University of Glasgow

T2K

NOvA

A WORLD TOP 100 UNIVERSITY

Results from the T2K+NOvA Joint Analysis

Dr. Veera Mikola on behalf of T2K and NOvA collaborations

FPCP Conference 28/5/2024

WORLD CHANGING GLASGOW

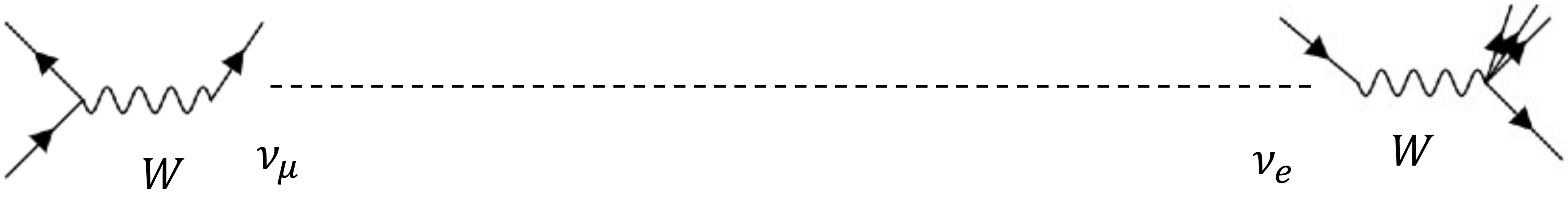
27/05/2024

THE TIMES THE SUNDAY TIMES GOOD UNIVERSITY GUIDE 2024 SCOTTISH UNIVERSITY OF THE YEAR

Neutrino Physics

Three Flavor Mixing in Lepton Sector

- Create neutrinos in one lepton flavour state, observe in another state
- Flavour and mass states mixing quantum mechanically; each flavour state is a superposition of different mass states



Source

Detector

Three Flavor Mixing in Lepton Sector

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

m_1, m_2, m_3

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

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\beta j}\, e^{-i\frac{m_j^2 L}{2E}}\, U_{\alpha j} \right|^2$$

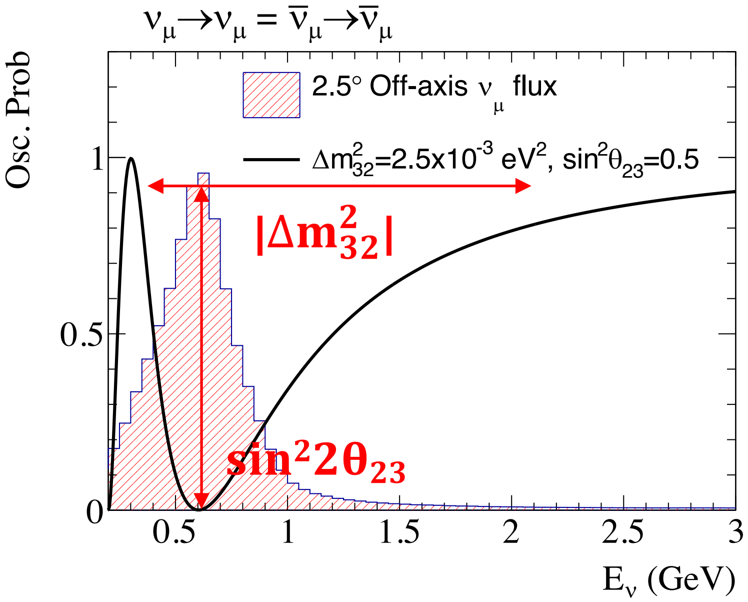
3 angles and 1 complex phase:

$\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}}$

➡ $\boldsymbol{\Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{31}}$

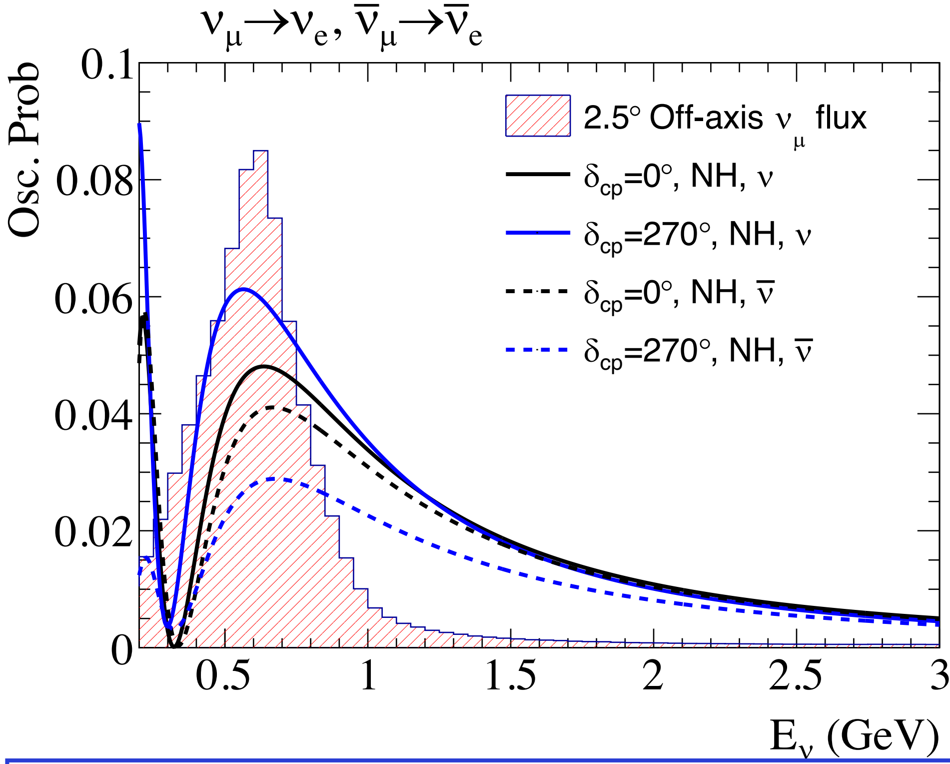
ν_μ Disappearance Channel

$$P_{\mu\to x} \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$



Matter effects: Coherent forward scattering in $\nu_e \rightarrow$ **modifies oscillations compared to vacuum, dependent on the sign on Δm^2_{32}**

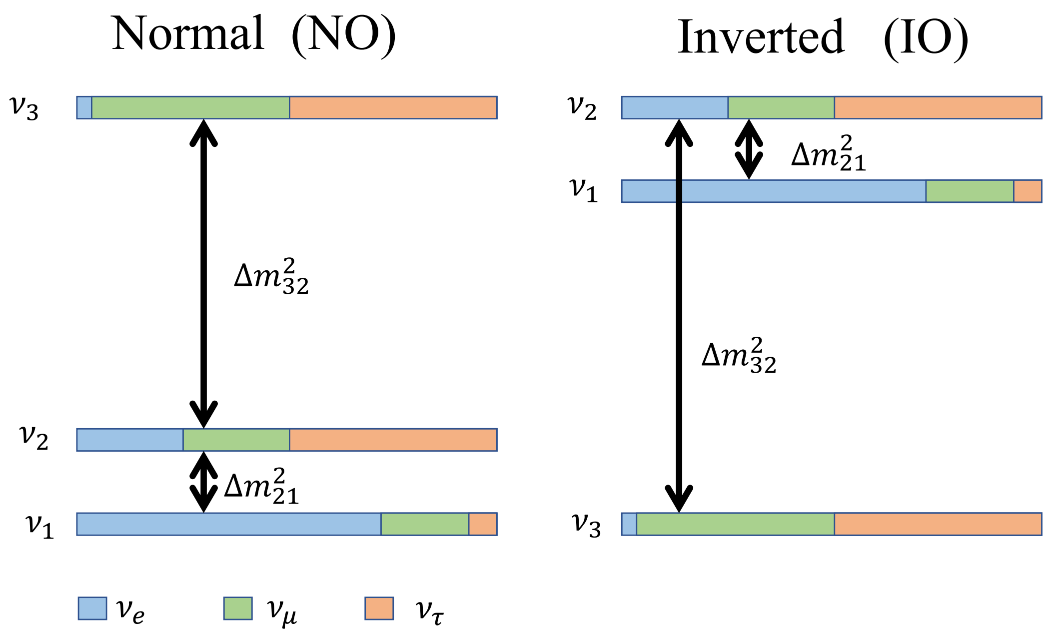
ν_e Appearance Channel



$$P_{\mu\to e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{23} L}{4E_\nu}\right)$$

Leading term only

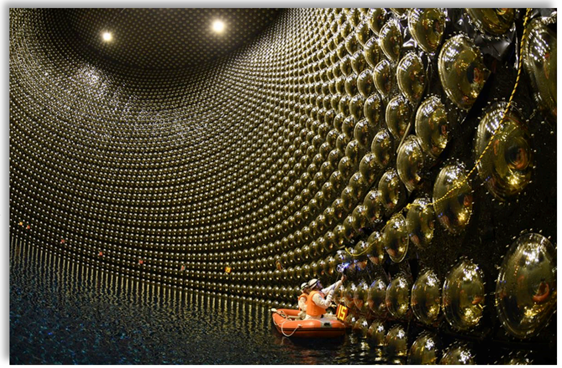
Open Questions

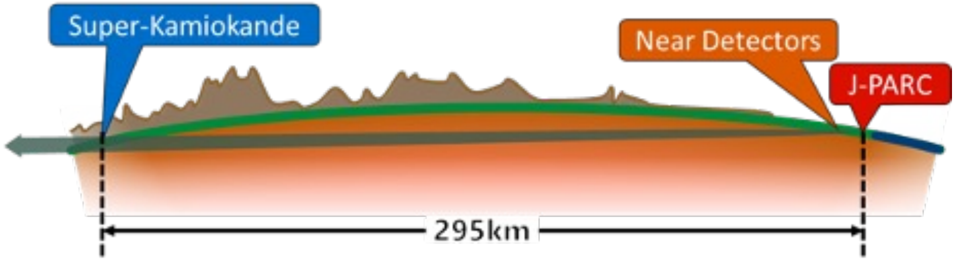


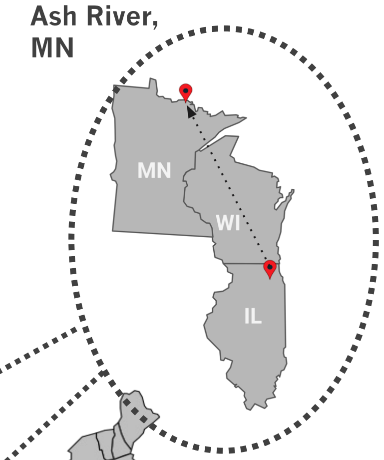
- What is the order of the masses?
- Octant of $\boldsymbol{\theta_{23}}$?
  - If $\boldsymbol{\theta_{23}}$ = 45° then $|U_{\mu 3}| = |U_{\tau 3}|$
    - Maximal mixing
- CP Violation in the lepton sector?
  - Leptogenesis?

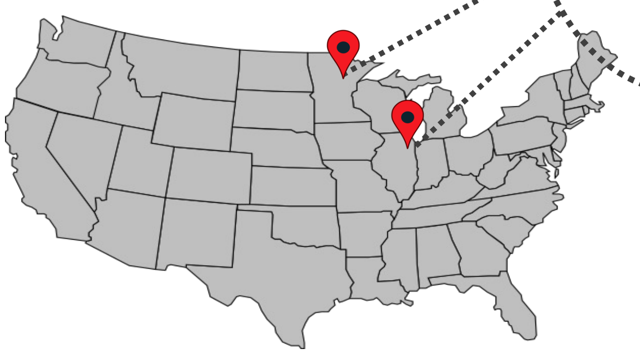
T2K and NOvA Experiments

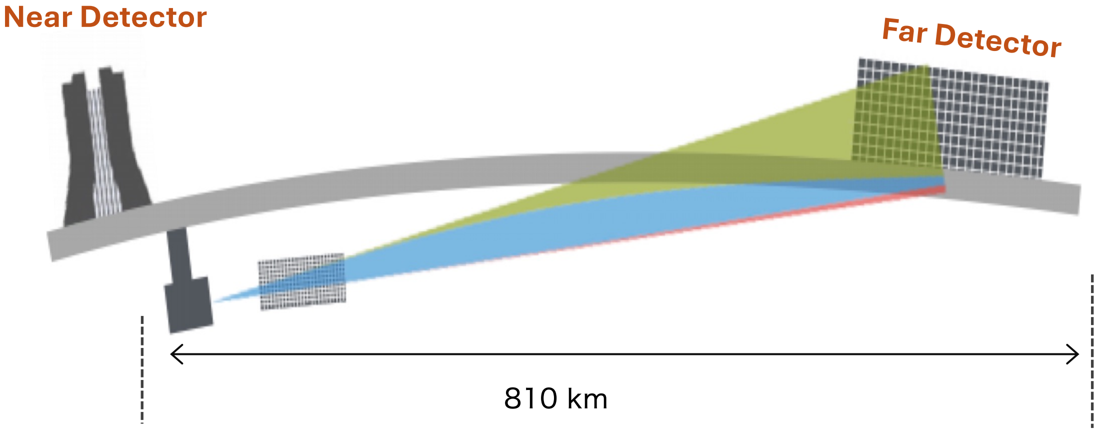

Japan
Kamioka
295 km
Tokai




Super-Kamiokande
Near Detectors
J-PARC
295km

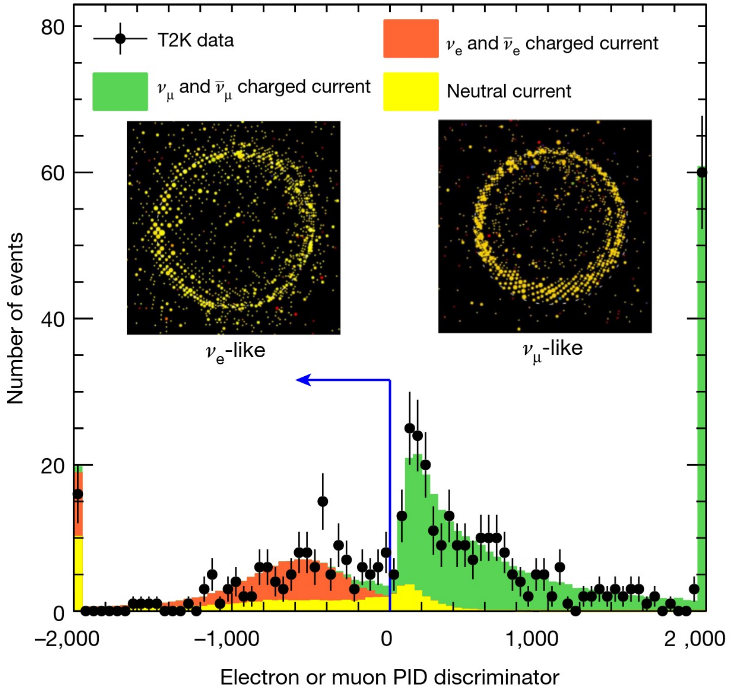

Ash River, MN
MN
WI
IL

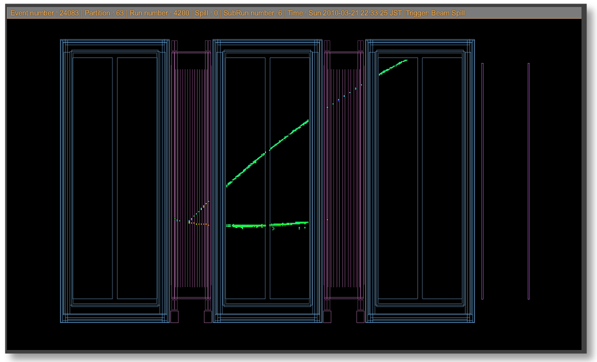



Near Detector
Far Detector
810 km

T2K Experiment

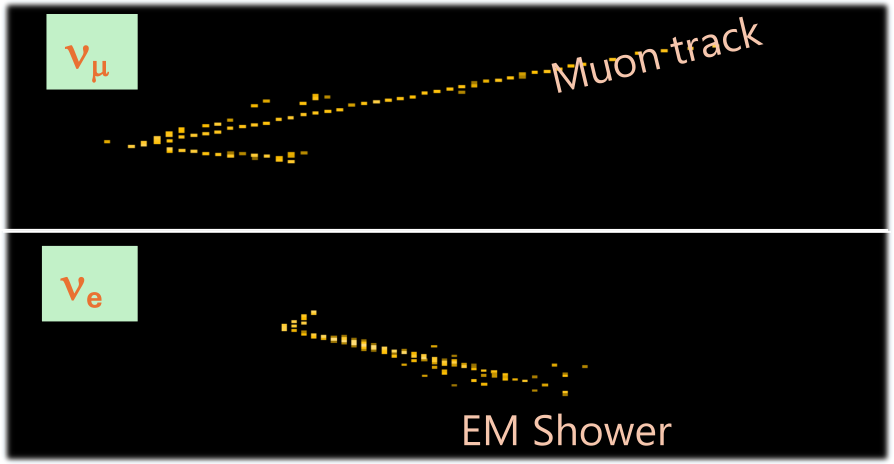
- T2K uses different technologies for its far and near detectors
- Energy of the incoming neutrino is reconstructed using QE kinematics:
  - ND: Selection based on reconstructed muon track and number of pions
  - FD: Cherenkov rings (incoming angle and momentum)



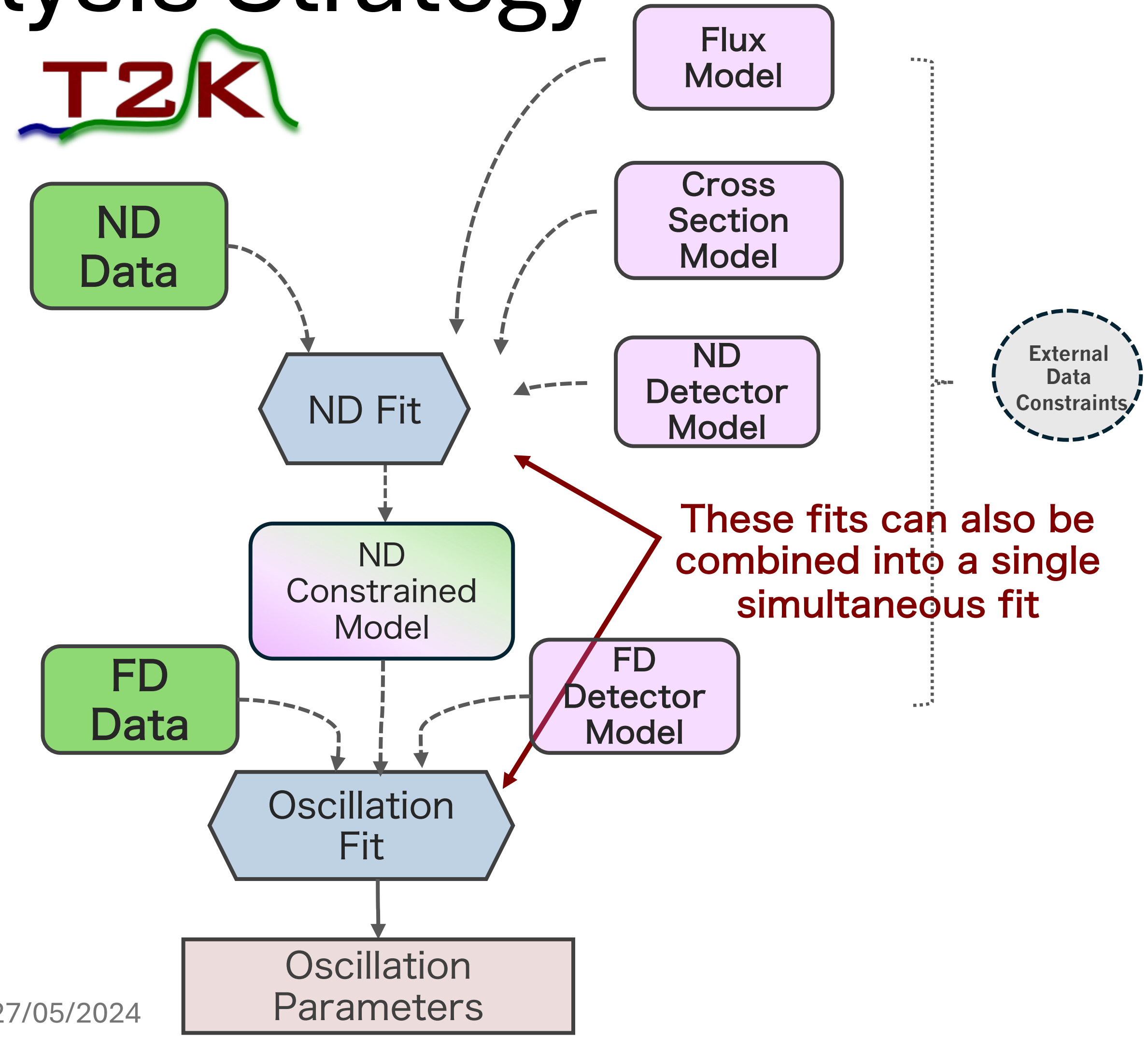


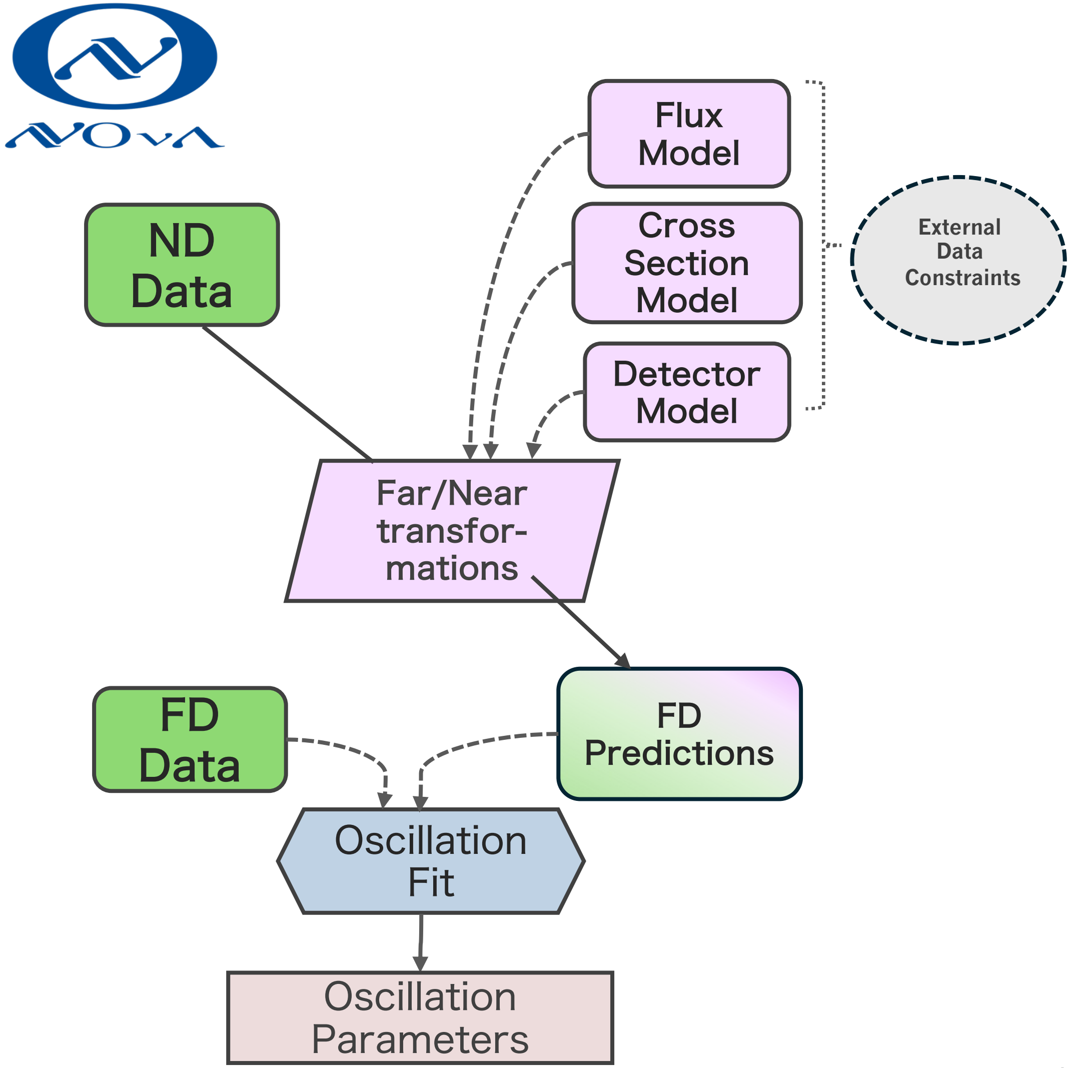
NOvA Experiment

- Two functionally identical, finely granulated tracking calorimeter detectors
- Energy reconstruction for both detectors use combination of lepton and hadronic component



Analysis Strategy





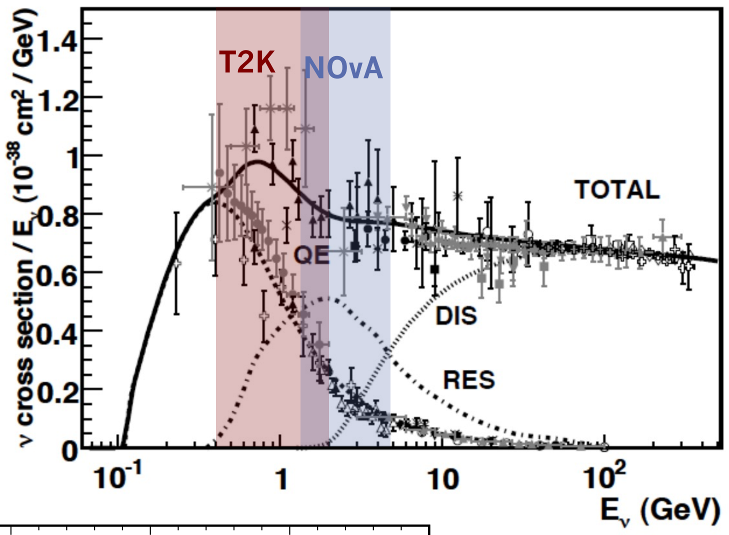
Why Joint Fit?
How?

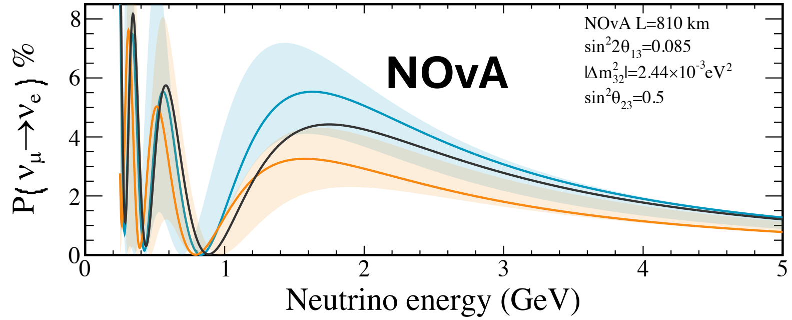
Why Joint Fit?

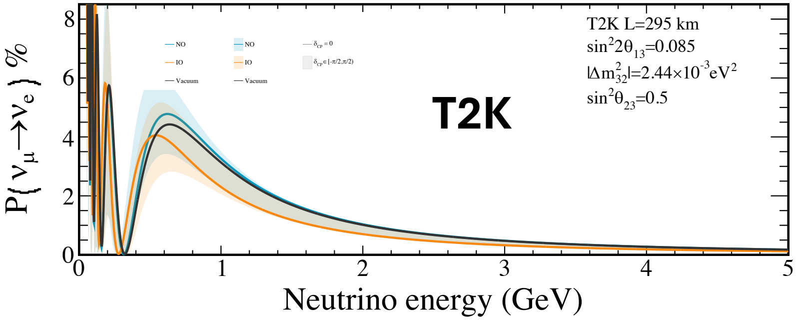
- Different baselines, energies → lift degeneracies in δ_{CP} and sign of Δm^2_{32}
- Different peak neutrino energies

  T2K: primarily Quasi-Elastic and 2p2h interactions

  NOvA: mix of Quasi-Elastic, 2p2h, Resonant and DIS interactions
- NOvA baseline much longer than T2K
  - Different dependance on matter effects; NOvA more sensitive to mass hierarchy
- T2K flux had larger relative impact on δ_{CP}
- More Data!

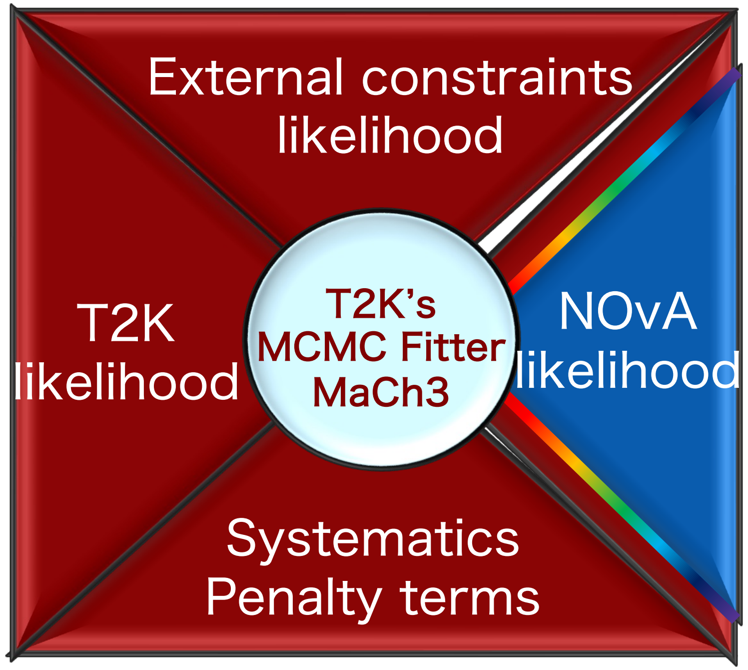


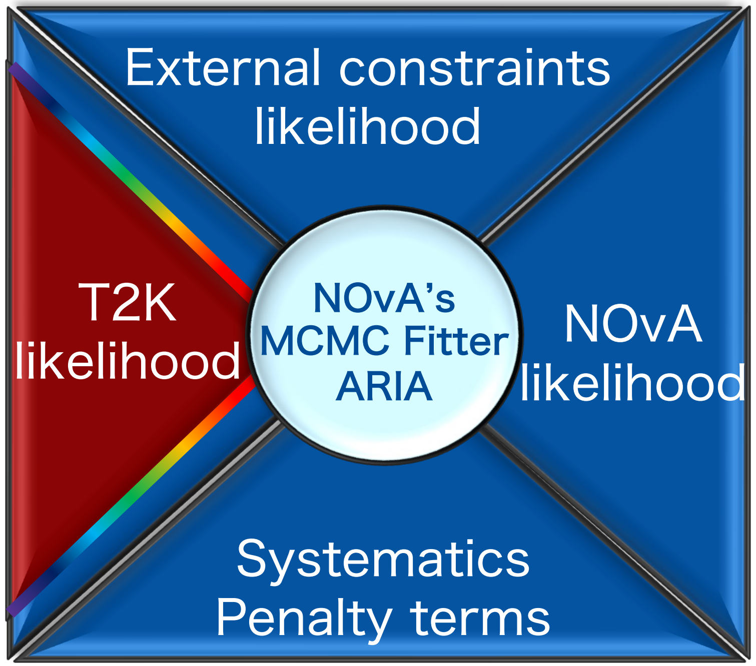




Joint Analysis Strategy

- **Construction:**
  - Poisson likelihood from each experiment
  - Systematics marginalised using data-driven priors
  - External constraints on $\theta_{13}, \theta_{12}, \Delta m^2_{21}$
- **Output:** posterior densities and credible intervals for bayes factor for discrete model preferences





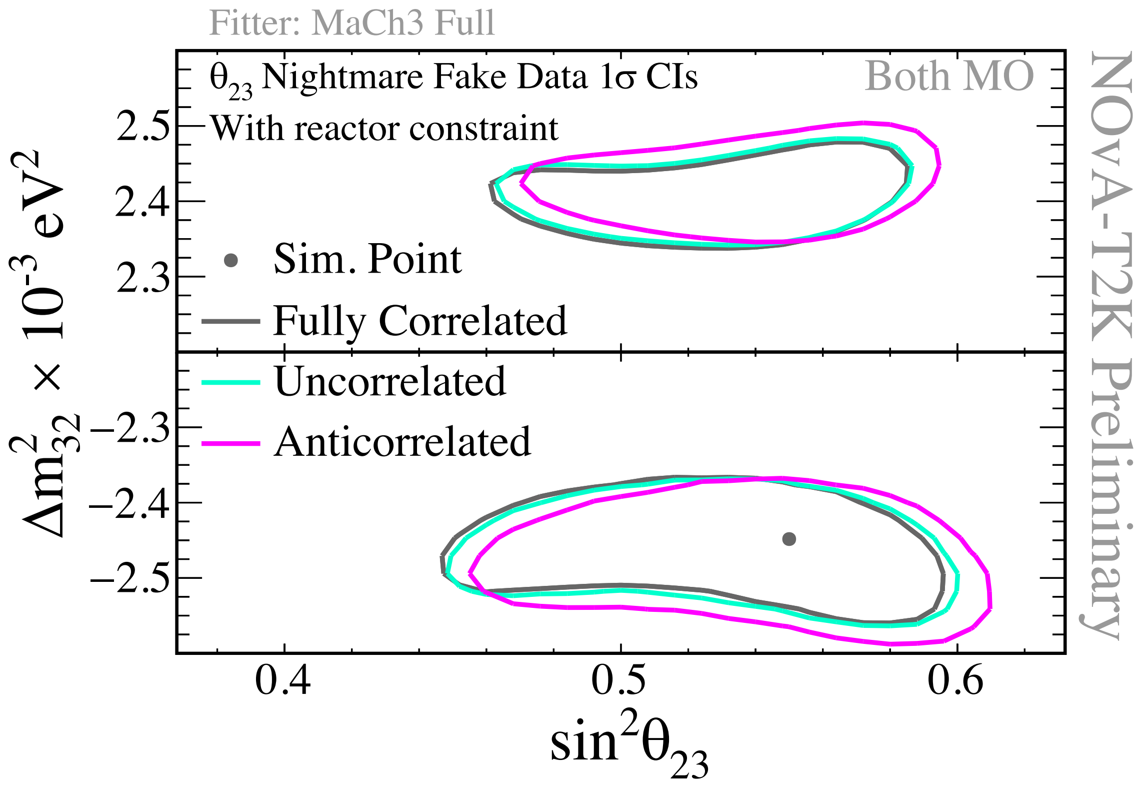
Red represents T2K codebase & blue shows NOvA codebase.

Models & Systematics

- Flux and detector model
  - Different between experiments due to different energies, detector technology etc.
  - No significant correlations
- Cross-section model
  - Use different interaction models and generators
  - Investigate impact of models and correlations

Correlations in cross-section systematic parameters

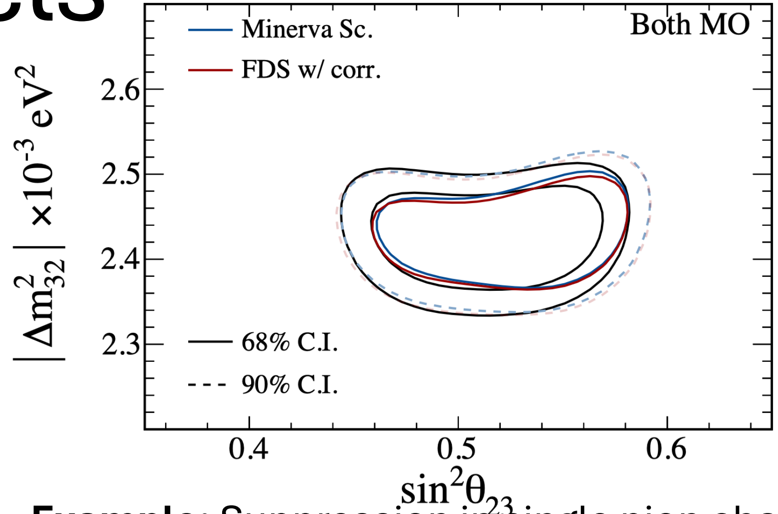
- Evaluate a range of artificial scenarios to evaluate the impact of possible correlations
- Example: Fabricated parameters for each experiment which bias oscillation parameters and study impact of correlating, uncorrelating and anti-correlating parameters
- Final conclusion: **no need to correlate systematic parameters at this exposure**
- Exception: ${}^{\nu_\mu}/_{\nu_e}$ and ${}^{\bar{\nu}_\mu}/_{\bar{\nu}_e}$ cross-section uncertainties where treatment is identical*
  - Fully correlated in the fit



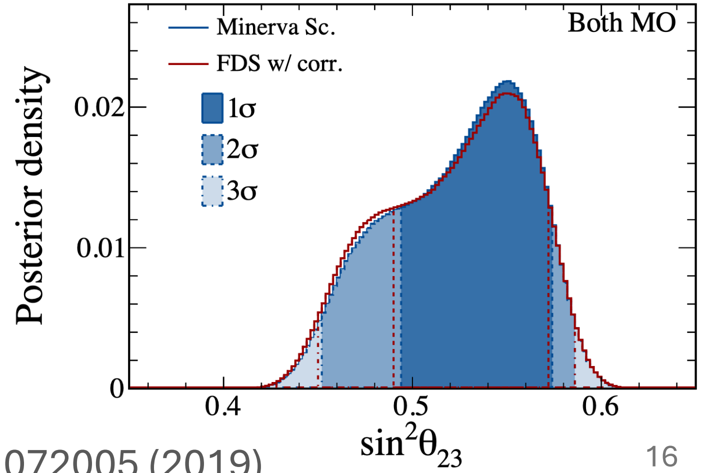
*Phys. Rev. D **86**, 053003 (2012)

Alternate Neutrino Interaction Models

- Evaluate the robustness of the fit against various alternate models
- Pre-decided thresholds for bias:
  - Change in the width of the 1D intervals <10%
  - Change in central value < 50% of systematic uncertainty
- **Conclusion:** No alternate model tests failed the preset threshold bias criteria



- **Example:** Suppression in single pion channel based on tune to the MINERvA data*



*Phys. Rev. D **100**, 072005 (2019)

Results

Data Samples

- This fit uses data collected by both experiments up until 2020 * **
- Reactor constraint used: $\sin^2 2\theta_{13} = 0.0850 \pm 0.0027$
- Goodness of fit evaluated using **posterior predictive p-values**
  - Compare likelihood best fit data and fluctuated predictions
  - Criteria for this analysis requires the post-fit model p-value is **greater than 0.05**
- Also checked p-values for individual detector samples

Channel	P-value	NOvA	T2K
ν_e	0.62	0.90	0.19 (ν_e), 0.79 ($\nu_e 1\pi$)
$\bar{\nu}_e$	0.40	0.21	0.67
ν_μ	0.62	0.68	0.48
$\bar{\nu}_\mu$	0.72	0.38	0.87
Total	0.75	0.64	0.72

Channel	NOvA	T2K	Combined
ν_e	82	$94^{(\nu_e)}$ $14^{(\nu_e 1\pi)}$	190
$\bar{\nu}_e$	33	16	49
ν_μ	211	318	529
$\bar{\nu}_\mu$	105	137	242
Total	431	579	1010

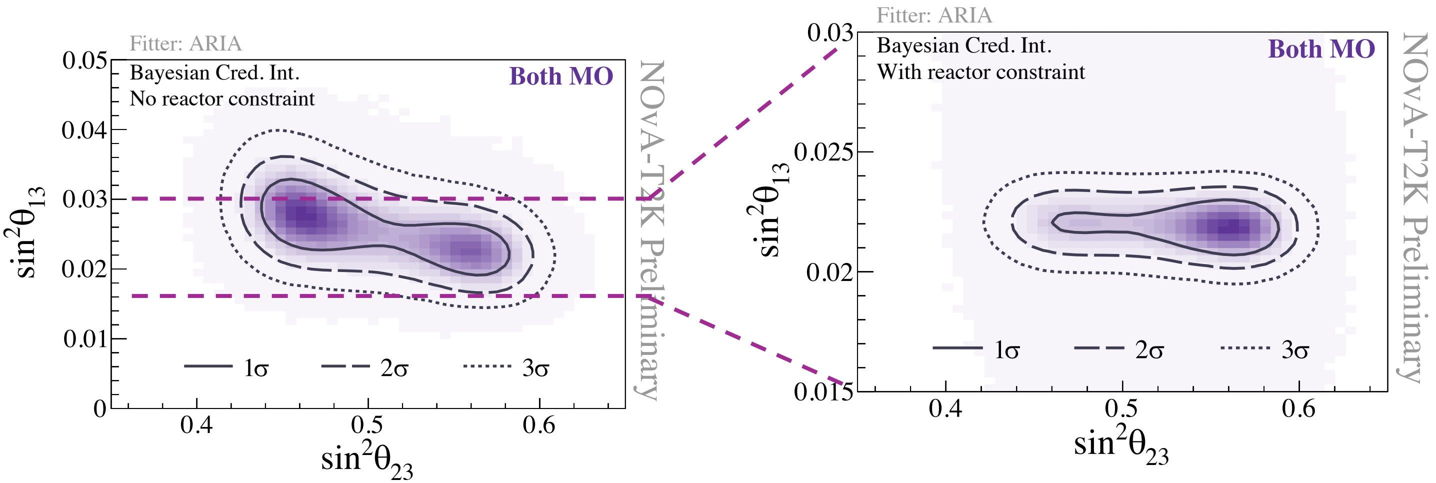
- The oscillation fits can be marginalised over each mass ordering : inverted, normal and both
  - **Conditional**: intervals constructed in a particular mass ordering
  - **Non-conditional**: intervals constructed across both mass orderings

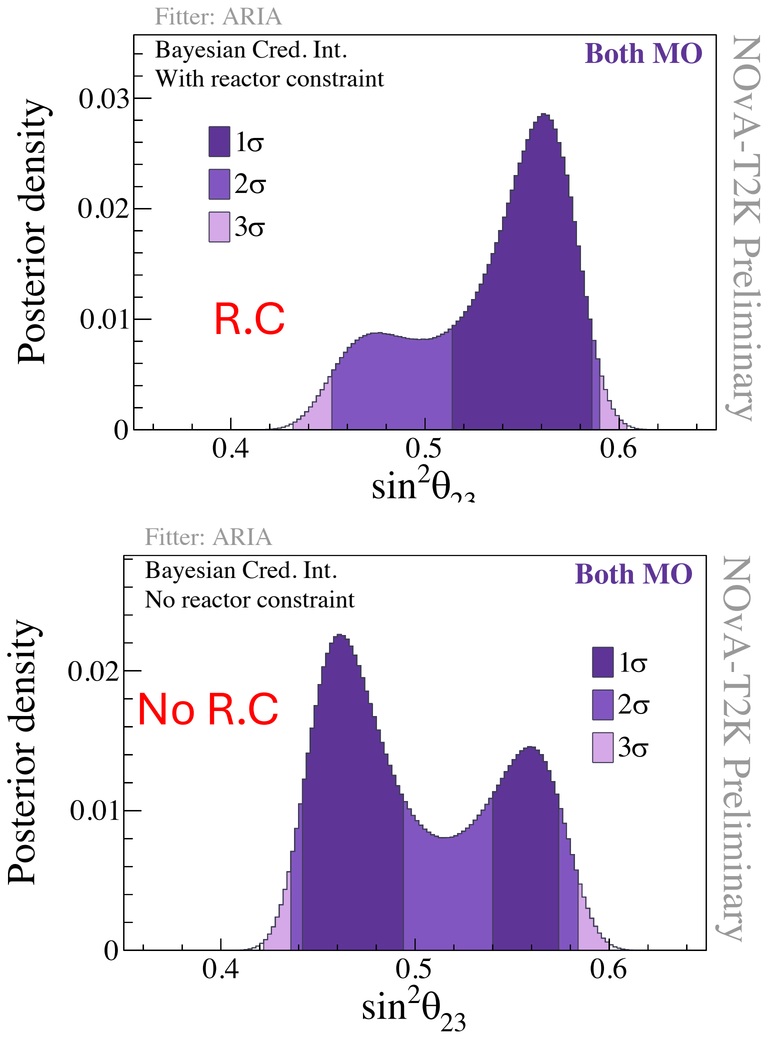
*K. Abe et al., Phys. Rev. D **103**, 112008 (2021)
** M. A. Acero et al, Phys. Rev. D **106**, 032004 (2022)

Results: $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$

- Small preference for lower octant of θ_{23} if no reactor constraints applied
- Upper octant preferred if PDG reactor constraint applied
- Without reactor constraints the joint fit measurements have a degeneracy in the mixing angles

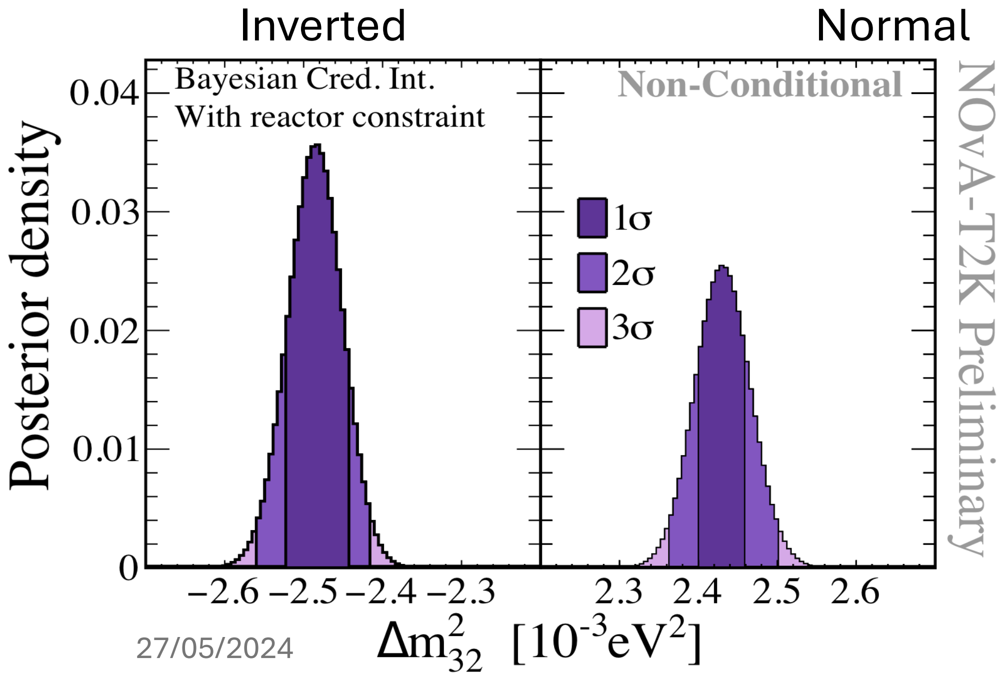
	No reactor constraint	1D reactor constraint
Bayes factor Posterior density	1.17 54% (LO) : 46% (UO)	3.58 78% (UO): 22% (LO)





Results: Mass Ordering

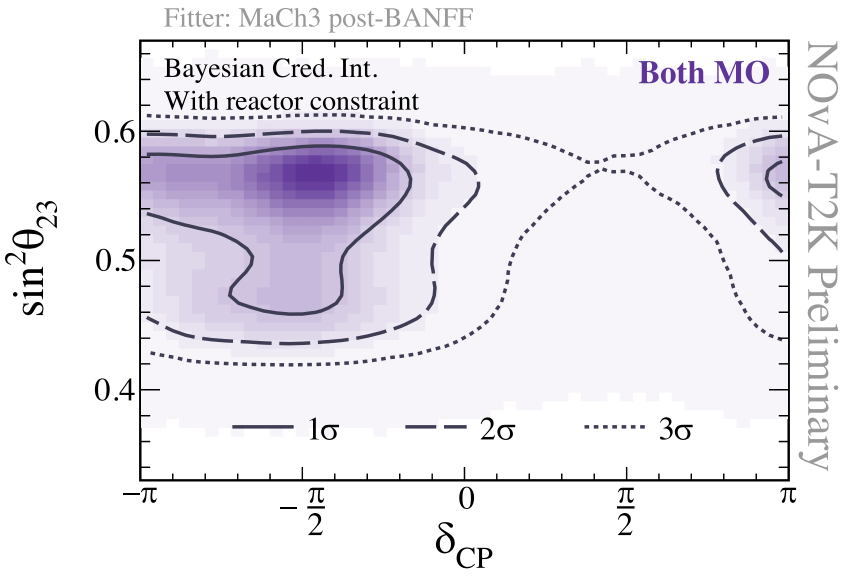
- Small preference for inverted ordering from the fraction of posterior density
- Bayes factors give no conclusive statement about preferred mass ordering

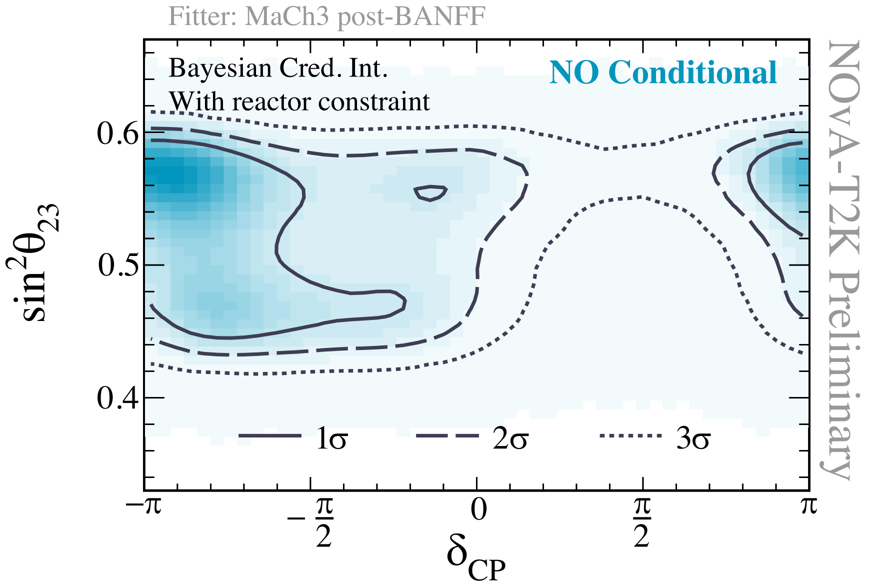


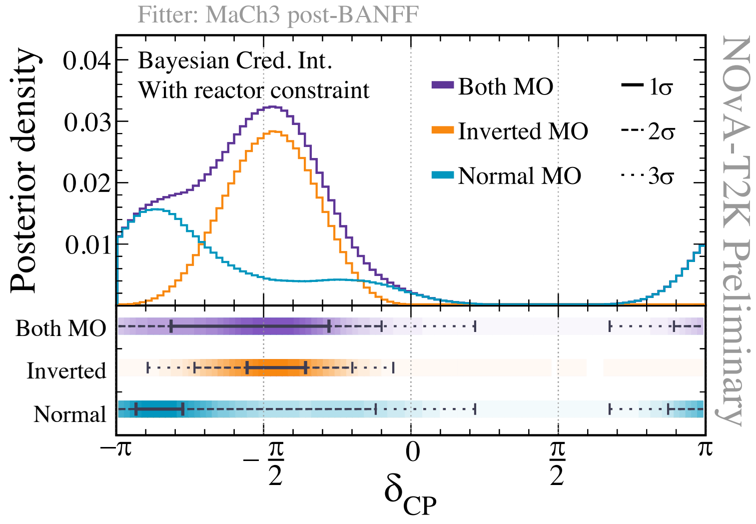
	No reactor constraint	1D reactor constraint
Bayes factor Posterior density	2.45 71% (IO) : 29% (NO)	1.38 58% (IO): 42% (NO)

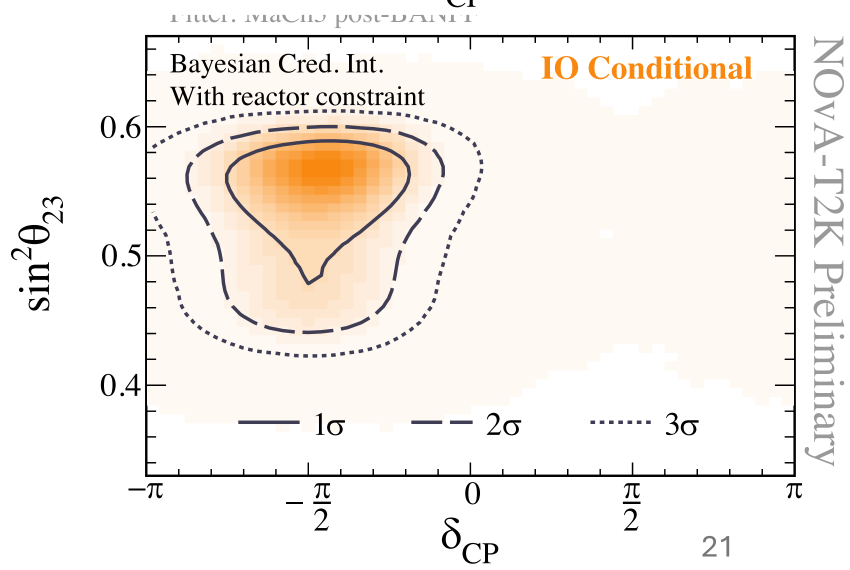
Results: δ_{CP}

- Both MO: higher posterior density around $\delta_{CP} = -\frac{\pi}{2}$
- NO: Wider range of values, higher posterior density close to $\delta_{CP} = \pm\pi$
- IO: Enhanced preference for $\delta_{CP} = -\frac{\pi}{2}$









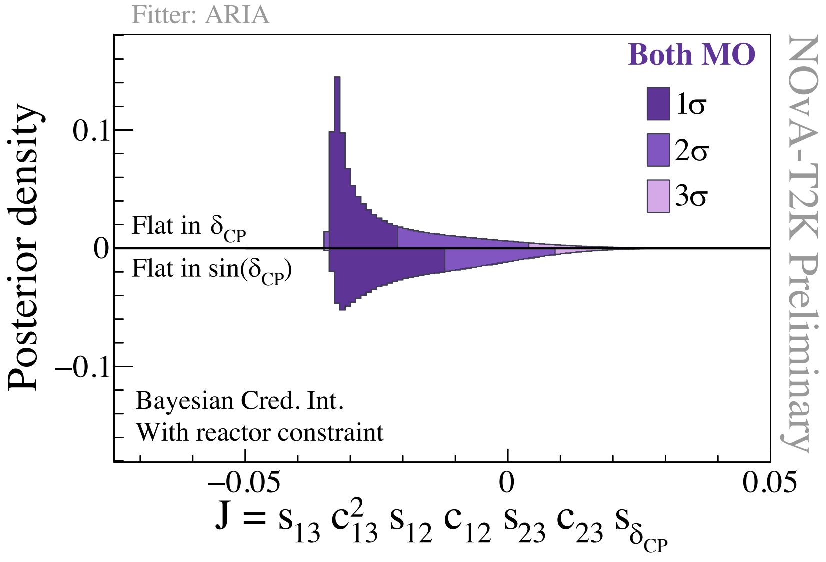
Results: Jarlskog Invariant

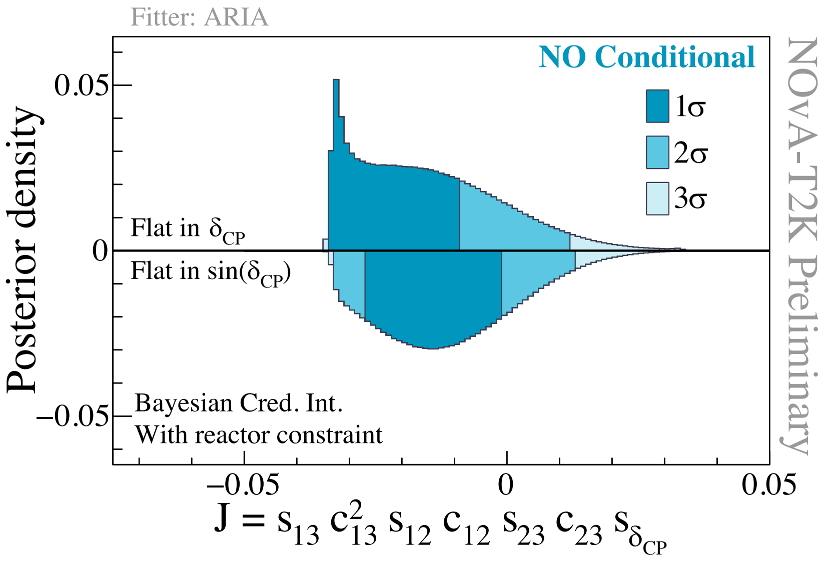
- Parameterisation independent measure of CPV:

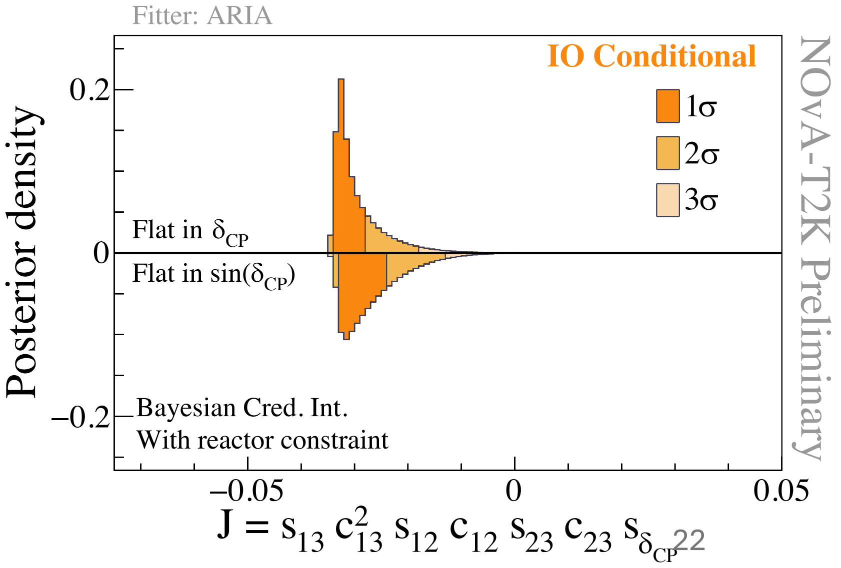
$$J = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}sin\delta_{CP}$$

- If $J = 0$ → CP conservation
- If $J \neq 0$ → CP violation

- Both MO: Broad range of probable J
- NO: Broad range of probable J
- IO: $J = 0$ point is outside 3σ credible interval, also true for a change in the prior on δ_{CP} to be flat in $\sin\delta_{CP}$

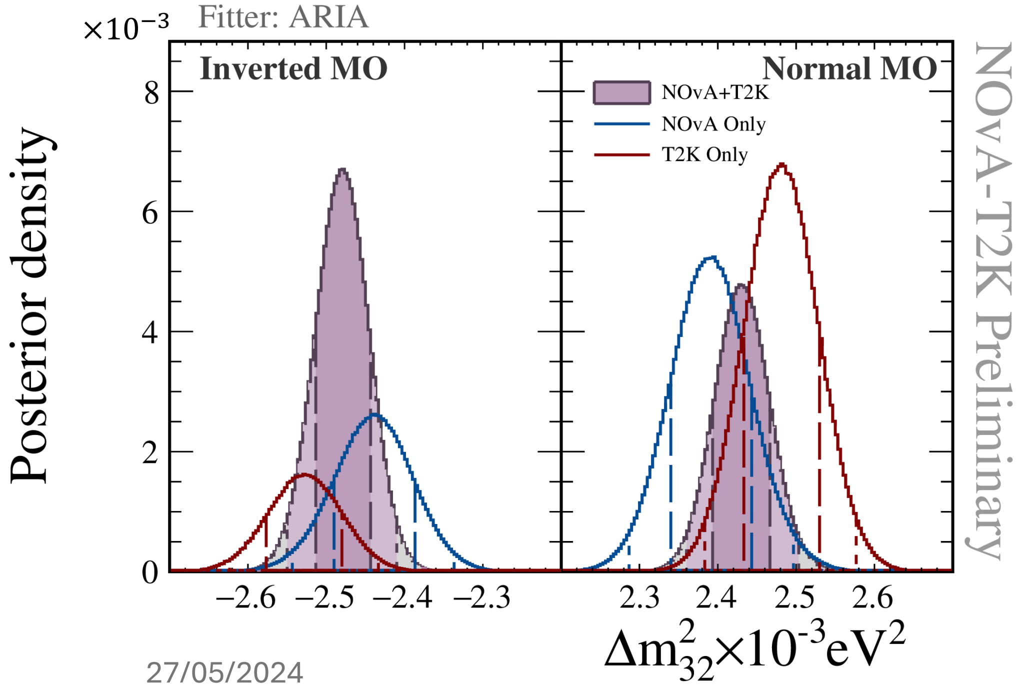


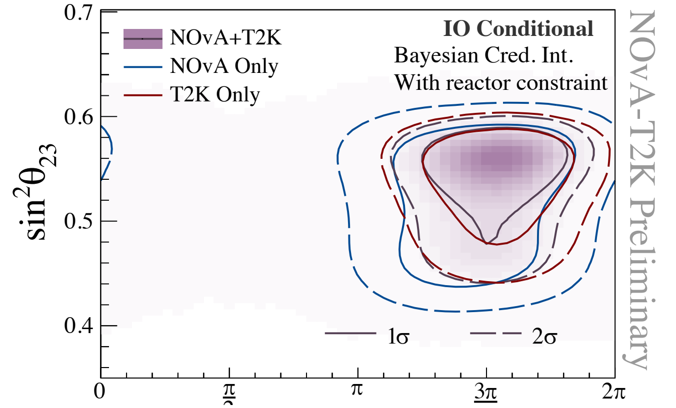


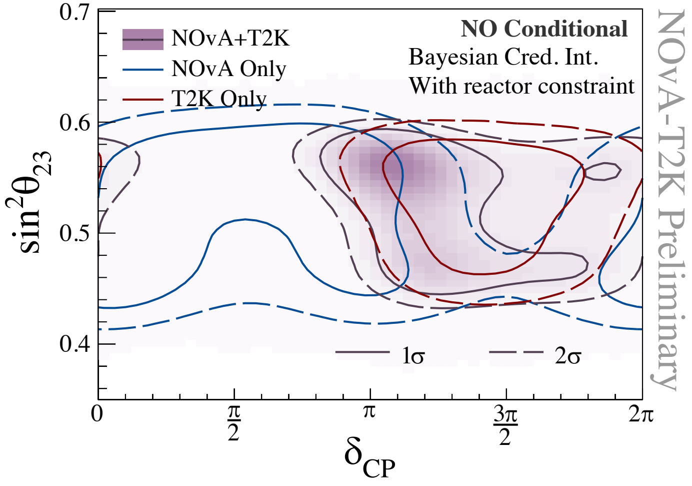


Comparison to T2K Only and NOvA Only Results

- Joint fit gives a tighter constraint in IO and relieves differences in NO
- Small preference for mass ordering flips with the joint fit
- Enhances the precision for Δm^2_{32}

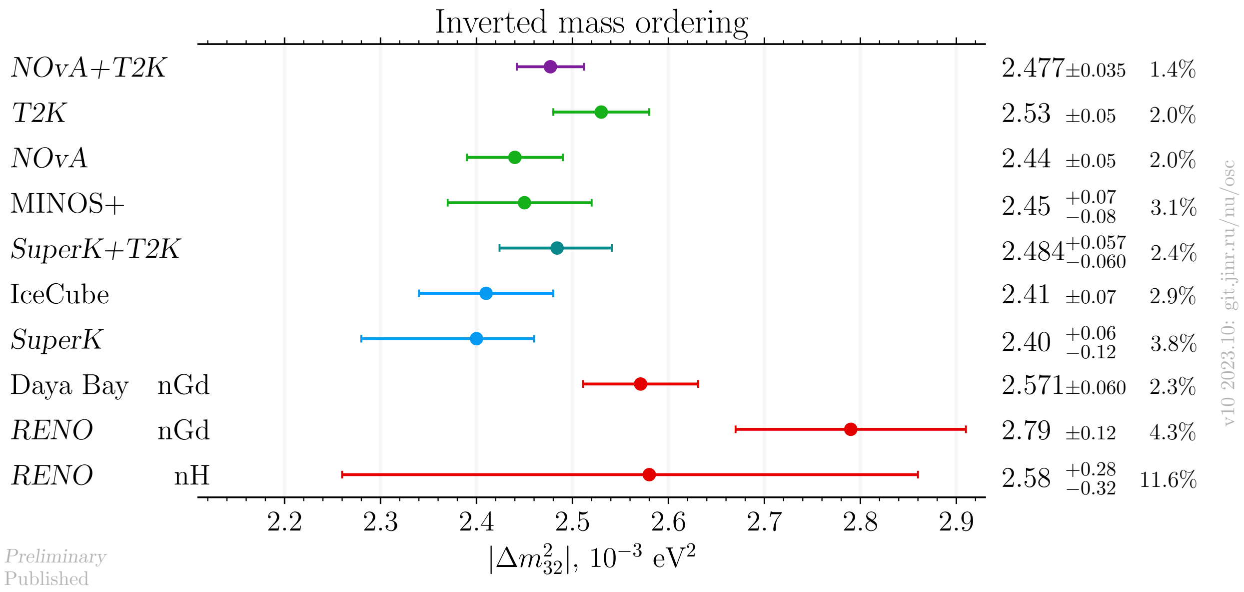


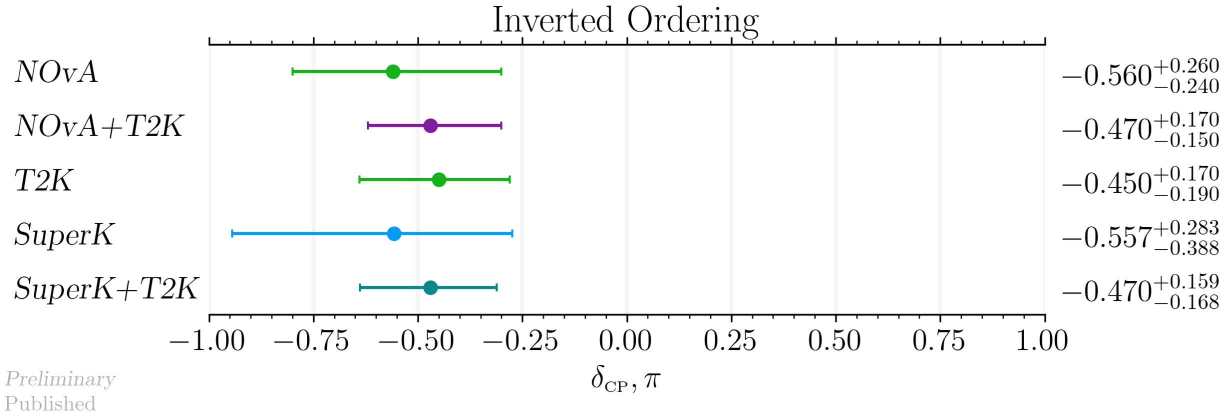




Comparison to Other Experiments

- T2K-NOvA joint fit has the smallest uncertainty on Δm^2_{32} compared to previous measurements





- T2K-NOvA joint fit is consistent with other δ_{CP} measurements

Summary

- Joint analysis **fits both experiments datasets successfully**
- No strong preference for mass ordering, small preference (58%:42%) for inverted ordering
  - Both experiments previously had a small preference for NO
- Normal Ordering allows for a wide range of δ_{CP} values, while in Inverted Ordering CP conserving values fall outside of the 3σ credible intervals
  - Similar conclusions found for Jarlskog invariant
- **Strong constraint on Δm^2_{32}**
- Both experiments continue to collect data and improve individual analyses
  - T2K ND upgrade, improved models, continue data collection

Future

Current Generation

T2K NOvA

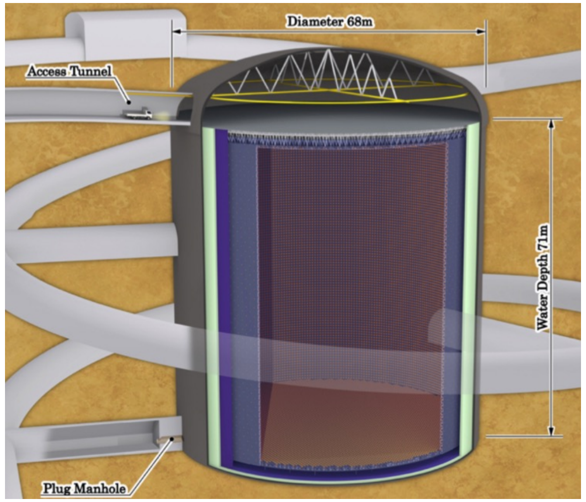
MINOS
K2K
OPERA

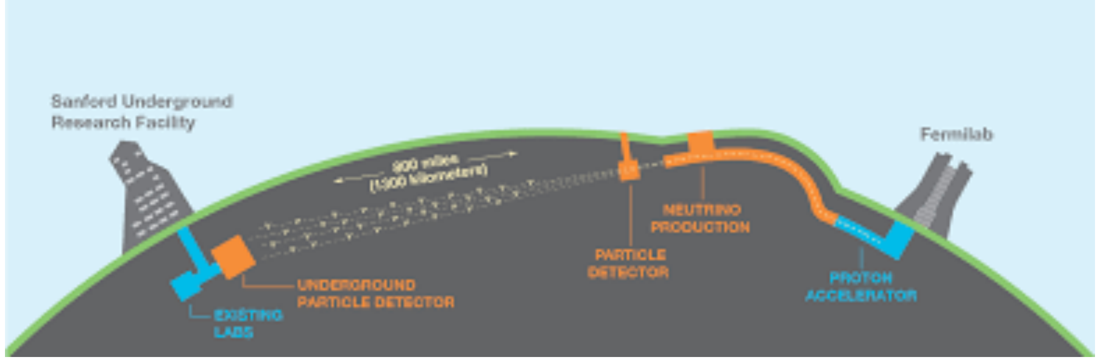
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT
Hyper-Kamiokande

2010
2020
2030

NOvA collects first beam data.

T2K collects first beam data.





University of Glasgow

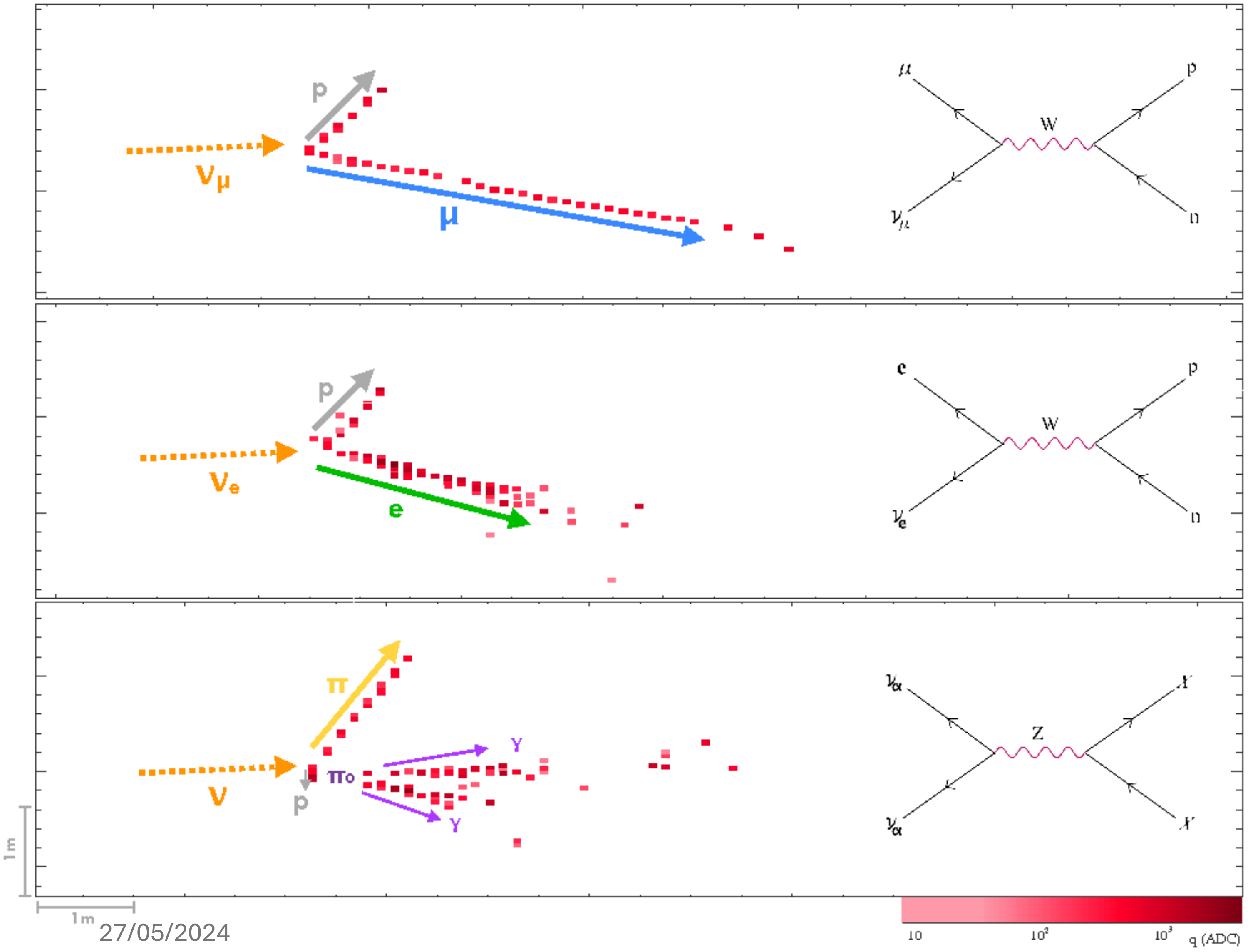
NOvA T2K

Thank you for listening!
Any questions?

#UofGWorldChangers

@UofGlasgow

Backup



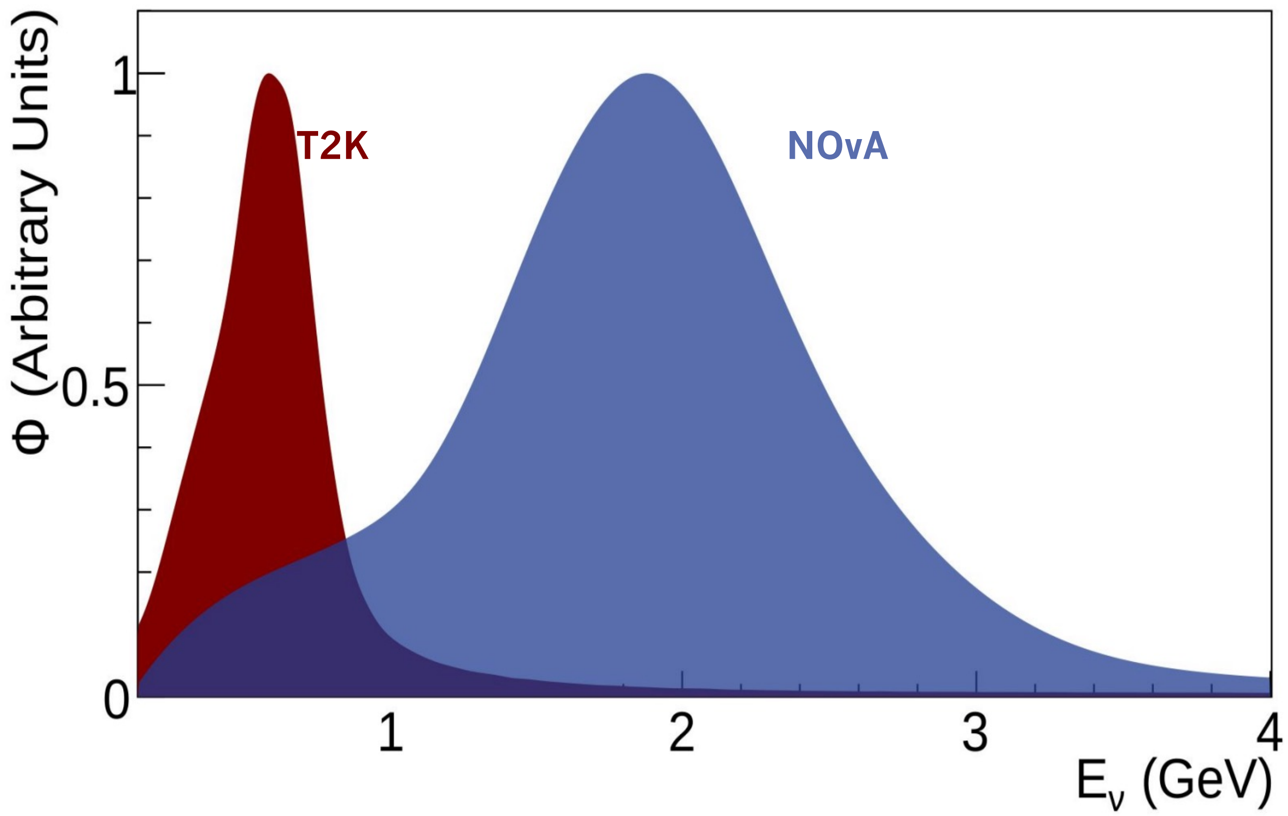
υ_μ CC Event

υ_e CC Event

NC Event

Energy Spectrum

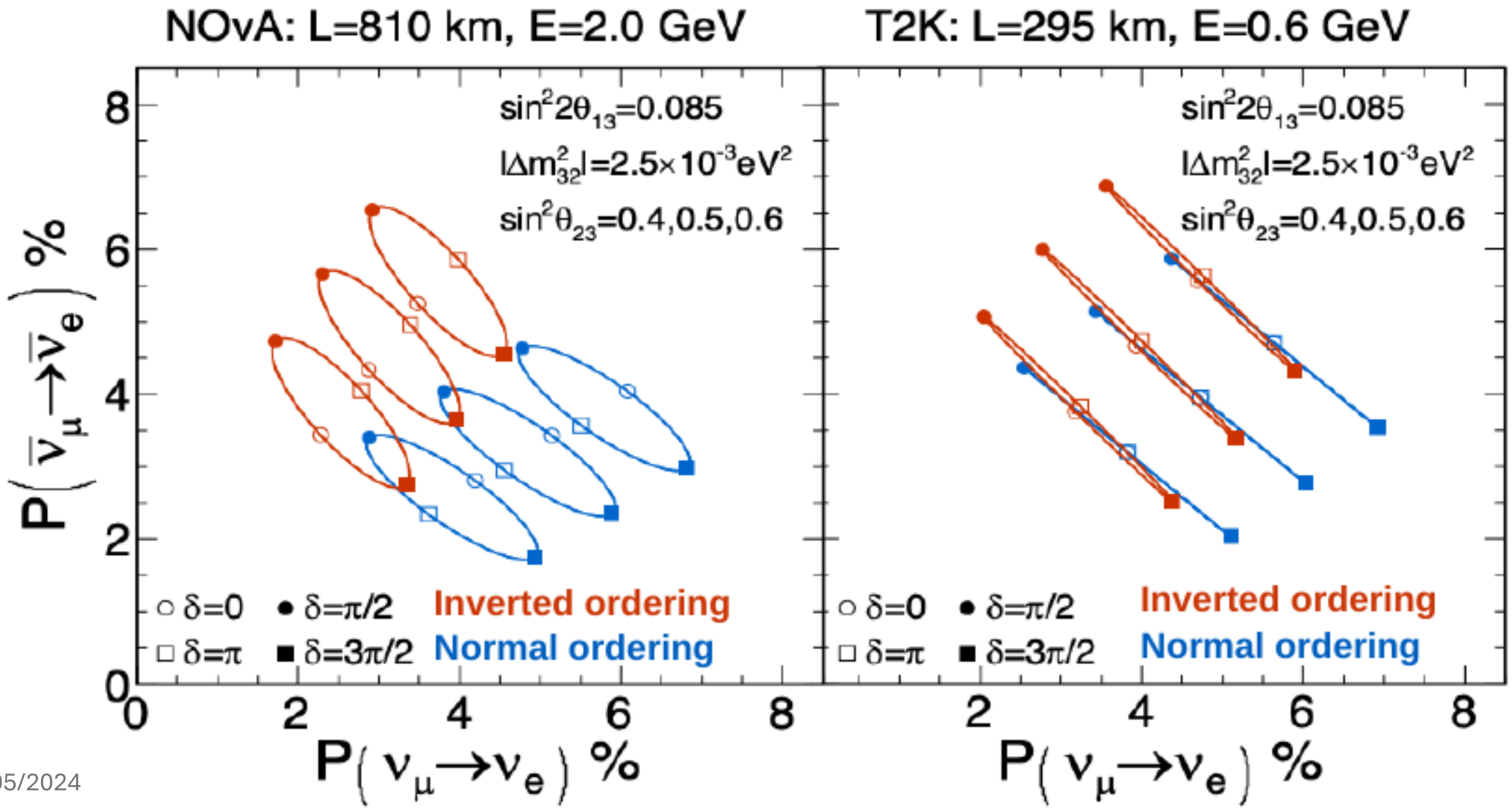
Neutrino flux



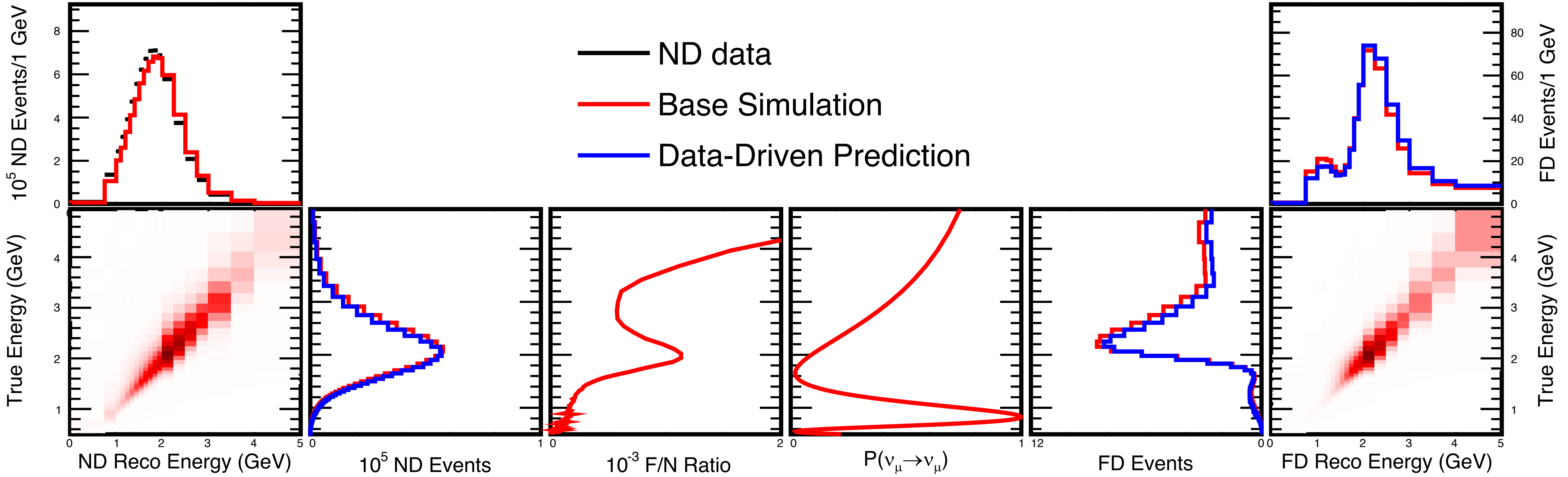
Priors

Parameter	ARIA sampling prior	MaCh3 sampling Prior	Priors used for the analysis
θ_{23}	Uniform in θ_{23}	Uniform in $\sin^2\theta_{23}$	Uniform in $\sin^2\theta_{23}$
θ_{13}	Uniform in θ_{13}	Uniform in $\sin^2 2\theta_{13}$	Uniform in $\sin^2 2\theta_{13}$ & Gaussian reactor constraint
$\lvert\Delta m^2_{32}\rvert$	Uniform in $\lvert\Delta m^2_{32}\rvert$	Uniform in $\lvert\Delta m^2_{32}\rvert$	Uniform in $\lvert\Delta m^2_{32}\rvert$
MO	Uniform in MO with a 50% switch probability	Uniform in MO with a 50% switch probability	Uniform in MO with a 50% switch probability
δ_{CP}	Uniform in δ_{CP}	Uniform in δ_{CP}	Uniform in δ_{CP} & Uniform in $\sin\delta_{CP}$ (for J)

Why Joint Fit?

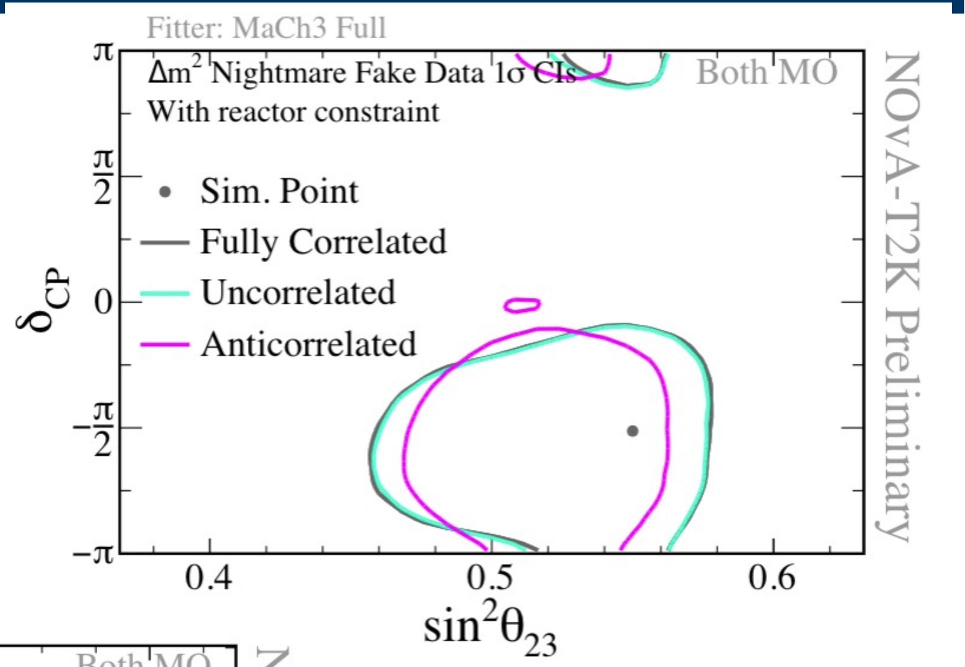


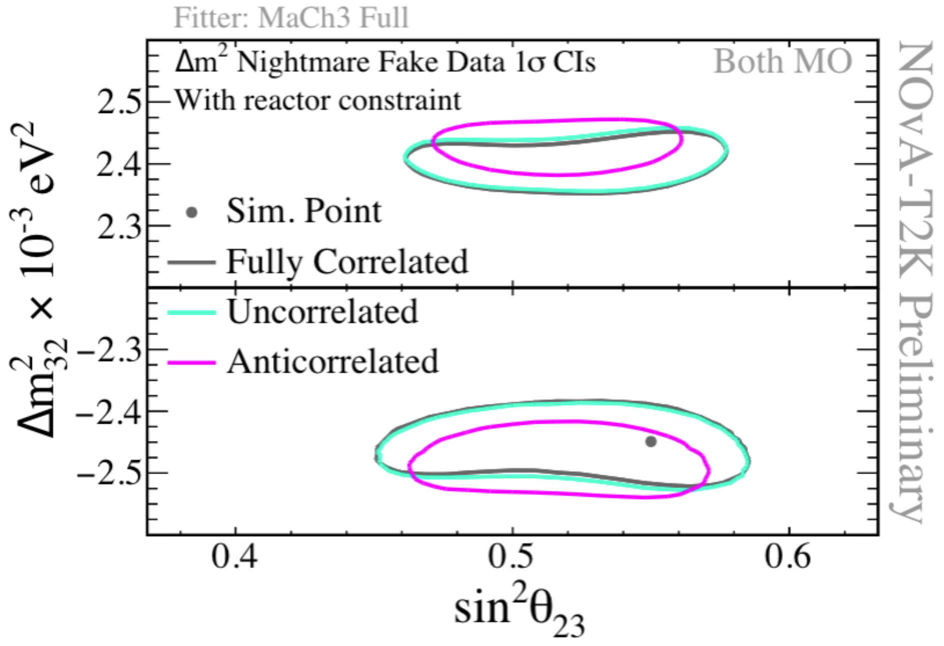
NOvA Extrapolation

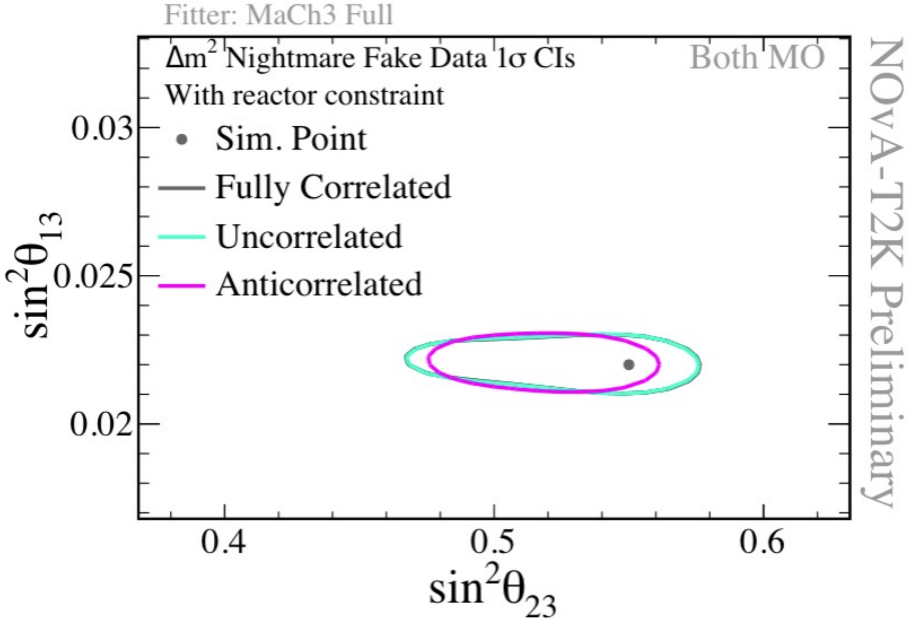


Correlations

- Δm^2_{32} bias mock data (nightmare) study (fully correlated = correct assumption)

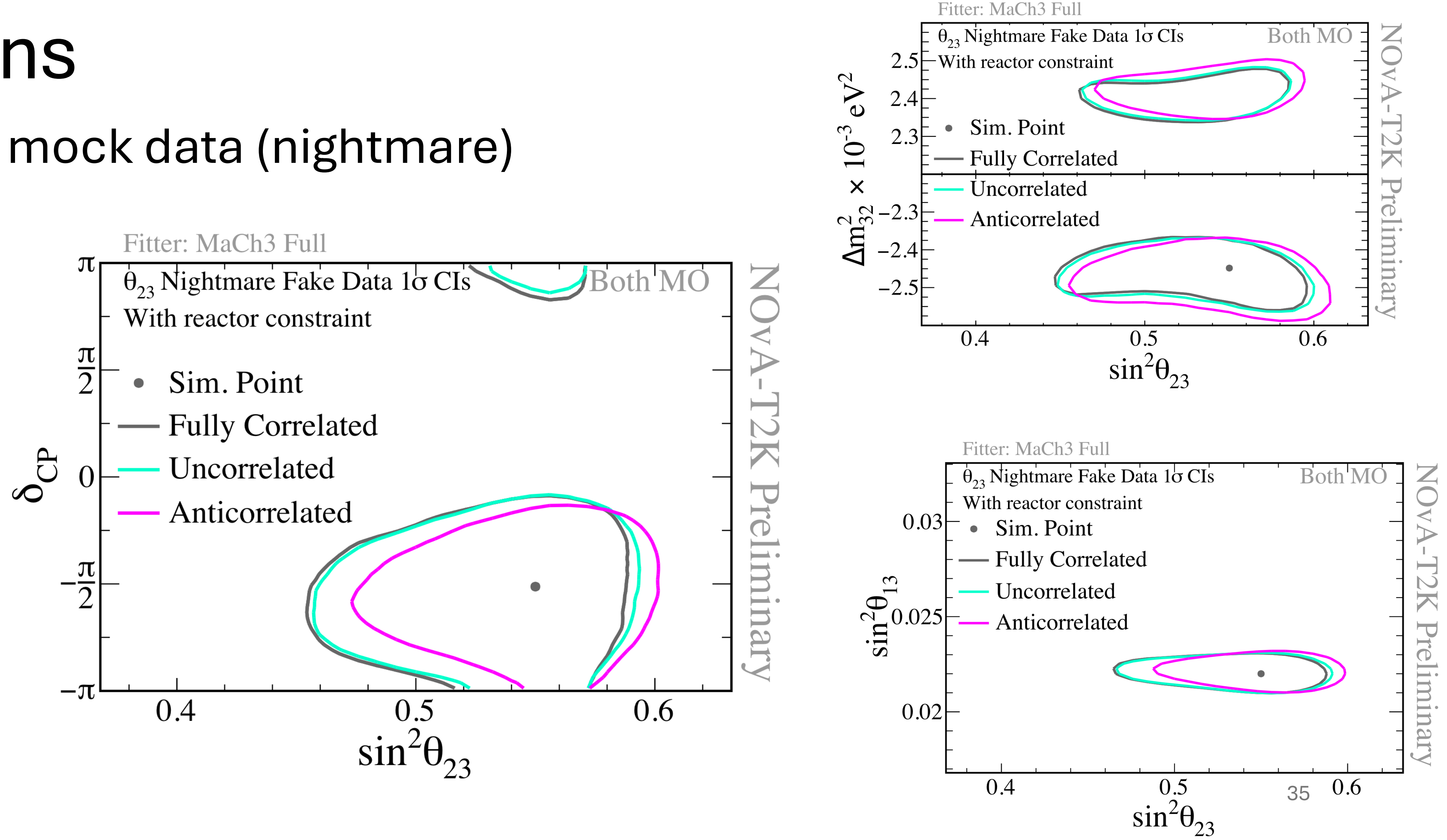




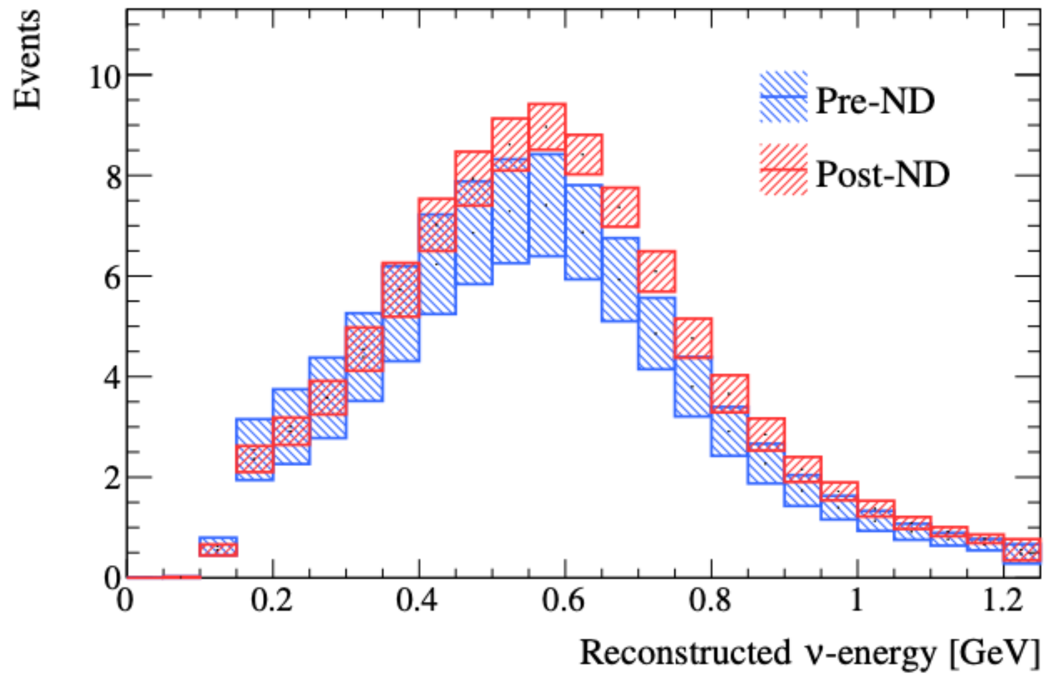


Correlations

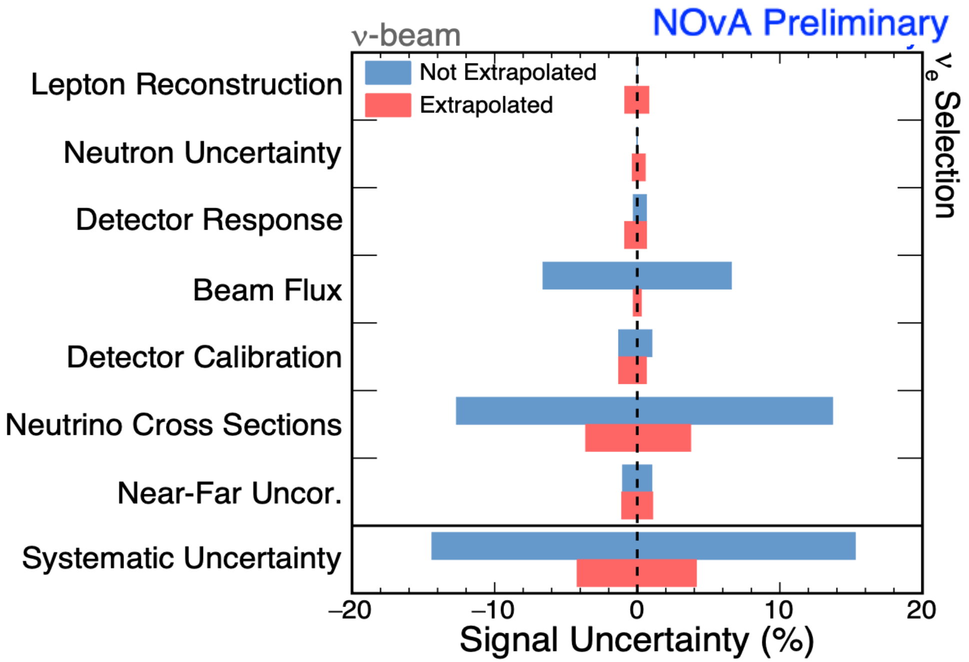
- $\sin^2\theta_{23}$ bias mock data (nightmare) study



Systematics



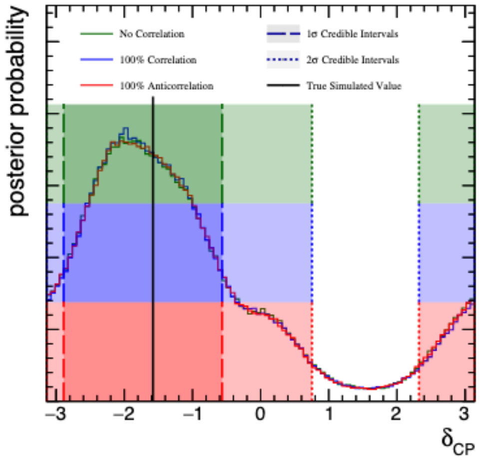
Eur. Phys. J. C (2023) 83:782 (2023)



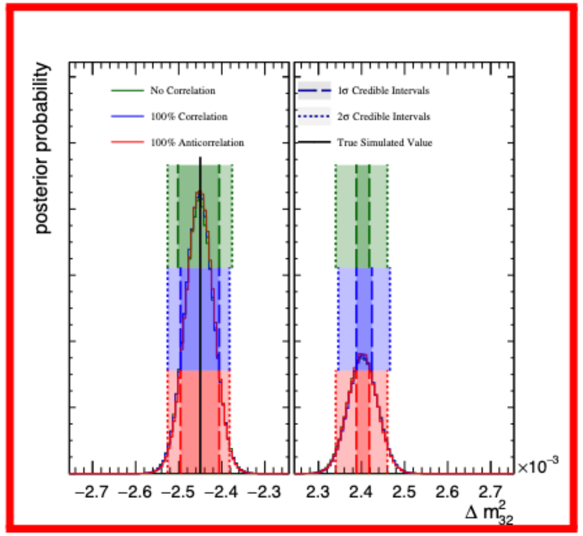
Correlations

Oscillation Parameter	Largest NOvA Systematic	Largest T2K Systematic
δ_{CP}	second class currents	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$ cross section
	and radiative corrections	and antineutrino equivalents
$\sin^2\theta_{23}$	neutron visible energy	2p2h C-O scaling
Δm^2_{32}	calibration	7% SK energy-scale*

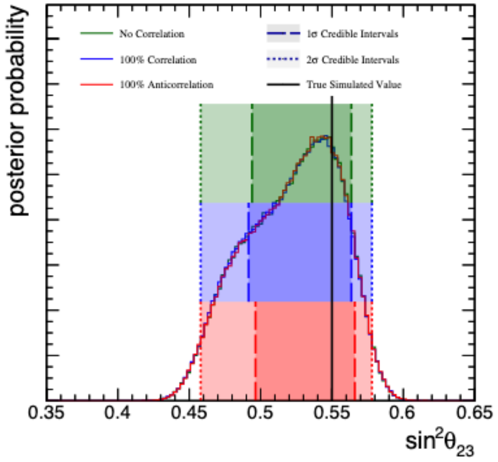
- Correlating largest systematics on $\mathbf{\Delta m^2_{32}}$ across both experiments.



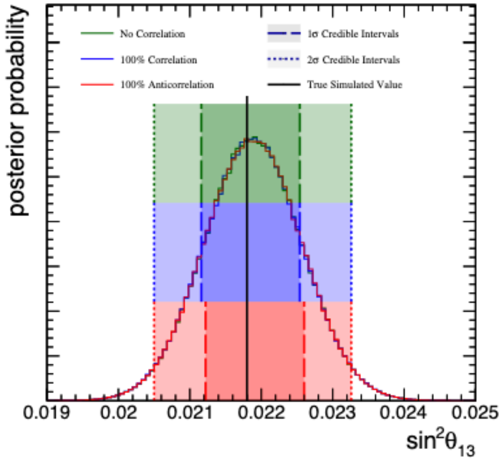
(a) δ_{CP}



(b) Δm^2_{32}



(c) $\sin^2\theta_{23}$

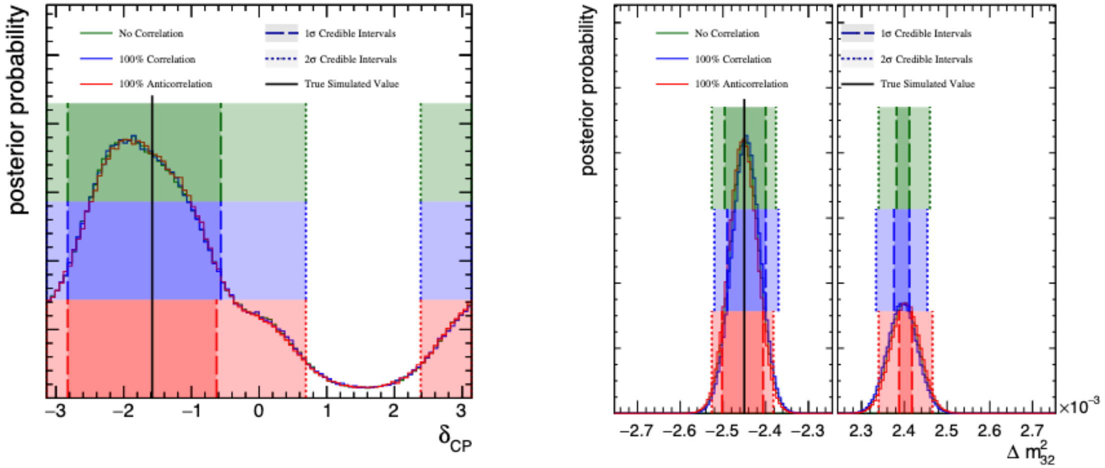


(d) $\sin^2\theta_{13}$

Correlations

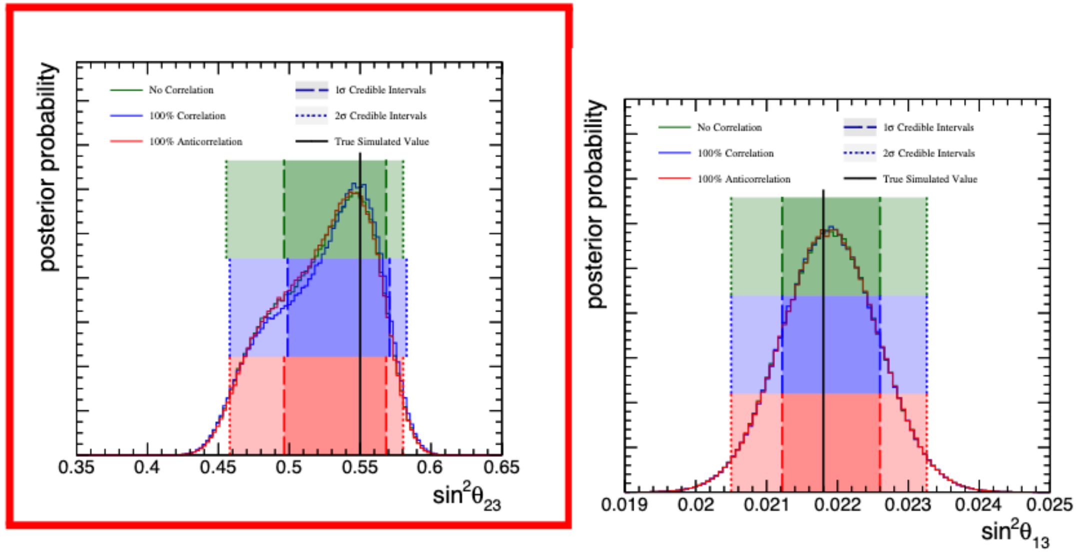
Oscillation Parameter	Largest NOvA Systematic	Largest T2K Systematic
δ_{CP}	second class currents and radiative corrections	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$ cross section and antineutrino equivalents
$\sin^2\theta_{23}$	neutron visible energy	2p2h C-O scaling
Δm^2_{32}	calibration	7% SK energy-scale*

- Correlating largest systematics on $\sin^2\theta_{23}$ across both experiments.



(a) δ_{CP}

(b) Δm^2_{32}



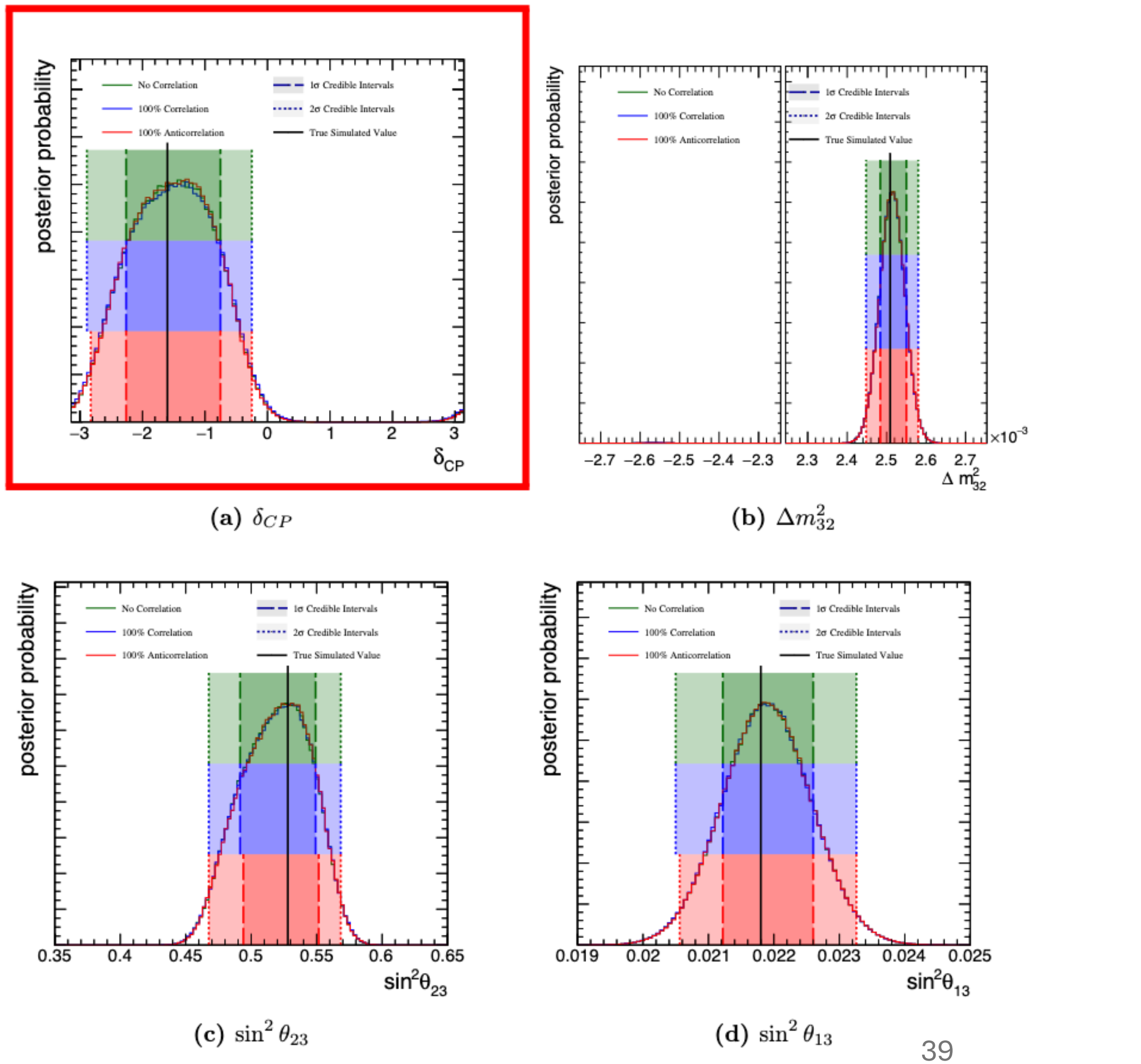
(c) $\sin^2\theta_{23}$

(d) $\sin^2\theta_{13}$

Correlations

Oscillation Parameter	Largest NOvA Systematic	Largest T2K Systematic
δ_{CP}	second class currents and radiative corrections	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$ cross section and antineutrino equivalents
$\sin^2\theta_{23}$	neutron visible energy	2p2h C-O scaling
Δm^2_{32}	calibration	7% SK energy-scale*

- Correlating largest systematics on $\sin^2\theta_{23}$ across both experiments.



Alternate Models

- Alternate models that had the largest impact on T2K's 2020 fit and the two cross-experiment model checks were done for the joint analysis:
  - **Non-QE**: ND280 CC0π data are under-predicted by the T2K pre-fit prediction. This difference can be taken accounted for by the large freedom in the CCQE model. To check this large freedom does not cause bias, an alternate model where this under-prediction is attribution to only non-QE processes is produced.
  - **Minerva1Pi**: suppression of CC and NC resonant pion production at low-Q^2 to describe for GENIE v2 implementation of Rein-Seghal model to describe the data.
  - **Pion SI**: replaced GEANT4 model* was replaced with NEUT's Salcedo–Oset model**

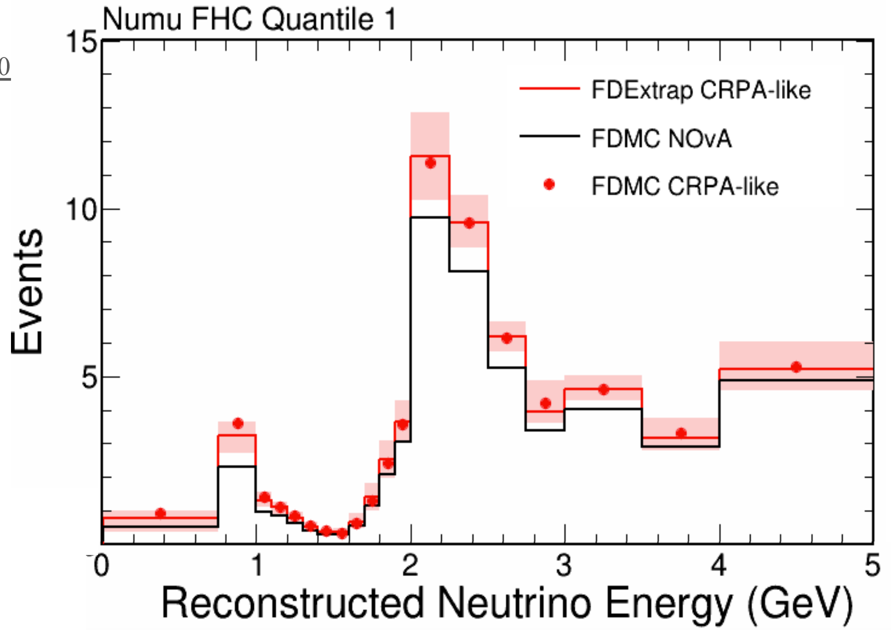
* S. Agostinelli et al., (The GEANT4 collaboration), Nucl. Instrum. Meth. A 506 (2003) 250–303 SLAC-PUB-9350

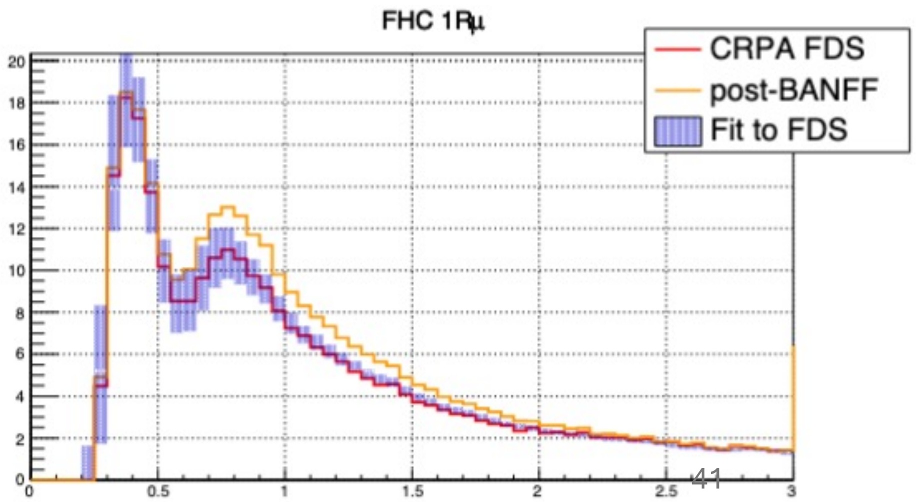
** L. L. Salcedo, E. Oset, M. J. Vicente-Vacas, and C. Garcia-Recio, Nucl. Phys. A 484 (1988) 557–592 Print-87-1084 (Valencia)

Alternate Models: HF-CRPA

* Phys. Rev. D 106, 0730

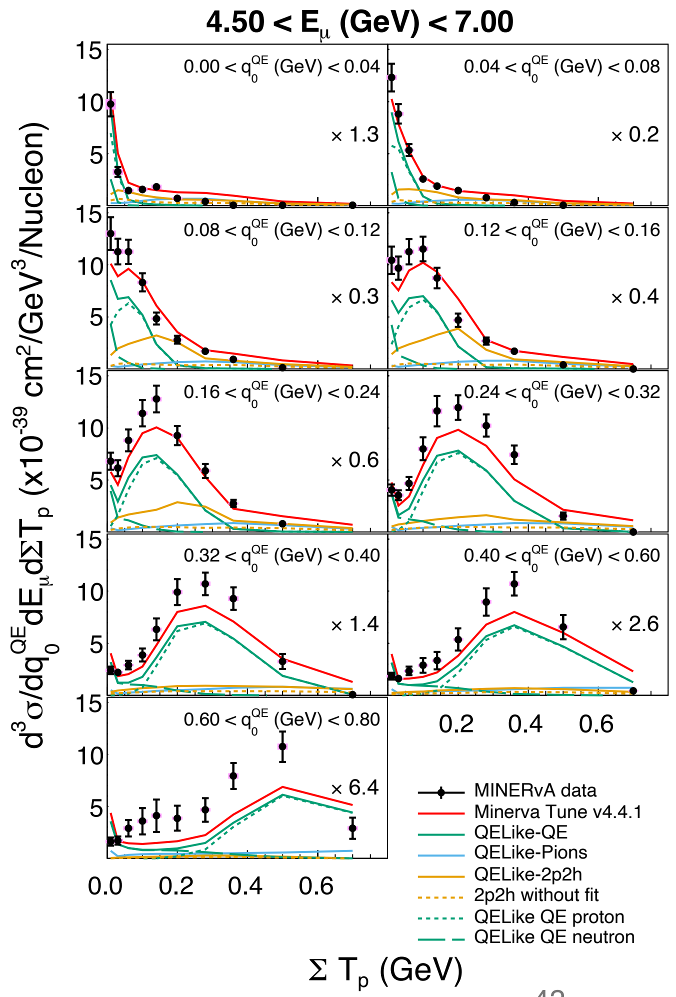
- Hartree Fock (HF) – Continuum Random Phase Approximation (CRPA)*
- Applies modifications to the nuclear models (Spectral Function for T2K, Local Fermi Gas for NOvA)
- Recent T2K analyses have included an additional smearing on Δm^2_{32} based on variations seen when considering the HF-CRPA nuclear model.
  - Both NOvA and T2K independently studied the impact of this alternate nuclear model on their 2020-era analyses.
  - When taken together in the context of the joint fit, the bias is no larger than the thresholds set for any of the fake data metrics.



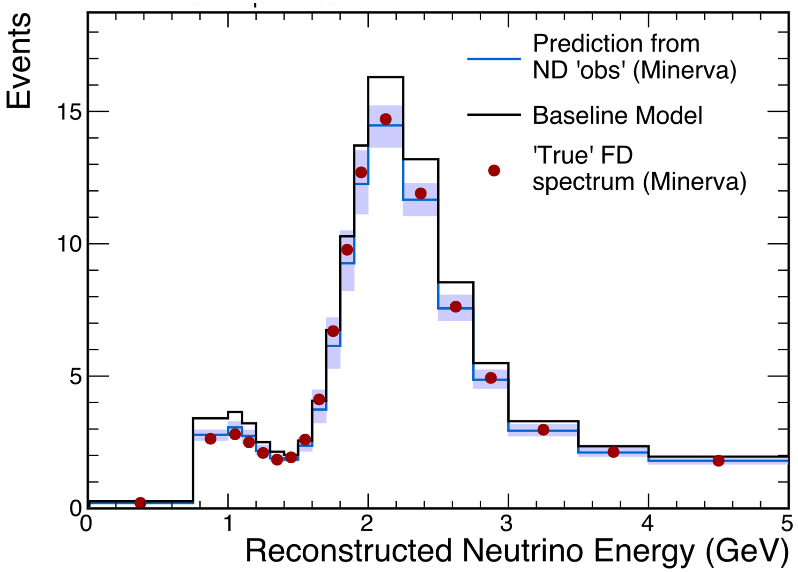


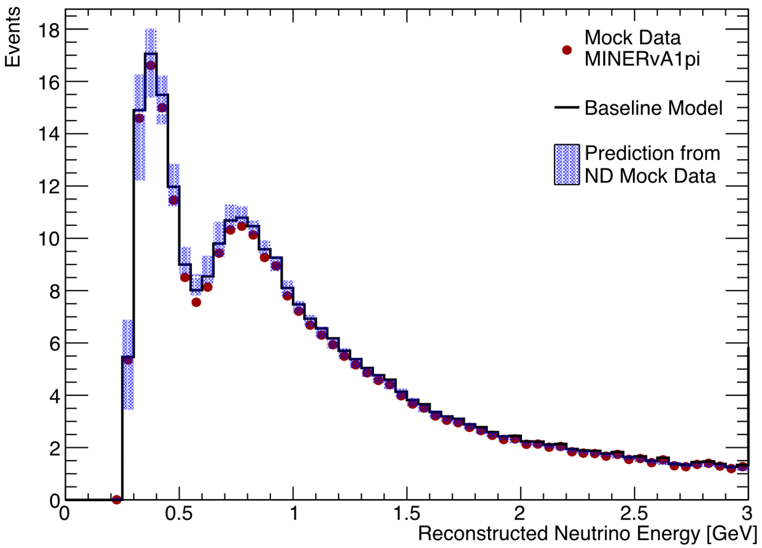
Alternate Models: CC0π $E_{n,reconstructed}$-E_{lepton} in T2K vs NOvA

- In T2K the p_T of the lepton is used to measure the recoiling energy by two body quasielastic kinematics.
- In NOvA, the visible recoil is measured.
- In this T2K-NOvA analysis, we are not relying on a single model to simultaneously describe these variables, but we may in the future
- MINERvA compares the two types of energy measures: recoil in bins of q_0^{QE} (the energy T2K adds to the muon energy)
  - Agreement with this model is poor
  - Events where the QE hypothesis says there should be lots of proton energy added, but MINERvA does not see that energy!
- T2K and NOvA naturally continue to investigate improvements in their cross section models. We appreciate the continued theoretical and experimental effort in the community



Alternate Models



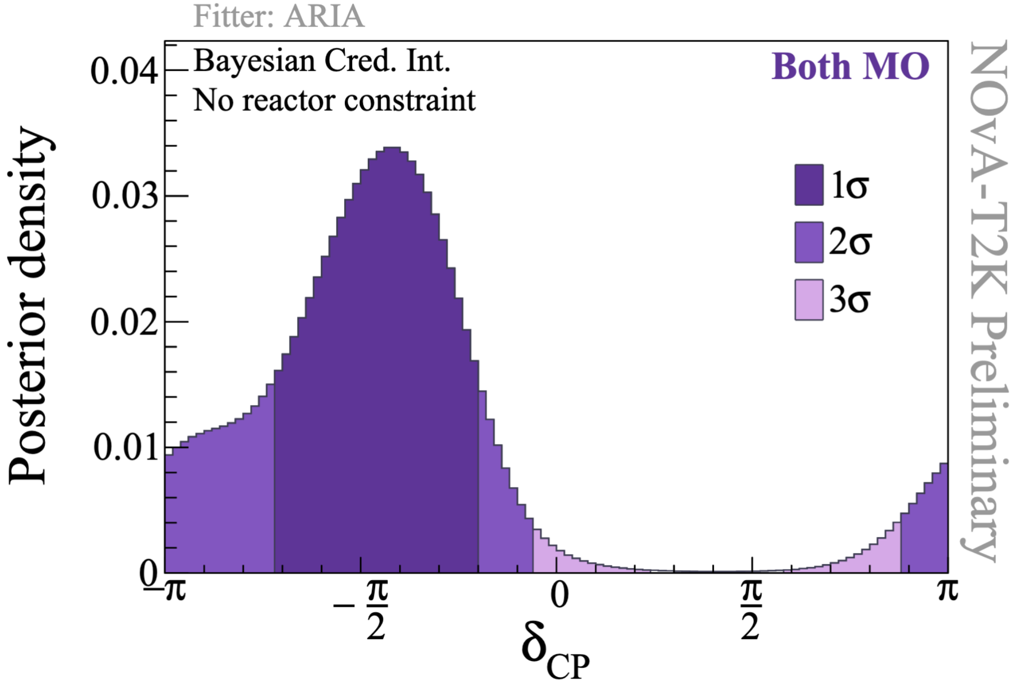


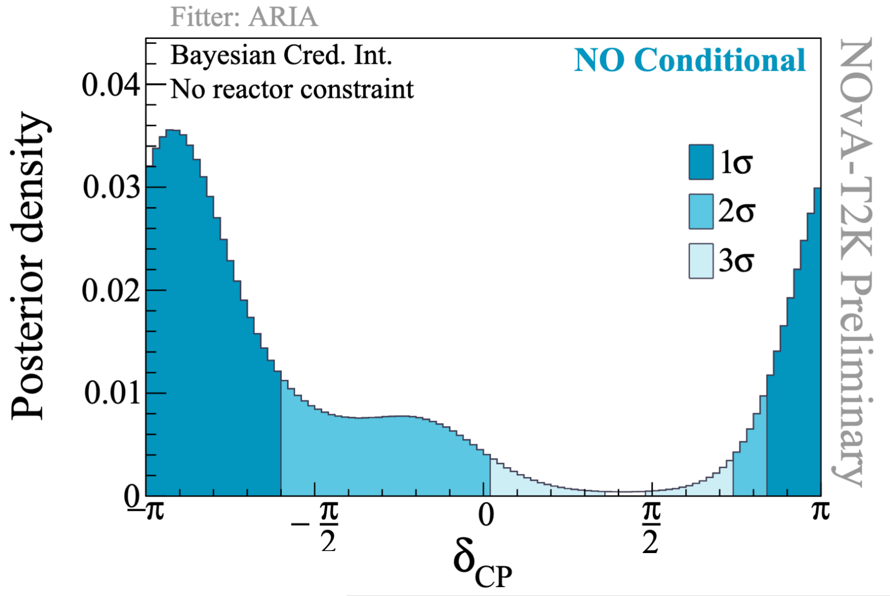
NOvA ν_μ sample

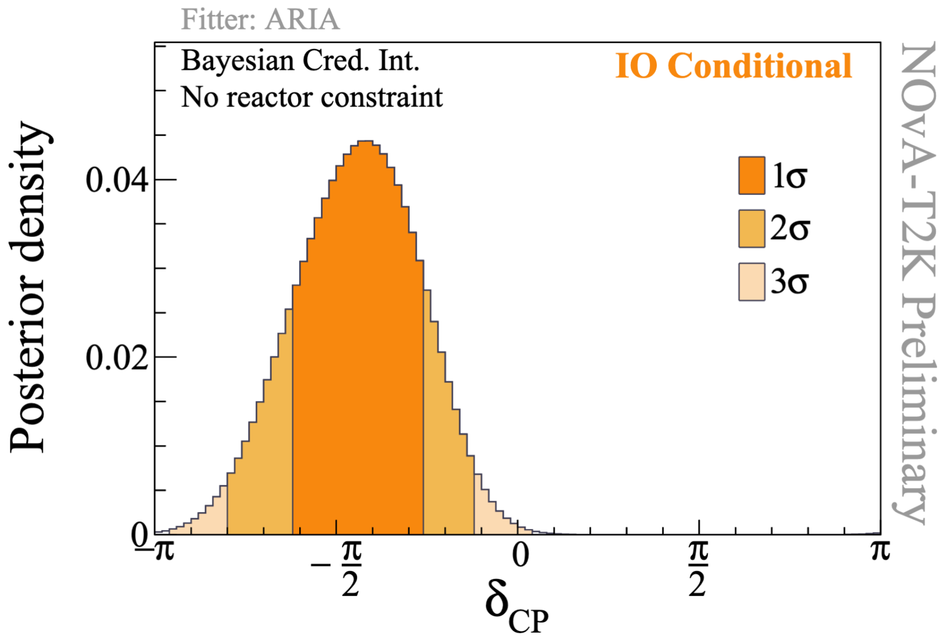
T2K ν_μ sample

*Phys. Rev. D 100, 072005 (2019)

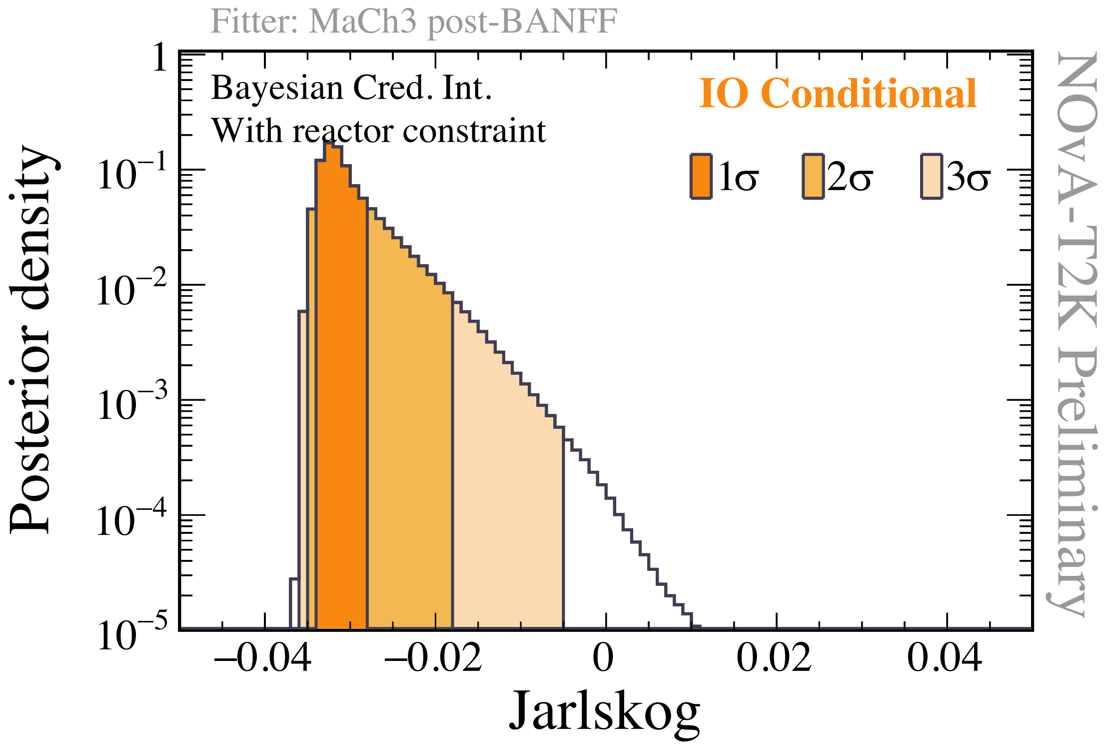
Results: δ_{CP}, no reactor constraints

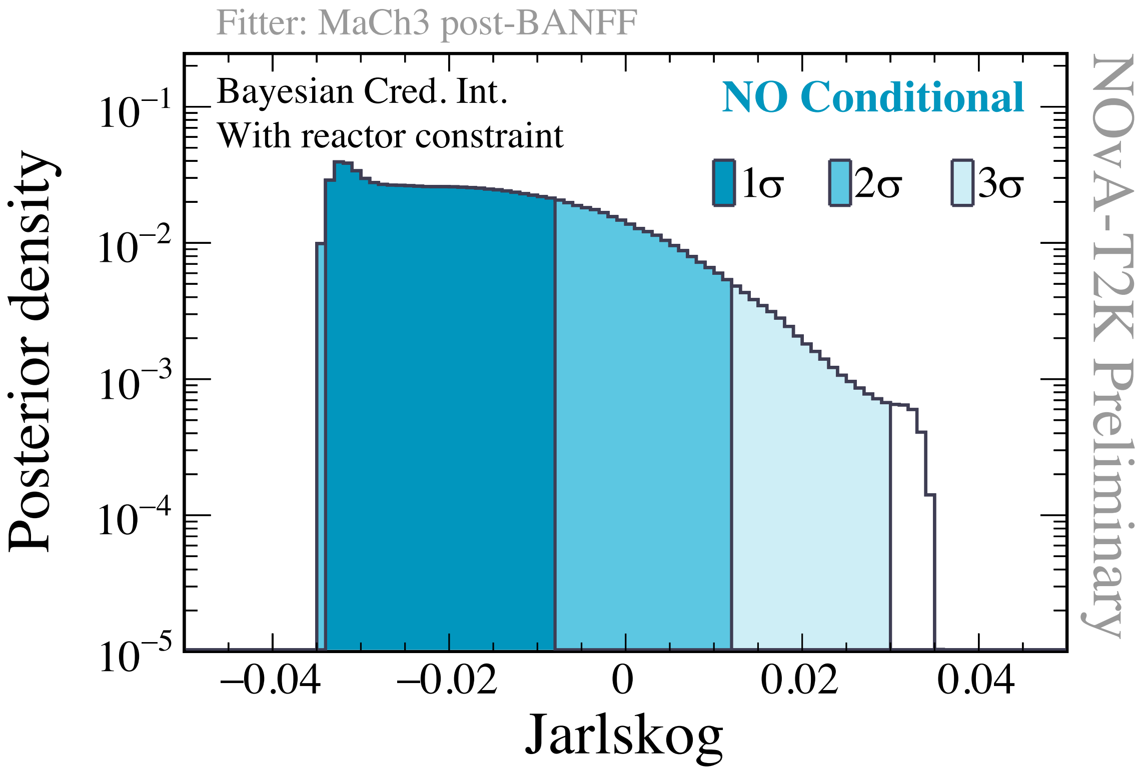




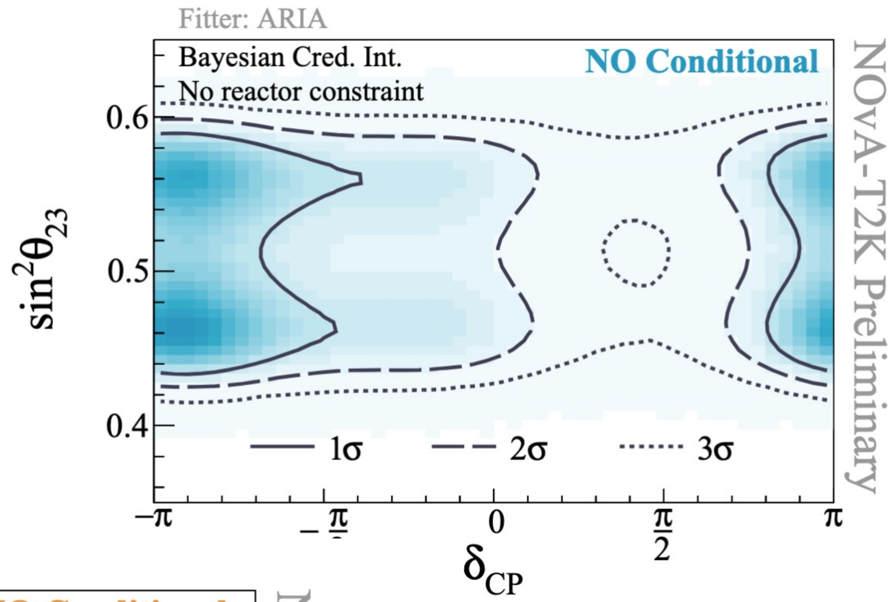


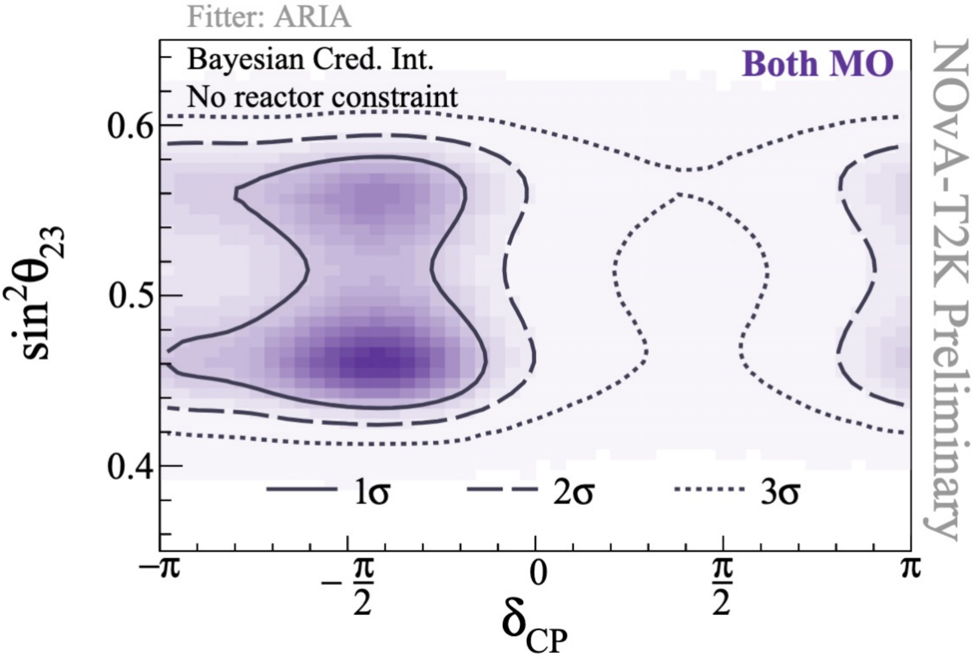
Results: Jarlskog Invariant

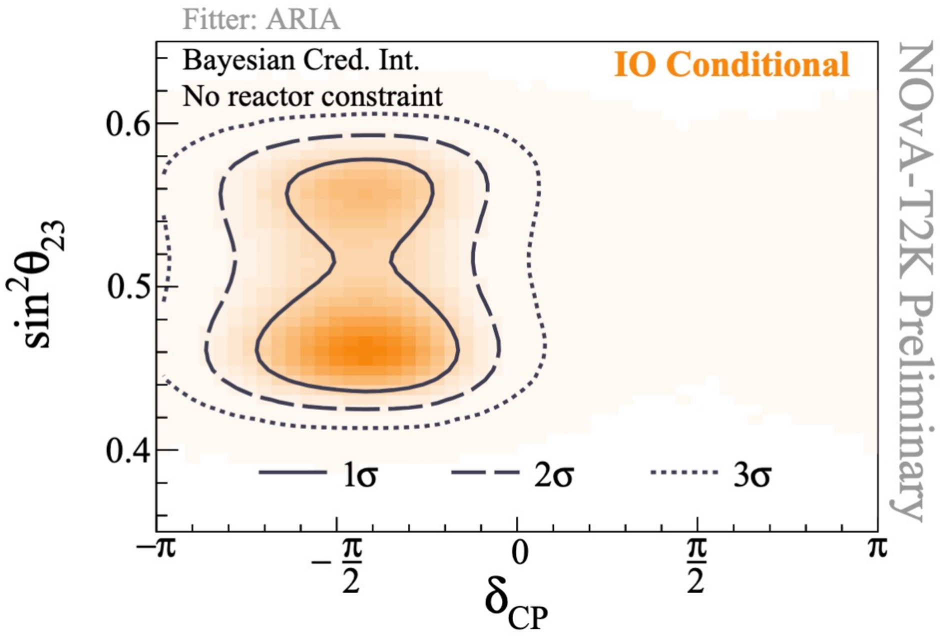




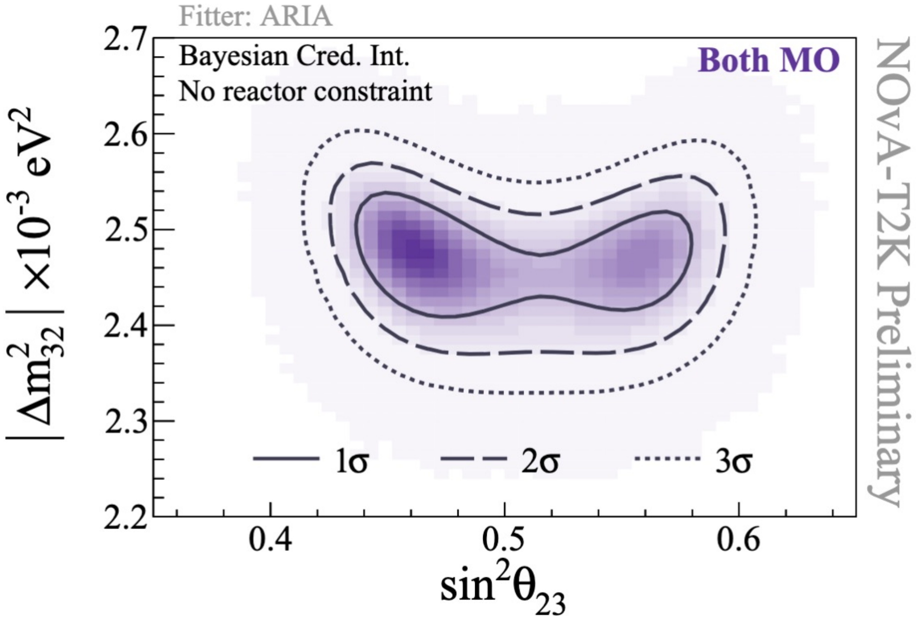
Results: δ_{CP}, no reactor constraints

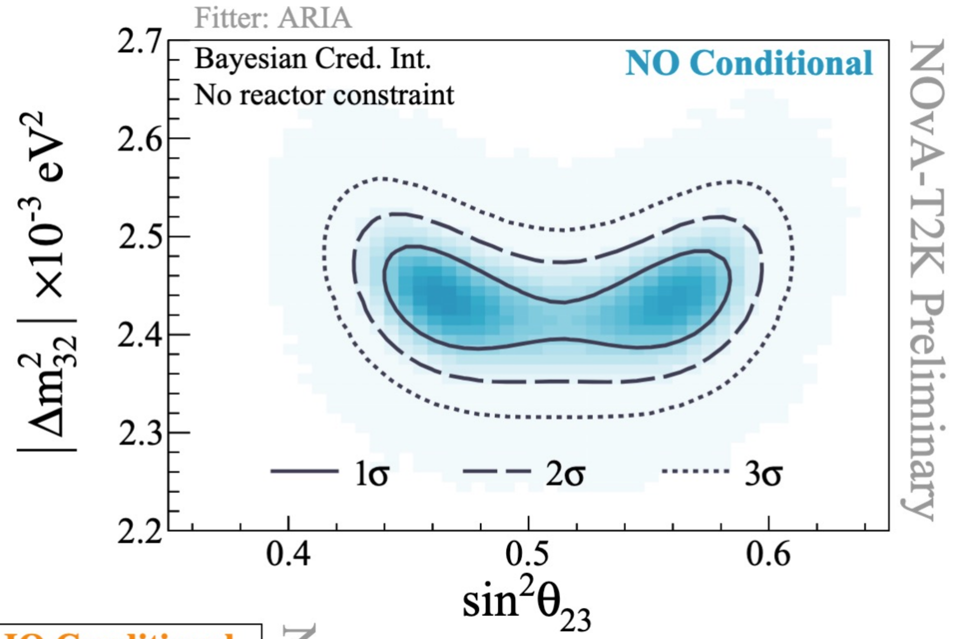


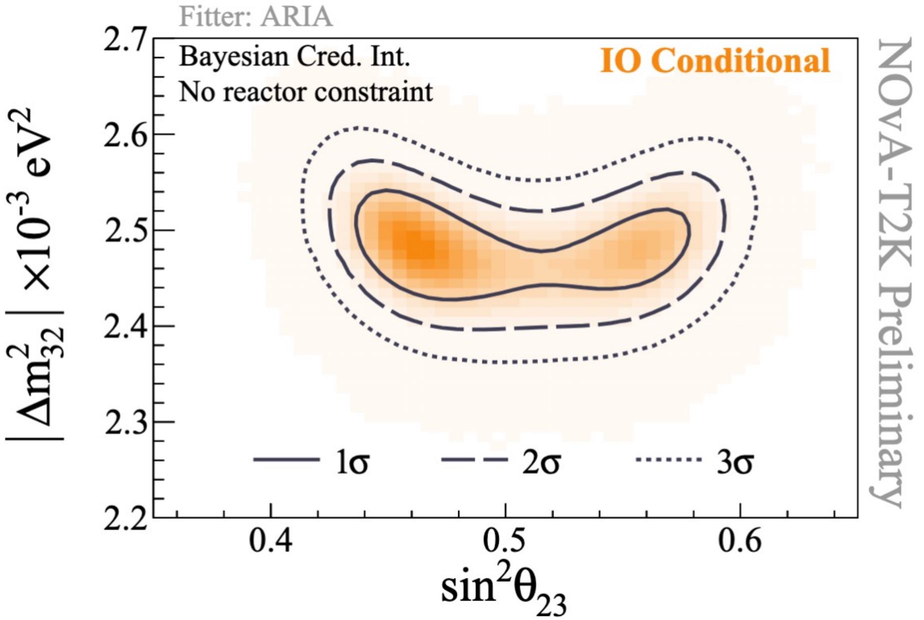




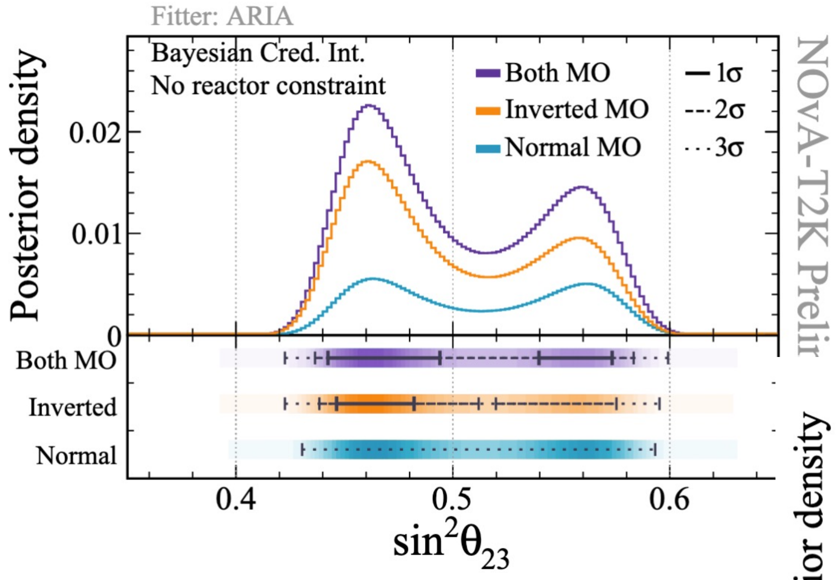
Results: Δm^2_{32} and $\sin^2\theta_{23}$, no reactor constraints

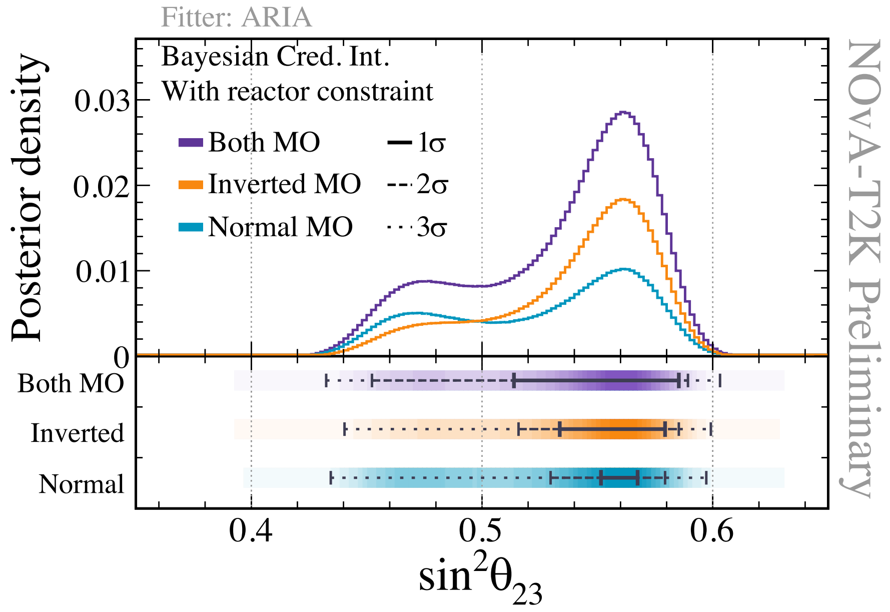


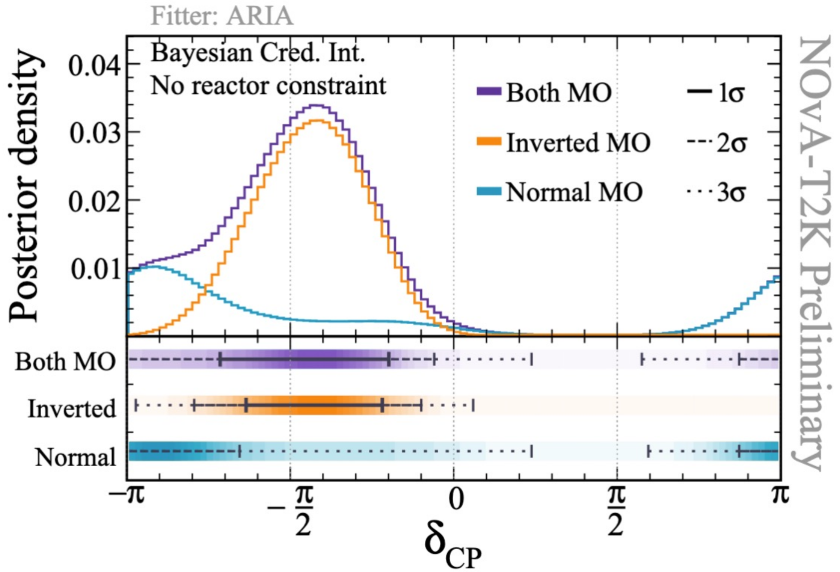




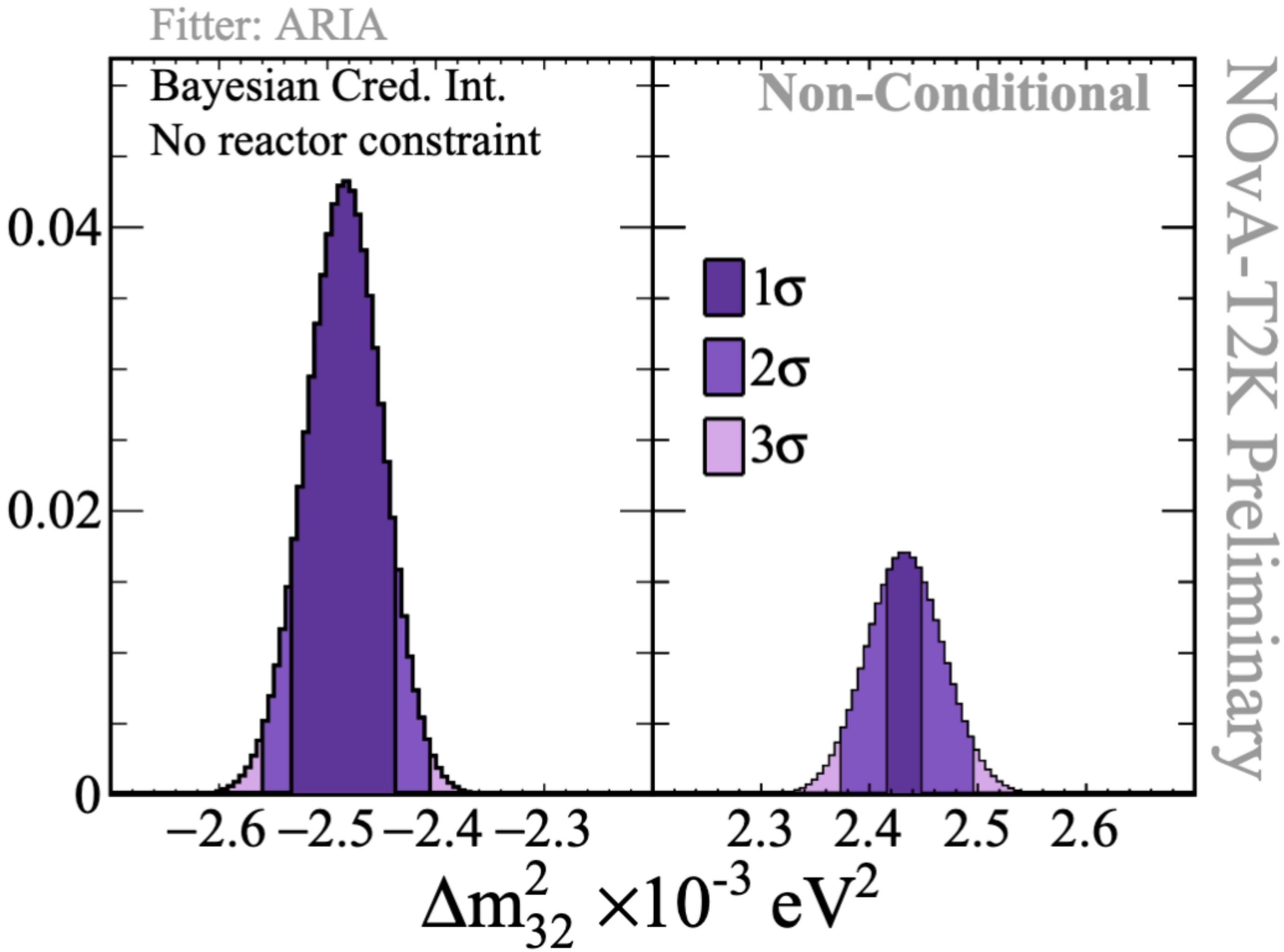
Results: Δm^2_{32}, no reactor constraints



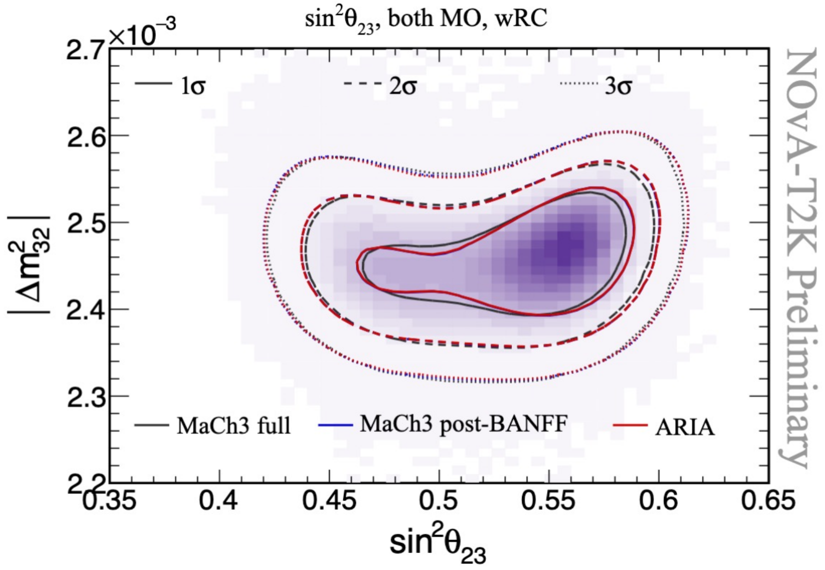


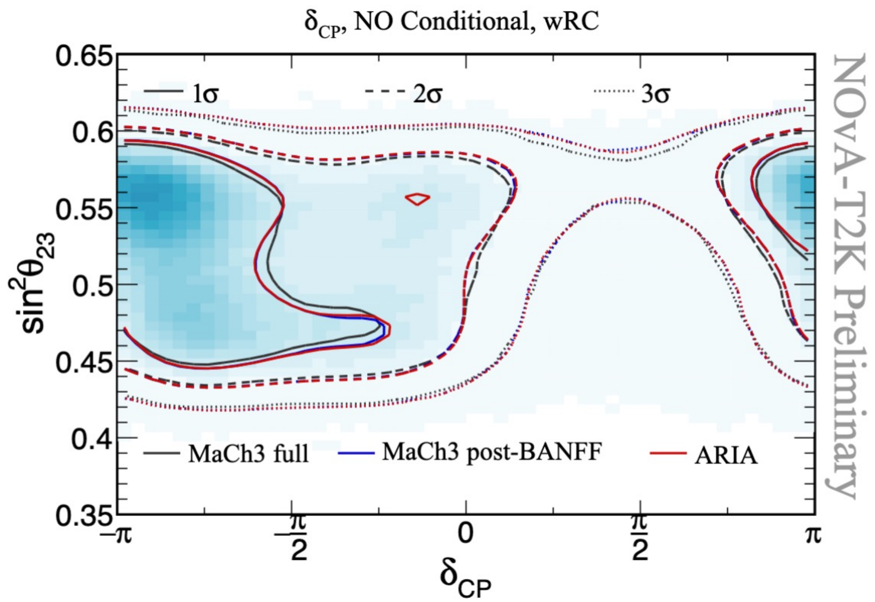


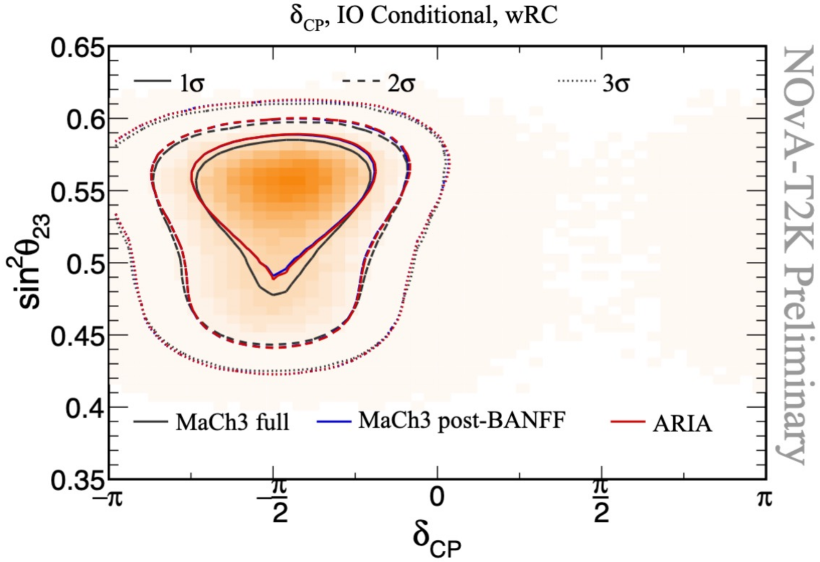
Results: Δm^2_{32}, no reactor constraints



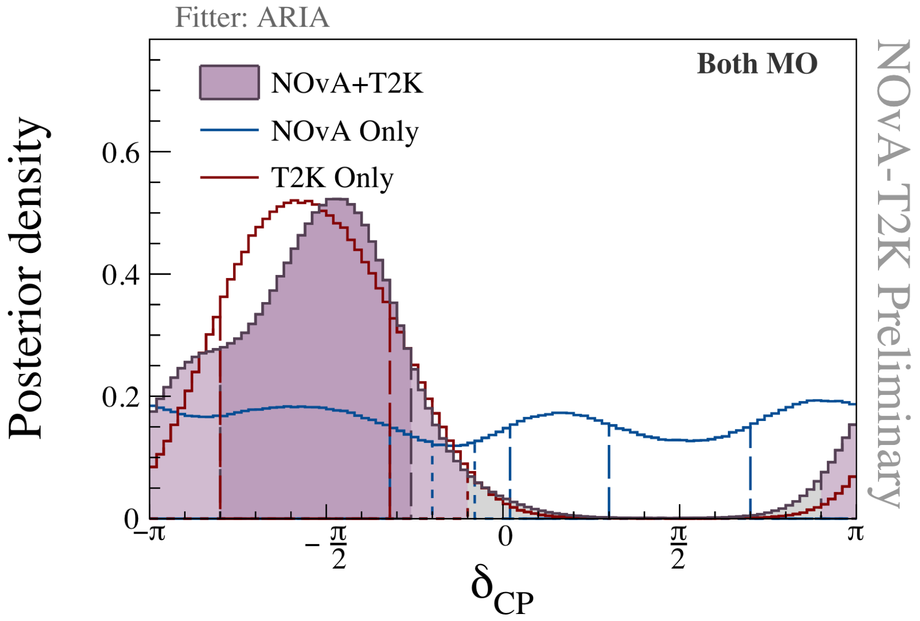
Fitter Comparisons

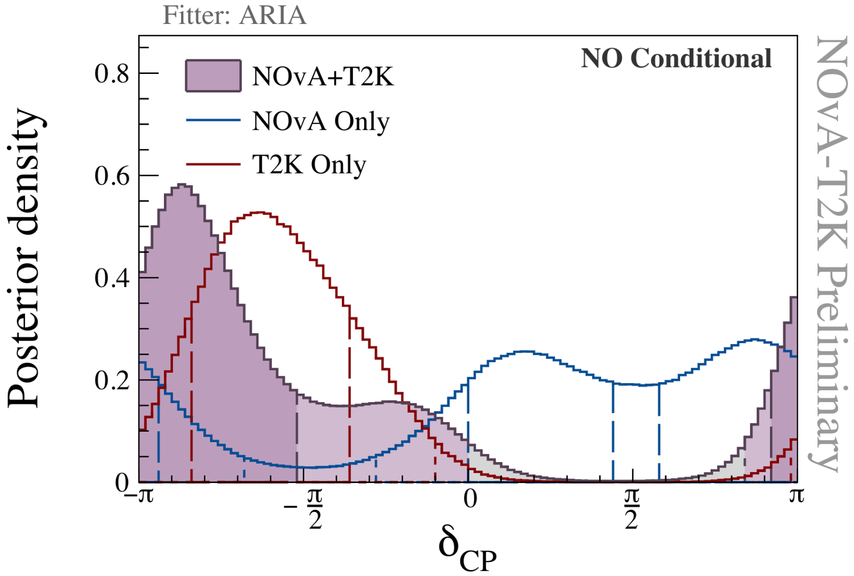


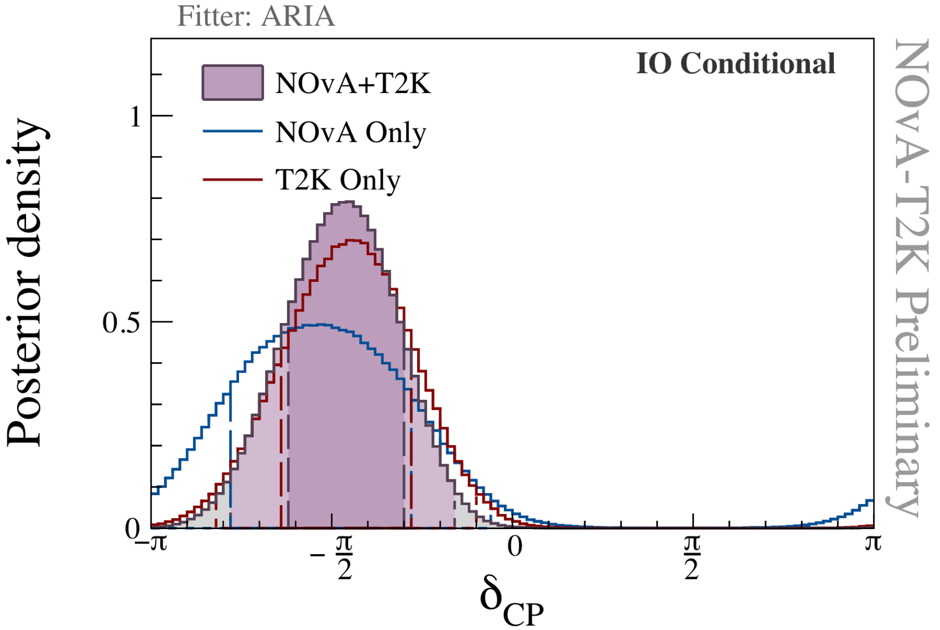




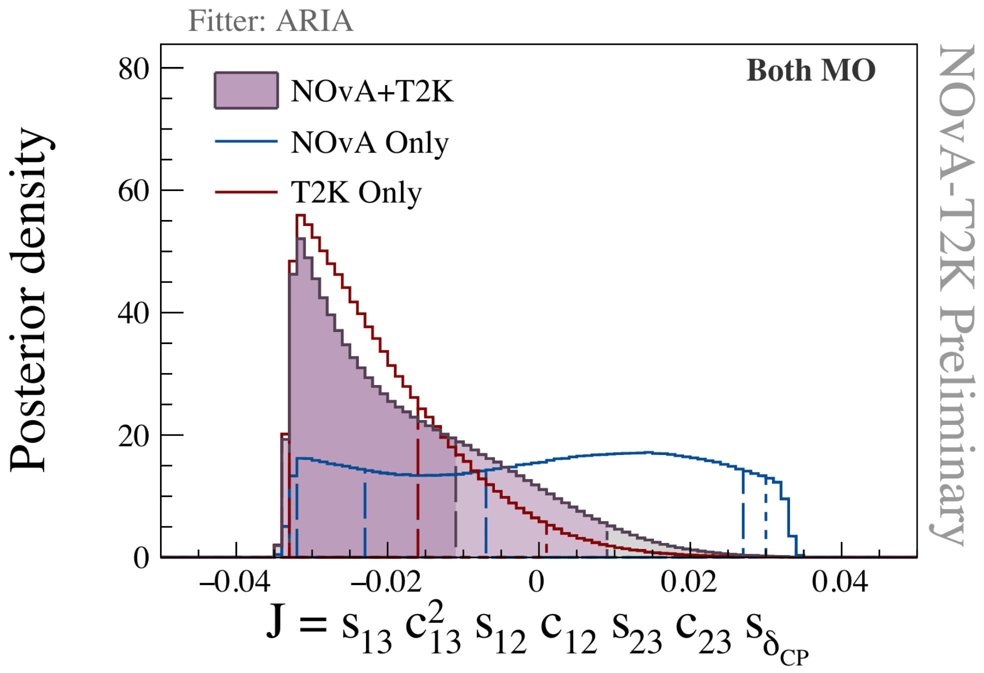
T2K & NOvA Comparisons

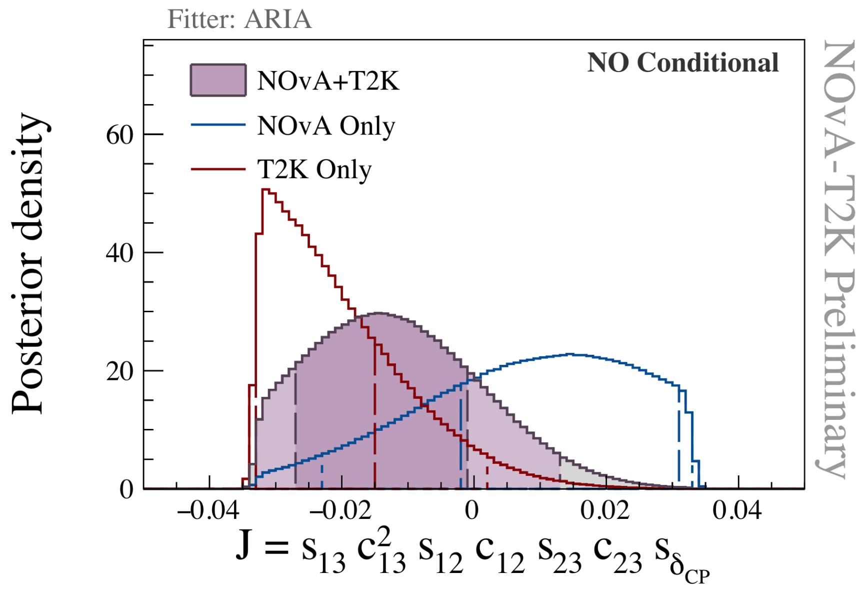


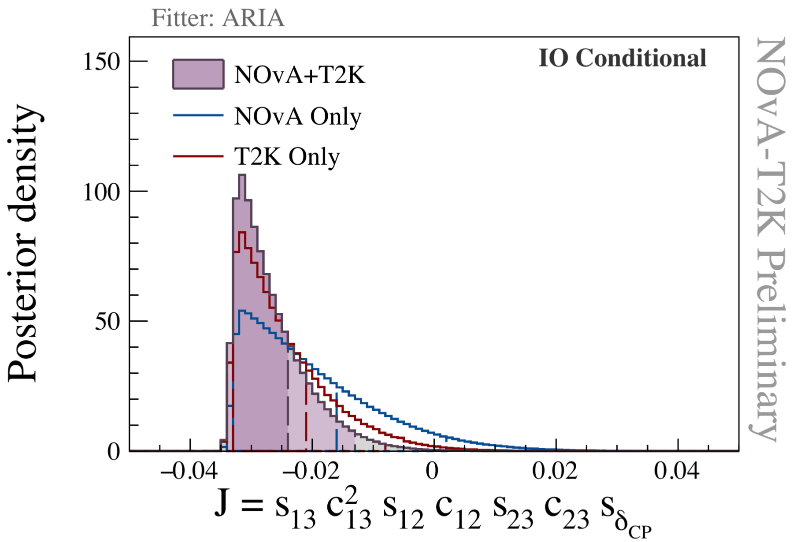




T2K & NOvA Comparisons

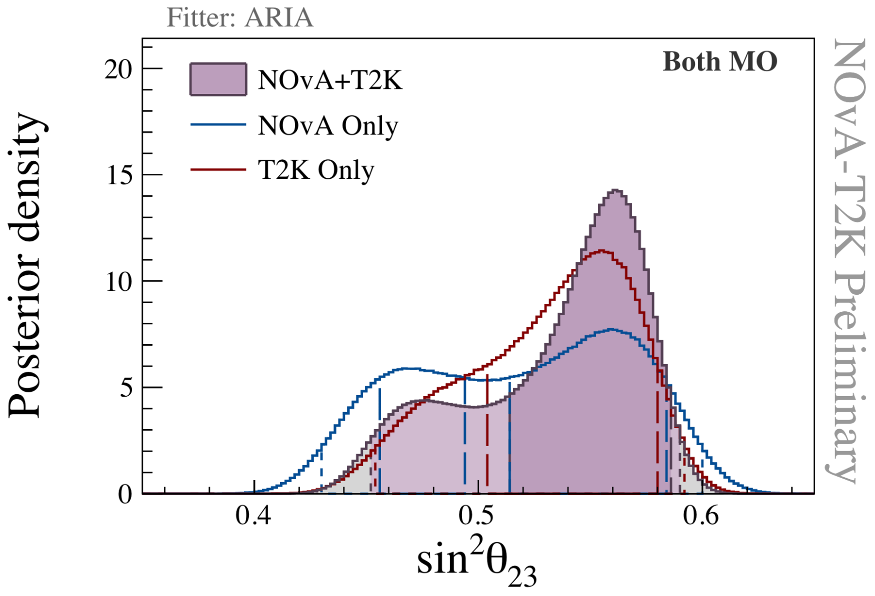


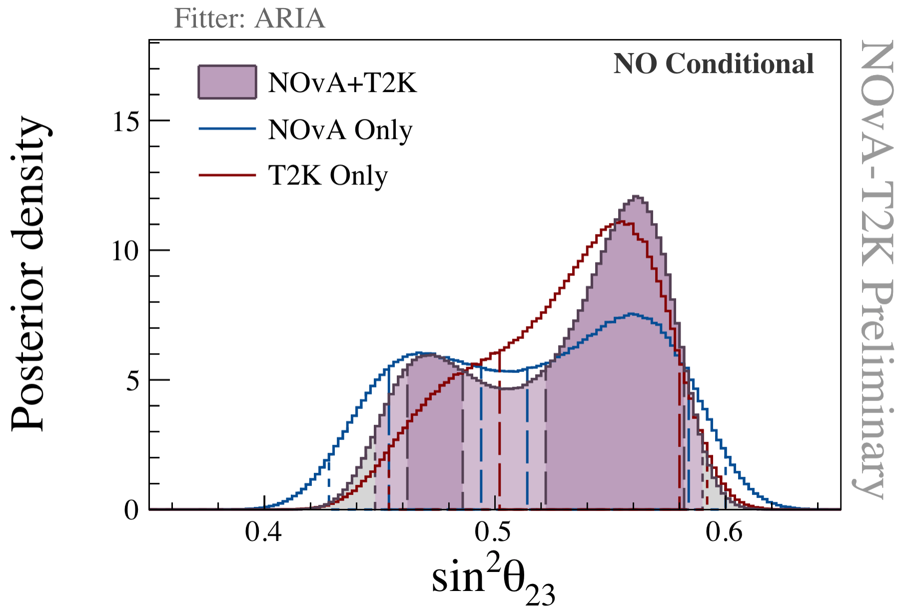


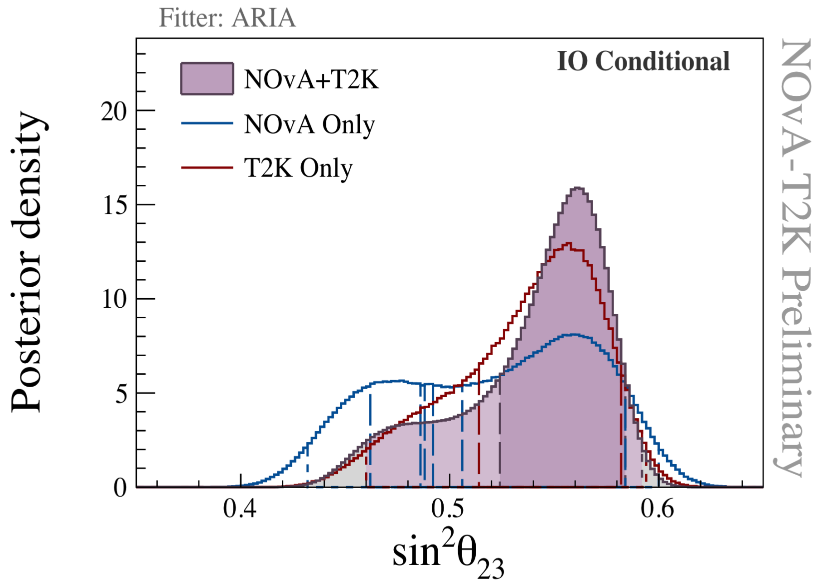


- Prior: Flat in δ_{CP}

T2K & NOvA Comparisons







Comparison to Other Experiments

- Daya Bay highest precision on $\sin^2\theta_{13}$
- In general, LBL experiments have much less precise measurements but are consistent with reactor experiment results