Neutrino Oscillations in T2K: Recent Results and Future Sensitivities

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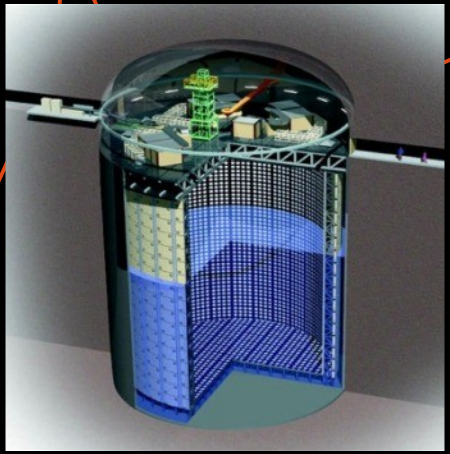
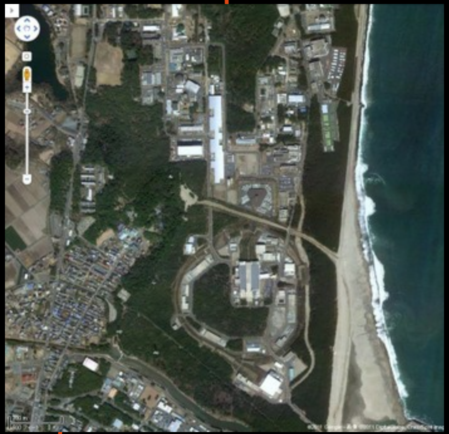




International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

Kavli Institute for Physics and Mathematics of the Universe,
The University of Tokyo
November 11-13, 2013

Outline

- Neutrino Oscillations
- The T2K Experimental Design
- Constraining the T2K Unoscillated Event Rate in Super-Kamiokande (SK)
- The recent $\nu_\mu \rightarrow \nu_\mu$ Measurement
- The recent $\nu_\mu \rightarrow \nu_e$ Measurement
- Future Sensitivities

Questions in Neutrino Physics

- This has been an exciting year in ν physics
- Non-zero θ_{13} opens a lot of doors both theoretically and **experimentally**
  - Indications of non-zero θ_{13} was shown by T2K (2.5σ) and MINOS (89% CL)
  - $\sin^2(2\theta_{13})$ measured by reactor $\bar{\nu}_e$- disappearance experiments
  - Discovery of $\nu_\mu \rightarrow \nu_e$ oscillations by T2K ($\sin^2(2\theta_{13}) \neq 0$ at 7.4σ)
- There are still many questions that need answers
  - What is the Mass Hierarchy (MH)
  - What is δ_{cp}? is $\delta_{cp} \neq 0$?
  - Is θ_{23} maximal?, If not is it above or below 45° (what is the θ_{23} octant)?
  - Combined analyses (T2K + reactor) allow for measurements of $\sin^2(\theta_{23})$ and $\sin(\delta_{cp})$
- Recent T2K results can provide insight into these questions and provide high precision confirmation of previous results
- With full statistics T2K has the capability of measuring an indication of CP violation ($\delta_{cp} \neq 0$), and determining the θ_{23} octant
- Combined fits with NOνA may help determine the MH and increase sensitivity to CP violations and the θ_{23} octant

Neutrino Oscillation Formalism

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

For the T2K baseline (295km) and peak energy (0.6 GeV) the ν_e- appearance oscillation probability, as a function of δ_{cp} is (NH):

$$P(\nu_\mu \rightarrow \nu_e) \approx \mathbf{0.051 - 0.014 \sin}\delta_{cp} - \mathbf{0.00002 \cos}\delta_{cp}$$

- T2K expects ~5% of the ν_μ to oscillate to ν_e at the peak energy
- There is a 27% max asymmetry between P($\nu_\mu \rightarrow \nu_e$) and P($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$)
  - Assuming δ_{cp} = - 90° and θ_{23} = 45°
  - The max asymmetry increases to 39% for θ_{23} = 39°

The T2K Collaboration

Large international collaboration with:

~500 members from
59 institutions in
11 different countries

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

Spain
IFAE, Barcelona
IFIC, Valencia

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

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

Russia
INR

Germany
Aachen U.

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

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

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

Switzerland
ETH Zurich
U. Bern
U. Geneva

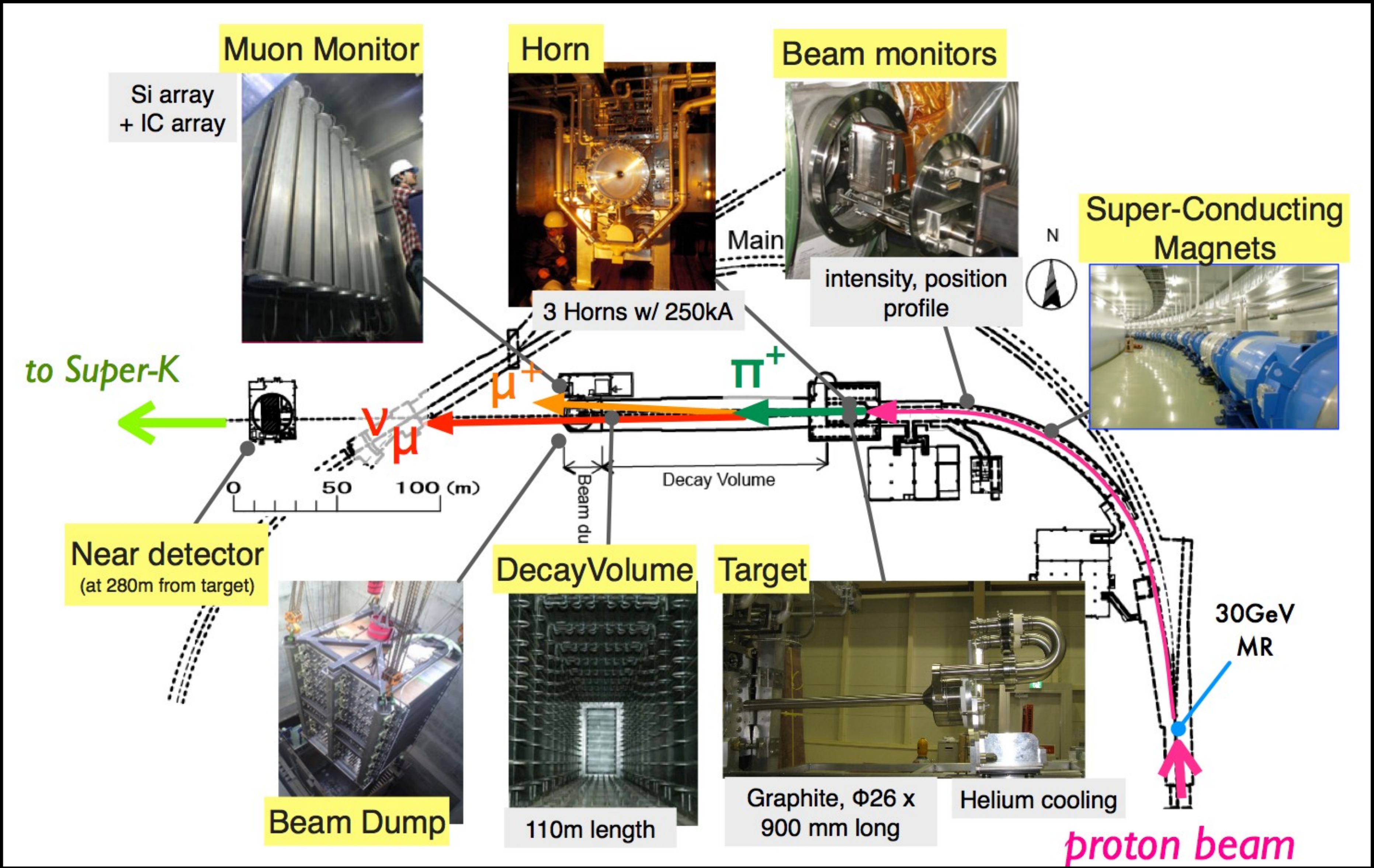
The T2K Experiment

- Study ν oscillations
- Generate high purity ν_μ beam
- Constrain unoscillated flux and cross sections
  - Beam monitoring
  - INGRID (on-axis)
  - ND280 (off-axis)

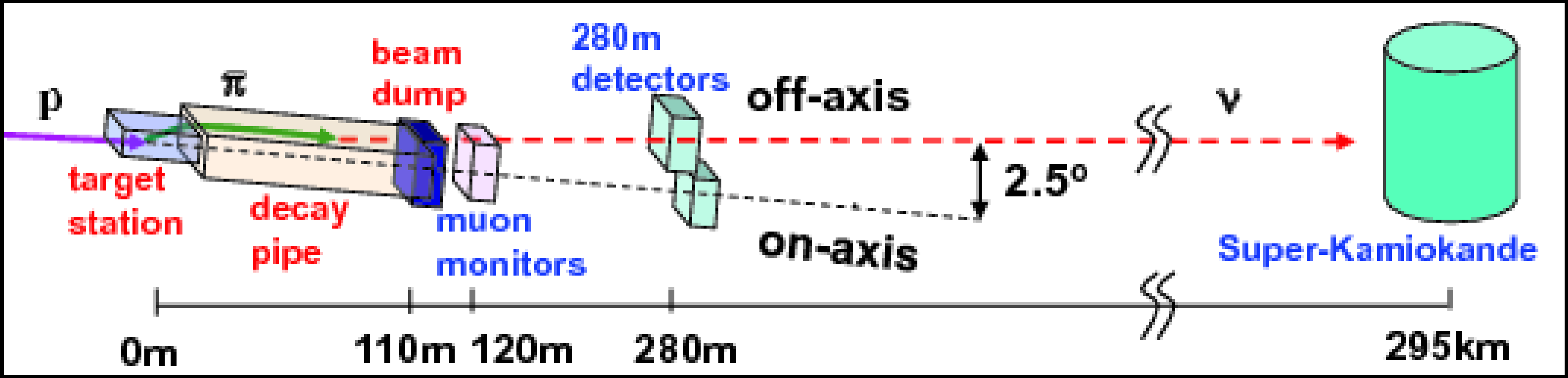
J-PARC

- Measure oscillated event rates 295 km downstream at Super-Kamiokande (SK)
  - ν_μ- disappearance
    $P(\nu_\mu \rightarrow \nu_\mu) \propto \sin^2(2\theta_{23}), \Delta m^2_{32}$
  - ν_e- appearance
    $P(\nu_\mu \rightarrow \nu_e) \propto \sin^2(2\theta_{13}), \sin^2(\theta_{23}), \sin(\delta_{cp})$

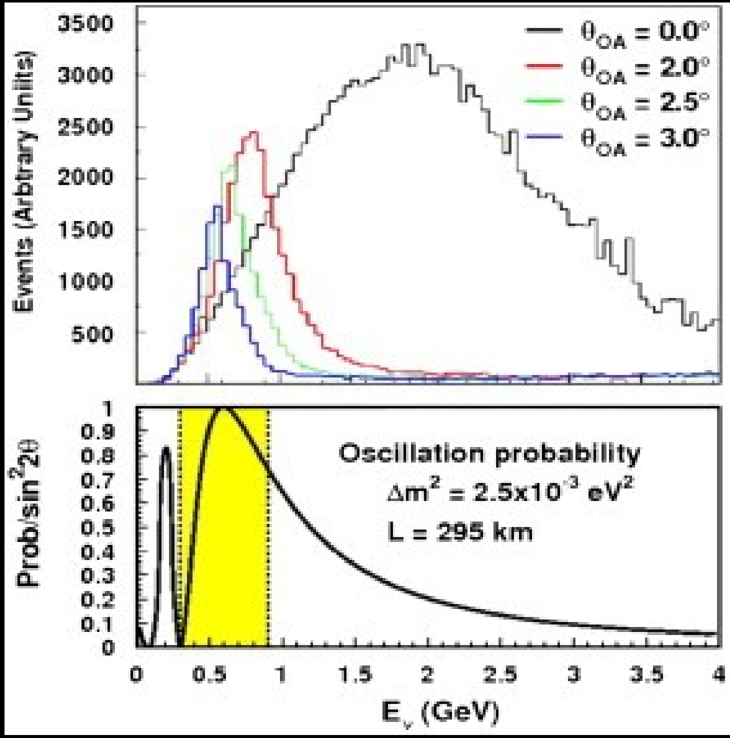
T2K ν Beamline



Off-Axis Flux Optimization

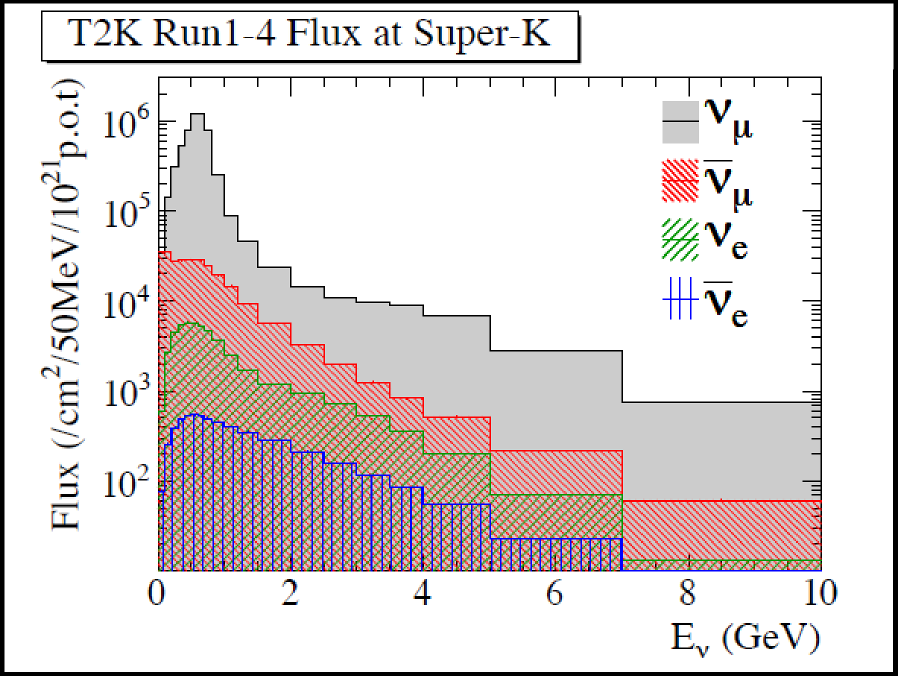


- Off-axis beam provides:
  - Peak energy at $\sin^2(\Delta m^2\ L/E)$ maximum
  - Narrow band spectrum
  - Reduced NC background
  - Dominant interaction at SK: CC quasi-elastic
- Optimal angle: 2.5°
- On-axis ND: INGRID
- Off-Axis ND: ND280
- Off-Axis FD: Super-Kamiokande (SK)

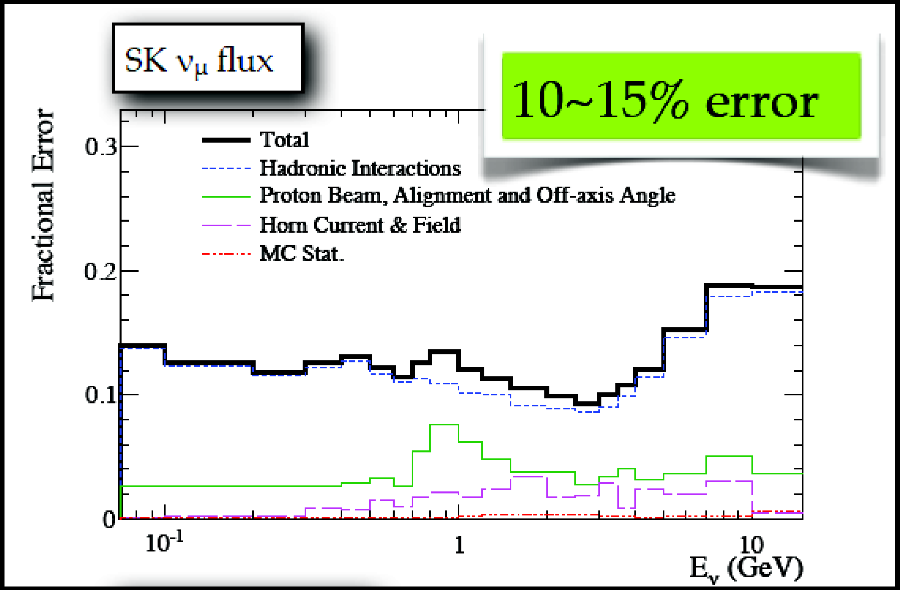


Flux Predictions and Uncertainties

- Interaction of 30 GeV protons with graphite target
  - Modeled with FLUKA2008
  - Tuned with NA61/SHINE data
- Propagation, focusing and decay of resulting π and K
  - GEANT3
  - GCALOR (neutrons)



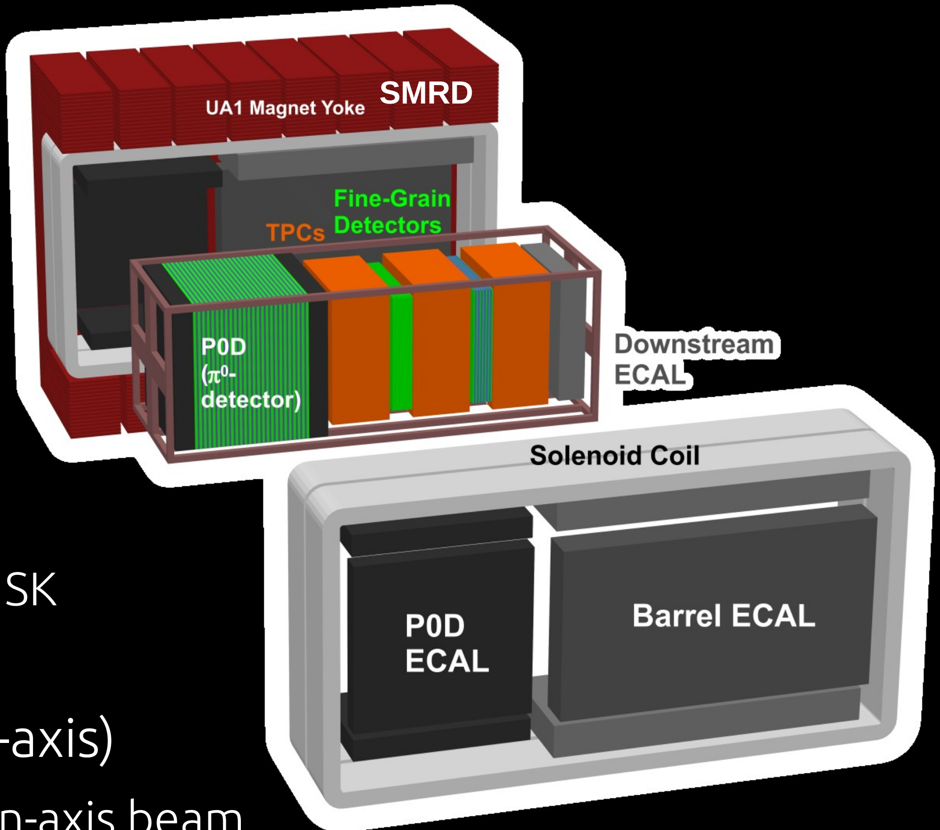
Phys. Rev. D 87, 012001 (2013)

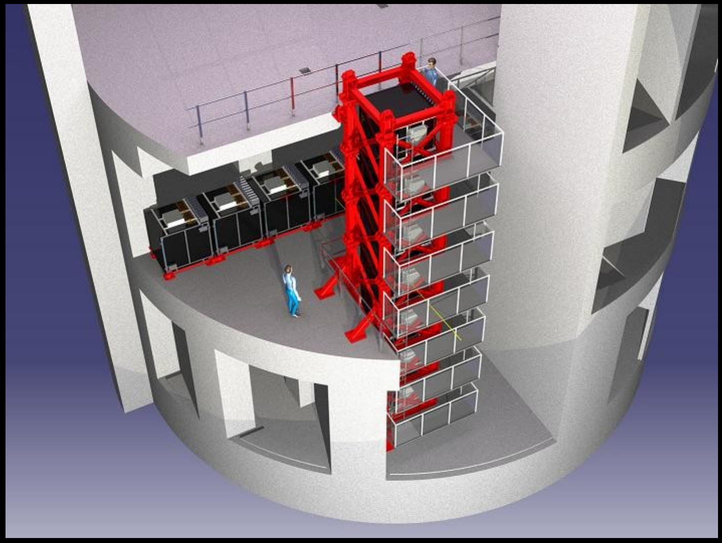


- **Flux prediction tuned with experimental data from:**
  - Proton flux measurements
  - Horn current monitoring
  - Beamline alignment studies
  - Beam direction (INGRID & μ monitor data)
  - Hadron production uncertainties propagated from NA61/SHINE
- Experimental errors from above propagated to flux uncertainties

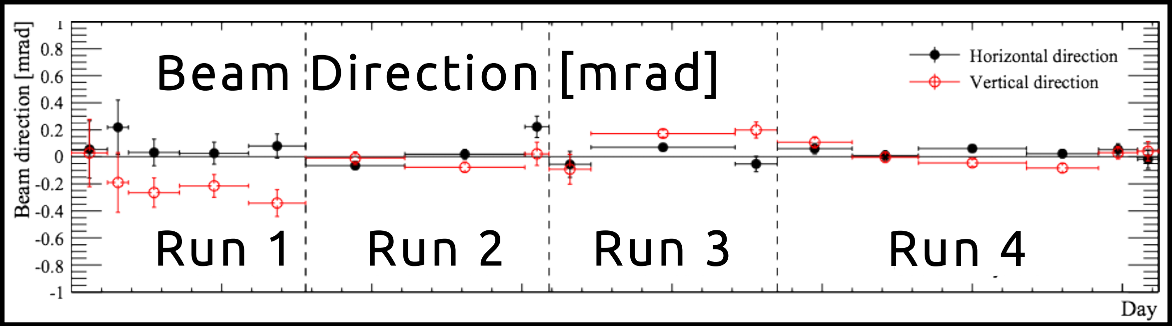
INGRID and ND280

- T2K off-axis Near Detector (ND280)
  - Measure cross sections on water
  - Multiple sub detectors
  - Magnetic field (0.2 T)
    - Charge discrimination
    - Momentum determination
  - Low energy cross section measurements
  - Data used to constrain T2K event rate at SK



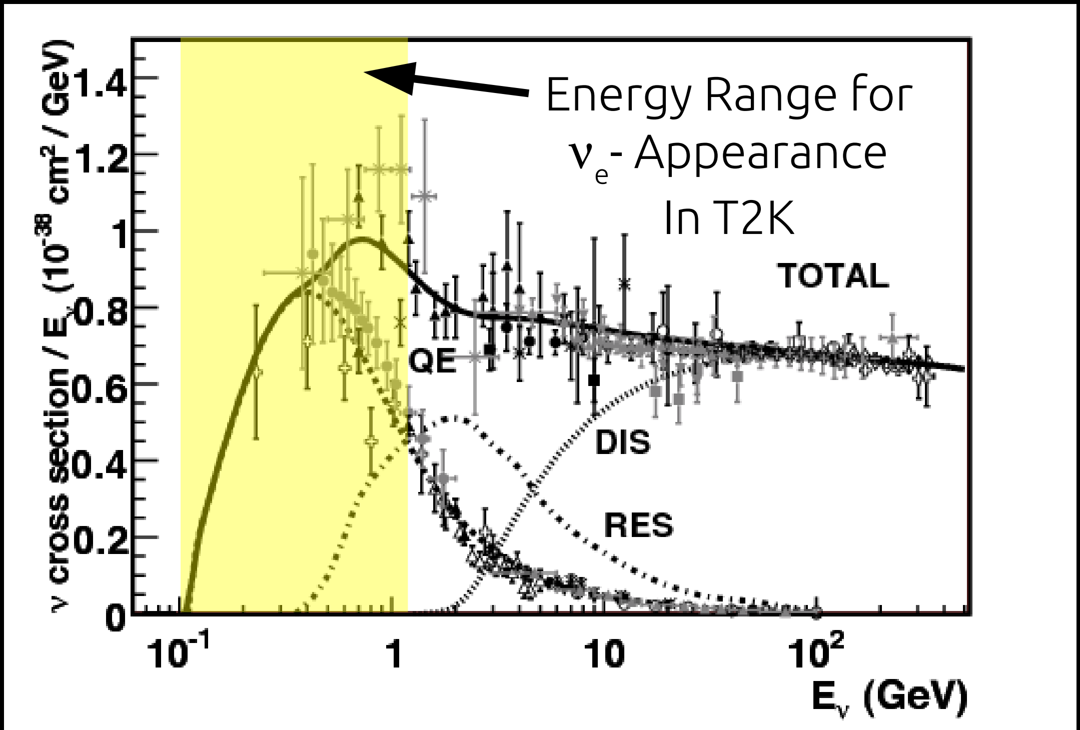


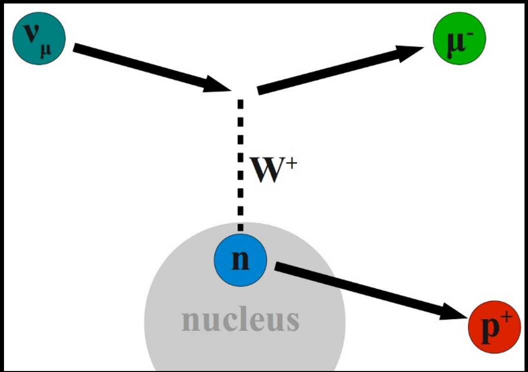
- INGRID (on-axis)
  - Monitor on-axis beam
  - Stability of direction and event rate



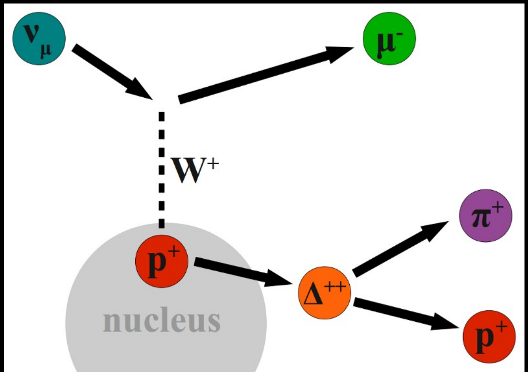
Cross Section Models

- NEUT MC generator used simulate interactions
- T2K energy region dominated by (quasi)elastic interactions
- Resonant π production contributes significantly above ~750 MeV
- Current questions:
  - <u>M</u>eson <u>E</u>xchange <u>C</u>urrents vs M_A^{eff}
  - <u>R</u>elativistic <u>F</u>ermi <u>G</u>as model vs Spectral Functions
  - Resonant π kinematics
- Constraints on the cross sections provided by:
  - **ND280 (flux + xsec fit)**
  - External data (MiniBooNE)





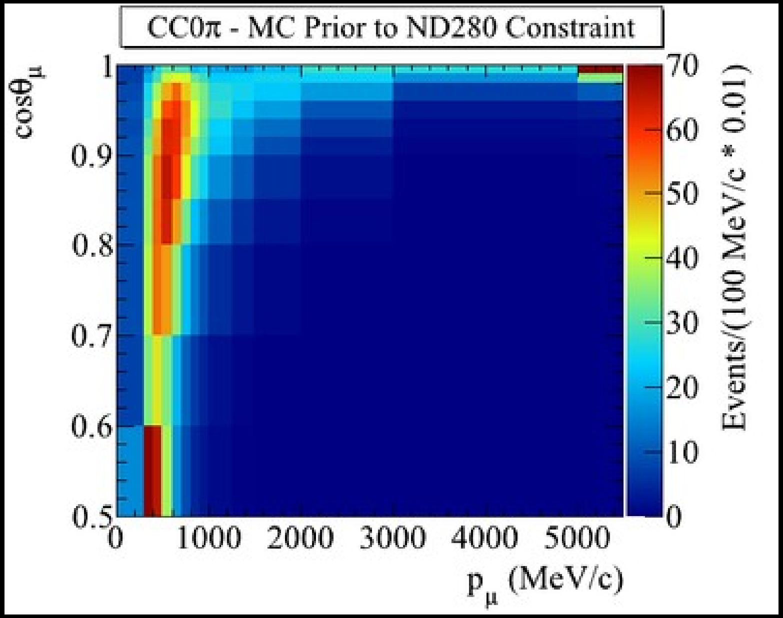
Qausi-elastic

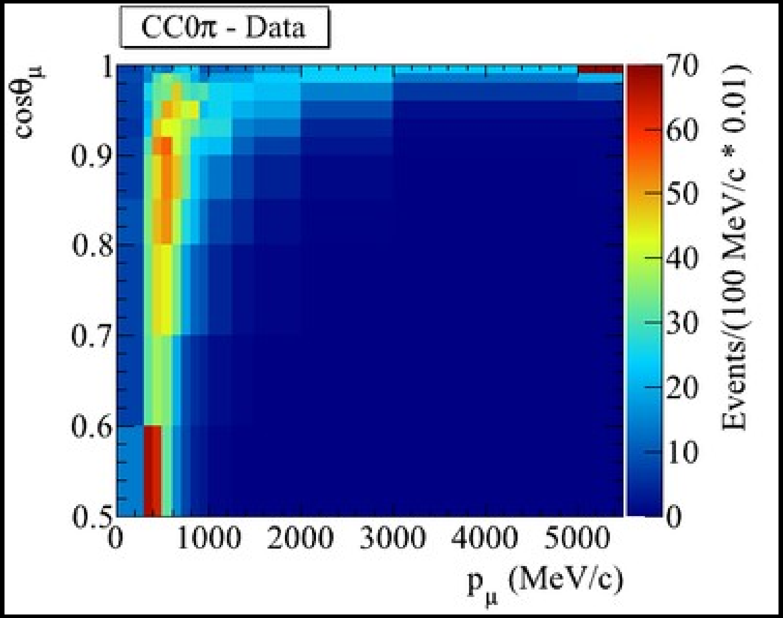


Resonance

Cross Section Data

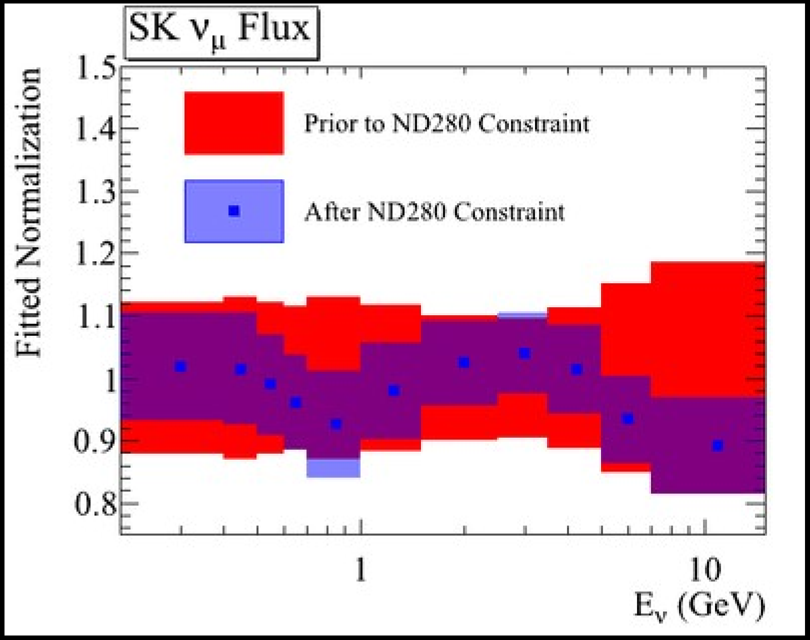
- Data from ND280 is used to constrain the **flux ⊗ cross section** prediction for T2K in SK
- ND280 data are divided by **topology**
  - 0 π tracks (QE - like, right)
  - 1 π track (resonance - like)
  - Multi π tracks (DIS - like)
- Each sample is binned in p_μ - θ_μ
- **The MC is fit to the data**
- **Fit results are propagated to the T2K prediction at SK**
- Cross section parameters are split into two groups:
  - Best-fit central values used to generated T2K prediction at SK
  - Nuisance parameters which are marginalized
- Flux parameters are fit simultaneously (within uncertainties shown on Slide 8)





Constrain the T2K Prediction at SK: Flux ⊗ Cross Section Fit

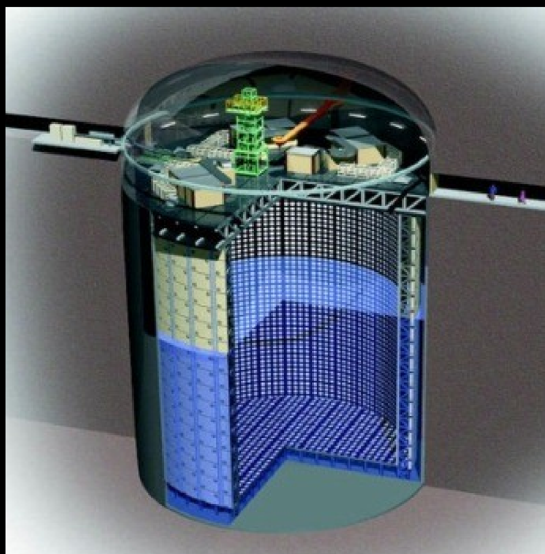
- Fit to the ND280 data greatly improves constraints on flux ⊗ cross section
- Results of fit to ND280 data:
  - Flux normalizations (top right, ν_μ)
  - Cross section params. propagated to T2K prediction for SK (bottom right)
- Other fit params (cross section and detector response) marginalized
- **Dominant residual error**: Lack of constraints on marginalized cross section parameters
- New ND280 data samples are being explored / incorporated to improve constraints for future analyses



Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25

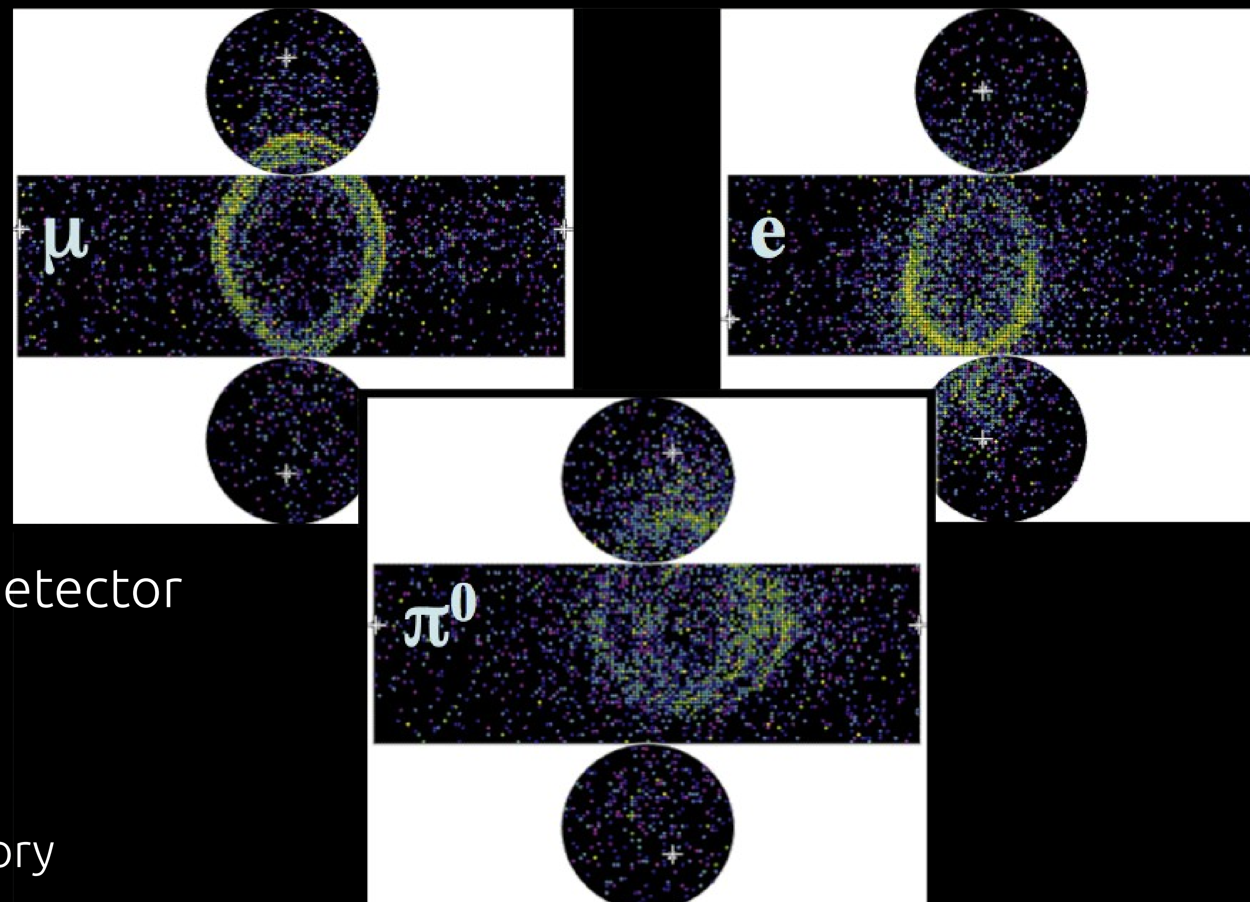
*For E_ν<1.5 GeV **For E_ν<2.5 GeV

T2K Events in the SK Detector



- 50 kt Water Cherenkov Detector
- 22.5 kt Fiducial Volume
- μ - ring
  - Relatively straight trajectory
  - Clear ring edges
- e^- - ring
  - e^- scatter more than μ^-
  - 'Fuzzy' ring edges

Monte Carlo Simulations



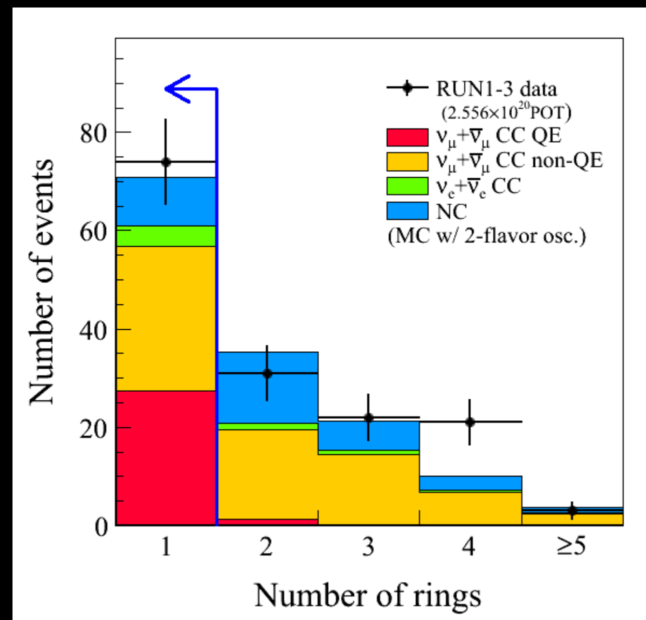
- π^0 induced backgrounds
  - $\pi^0 \rightarrow \gamma + \gamma$, produce two e^- - like rings
  - Must resolve both rings to reject

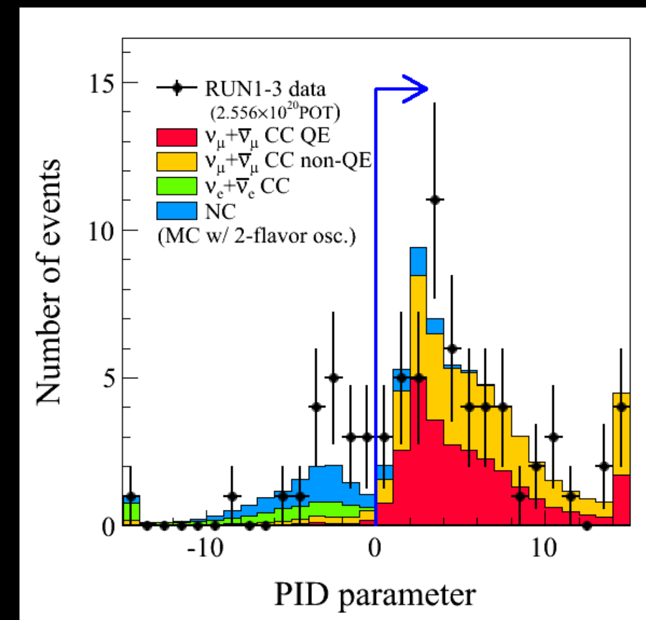
ν_μ- Disappearance Event Selection

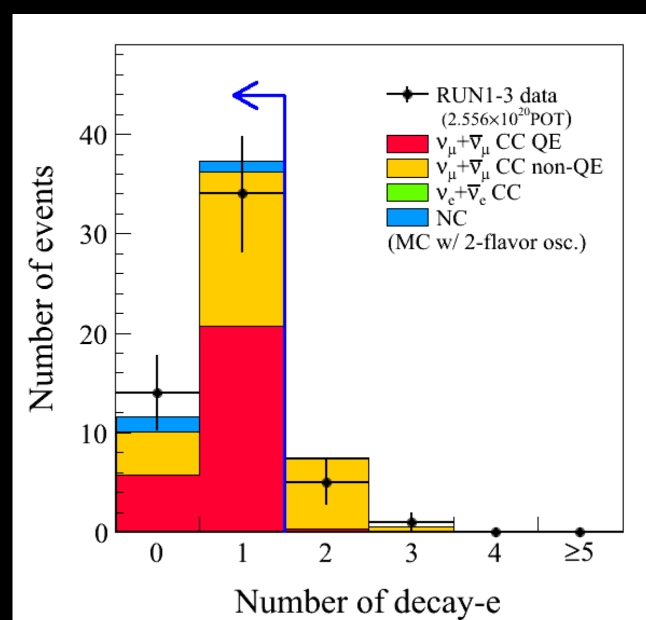
<u>SK Selection Cuts</u>

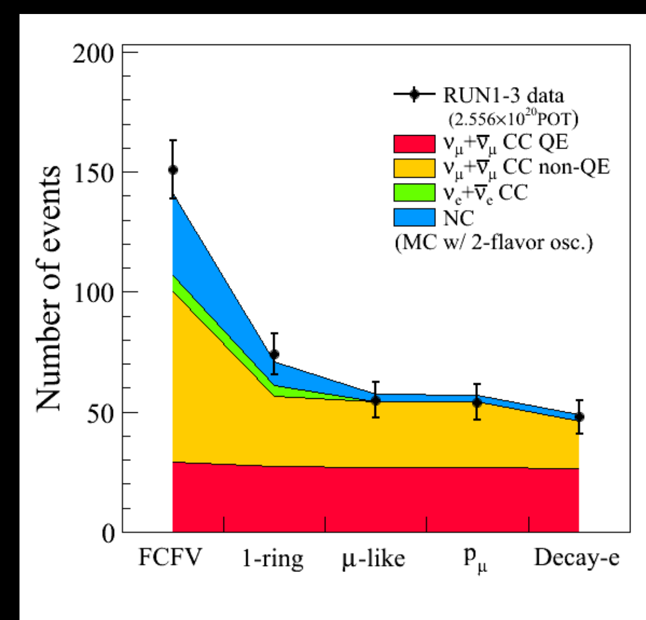
- E_{vis} > 100 MeV
- Veto hits < 16
- Fully contained
  (Fid. Vol. = 200 cm)

- Single ring
- Muon-like
- p_μ > 200 MeV
- 0 or 1 Michel e^-



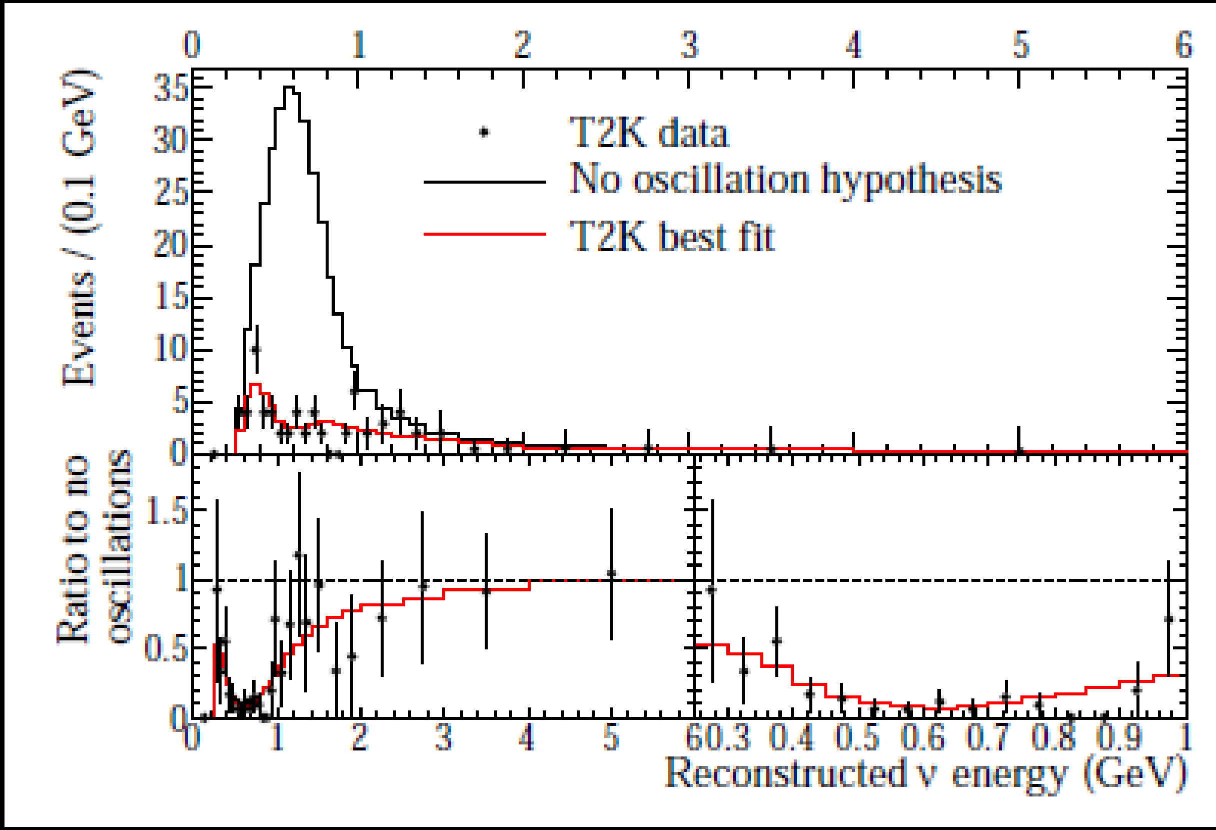






ν_μ- Disappearance Fitting

- Scan over values of:
  - Δm^2_{32}
  - $\sin^2(2\theta_{23})$
- Scan 1st and 2nd octant separately
- Calculate likelihood of data originating from prediction



$$\chi^2 = 2\sum_{E_r}\left(N_{SK}^{data}\ln\frac{N_{SK}^{data}}{N_{SK}^{\exp}} + \left(N_{SK}^{\exp} - N_{SK}^{data}\right)\right) + \left(\mathbf{f} - \mathbf{f_0}\right)^{\mathbf{T}}\mathbf{C}^{-1}\left(\mathbf{f} - \mathbf{f_0}\right)$$

Statistical Constraints in E_ν Bins

Systematic Prior Constraints

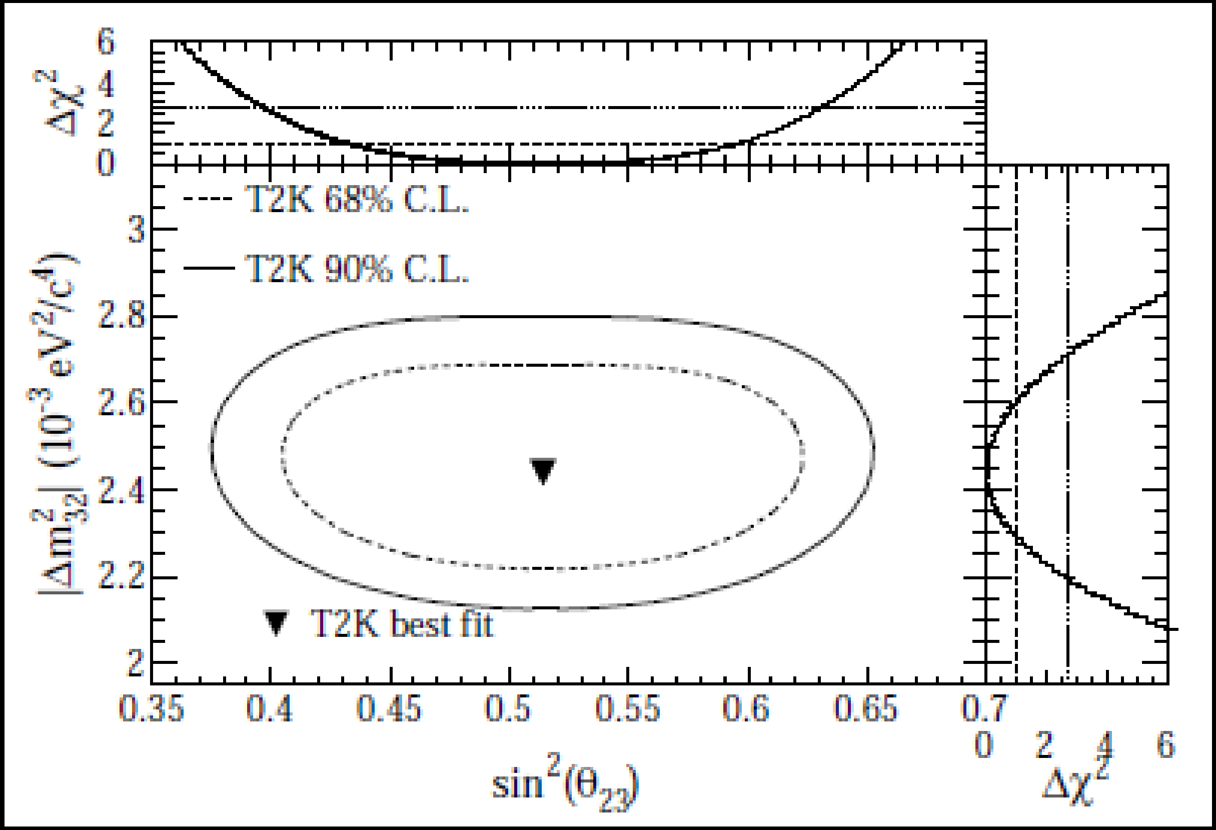
ν_μ- Disappearance Results

- Best-fit oscillation parameter values:

$$\sin^2(\theta_{23}) = 0.514 \pm 0.082$$

$$\left|\Delta m^2_{32}\right| = 2.44^{+0.17}_{-0.15} \times 10^{-3}\, eV^2/c^2$$

- Data prefers 2nd θ_{23} octant
- 1σ confidence intervals are consistent with:
  - Maximal mixing ($\sin^2(\theta_{23})$)
  - The MINOS result (Δm^2_{32})

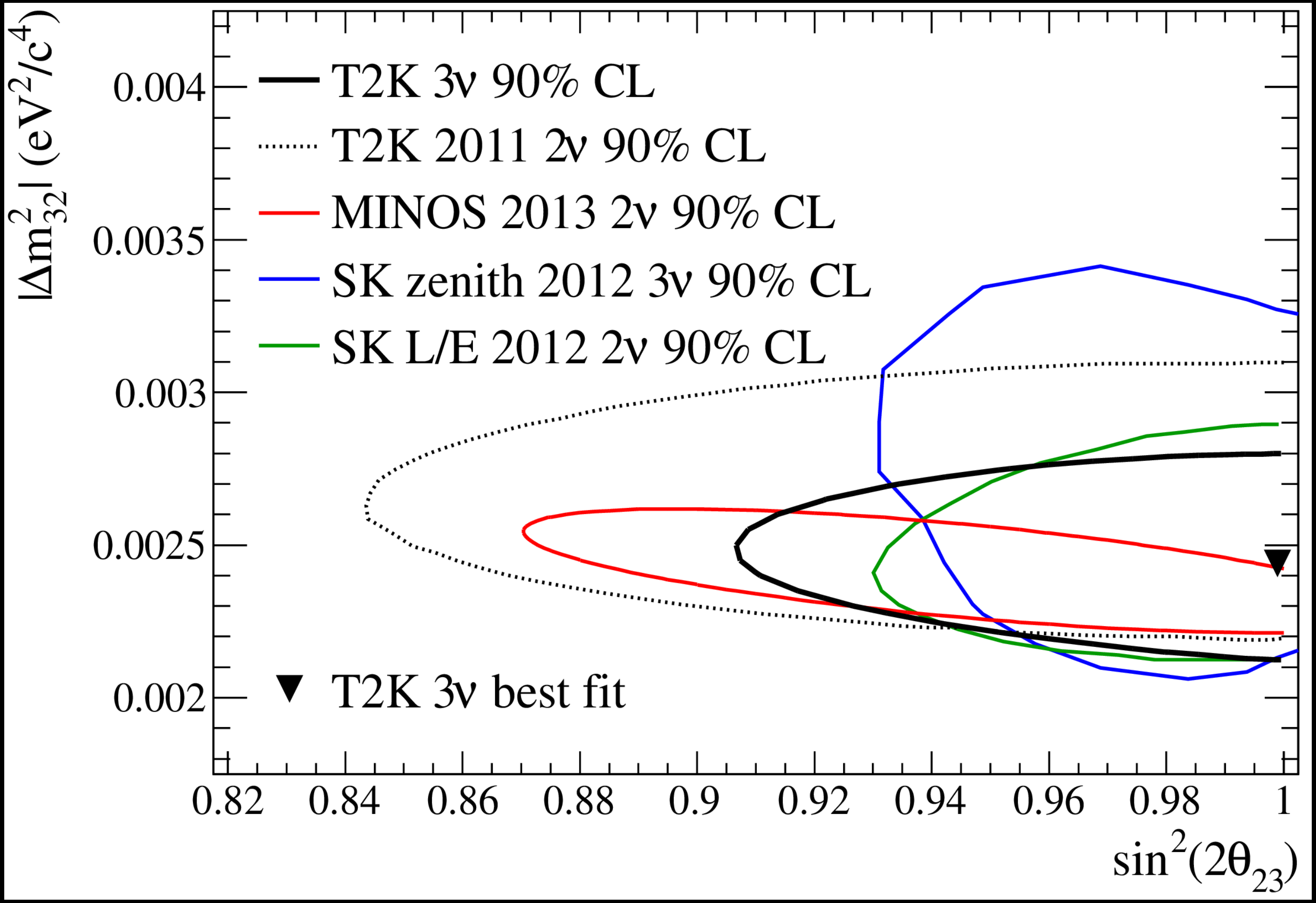


$$\chi^2 = 2\sum_{E_r}\left(N^{data}_{SK}\ln\frac{N^{data}_{SK}}{N^{exp}_{SK}} + \left(N^{exp}_{SK} - N^{data}_{SK}\right)\right) + (\mathbf{f}-\mathbf{f_0})^{\mathbf{T}}\mathbf{C}^{-1}(\mathbf{f}-\mathbf{f_0})$$

Statistical Constraints in E_ν Bins

Systematic Prior Constraints

ν_μ- Disappearance Comparison



	$\sin^2 2\theta_{23}$	Δm_{32}^2	χ^2 / ndf	N_{obs}	N_{exp}	p-value
$\theta_{23} \leq \pi/4$	1.000	2.44e-3	56.04 / 71	58	57.97†	0.83
$\theta_{23} \geq \pi/4$	0.999	2.44e-3	56.03 / 71		57.92†	0.82

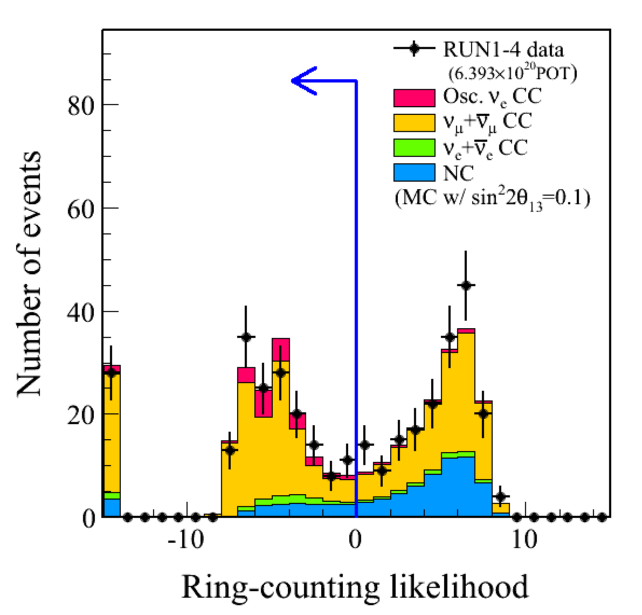
† Null Oscillation Expectation 204.7±16.7

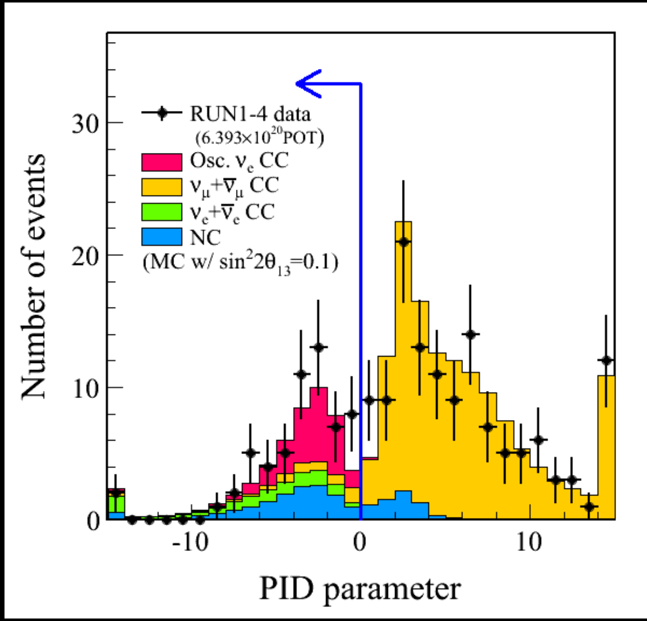
ν_e- Appearance Event Selection

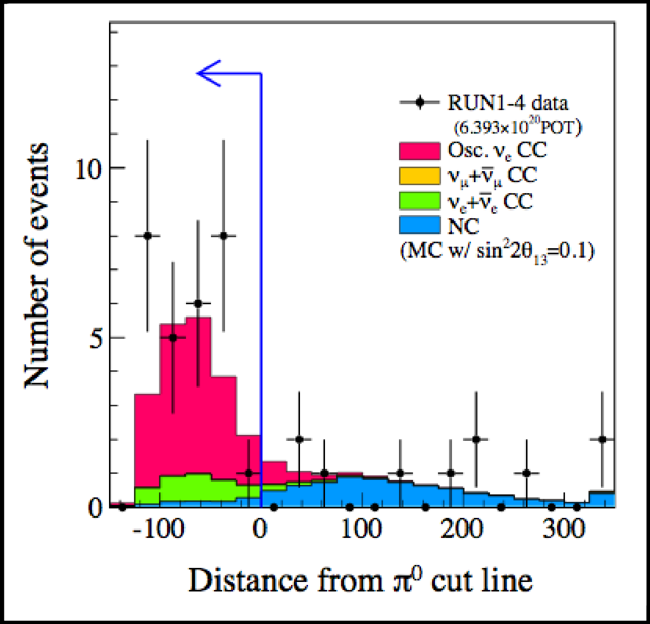
<u>SK Selection Cuts</u>

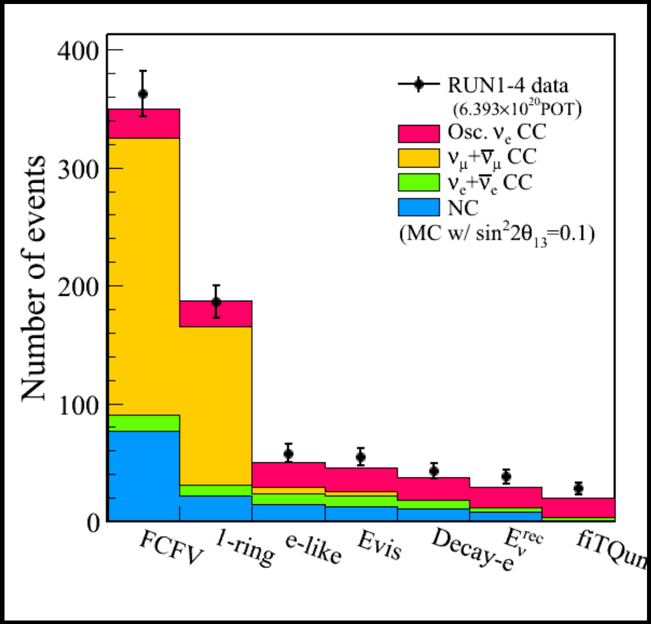
- Veto hits < 16
- Fully contained (Fid. Vol. = 200 cm)
- E_{vis} > 100 MeV

- Single ring
- Electron-like
- 100 < E_ν < 1250 MeV
- 0 Michel e^-
- Cut to remove π^0 background



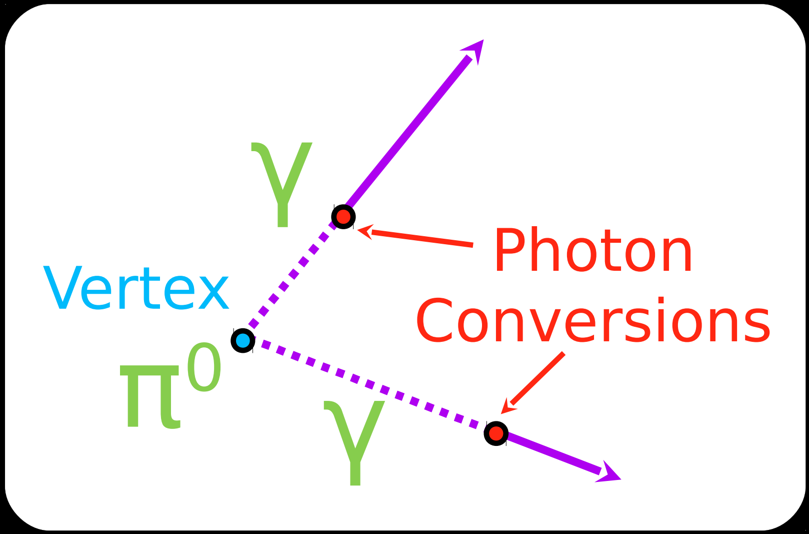


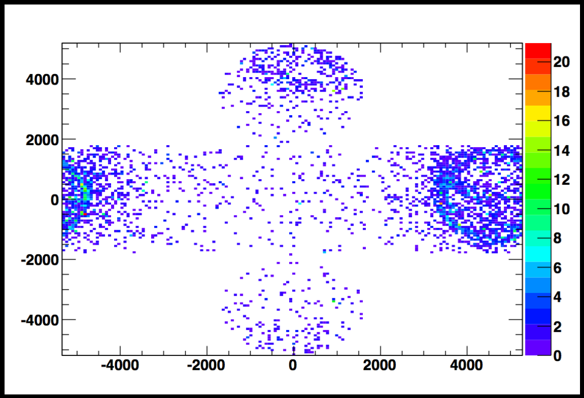




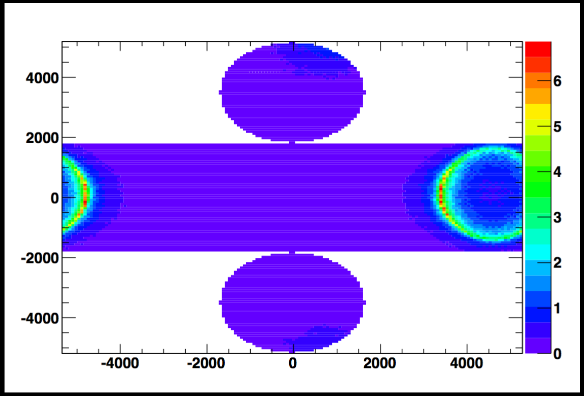
Event Selections Improvements

- Old π^0 cut: 2nd ring finder + π^0 mass
- **New π^0 cut: Add fitter**
  - Forces fits to π^0 and e^- hypotheses
  - Fits 12 parameters
    - Vertex (4)
    - Direction (2x2)
    - Momenta (2)
    - Conversion distances (2)

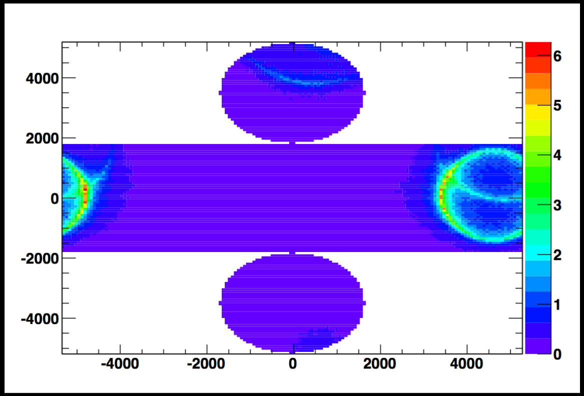




Measured Charge



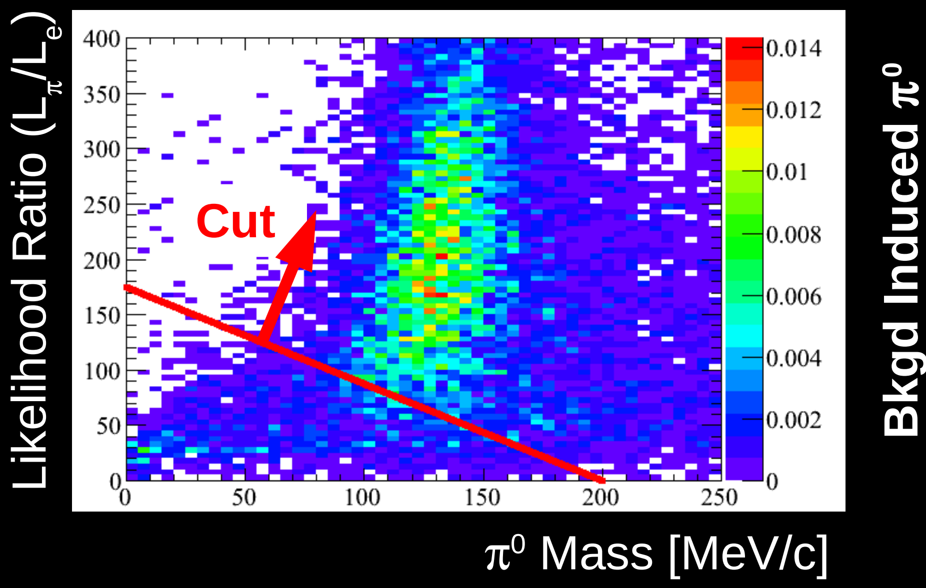
Predicted Charge: Single Ring (e-like) fit

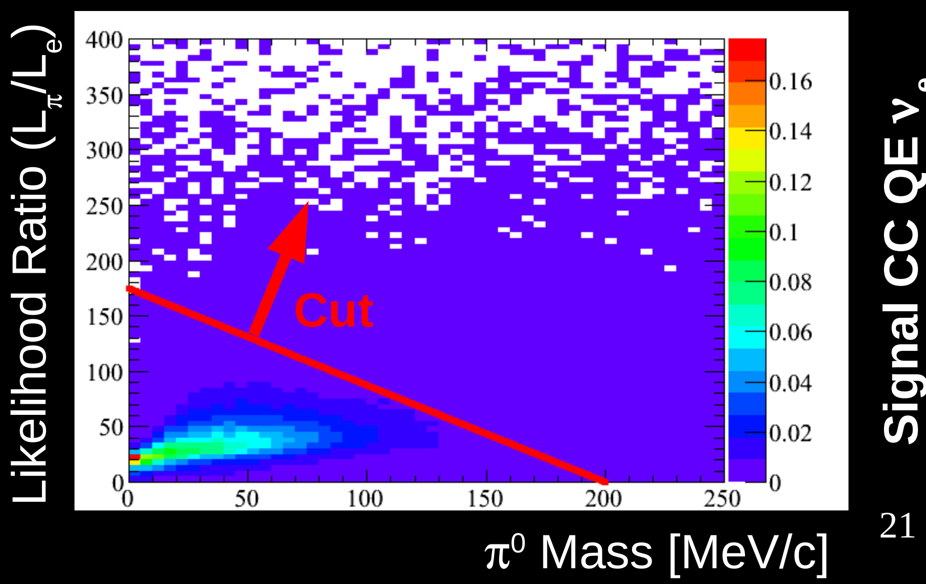


Predicted Charge: Two Ring (π^0-like) fit

Event Selections Improvements

- Old π^0 cut: 2^{nd} ring finder + π^0 mass
- **New π^0 cut: Add fitter**
  - Forces fits to π^0 and e^- hypotheses
  - Fits 12 parameters
    - Vertex (4)
    - Direction (2x2)
    - Momenta (2)
    - Conversion distances (2)
  - Calculate likelihood for each hypothesis
  - Also reconstruct π^0 mass
- 2D cut **removes 70% more π^0 background** than previous method
- More sensitive to low energy photons
- Better discrimination in π^0 mass tail





ν_e- Appearance Event Rate Prediction and Uncertainties

2013 Event Rate Predictions

Parameters	Total	ν_e sig.	ν_e bkg.
Nominal SK MC	21.64	17.36	3.02
Before ND280 fit	22.57	17.94	3.24
After ND280 fit	20.44	16.42	2.93
ND280+Old π^0 cut	22.50	16.78	3.08
ND280+New π^0 cut	21.90	17.35	3.30

Parameters	ν_μ bkg.	$\overline{\nu}_\mu$ bkg.	$\overline{\nu}_e$ bkg.
Nominal SK MC	1.05	0.06	0.15
Before ND280 fit	1.17	0.07	0.16
After ND280 fit	0.89	0.05	0.14
ND280+ Old π^0 cut	2.33	0.13	0.16
ND280+ New π^0 cut	1.03	0.06	0.17

Run 1-4 → 6.393×10^{20} POT

(partial run 4)

Systematic Uncertainties

		$\sin^2 2\theta_{13} = 0.1$	
Error source		w/o ND280 fit	w/ ND280 fit
Beam only	Fit to ND280	11.6	7.5
M_A^{QE}		21.5	3.2
M_A^{RES}		3.3	0.9
CCQE norm. ($E_\nu < 1.5$ GeV)		9.3	6.3
CC1π norm. ($E_\nu < 2.5$ GeV)		4.2	2.0
NC1π^0 norm.		0.6	0.4
CC other shape	Other Cross Section	0.1	0.1
Spectral Function		6.0	6.0
p_F		0.1	0.1
CC coh. norm.		0.3	0.2
NC coh. norm.		0.3	0.2
NC other norm.		0.5	0.5
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$		2.9	2.9
W shape		0.2	0.2
pion-less Δ decay		3.7	3.5
SK detector eff.	SK	2.4	2.4
FSI		2.3	2.3
PN		0.8	0.8
SK momentum scale		0.6	0.6
Total		28.1	8.8

ν_e- Appearance Event Rate Prediction and Uncertainties

2013 Event Rate Predictions

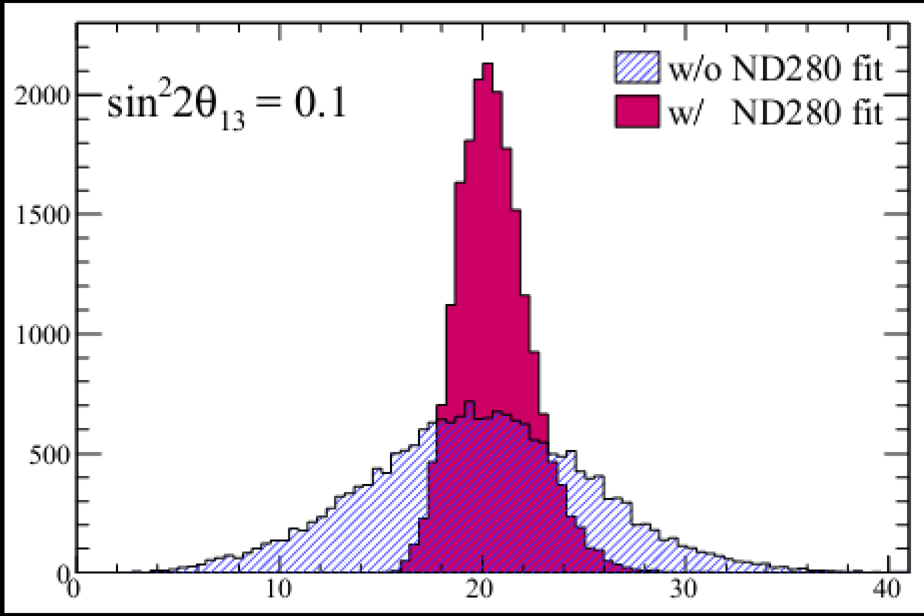
Parameters	Total	ν_e sig.	ν_e bkg.
Nominal SK MC	21.64	17.36	3.02
Before ND280 fit	22.57	17.94	3.24
After ND280 fit	20.44	16.42	2.93
ND280+Old π^0 cut	22.50	16.78	3.08
ND280+New π^0 cut	21.90	17.35	3.30

Parameters	ν_μ bkg.	$\overline{\nu}_\mu$ bkg.	$\overline{\nu}_e$ bkg.
Nominal SK MC	1.05	0.06	0.15
Before ND280 fit	1.17	0.07	0.16
After ND280 fit	0.89	0.05	0.14
ND280+ Old π^0 cut	2.33	0.13	0.16
ND280+ New π^0 cut	1.03	0.06	0.17

Run 1-4 → 6.393×10^{20} POT

(partial run 4)

Systematic Uncertainties



Predicted Number of T2K ν_e- appearance Events in SK (Signal + Background)

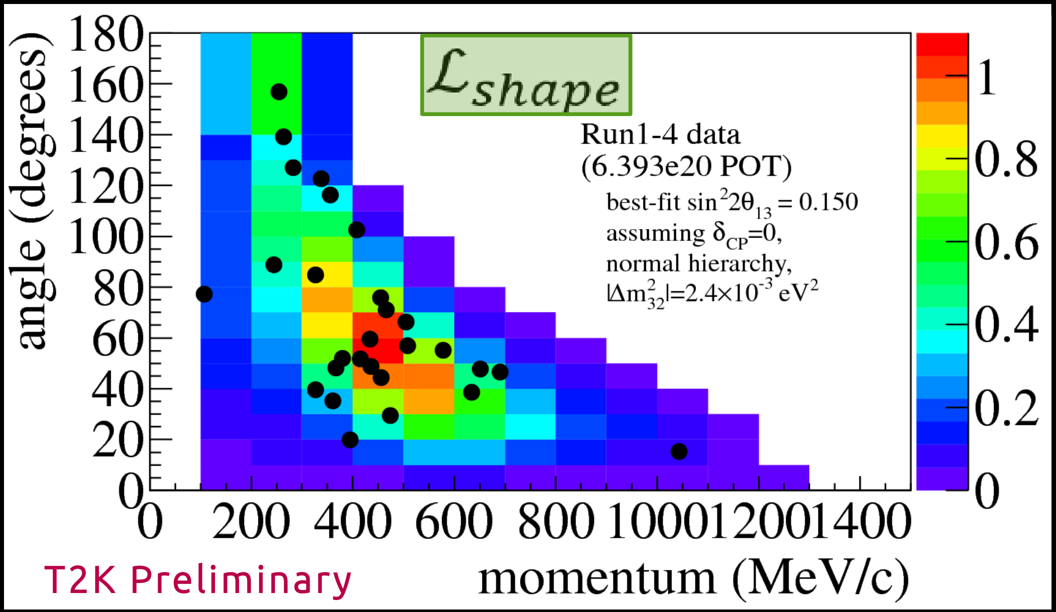
ν_e- Appearance Fitting and Results

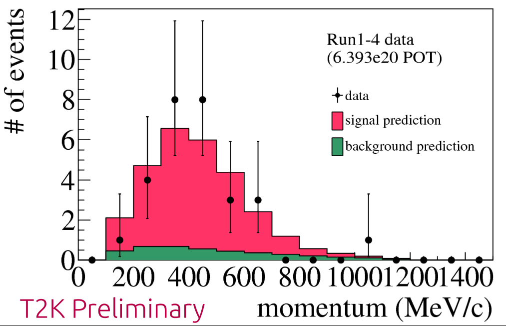
- Fit to maximize the likelihood that:
  - $N_{obs} = P_{poisson}(N_{pred})$
  - An e^- has a particular p_e- θ_e
  - Systematic fluctuations are consistent with priors
- Scan over $\sin^2(2\theta_{13})$ space
- Other osc. params. are fixed
  - $\Delta m^2_{32} = 2.4\text{x}10^{-3}$ eV^2
  - $\sin^2(2\theta_{23}) = 1.0$
  - $\delta_{cp} = 0°$
- Best fit, assuming above params.

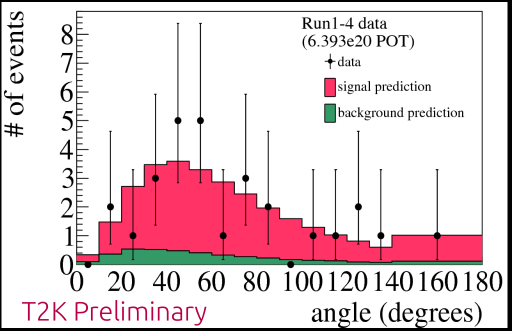
$$NH: \sin^2(2\theta_{13}) = 0.150^{+0.039}_{-0.034}$$
$$IH: \sin^2(2\theta_{13}) = 0.182^{+0.046}_{-0.040}$$

  - 1σ C.L. errors
  - Excludes $\sin^2(2\theta_{13}) = 0$ at 7.4σ

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

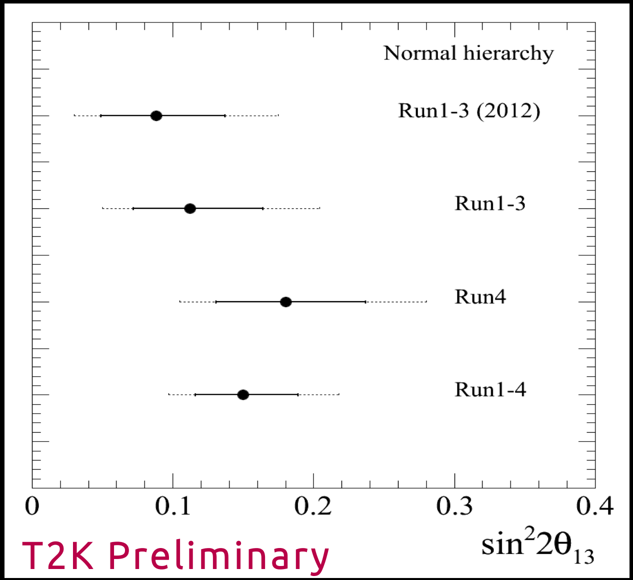


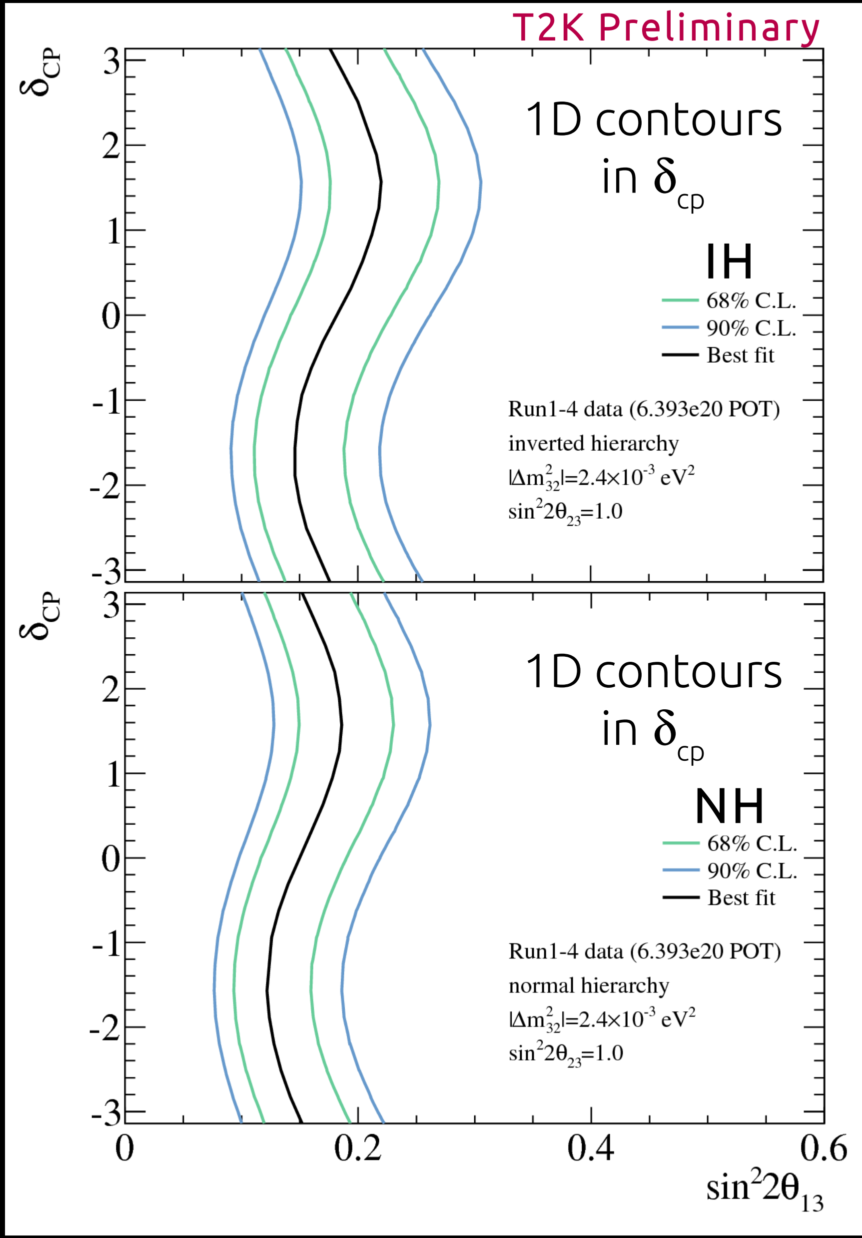




ν_e- Appearance Results

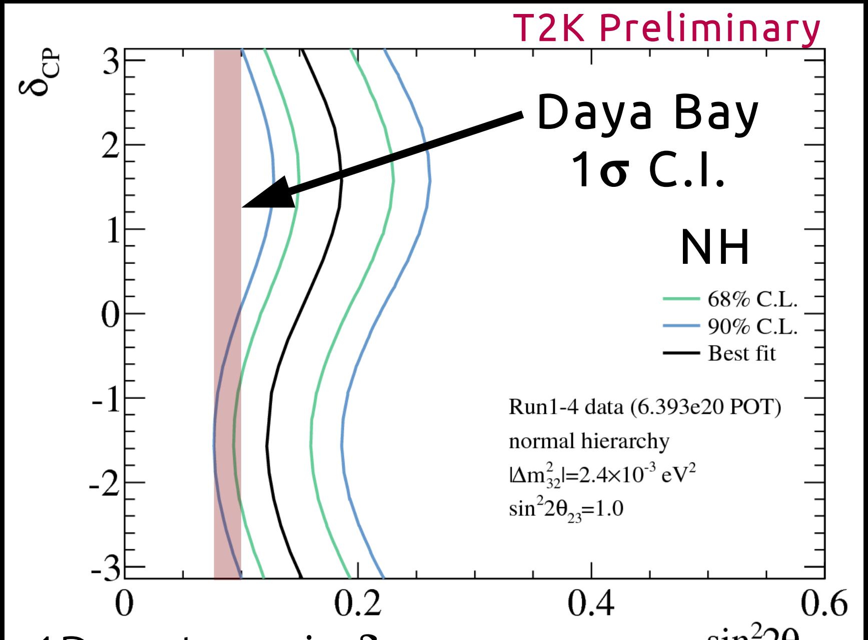
- Repeat fit for other oscillation parameter values
  - $-\pi < \delta_{cp} < \pi$
  - MH ($\pm|\Delta m^2_{32}|$)
  - $\sin^2(\theta_{23})$ (backup slide)
- Results consistent across runs





Future Sensitivities

- Reactor Experiments:
  - Measures $\bar{\nu}_e$**- disappearance**
  - $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \propto \sin^2(2\bar{\theta}_{13})$
  - Very high precision
- T2K:
  - Measures ν_e**- appearance**
  - $P(\nu_\mu \rightarrow \nu_e) \propto \sin^2(2\theta_{13}), \sin^2(\theta_{23}), \sin(\delta_{cp})$
  - **Differences due to θ_{23} and δ_{cp}**
- If the Daya Bay result is assumed in T2K fits then T2K is sensitive to:
  - CP violation
  - The θ_{23} octant
  - MH (with NOνA)

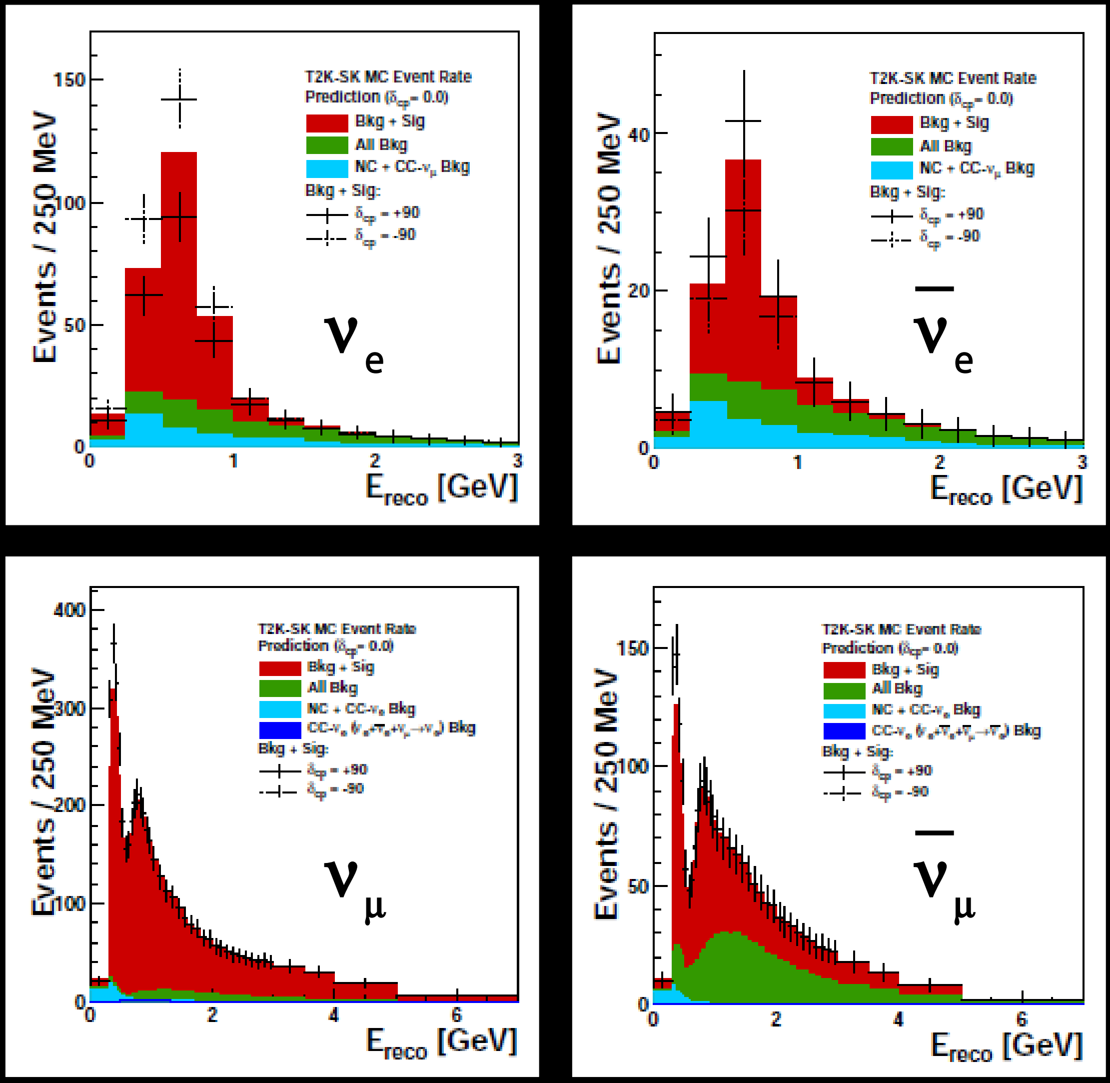


1D contours in δ_{cp}

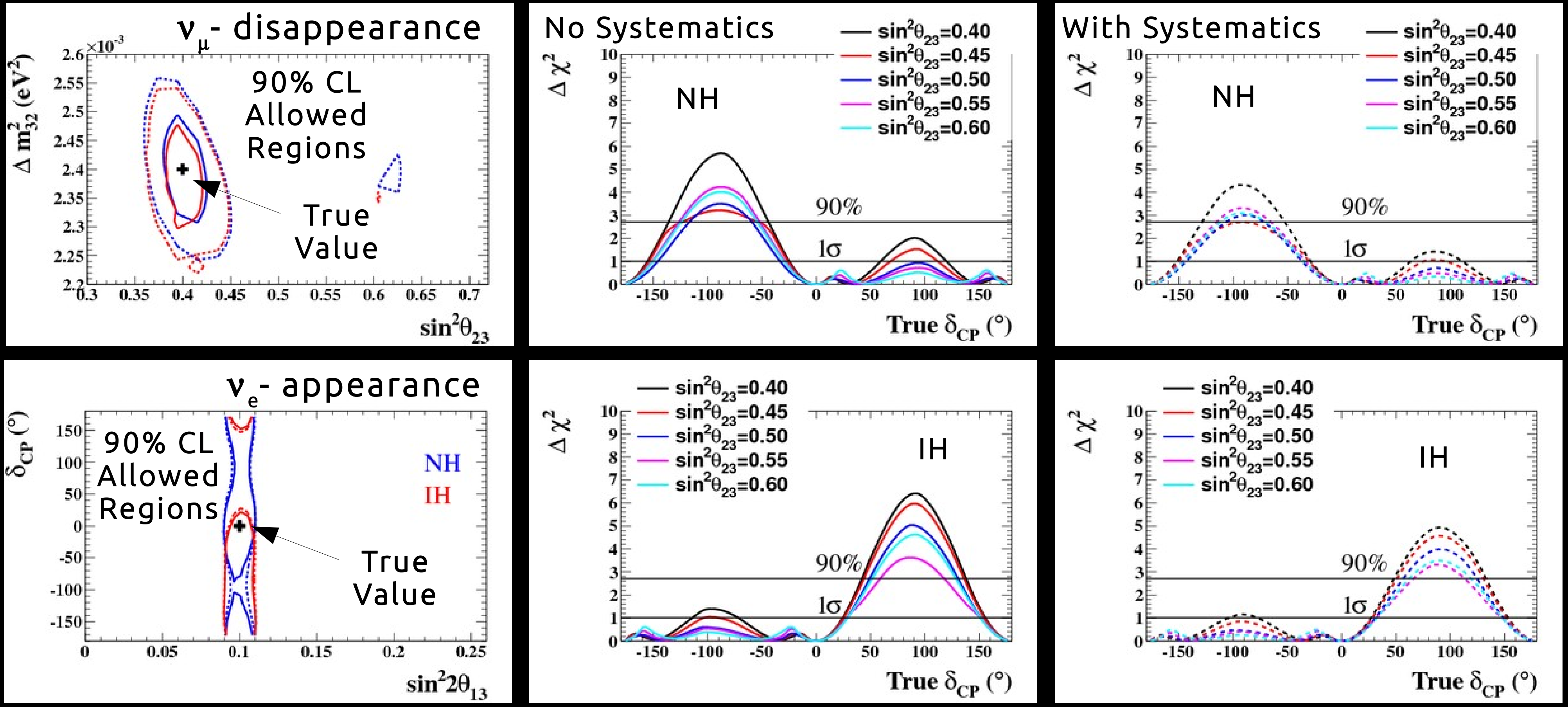
- Study T2K sensitivity w.r.t.:
  - Exposure: up to 7.8×10^{21} POT
  - Run plan: ν vs $\bar{\nu}$ beam
  - Combined analysis: T2K + NOνA
  - Systematic uncertainty projections

T2K Spectra at SK for $7.8\text{x}10^{21}$ POT

- Calculated FD spectra for full T2K statistics
  - Project SK MC to higher exposure
  - Estimate $\bar{\nu}$ beam MC from flux ratios
- Simultaneous fit of ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$ samples
- Oscillation parameter uncertainties
  - Fix solar terms
  - Allow atmospheric terms to float within current uncertainties
  - Project θ_{13} uncertainties to Daya Bay systematic uncertainty:
    $(\sin^2(2\theta_{13}) = 0.1 \pm 0.005)$
  - MH and δ_{cp} are unconstrained
- Assume various true values for:
  θ_{13}, θ_{23}, δ_{cp}, and MH



T2K 50% ν / 50% $\bar{\nu}$ + Daya Bay



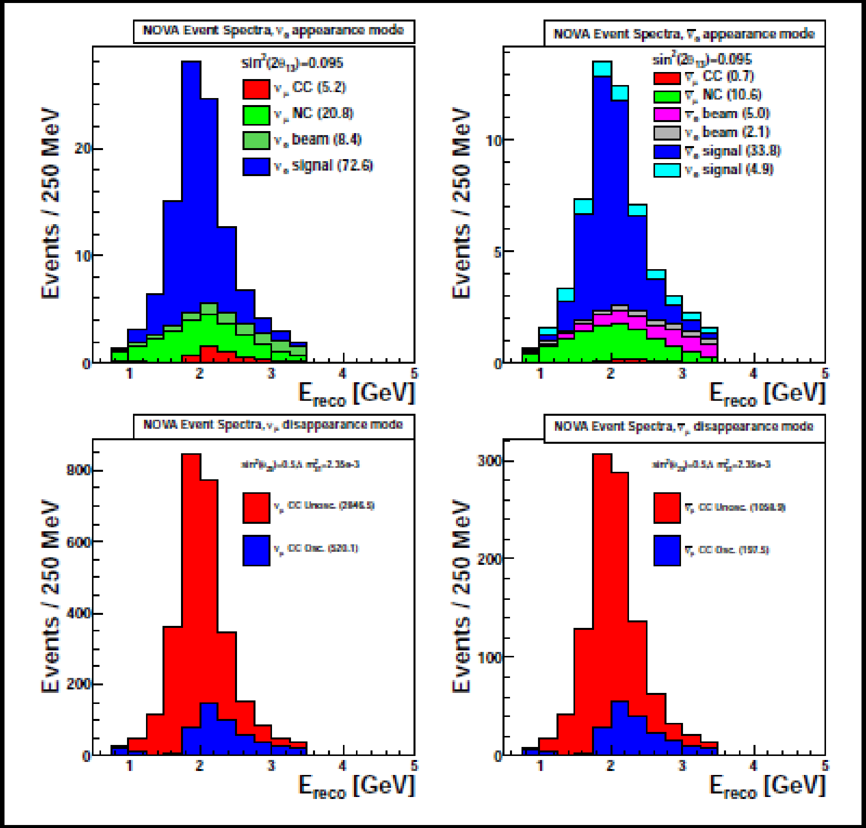
Ability to determine CP violation as a function of true δ_{cp}

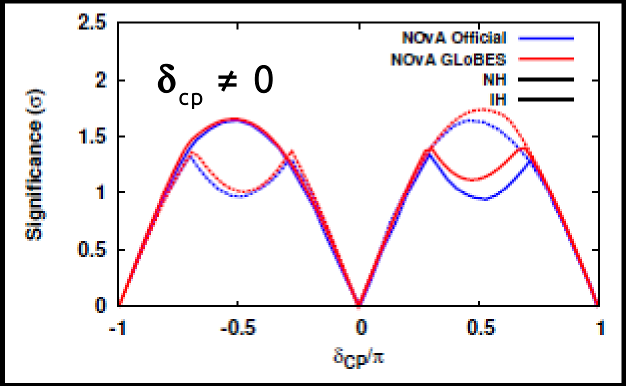
- No Systematics (**solid**)
- With systematics (**dashed**) ~10% for ν_e and ~13% for ν_μ
  - ν samples assumes 2012 level systematics
  - $\bar{\nu}$ samples assume +10% additional uncertainty

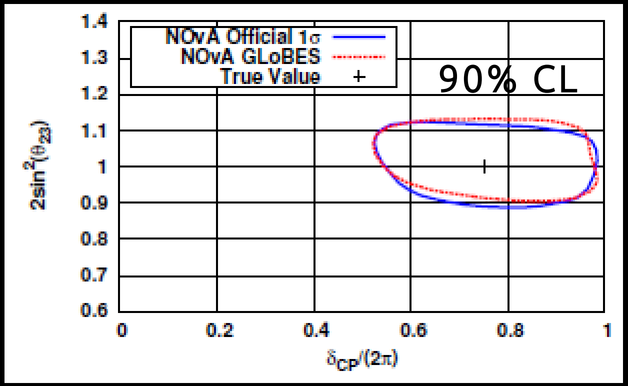
GLoBES: Comput.Phys.Commun. 167 (2005) 195
Comput.Phys.Commun.177:432-438,2007

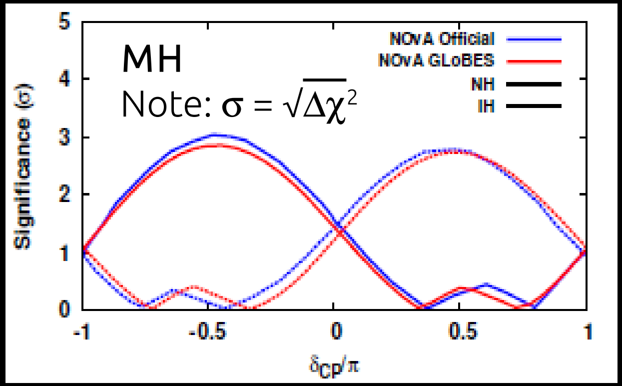
T2K + NOνA + Daya Bay

- Produce T2K spectra in GLoBES
- Reproduce NOνA event spectra in GLoBES (right)
- Reproduce NOνA results (below) using generated spectra
- **Systematic Uncertainties:**
  - Treat T2K and NOνA equally
  - Allow normalizations to float
    - Signal: 5%
    - Background: 10%
- T2K-only consistent across both studies





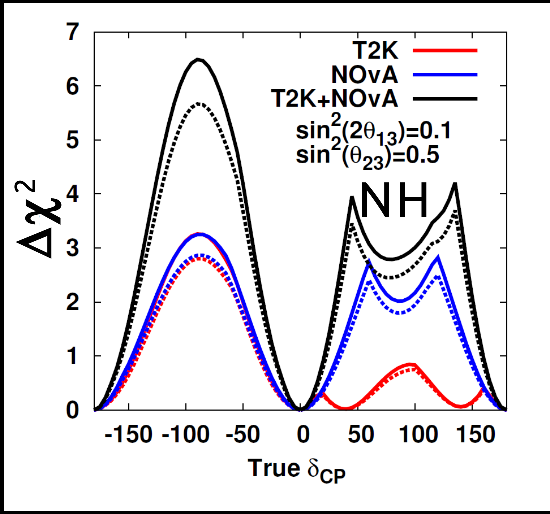


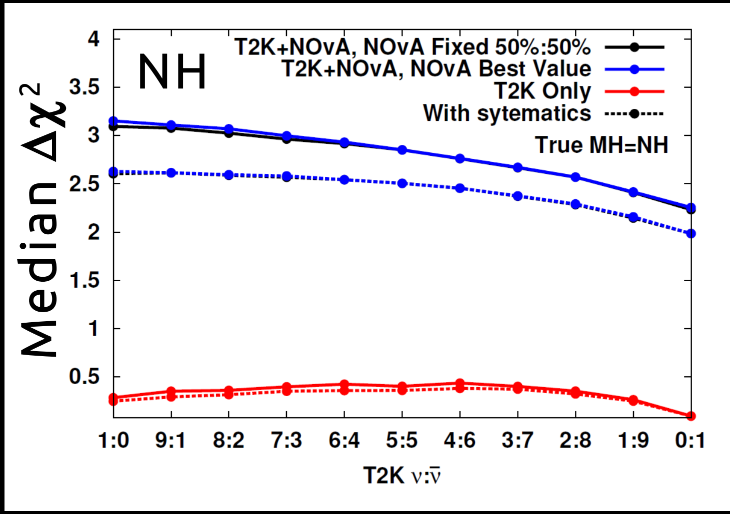


Combined Sensitivities and Optimal Run Plan

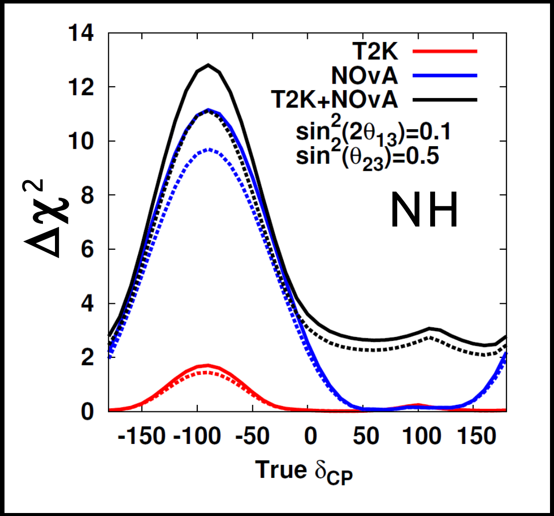
- CPV sensitivity
  - Greatly enhanced by combined fit
  - **Flat for run ratios ν > 30%/70% $\nu/\bar{\nu}$**
- Mass Hierarchy
  - Almost no sensitivity alone
  - Large enhancement to NOνA degenerate region
  - **Prefers more ν running in combined fit**
- Evaluated other metrics
- Metrics mostly flat for: 70%/30% < $\nu/\bar{\nu}$ < 30%/70%

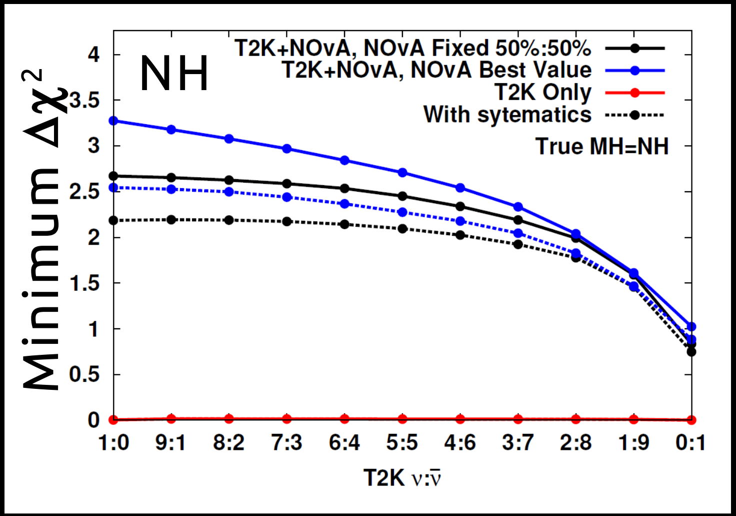
CPV Determination





MH Determination





50%/50% $\nu/\bar{\nu}$ running

Variable $\nu/\bar{\nu}$ running

Conclusions

- **The T2K experiments doubled its statistics in the past year and results are improving**
- Analysis techniques continue to improve
  - Improved data based constraints on the flux
  - Better constraints from ND280
  - Improved π^0 rejection at Super-Kamiokande
- **Measured $\nu_\mu \rightarrow \nu_e$ oscillations rejecting $\theta_{13} = 0$ at 7.4σ**
- Updated $\nu_\mu \rightarrow \nu_e$ result expected soon
- Continue to improve constraints in Δm^2_{32} and θ_{23}
- Future will bring improved measurements and **sensitivity to CP violation, the θ_{23} octant, and the mass hierarchy**
  - Beam upgrades will accelerate POT accumulation
  - Antineutrino running pilot run proposed for 2014
  - Combined fits with NOνA and Daya Bay will open doors to new physics

Backup Slides

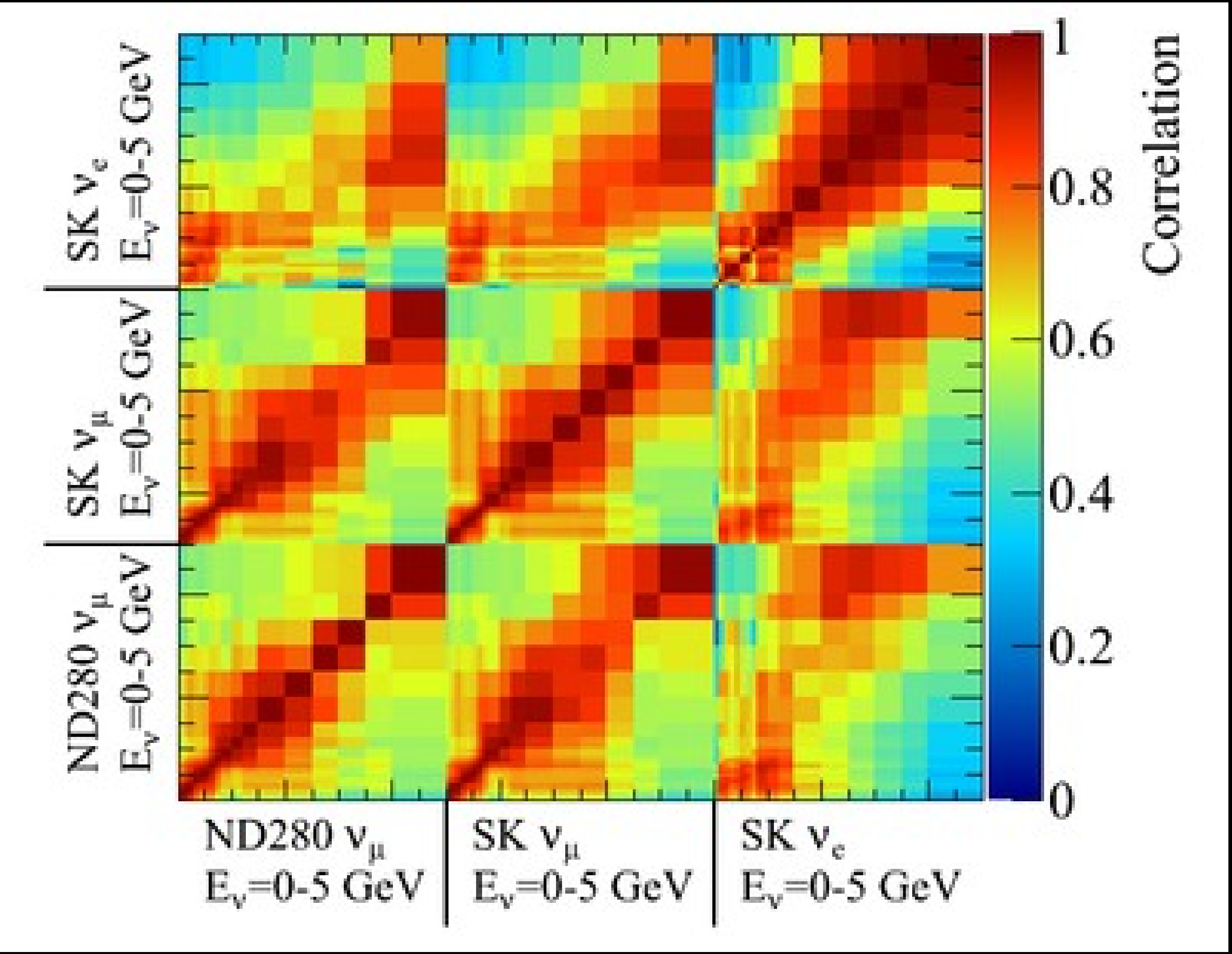
Neutrino Oscillation Formalism

$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

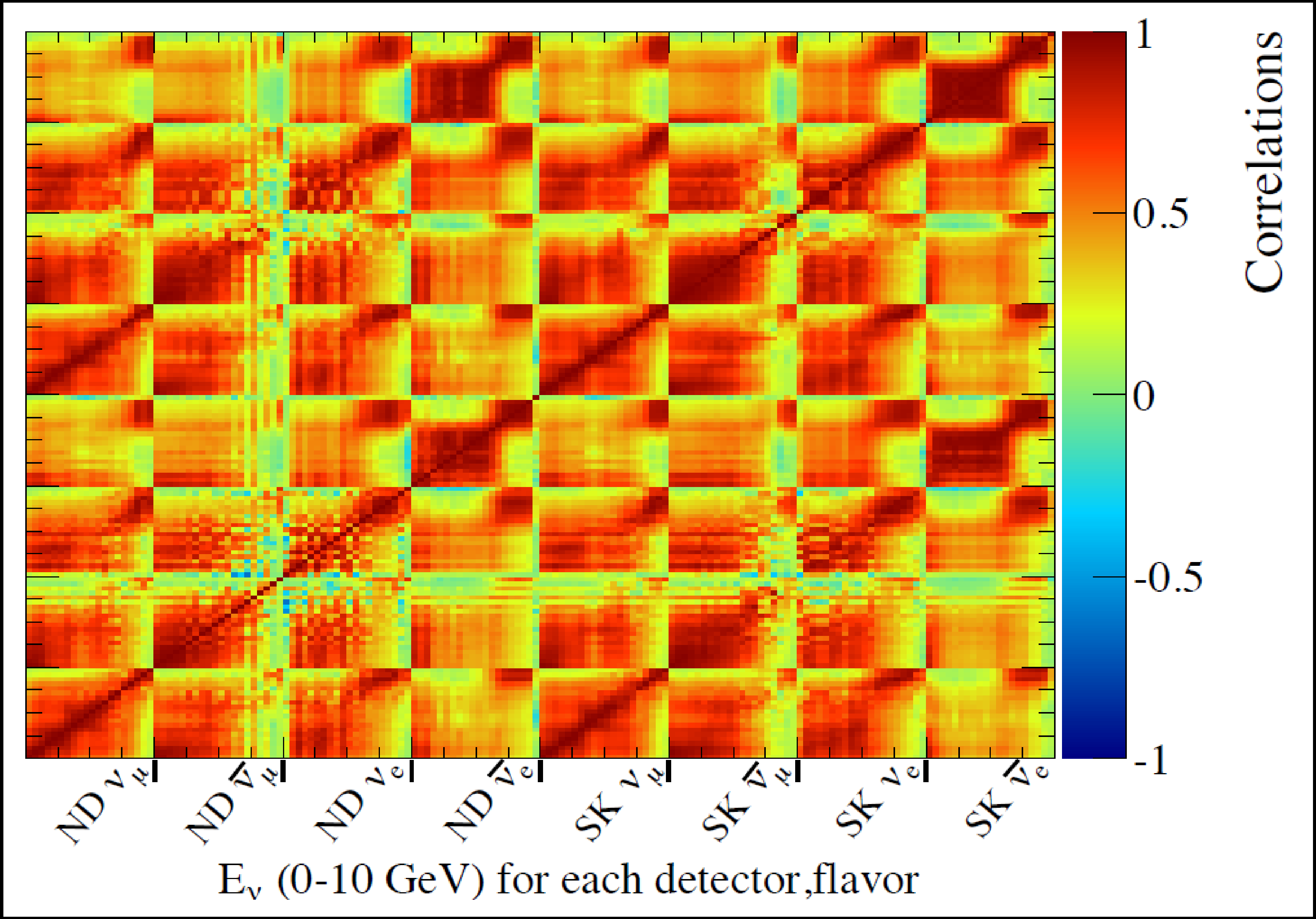
$$U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{cp}} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Phi_{31}\left(1+\frac{2a}{\Delta m_{31}^2}(1-2s_{13}^2)\right)$$
$$+\,8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos(\delta_{cp}) - s_{12}s_{13}s_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$-\,8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin(\delta_{cp})\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$+\,4s_{12}^2c_{13}^2(c_{12}^2c_{23}^2 + s_{12}^2s_{23}^2s_{13}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos(\delta_{cp}))\sin^2\Phi_{21}$$
$$-\,8c_{13}^2s_{13}^2s_{23}^2(1-2s_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

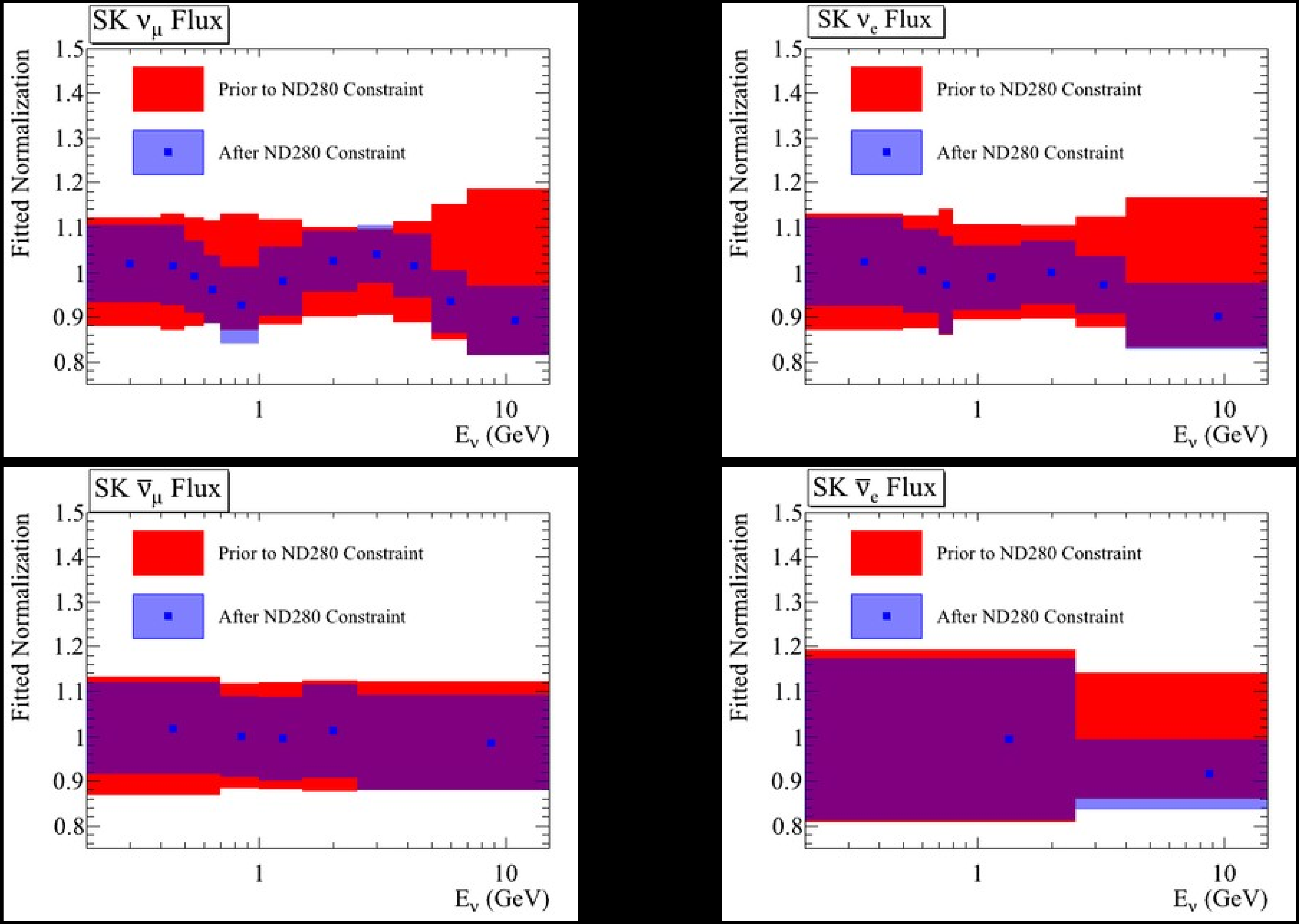
Pre-fit ND280 / SK Flux Correlations



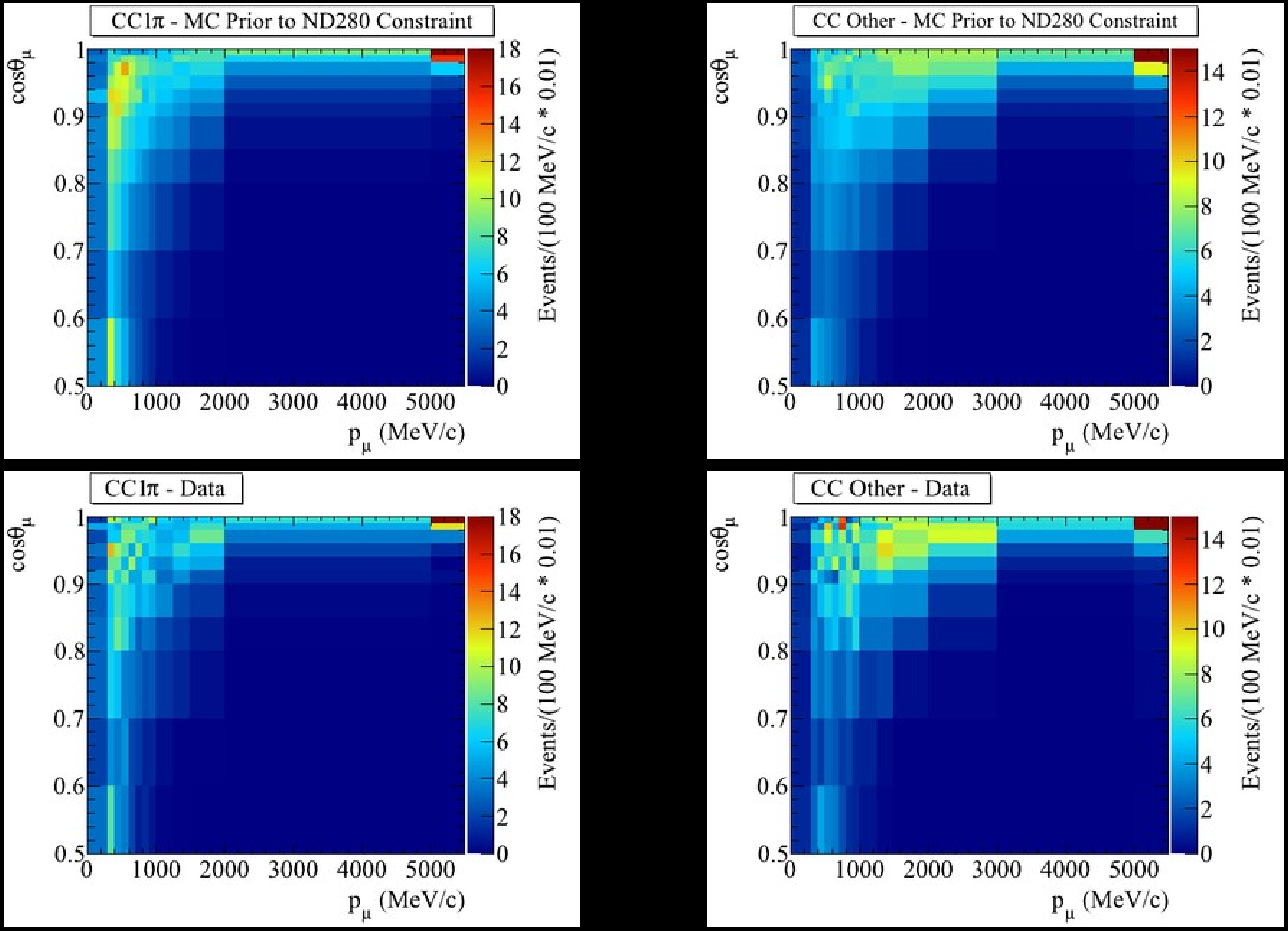
Pre-fit ND280 / SK Flux Correlations



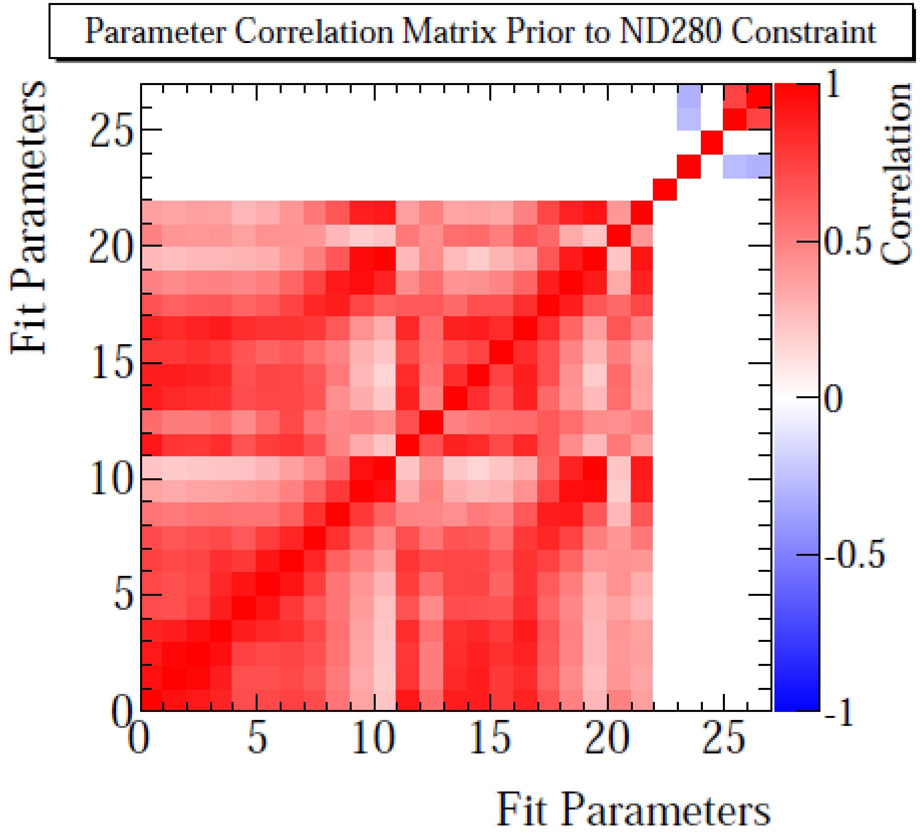
Flux Constraints – All ν Samples

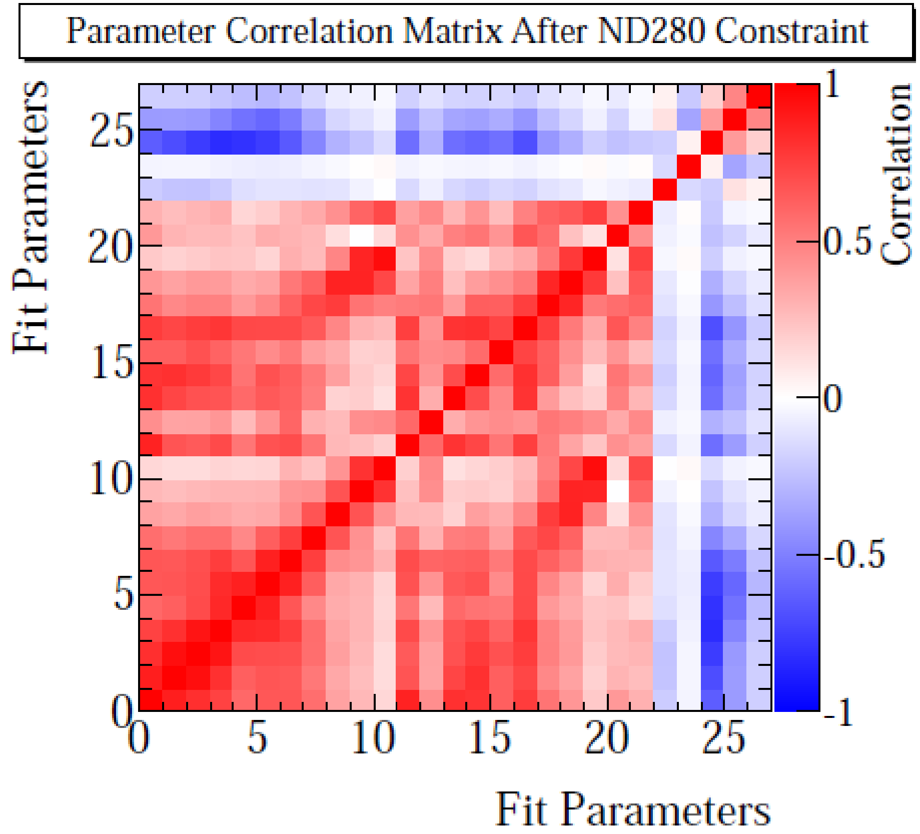


CC 1π and CC multi π samples



ND280 Pre-fit and Post-fit Matrices





Fixed Oscillation Parameters in Oscillations Fits to SK Data

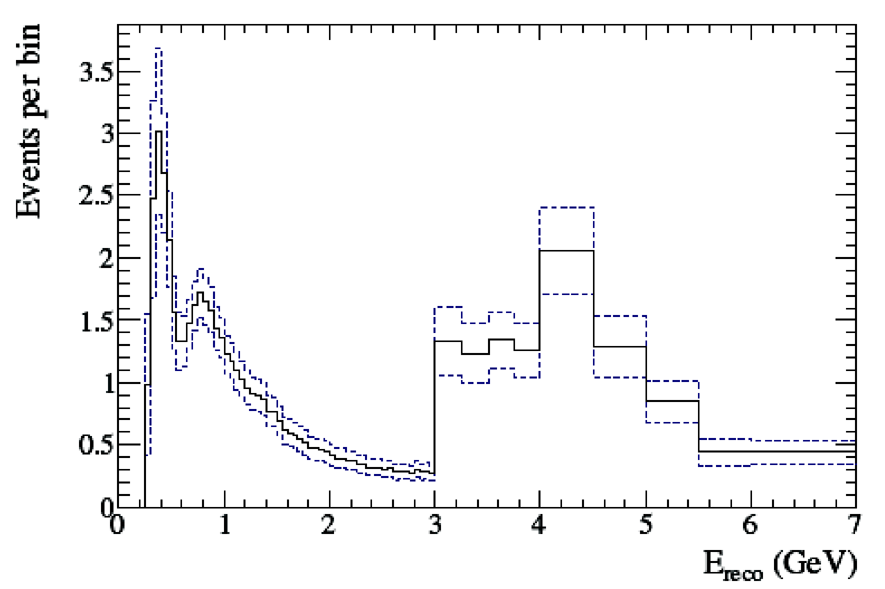
Parameter	Value
Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$
Δm^2_{32}	$2.4 \times 10^{-3}\mathrm{eV}^2$
$\sin^2 2\theta_{12}$	0.8704
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{13}$	0.1 (or 0)
δ_{CP}	0
Mass hierarchy	Normal
ν travel length	295 km
Earth density	$2.6\mathrm{g/cm}^3$

Fit Parameter in Disappearance Fits

Fit Parameter in Appearance Fits

ν_μ- Disappearance Event Rate

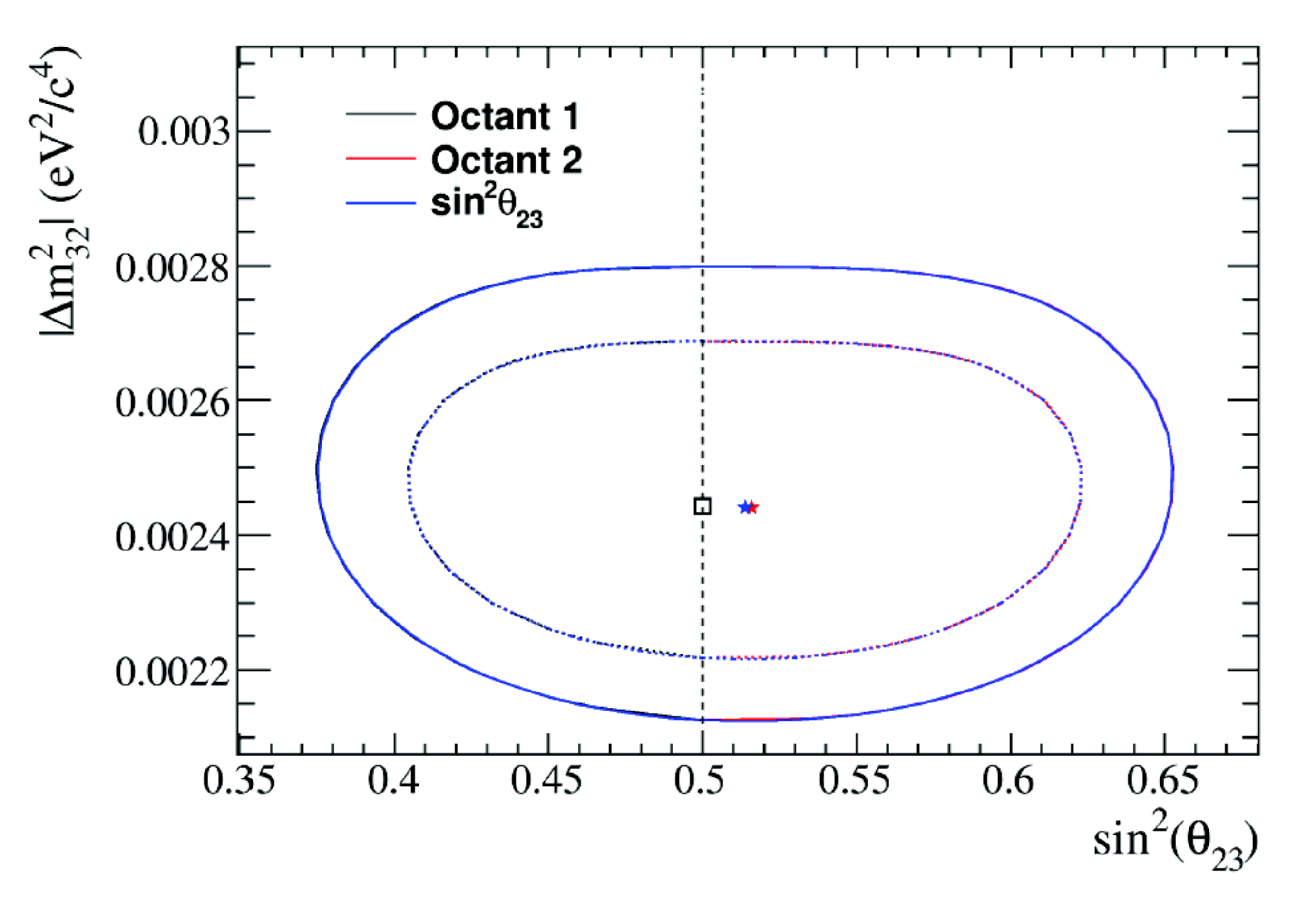
RUN1+2+3 $(\sin^2 2\theta_{23}, \Delta m^2_{32})$=(1.0, 2.4×10^{-3} eV^2)	Data	Expected				
		MC total	$\nu_\mu + \overline{\nu}_\mu$ CCQE	$\nu_\mu + \overline{\nu}_\mu$ CC non-QE	$\nu_e + \overline{\nu}_e$ CC	NC
TrueFV	-	299.35	49.67	109.50	8.62	131.56
FCFV	174	168.86	37.60	82.80	8.24	40.23
Single-ring	88	85.65	35.27	33.67	5.28	11.43
Muon-like PID	66	69.67	34.58	31.61	0.04	3.43
$p_\mu > 200\text{MeV}/c$	65	69.25	34.34	31.54	0.04	3.33
$N_{\text{decay-e}} \leq 1$	58	59.86	33.90	22.73	0.04	3.19
Efficiency from Interaction [%]	-	20.0	68.2	20.8	0.4	2.4
Efficiency from FCFV [%]	-	35.4	90.2	27.5	0.4	7.9



Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SuperK detector	10.05%	3.20%
BANFF (prefit)	21.66%	24.57%
BANFF (postfit)	4.13%	4.71%
Uncorrelated XSec	6.34%	4.18%
FSI+SI	3.49%	2.30%
Total (BANFF prefit)	25.33%	25.14%
Total (BANFF postfit)	13.32%	7.52%

$$E_\nu^{\text{rec}} = \frac{(M_n - V_{nuc}) \cdot E_l - m_l^2/2 + M_n \cdot V_{nuc} - V_{nuc}^2/2 + \left(M_p^2 - M_n^2\right)/2}{M_n - V_{nuc} - E_l + P_l \cos\theta_{\text{beam}}},$$

ν_μ- Disappearance Comparison

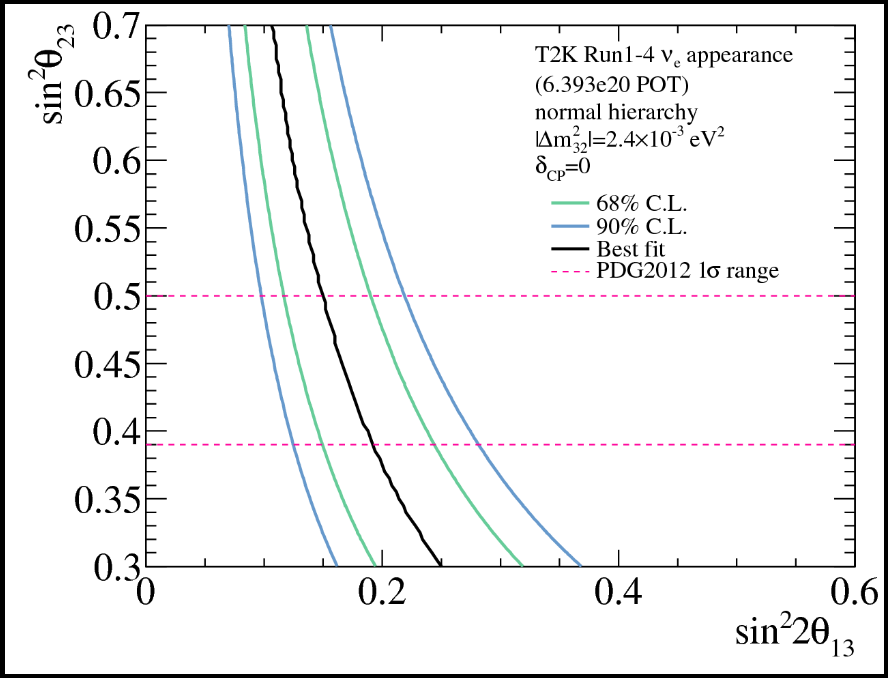


	$\sin^2 2\theta_{23}$	Δm_{32}^2	χ^2 / ndf	N_{obs}	N_{exp}	p-value
$\theta_{23} \leq \pi/4$	1.000	2.44e-3	56.04 / 71	58	57.97†	0.83
$\theta_{23} \geq \pi/4$	0.999	2.44e-3	56.03 / 71		57.92†	0.82

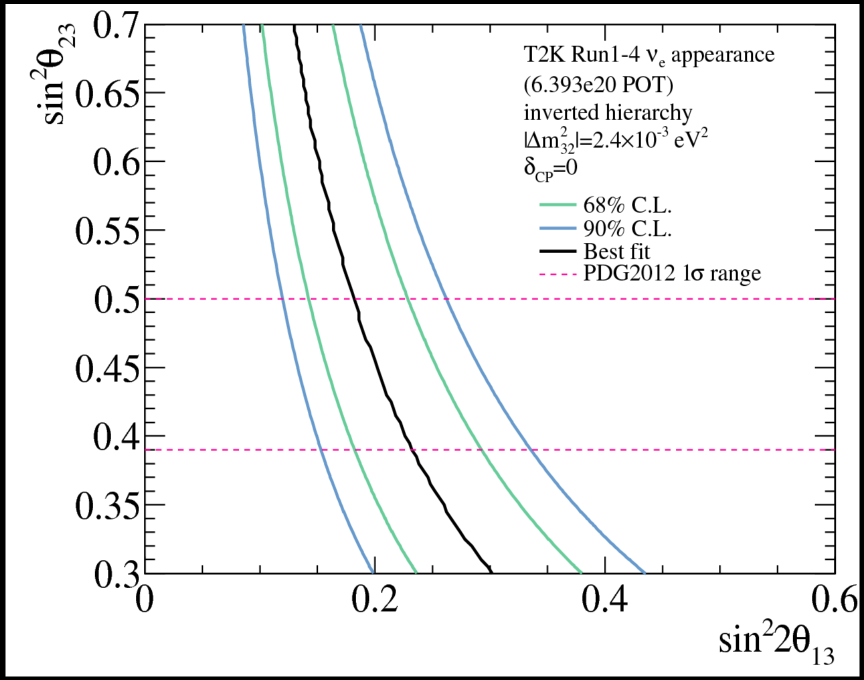
† Null Oscillation Expectation 204.7±16.7

ν_e- Appearance $\sin^2(\theta_{23})$ -vs- $\sin^2(2\theta_{13})$

Normal Hierarchy

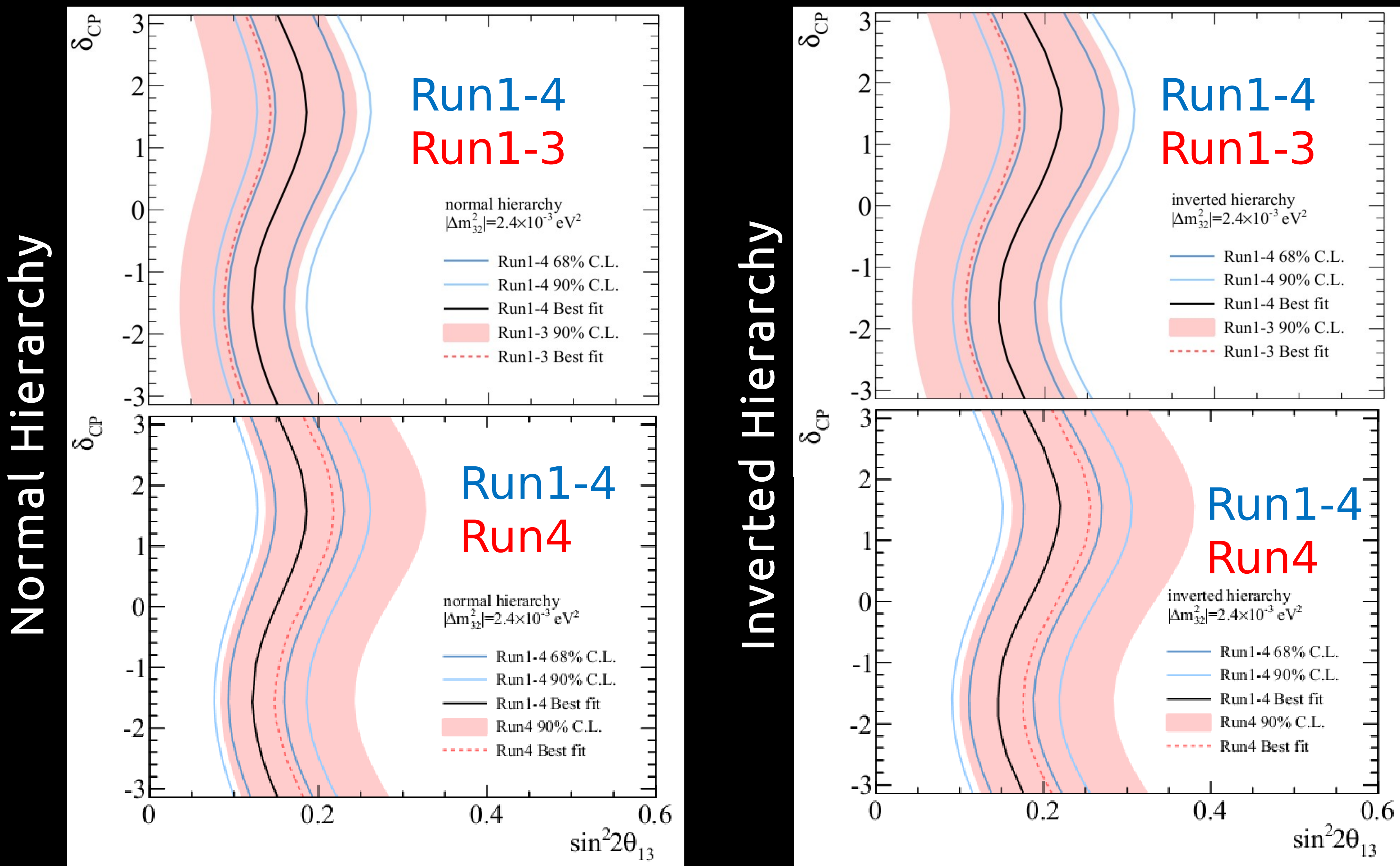


Inverted Hierarchy



- Dotted lines indicate 2012 1σ range on $\sin^2(\theta_{23})$
- Large effect on the best-fit central value
- Error bands increase for lower values of $\sin^2(\theta_{23})$

ν_e- Appearance Runs 1-3 vs Run 4



ν_e- Appearance Event Rate Prediction and Uncertainties

2013 Event Rate Predictions

$\sin^2 2\theta_{13} = 0.1$	Nominal	Pre ND280 fit	Post ND280 fit
ν_e CC signal	17.4	17.9	16.0
ν_μ background	1.1	1.2	0.9
$\overline{\nu}_\mu$ background	0.1	0.1	0.1
ν_e background	3.0	3.3	2.9
$\overline{\nu}_e$ background	0.2	0.2	0.1
Total	21.6	22.6	20.4

$\sin^2 2\theta_{13} = 0.0$	Nominal	Pre ND280 fit	Post ND280 fit
ν_e CC signal	0.4	0.4	0.4
ν_μ background	1.1	1.2	0.9
$\overline{\nu}_\mu$ background	0.1	0.1	0.1
ν_e background	3.3	3.5	3.2
$\overline{\nu}_e$ background	0.2	0.2	0.2
Total	4.9	5.3	4.6

Run 1-4 → 6.393×10^{20} POT

Systematic Uncertainties

Error source		$\sin^2 2\theta_{13} = 0.1$	
		Pre ND280 fit	Post ND280 fit
Flux	Fit to ND280	11.6	7.6
M_A^{QE} (GeV)		21.2	3.2
M_A^{RES} (GeV)		3.4	1.0
CCQE norm ($E_\nu < 1.5$ GeV)		9.1	6.3
CC1π norm ($E_\nu < 2.5$ GeV)		4.0	2.1
NC1π^0 norm		0.6	0.4
CC other shape (GeV)	Other Cross Section	0.1	0.1
Spectral function		6.1	6.1
p_F (MeV)		0.1	0.1
CC coherent norm		0.2	0.2
NC coherent norm		0.2	0.2
NC1$\pi^\pm$+NC other norm		0.5	0.5
$\sigma_{\nu_e CC}/\sigma_{\nu_\mu CC}$		2.9	2.9
W shape (MeV)		0.2	0.2
Pionless delta decay		3.6	3.6
SK detector efficiency	SK	2.4	2.4
FSI+SI		2.3	2.3
Photo-nuclear		0.8	0.8
SK energy scale		0.5	0.5
Total		27.9	8.9

ν_e- Appearance Event Rate Prediction and Uncertainties

2013 Event Rate Predictions

$\sin^2 2\theta_{13} = 0.1$

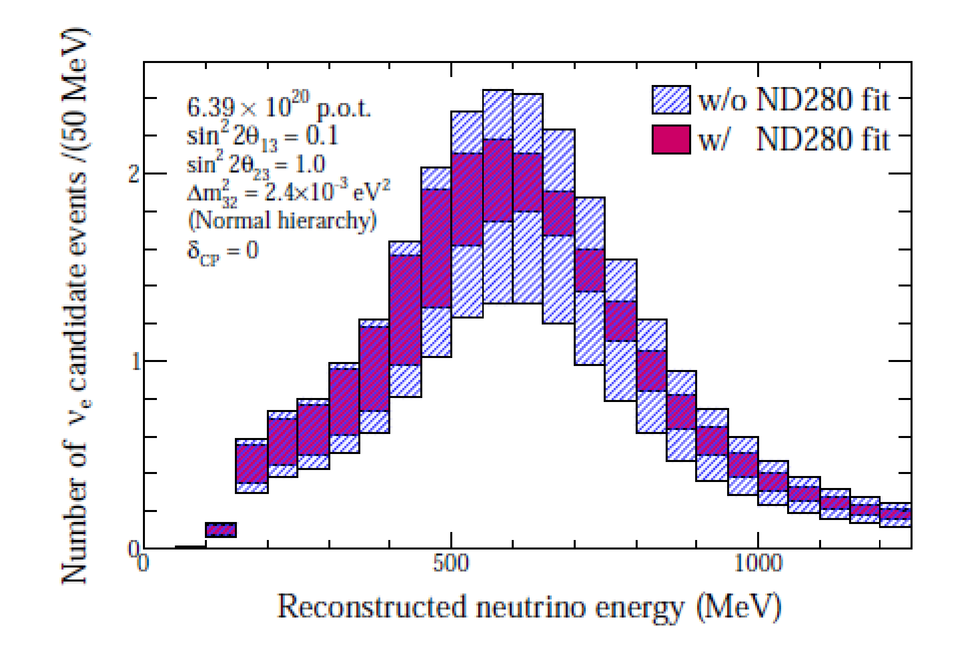
	Nominal	Pre ND280 fit	Post ND280 fit
ν_e CC signal	17.4	17.9	16.0
ν_μ background	1.1	1.2	0.9
$\overline{\nu}_\mu$ background	0.1	0.1	0.1
ν_e background	3.0	3.3	2.9
$\overline{\nu}_e$ background	0.2	0.2	0.1
Total	21.6	22.6	20.4

$\sin^2 2\theta_{13} = 0.0$

	Nominal	Pre ND280 fit	Post ND280 fit
ν_e CC signal	0.4	0.4	0.4
ν_μ background	1.1	1.2	0.9
$\overline{\nu}_\mu$ background	0.1	0.1	0.1
ν_e background	3.3	3.5	3.2
$\overline{\nu}_e$ background	0.2	0.2	0.2
Total	4.9	5.3	4.6

Run 1-4 → 6.393×10^{20} POT

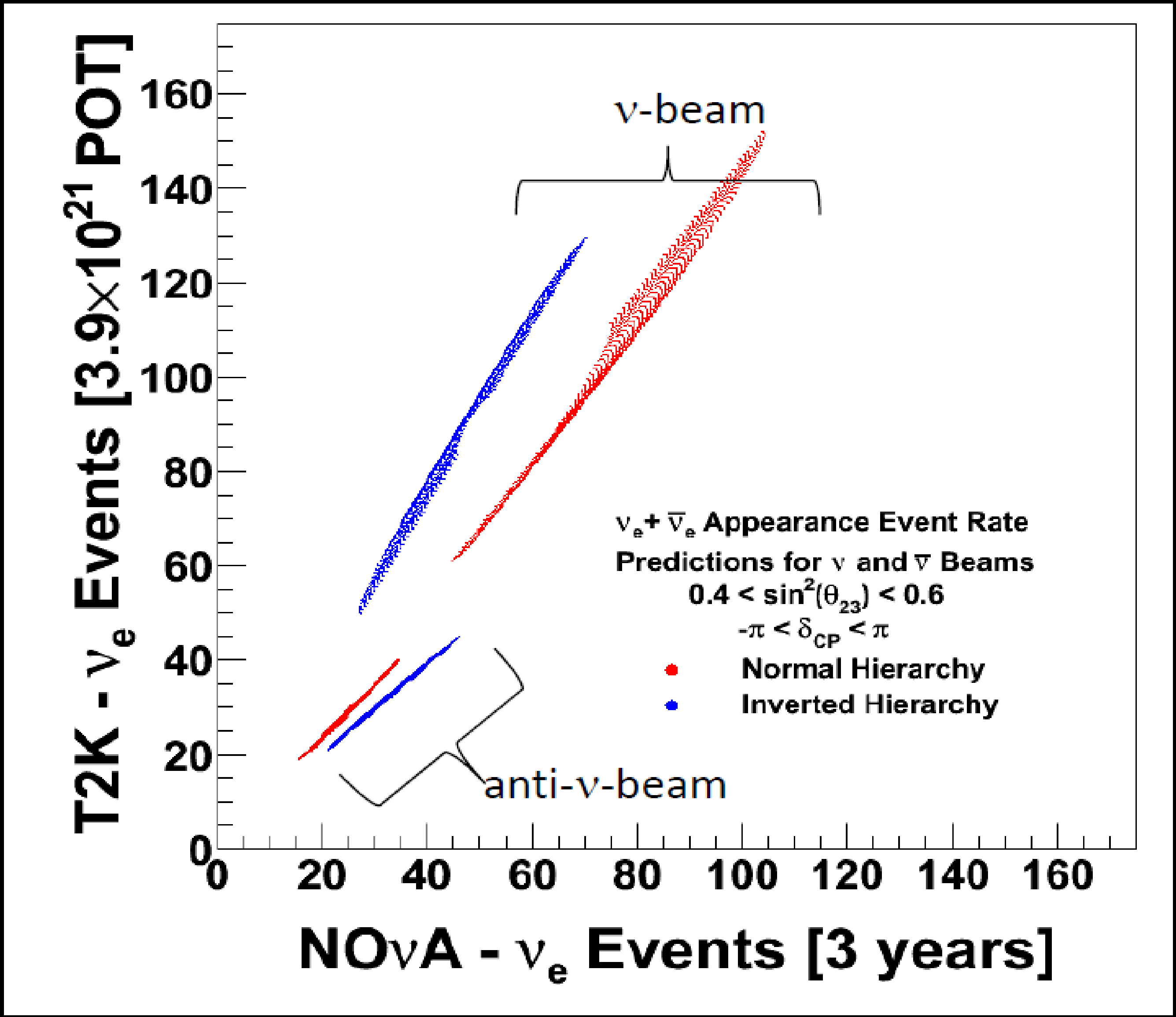
Systematic Uncertainties



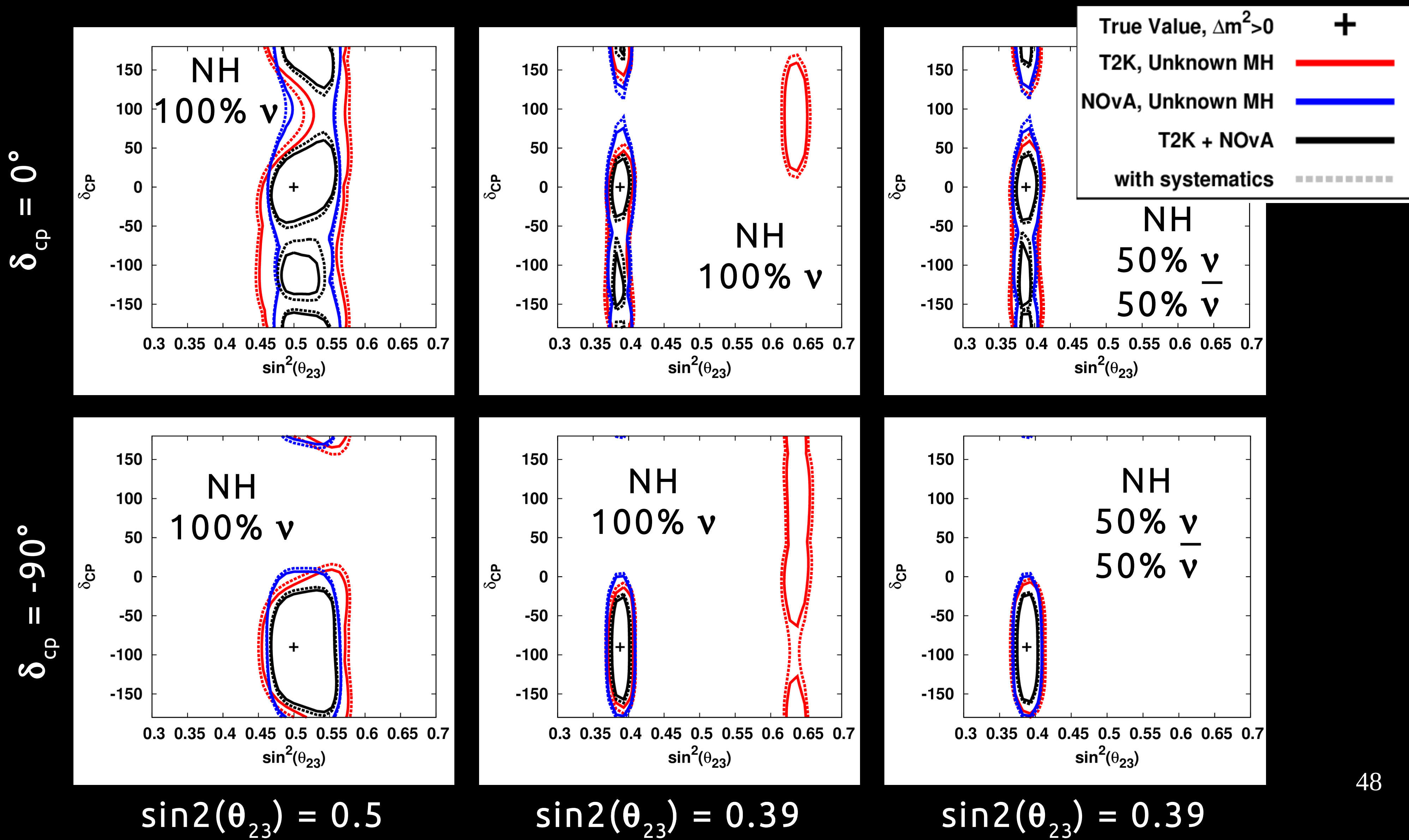
$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)},$$

- Other Backup for nue?:
  - contribution of rate and shape terms?
  - P-value calculation
  - Erec analyis

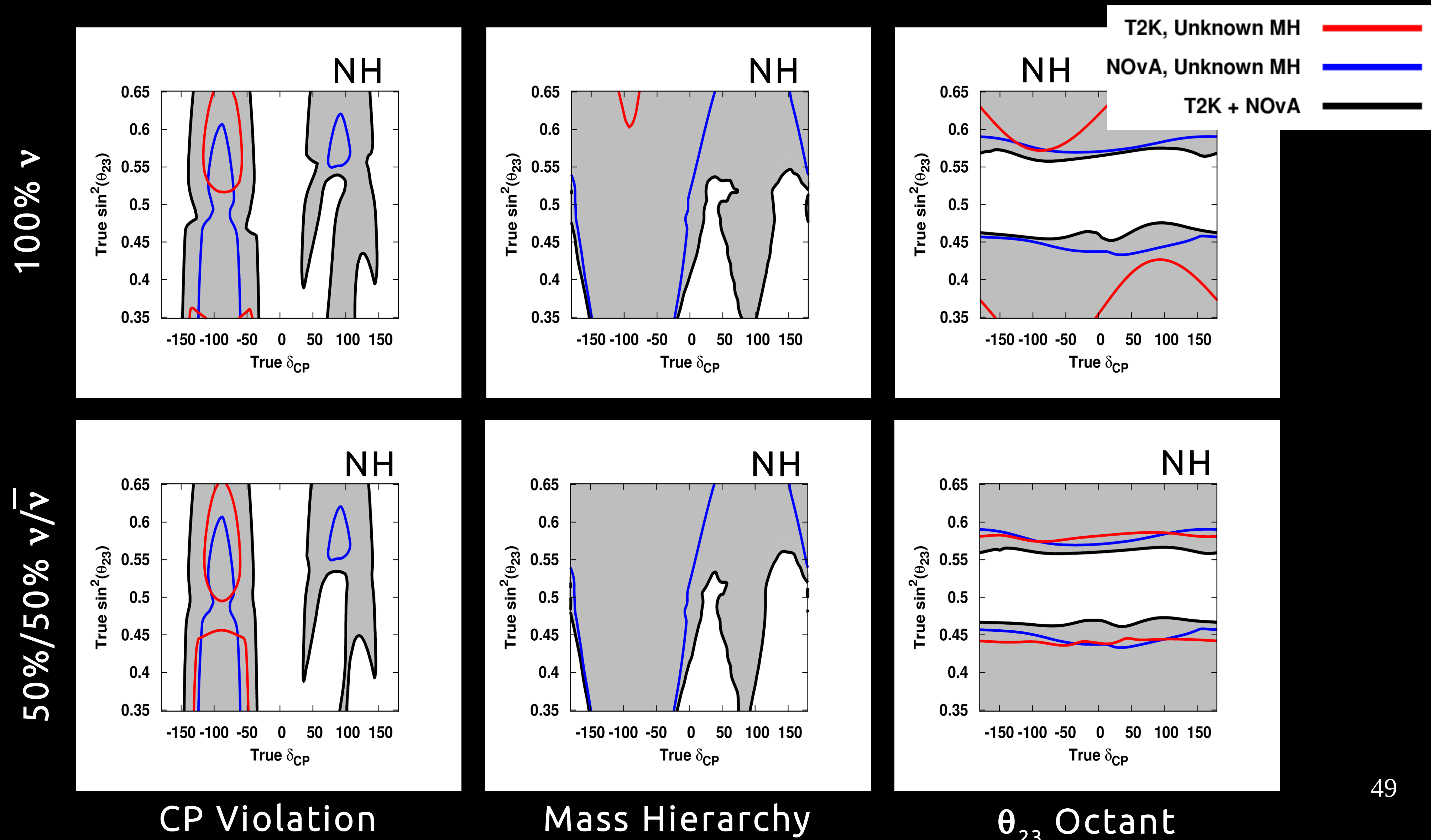
Event Rate Expectations for T2K and NOνA



T2K + NovA + Daya Bay: Allowed Regions in δ_{cp}-vs- $\sin^2(\theta_{23})$



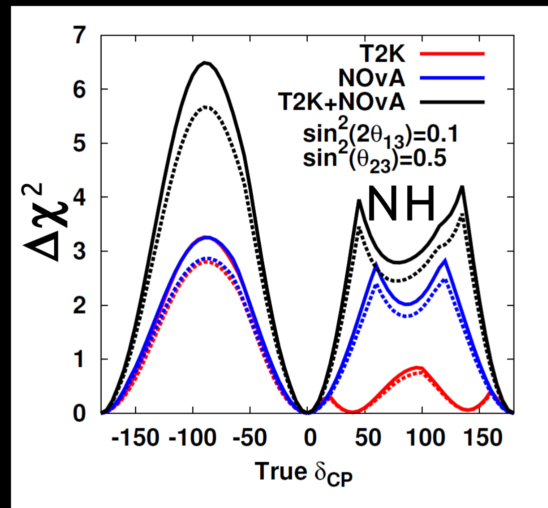
T2K + NoνA + Daya Bay: 90% C.L. Regions in δ_{cp}-vs- $\sin^2(\theta_{23})$

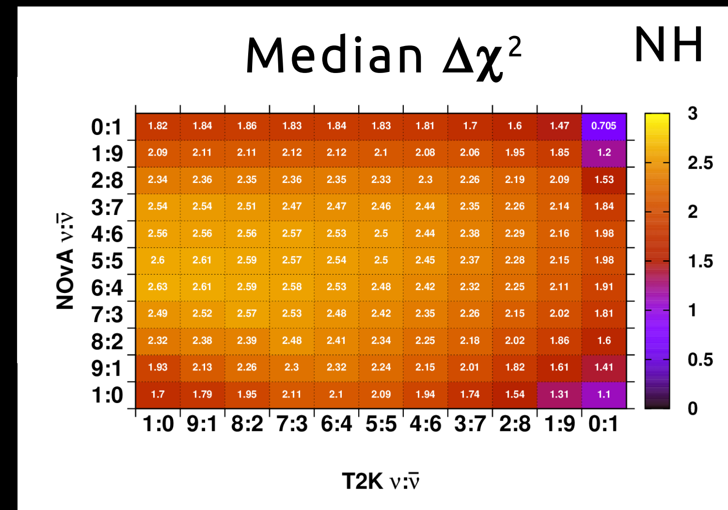


Combined Sensitivities and Optimal Run Plan

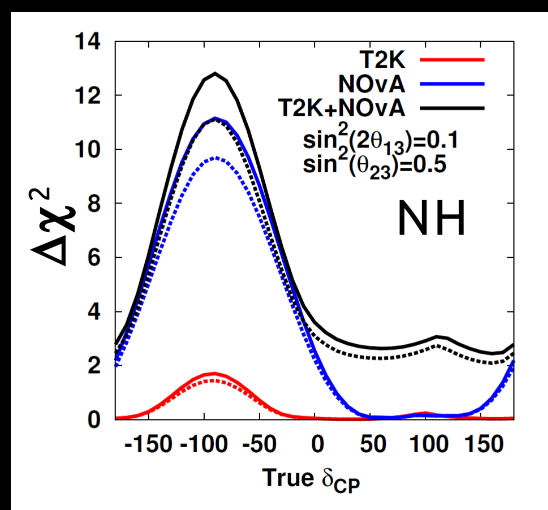
- CPV sensitivity
  - Greatly enhanced by combined fit
  - **Flat for run ratios $\nu > 30\%/70\%\ \nu/\bar{\nu}$**
- Mass Hierarchy
  - Almost no sensitivity alone
  - Large enhancement to NOvA degenerate region
  - **Prefers more ν running in combined fit**
- Evaluated other metrics
- Metrics mostly flat for: $70\%/30\% < \nu/\bar{\nu} < 30\%/70\%$

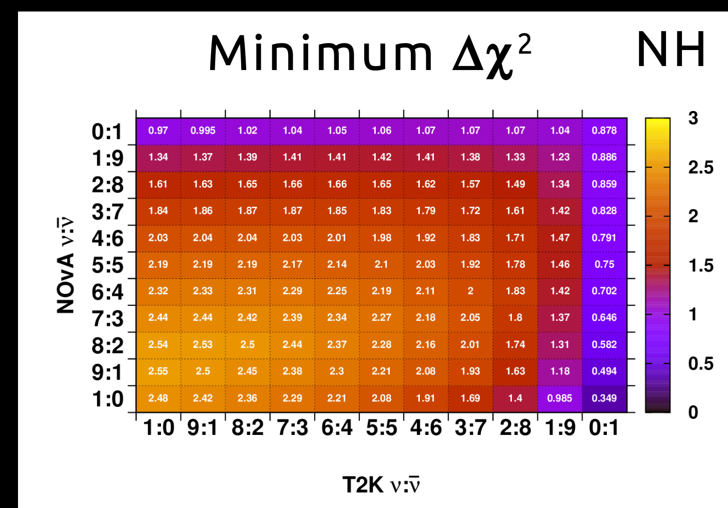
CPV Determination





MH Determination





$50\%/50\%\ \nu/\bar{\nu}$ running

Variable $\nu/\bar{\nu}$ running