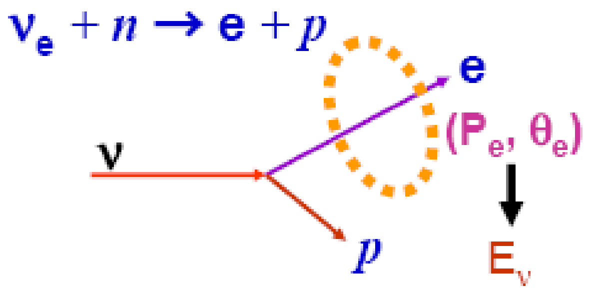
OSCILLATION ANALYSIS TECHNIQUE

Oscillation Prediction

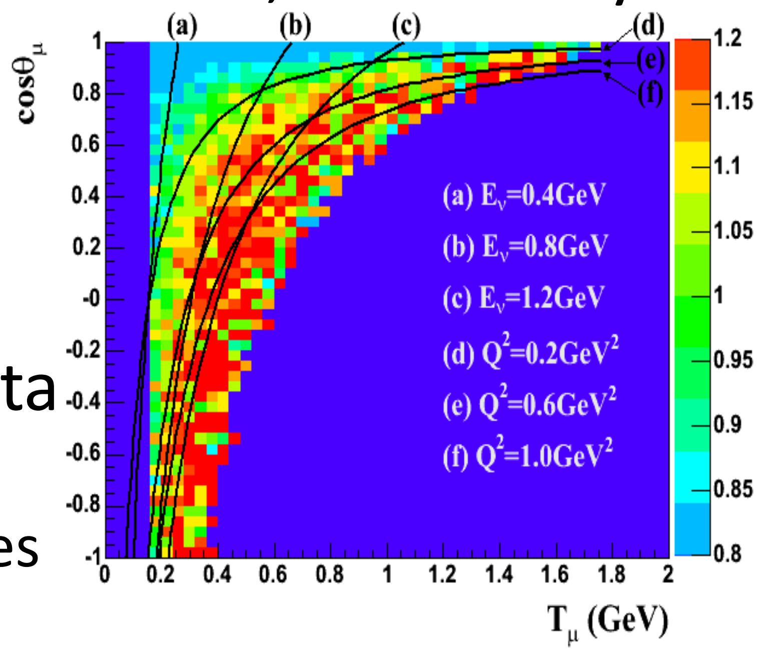
Our MC is based on the ν flux and cross section predictions from external data and models. We further constrain those predictions by the near detector measurement.



Cross-section Model: CCQE



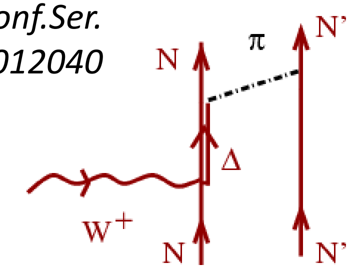
- Signal reaction for T2K energies
  - Elastic kinematics allow us to measure neutrino energy from muon
- T2K, like all practitioners in this business, is currently using a very simple model
  - Nucleon form factors from e^- scattering and νD_2 scattering
  - Model of nucleus is Fermi gas
- Problem: doesn't agree with data
- Approach: add effective parameters (M_A, normalization) with uncertainties that span base model and data



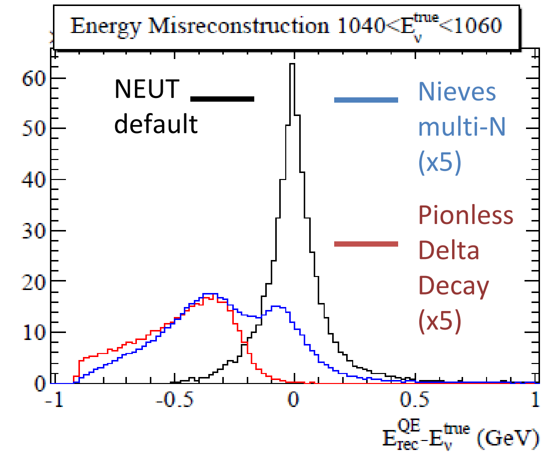
MiniBooNE (*Phys. Rev.* ***D81*** *092005, 2010)*

Multi-Nucleon Contributions to CCQE

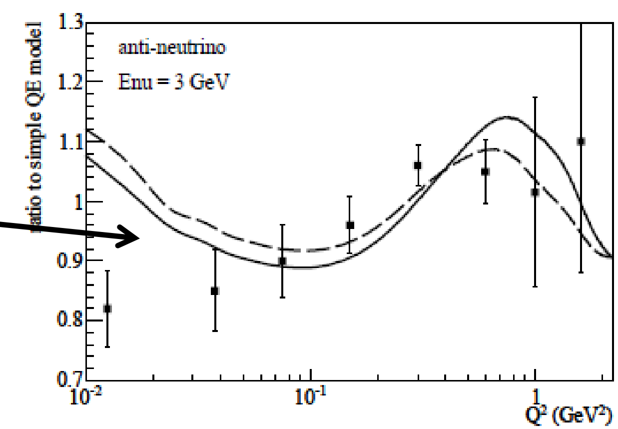
Nieves, J. et al. J.Phys.Conf.Ser. 408 (2013) 012040



- There is growing evidence that the underlying physics behind this discrepancy is due to multi-nucleon correlations in nucleus
- This is worrying because such effects will disrupt the elastic scattering kinematics we use to measure neutrino energy
  - Particularly problematic for $\nu_\mu \rightarrow \nu_\mu$



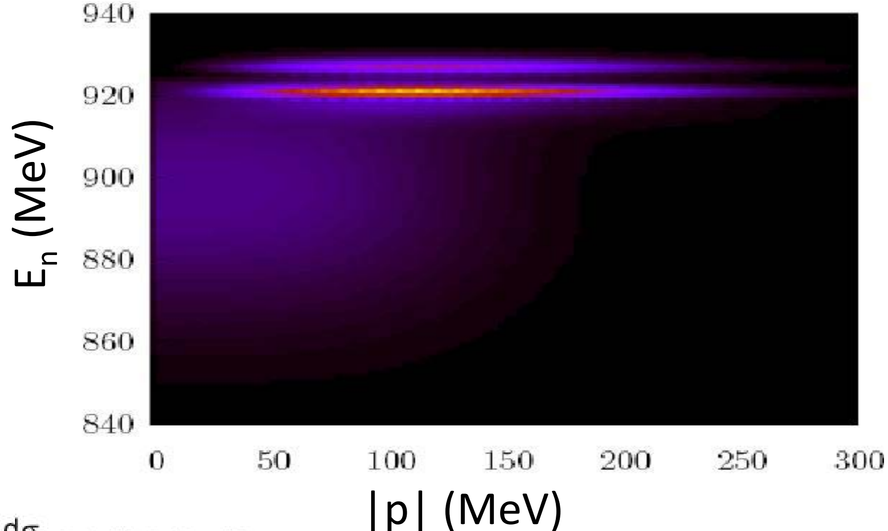
- Fortunately, the growing evidence also suggests that recent microphysical models are describing this physics
  - MINERvA data PRL 111, 022501 and 022502 reasonably described with such a model
- More later…

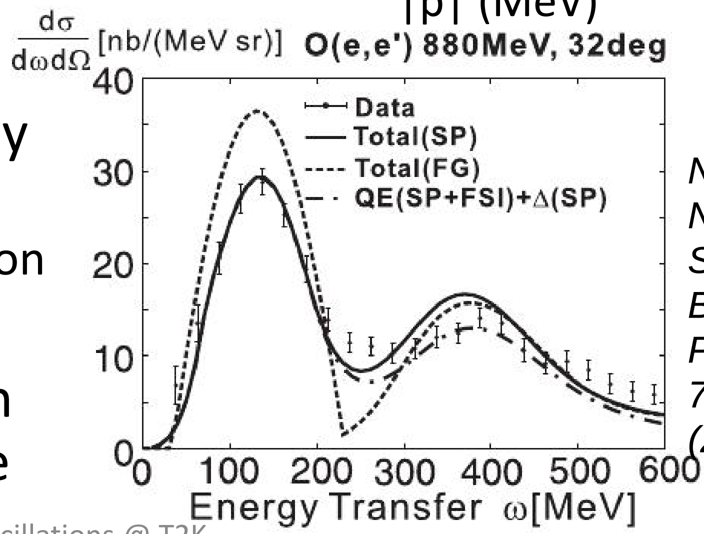


Beyond Fermi Gas for CCQE

- 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

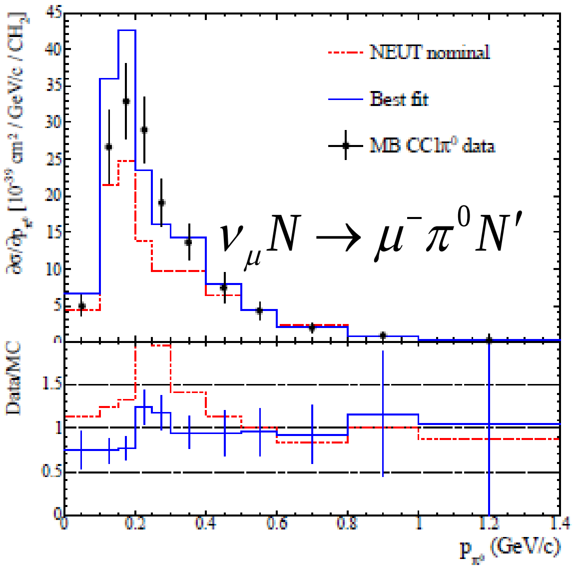


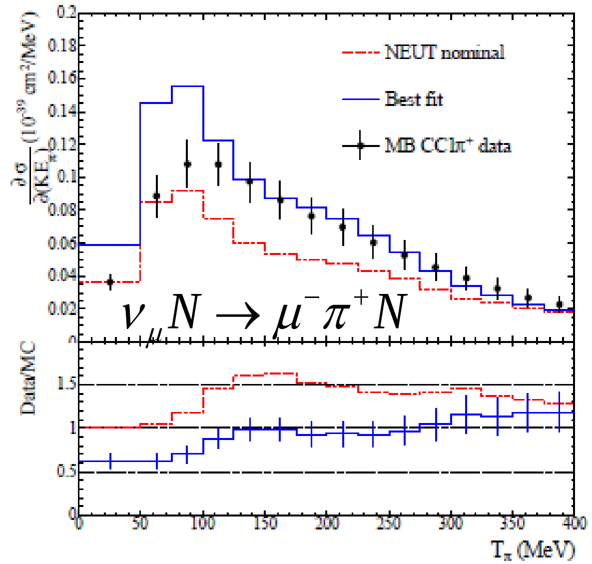


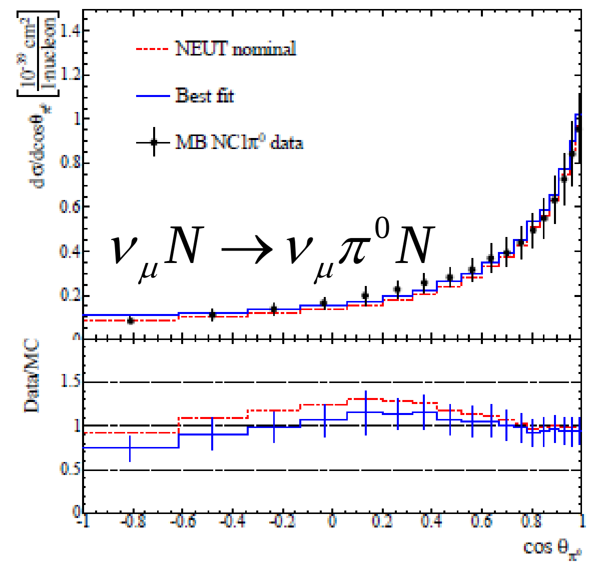
Nakamura, Nasu, Sakuda and Benhar, Phys. Rev. C 76, 065208 (2007)

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 this data well
- Again, systematic uncertainties assigned to this span reference model and data as effect parameters

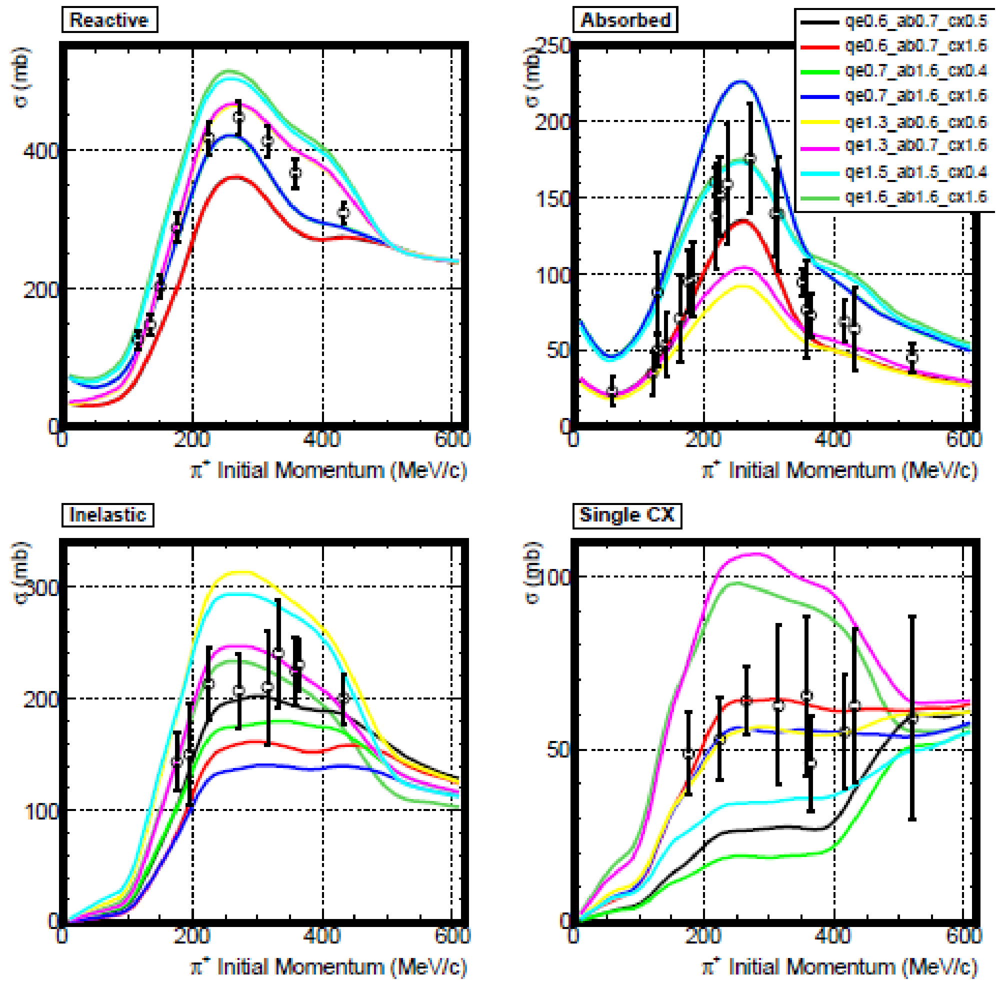




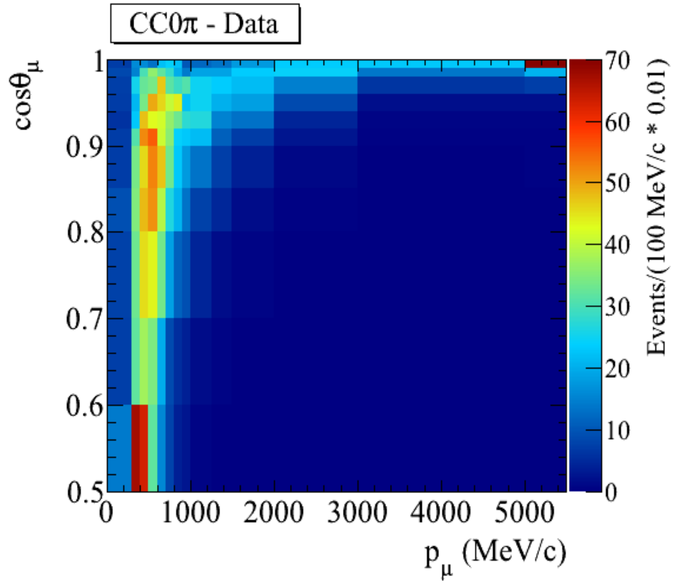


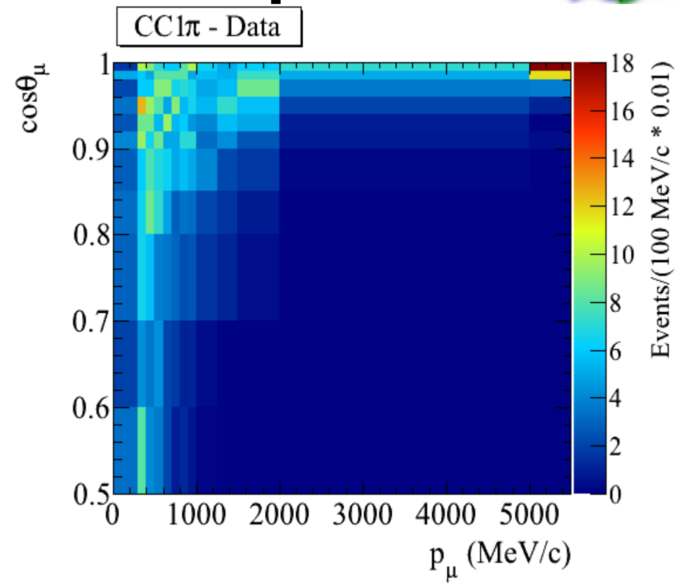
Cross-section: Final State Interactions

- 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



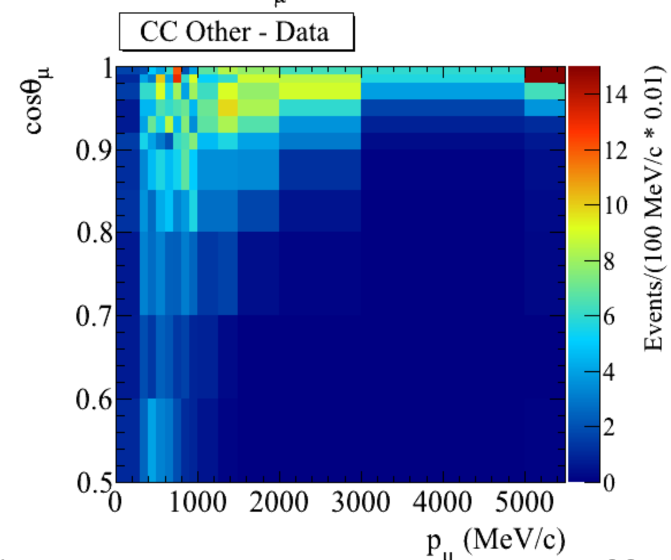
ND280 Constraint Fit Inputs



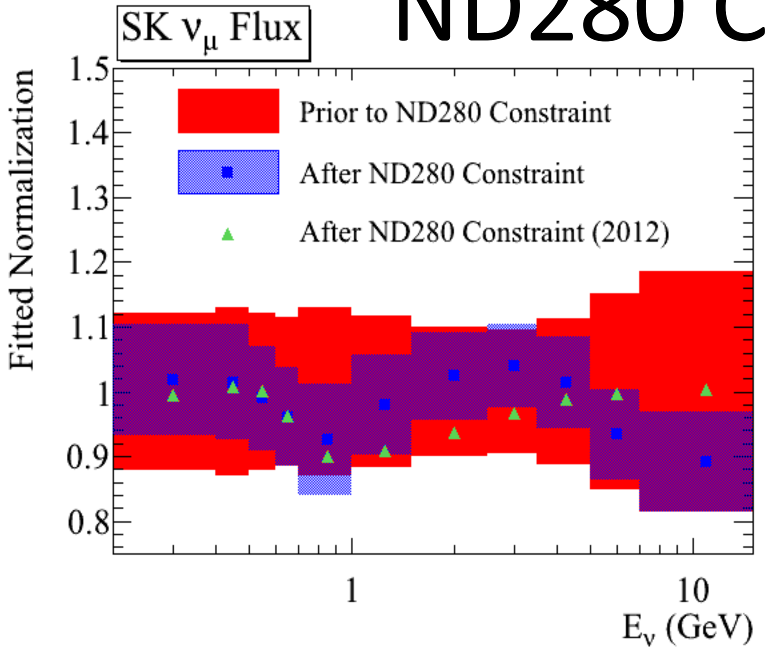


Data from T2K Runs 1-4, binned in muon momentum (p) and angle (cosθ)

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_ν<1.5 GeV **For E_ν<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

Far Detector Prediction after ND280 Constraint

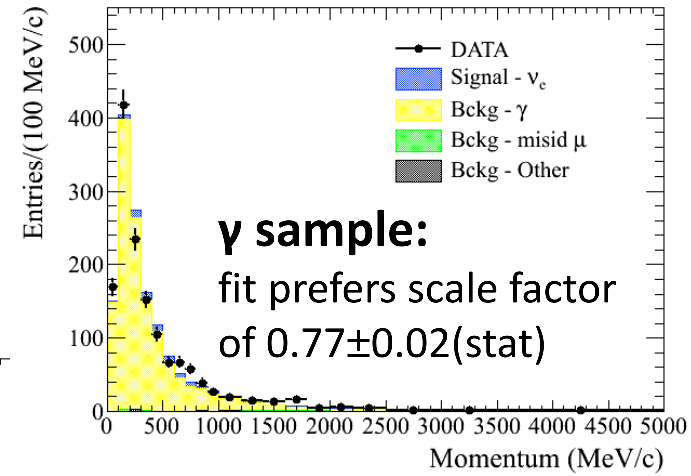
	$\sin^2 2\theta_{13}=0.1$		$\sin^2 2\theta_{13}=0.0$	
	ν_e Prediction (Events)	Error from Constrained Parameters	ν_e Prediction (Events)	Error from Constrained Parameters
No ND280 Constraint	22.6	26.5%	5.3	22.0%
ND280 Constraint (2012, Runs 1-3, disappearance)	21.6	4.7%*	5.1	6.1%*
ND280 Constraint (Runs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

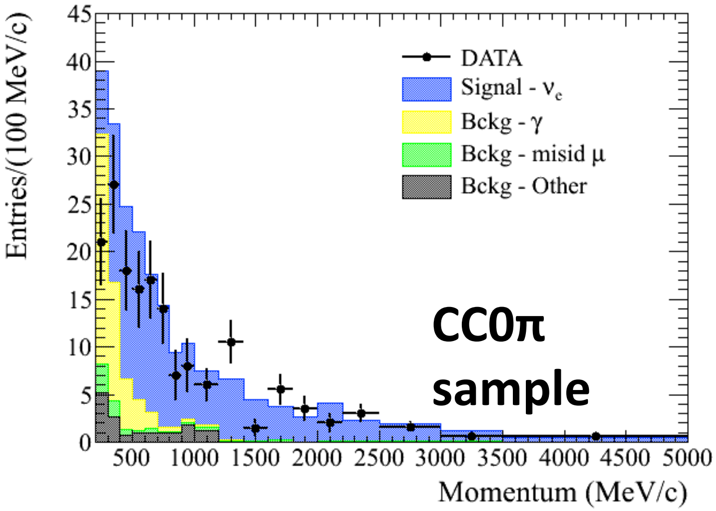
- Far detector prediction uncertainties after ND280 constraint are smaller due to recent improvements (Run 1-3 → Runs 1-4)
  - Improved ND280 reconstruction and selections
  - Finer binning in p-θ

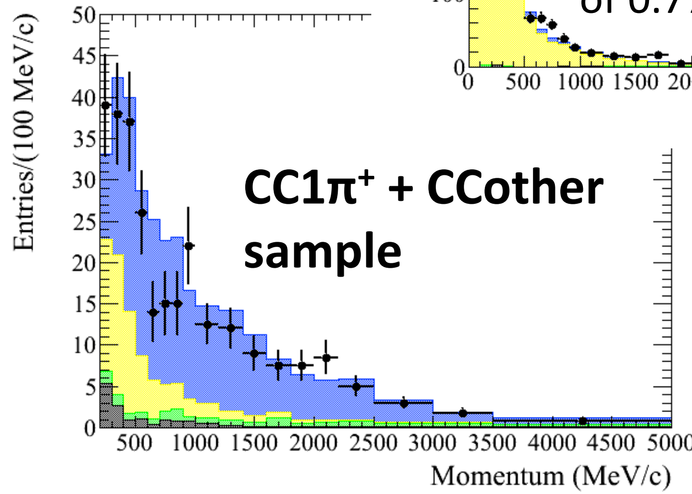
*Uncertainties reduced from previous T2K result due to new SK π^0 rejection algorithm

ND280 ν_e Measurement

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



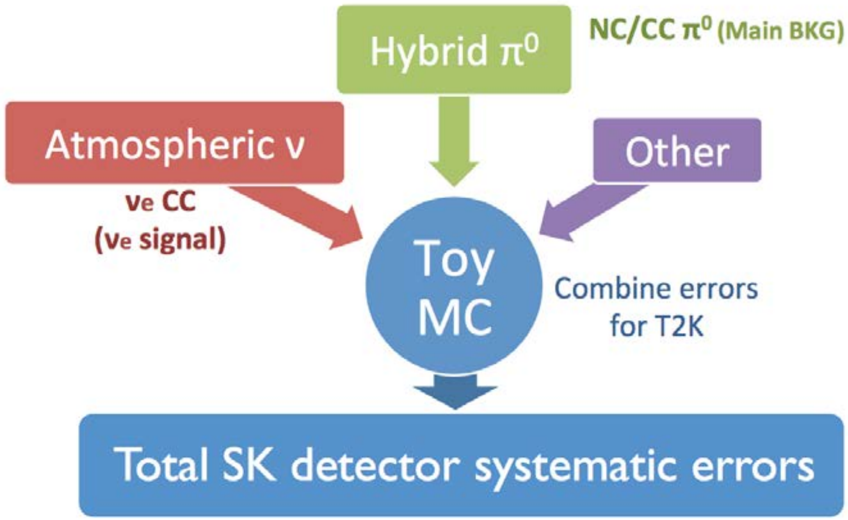




$$\frac{\text{measured } \nu_e \text{ flux}}{\text{predicted } \nu_e \text{ flux}} = 1.06 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$$

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 ν_e
  - Hybrid π^0 (electron from ν_e CC and MC photon)
  - Cosmic ray muon samples
- Combine errors with Toy MC method

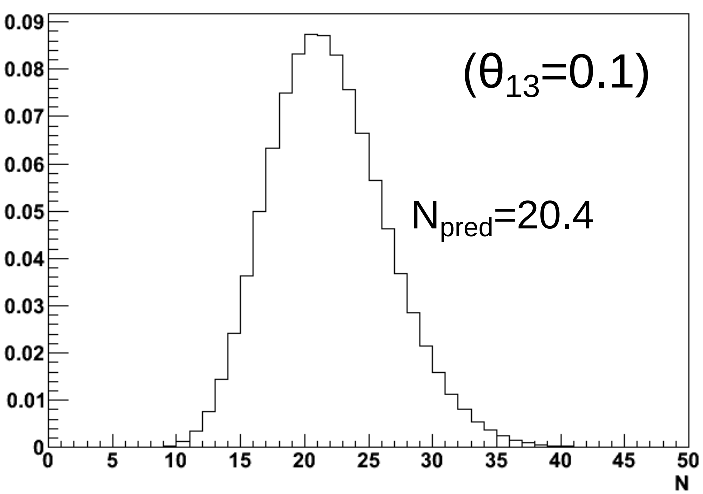
Oscillation Likelihood Fits

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

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

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

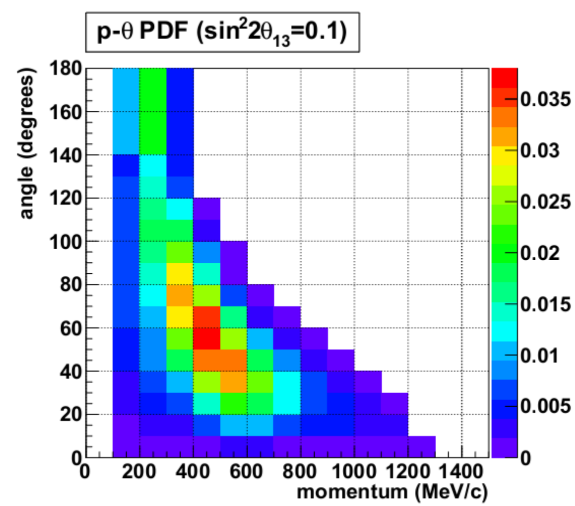
L_{norm} is the probability to have N_{obs} when the predicted number of events is the Poisson distribution with mean = N_{pred}.



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

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

φ: Predicted p-θ distribution (PDF) .



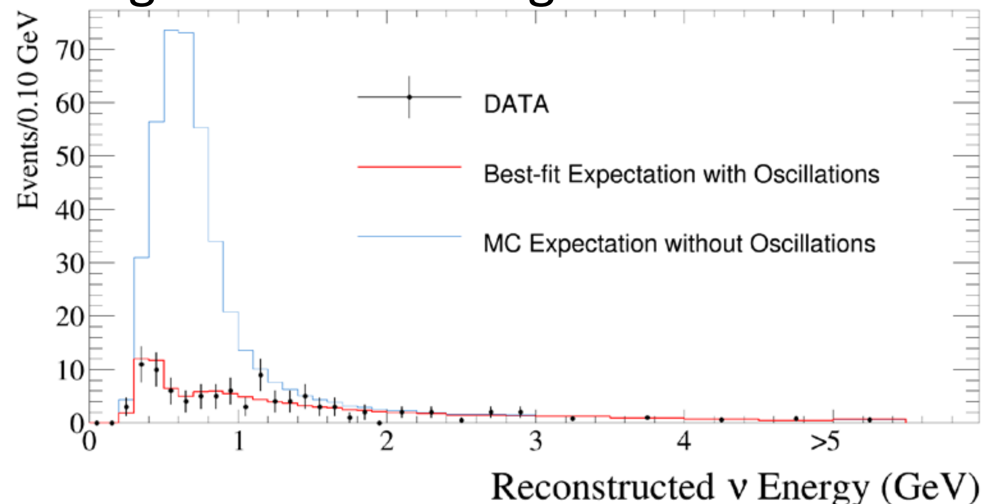
$\nu_\mu \rightarrow \nu_\mu$ RESULTS

T2K collaboration, arXiV.1403.1532, submitted to PRL
(Run 1-3 result in Phys. Rev. Lett. 111 (2013) 211803)

Reconstructed ν_μ Spectrum

T2K

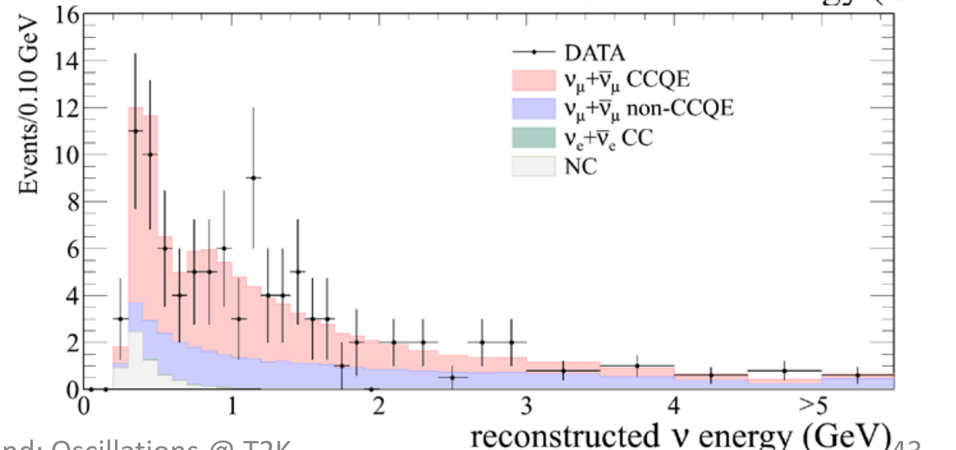
- Selected far detector ν_μ CCQE candidates
  - Fully contained and fiducial single muon-like ring
  - p_μ>200 MeV, no more than one decay e^-
  - 120 signal events



- Neutrino energy from elastic kinematics

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

  - E_b is mean binding energy



Systematic Uncertainties with Near Detector Constraint

Systematic uncertainties of # of events*

$(\sin^2\theta_{23}, \Delta m^2_{32})=(0.5, 2.4 \times 10^{-3}\ \text{eV}^2)$

Systematics	Uncertainties
Flux/XSEC (ND280 constraint)	2.7%
Other XSEC	4.9%
Super-K +FSI	5.6%
Total	8.1%

N_{SK} per bin w/ error

$(\sin^2\theta_{23}, \Delta m^2_{32})=(0.5, 2.4 \times 10^{-3}\ \text{eV}^2)$

w/o ND280 constraint

w/ ND280 constraint

N_{SK} per bin w/ error

Reconst. E (GeV)

* Binding energy/SK energy scale are some of the dominant uncertainties affecting T2K Δm^2_{32} precision, but they don't appear in the left table of # of events since they don't affect overall normalization.

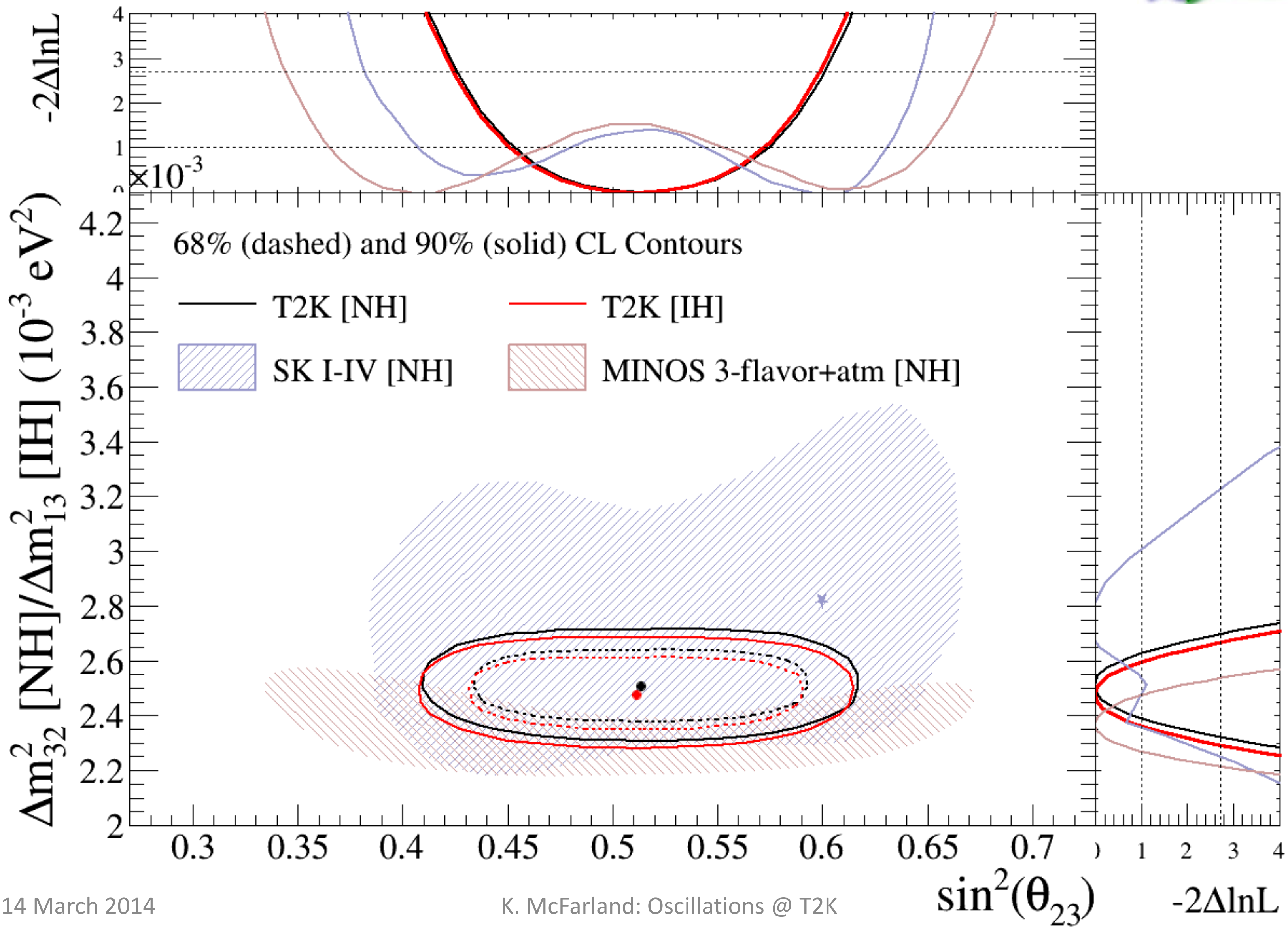
Parameter	Value
Δm^2_{21}	$7.50\times10^{-5}\text{eV}^2$
$\sin^2 2\theta_{12}$	0.857
$\sin^2 2\theta_{13}$	0.098
δ_{CP}	0
Mass hierarchy	Normal
Baseline length	295 km
Earth density	$2.6\ \text{g/cm}^3$

Oscillation Parameter Fit

- Fit is fully three flavor and considers both mass hierarchies
- Marginalize over other oscillation parameters
- Confidence intervals set using Feldman-Cousins procedure with systematic uncertainties incorporated using Cousins-Highland framework

Parameter	**Value**
Δm^2_{21}	$7.5 \pm 0.2 \times 10^{-5} eV^2$
$\sin^2\theta_{12}$	0.312 ± 0.016
$\sin^2\theta_{13}$	0.0251 ± 0.0035
δ_{CP} (doesn't matter for disappearance)	unconstrained
Baseline length	295 km
Earth density	2.6 g/cm^3

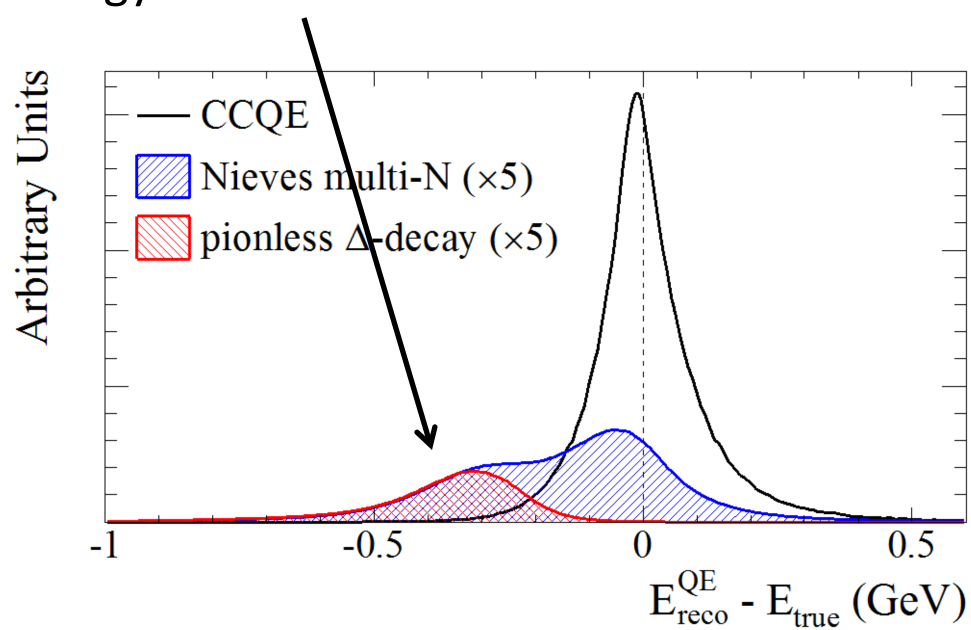
Results



68% (dashed) and 90% (solid) CL Contours
T2K [NH]
T2K [IH]
SK I-IV [NH]
MINOS 3-flavor+atm [NH]
-2ΔlnL
×10^-3
Δm^2_32 [NH]/Δm^2_13 [IH] (10^-3 eV^2)
sin^2(θ_23)
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2

Multi-Nucleon Systematic Uncertainty

- Not incorporated directly into analysis
- But have a large systematic uncertainty (100%), unconstrained by ND280 data, on NEUT decays of Δ resonances w/ prompt pion absorption ("pionless")
  - Has similar impact on neutrino energy reconstruction as a 100% uncertainty in Nieves model
- Future results will incorporate microphysical models directly



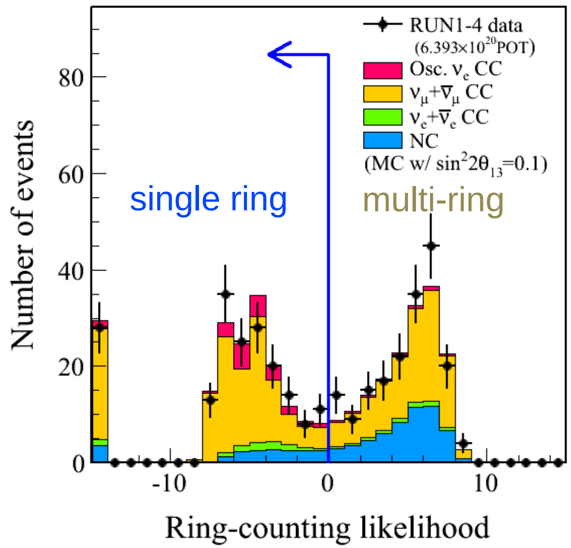
$\nu_\mu \rightarrow \nu_e$ RESULTS

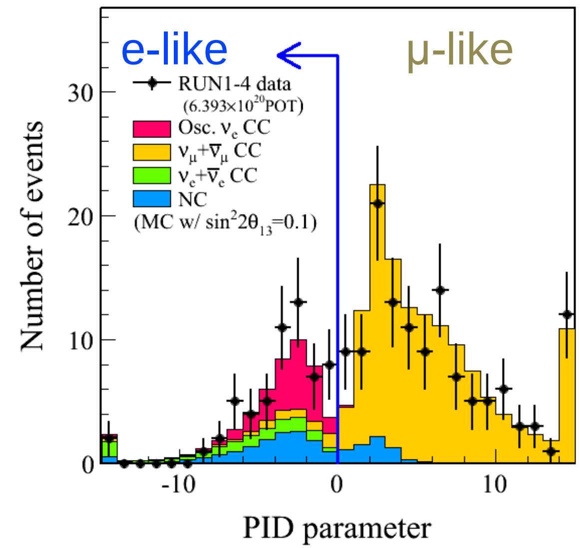
Phys. Rev. Lett. 112, 061802 (2014)

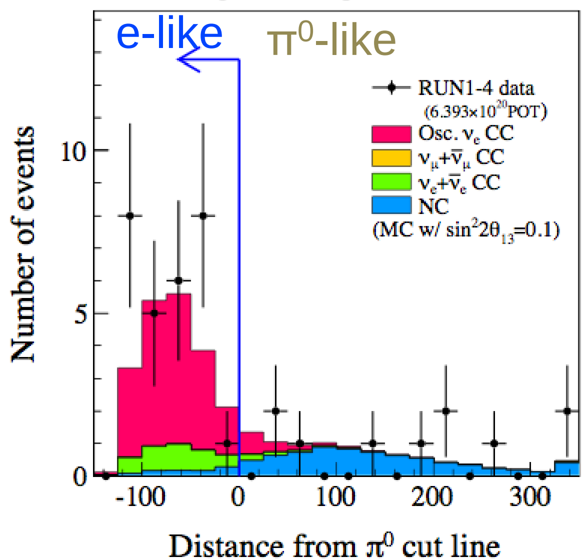
T2K ν_e Event Selection

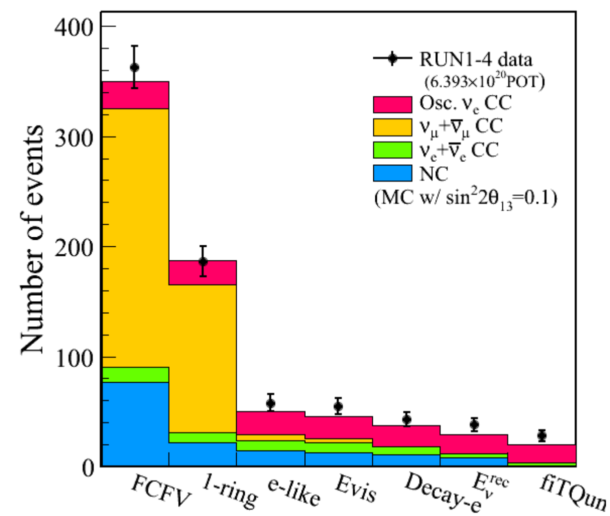
<u>**ν_e Selection Cuts**</u>

- # veto hits < 16
- Fid. Vol. = 200 cm
- # of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- fiTQun π^0 cut
- 0 < E_ν < 1250 MeV



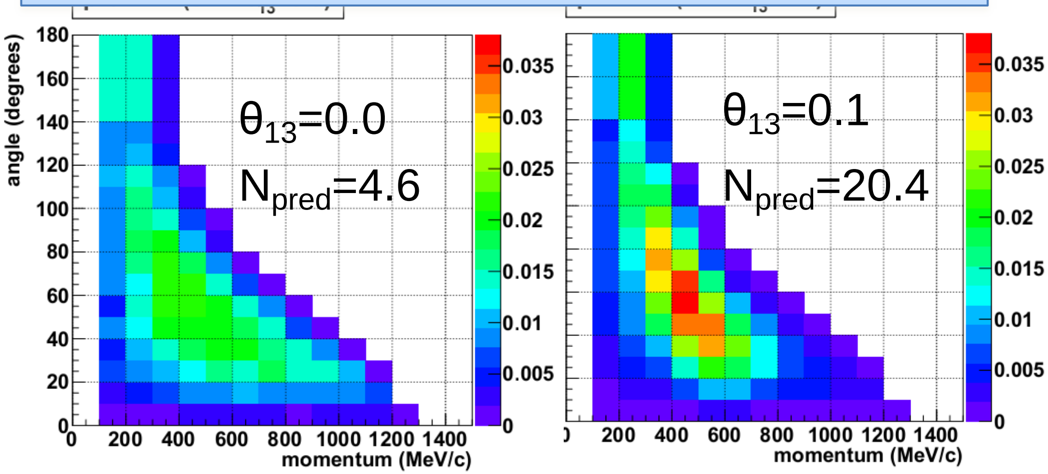






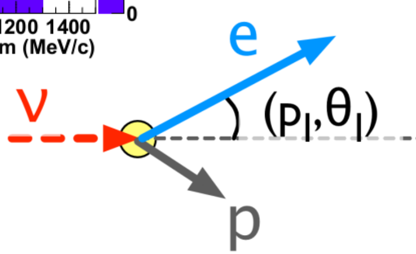
Neutrino Oscillation Parameters

Electron momentum vs. angle distribution (MC)



Fixed 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 fit method is not changed from 2012 analysis.

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

Predicted number of events and systematic uncertainties

Predicted # of events w/ 6.4×10^{20} POT

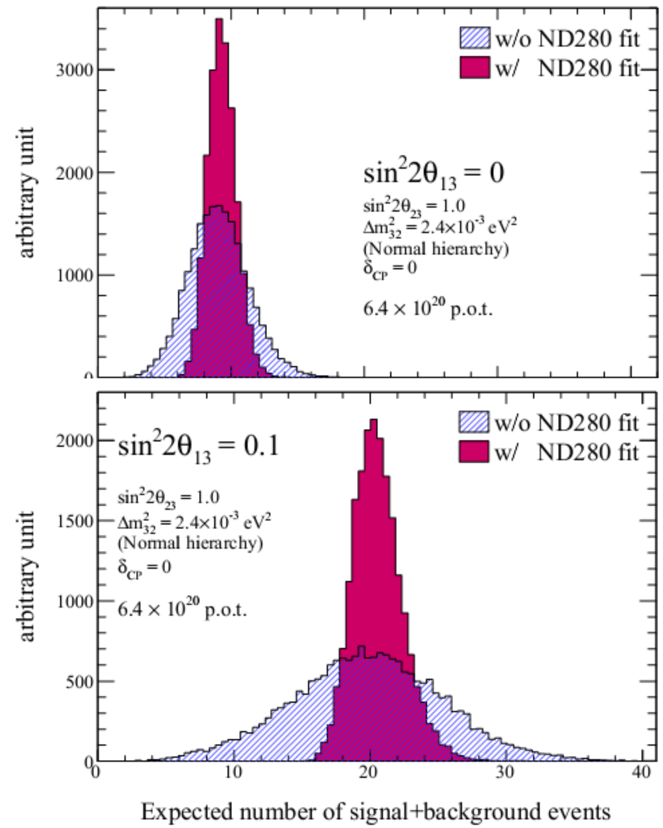
Event category	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
ν_e signal	0.38	16.42
ν_e background	3.17	2.93
ν_μ background (mainly NCπ^0)	0.89	0.89
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.20	0.19
Total	4.64	20.44
Total (w/ 2012 flux & cross section parameters)	5.15	21.77

Near detector constraint in 2013 predicts 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 + ν int. in T2K fit	4.9 %	3.0 %
ν 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 %

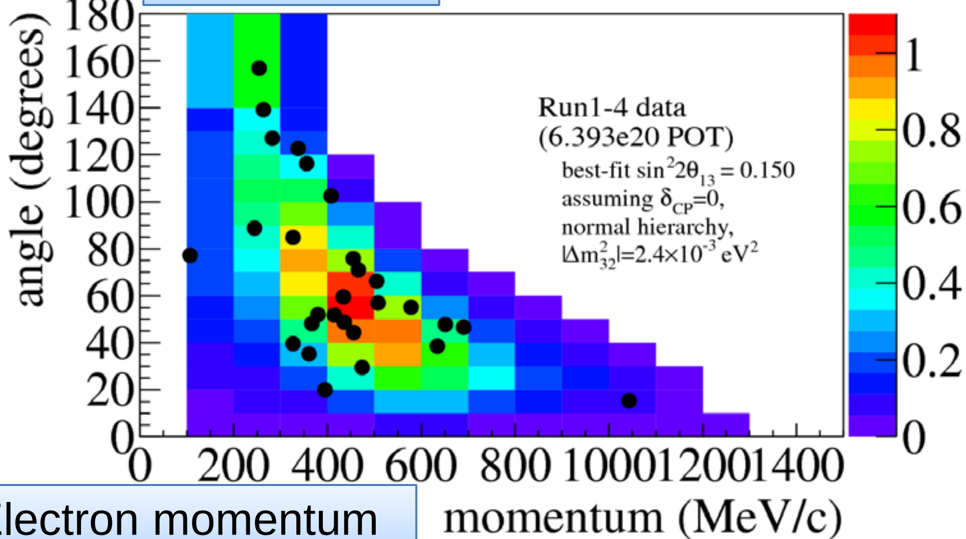
Distribution of predicted number of events



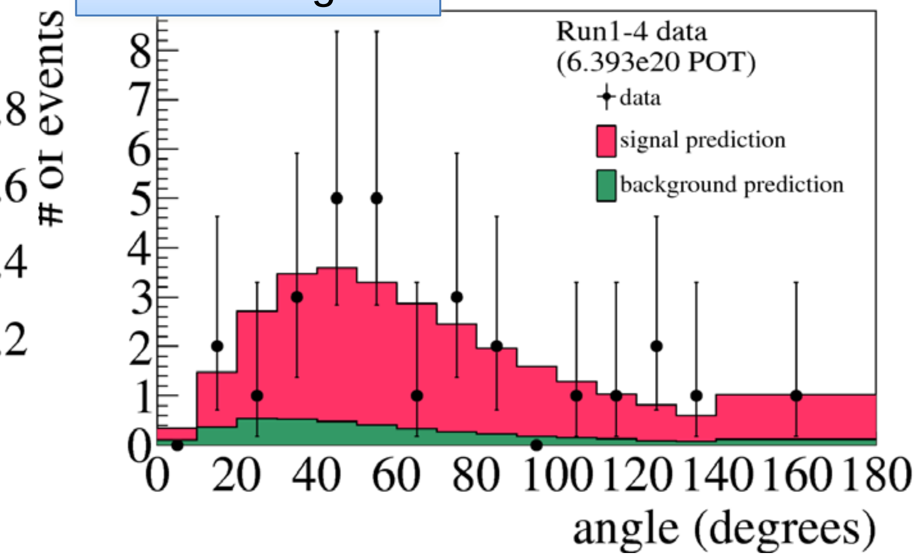
Errors are reduced from 2012 mainly due to near detector analysis improvement.

Results

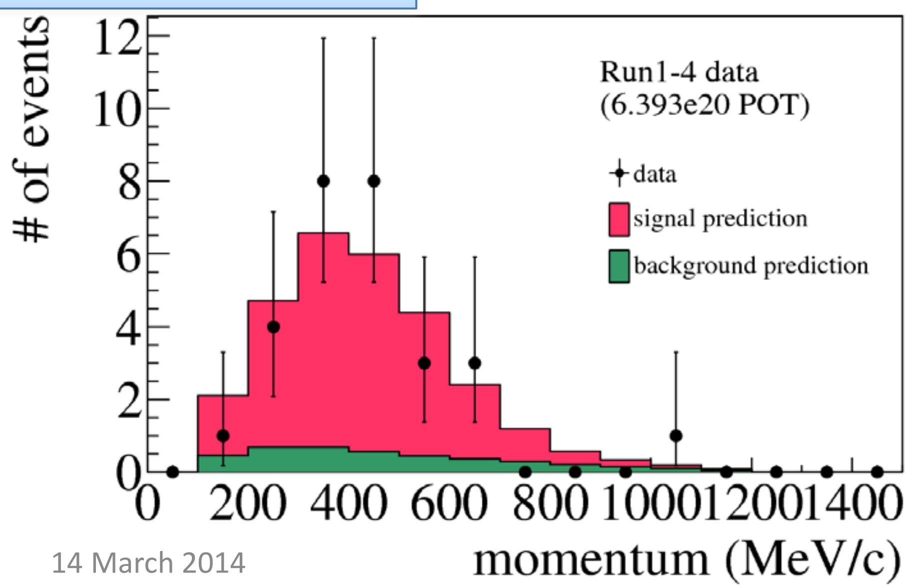
Electron p-θ



Electron angle



Electron momentum



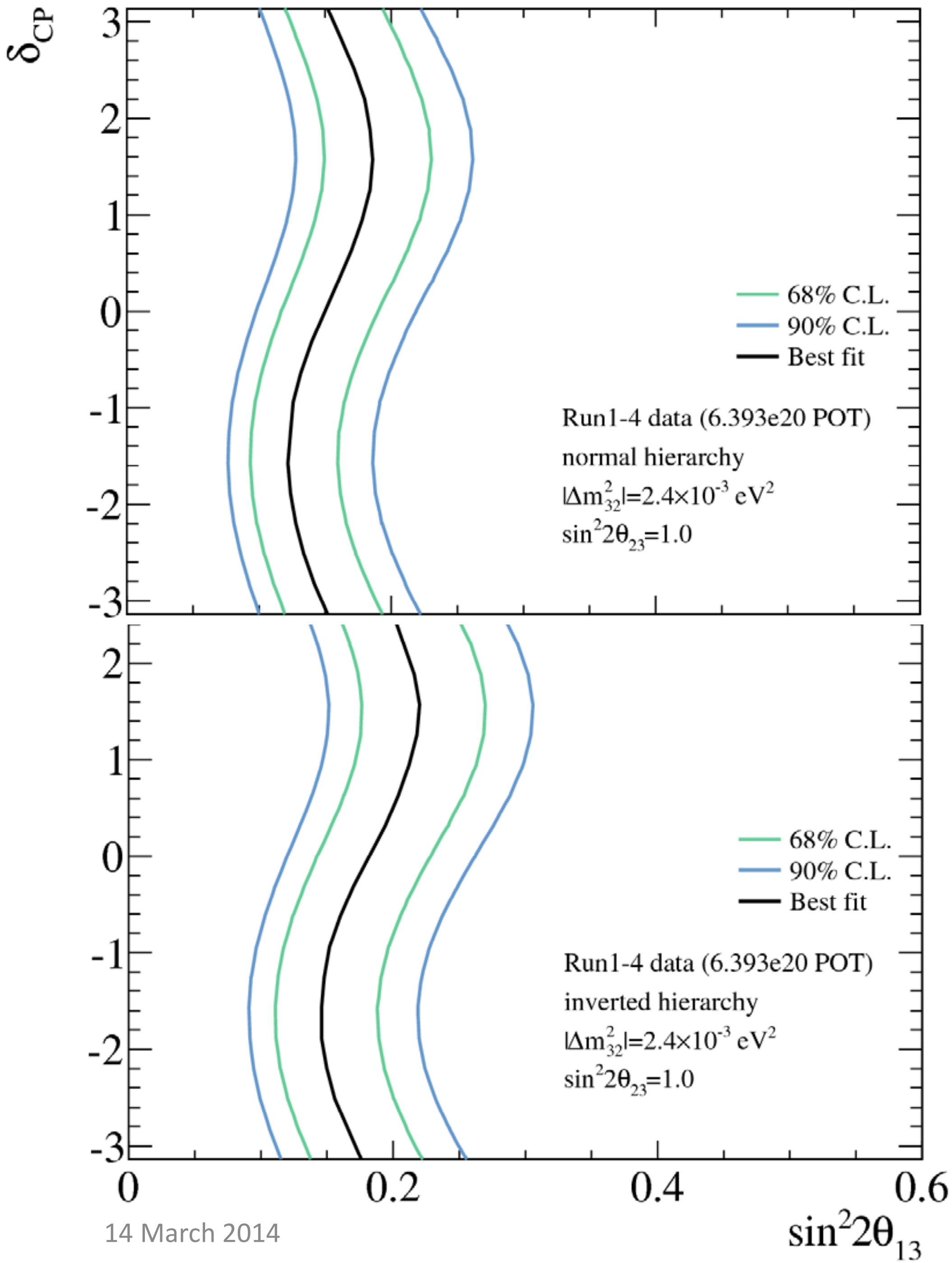
Assuming $\delta_{CP}=0$, normal hierarchy, $|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$

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 δ_{CP}

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

normal hierarchy:

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

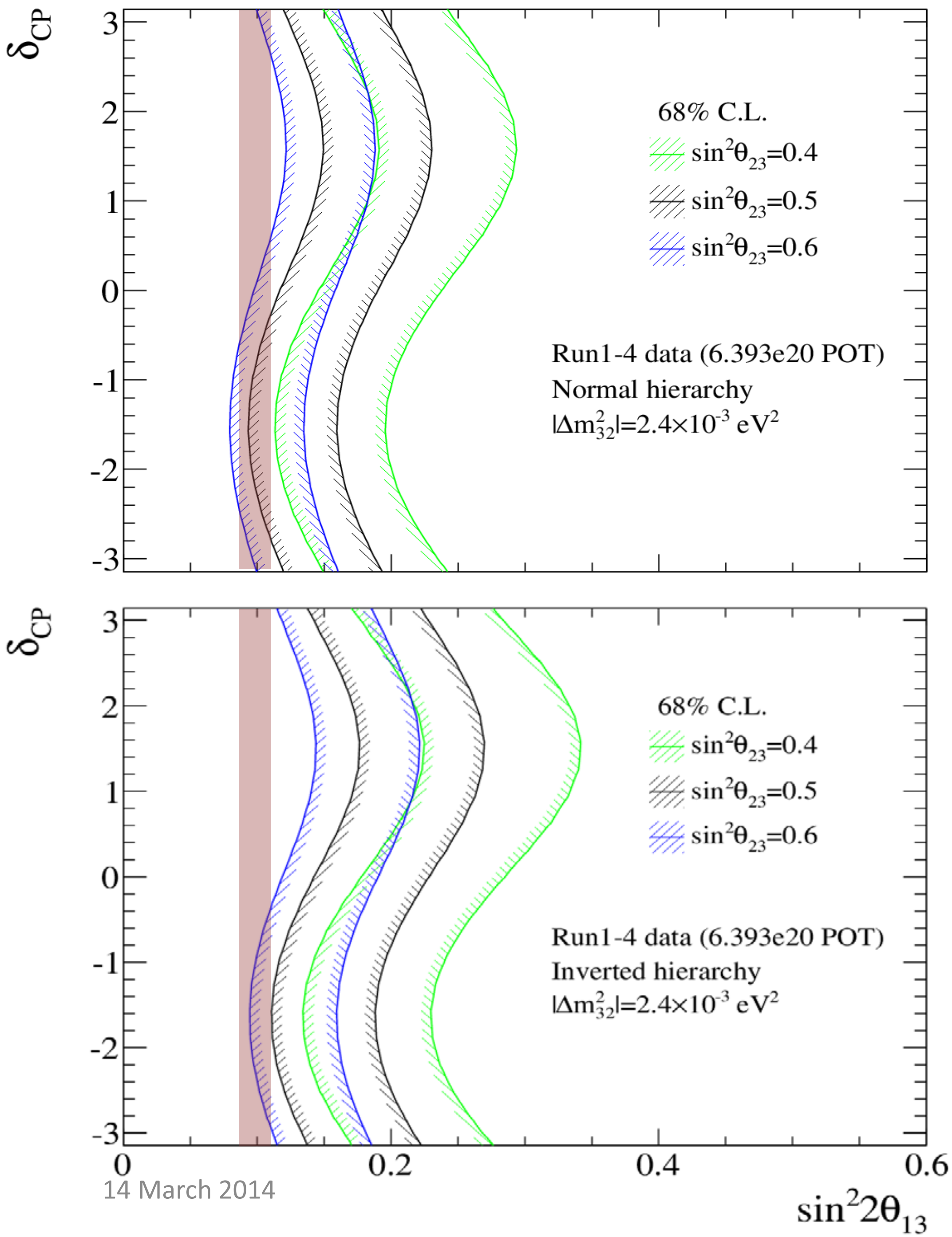
inverted hierarchy:

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

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

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

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



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

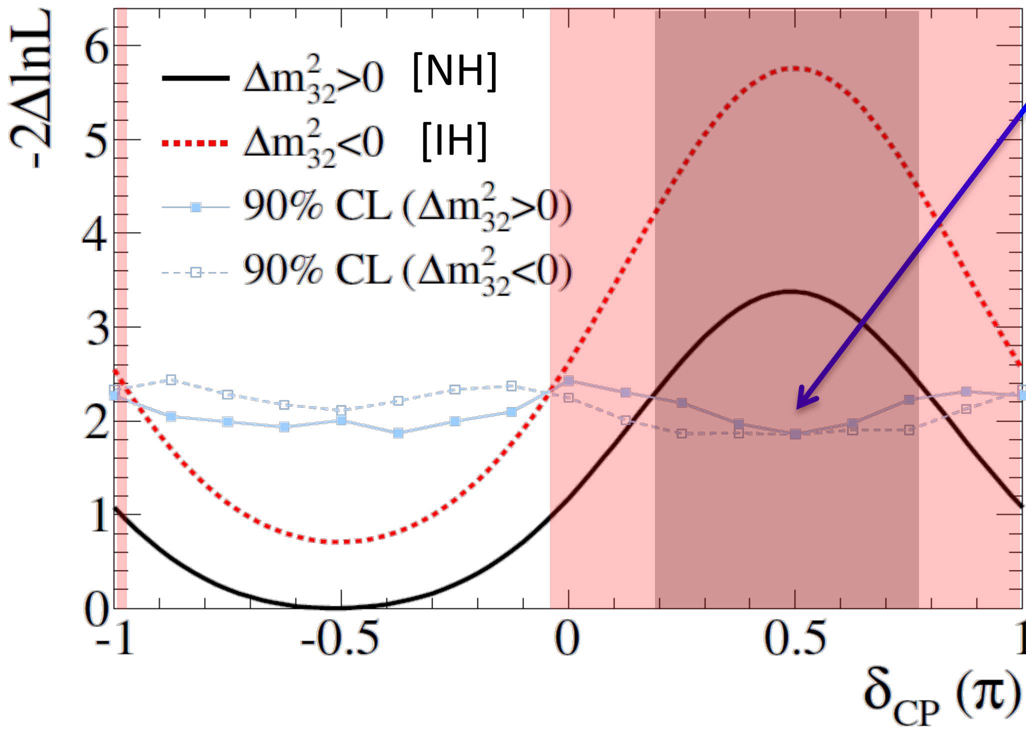
- Green and Blue bands are at edge of disappearance 90% confidence interval

Pink band represents PDG2012 reactor average value of $\sin^2 2\theta_{13}=(0.098\pm0.013)$

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

Results of ν_e appearance analysis

Combination of T2K + Reactor ($\sin^2 2\theta_{13}$=0.098±0.013 from PDG2012)



90% C.L. limits by Feldman-Cousins

$\sin^2\theta_{23}$ marginalized over less precise Run1-3 result. Full Run1-4 fit next week.

90% C.L. excluded region

[NH]: 0.19π ~ 0.80π

[IH]: -0.04π ~ 1.03π

[NH] Normal hierarchy,
[IH] Inverted hierarchy

- Best fit is found at very interesting point, δ_{CP} ~ -π/2.
- If it is the true value, NOvA and T2K just heard the starter's gun

CONCLUSIONS AND FUTURE PROSPECTS

T2K and J-PARC Run Plans

- T2K's 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 by 2018 (depends on funding). Up to 750 kW
  - Possible scenario:
    - Double current protons on target by mid-2015
    - Next-to-next doubling by early 2017
    - If MR upgrade done in 2018, reach full planned statistics (78E20 POT), roughly 12x the current exposure, roughly end of 2020
- 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 θ_{13} with 7σ significance by observation of $\nu_\mu \longrightarrow \nu_e$
- Now also have best measurement of $\nu_\mu \longrightarrow \nu_\mu$ which favors maximal mixing
- Accelerator oscillations at "atmospheric" baseline are now precision measurements
- Promise for the near future with interplay of T2K and NOvA in the coming years

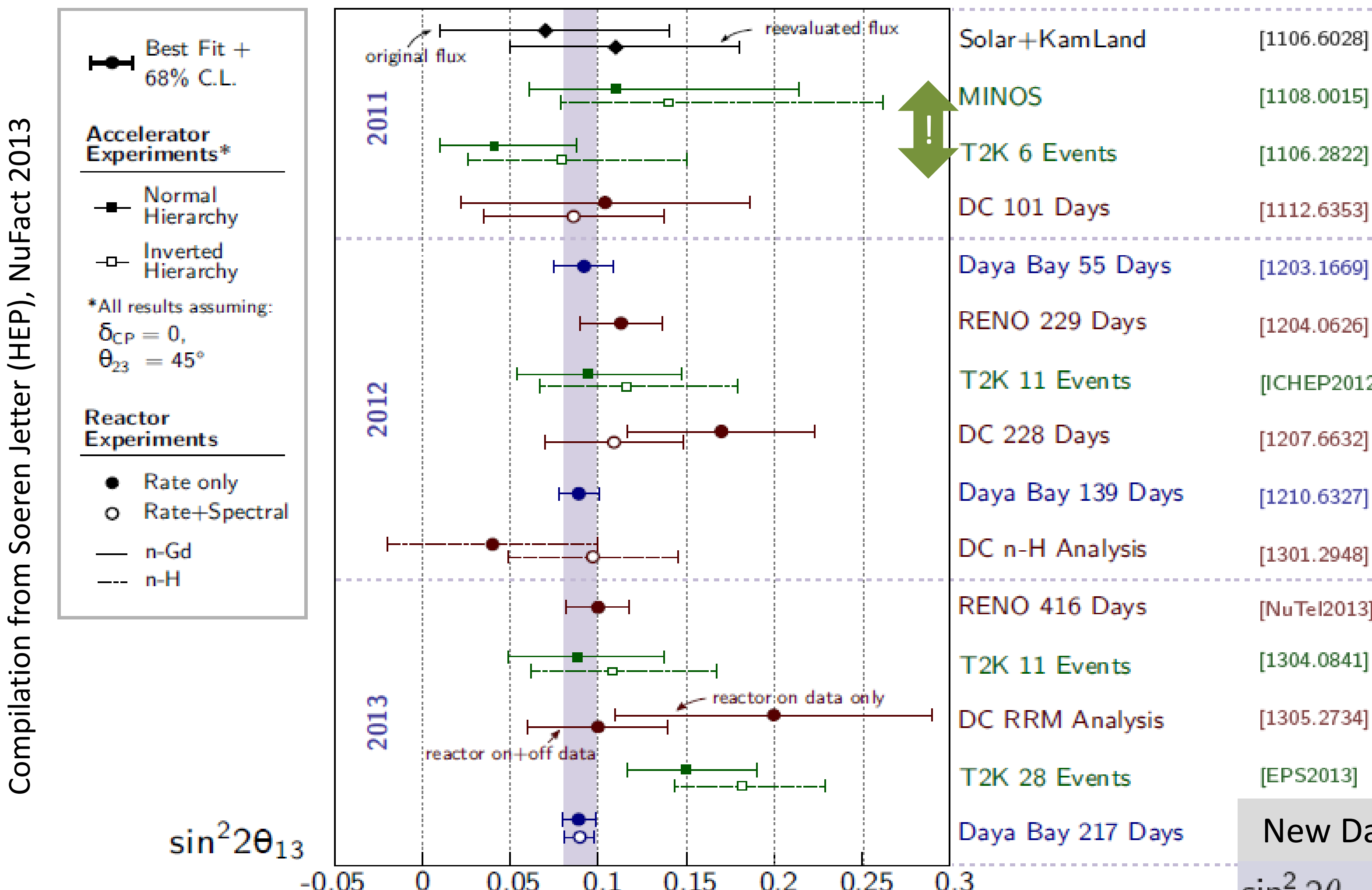
PLEASE CONTINUE TO ENJOY NEUTRINO OSCILLATIONS

PLEASE CONTINUE TO ENJOY ^ NEUTRINO OSCILLATIONS

precision measurements of

BACKUP PLOTS

Global θ_{13}
(includes Daya Bay spectrum results)



New Daya Bay Result

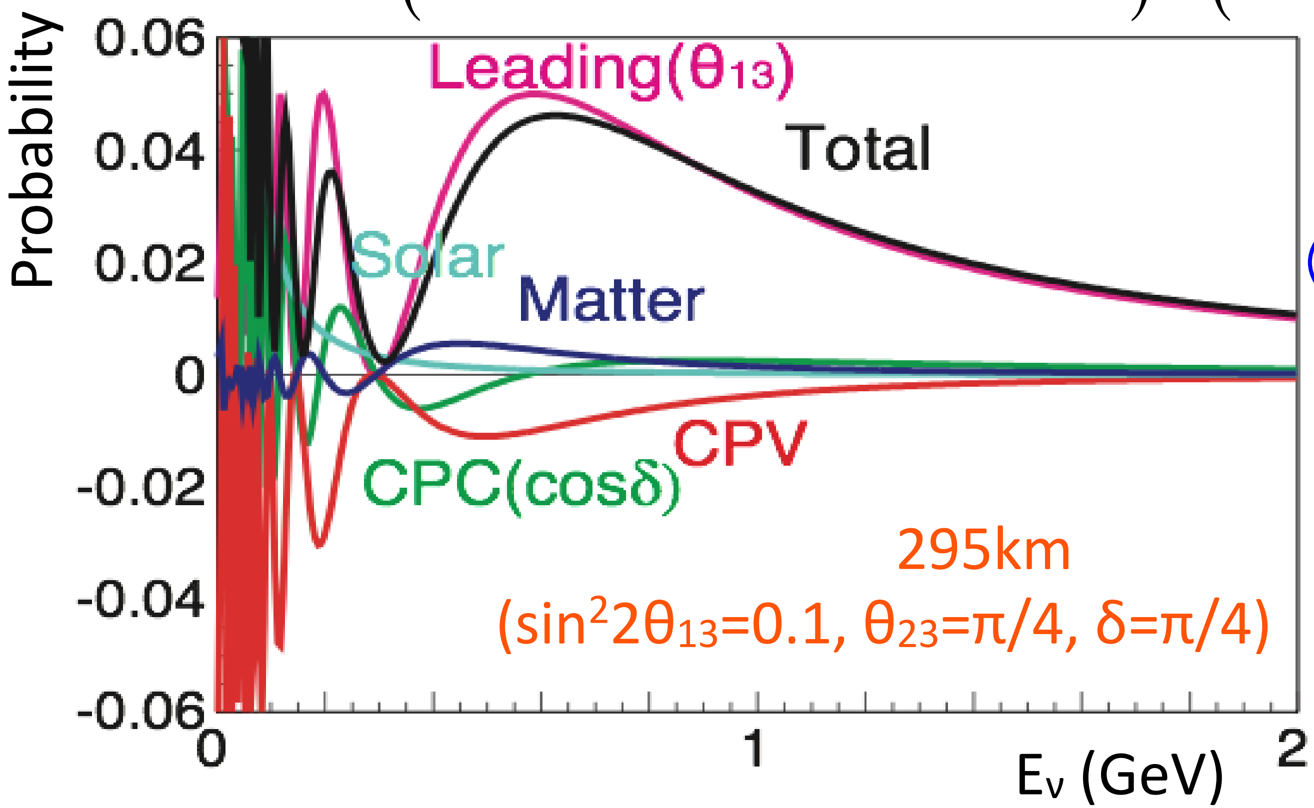
$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

OSCILLATION PROBABILITIES

Oscillation Probabilities at T2K

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{32} \cdot L}{4E} + (\text{solar term})$$

$$+ (\text{interference or "CP" terms}) + (\text{matter term})$$



Leading

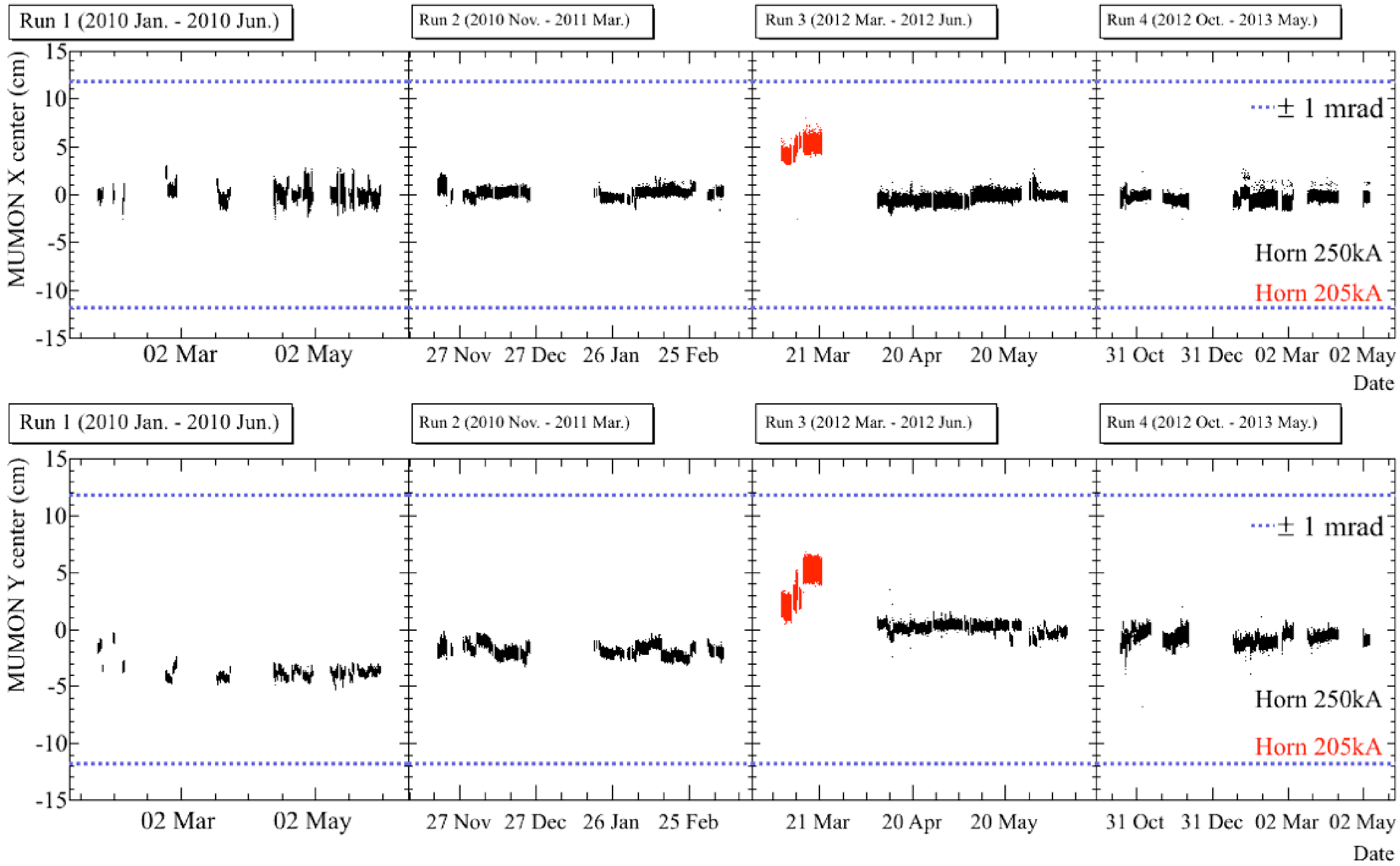
Differentiates 1st/2nd octants of θ_{23}

BEAM STABILITY

ν beam stability

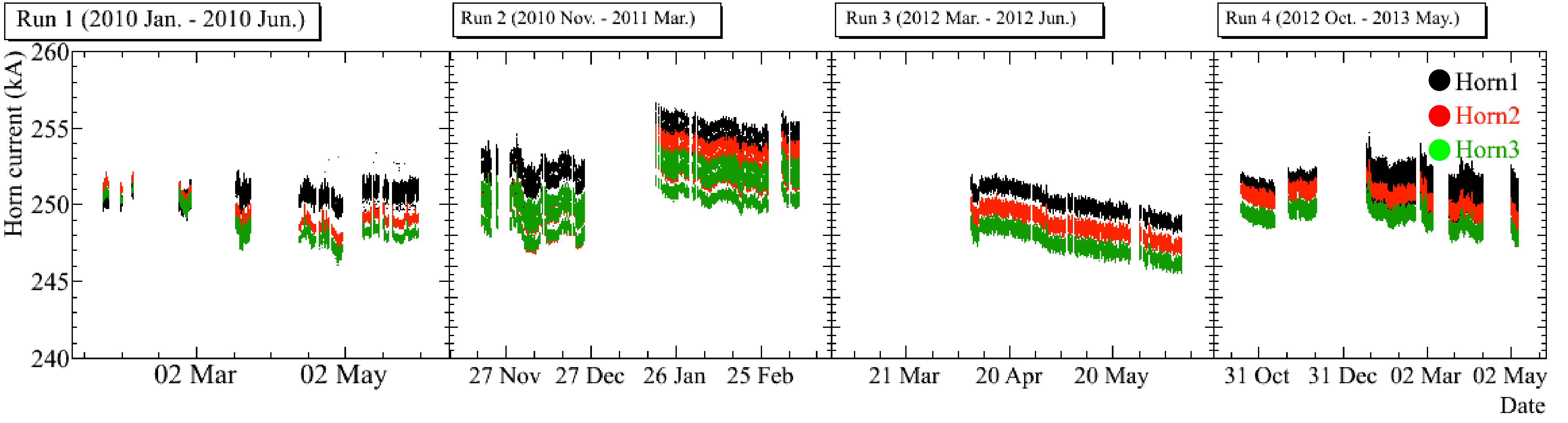
Stability of beam direction (Muon monitor)

Stability of beam direction is less than 1mrad(*) during whole run period



(*) 1 mrad change of ν beam direction results in
2-3% change of the neutrino energy scale (~16MeV)

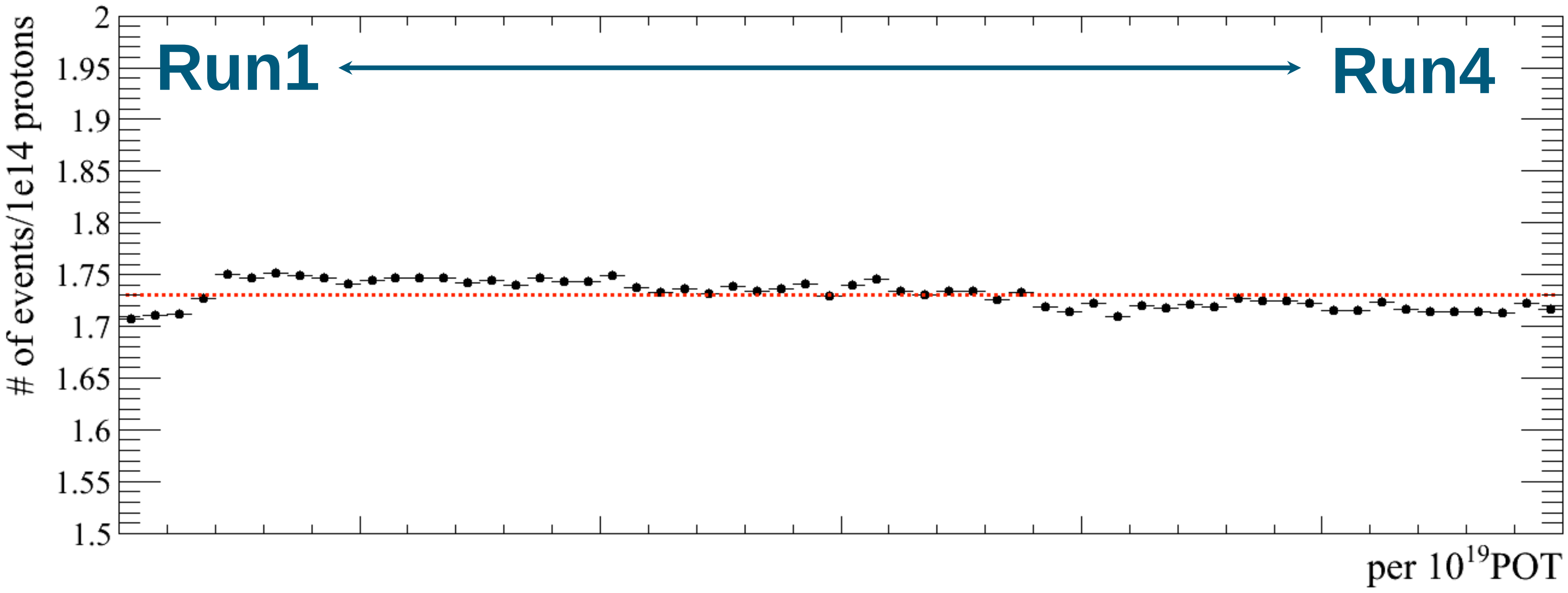
Stability of horn current



* Nominal horn current is 250kA
* 205kA horn operation in the beginning of Run3 (13% flux reduction at peak)
* We used averaged horn current of each run period in the flux prediction
* Horn current is stable within ±5kA of the averaged current of each run period

ν beam stability

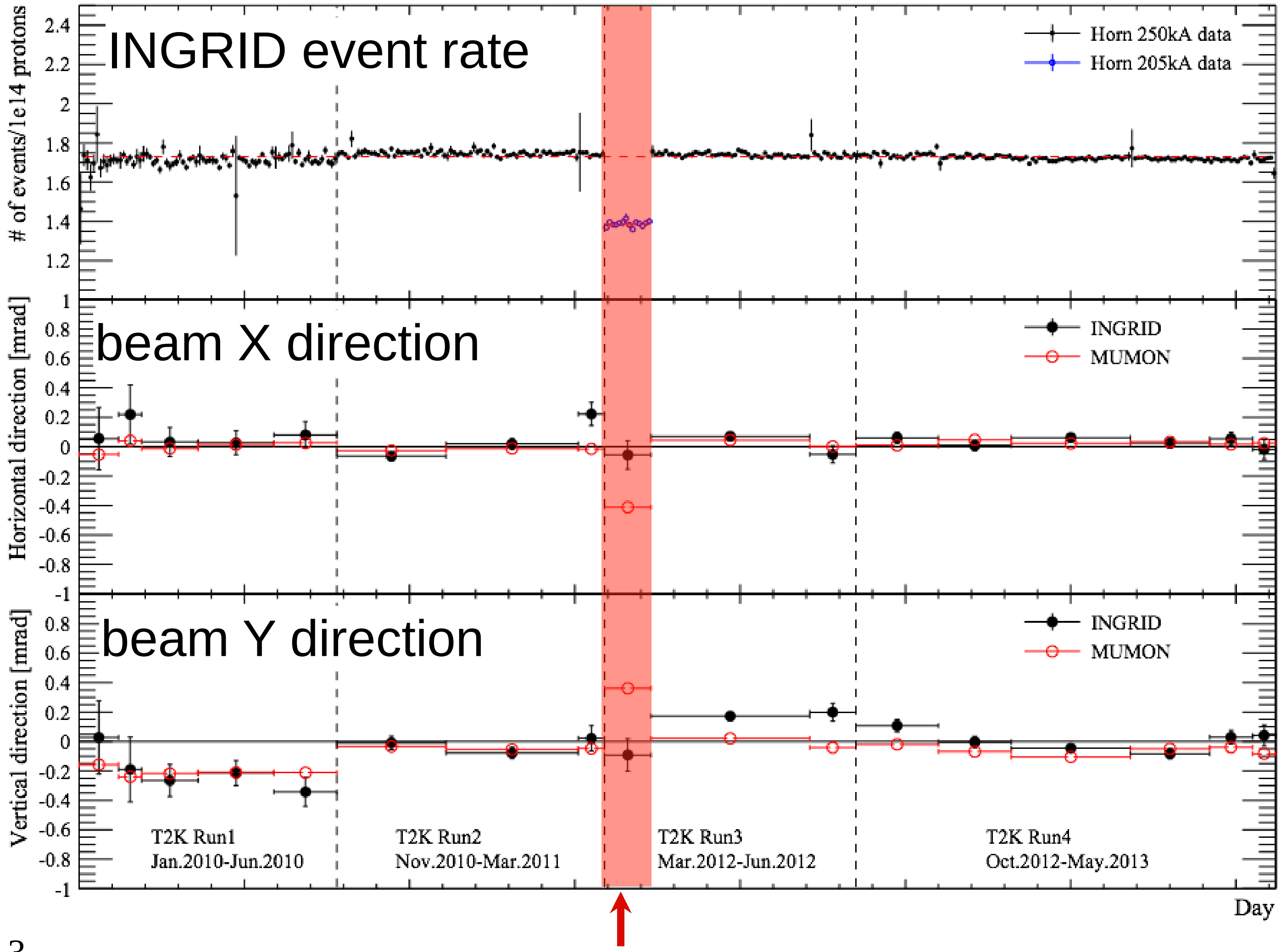
Neutrino event rate per 10^{19} p.o.t measured by INGRID from Run1 to Run4



RMS/Mean of the event rate for whole period is approximately 0.7%

Achieved good stability

205kA operation

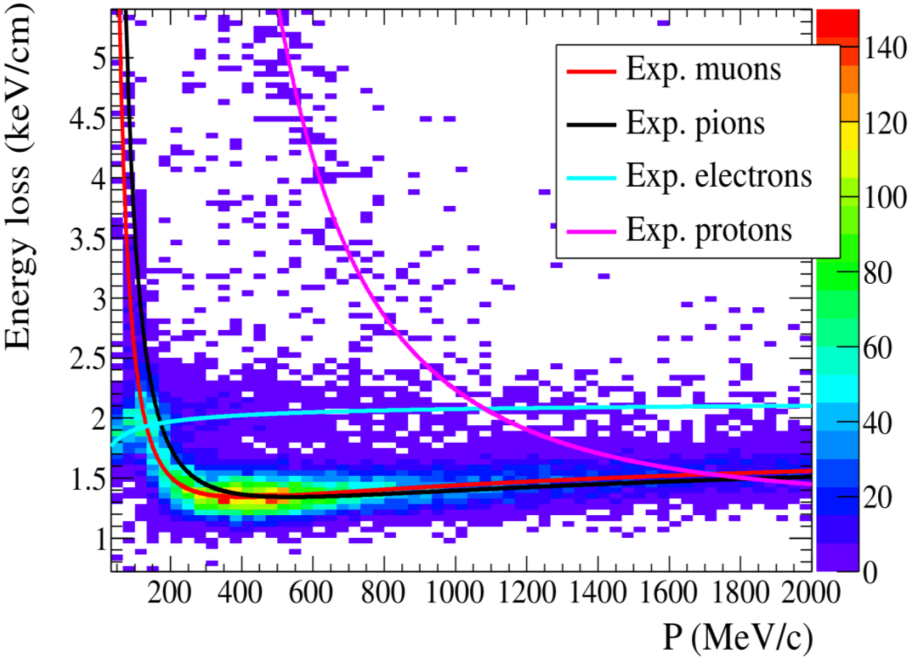


- In Run 3
  - One of power supplies of horns was broken before starting Run 3 operation
  - Replaced it with an old power supply used in K2K experiment
  - **205kA** operation was done in the beginning of Run 3
    - Then came back to 250kA operation after improving the old power supply

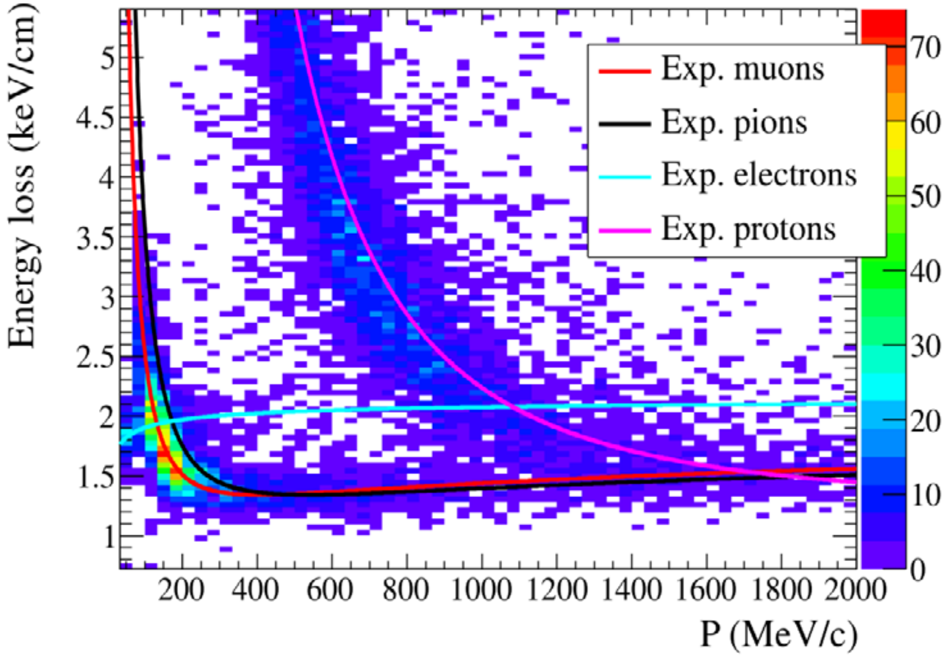
ND280 MEASUREMENTS

ND280 TPC Particle ID by dE/dx

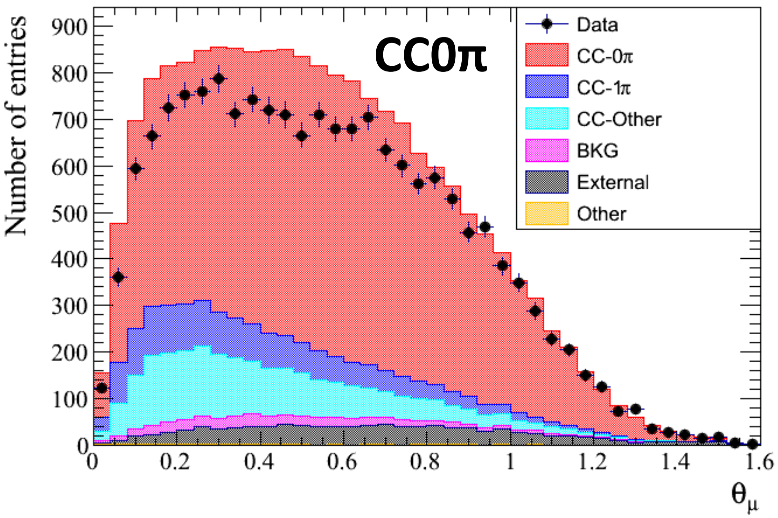
Negative tracks in the TPC.

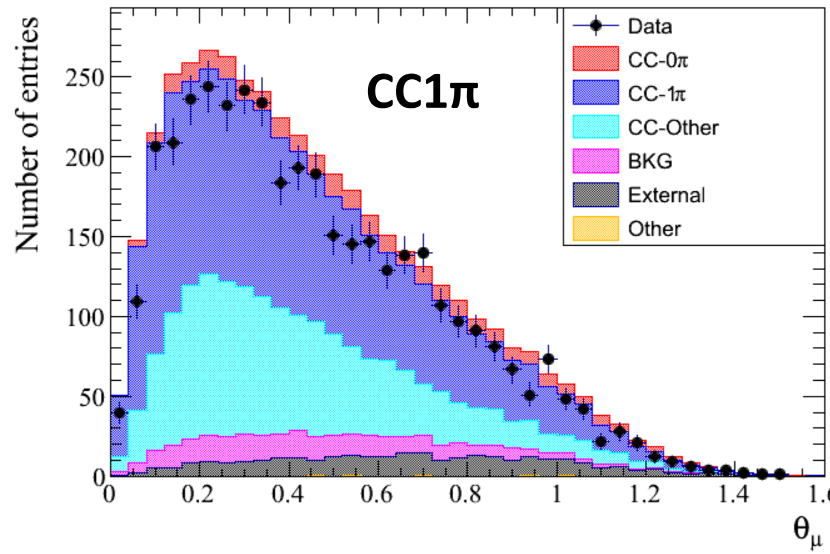


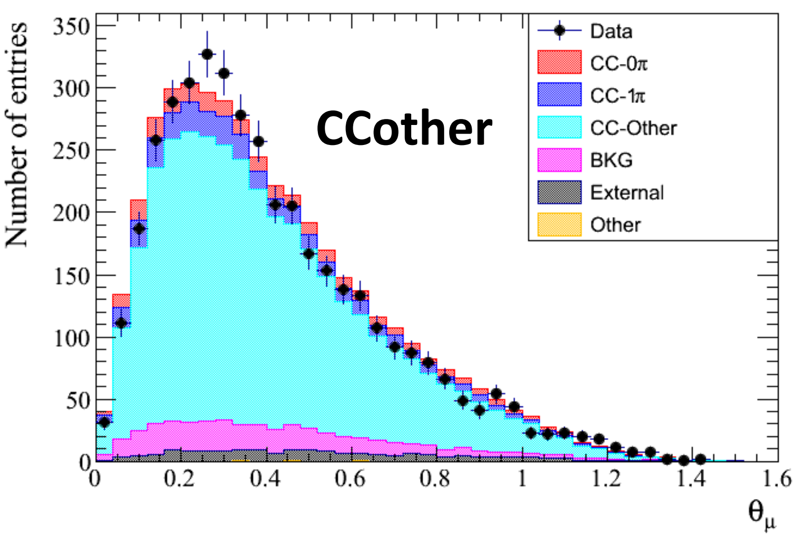
Positive tracks in the TPC.



Muon Angle in ND280

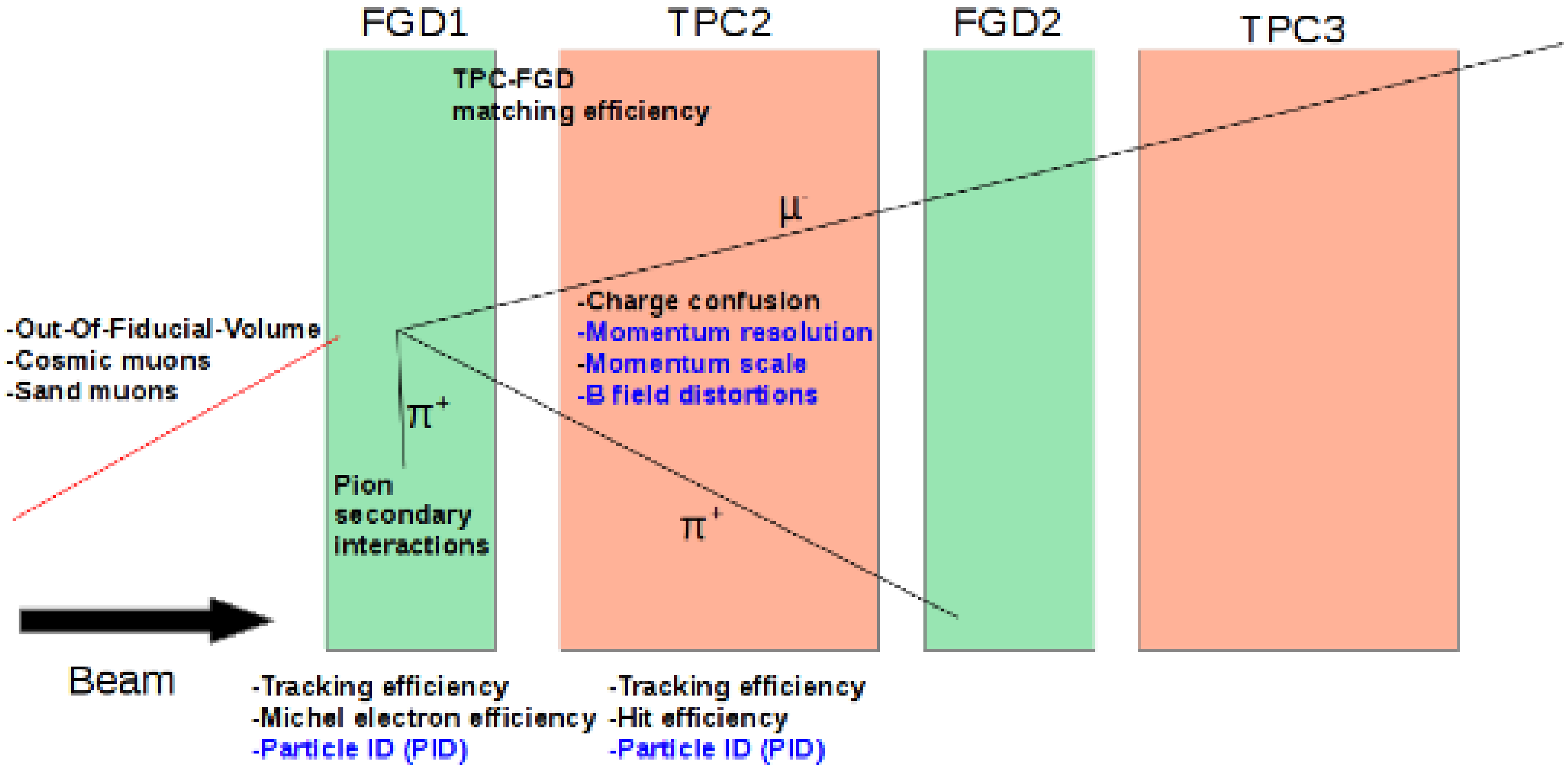






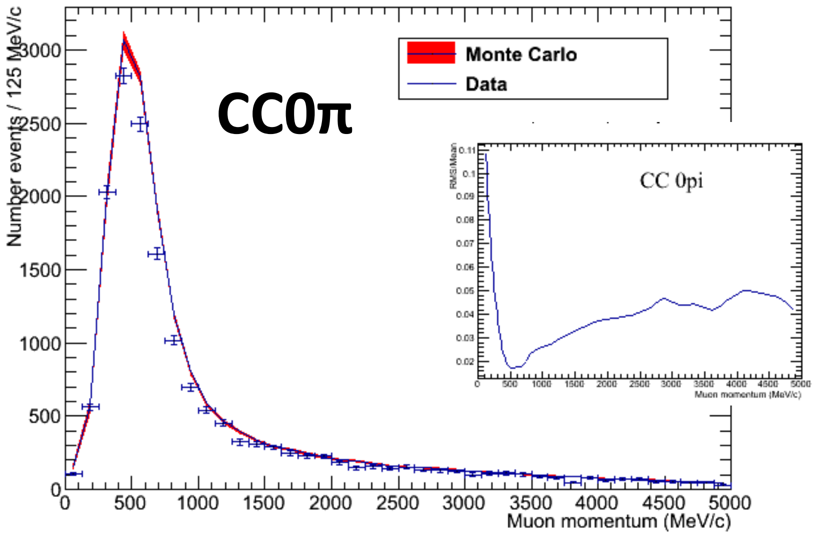
	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

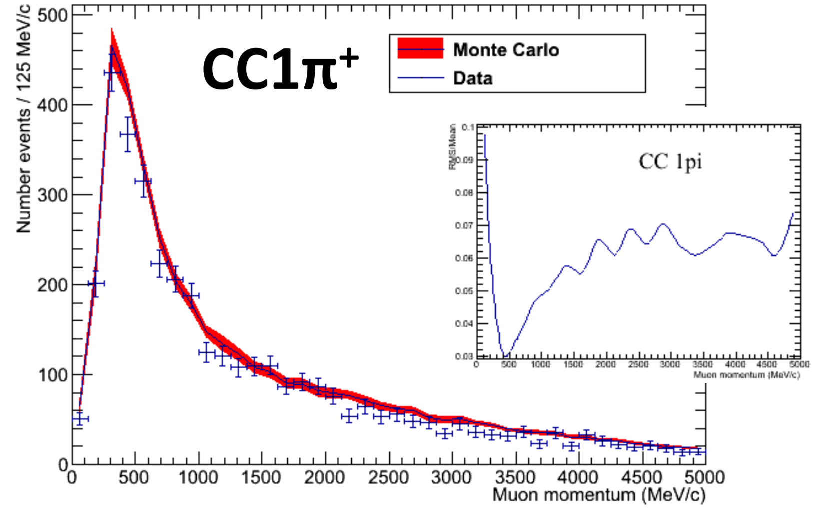
ND280 Systematic Errors

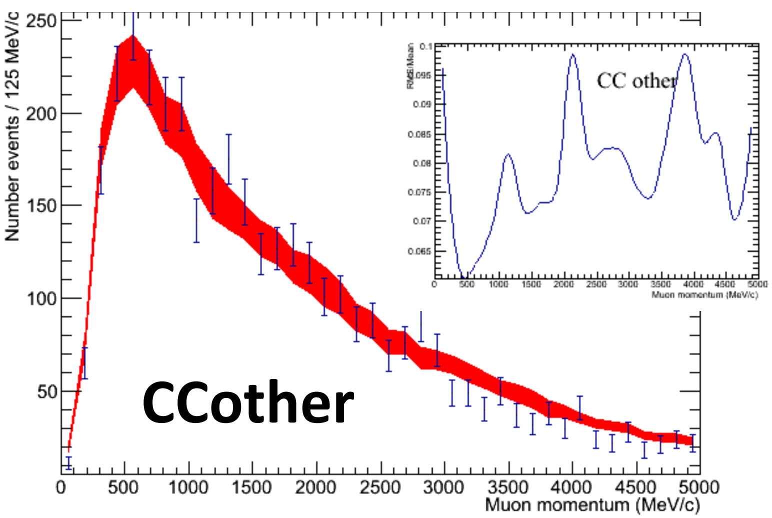


- Many sources of systematic error have been evaluated for the ND280 constraint
  - All errors are assigned using data control samples

ND280 Detector systematics



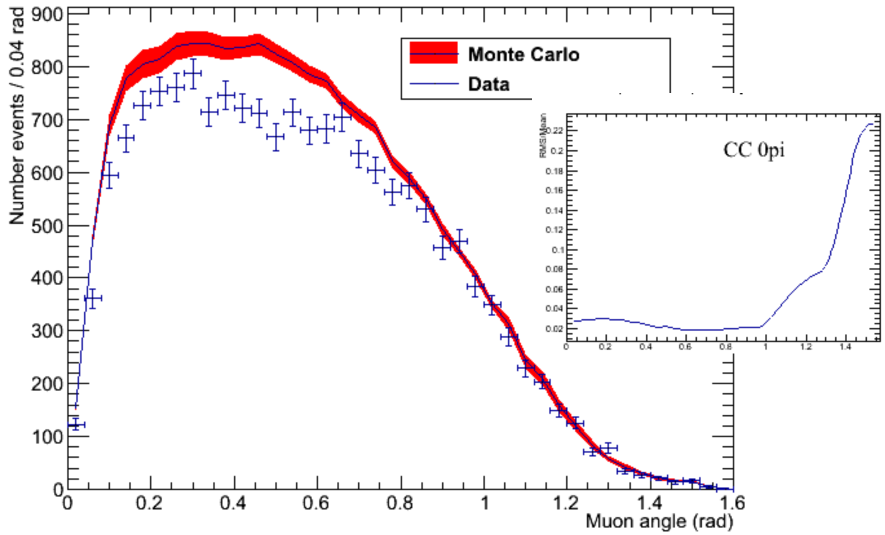


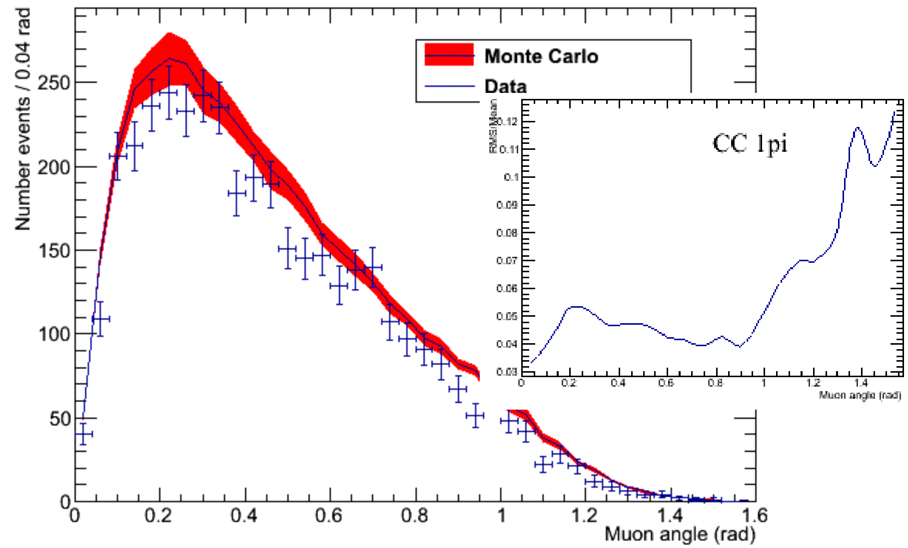


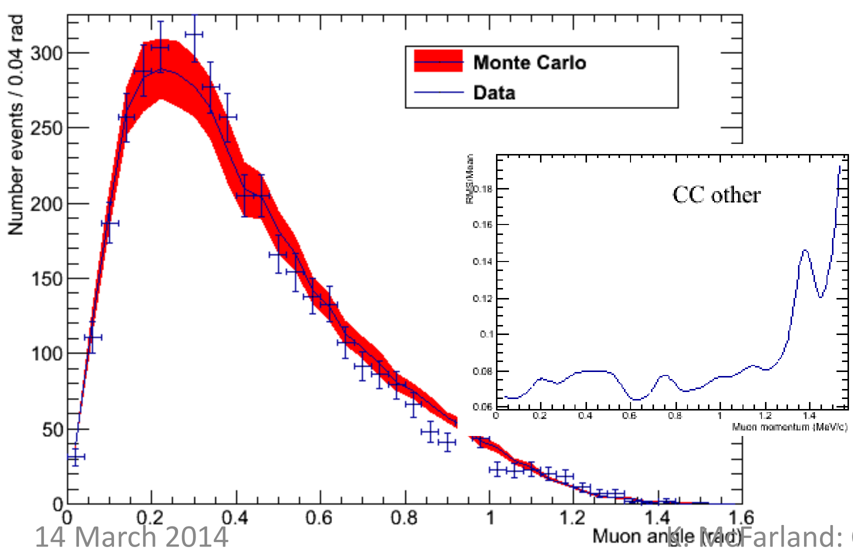
Largest relative error in all momentum bins in all categories

B Field distortion (0.3%)	TPC Tracking efficiency (0.6%)
TPC-FGD matching efficiency (1%)	**TPC Charge confusion (2.2%)**
TPC Momentum scale (2%)	**TPC Momentum resolution (5%)**
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	**Out of Fiducial Volume (10%)**
Pile-up (0.07%)	Sand muon (0.02%)
TPC PID (3.5%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	**Pion secondary interaction (8%)**

ND280 Detector systematics







B Field distortion (0.3%)	TPC Tracking efficiency (0.2%)
TPC-FGD matching efficiency (1.8%)	***TPC Charge confusion (5.0%)***
TPC Momentum scale (2%)	***TPC Momentum resolution (5%)***
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	***Out of Fiducial Volume (22%)***
Pile-up (0.07%)	Sand muon (0.02%)
TPC PID (9.0%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	***Pion secondary interaction (8%)***

Largest relative error in all angle bins in all categories

FLUX PREDICTION AND UNCERTAINTIES

Fraction of the neutrino flux for each parent particle

Fraction for each flavors

	Flux Percentage of Each Flavors			
Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0%	41.8%	31.9%	2.8%
$K^\pm$	4.0%	4.3%	26.9%	11.3%
K_L^0	0.1%	0.9%	7.6%	49.0%
Tertiary				
$\pi^\pm$	34.4%	50.0%	20.4%	6.6%
$K^\pm$	1.4%	2.6%	10.0%	8.8%
K_L^0	0.0%	0.4%	3.2%	21.3%

Total fraction for all flavors

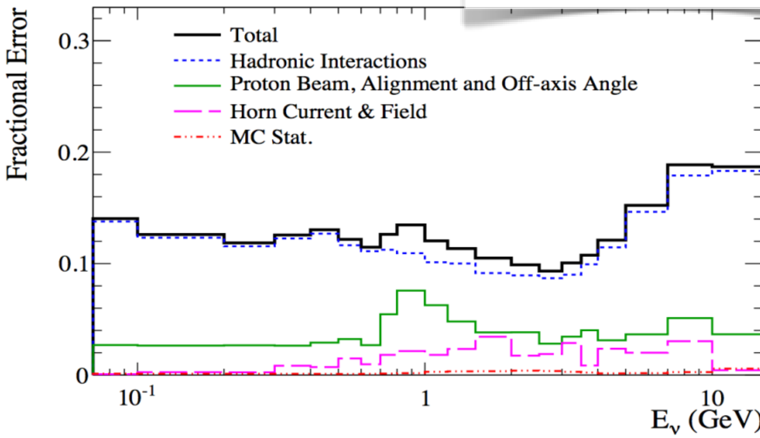
	Flux Percentage of All Flavors			
Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\pi^\pm$	87.5%	5.5%	0.6%	0.0%
$K^\pm$	5.0%	0.5%	0.4%	0.0%
K_L^0	0.1%	0.2%	0.1%	0.1%

Flux uncertainty as a function of energy

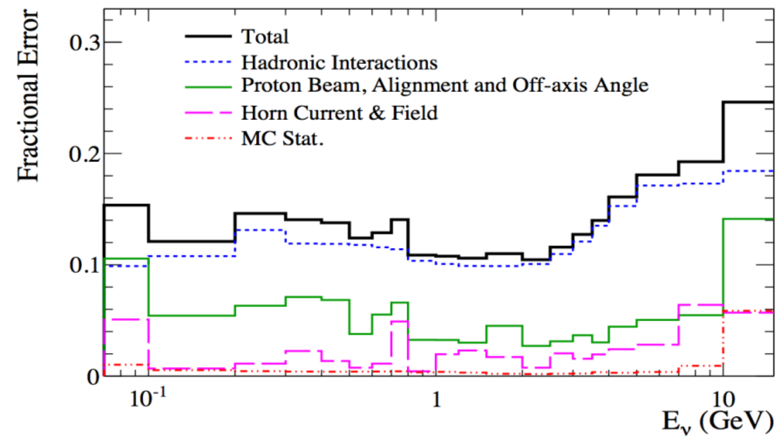
uncertainties are evaluated based on NA61 measurements and T2K beam monitor measurements

SK ν_μ flux

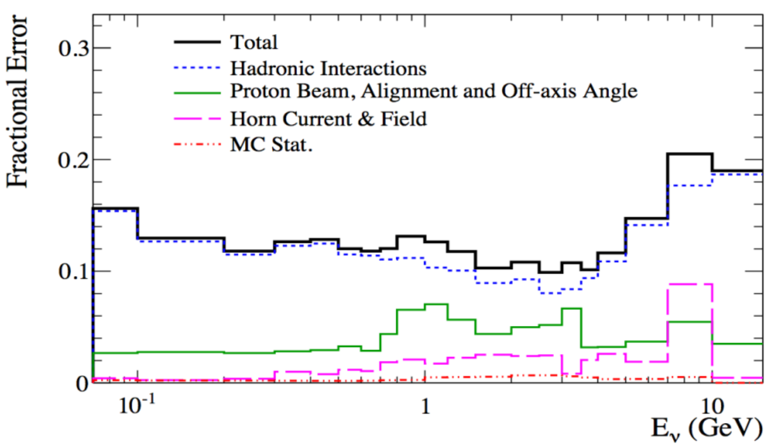
10~15% error



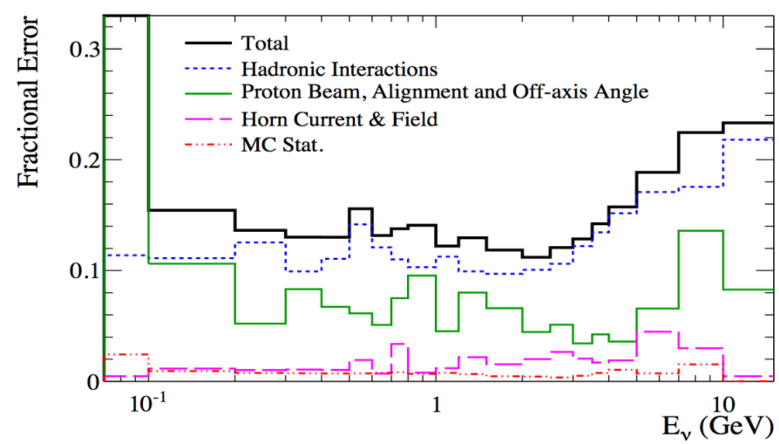
SK ν_e flux



ND280 ν_μ flux



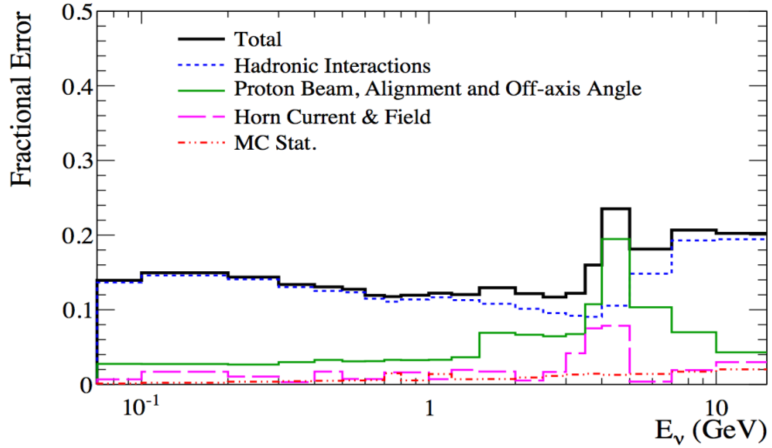
ND280 ν_e flux



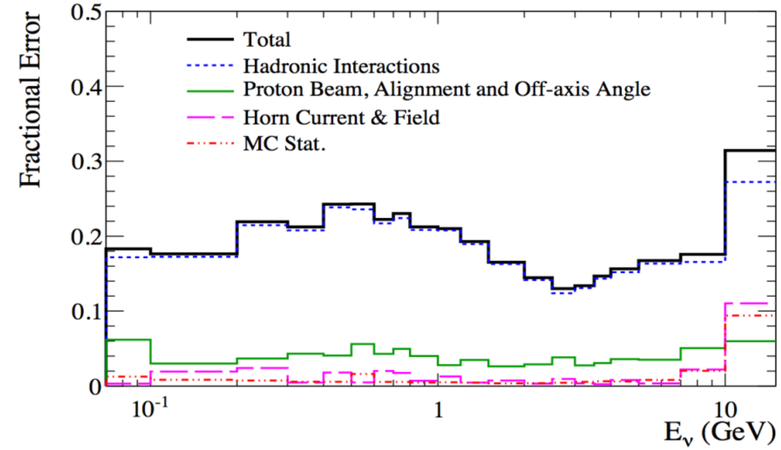
Flux uncertainty as a function of energy

uncertainties are evaluated based on NA61 measurements and T2K beam monitor measurements

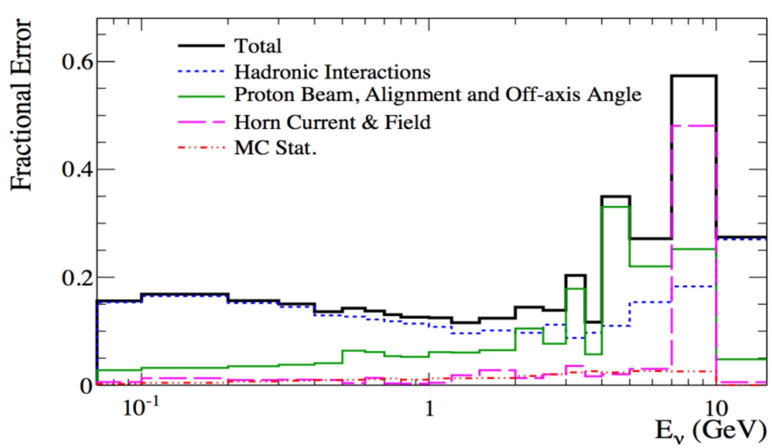
SK ν_μ flux



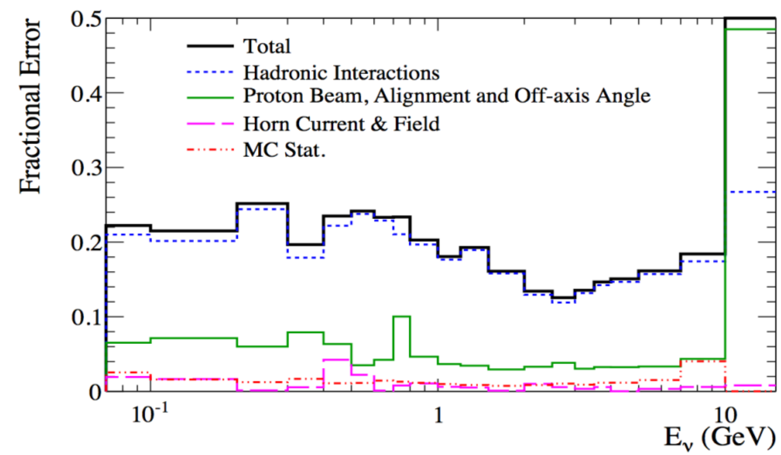
SK ν_e flux



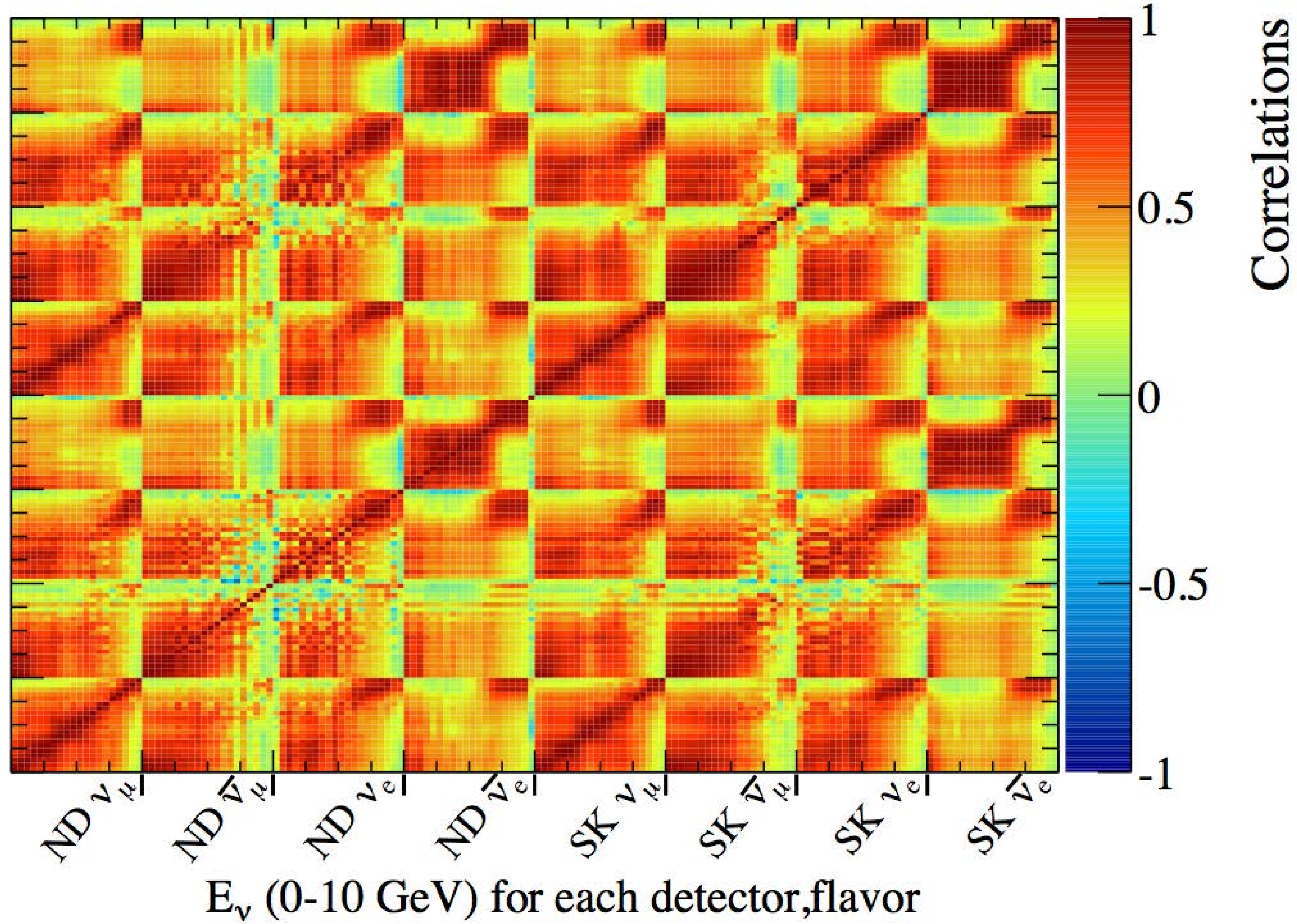
ND280 ν_μ flux



ND280 ν_e flux

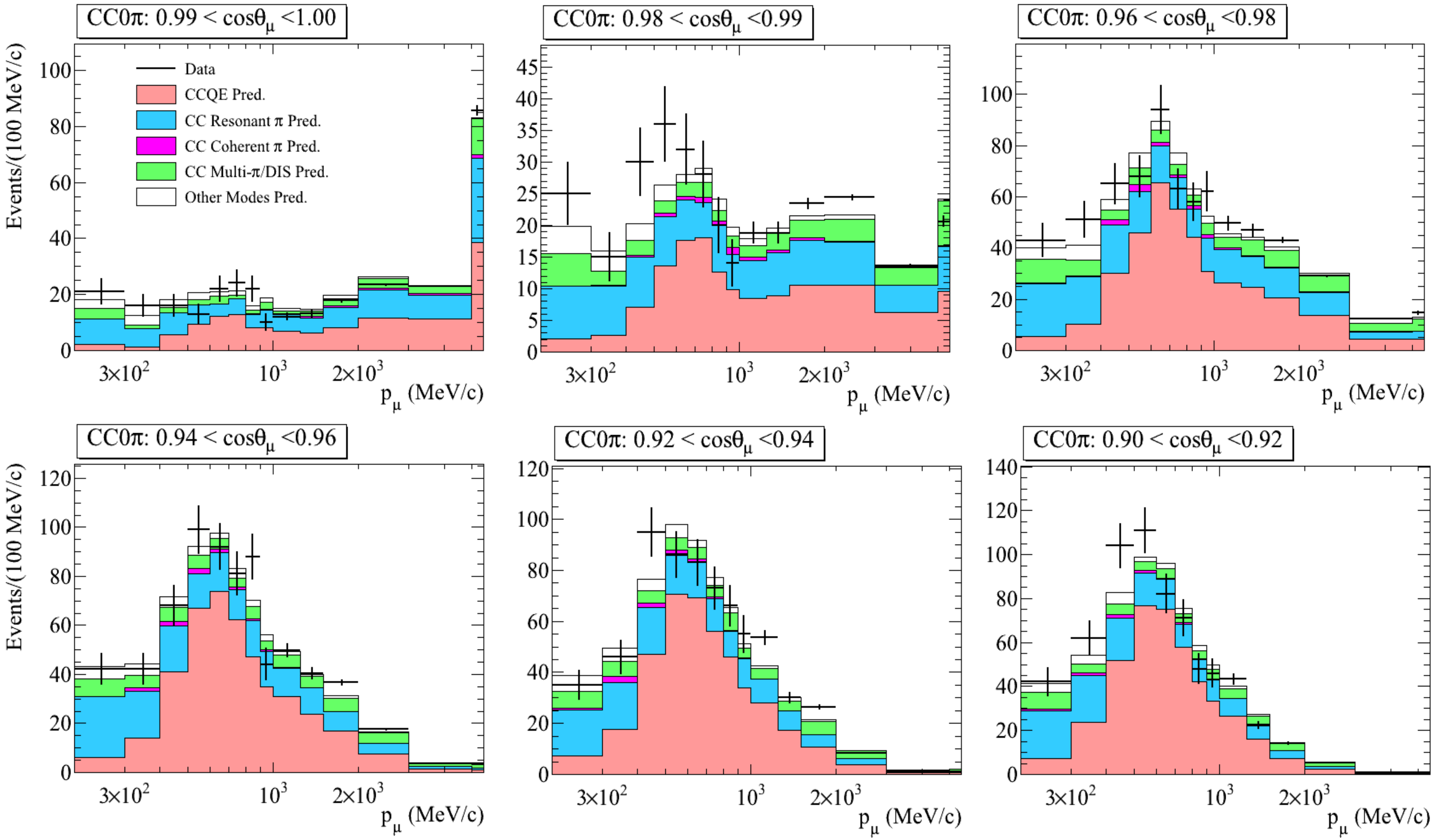


energy dependent errors w/ full correlations among ν types and between detectors(ND280, SK) are taken into account

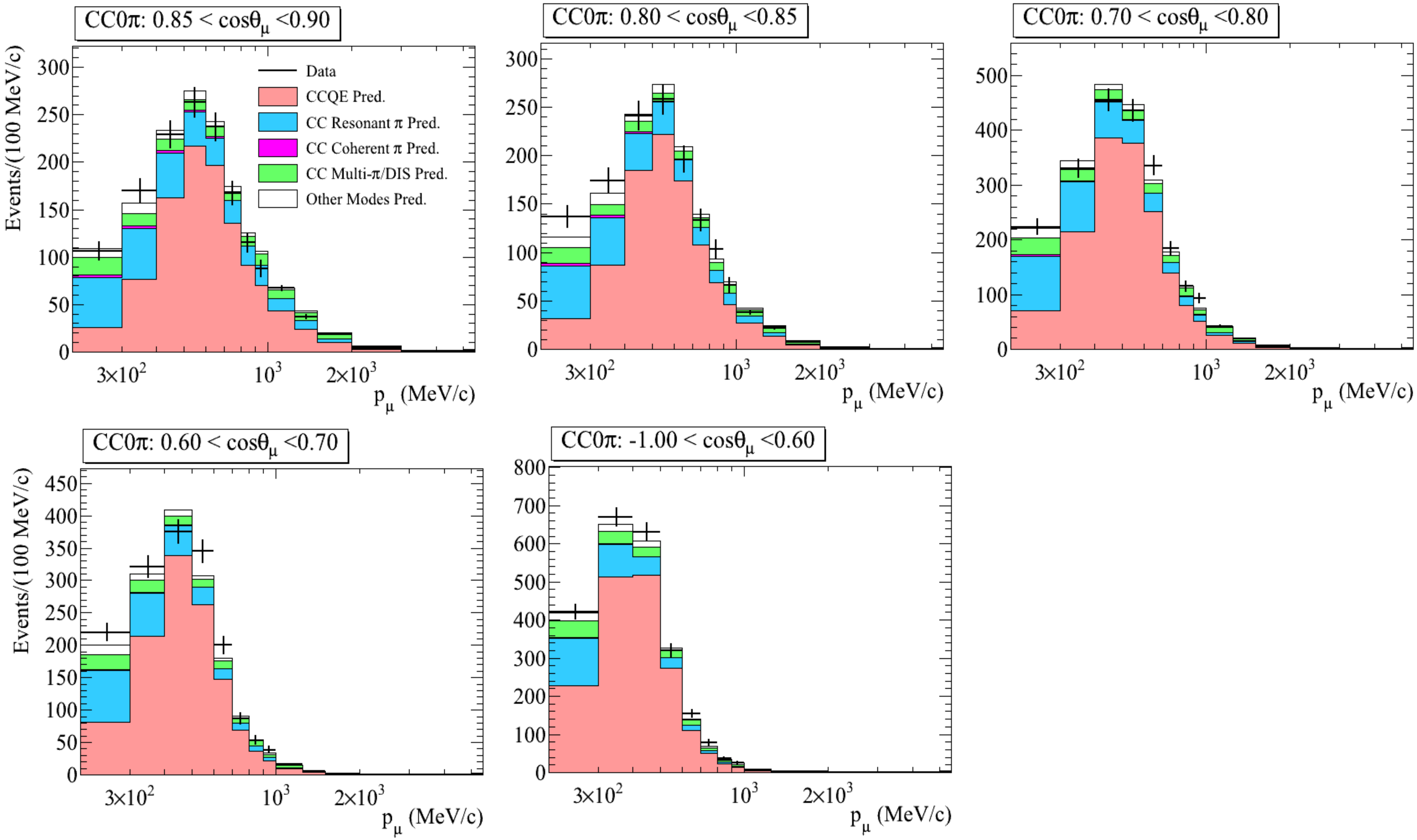


ND280 CONSTRAINT FITS

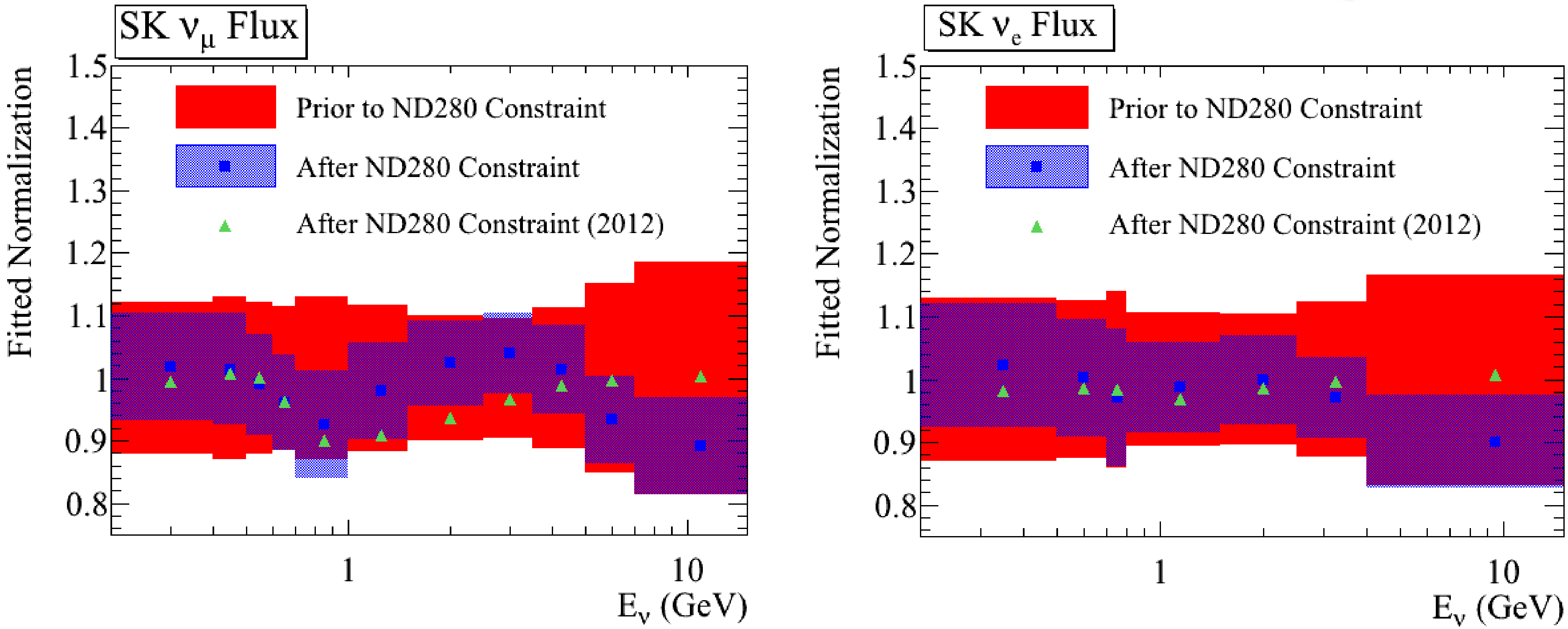
ND CC0π Prediction and Data after ND280 Constraint



ND CC0π Prediction and Data after ND280 Constraint



Flux after ND280 Constraint



Far detector ν_μ and ν_e flux predictions are constrained by the fit, as illustrated by the central values and error bands for normalization vs. neutrino energy, before and after ND280 constraint.

(Central values are changed from 2012 results: due to finer bins and new ND280 selection)

Cross-Section Parameters after ND280 Constraint

Parameter	Prior to ND280 Constraint	After ND280 Constraint (Runs 1-4)	After ND280 Constraint (2012 analysis, Runs 1-3)
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072	1.269 ± 0.194
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063	1.223 ± 0.127
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076	0.951 ± 0.086
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16	1.37 ± 0.20
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25	1.15 ± 0.27

*For E_ν<1.5 GeV **For E_ν<2.5 GeV

Significant changes to M_A^{RES} and CC1π normalization parameters and reduction in uncertainties since 2012 analysis due to finer bins and new selection that explicitly identified CC1π^+ events.

ND280 Fit $\Delta\chi^2$

$$\Delta\chi^2 = 2\sum_{i}^{p,\cos\theta\ bins} N_i^{pred}(\vec{b},\vec{x},\vec{d}) - N_i^{data} + N_i^{data}\ln[N_i^{data}/N_i^{pred}(\vec{b},\vec{x},\vec{d})]$$

$$+\sum_{i}^{E_\nu\ bins}\sum_{j}^{E_\nu\ bins}(1-b_i)(V_b^{-1})_{i,j}(1-b_j)+\sum_{i}^{xsec\ pars}\sum_{j}^{xsec\ pars}(x_i^{nom}-x_i)(V_x^{-1})_{i,j}(x_j^{nom}-x_j)$$

$$+\sum_{i}^{p,\cos\theta\ bins}\sum_{j}^{p,\cos\theta\ bins}(d_i^{nom}-d_i)(V_d^{-1})_{i,j}(d_j^{nom}-d_j)$$

b = flux nuisance parameters
x = cross section nuisance parameters
d = detector/reconstruction model nuisance parameters
V_b, V_x, V_d = covariance matrices (pre-fit uncertainties)

$$N_i^{pred}(\vec{b},\vec{x},\vec{d}) = d_i\sum_{j=1}^{MC\ Events} b_j x_j^{norm} w_j^x(\vec{x})$$

Pre-calculated weight function for cross section parameters with non linear response

Results from Fit to ND280 Data

Selection	Number of Events (Data)	Number of Events (MC before ND280 constraint)	Number of Events (MC after ND280 constraint)
CC0π	16912	20016	16803
CC1π	3936	5059	3970
CC Other	4062	4602	4006
CC Inclusive	24910	29678	24779

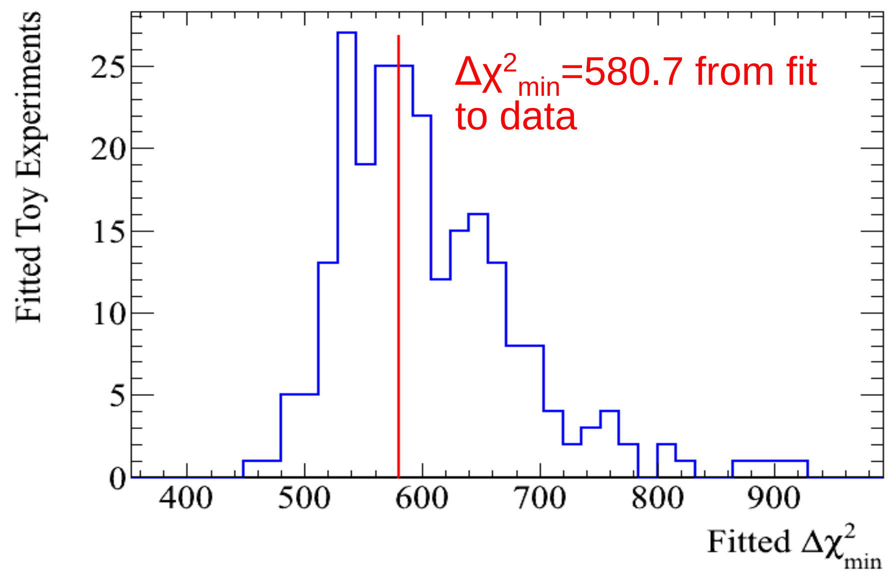
Test the data and constrained MC agreement with toy experiments:

Generated variations of models within prior uncertainties

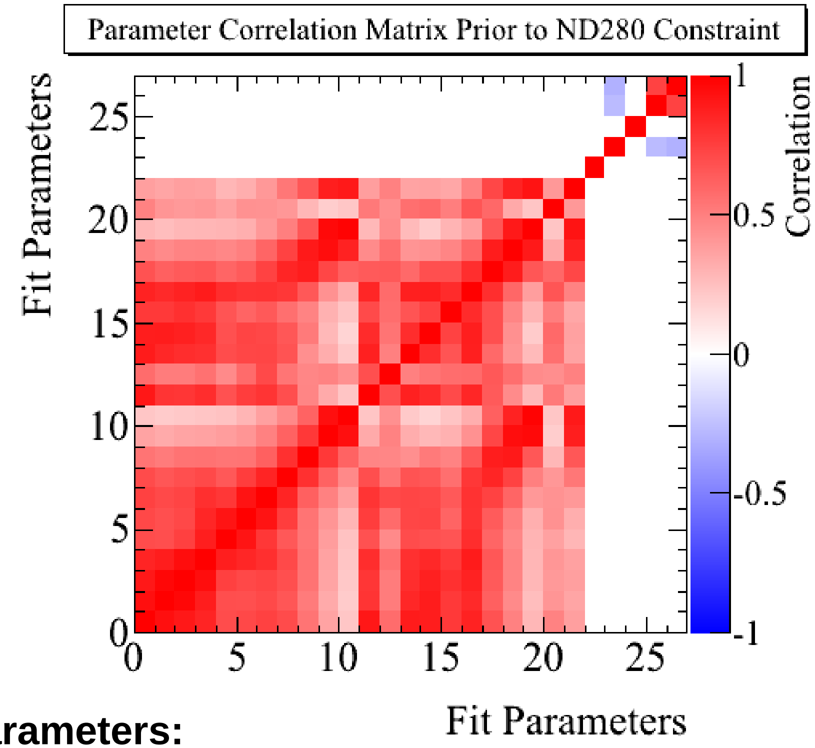
Fit toy data in same manner as data

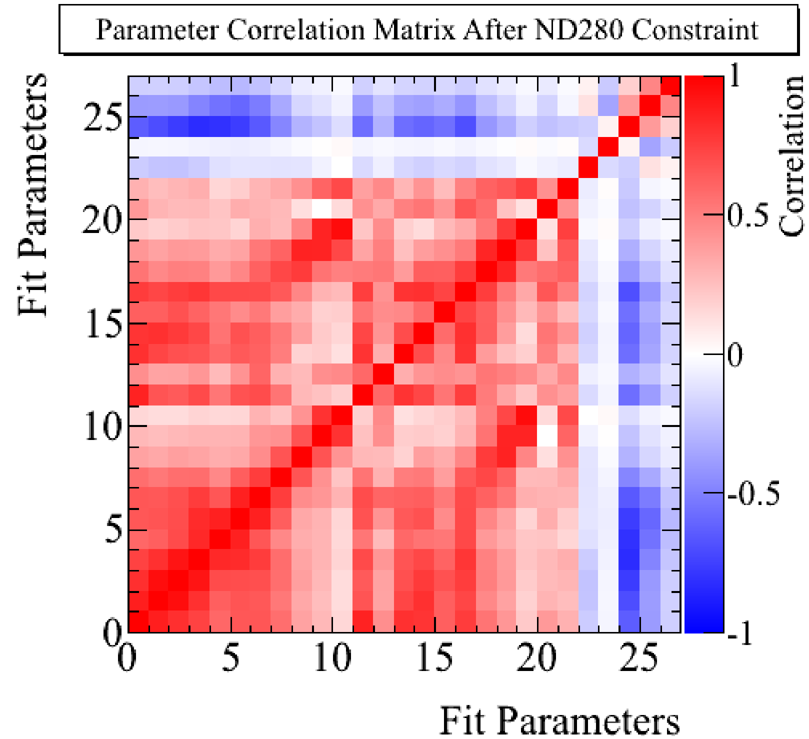
Record $\Delta\chi^2$ at minimum for each toy fit

$\Delta\chi^2_{min}$=580.7 for data has p-value of 0.57



Parameter Correlations





Parameters:

0-10: SK ν_μ flux

11-12: SK $\bar{\nu}_\mu$ flux

13-19: SK ν_e flux

20-21: SK $\bar{\nu}_e$ flux

22: M_A^{QE}

23: M_A^{RES}

24: CCQE Norm.

25: CC1π Norm.

26: NC1π^0 Norm.

The constraint from the measured event rates causes anti-correlations between flux and cross section nuisance parameters

SK Uncertainty Reduction

Reduction of uncertainty on the SK prediction from constrained flux and cross section nuisance parameters is due to increased statistics and improved SK and ND280 analysis techniques

ND280 Analysis	ND280 Data	SK Selection	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
No Constraint	--	Old	22.6%	18.3%
No Constraint	--	New	26.9%	22.2%
2012 method*	Runs 1-2	Old	5.7%	8.7%
2012 method**	Runs 1-3	Old	5.0%	8.5%
2012 method	Runs 1-3	New	4.9%	6.5%
2012 method***	Runs 1-3	New	4.7%	6.1%
2013 method	Runs 1-3	New	3.5%	5.2%
2013 method	Runs 1-4	New	3.0%	4.9%

Factor 2.4 more ND280 POT

Improved SK π^0 rejection

New ND280 reconstruction, selection, binning

Factor 2.2 more ND280 POT

*Results presented at Neutrino 2012 conference
**Published results, arXiv:1304.0841v2
***Update to NEUT tuning with MiniBooNE data

SUPER-K DETECTOR SYSTEMATIC UNCERTAINTIES

SK errors with atmospheric-νe

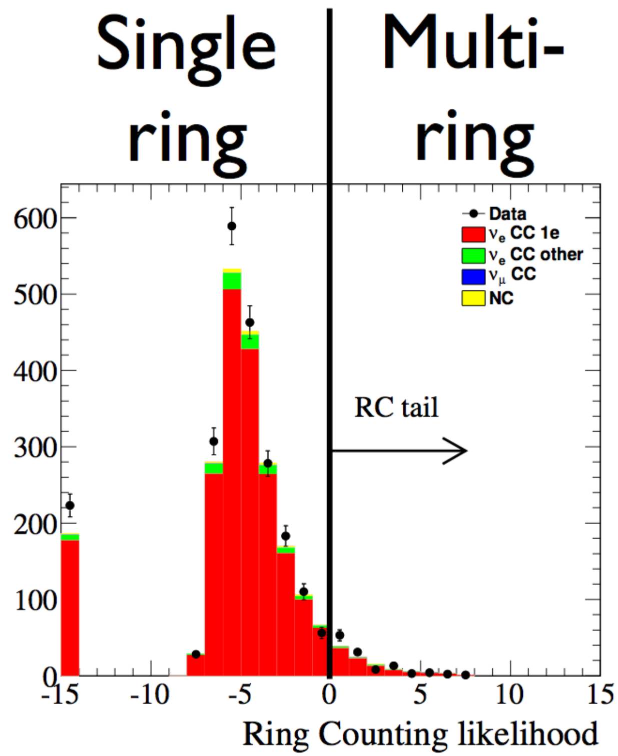
- Evaluate the errors on 'νe selection efficiencies' using SK atmospheric neutrino samples
  - Errors on ring counting (RC), particle identification (PID), and $\pi 0$ rejection
  - (cf. νe candidates: 1-ring & e-like & no $\pi 0$-like)

- Use SK atmospheric neutrino data of 1417.4 days live-time for the 2013 analysis

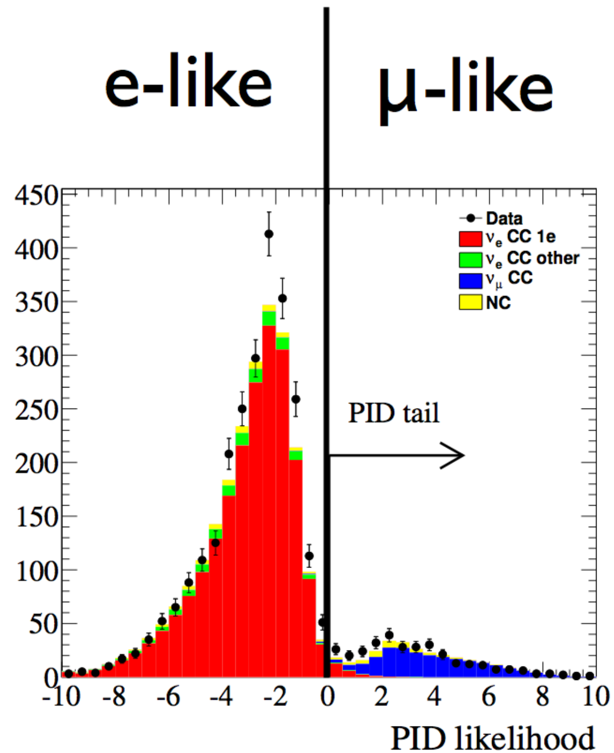
Control Samples

- νe candidate sample ("core" sample) + rejected samples (three "tail" samples)
  - Selections: ring counting, PID, and π0 rejection
  - (cf. νe candidates: 1-ring & e-like & none π0-like)

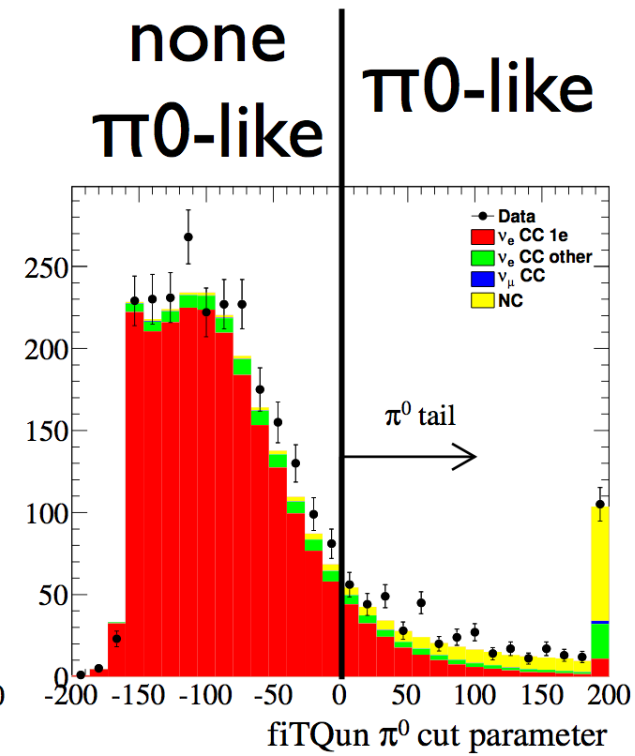
Ring Counting



PID

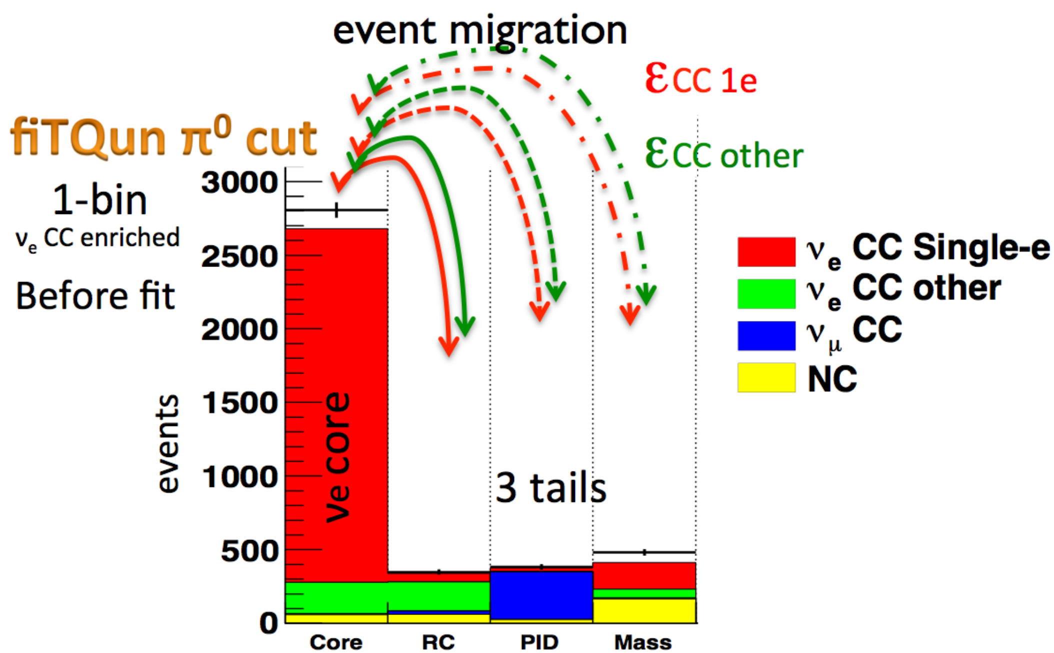


π0 rejection



Atmospheric ν fit

- Evaluate errors on 'νe selection efficiencies' by fit the MC predictions to data by introducing the efficiency parameters ε, that describes event migration between 'core' and 'tail' samples

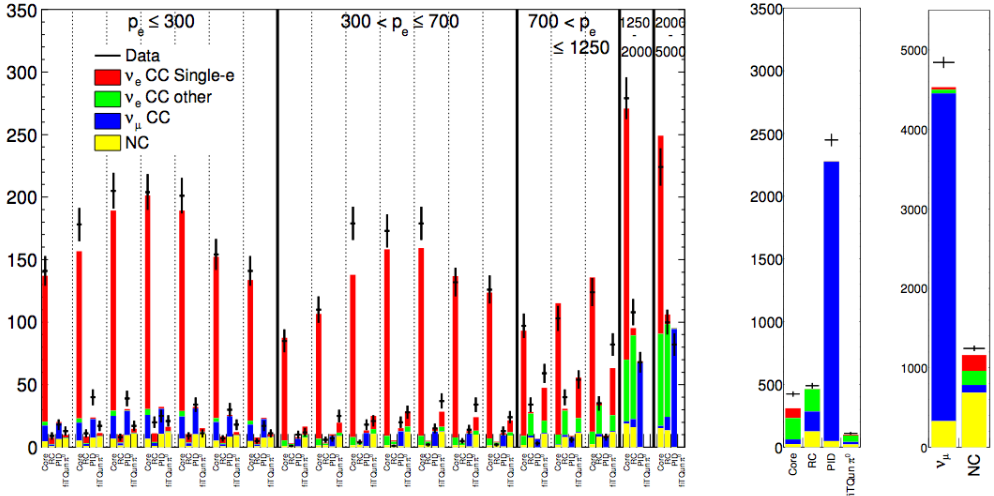


- Evaluate the errors in bins of momentum (p) and scattered angle (θ)
  - p bins: 100, 300, 700, 1250, 2000, 5000 MeV/c
  - θ bins: 0, 40, 60, 80, 100, 120, 140, 180 deg.

atm-ν fit results

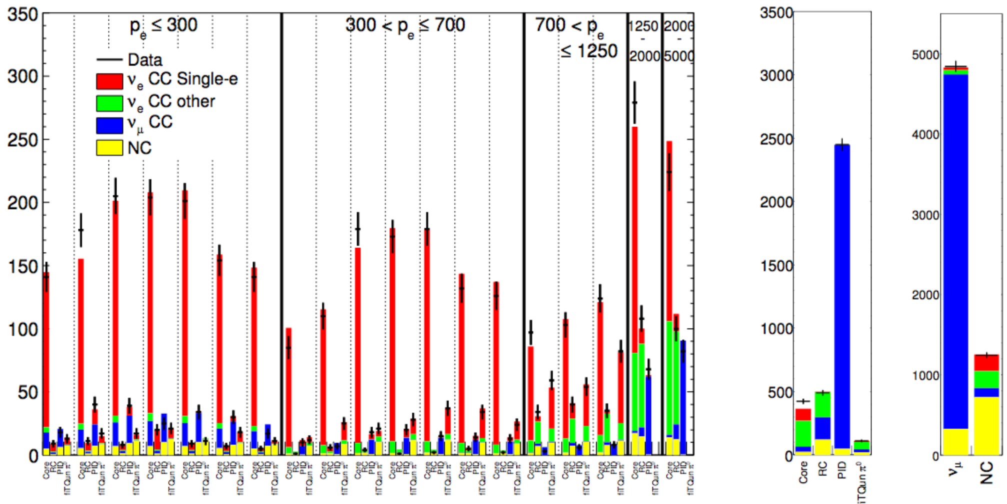
Number of events in p-θ bins and control samples.

Before fit



(a) Before atm-ν fit (Original MC) ($\chi^2 = 336.8$)

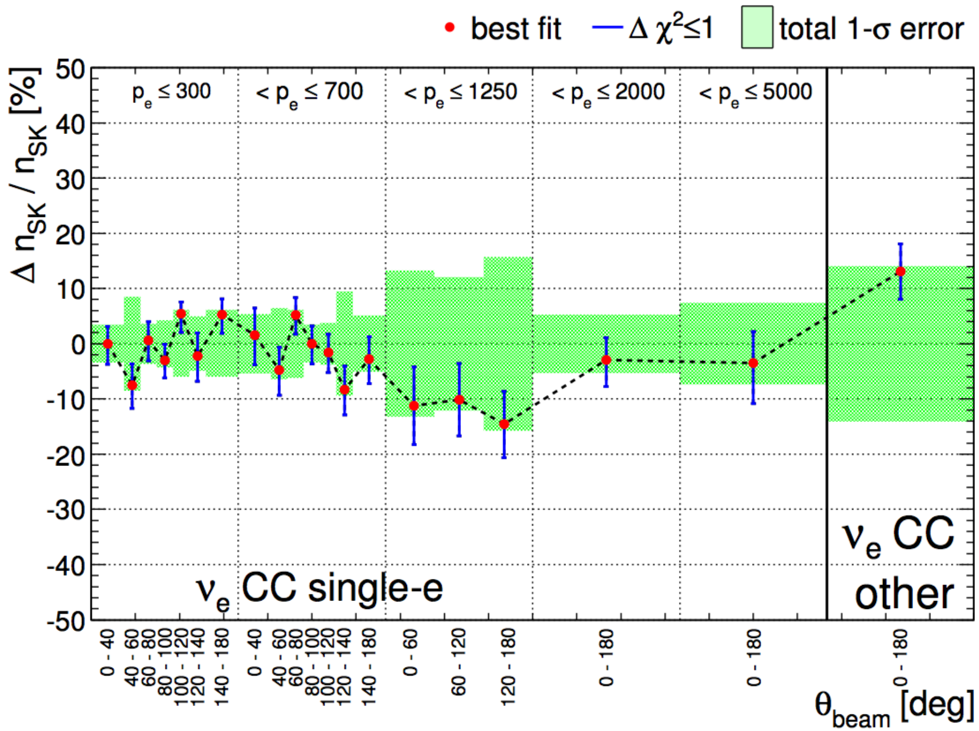
Best fit



(b) Best fit (Minimized all parameters) ($\chi^2 = 165.4$) / ($d.o.f. = 186\text{bins} - 58 = 128$)

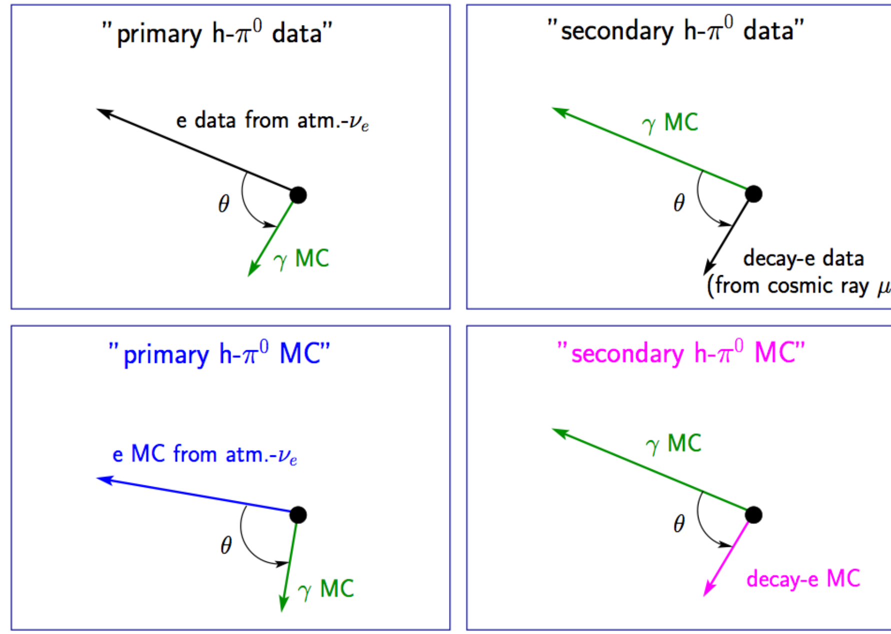
SK error w/ atm-ν fit

- Errors on number of νe candidates (n_{SK}) in 19 p-θ bins for 'νe CC single-electron' events and 1 bin for 'νe CC other' events
  - Correlated error (red point): difference from the 'best fit'
  - Uncorrelated error (blue bar): fit error (stat. error)



“Hybrid-π0” samples

- “Hybrid-π0” samples
  - Electron track from atm-ν data is combined with γ from MC following π0 decay kinematics



- Control samples:
  - Primary: electron from atm-ν is used for the higher energy “γ”, and the lower energy γ from MC
  - Secondary: electron of atm-νe (and decay-e from cosmic-ray μ) is the lower energy “γ”, and higher energy γ from MC

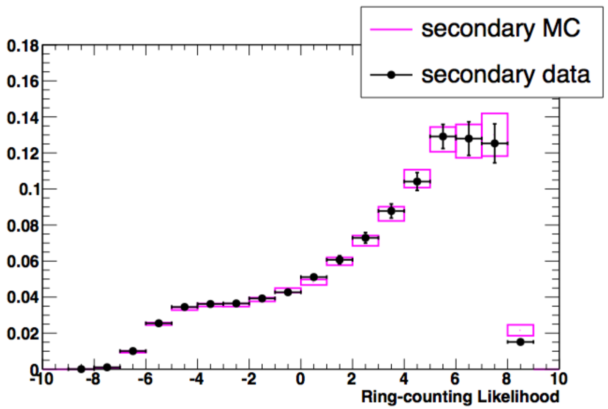
Control samples

- Three type of control samples:
  - "NC hybrid-$\pi 0$" sample
  - "NC hybrid-$\pi 0$ + other" sample
  - "$\nu\mu$ CC hybrid-$\pi 0$ + other" sample
  - where "other" includes charged pions, and protons (and their combinations)
- All samples have 'primary' and 'secondary' samples

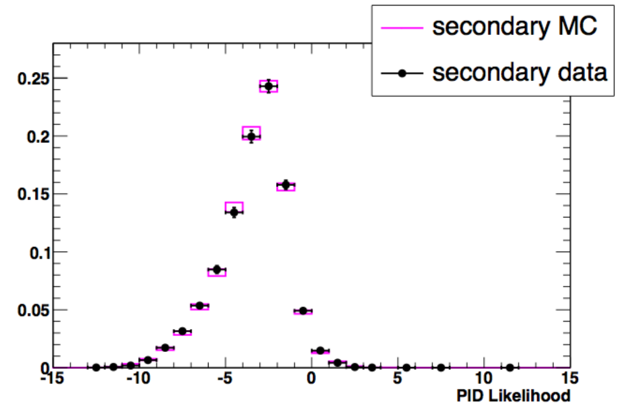
- The errors are evaluated in p-θ bins (the same definition as atm-ν fit)

Basic distributions

Ring Counting

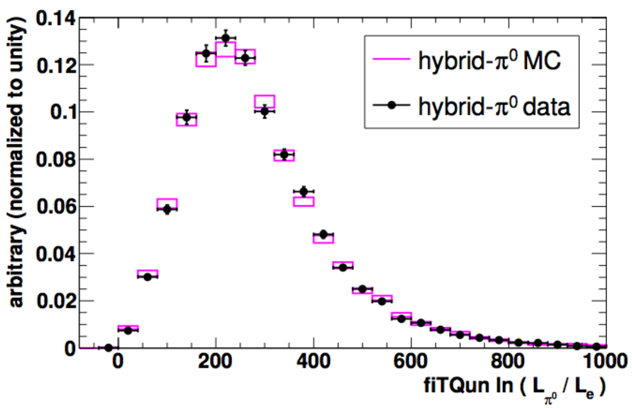


PID

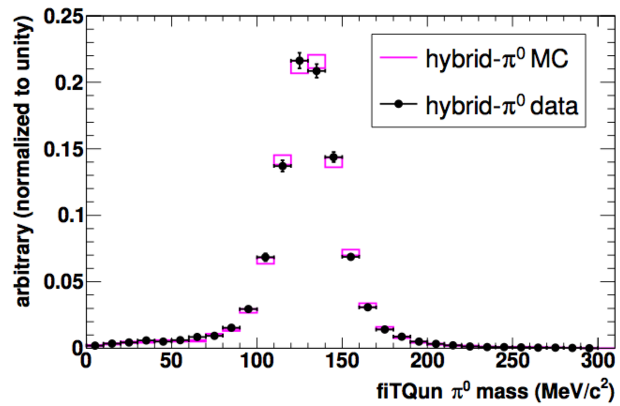


π0 rejection

π0/e likelihood ratio



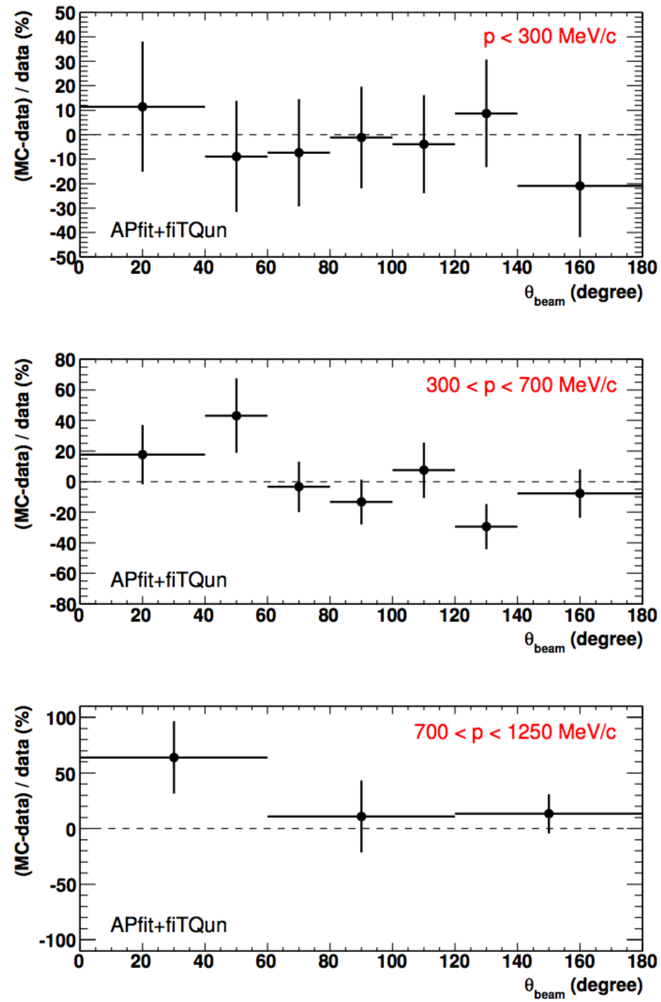
π0 mass



SK error w/ hybrid-π0

Correlated error:(MC-Data)/Data

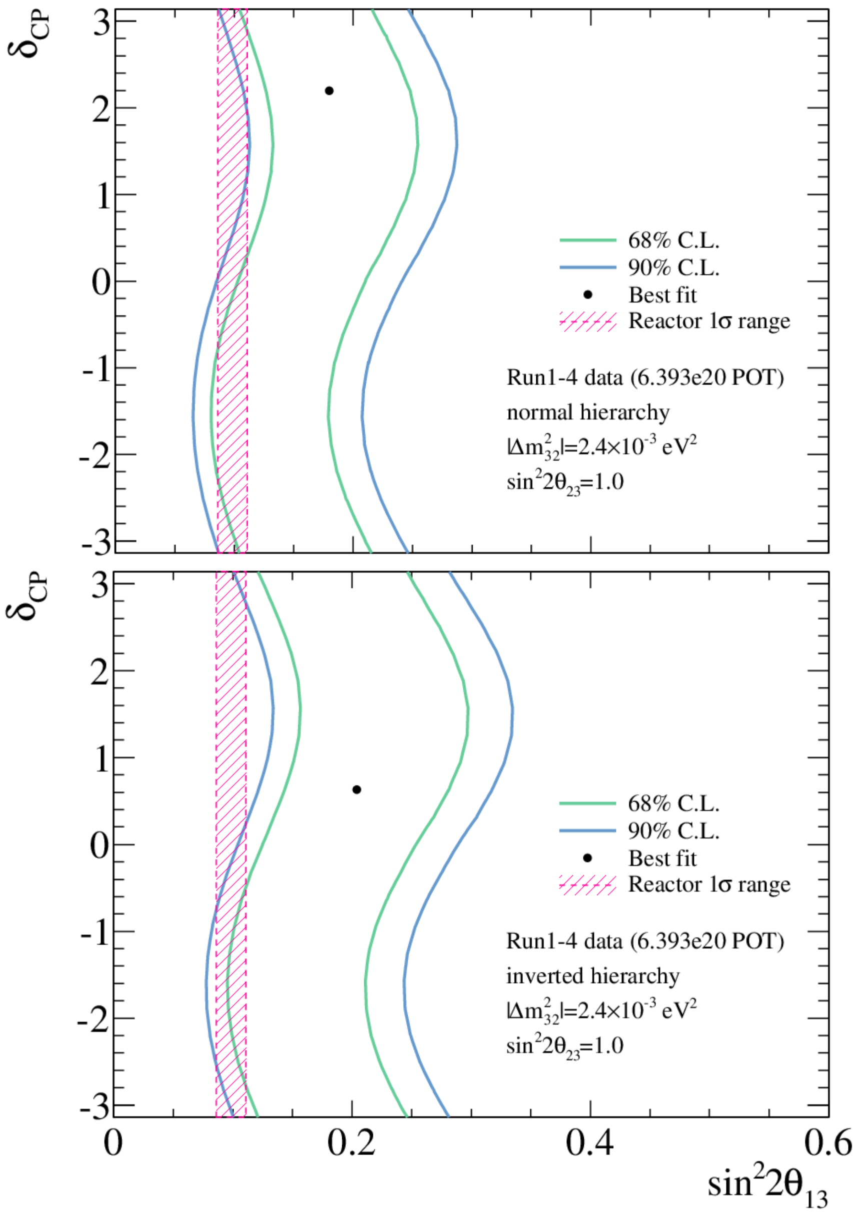
Uncorrelated error: Statistical uncertainties



MUON NEUTRINO DISAPPEARANCE ANALYSIS

ELECTRON NEUTRINO APPEARANCE ANALYSIS

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

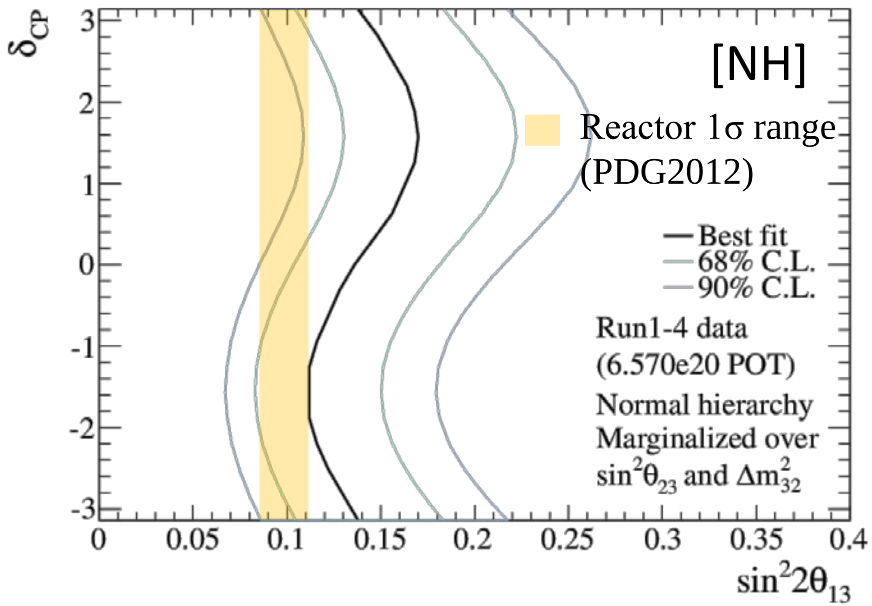


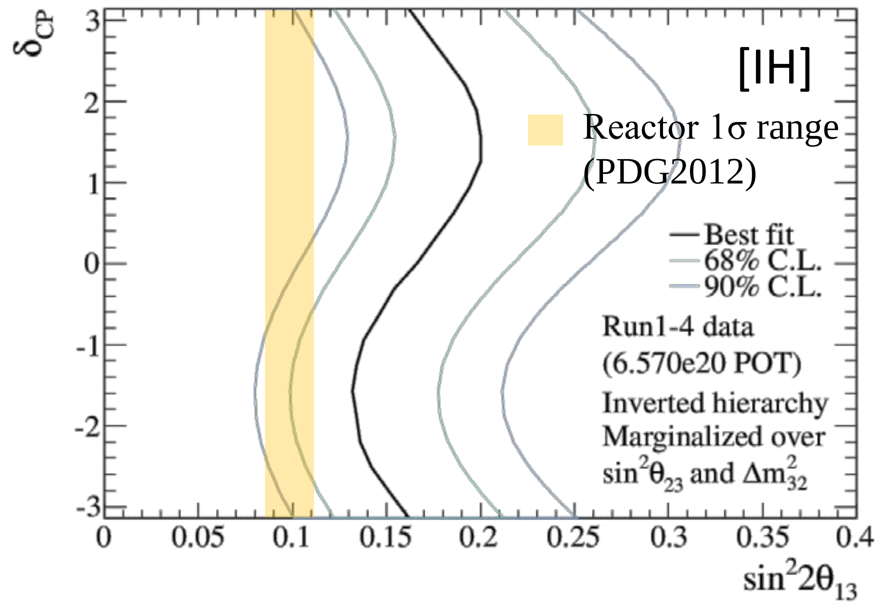
In these plots, the contours are calculated in 2D space.

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

Marginalizing over Disappearance Parameters

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





[NH] Normal hierarchy,
[IH] Inverted hierarchy

Note

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

Systematic errors for N_{exp}

Black: 2013
Blue: 2012

(unit: %)

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit		$\sin^2 2\theta_{13} = 0$ w/ ND280 fit		$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit		$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit	
Beam only	10.6	10.8	7.3	7.5	11.6	11.9	7.5	8.1
M_A^{QE}	15.6	9.5	2.4	4.0	21.5	16.3	3.2	6.7
M_A^{RES}	7.2	4.5	2.1	3.9	3.3	2.0	0.9	1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1	4.9	4.8	3.8	9.3	7.9	6.3	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1π^0 norm.	2.7	7.9	1.9	7.3	0.6	2.3	0.4	2.2
CC other shape	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Spectral Function	4.7	3.3	4.8	3.3	6.0	5.7	6.0	5.7
p_F	0.1	0.3	0.1	0.3	0.1	0.0	0.1	0.0
CC coh. norm.	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.2
NC coh. norm.	1.1	2.1	1.1	2.0	0.3	0.6	0.2	0.6
NC other norm.	2.3	2.6	2.2	2.6	0.5	0.8	0.5	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4	1.8	2.4	1.8	2.9	2.6	2.9	2.6
W shape	1.0	1.9	1.0	1.9	0.2	0.8	0.2	0.8
pion-less Δ decay	3.3	0.5	3.1	0.5	3.7	3.2	3.5	3.2
SK detector eff.	5.7	6.8	5.6	6.8	2.4	3.0	2.4	3.0
FSI	3.0	2.9	3.0	2.9	2.3	2.3	2.3	2.3
PN	3.6		3.5		0.8		0.8	
SK momentum scale	1.5	0.0	1.5	0.0	0.6	0.0	0.6	0.0
Total	24.5	21.0	11.1	13.0	28.1	24.2	8.8	9.9

Systematic errors for N_{exp}

Black: 2013
Blue: 2012

(unit: %)

	$\sin^2 2\theta_{13} = 0$				$\sin^2 2\theta_{13} = 0.1$			
Error source	w/o ND280 fit		w/ ND280 fit		w/o ND280 fit		w/ ND280 fit	
Beam only	10.6	10.8	7.3	7.5	11.6	11.9	7.5	8.1
M_A^{QE}	15.6	9.5	2.4	4.0	21.5	16.3	3.2	6.7
M_A^{RES}	7.2	4.5	2.1	3.9	3.3	2.0	0.9	1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1	4.9	4.8	3.8	9.3	7.9	6.3	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1π^0								
CC oth								
Spectra								
p_F								
CC coh								
NC coh								
NC oth								
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$								
W sha								
pion-less Δ decay	3.3	0.5	3.1	0.5	3.7	3.2	3.5	3.2
SK detector eff.	5.7	6.8	5.6	6.8	2.4	3.0	2.4	3.0
FSI	3.0	2.9	3.0	2.9	2.3	2.3	2.3	2.3
PN	3.6		3.5		0.8		0.8	
SK momentum scale	1.5	0.0	1.5	0.0	0.6	0.0	0.6	0.0
Total	24.5	21.0	11.1	13.0	28.1	24.2	8.8	9.9

- Photo Nuclear effect is added in SK MC.
- SK momentum scale was only implemented as PDF error, but now it is also implemented for N_{exp} error. (It was already implemented for E_{rec}.)
- Enu 1pi shape error is removed from BANFF.
- SK error is improved thanks to additional atm. nu. data set and MC improvements.

Systematic errors for N_{exp}

Black: 2013
Blue: 2012

(unit: %)

	$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$	
Error source	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit
Beam only	10.6 10.8	7.3 7.5	11.6 11.9	7.5 8.1
M_A^{QE}	15.6 9.5	2.4 4.0	21.5 16.3	3.2 6.7
M_A^{RES}	7.2 4.5	2.1 3.9	3.3 2.0	0.9 1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1 4.9	4.8 3.8	9.3 7.9	6.3 6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9 5.1	2.4 3.5	4.2 5.2	2.0 3.5
NC1π^0 norm.	2.7 7.9	1.9 7.3	0.6 2.3	0.4 2.2
CC other shape	0.3 0.2	0.3 0.2	0.1 0.1	0.1 0.1
Spectral Function	4.7 3.3	4.8 3.3	6.0 5.7	6.0 5.7
p_F	0.1 0.3	0.1 0.3	0.1 0.0	0.1 0.0
CC coh. norm.				
NC coh. norm.				
NC other norm.				
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$				
W shape				
pion-less Δ decay				
SK detector eff.	5.7 6.8	5.6 6.8	2.4 3.0	2.4 3.0
FSI	3.0 2.9	3.0 2.9	2.3 2.3	2.3 2.3
PN	3.6	3.5	0.8	0.8
SK momentum scale	1.5 0.0	1.5 0.0	0.6 0.0	0.6 0.0
Total	24.5 21.0	11.1 13.0	28.1 24.2	8.8 9.9

By using fiTQun, the fraction of ν_e signal events (i.e. CCQE events) increased. Therefore, the dominant error (M_A^{QE}) increased and the total error increased.
(This is a fractional error. The absolute error is decreased.)

Systematic errors for N_{exp}

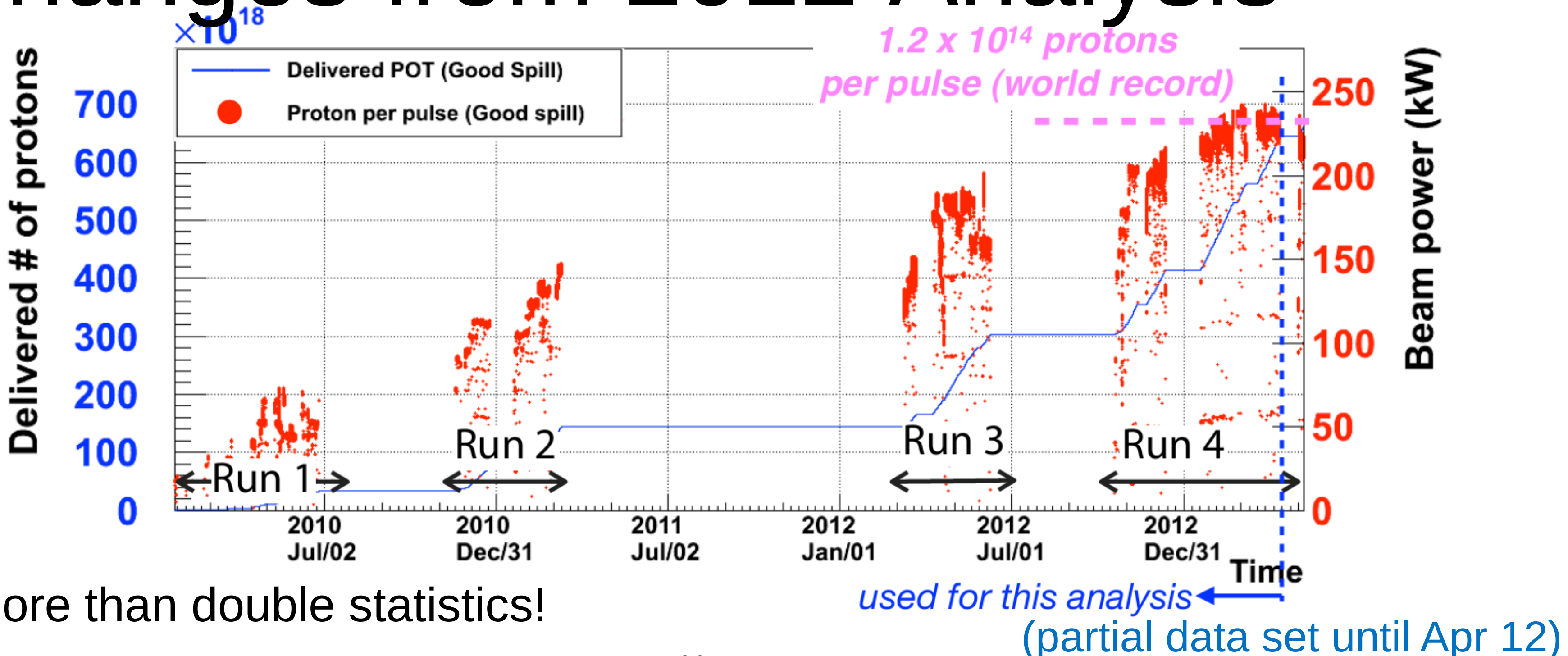
Black: 2013
Blue: 2012

(unit: %)

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit (2013)	(2012)	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit (2013)	(2012)	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit (2013)	(2012)	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit (2013)	(2012)
Beam only	10.6	10.8	7.3	7.5	11.6	11.9	7.5	8.1
M_A^{QE}	15.6	9.5	2.4	4.0	21.5	16.3	3.2	6.7
M_A^{RES}	7.2	4.5	2.1	3.9	3.3	2.0	0.9	1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1	4.9	4.8	3.8	9.3	7.9	6.3	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1π^0 norm.	2.7	7.9	1.9	7.3	0.6	2.3	0.4	2.2
CC other shape	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Spectral Function	4.7	3.3	4.8	3.3	6.0	5.7	6.0	5.7
p_F	0.1	0.3	0.1	0.3	0.1	0.0	0.1	0.0
CC coh. norm.								
NC coh. norm.								
NC other norm.								
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4	1.8	2.4	1.8	2.9	2.0	2.9	2.0
W shape	1.0	1.9	1.0	1.9	0.2	0.8	0.2	0.8
pion-less Δ decay	3.3	0.5	3.1	0.5	3.7	3.2	3.5	3.2
SK detector eff.	5.7	6.8	5.6	6.8	2.4	3.0	2.4	3.0
FSI	3.0	2.9	3.0	2.9	2.3	2.3	2.3	2.3
PN	3.6		3.5		0.8		0.8	
SK momentum scale	1.5	0.0	1.5	0.0	0.6	0.0	0.6	0.0
Total	24.5	21.0	11.1	13.0	28.1	24.2	8.8	9.9

On the other hand, the post-fit error is reduced because the cross section errors are significantly reduced by new BANFF.

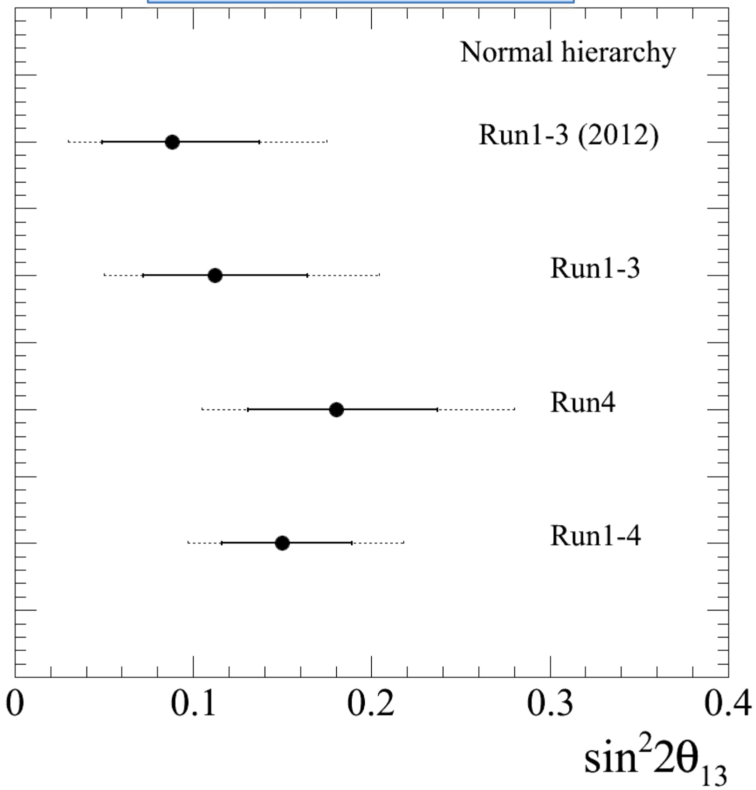
Changes from 2012 Analysis



- 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.

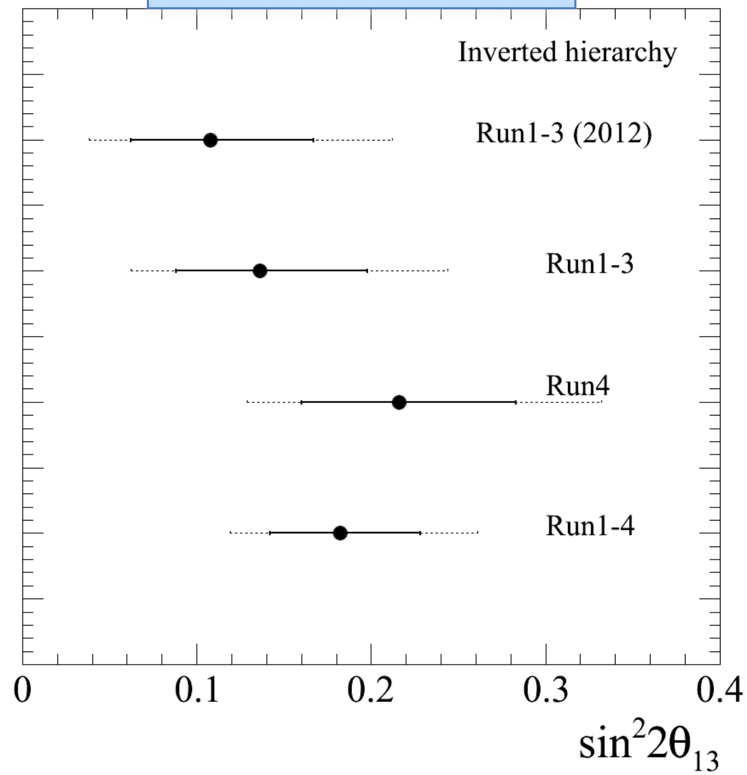
Current and Previous Results

Normal hierarchy



—68% C.L.
- - -90% C.L.

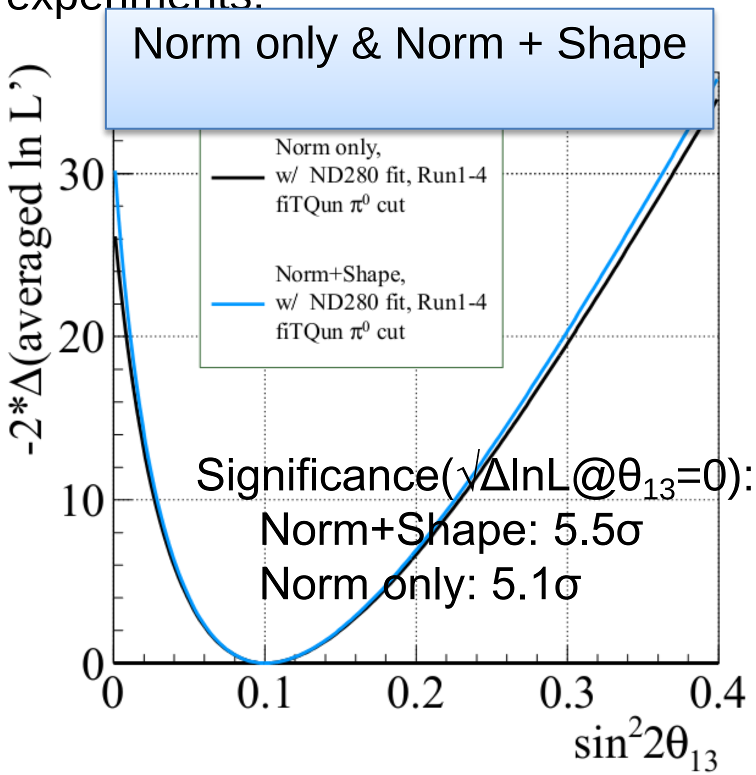
Inverted hierarchy

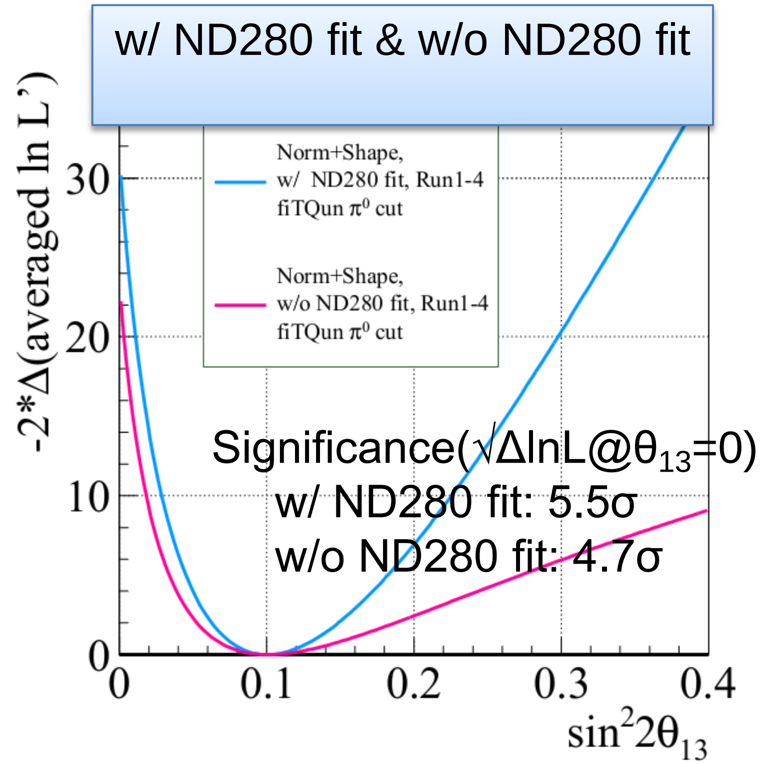


- Run 4 best fit value is higher than the others.
- Run1-3 (2012) looks different from Run1-3, because:
  - N_{pred} decreased by using new Super-K reconstruction, while N_{obs} did not change.
  - N_{pred} decreased with Run 1-4 near detector fit.

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.



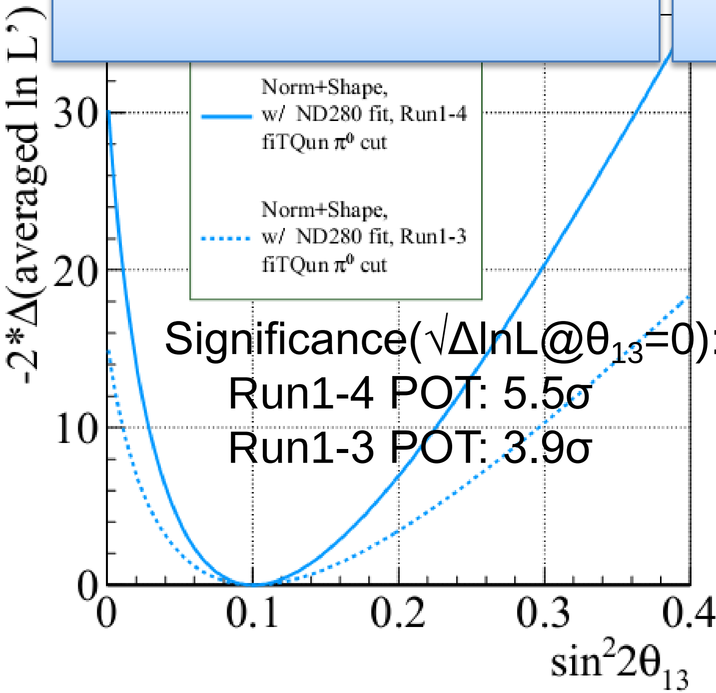


Effect of using shape information is not significant but important.

ND280 fit makes relatively large improvement.

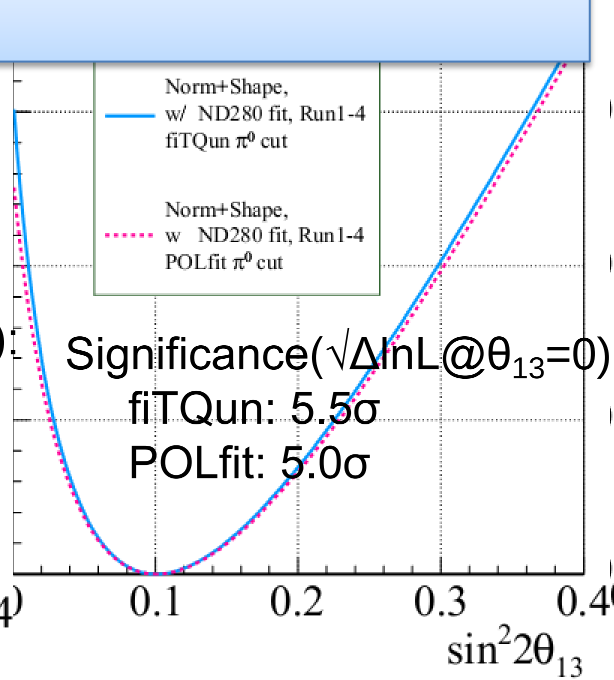
Sensitivity checks

Run1-4 POT & Run1-3 POT



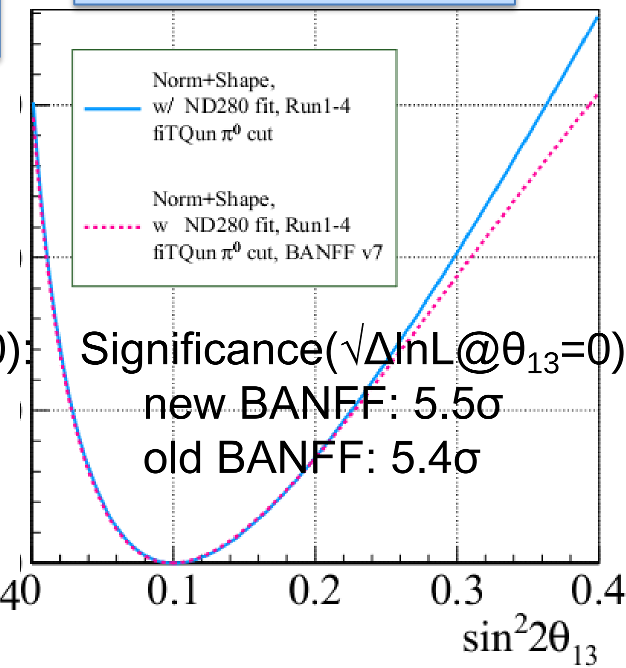
Significance($\sqrt{\Delta \ln L}$@θ_{13}=0):
Run1-4 POT: 5.5σ
Run1-3 POT: 3.9σ

fiTQun π^0 cut & POLfit π^0 cut



Significance($\sqrt{\Delta \ln L}$@θ_{13}=0):
fiTQun: 5.5σ
POLfit: 5.0σ

old & new BANFF



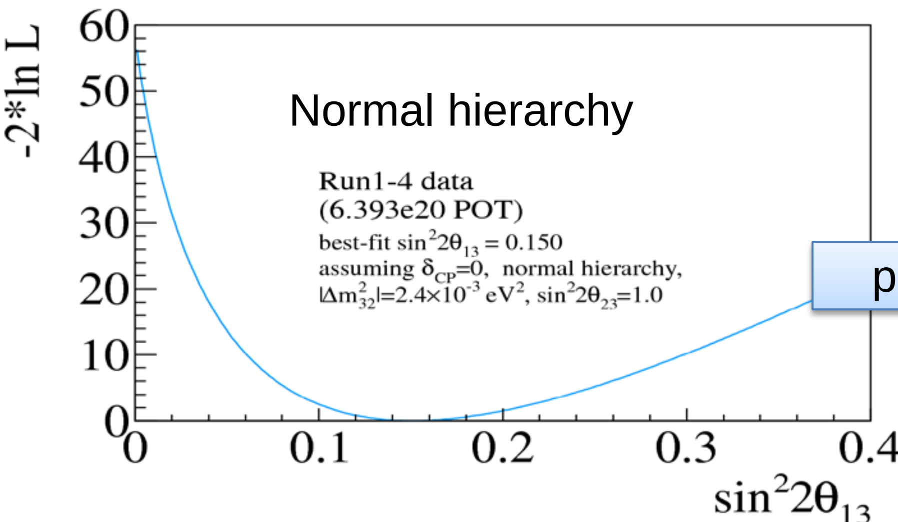
Significance($\sqrt{\Delta \ln L}$@θ_{13}=0)
new BANFF: 5.5σ
old BANFF: 5.4σ

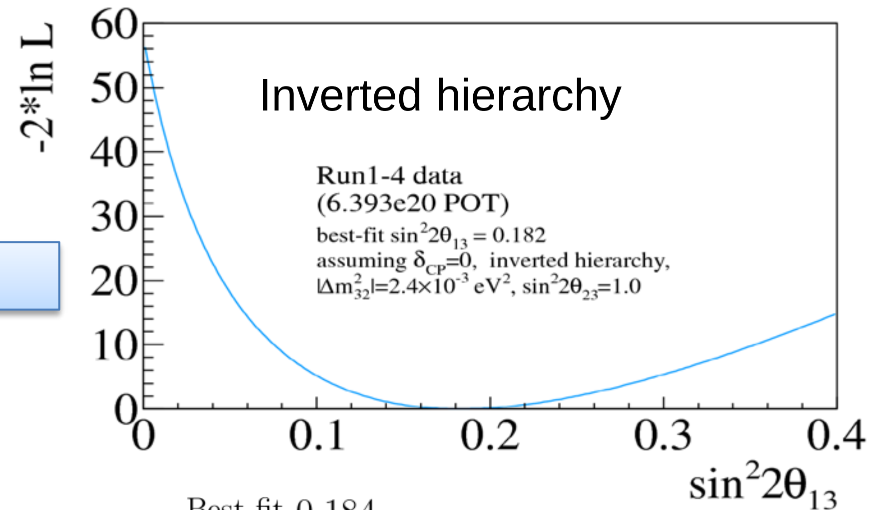
Significance becomes much larger by adding Run4.

Effect of using fiTQun is not significantly large but important.

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

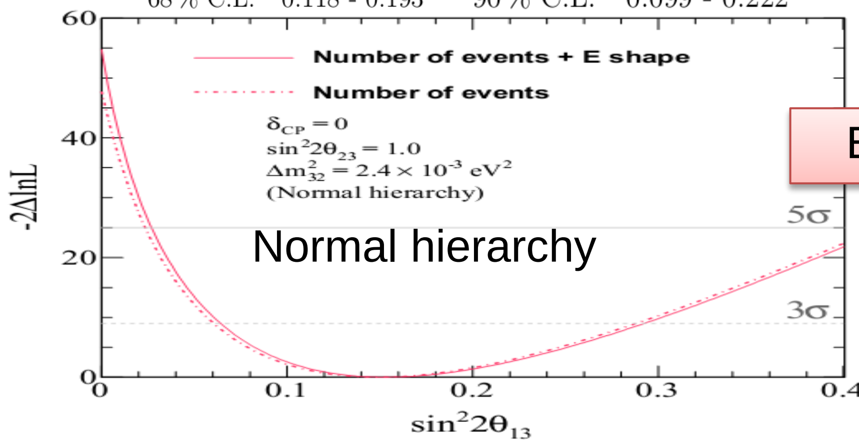




p-θ

Best fit 0.152

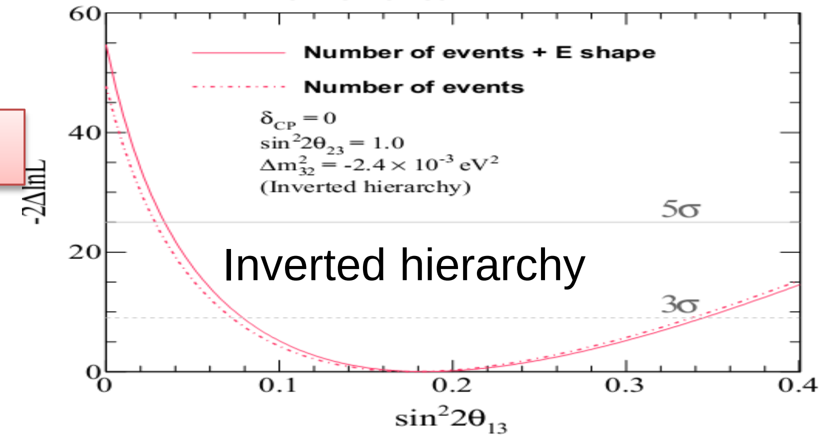
68 % C.L. 0.118 - 0.193 90 % C.L. 0.099 - 0.222



E_{rec}

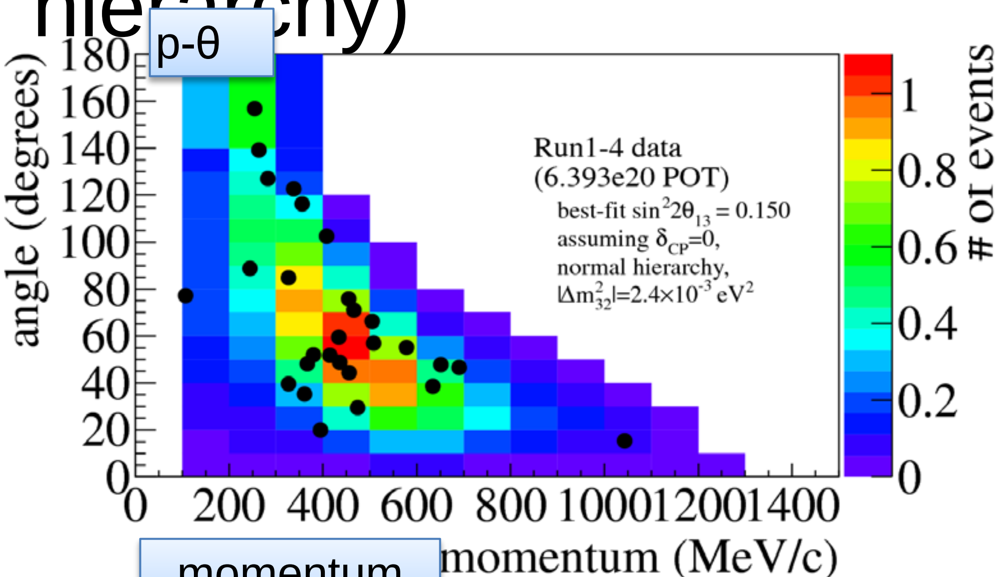
Best fit 0.184

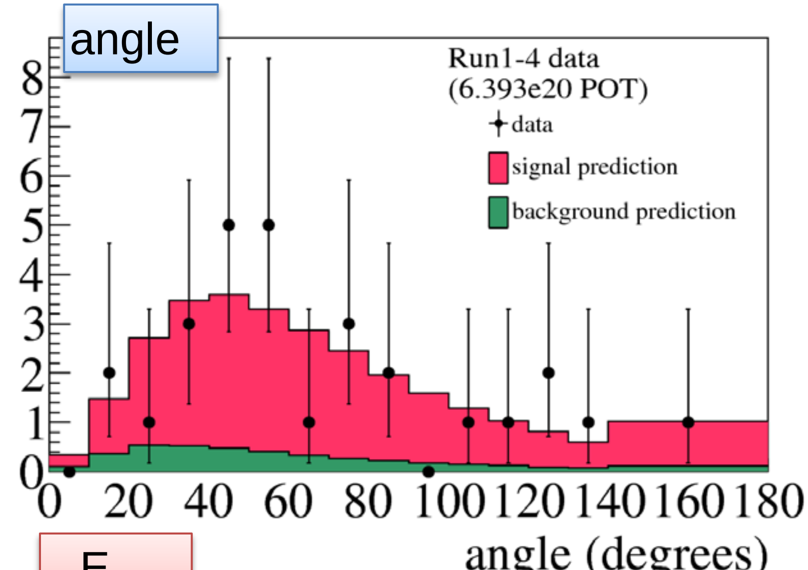
68 % C.L. 0.143 - 0.230 90 % C.L. 0.120 - 0.264

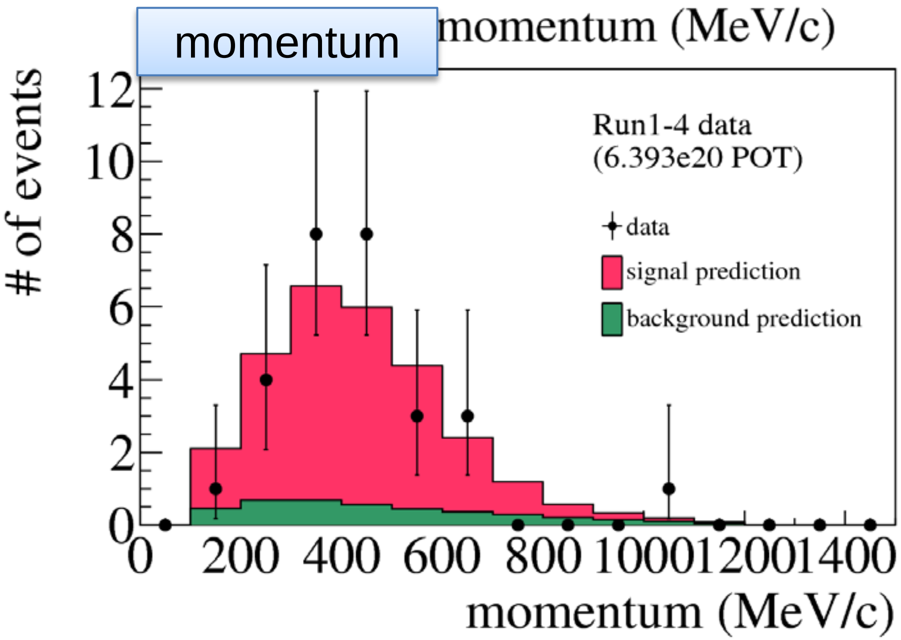


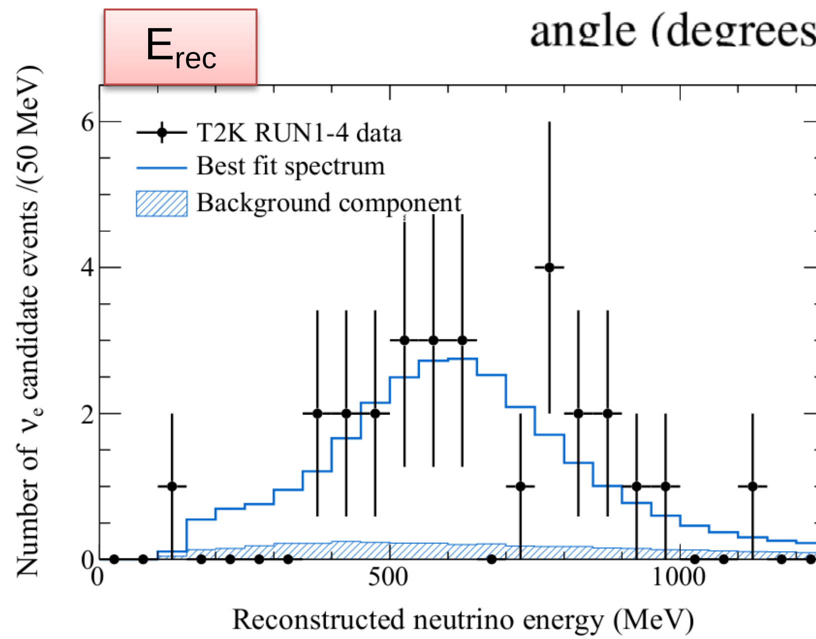
(summary table will be shown later.)

Best fit distributions (Run1-4, normal hierarchy)

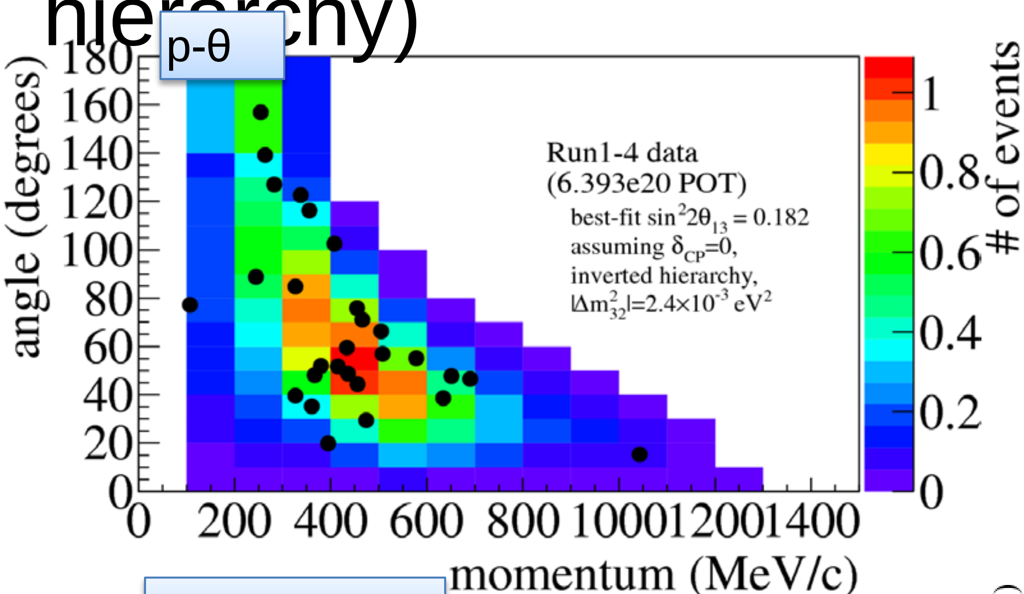


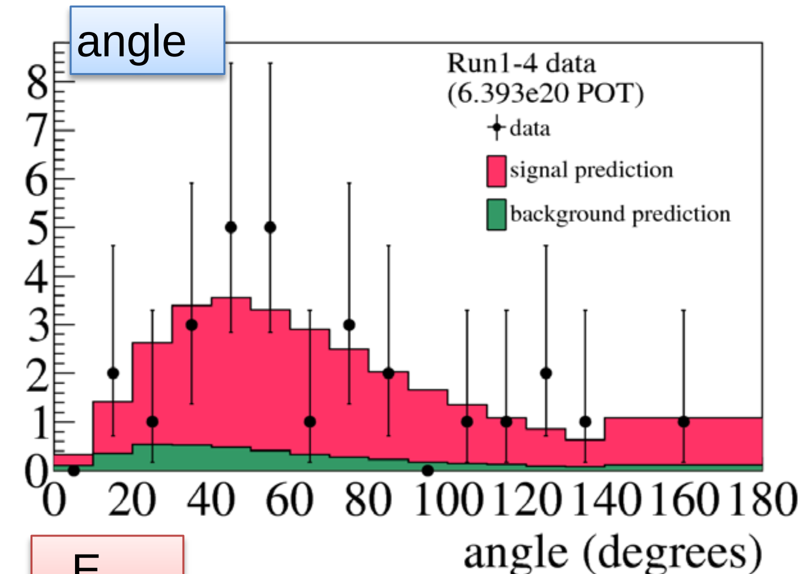


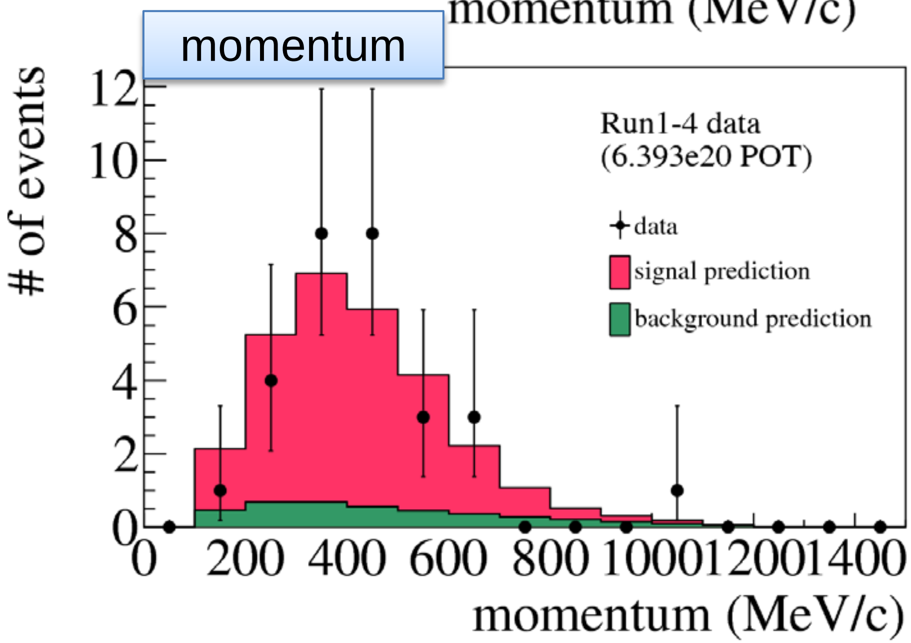


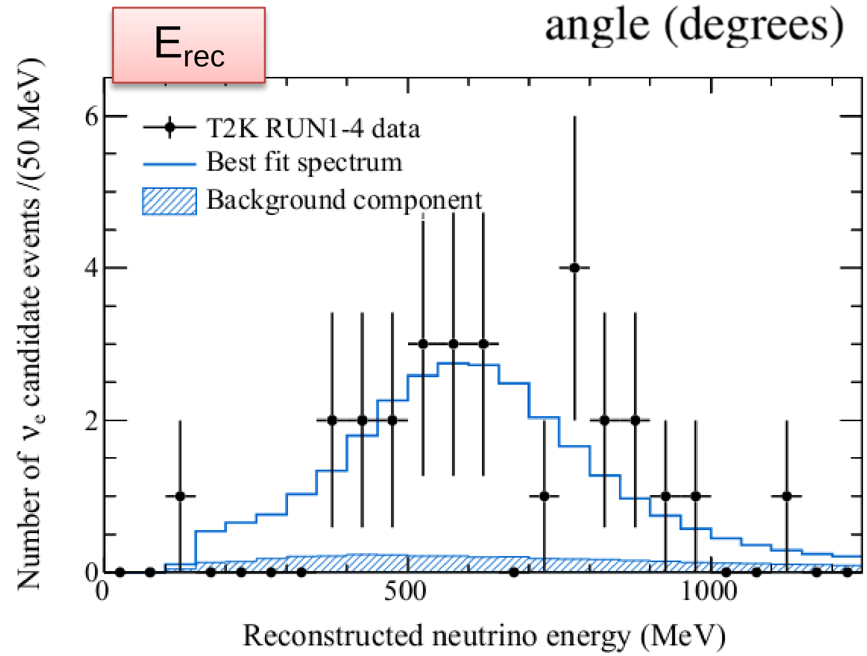


Best fit distributions (Run1-4, inverted hierarchy)









Fit summary table

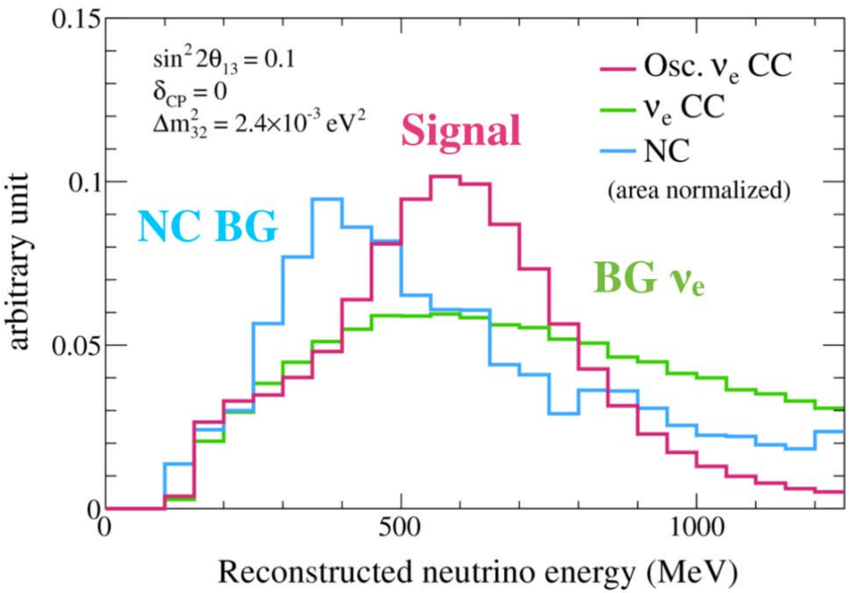
	Run1-4 (p-θ)	Run1-4 (E_{rec})	Run4 only	Run1-3 (2013 analysis)	Run1-3 (2012 analysis)
POT	6.39e20	6.39e20	3.38e20	3.01e20	3.01e20
Observed number of events	28	28	17	11	11
Normal hierarchy Best fit 90% C.L. 68% C.L.	 0.150 0.097 - 0.218 0.116 - 0.189	 0.152 0.099 - 0.222 0.118 - 0.193	 0.180 0.105 - 0.280 0.131 - 0.237	 0.112 0.050 - 0.204 0.072 - 0.164	 0.088 0.030 - 0.175 0.049 - 0.137
Inverted hierarchy 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

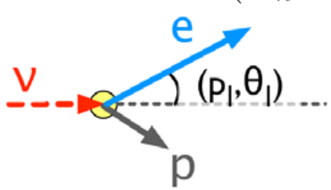
Method 2: Rate + reconstructed E_ν shape (1D)

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

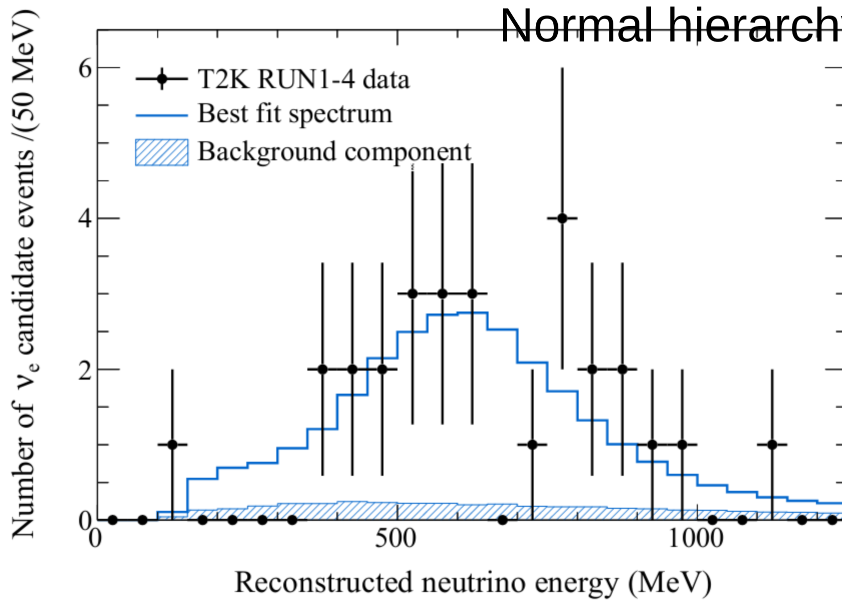
Fit data to the reconstructed energy distribution



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



Fit result



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

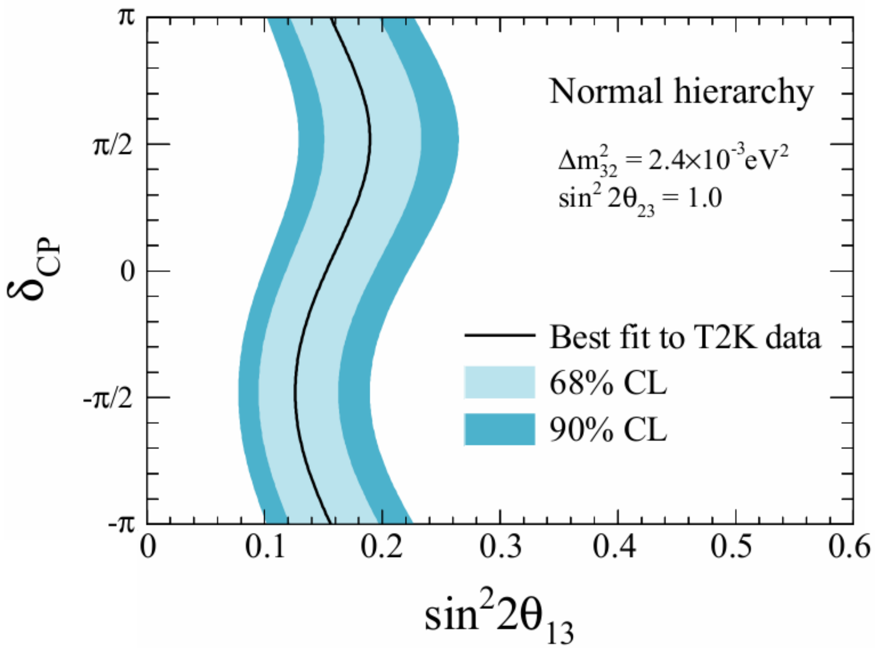
$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034}$$

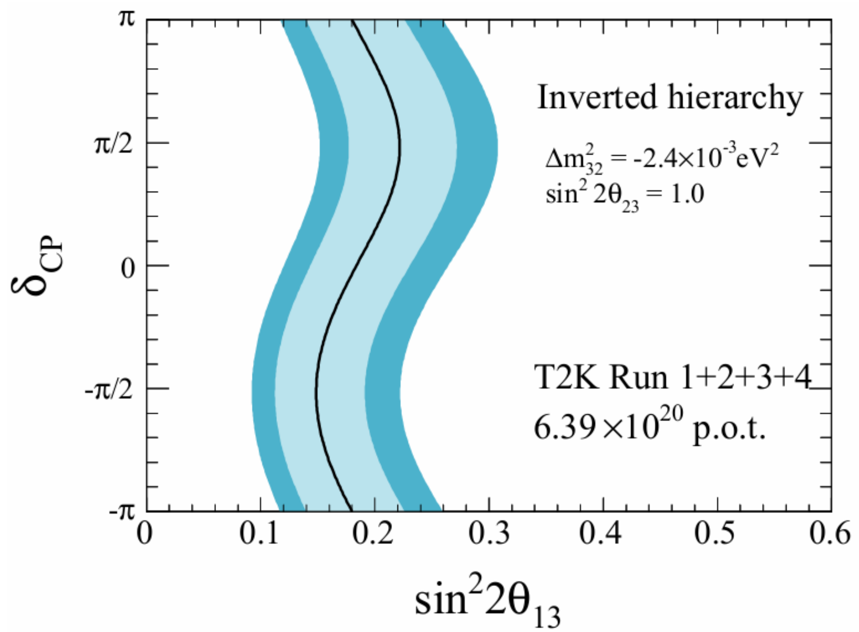
Oscillation analysis method 2

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

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

J-PARC ACCELERATOR UPGRADES

Slides from Koseki-san
at “Snowmass” April meeting

Upgrade plan of linac

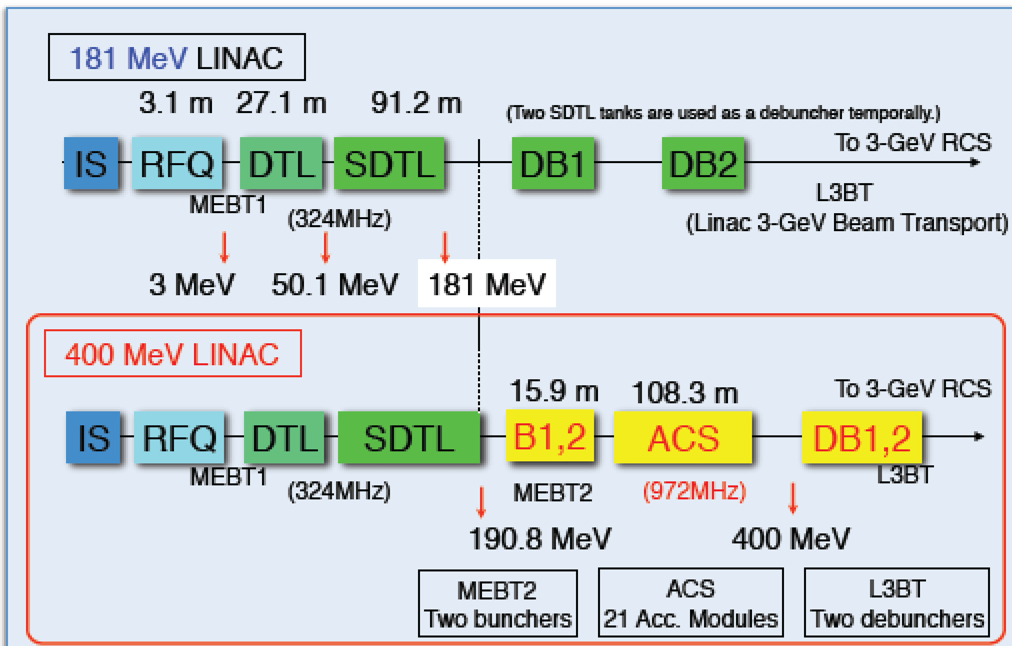
The design specification of the J-PARC facility (e.g. 1MW@RCS, 0.75MW@MR) cannot be realized with the present 181 MeV/30 mA linac.

For beam energy (Small emittance beam for the RCS injection) :

New accelerating structure, ACS(Annular Coupled Structure linac) will be installed to increase the extracted beam energy of the linac from 181 MeV to 400 MeV. Power supplies of RCS injection magnets will also be replaced for adopting 400 MeV injection beam.

For peak beam current :

Front-end part (IS+RFQ) will be replaced for increasing peak current from 30 mA to 50 mA.



T. Koseki, Snowmass Workshop on Frontier Capability, April 2013

Mid-term plan of MR

FX: We adopt the high repetition rate scheme to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.
SX: A part of SUS vacuum chambers will be replaced with Ti chambers to reduce residual radiation dose. After the replacement, 50 kW operation for users will be started. Beam power will be increased toward 100 kW carefully watching the residual activity. Local shields will also be installed if necessary.

JFY	2011	2012	2013	2014	2015	2016	2017
			LI. upgrade				
FX power [kW] SX power : User op. (study) [kW]	150 3 (10)	200 10 (50)	~ 300 <50	400 50 (100)			750 100
Cycle time of main magnet PS **New magnet PS for high rep.**	3.04 s	2.56–2.48 s R&D	2.48–2.40 s		Manufacture installation/test		1.3 s
Present RF system **New high gradient rf system**	Install. #7,8	Install. #9 R&D		Manufacture installation/test			
Ring collimators	Additional shields	Add. shields & collimators (2kW)	Add. shields & collimators (3.5kW)				
Injection system **FX system**	New inj. kicker	Kicker PS improvement, Septum1 manufacture /test LF septum, PS for HF septa manufacture /test					
SX collimator / Local shields	SX collimator				Local sheilds		
Ti ducts and SX devices with Ti chamber		Septum endplate	ESS, Beam ducts				

The new PS requires additional budget of ~ 60 oku-Yen. The budget request will be submitted to the government in 2014-2016.

FUTURE SENSITIVITY

$\nu_\mu \to \nu_e$ Oscillation Probability

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
- $\theta_{12} = 33.6^\circ \pm 1.0^\circ$
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90% C.L.) – is θ_{23} maximal?
- $\theta_{13} = 9.1^\circ \pm 0.6^\circ$ – from reactor

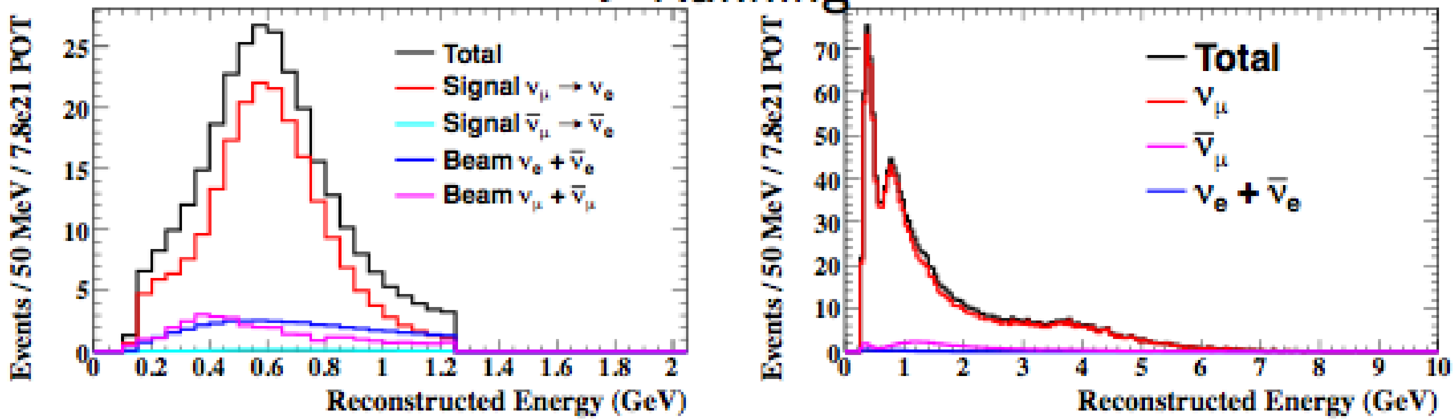
T2K Future Sensitivity Study

- 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 $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, normal MH
- Current T2K systematic errors used
  - ~10% for ν_e, ~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 $\sin^2 2\theta_{13}$ $(= 0.1 \pm 0.005)$

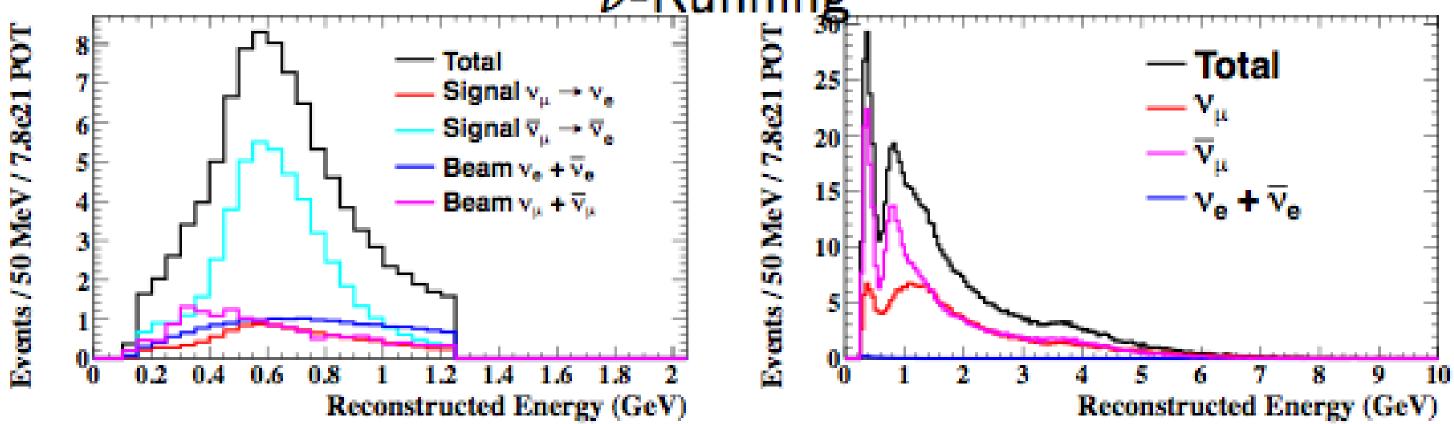
SK Reconstructed Energy Spectra at T2K Full Statistics (7.8×10^{21} POT)

ν_e Appearance | ν_μ Disappearance

ν-Running



$\bar{\nu}$-Running

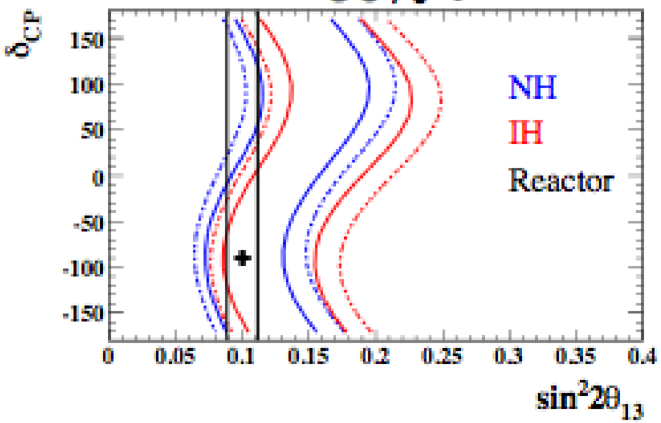


T2K 90% C.L. Regions for True $\delta_{CP} = -90°$, $\sin^2 2\theta_{13} = 0.1$

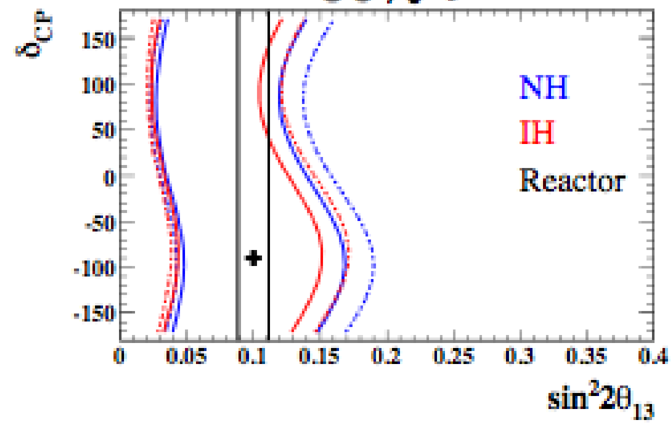
Solid: no sys. err., Dashed: with current sys. err.

True MH is NH; contours drawn for two MH assumptions

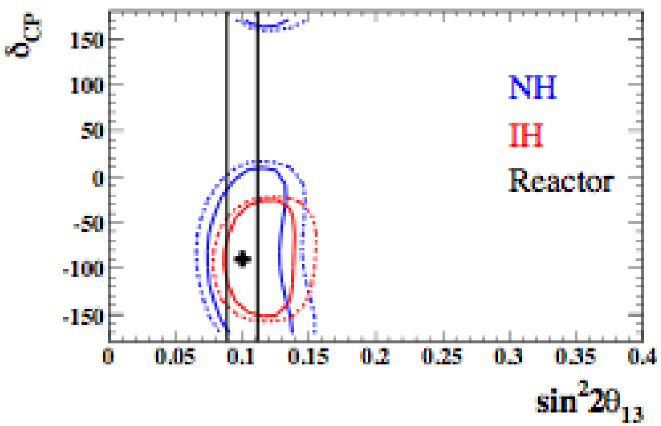
50% ν



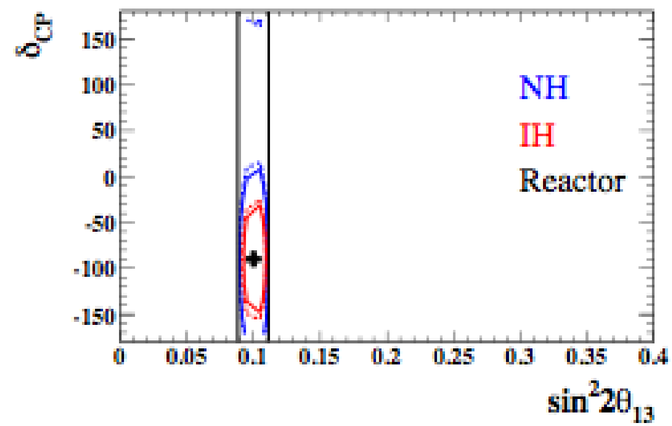
50% $\bar{\nu}$



50% ν + 50% $\bar{\nu}$



With Ultimate Reactor



Ultimate T2K 90% C.L. Regions for True $\delta_{CP} = 0°, \sin^2 2\theta_{13} = 0.1$

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

True MH is NH; contours drawn for two MH assumptions