CP-Violation search at T2K

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On behalf of the T2K Collaboration

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MICHIGAN STATE UNIVERSITY

T2K

Office of Science
U.S. Department of Energy

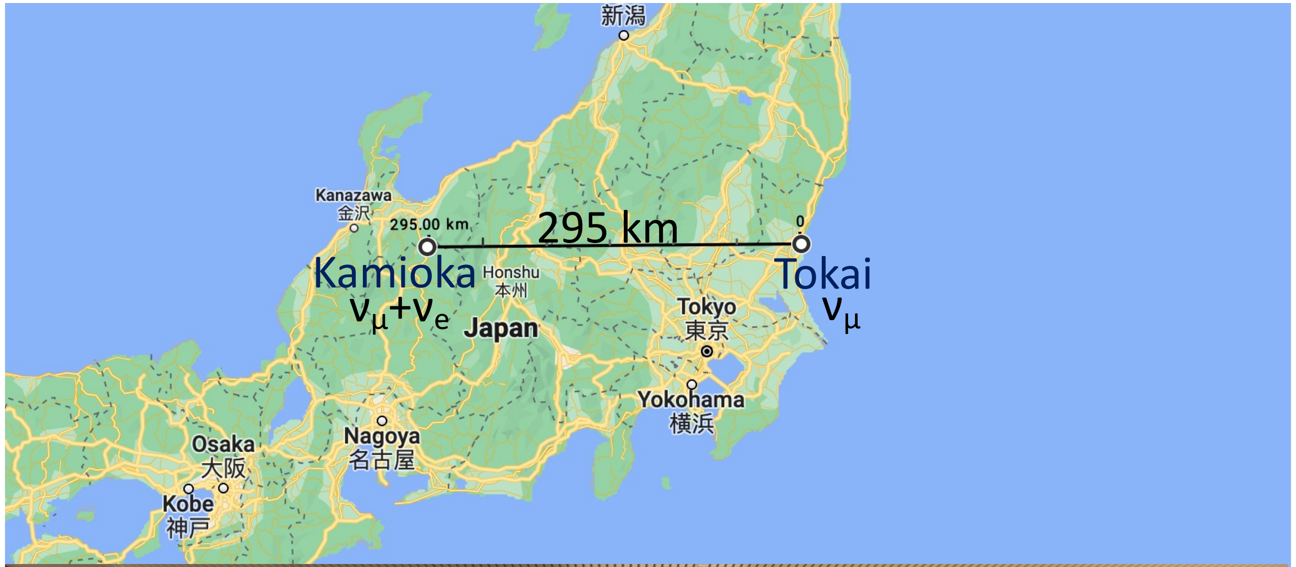
THE UNIVERSITY of MISSISSIPPI 1848

The T2K Experiment

The Tokai to Kamioka experiment

Goals of the T2K experiment:

1. Measure the mixing angles θ_{23} and θ_{13}
2. Measure and determine its sign of Δm^2_{32}
3. Constrain δ_{CP}
4. Measure neutrino interaction cross-sections



International collaboration of
~500 Members
From 78 Institutes
In 12 Countries

Neutrino Oscillations

In the 3-Flavor PMNS model:

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

$s_{ij} = \sin\theta_{ij}$

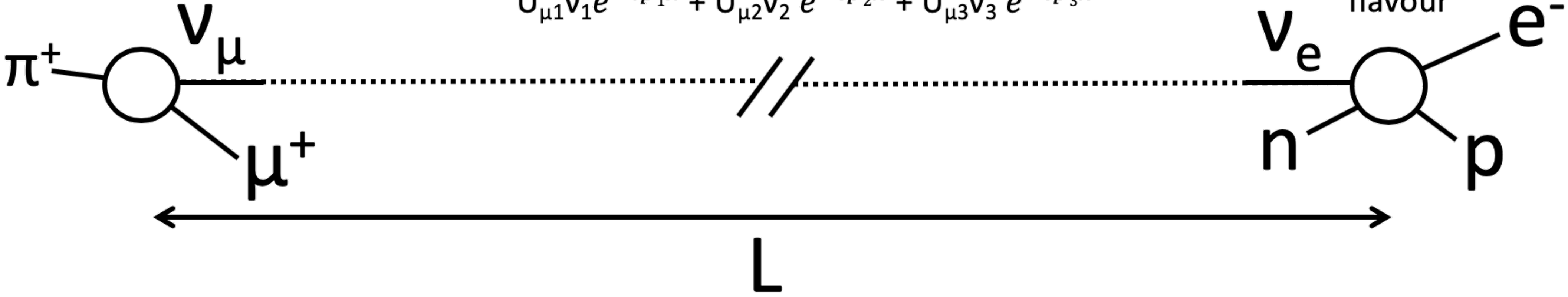
$c_{ij} = \cos\theta_{ij}$

Pure weak state is a combination of mass states

Mass states evolve and interfere as they travel

$U_{\mu 1}\nu_1 e^{-ip_1 x} + U_{\mu 2}\nu_2\, e^{-ip_2 x} + U_{\mu 3}\nu_3\, e^{-ip_3 x}$

No longer a pure weak state, the neutrino may interact as a different flavour



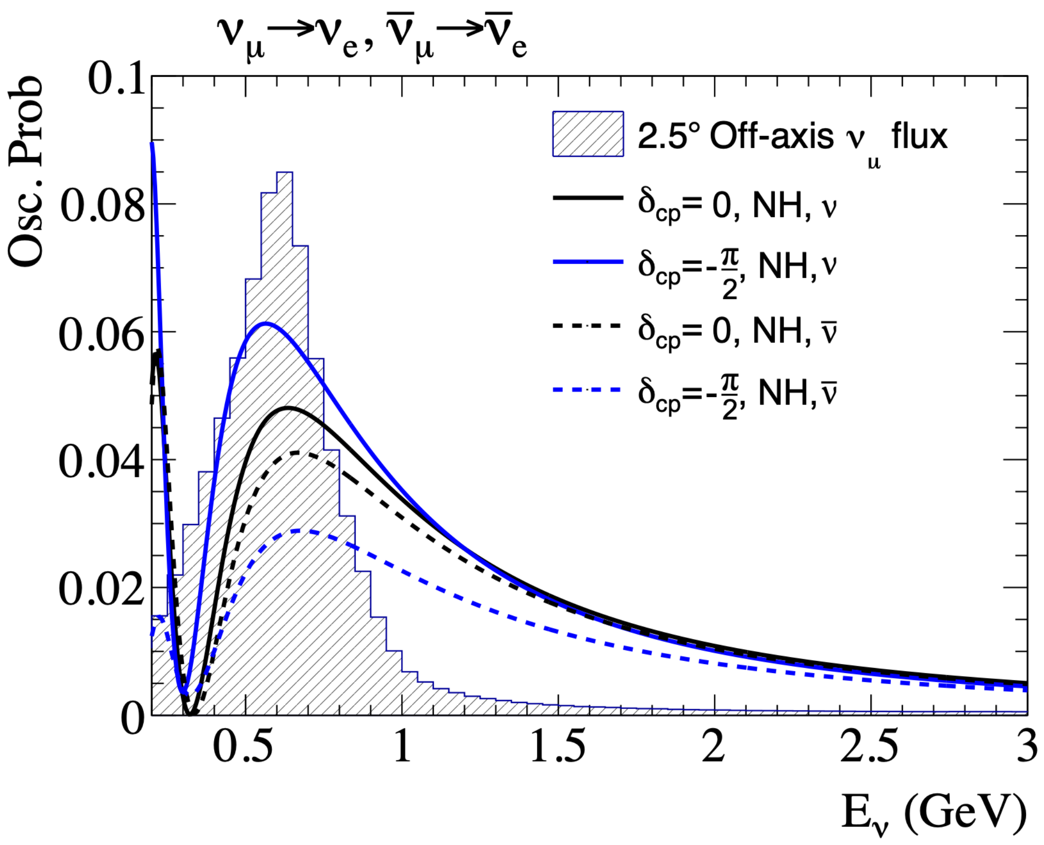
CPV searches in LBL experiments

$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$
$$\mp 1.27\Delta m^2_{32}\frac{L}{E_\nu} 8J_{CP}\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$

Sign flips for antineutrino

Jarlskog Invariant:

$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$$

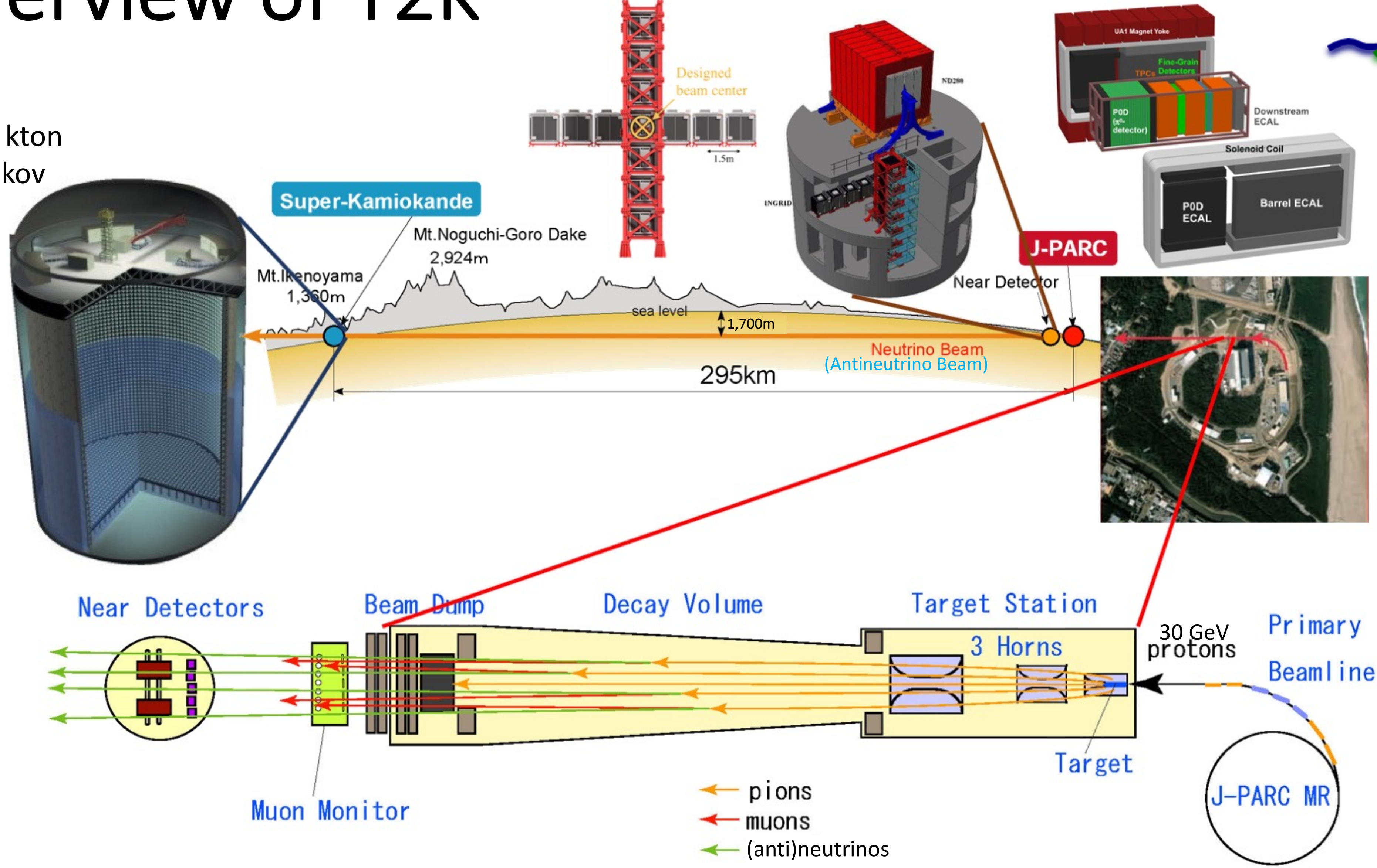


CP-Violation is indicated by the combined enhancement and suppression of opposite sign ν_e / $\bar{\nu}_e$ appearance signals

Overview of T2K

ND280 is a magnetized tracking detector

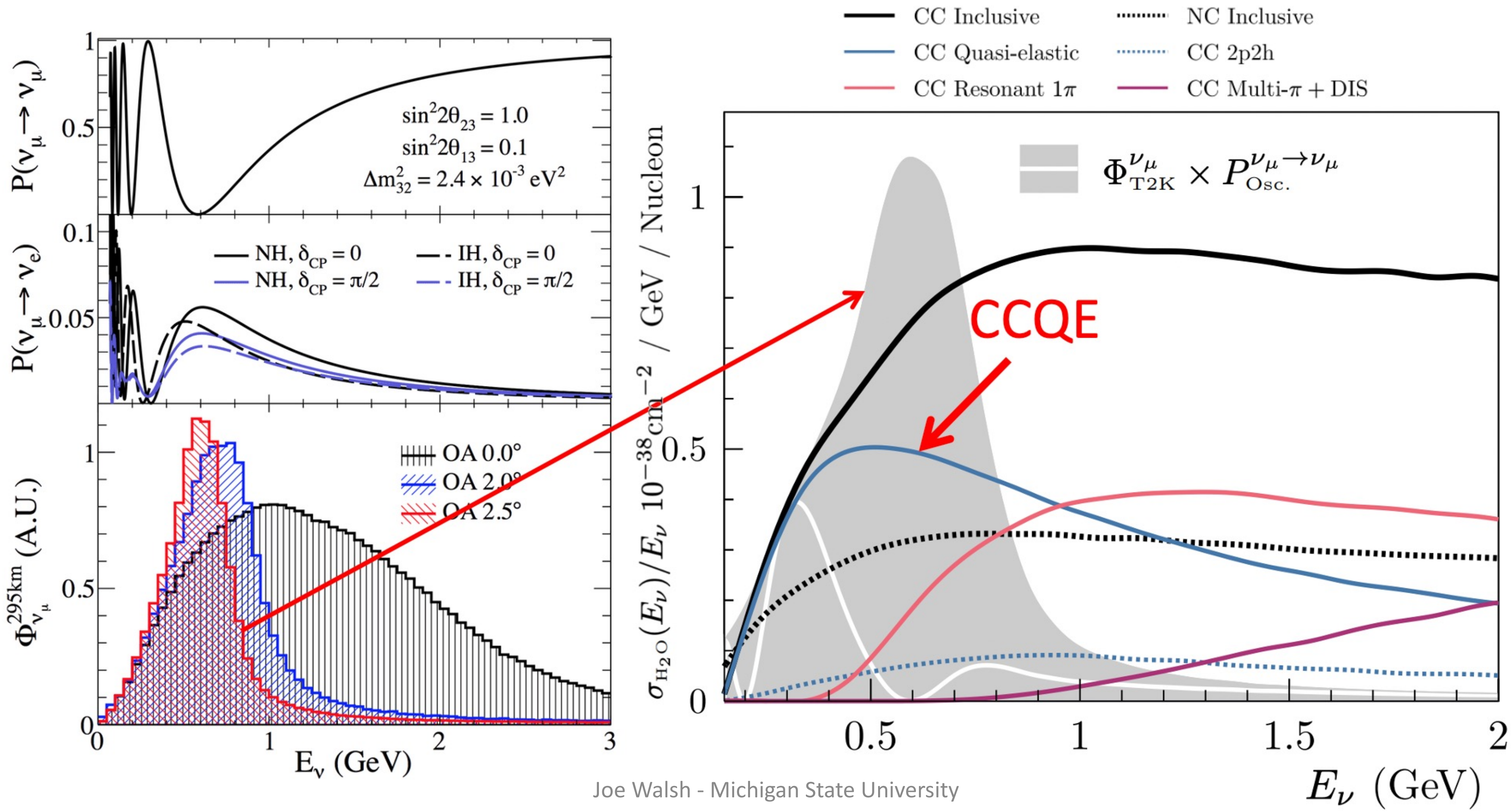
Super-K is a 50 kton water Cherenkov detector



Magnetic horns select for π^+ or π^- which decay producing ν or $\bar{\nu}$

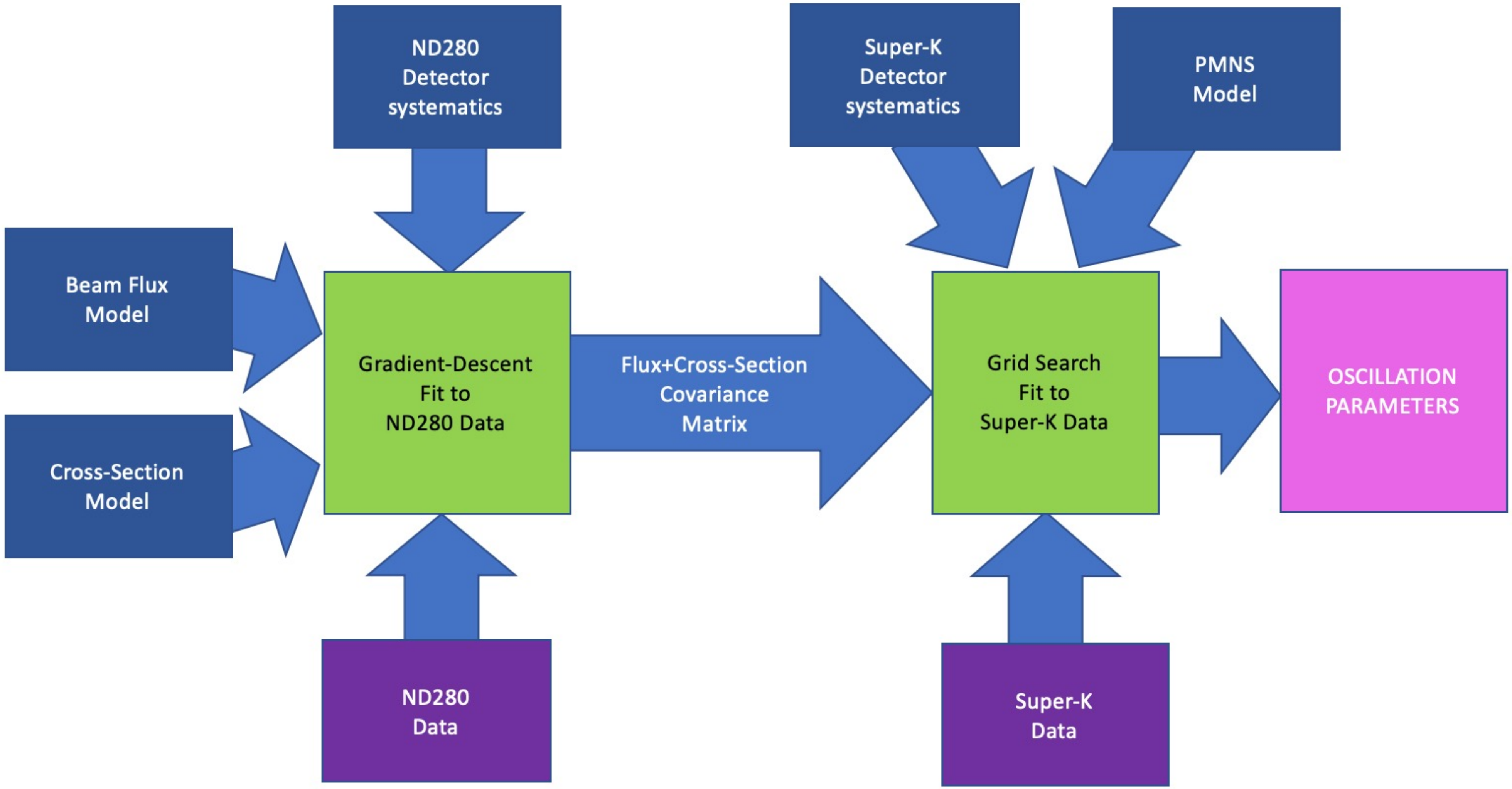
Off-axis angle

Enhances flux at 600 MeV maximizing oscillation probability for a baseline of 295 km



The T2K Analysis

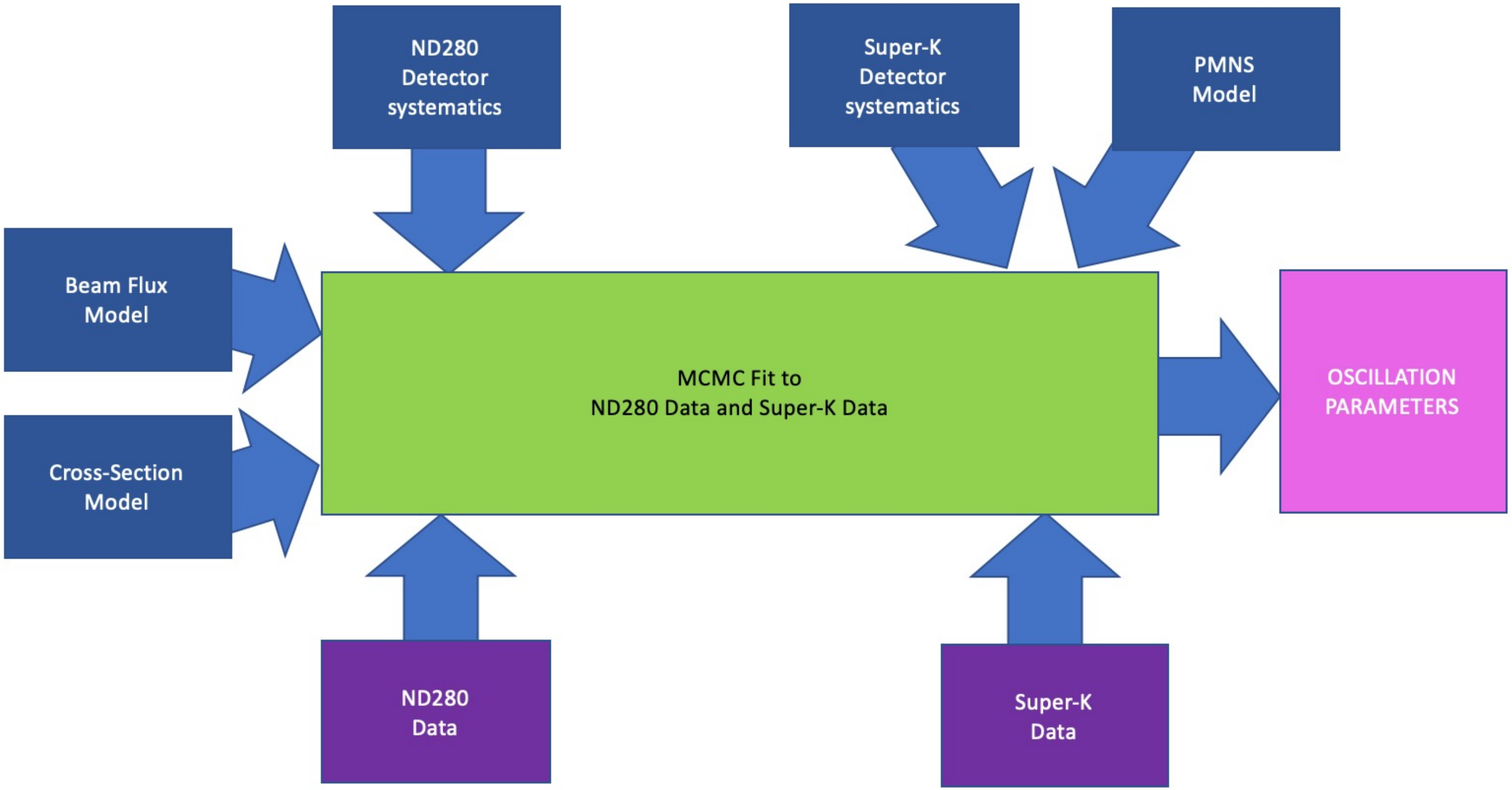
Sequential (Frequentist)



For more in-depth analysis details see Ali's talk

The T2K Analysis

Simultaneous (Bayesian)

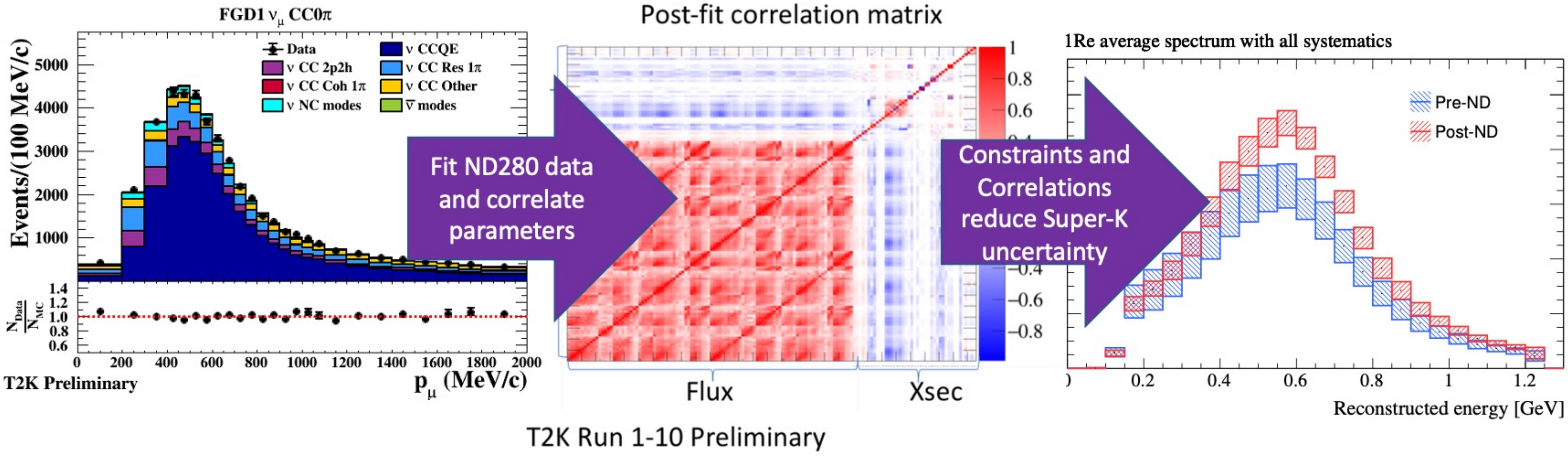


For more in-depth analysis details see Ali's talk

ND280 Constraint

Better predict SK spectra by fitting flux and xsec to ND280 spectra

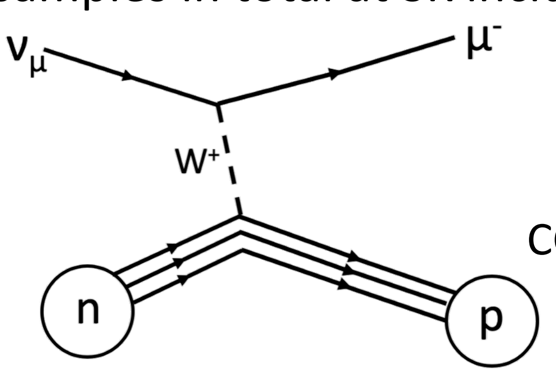
Constrain wrong-sign background (ν in $\bar{\nu}$-beam or $\bar{\nu}$ in ν-beam)



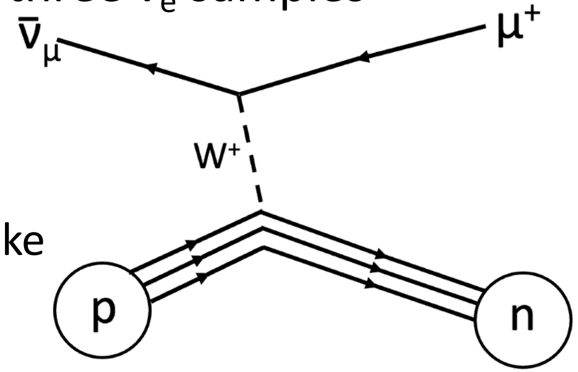
For more in-depth analysis details see Ali's talk

Super-K $\nu_e/\bar{\nu}_e$ data

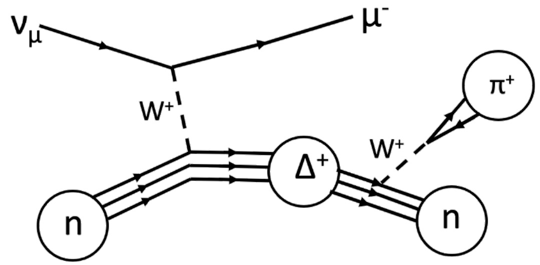
5 samples in total at SK including three ν_e samples

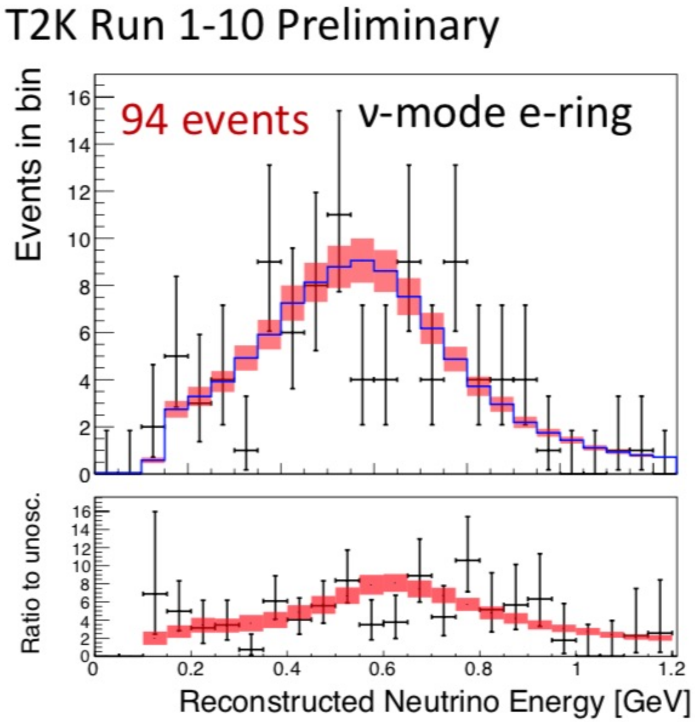


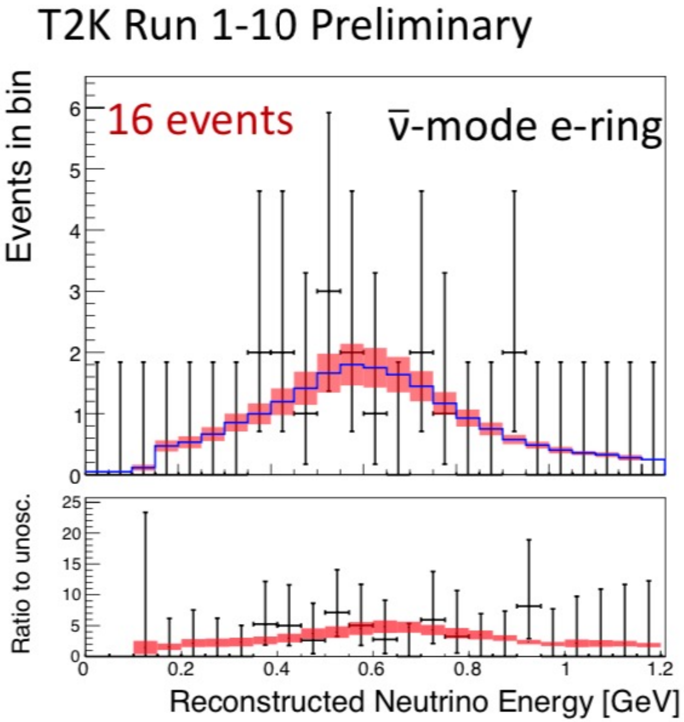
CCQE-like

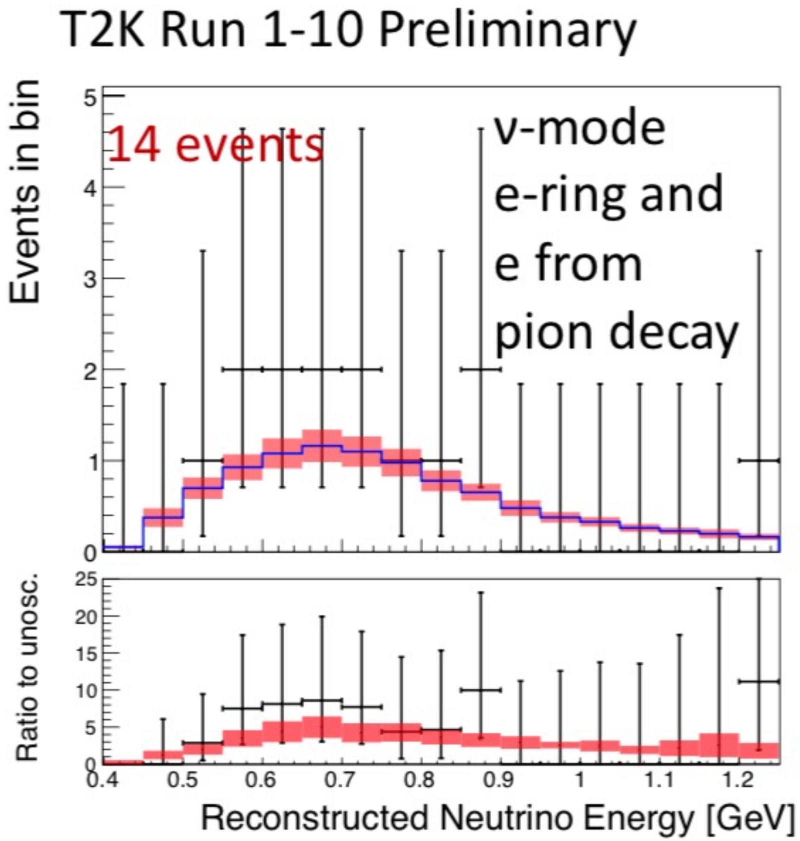


CC-Resonant-like

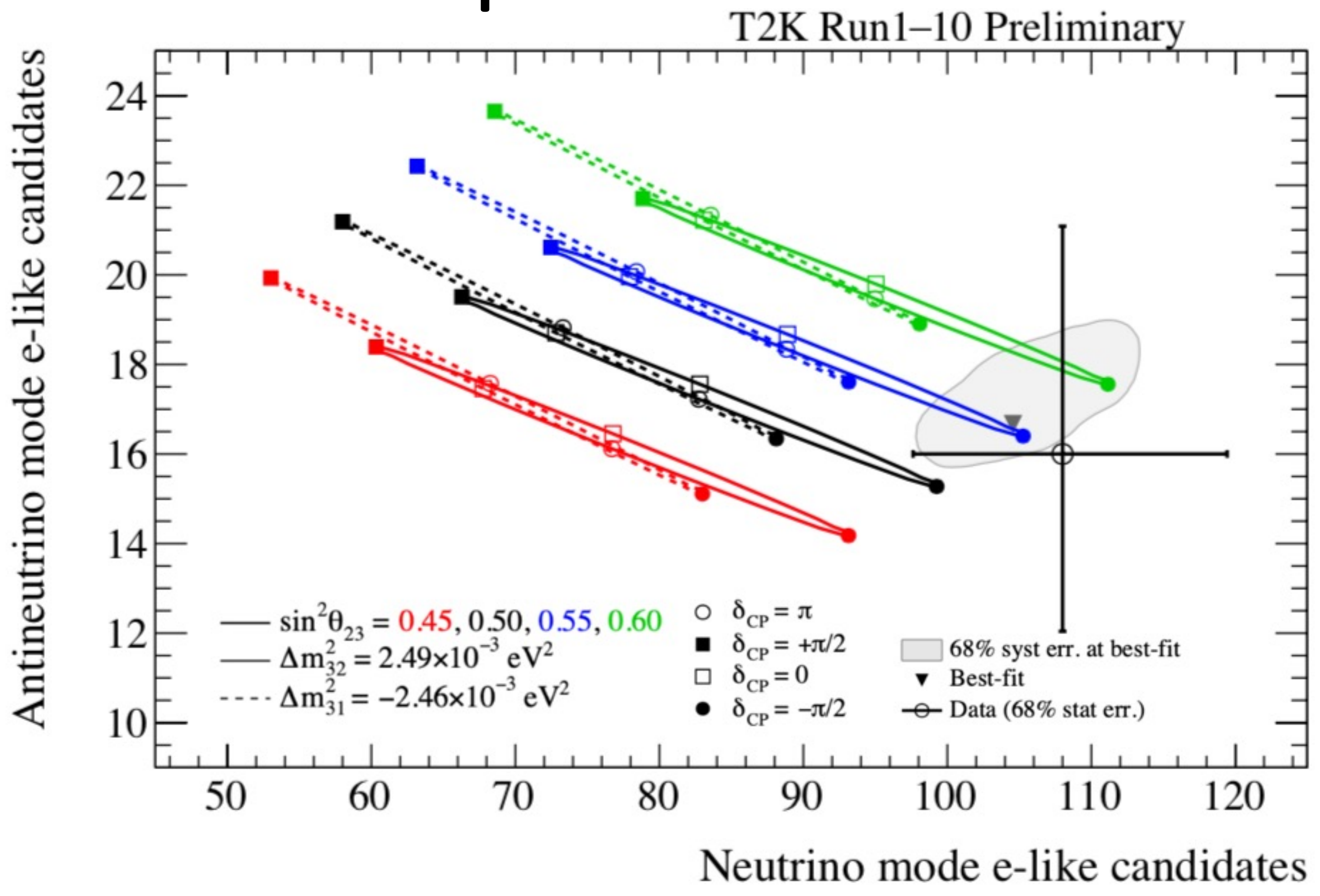


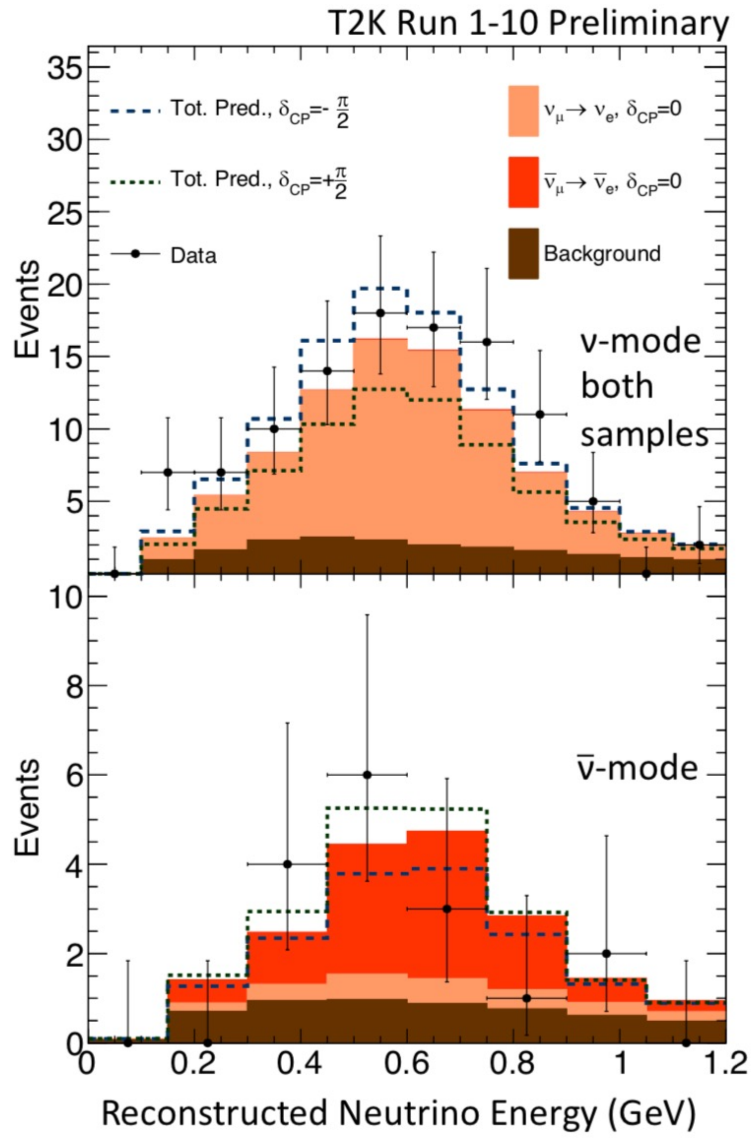






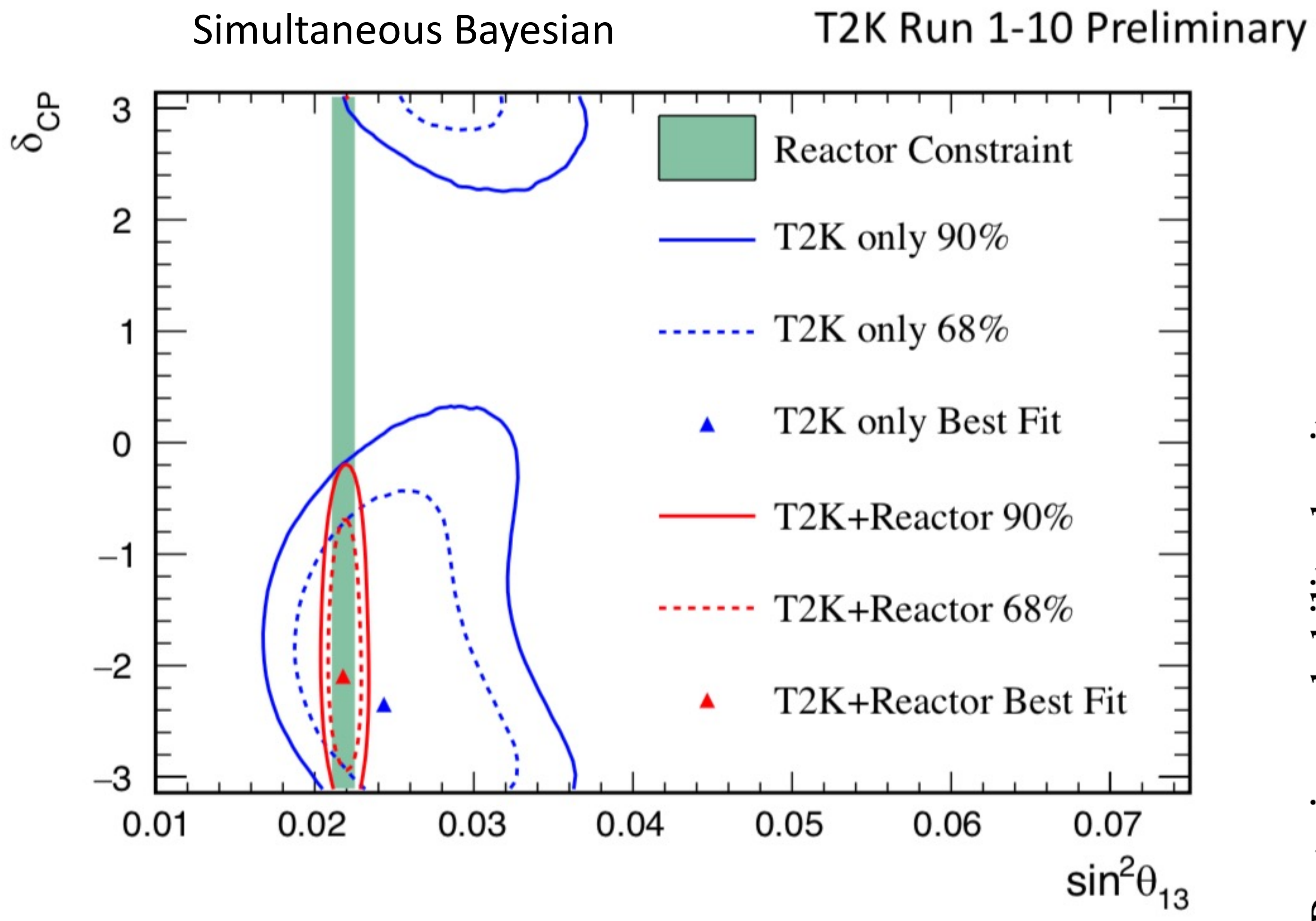
PMNS comparison



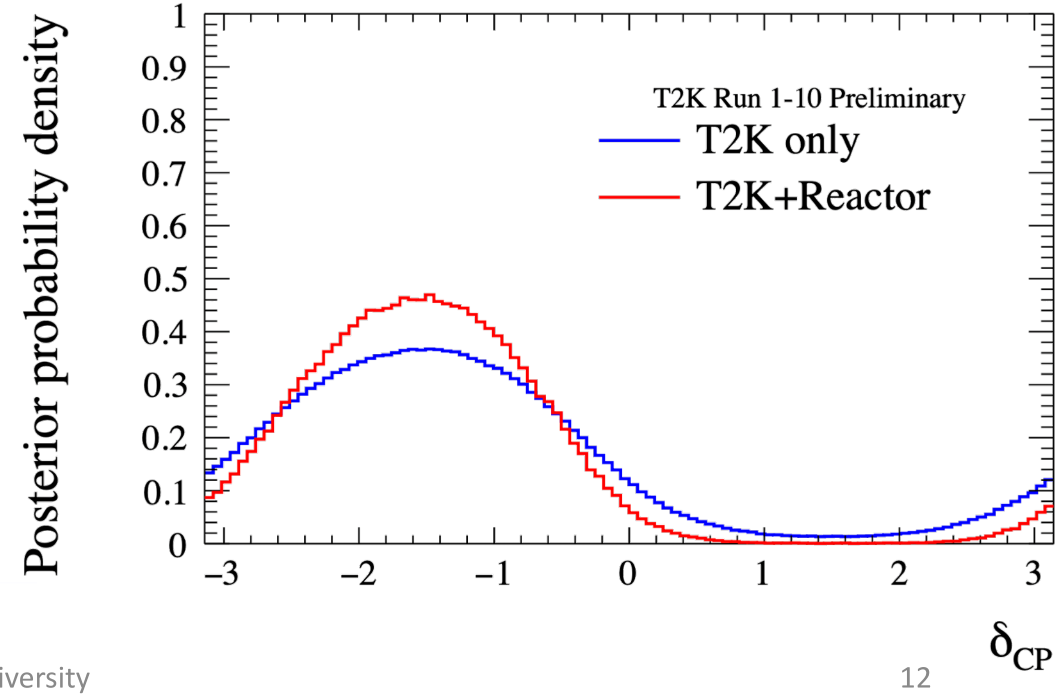


$\nu_e\ /\bar{\nu}_e$ data most consistent with $\delta_{\rm CP}$ =-π/2, upper octant θ_{23} and normal ordered masses

Reactor experiments constraint on θ_{13}



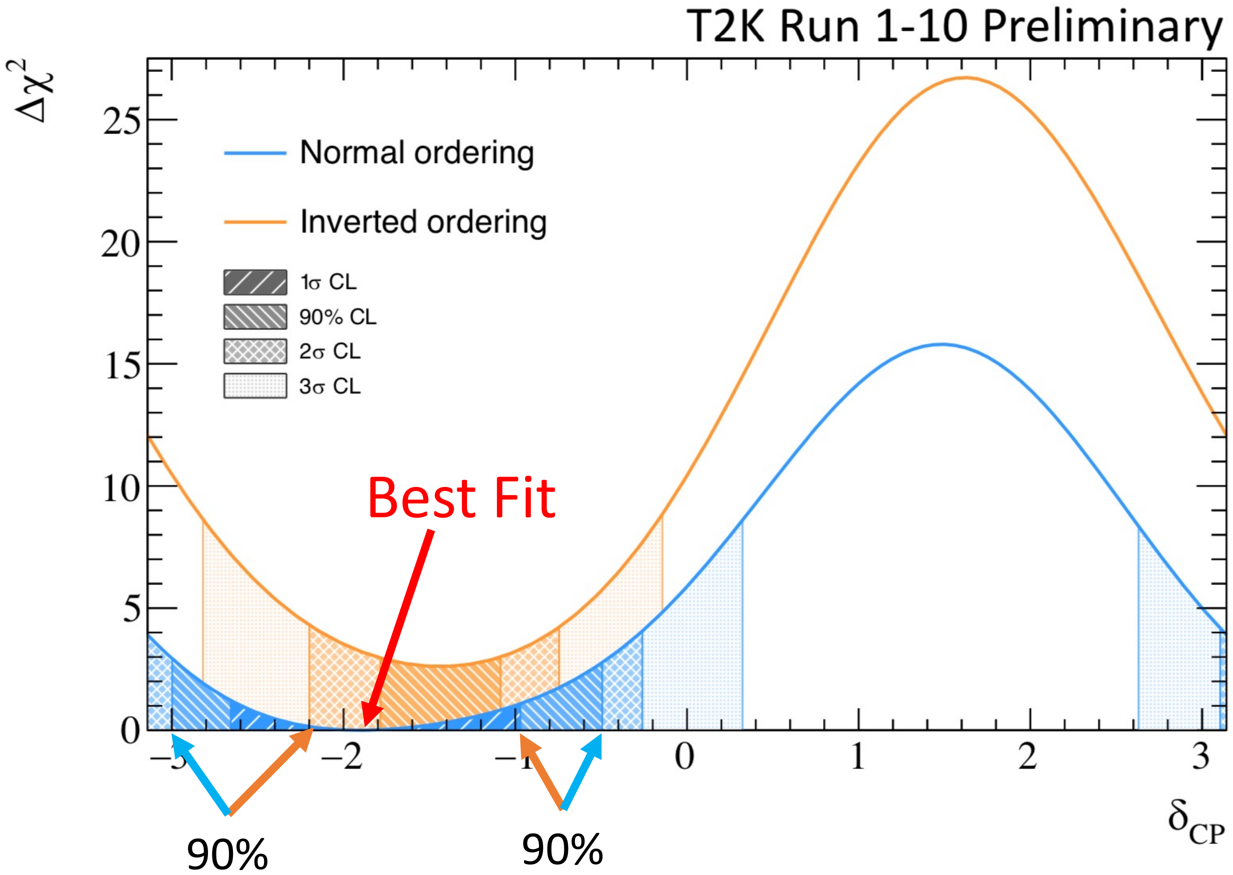
Using the PDG 2019 global average of the reactor neutrino experiment measurements of θ_{13} , we can get a better constraint on δ_{CP}



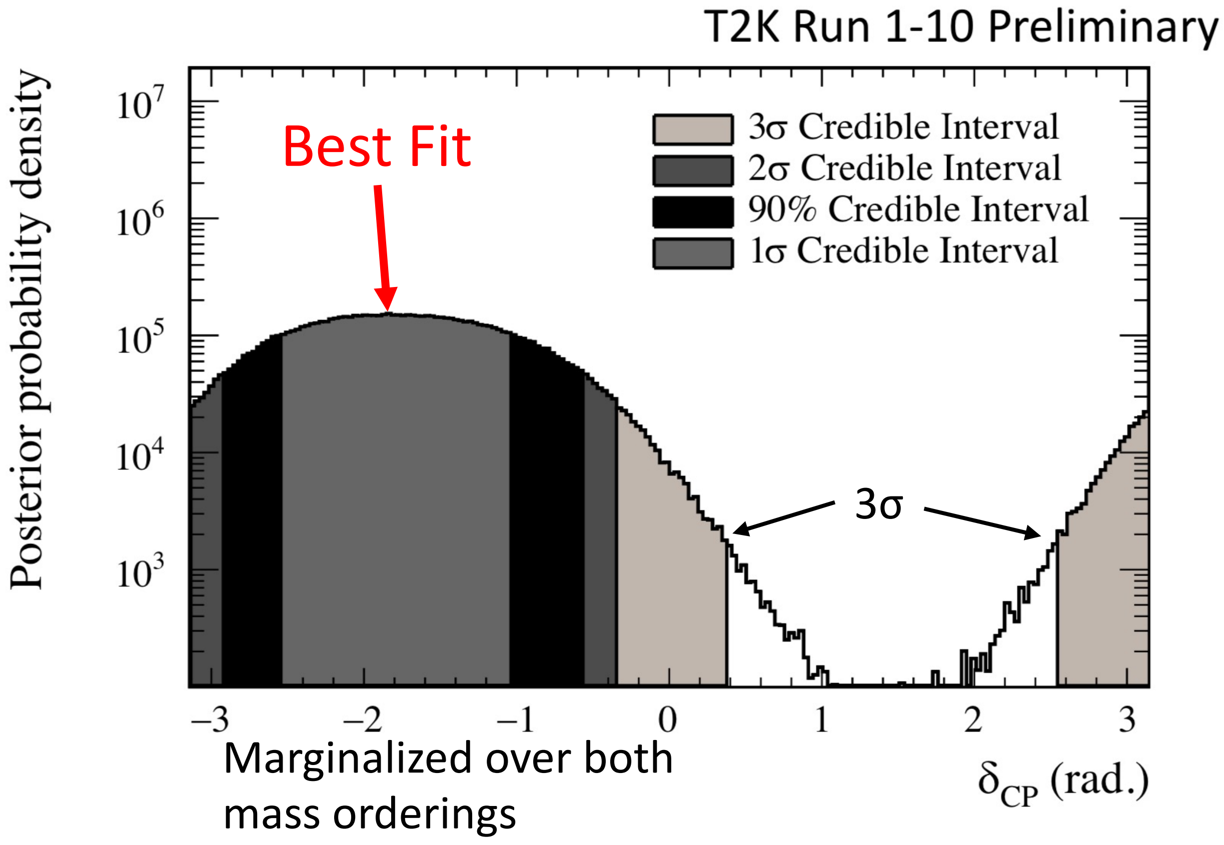
δ_{CP} constraint

Exclude CP-conserving values at the 90% CL across both mass orderings

Sequential (Frequentist)

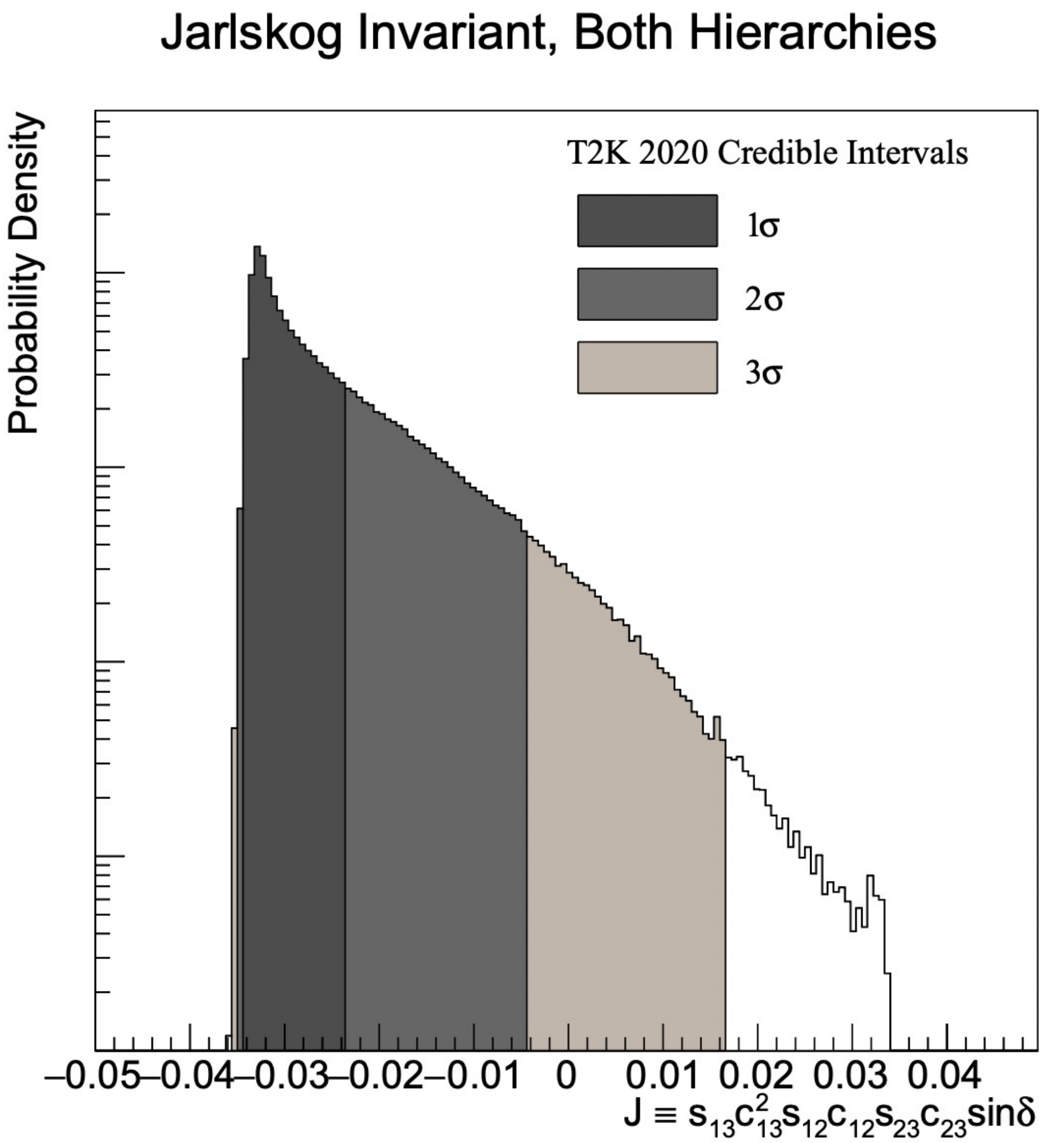


Simultaneous (Bayesian)



Exclude 35% around +π/2 to 3σ

Jarlskog Invariant



$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$$

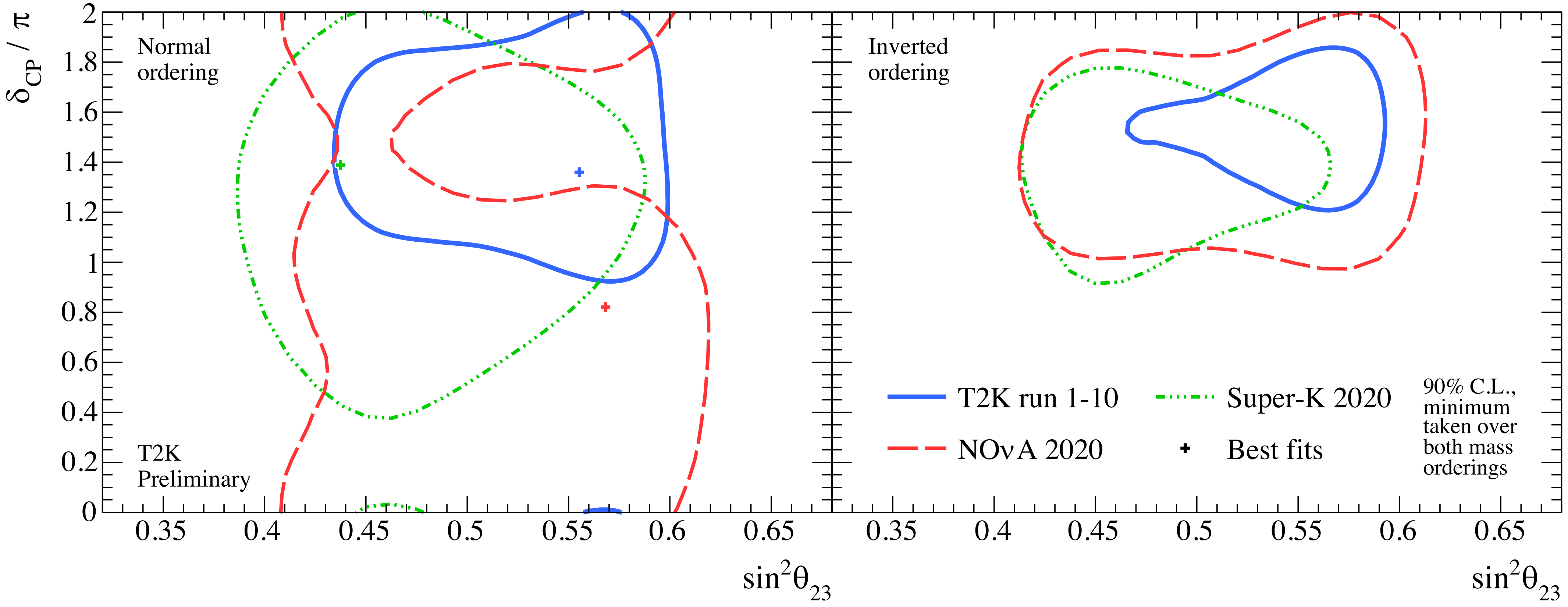
T2K is exploring parameterization of neutrino mixing other than 3-flavour PMNS

J_{CP} is a Parameterization independent quantity which indicates the size of CP-violation

Comparison to NOvA and Super-K

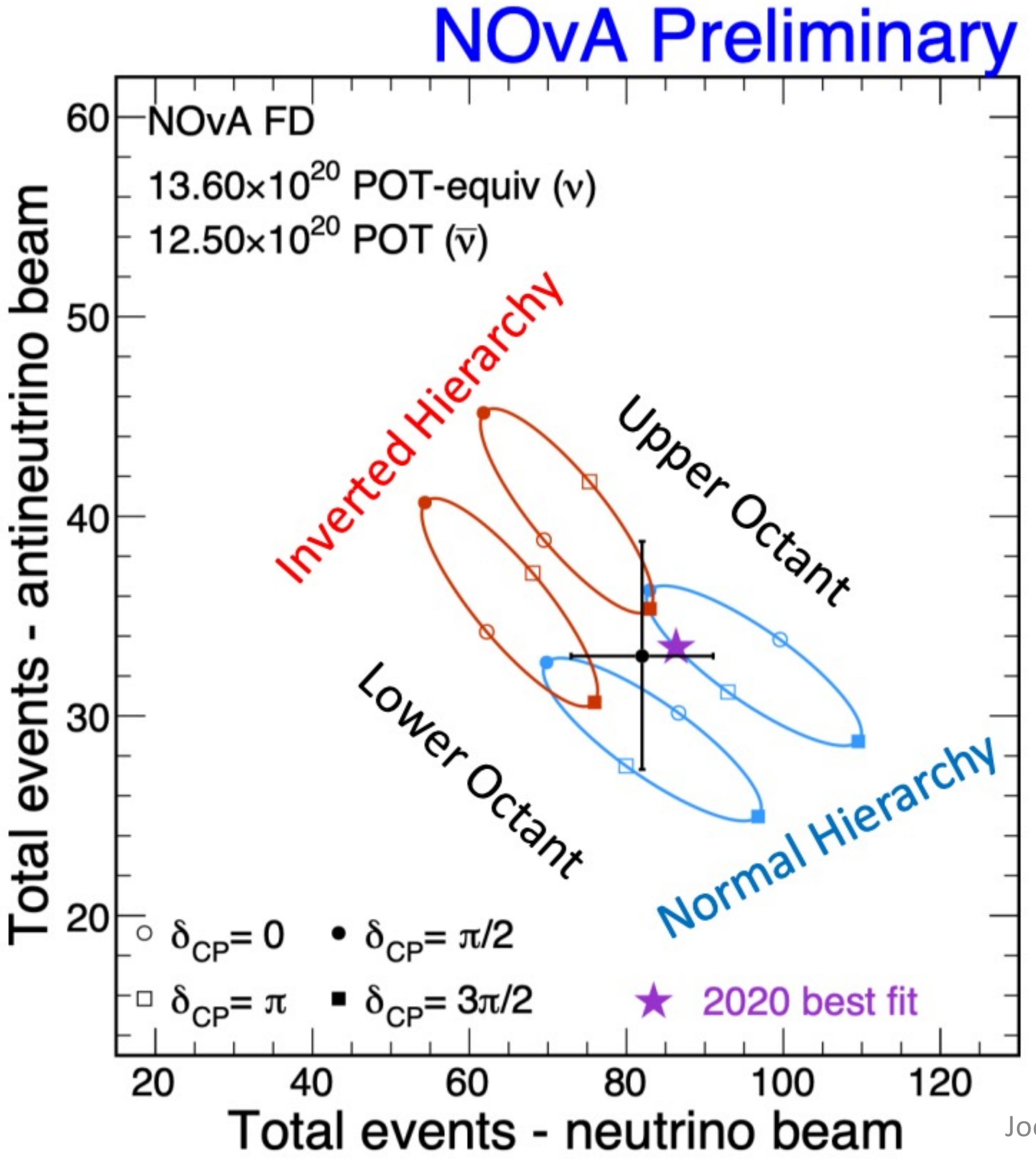
T2K and NOvA 90% contours overlap with best fit δ_{CP}- θ_{23} points just outside of 90% contours and similar θ_{23} best fit values

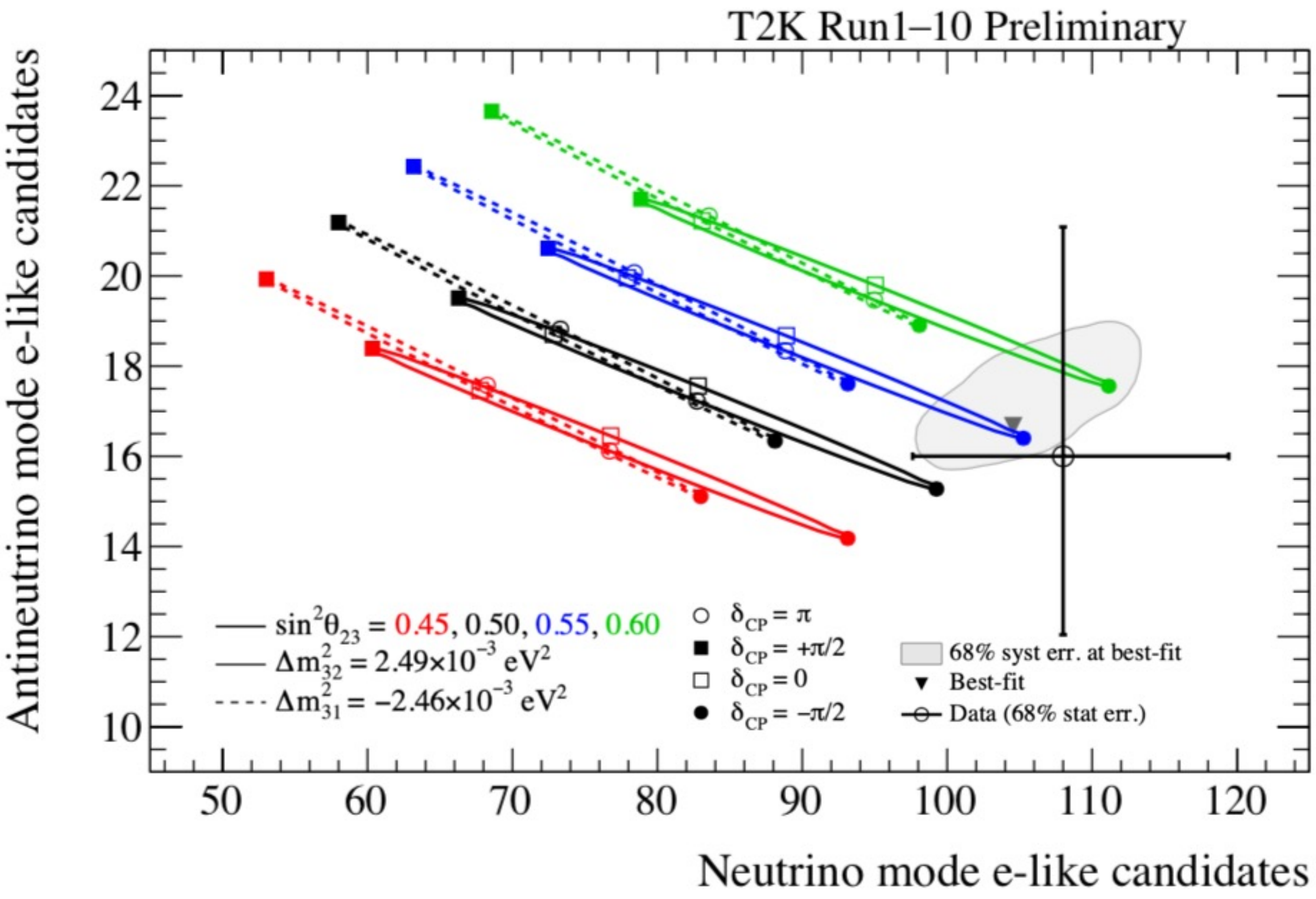
Consistent δ_{CP} with Super-K, but prefer different θ_{23} octant



T2K-NOvA

Sensitivity of each experiment may help break degeneracies for the other in a joint fit





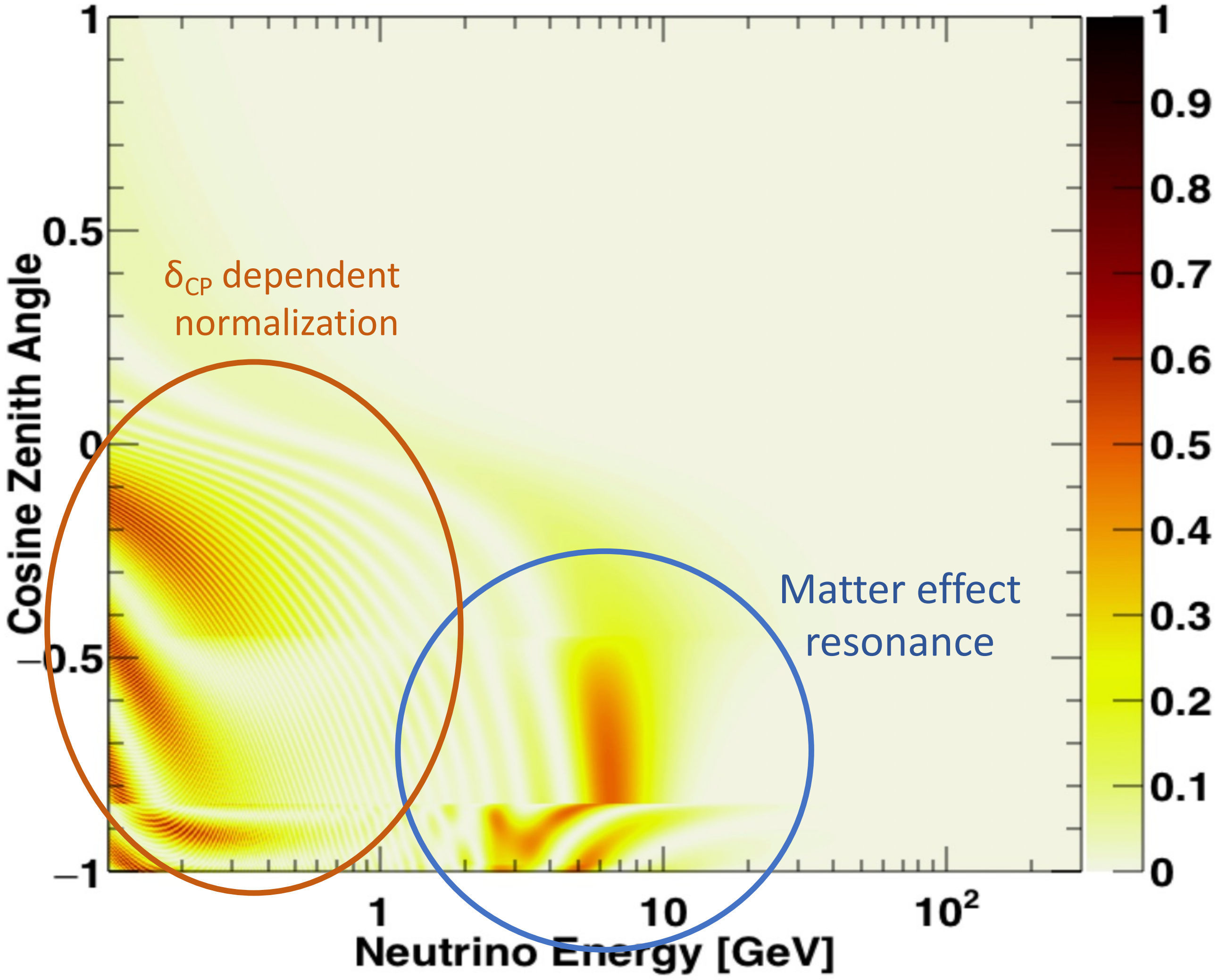
T2K-SK

Strong mass ordering dependent matter effects for upward going atmospheric ν_e

Strength is dependent on θ_{23} which T2K can provide and extra constraint on

δ_{CP} dependent normalization of low E_{ν} ν_e

$P(\nu_\mu \rightarrow \nu_e | \mathrm{NO})$



Future T2K analyses…

New samples and new models

ND280:

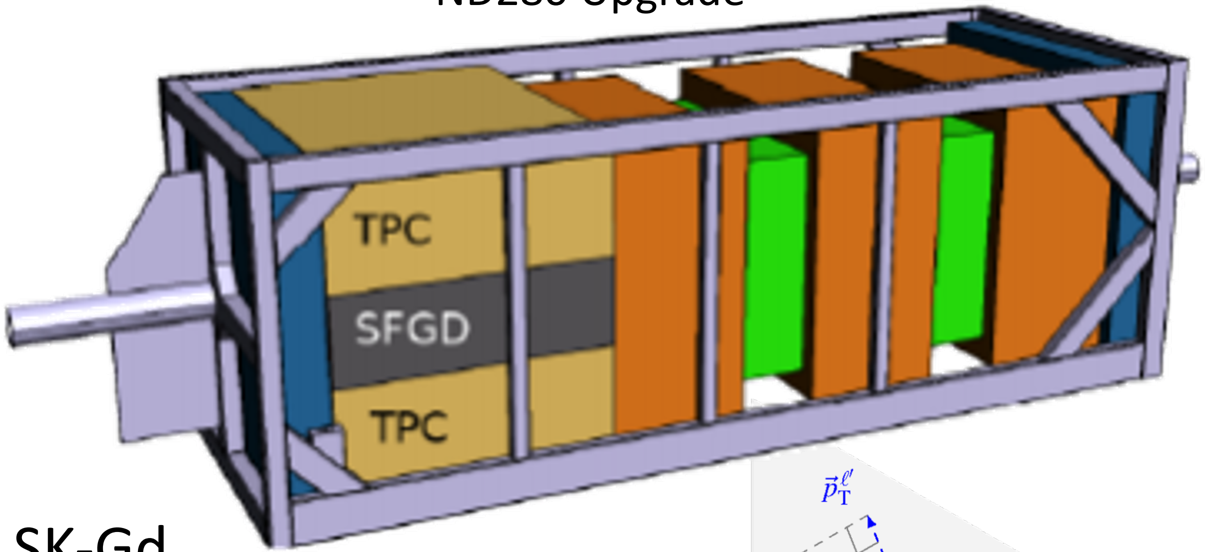
- Proton and photon tagging

Super-K:

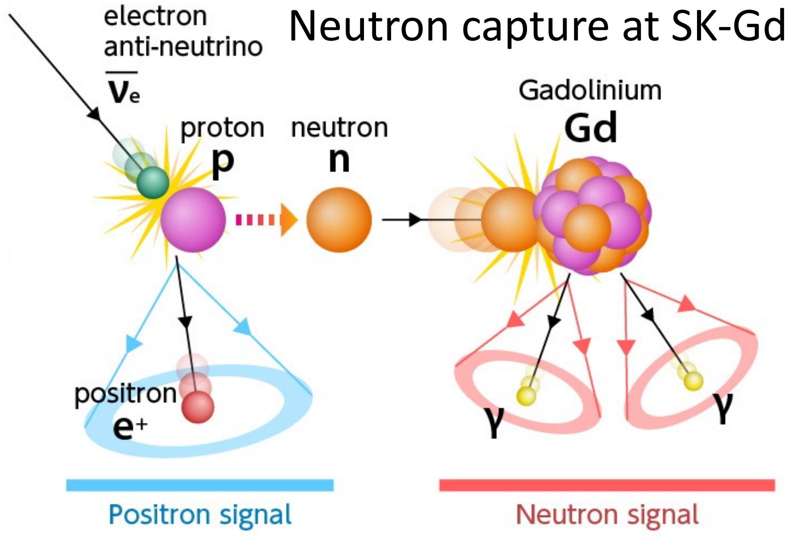
- Multiring ν_μ -like samples

Beam upgrade, New ND280 subdetectors, SK-Gd

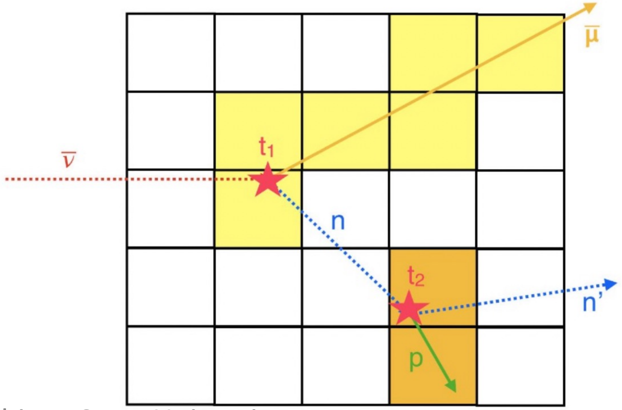
ND280 Upgrade

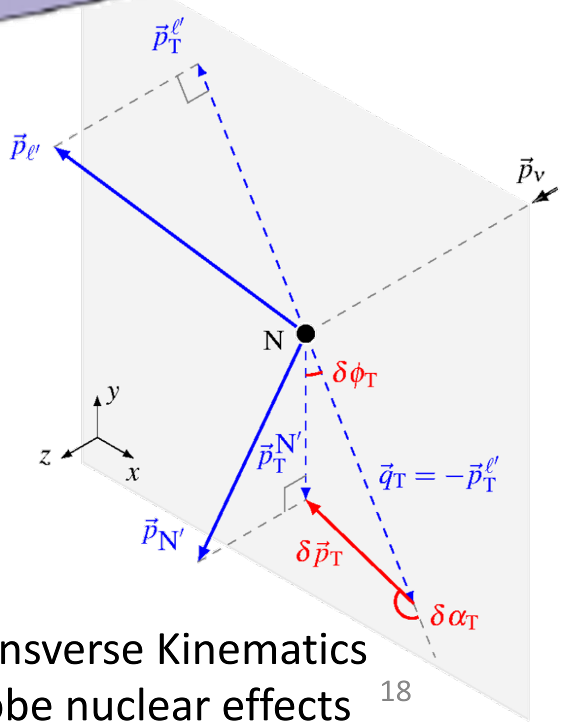


Neutron capture at SK-Gd



Neutron tagging at ND280 SFGD





Transverse Kinematics
Probe nuclear effects

In summary

T2K's δ_{CP} best fit is near –π/2 and excludes 35% of values around +π/2

CP-conserving values (0 and π) are excluded to 90% CL and CI

T2K-NOvA and T2K-SK joint fits may be able to lift some of the degeneracies in neutrino mixing (δ_{CP}, θ_{23}, Δm^2_{32})

New T2K detectors allowing new physics which will improve constraint

Thank you!

Please see Ali Ajmi's talk next on "Precision measurements of the PMNS parameters at T2K"

Photo from recent split J-PARC and
CERN collaboration meeting

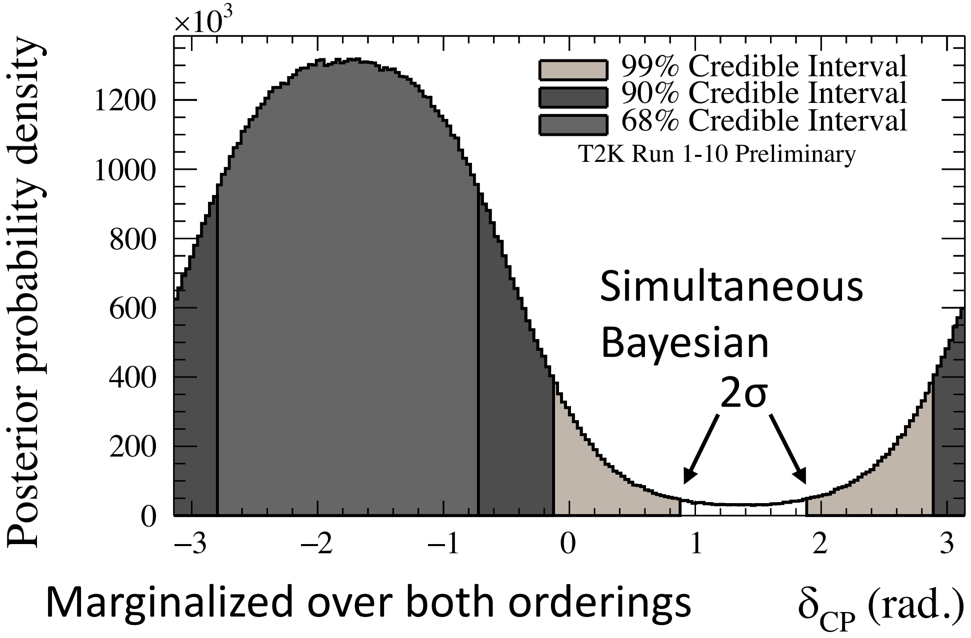
Support from: U.S. Department of Energy award DE-SC0015903

BACKUP

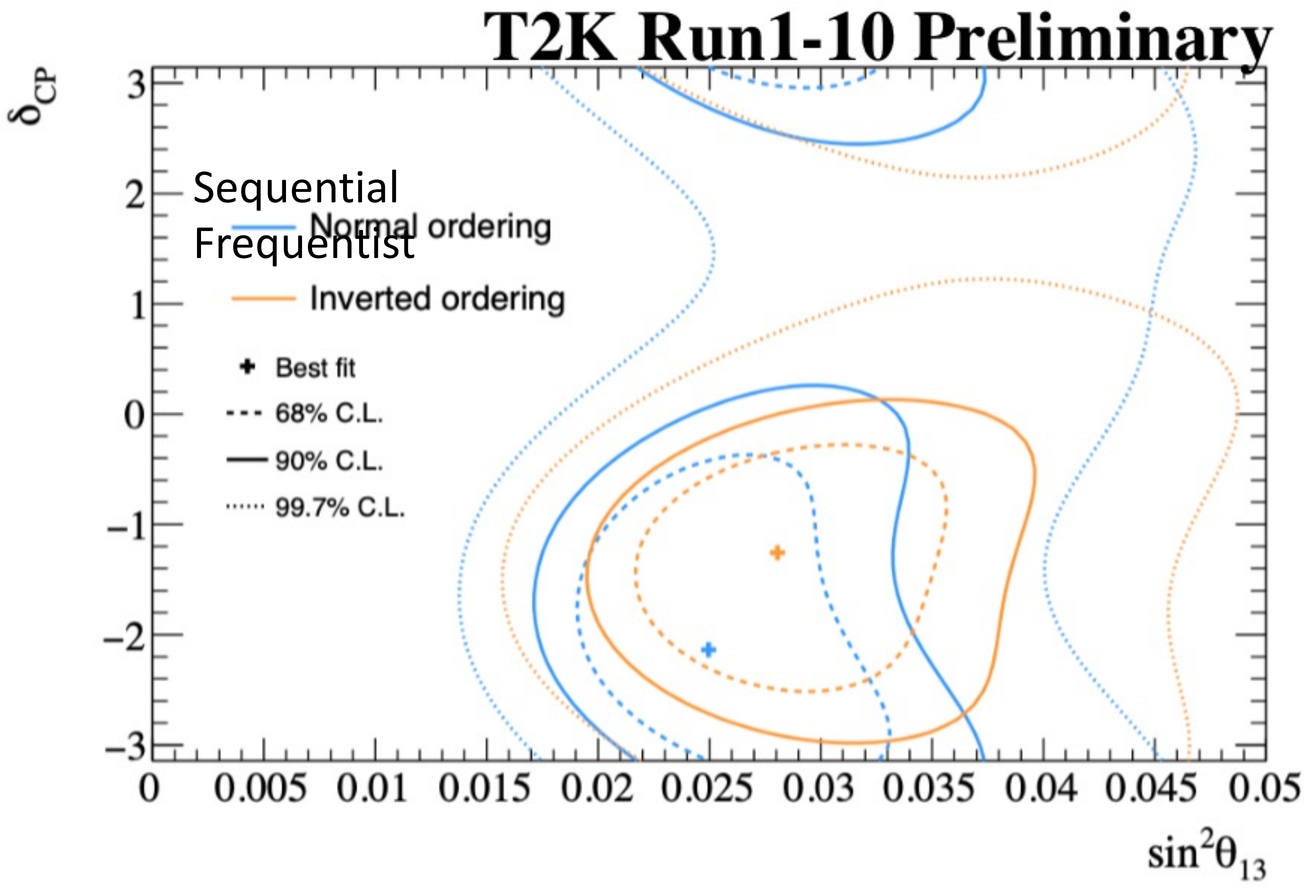
T2K-Only results

T2K can exclude regions of δ_{CP} close to +π/2 to a confidence level of 90% across both mass orderings and over 2σ in the inverted ordering

Best fit values for δ_{CP} are negative for both mass orderings

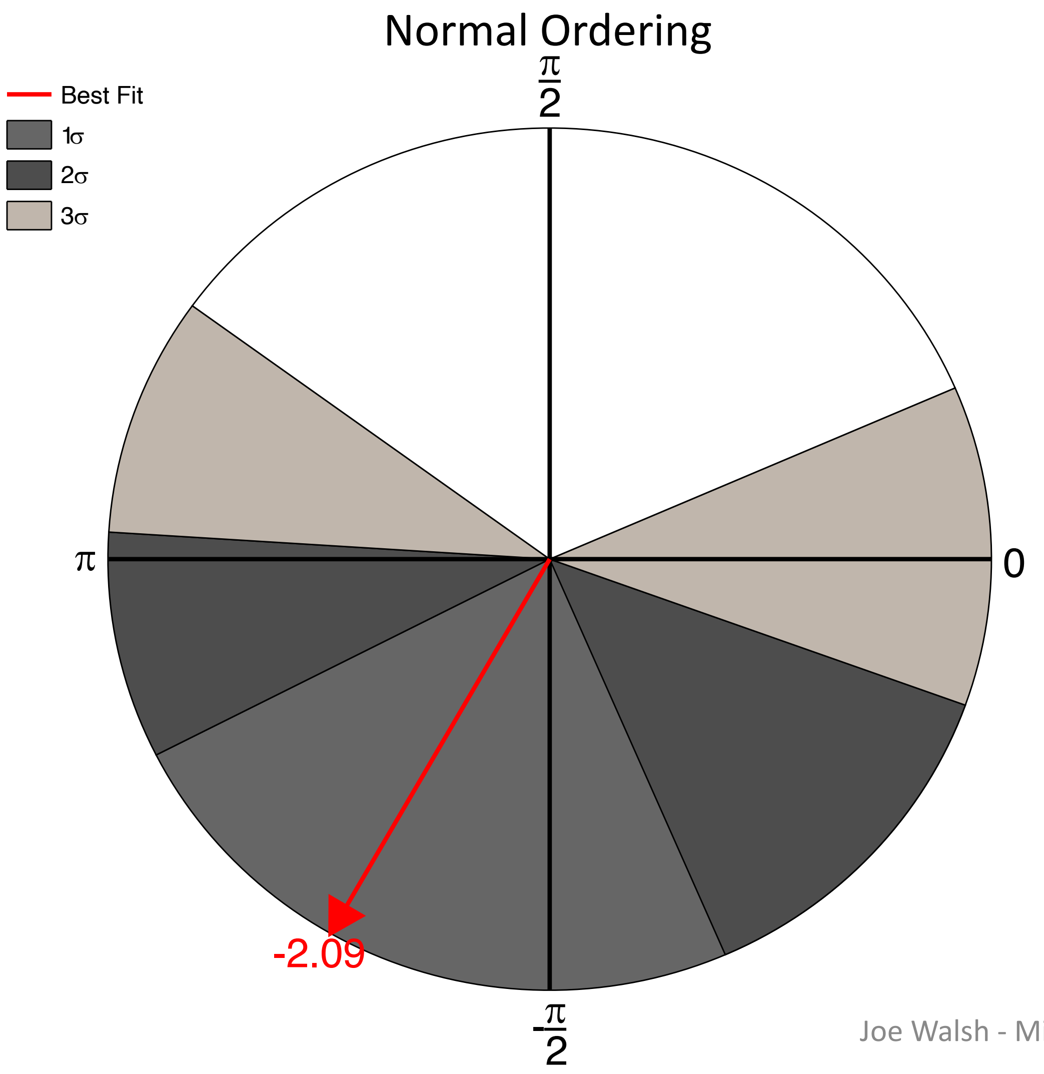


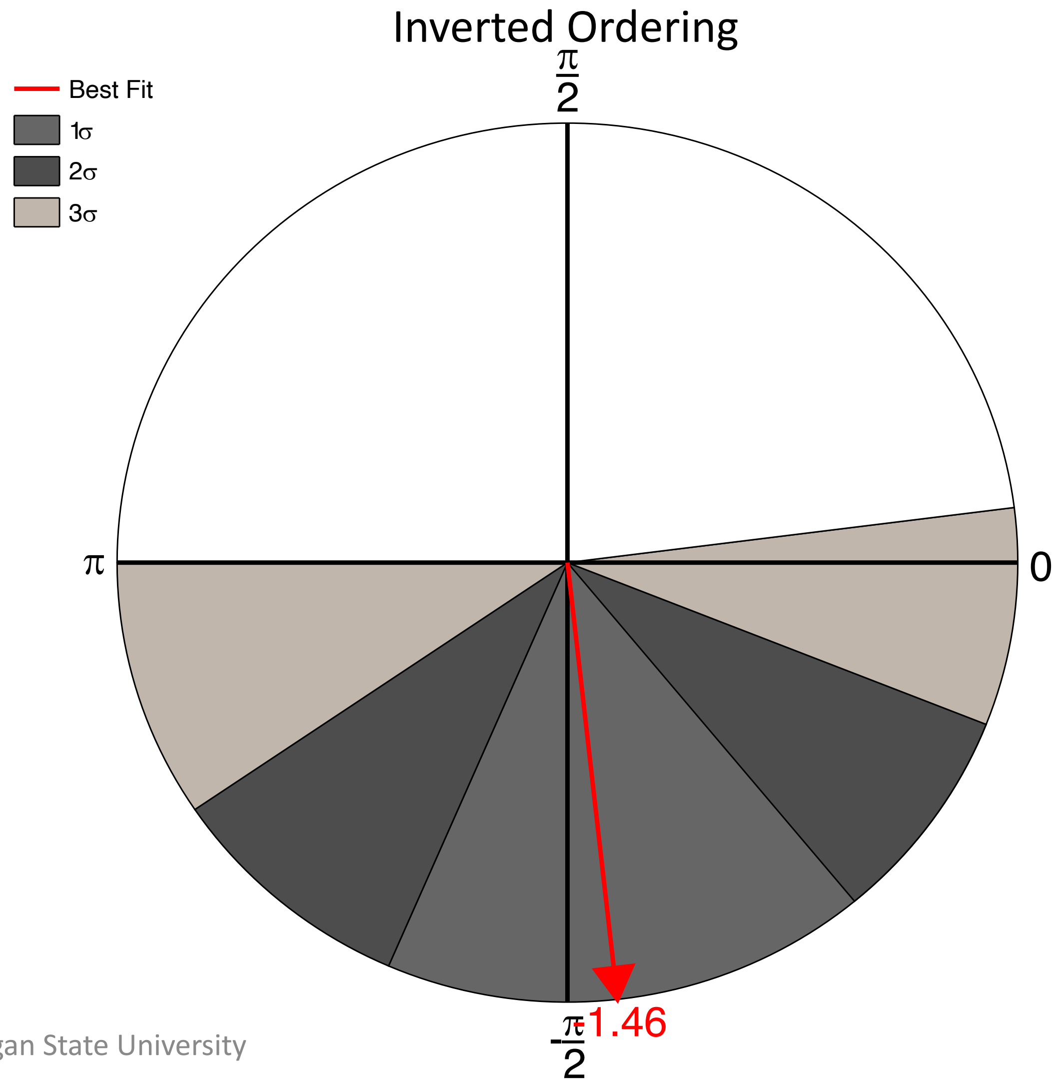
Marginalized over both orderings



δ_{CP} for each mass ordering

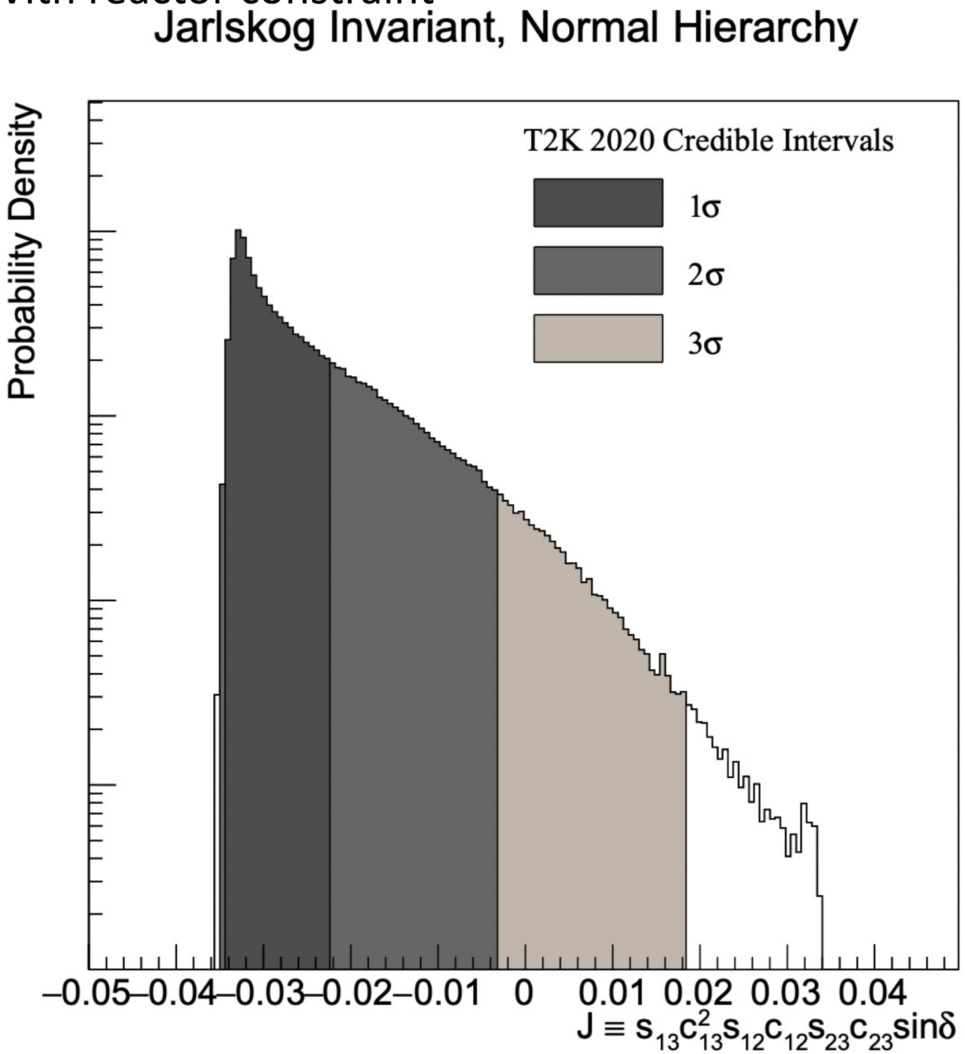
With reactor constraint

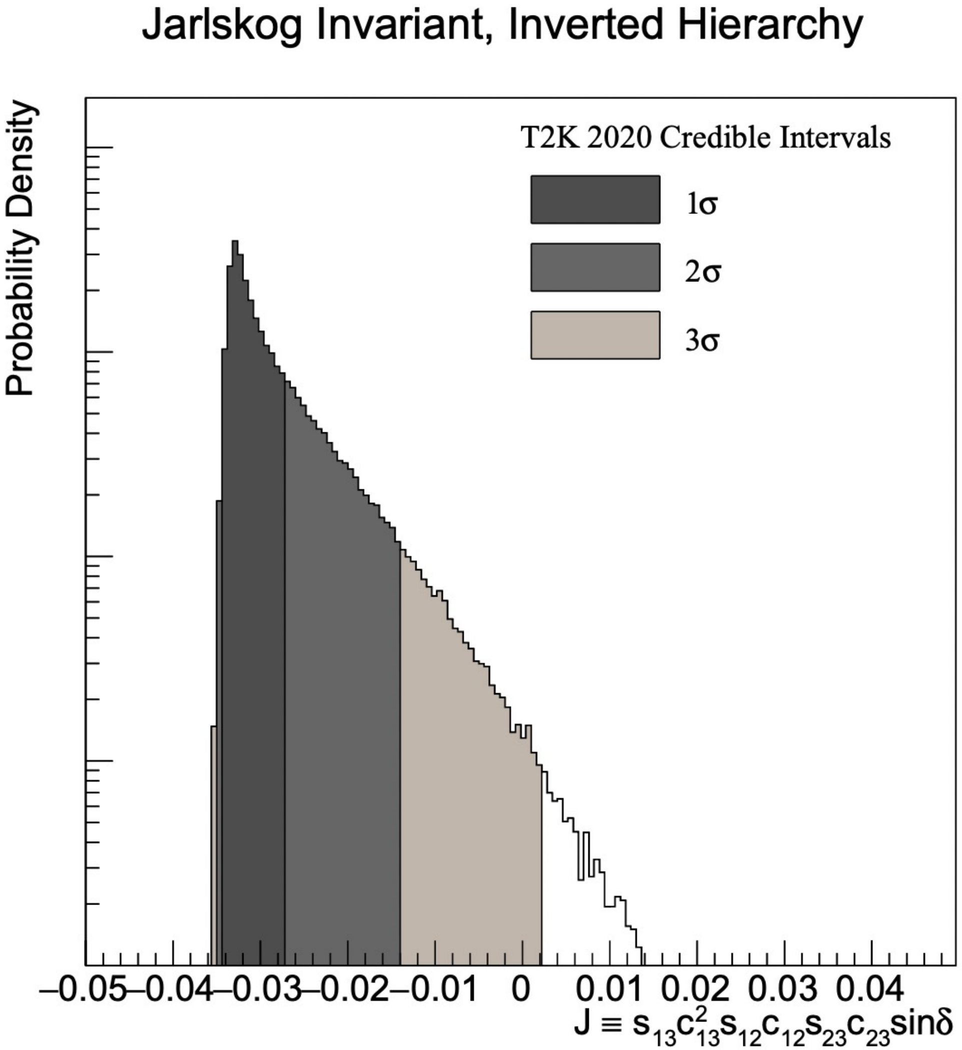




Jarlskog Invariant for each mass ordering

With reactor constraint





δ_{CP} Confidence Levels

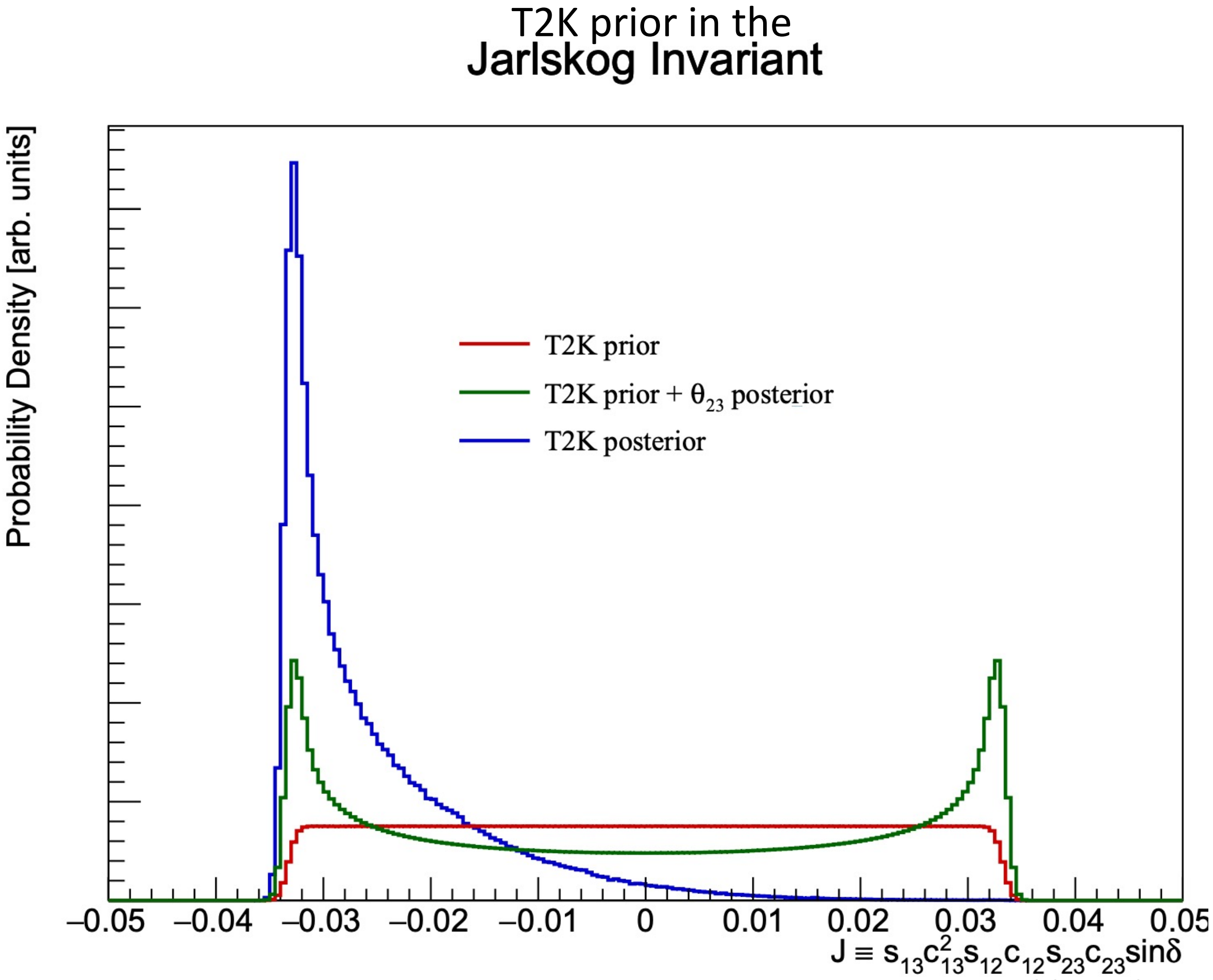
With reactor constraint

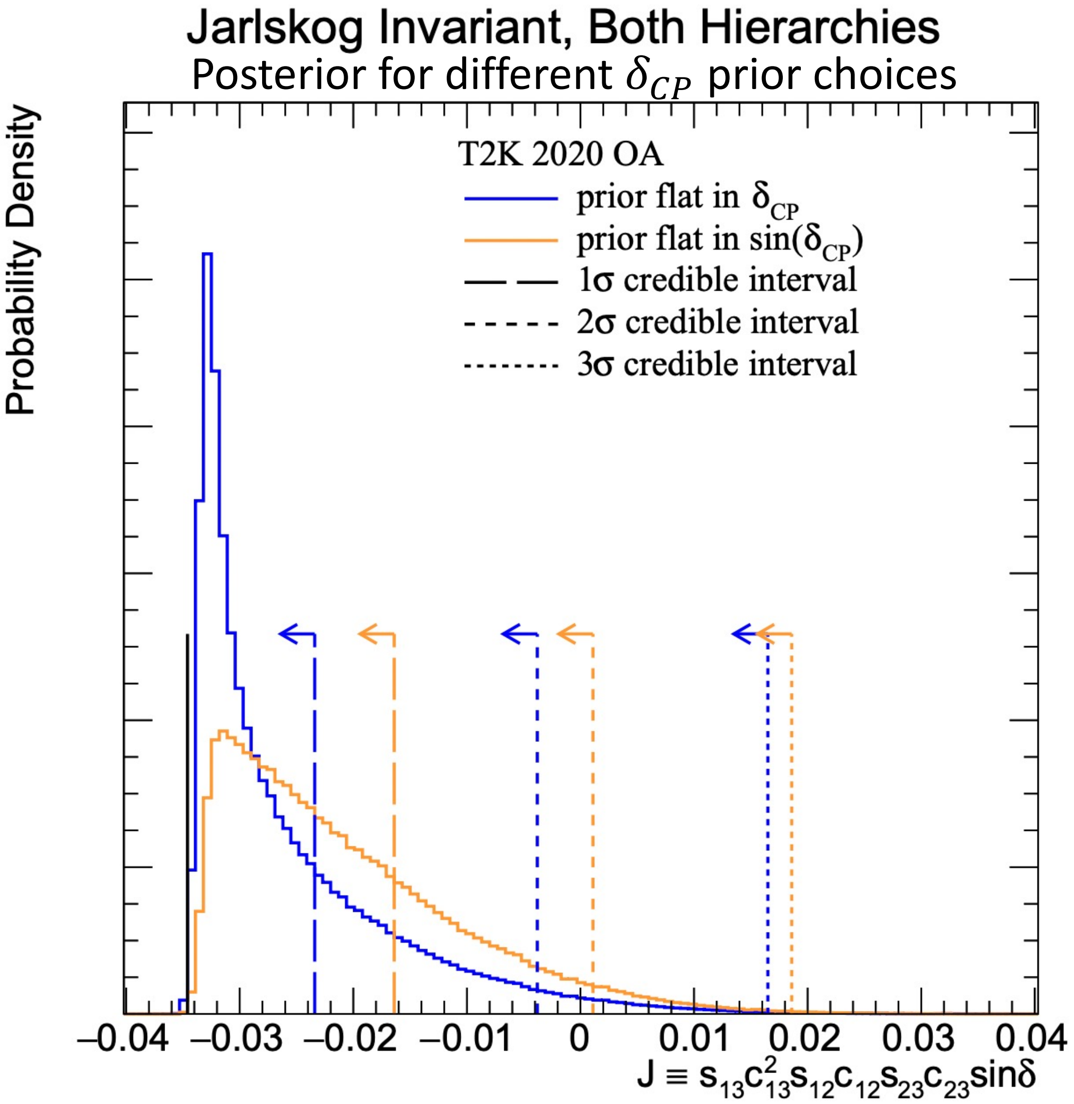
Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.66, -0.97]$	
90%	$[-3.00, -0.49]$	$[-1.79, -1.09]$
2σ	$[-\pi, -0.26] \cup [3.11, \pi]$	$[-2.20, -0.75]$
3σ	$[-\pi, 0.32] \cup [2.63, \pi]$	$[-2.82, -0.14]$

Feldman Cousins-corrected confidence level intervals marginalized over both mass orderings/hierarchies

The Jarlskog Invariant

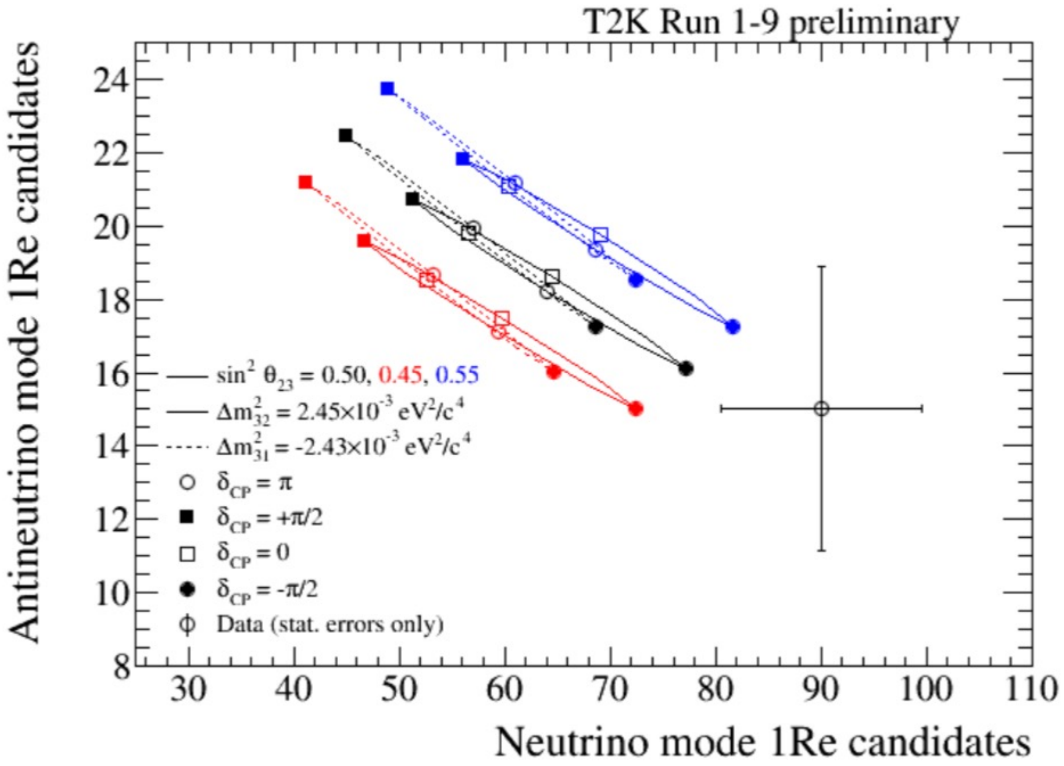
With reactor constraint

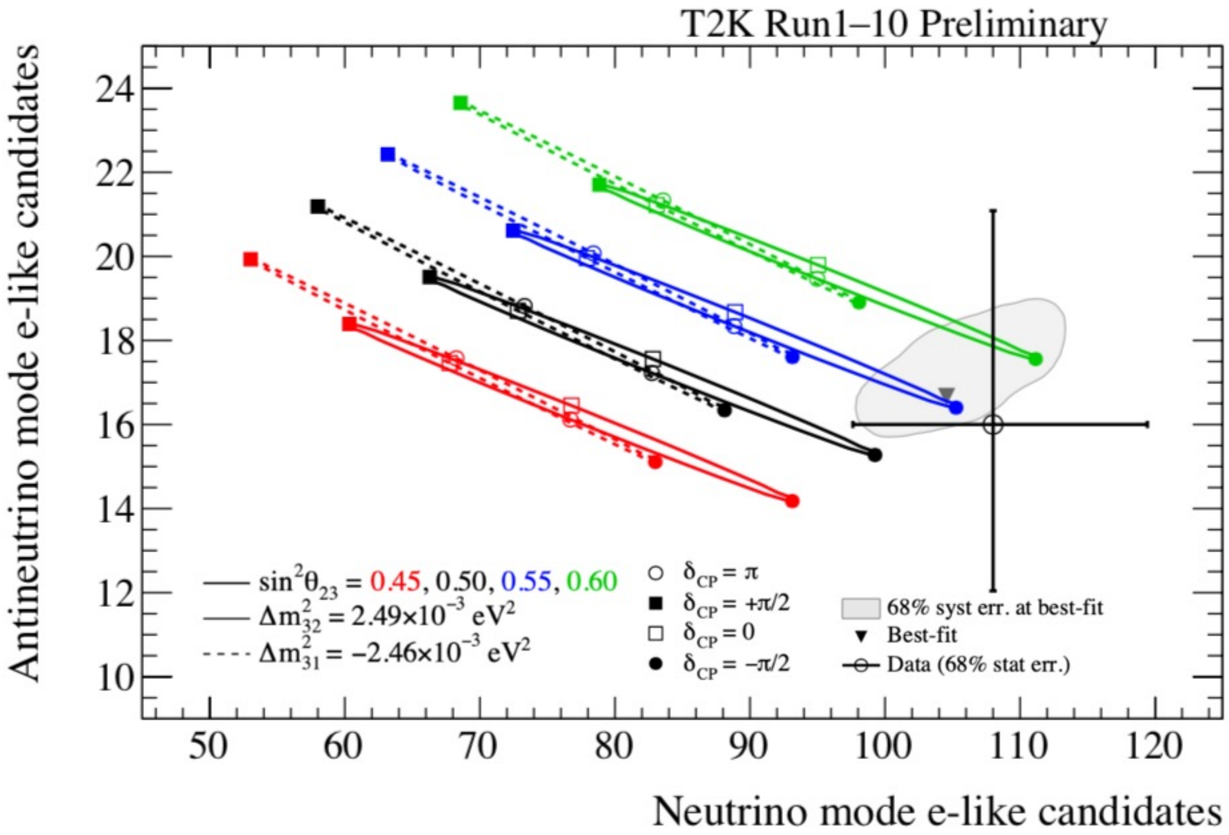




Comparison to previous result

With reactor constraint





Data is now more PMNS-like as statistical fluctuation in CC1π (1Re+1d.e.) sample has reverted to the mean
Significant analysis update but much of change was due to additional ν-mode data in Run 10

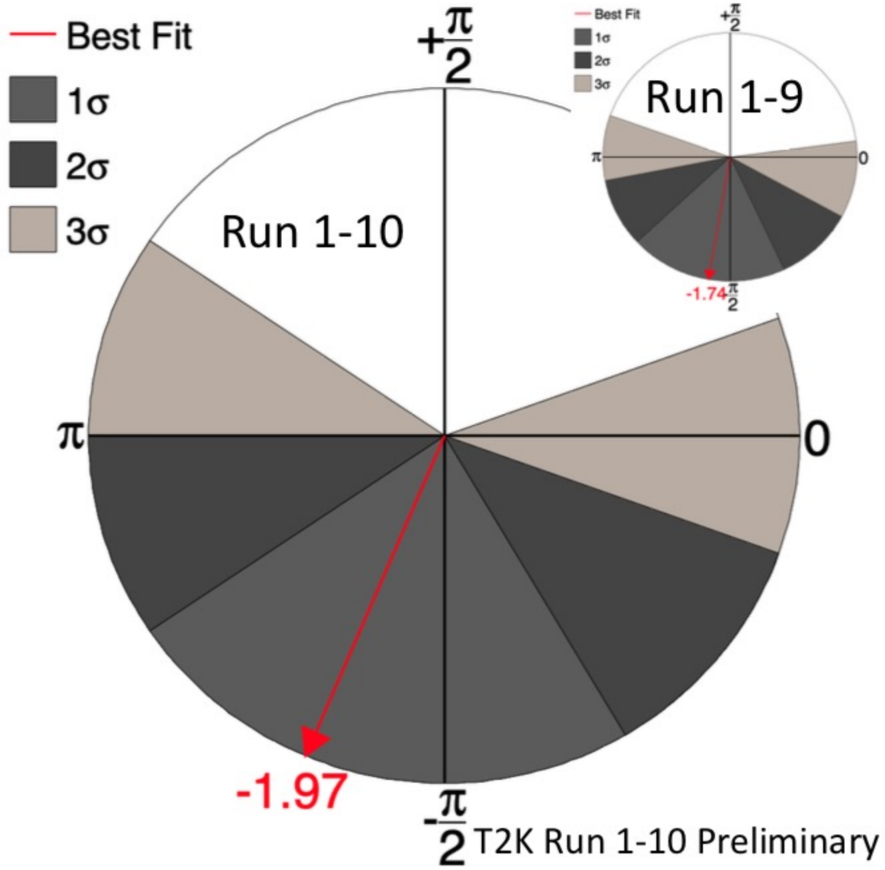
Comparison to previous result

With reactor constraint

Inclusion of new data saw a decrease in a statistical fluctuation in ν-CC1π which previously put T2K's exclusion above its sensitivity

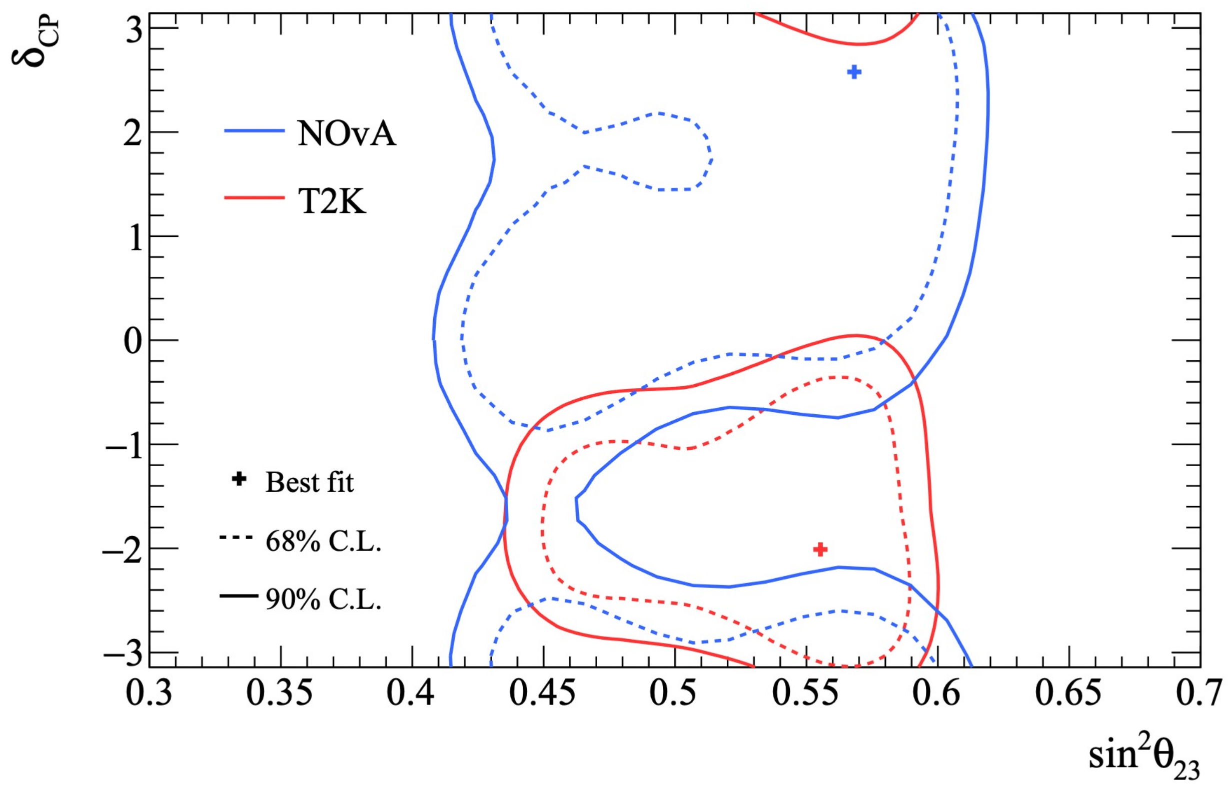
Shift in best fit away from maximally CPV value and broadening of 2σ contours leads to 2σ boundary sitting close to π

Robustness studies show small changes in boundary positions, but these do not impact 90% exclusion of CP-conservation

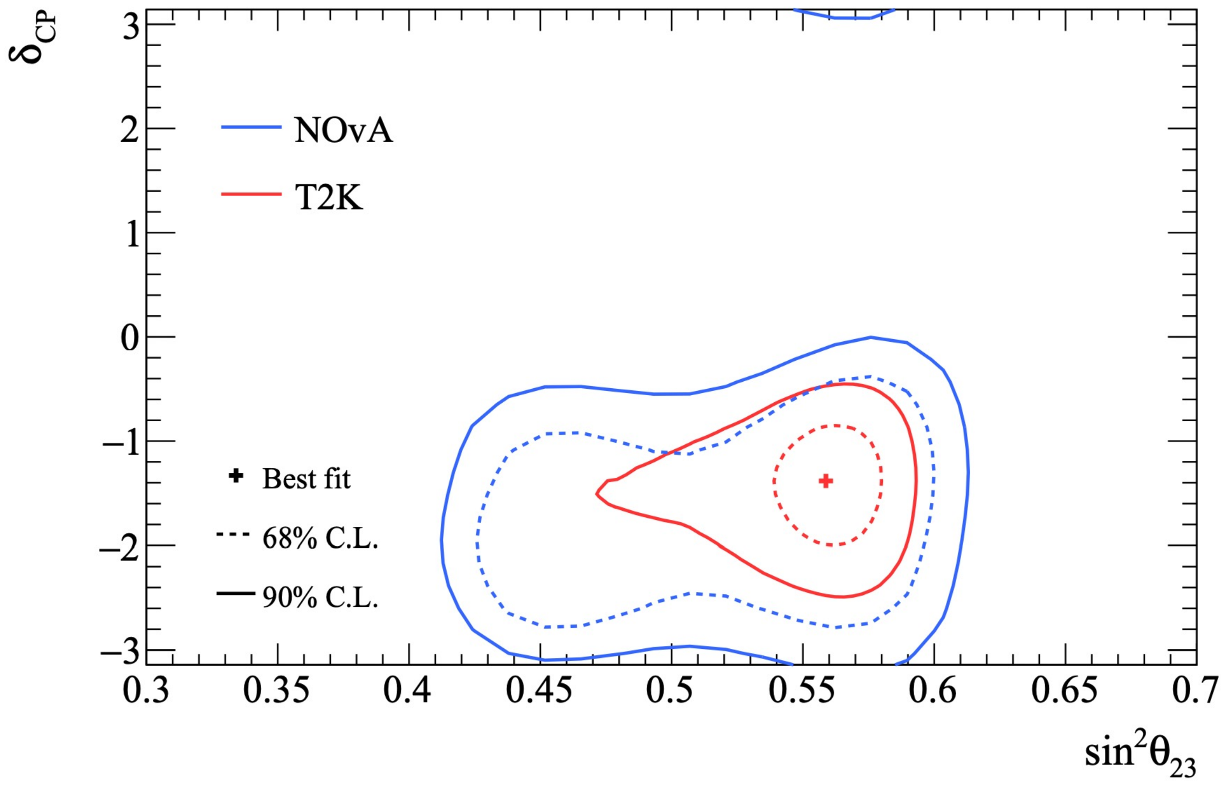


T2K and NOvA δ_{CP}-$\sin^2\theta_{23}$ constraints

Normal ordering



Inverted ordering



T2K Best Fit

With reactor constraint

Parameter	Best fit			
Data	T2K only		T2K + reactor	
Hierarchy	Normal	Inverted	Normal	Inverted
$\sin^2(2\theta_{13})$	0.109	0.120	0.0855	0.0860
$\sin^2(\theta_{13})$	28.0×10^{-3}	31.0×10^{-3}	21.9×10^{-3}	22.0×10^{-3}
δ_{CP}	-2.22	-1.29	-1.97	-1.44
Δm^2_{32} (NH)/$\lvert\Delta m^2_{31}\rvert$ (IH) [$\mathrm{eV}^2/\mathrm{c}^4$]	2.495×10^{-3}	2.463×10^{-3}	2.494×10^{-3}	2.463×10^{-3}
$\sin^2(\theta_{23})$	0.467	0.466	0.561	0.563
$-2\ln L$	597.72	598.56	598.05	600.49

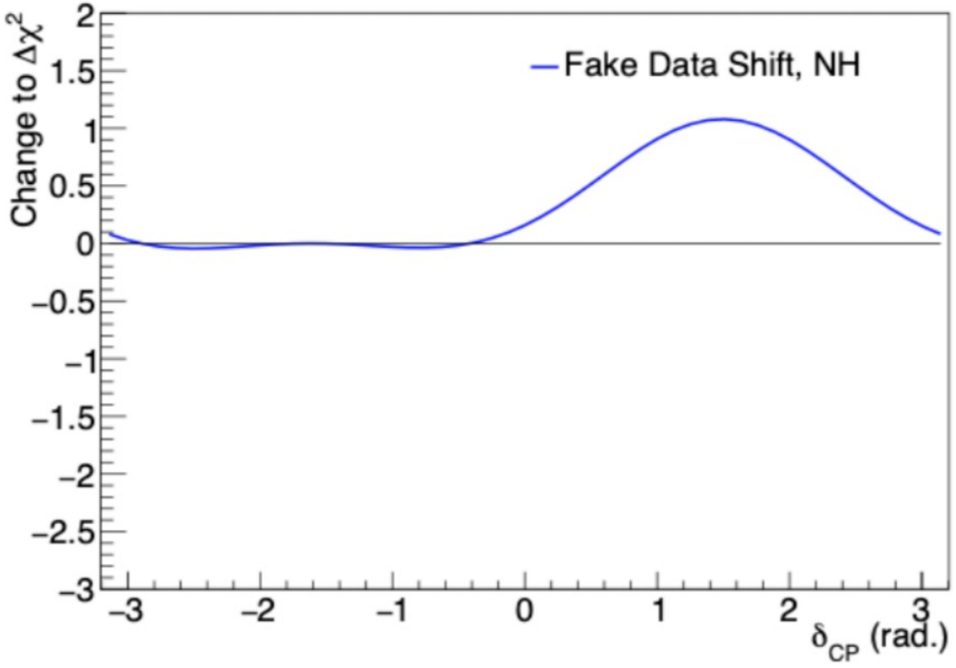
PMNS values and -2lnL ($\Delta\chi^2$) values for the T2K Global best fit point

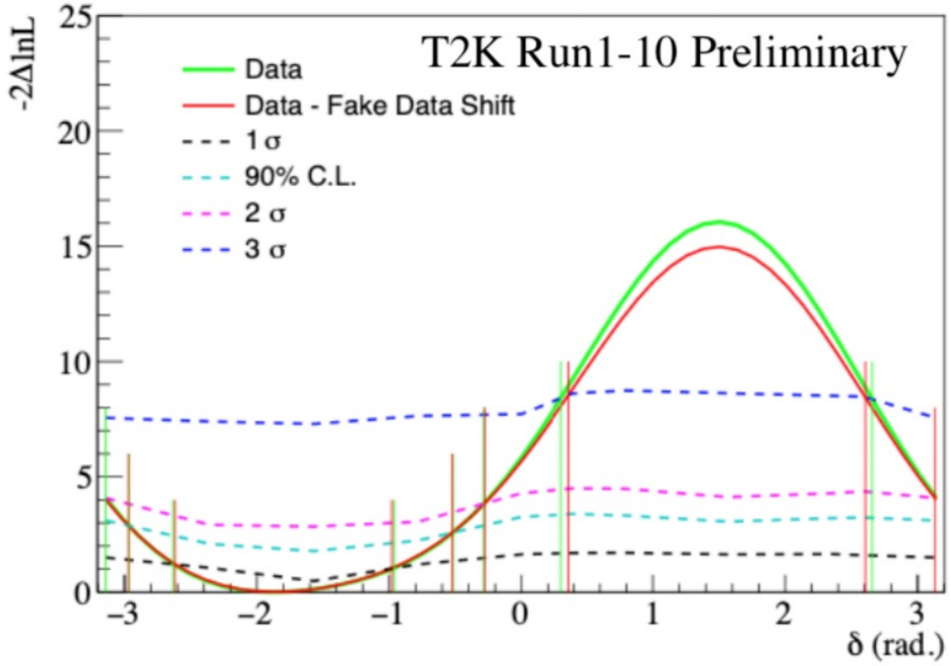
Robustness studies

We test our model uncertainty by fitting alternative models.

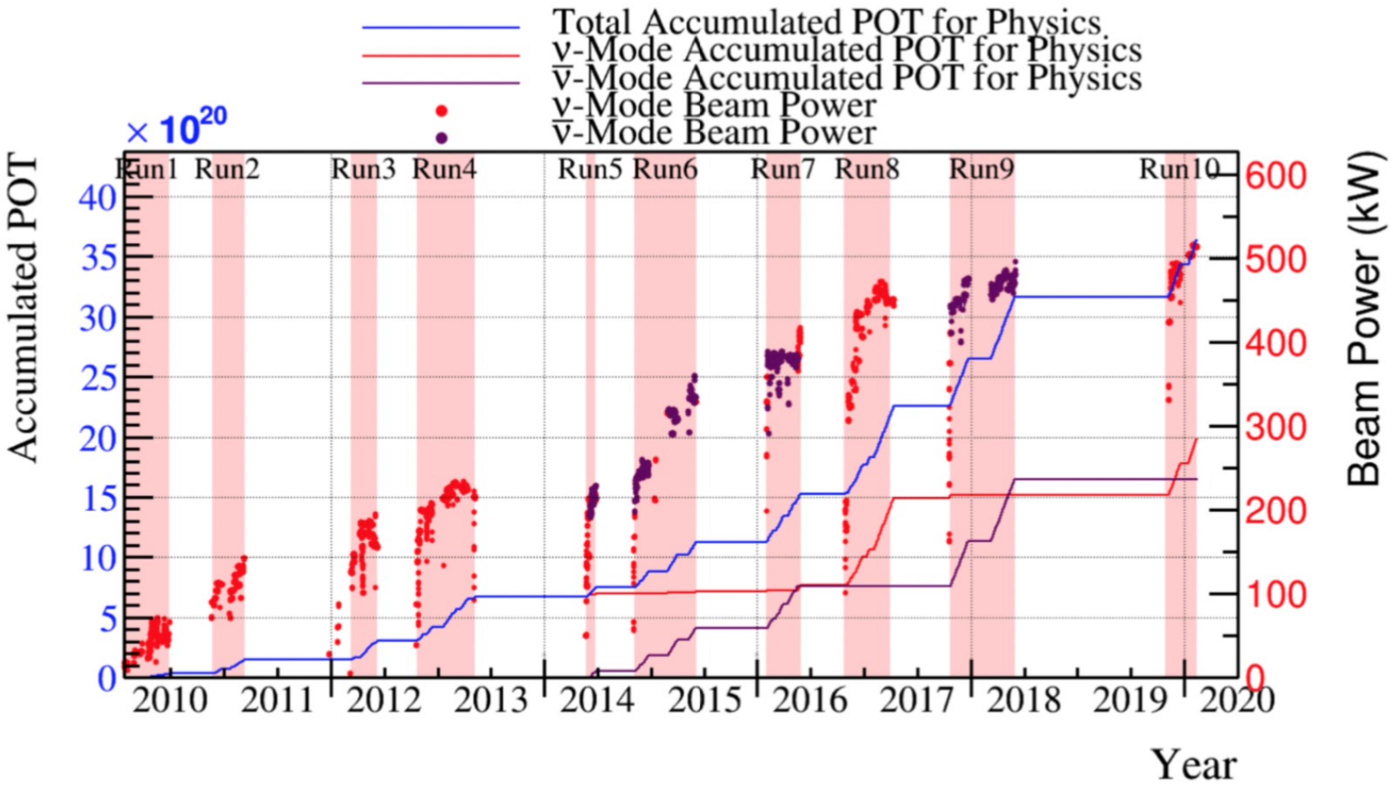
For δ_{CP} we assess the impact on $\Delta\chi^2$ and subtract it.

See how this change affects contours/intervals





Increase in data since previous result

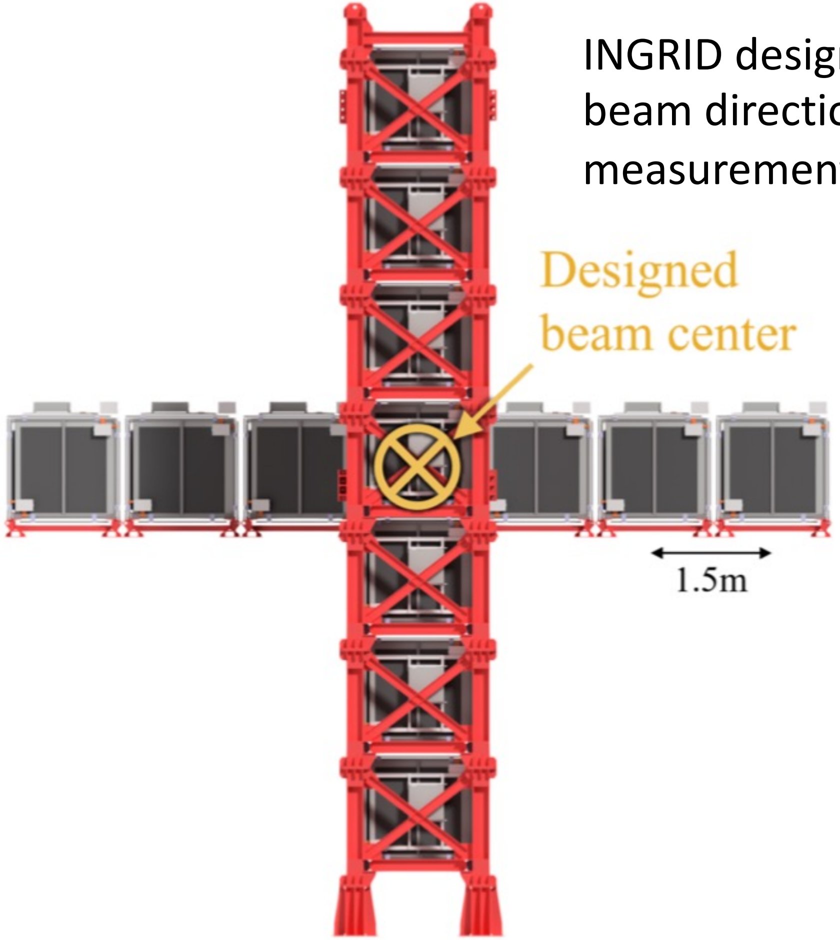


*POT = Protons On Target

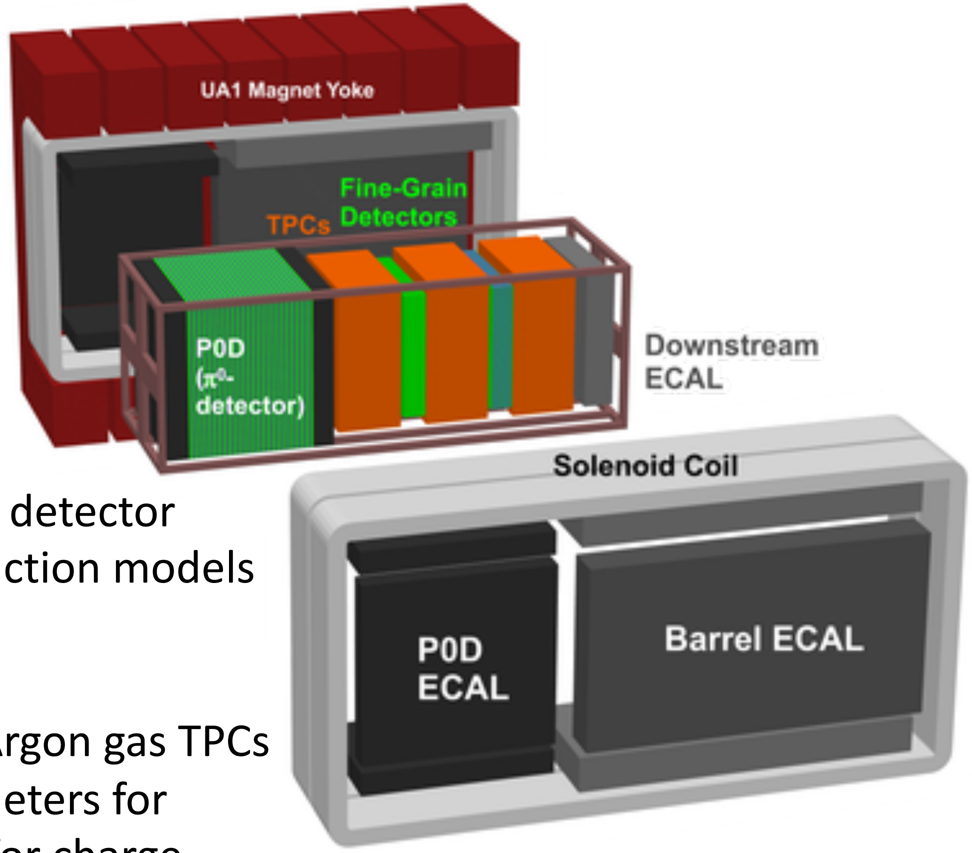
33% increase in ν-mode POT at Super-K and double the POT at ND280

ν-mode POT of 1.97×10^{21} and $\bar{\nu}$-mode POT of 1.63×10^{21}.

INGRID and ND280



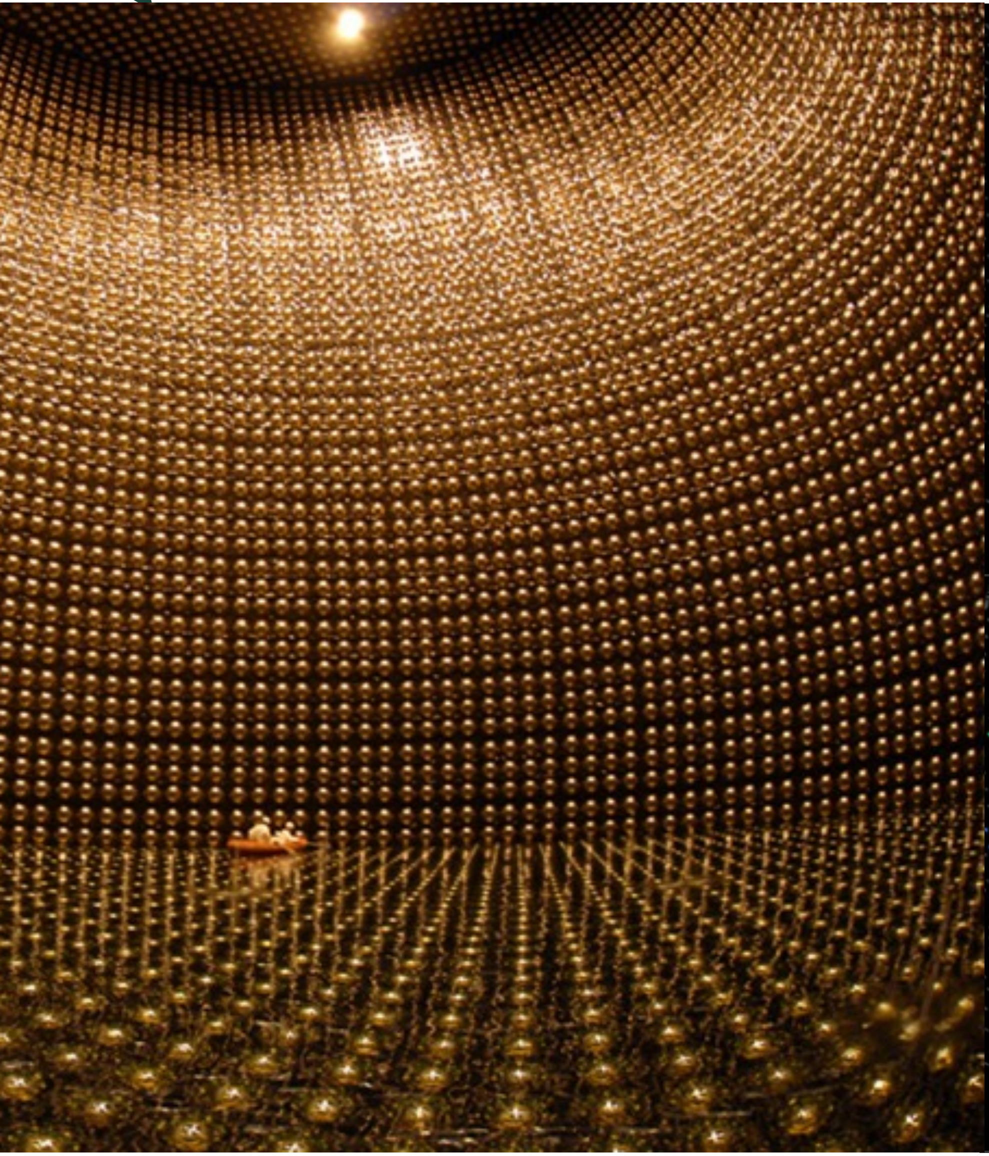
INGRID designed to give precise beam direction and intensity measurements

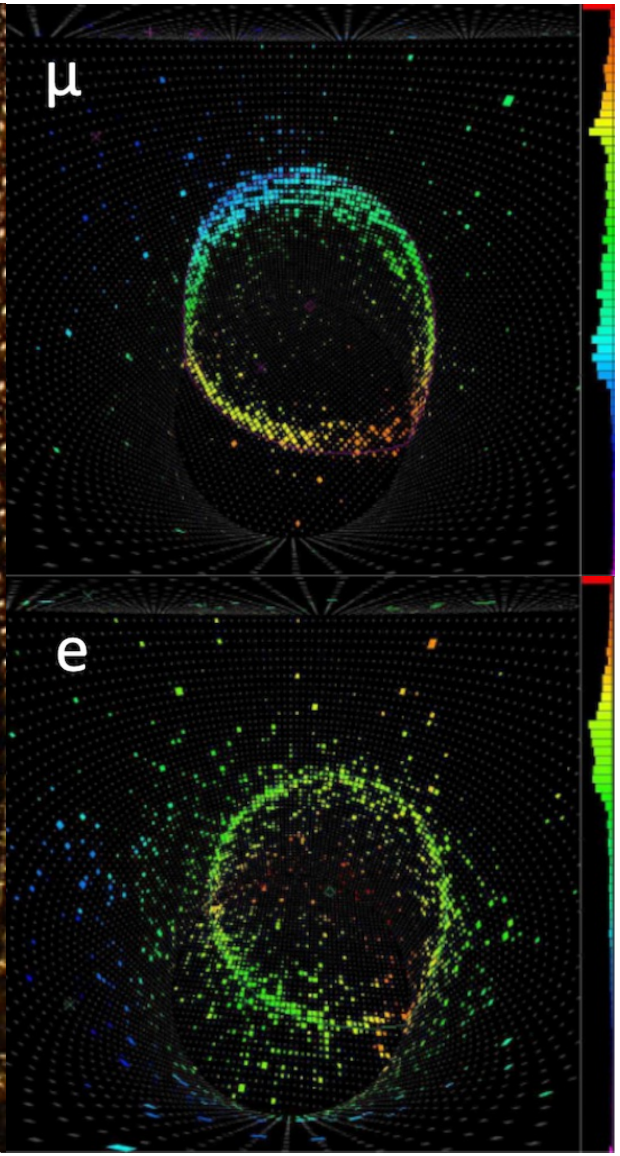


ND280 is a magnetized tracking detector which constrains flux and interaction models at the off-axis angle as SK

CH and H2O targets as well as Argon gas TPCs and lead-scintillator EM calorimeters for MIP/EM distinction. 0.2 T field for charge discrimination and dE/dx measurement

The Super-Kamiokande Detector





50 kiloton water Cherenkov detector

Parent neutrino flavor inferred from shape of charged lepton ring

Muons are MIP-like and so ν_μ interactions leave clear and defined rings

Electrons scatter more and so ν_e interactions leave fuzzy and diffuse rings

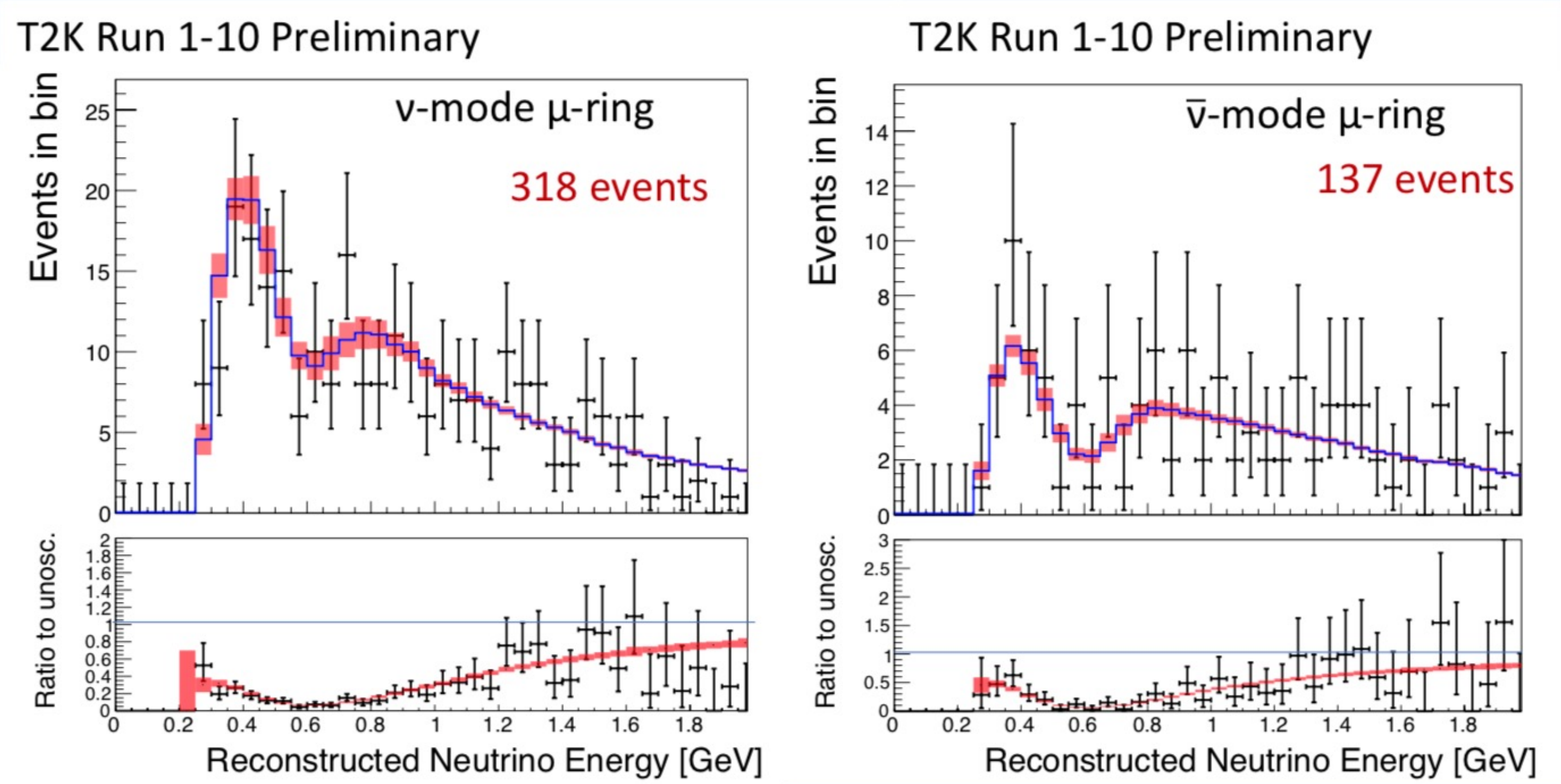
For single ring CCQE-like events:

$$E_\nu^{\text{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

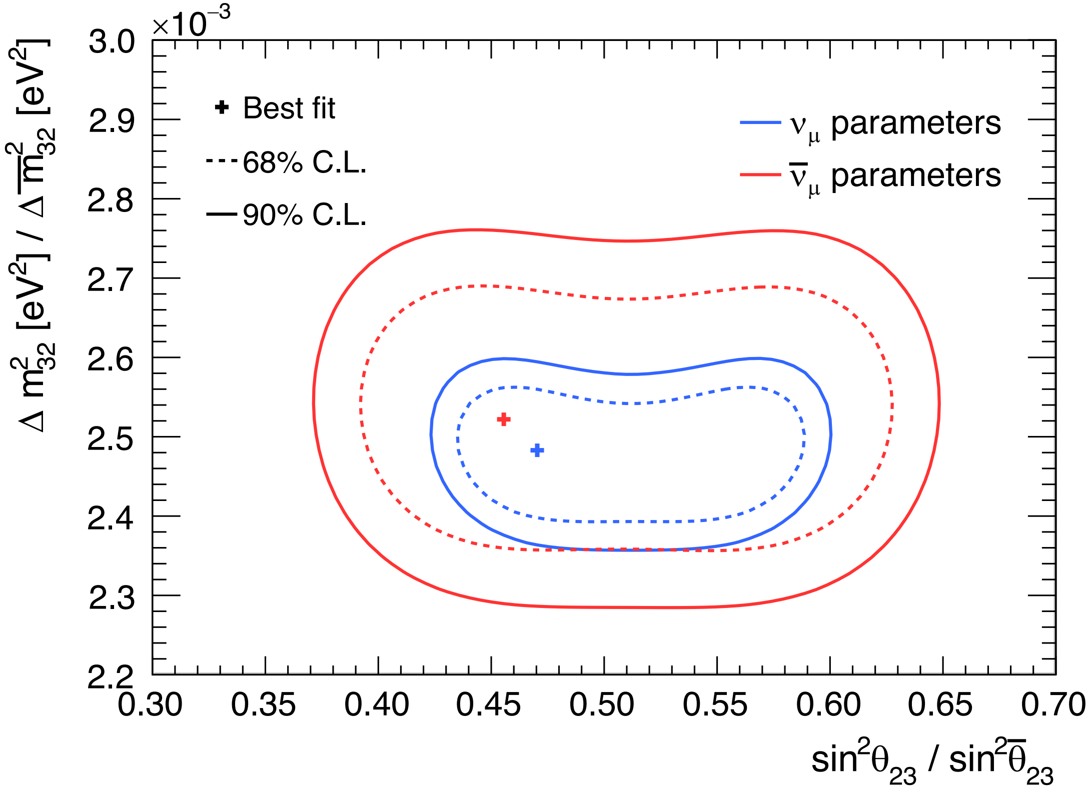
m_p and m_n are swapped for antineutrinos
E_b is a nuclear binding energy related term

Super-K ν_μ data

Two $\nu_\mu/\bar{\nu}_\mu$-like appearance samples at Super-K
Single muon-like rings (both ν and $\bar{\nu}$)



Unitarity test with $\nu_\mu/\bar{\nu}_\mu$ data



	ν_μ	$\bar{\nu}_\mu$
$\overset{(-)}{\Delta m^2}_{32}$	$2.48 \times 10^{-3}\,\mathrm{eV}^2$	$2.53 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2 \overset{(-)}{\theta}_{23}$	0.468	0.449

Comparison of independent ν_μ and $\bar{\nu}_\mu$ disappearance channel only mixing parameters.

Should be No PMNS-like CPV in $P(\nu_\mu \rightarrow \nu_\mu)$ channel

Difference in $\sin\theta_{23}$ and $\sin\bar{\theta}_{23}$ would require a non-unitary mixing matrix

θ_{23} and $\bar{\theta}_{23}$ are found to be consistent with each other in T2K run1-10 data

Currently no indication of non-unitarity at T2K

References

- Reactor Experiment Constraint

  https://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrino-mixing.pdf

- NOvA 2020 Result

  Paper: https://inspirehep.net/literature/1907127

  Talk: https://indico.fnal.gov/event/43209/contributions/187840/attachments/130740/159597/NOvA-Oscilations-NEUTRINO2020.pdf

- Atmospheric appearance probability plot

  M. Jiang et al. [Super-Kamiokande], “Atmospheric Neutrino Oscillation Analysis with Improved Event Reconstruction in Super-Kamiokande IV,” PTEP 2019 (2019) no.5, 053F01