New Results from the NOvA experiment & the joint-fit with T2K

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(on behalf of the NOvA collaboration)

NNN RIO 2024

Rio De Janeiro, Brazil
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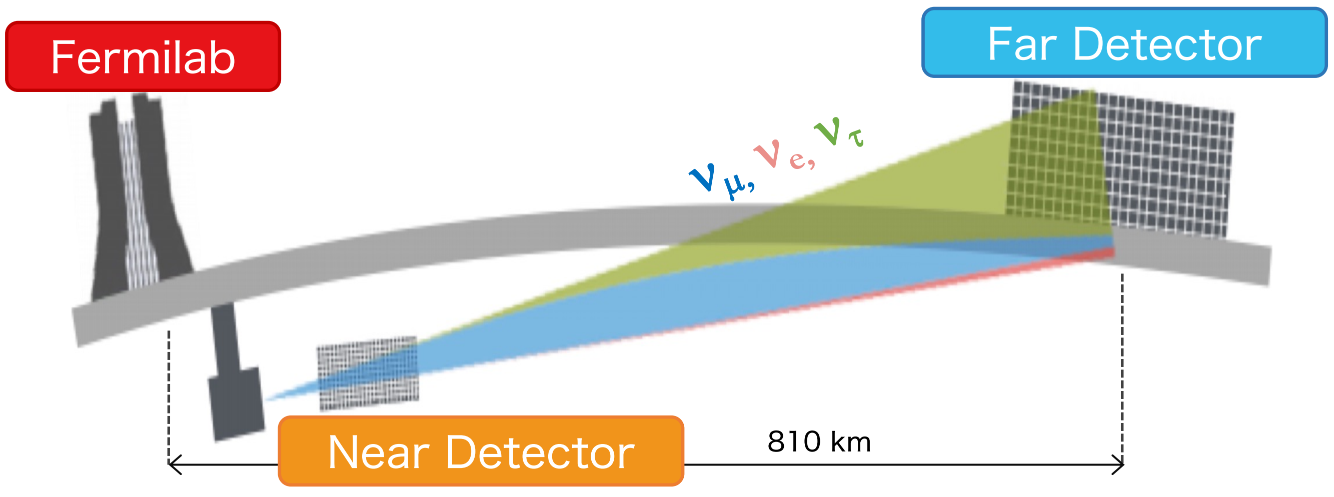
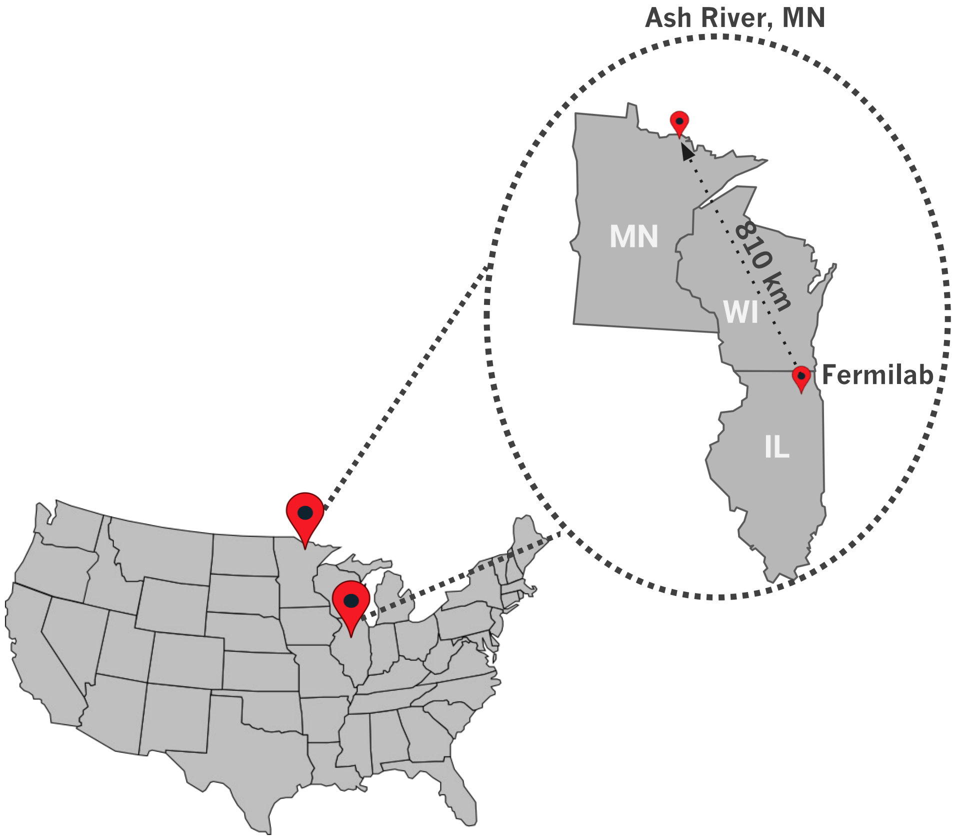
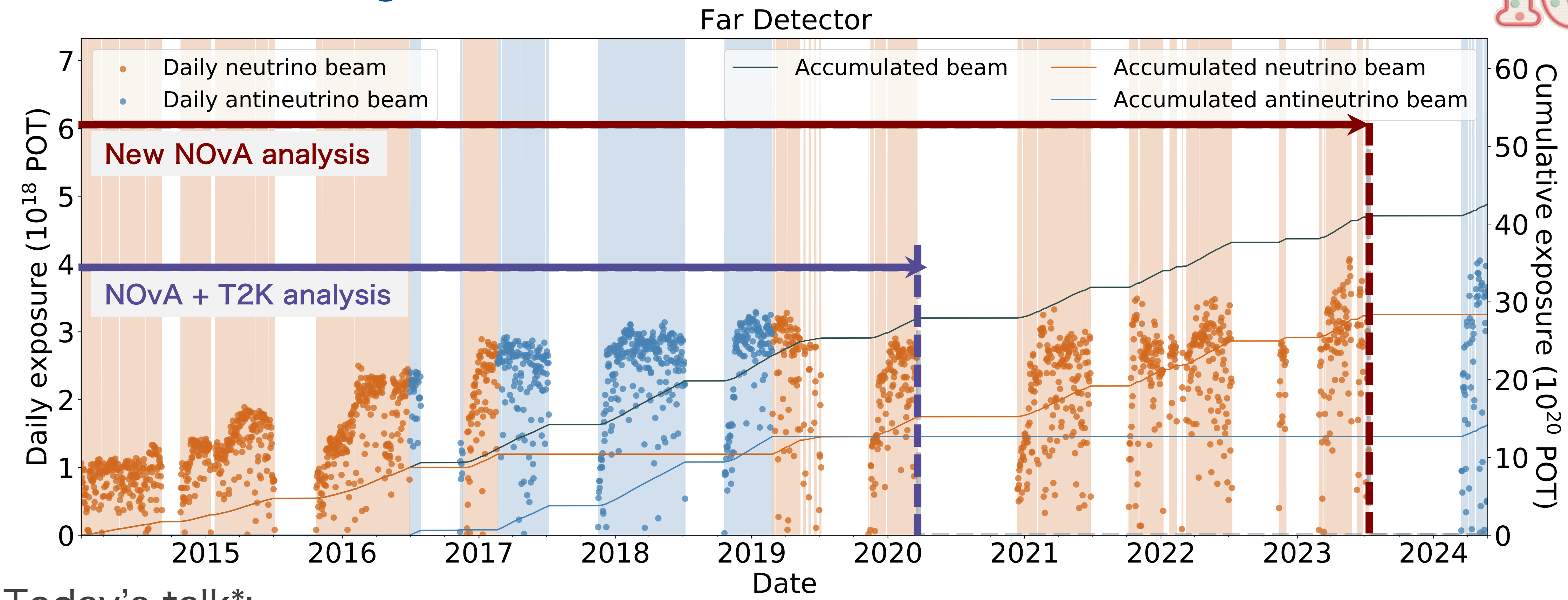
The NOvA Experiment





- Long-baseline neutrino oscillation experiment in the megawatt-capable NuMI beam facility at Fermilab.
- NOvA detectors are placed 14 mrad off-axis to the beam to produce a narrow peak muon (anti)neutrino flux peaked at 2 GeV.
- Over 200 collaborators from 50+ institutions in 8 countries.

10 years of NOvA data!

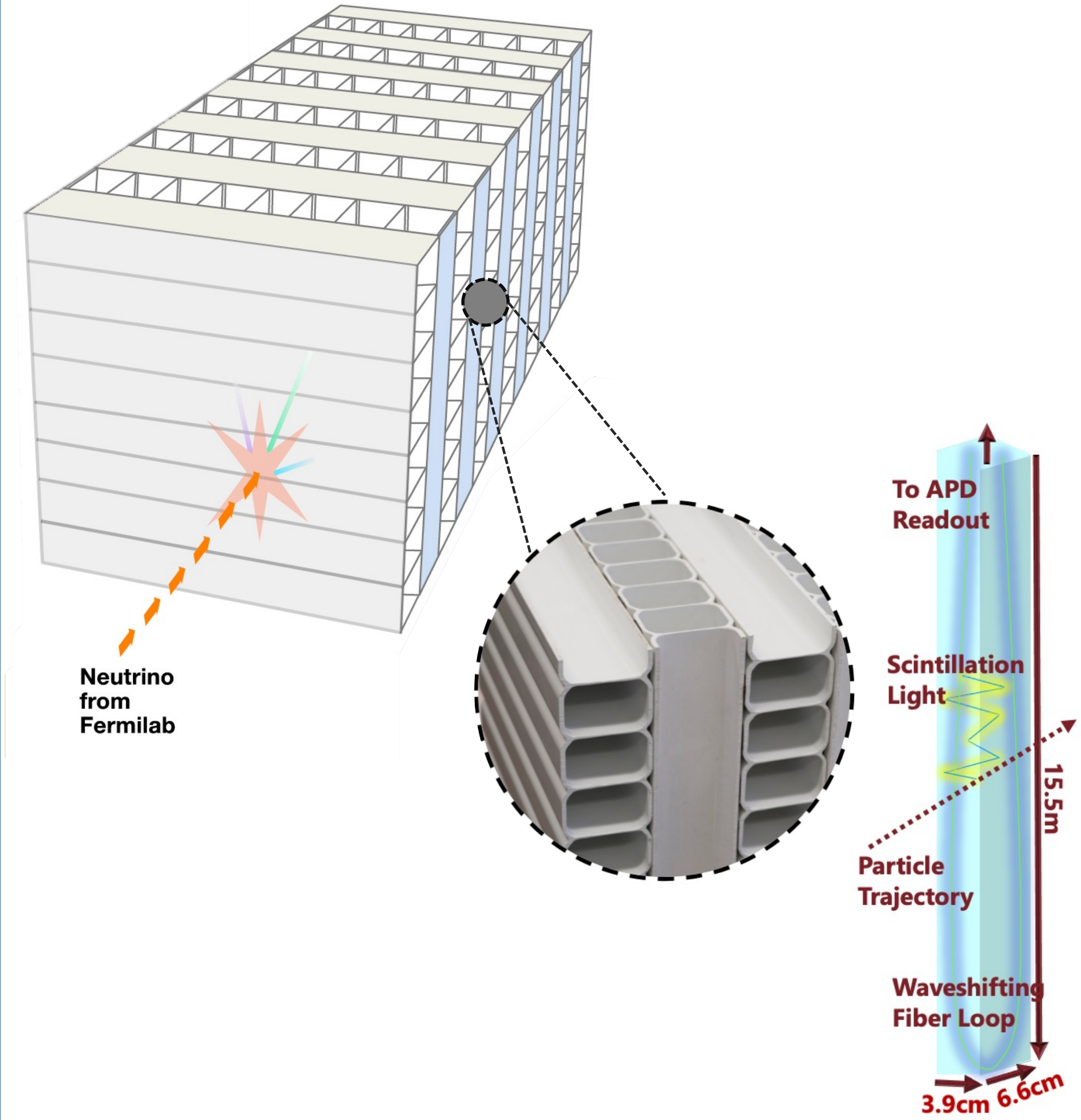


- Today's talk*:
  - NOvA+T2K analysis: data through 2020
  - New NOvA analysis: data through 2024
- New beam power record of 1.018 MW set this year!

~2x more neutrino mode data between the previous and current NOvA analysis!

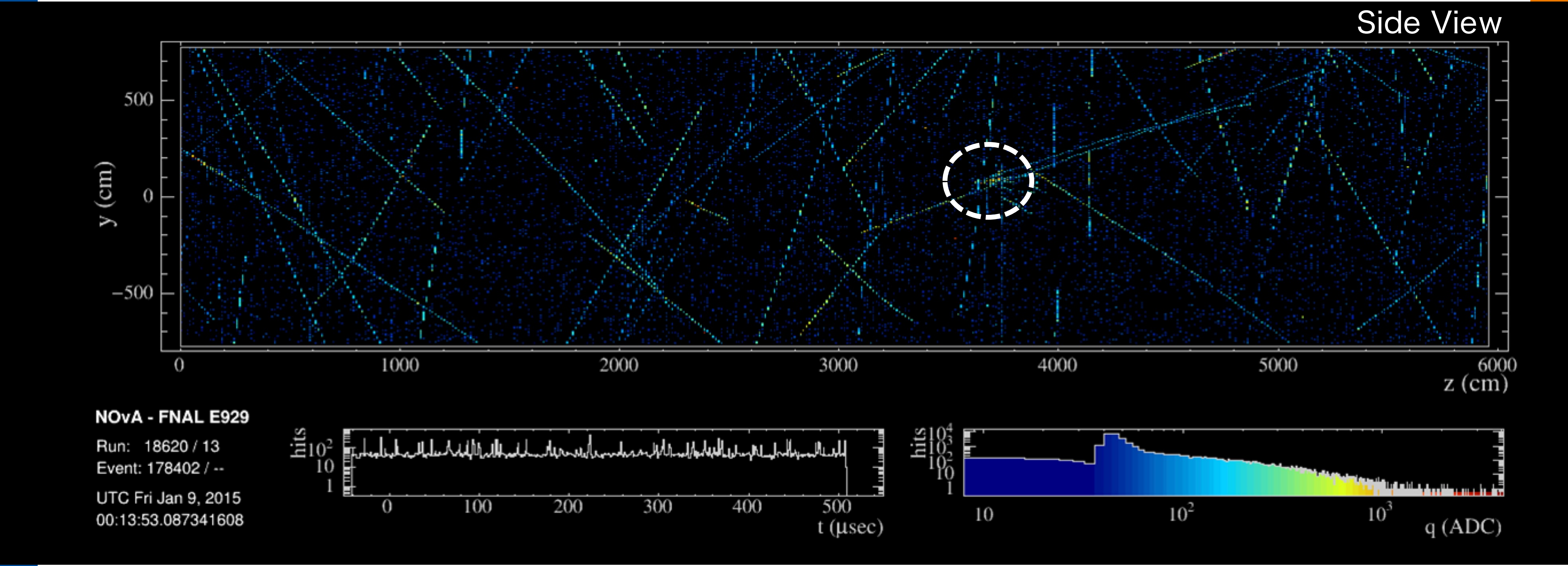
*Note: Limited to 3-flavor oscillation and will not cover the full scope of NOvA's physics program.

The NOvA Detectors



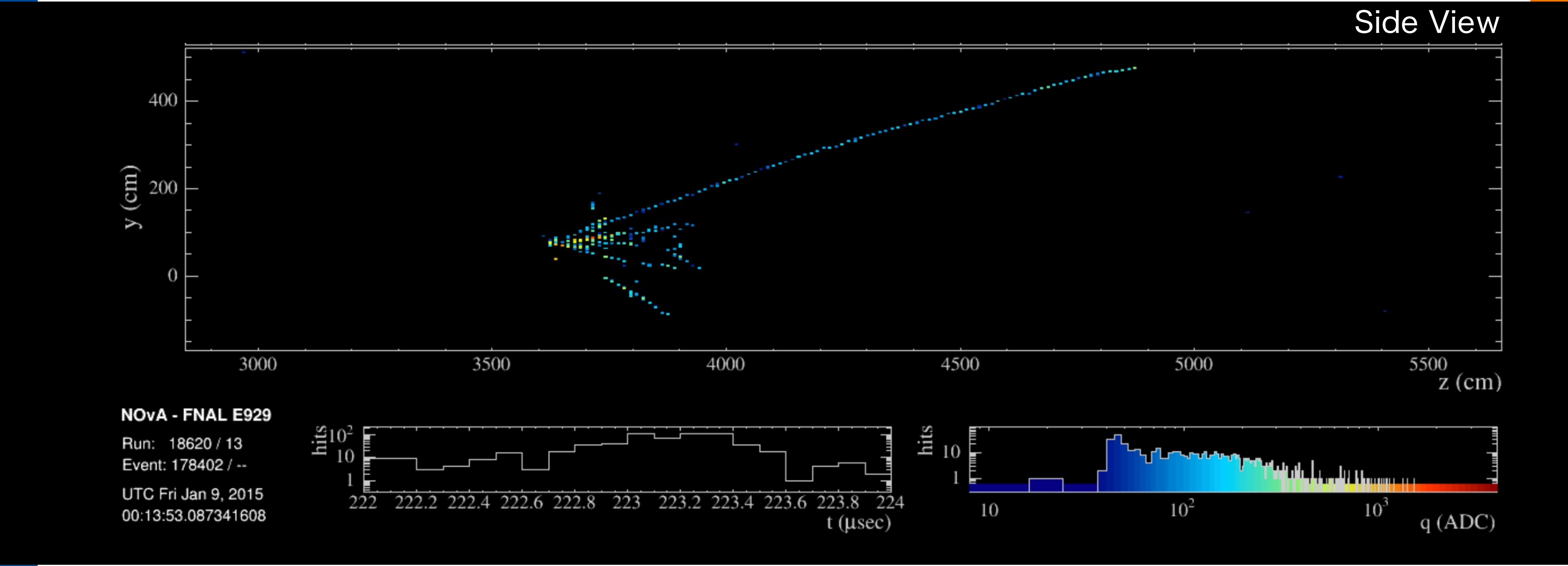
- The near detector(ND) and far detector (FD) are **functionally identical segmented liquid scintillator detectors.**
  - ND: ~0.3kt, 20k channels and ~100 m underground
  - FD: ~14 kt, 344k channels and on the surface

Neutrinos in NOvA



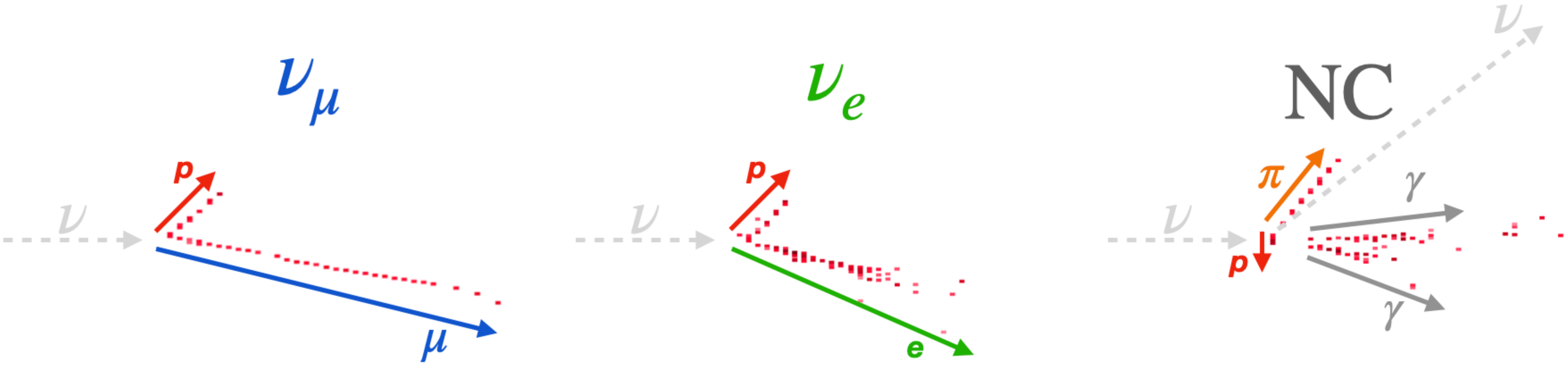
- ~150 kHz of cosmic rays at the FD which is on the surface.

Neutrinos in NOvA



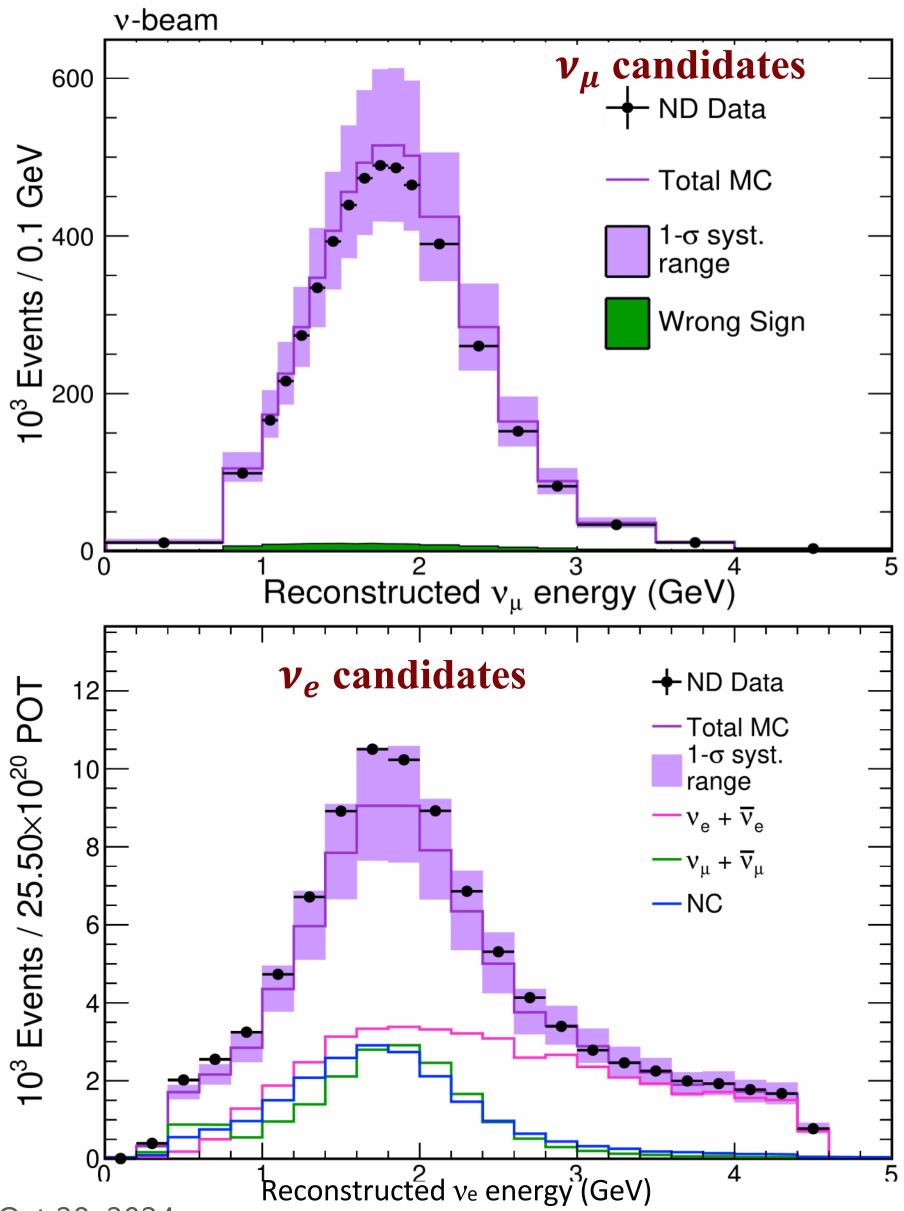
- Good spatial resolution (~few cm) and timing resolution (~10ns) allows to isolate neutrino interaction from 99% of cosmic backgrounds. Targeted BDTs and selections useful to get rid of the rest.

Neutrinos in NOvA



- Detectors are optimized for EM showers. ~6 samples per radiation length (~40 cm) making muon-electron disambiguation easy.
- Neutrino interaction candidates are identified using a **convolutional neural network (CNN)**
- Energy is reconstructed via **tracking (muon)** and **calorimetry** (electromagnetic, hadronic)

Near detector samples

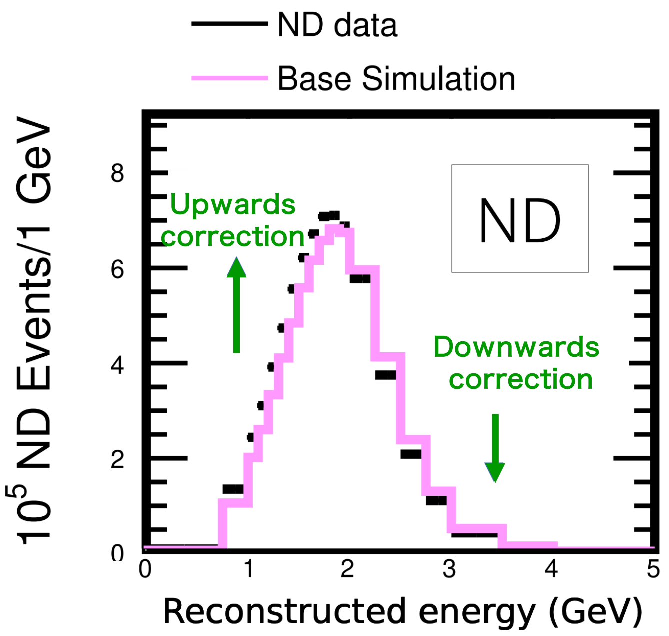


- Exceptional statistics at the ND leads to negligible statistical uncertainty.
  - ~6.5M ν_μ candidate events
    - Use this sample to predict both ν_μ and ν_e at the FD
  - ~100k ν_e candidate events
    - Background intrinsic beam ν_e prediction at the FD.
- Significant systematic uncertainties at the ND indicate a current, limited understanding of neutrino interactions and detection.

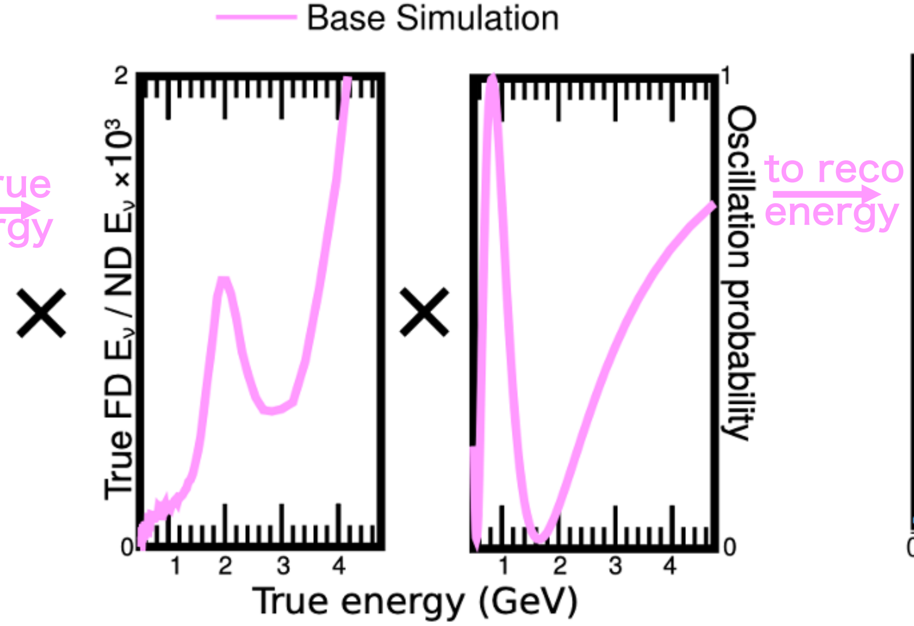
Building FD Predictions

- **ND data measures unoscillated neutrinos and determines the expected interaction rate at the FD in the absence of oscillation.**
  - Subdivided by hadronic energy fraction and transverse momentum of lepton for a better kinematical match between the samples.

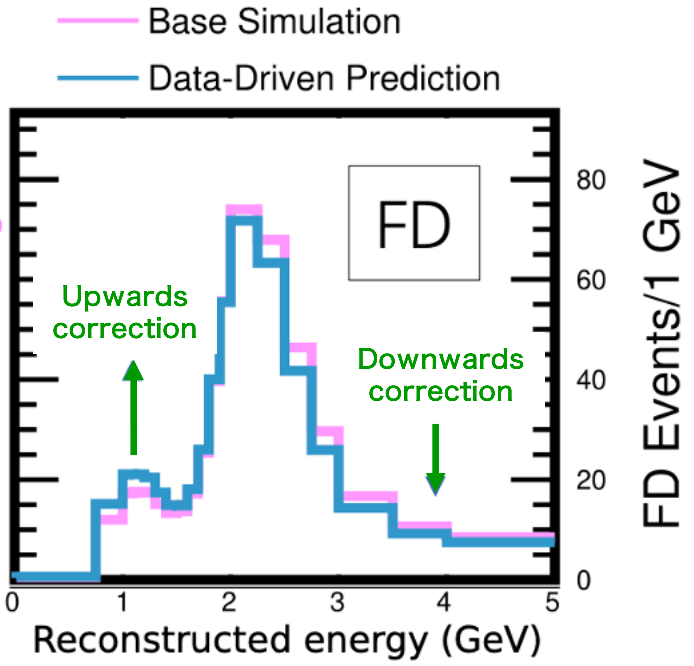
J. Wolcott



High statistics ND data



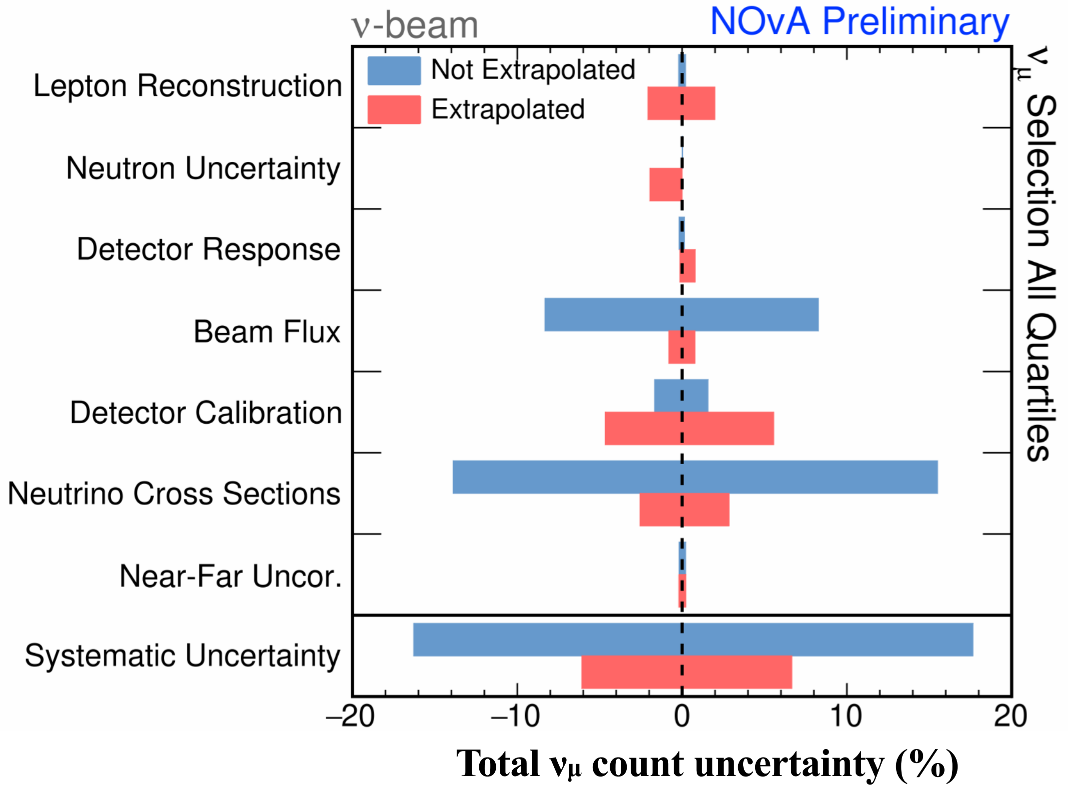
Far/Near transformations from simulation which primarily comprise well-understood effects

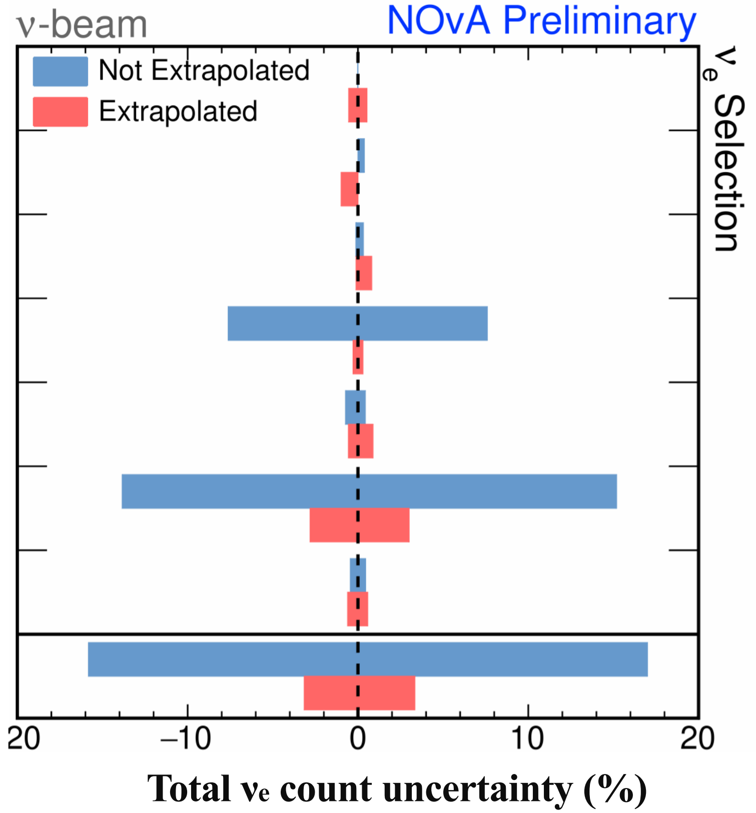


Used to build data-driven FD predictions before being fit with data

Systematic uncertainties

- Data-driven FD predictions limit model dependence and the impact of systematics at the FD.
- Systematic uncertainties in the FD predictions go from ~15% to 4-5%.
- Oscillation measurements are dominated by statistical uncertainties.

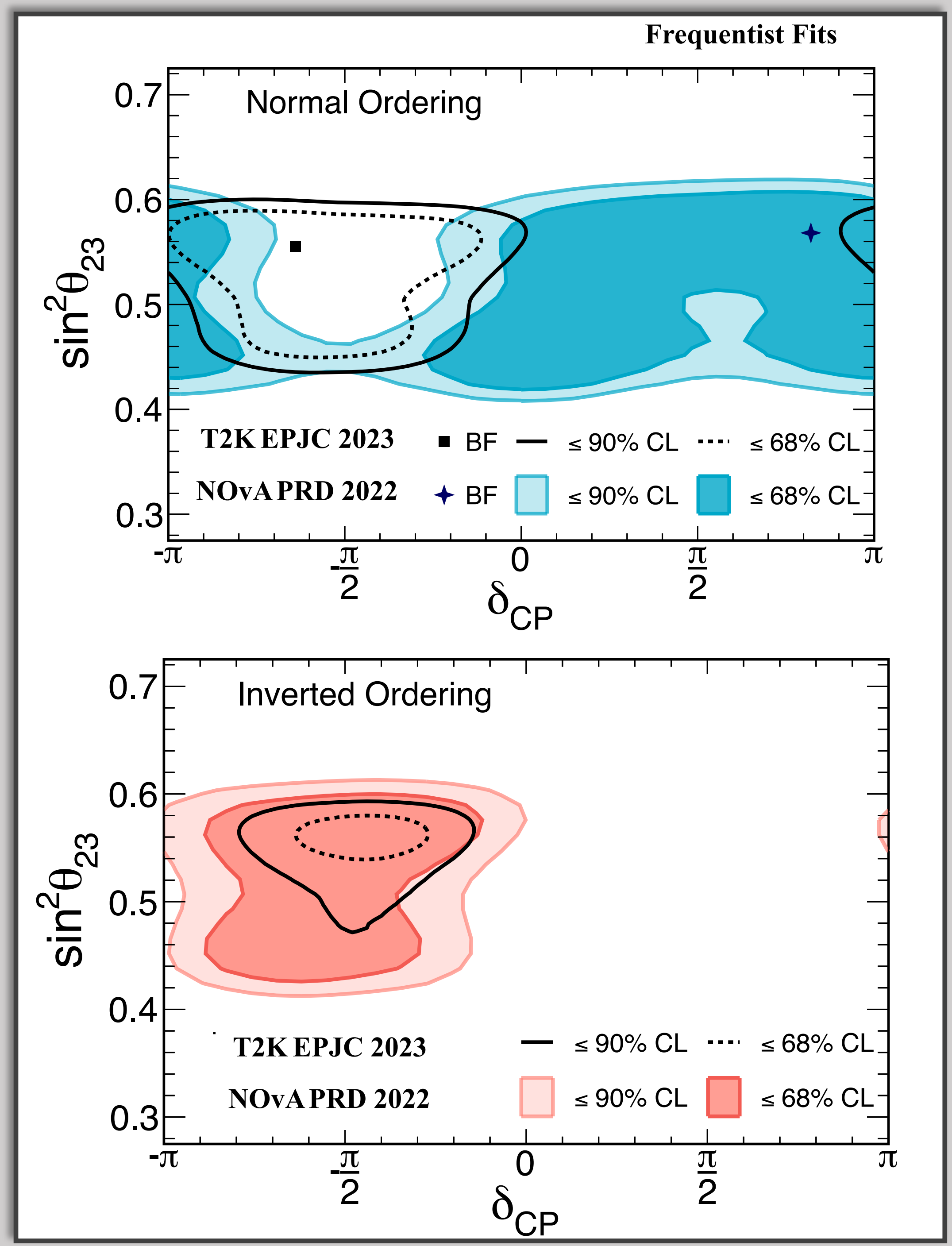




NOvA-T2K joint fit results

Why NOvA-T2K joint fit?

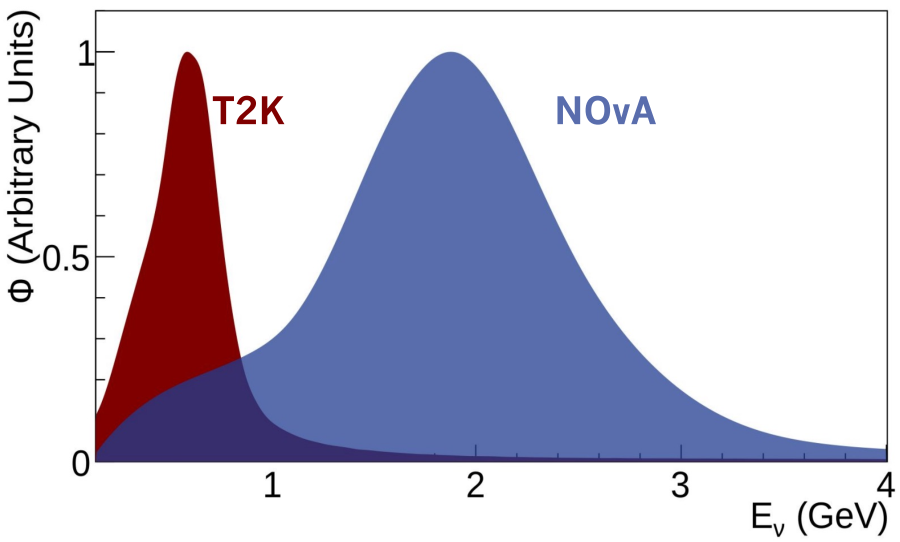
- The complementarity between the experiments provides the power to **break degeneracies.**
- Full implementation of:
  - ❑ **Energy reconstruction and detector response**
  - ❑ **Detailed likelihood**
  - ❑ Consistent **statistical inference across the full dimensionality**
- In-depth review of:
  - ❑ **Models, systematic uncertainties and possible correlations**
  - ❑ **Different analysis approaches** driven by contrasting detector designs



NOvA-T2K Complementarity

- Different neutrino fluxes:
  - detectors see qualitative different ν-interactions.
- Different baselines:
  - **NOvA sees larger matter effect** due to higher neutrino energy → **higher sensitivity to mass ordering.**
- T2K measurements isolate impact of CP violation while NOvA has significant **sensitivity to mass ordering.**
- **Joint analysis probes both spaces lifting degeneracies of individual experiments.**

Neutrino flux



	T2K	NOvA
L (baseline)	295 km	810 km
Energy (beam peak)	0.6 GeV	2 GeV
Matter effect*	~ ±9%	~ ±19%
CP effect*	~ ±30%	~ ±25%

*calculated at beam peak energy

Systematics & their correlations

- **Flux and Detector Systematics:** No significant correlations across experiments
- **Cross-section Systematics:** No direct mapping between the cross-section systematics parameters
  - Exception: **Uncertainties in ν_e / ν_μ** and $\bar{\nu}_e / \bar{\nu}_\mu$ cross-section have identical origin* and similar treatment
    - **Fully correlated in the joint fit.**

*Phys. Rev. D **86**, 053003

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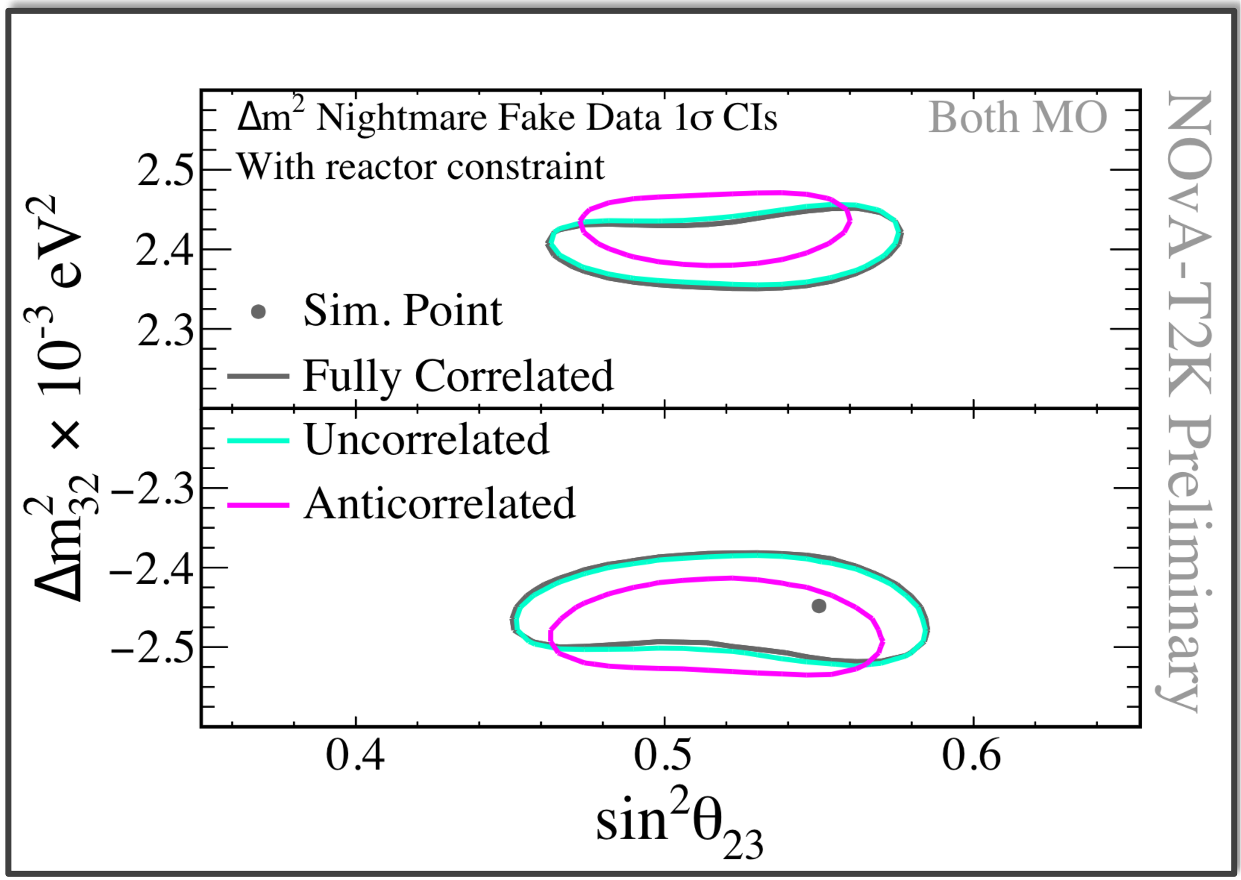
    - **Fully correlated in the joint fit.**

- **Strategy:** Explore a range of artificially crafted scenarios to bracket the impact
- Example: Fabricated systematics equal in size to total statistical uncertainty, causing a correlated bias in both experiments.
  - **Uncorrelated and correctly correlated show negligible differences**, while **incorrectly correlating systematics shows a bias**.
- Based on such studies → No additional correlations need be applied given current experimental exposures



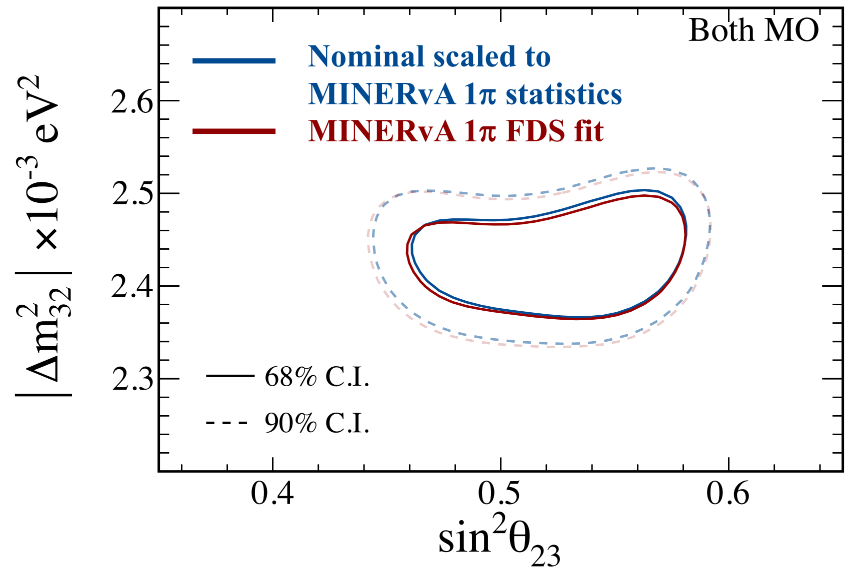
*Phys. Rev. D **86**, 053003

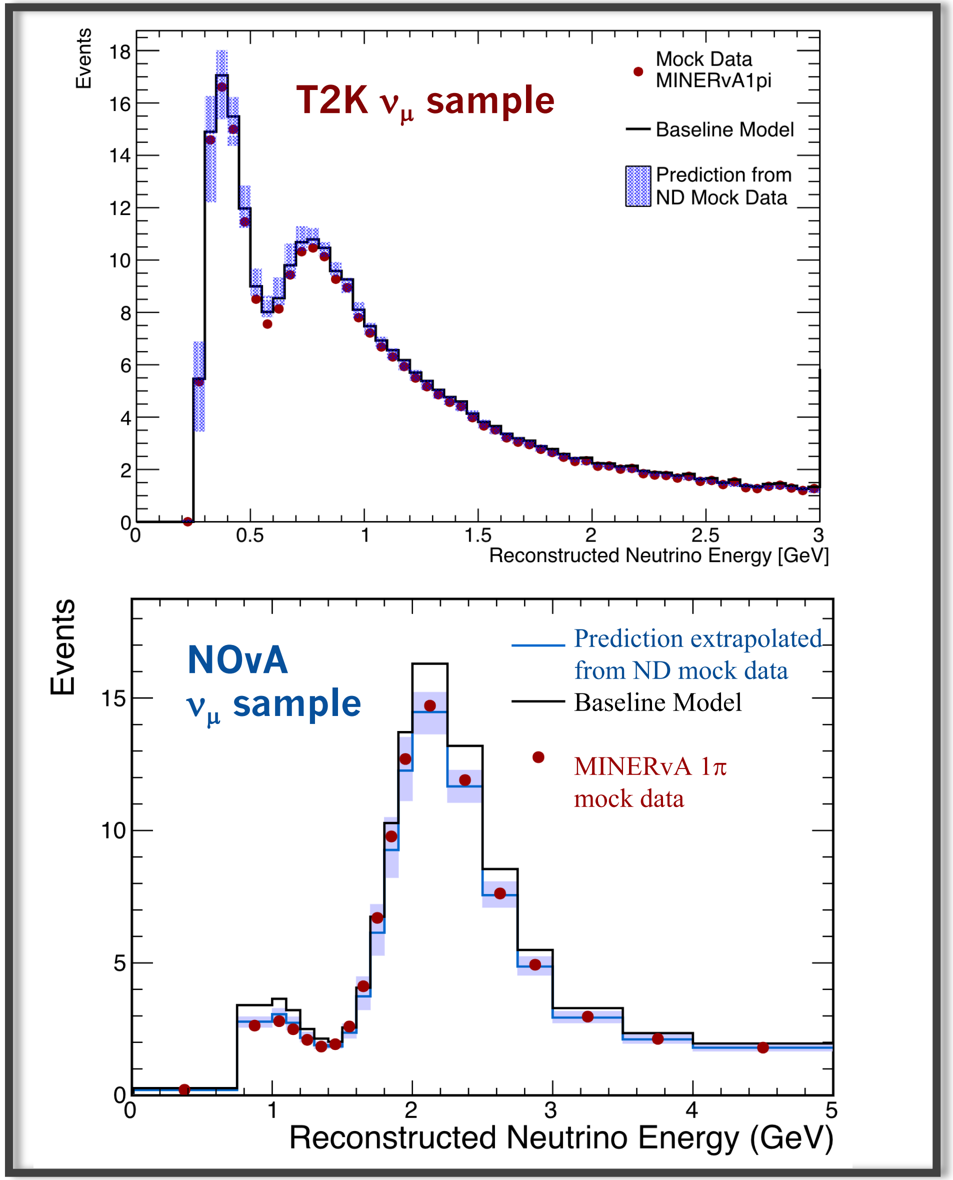
Robustness to alternate models

- Evaluate the robustness by fitting simulated fake data generated with various alternate models
  - Example: Suppression in single pion channel based on the tune to the MINERvA data*

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

- No alternate model tests failed the preset threshold bias criteria.





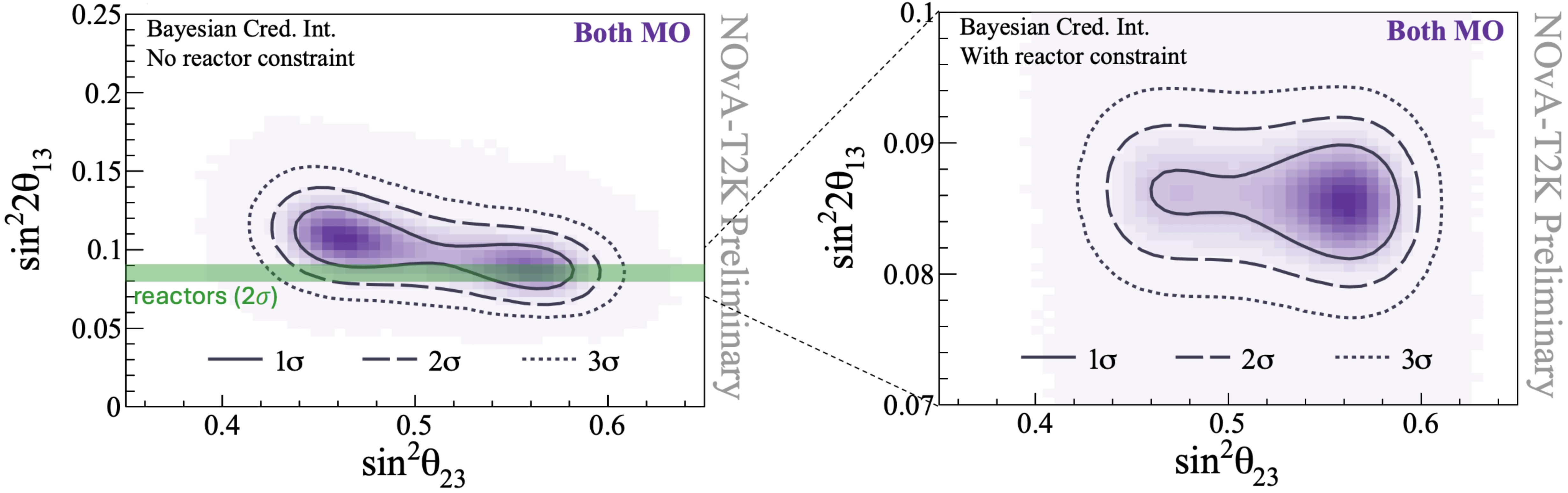
Mixing angles: θ_{23} and θ_{13}

- Degeneracy in $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$ parameters for long-baseline measurements.

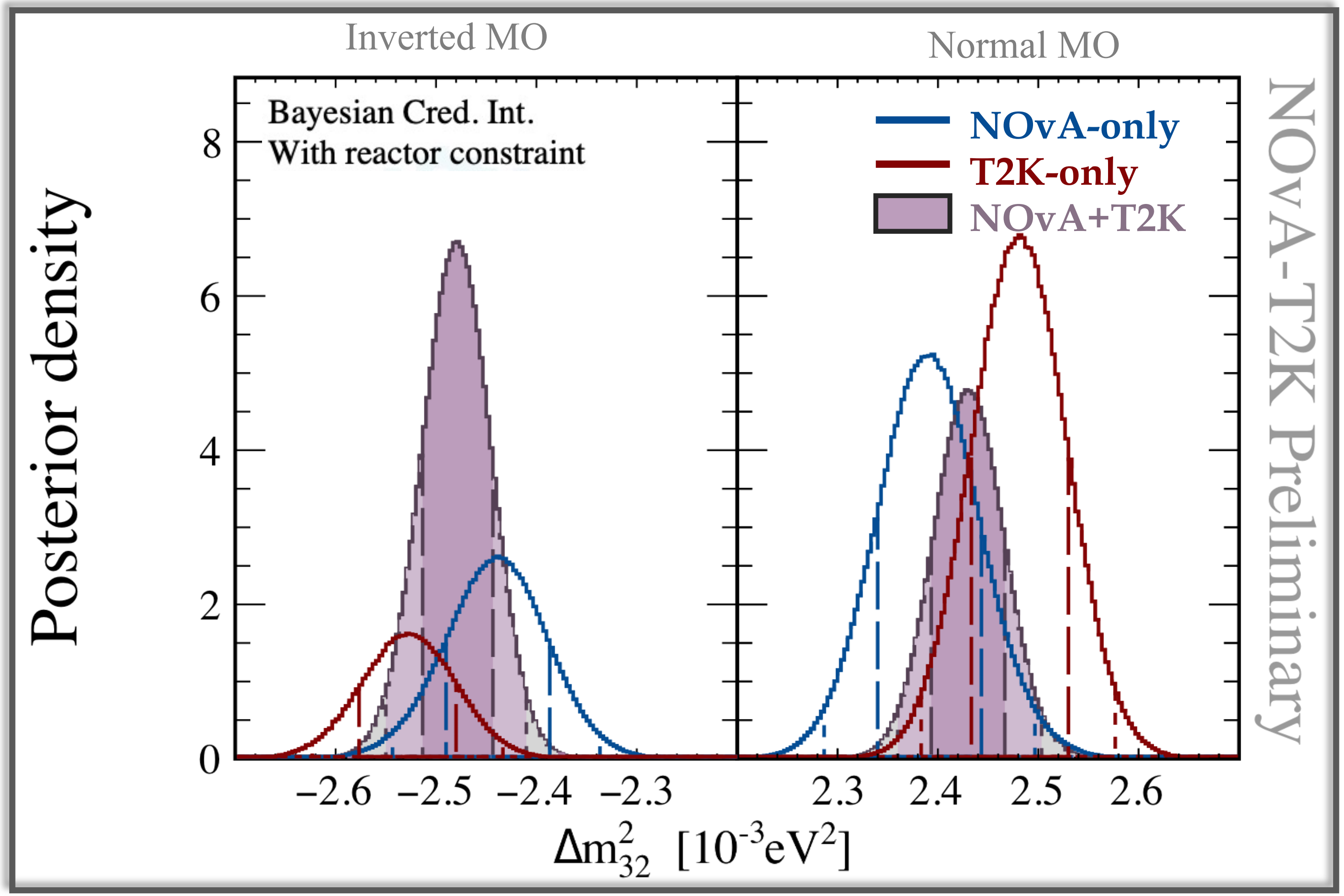
54% preference for lower octant (Bayes factor = 1.2)

θ_{13} constraint from reactor experiments

78% preference for upper octant (Bayes factor = 3.6)



Mass Ordering

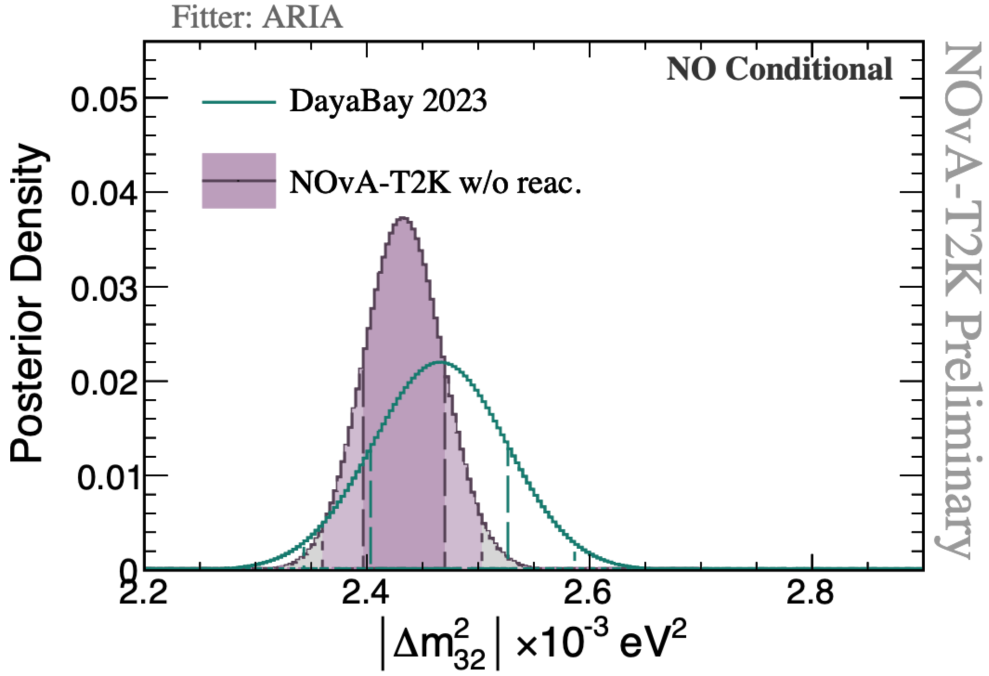


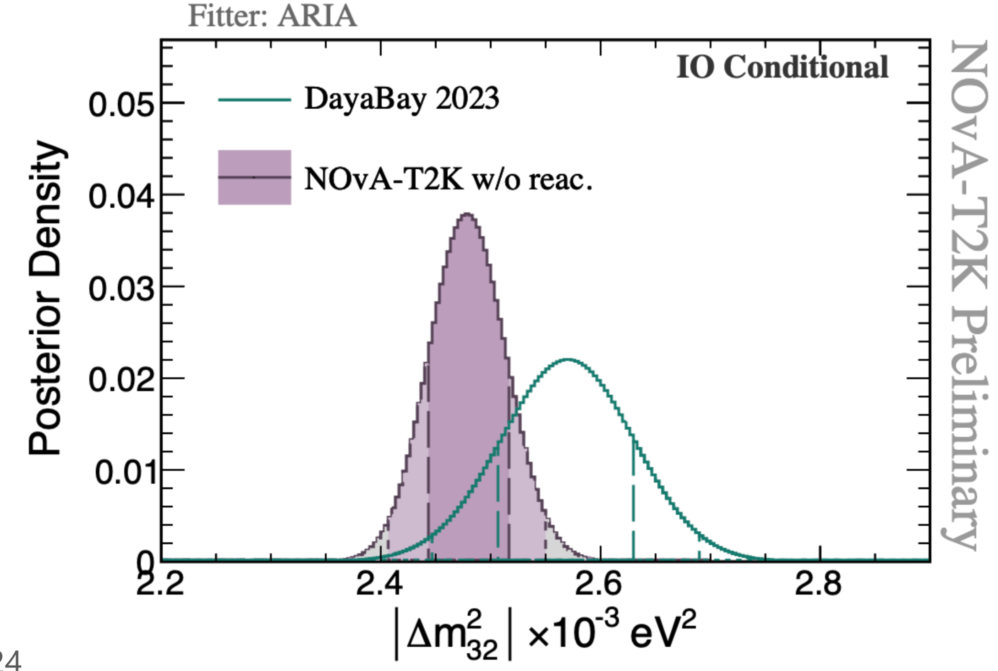
- NOvA-T2K joint fit has a modest preference for the Inverted Ordering, whereas individual experiments prefer Normal Ordering.
- The joint-fit enhances the precision of Δm^2_{32} over individual experiments.

	NOvA only	T2K only	NOvA+T2K
Bayes factor	2.07 Normal/Inverted ~67% : ~33% posterior	4.24 Normal/Inverted ~81% : ~19% posterior	1.36 Inverted/Normal ~58% : ~42% posterior

NOvA+T2K+Daya Bay

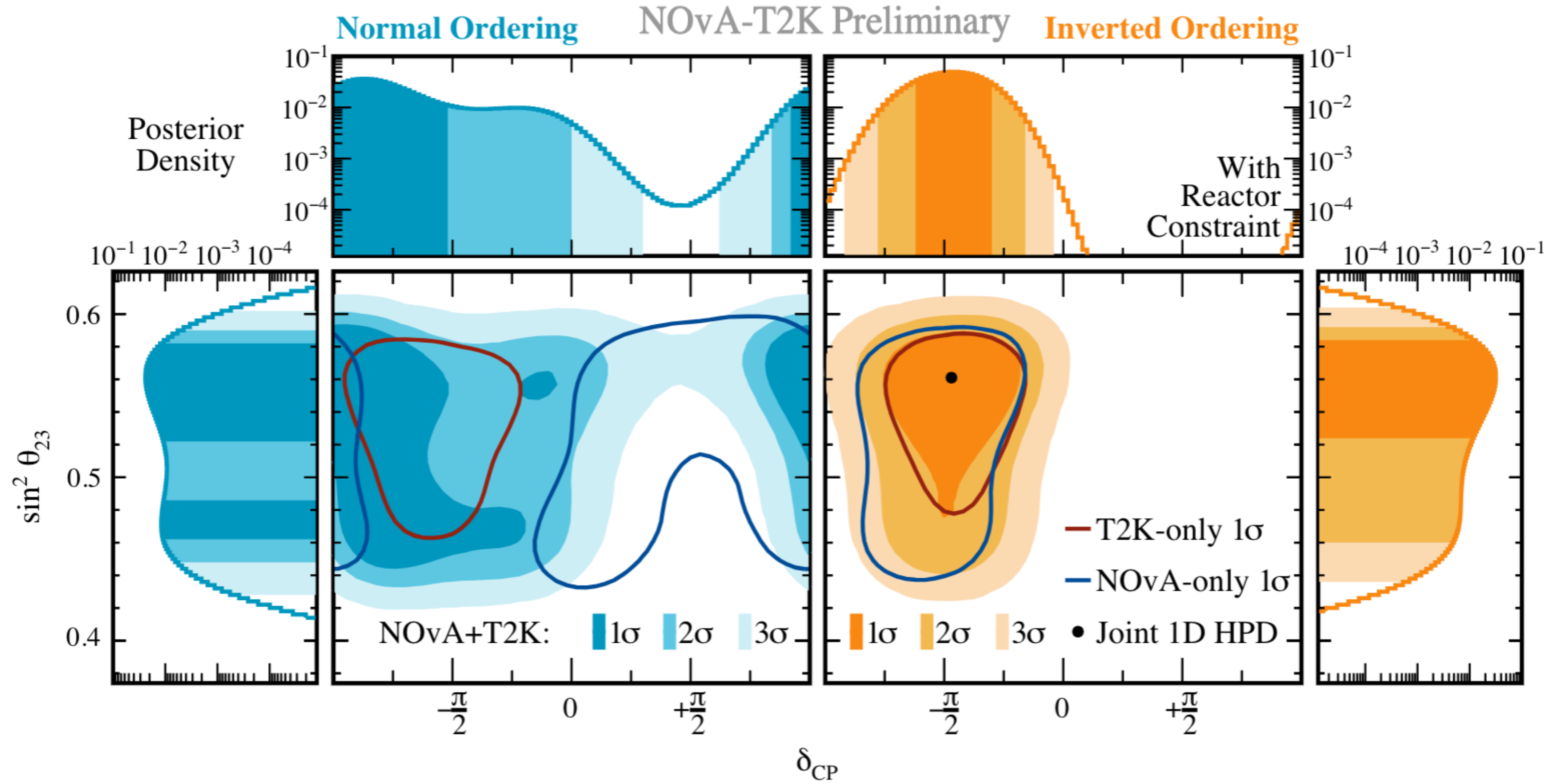
- Enhanced precision in Δm^2_{32} presents a lever on measuring neutrino mass-ordering.
  - Under wrong mass ordering assumption, reactor and long-baseline measurements of Δm^2_{32} will disagree*
- Including the Δm^2_{32} constraint from the Daya Bay**, reverse the mass ordering preference back to the Normal Ordering (~59%).
- **No significant preference for either mass ordering in the joint analysis.**





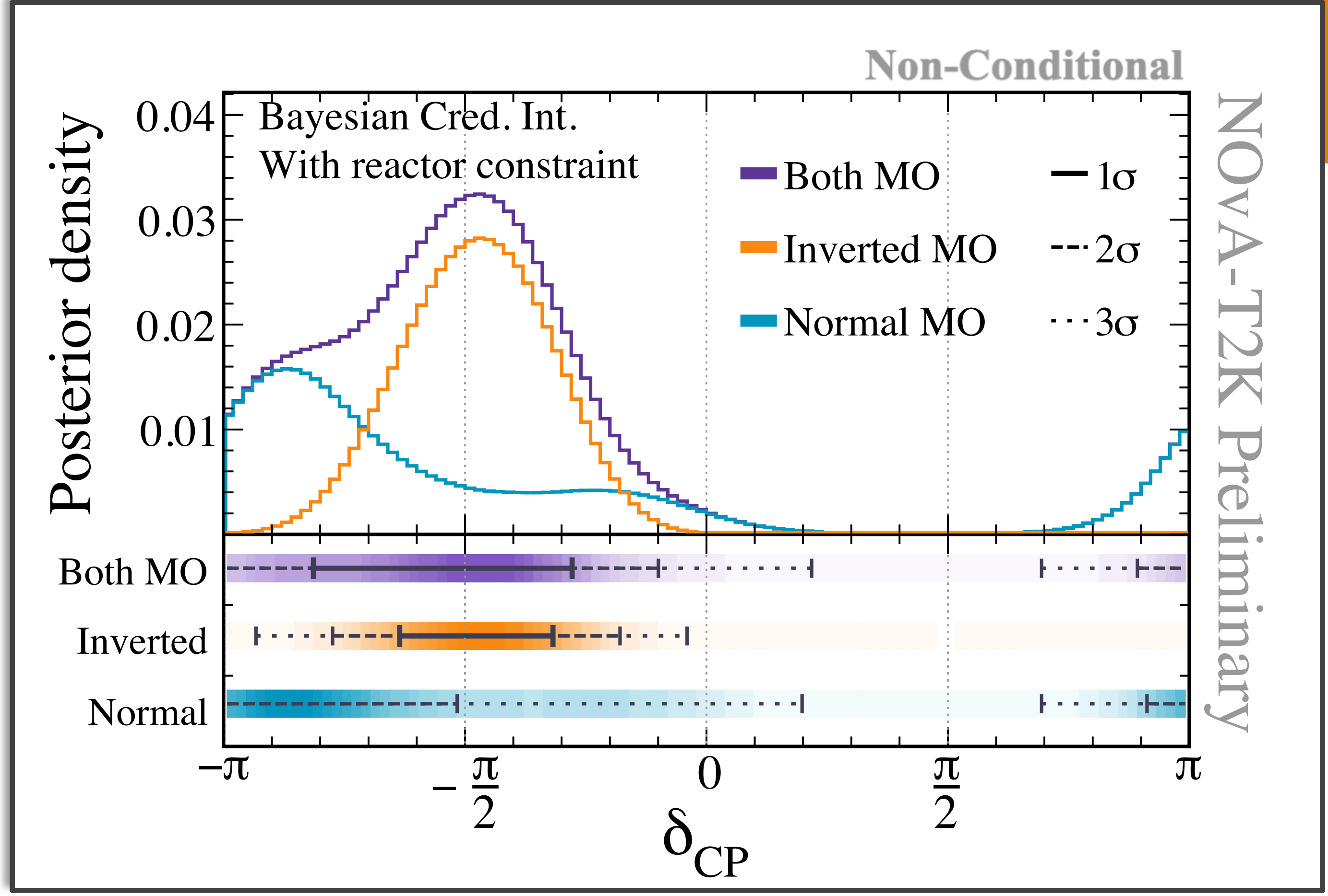
*Phys. Rev. D 72: 013009, 2005
Phys. Rev. Lett. **130, 161802, 2023

CP Violation



CP Phase: δ_{CP}

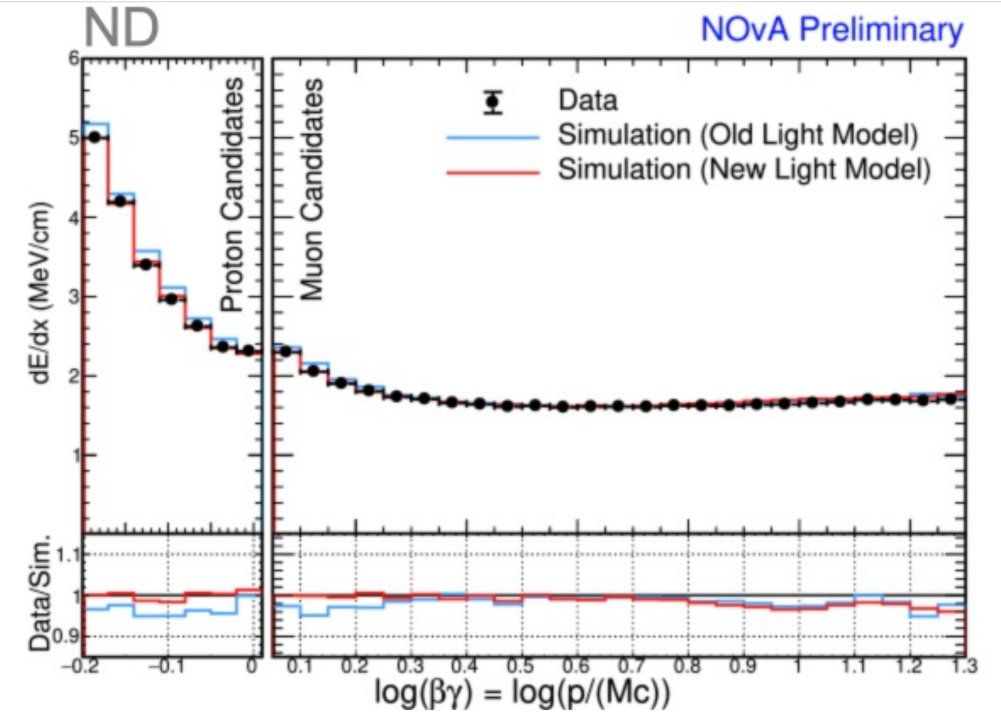
- For both mass orderings, $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval.
- Normal Ordering allows for a broad range of permissible δ_{CP}
- For the Inverted Ordering, CP conserving values of δ_{CP} (0, π) lie outside the 3-sigma credible interval.
  - Similar conclusions hold for Jarlskog invariant measurement for CP violation ($J_{CP} = 0$)

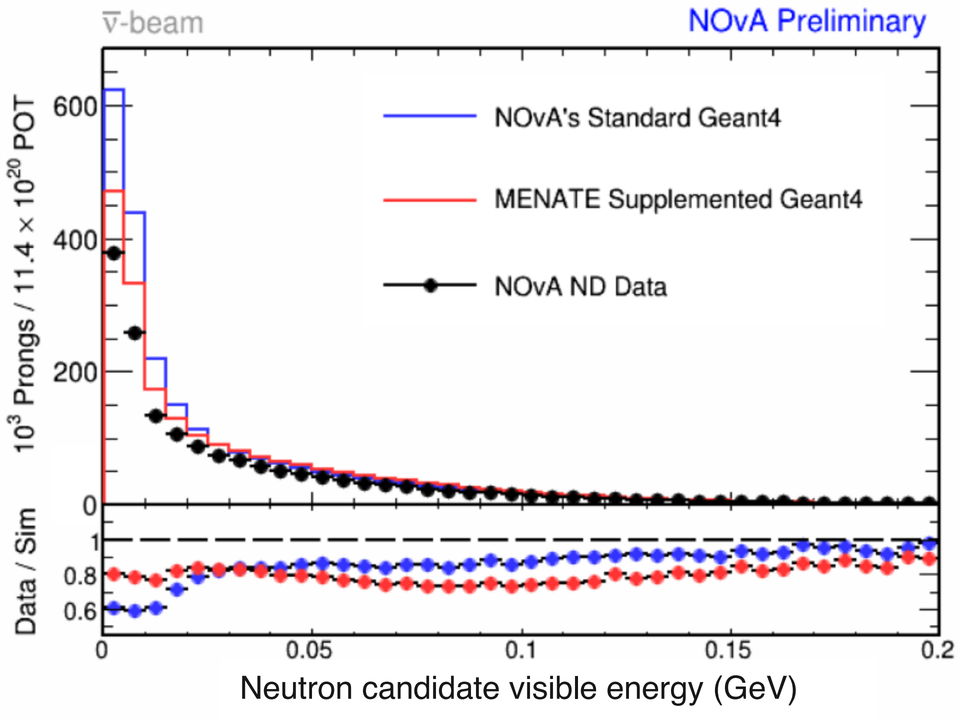


Latest results from NOvA analysis

Improved Simulation & Systematics

New for this analysis





Improved light production model from dedicated bench measurements & in situ stopping muon and proton tracks

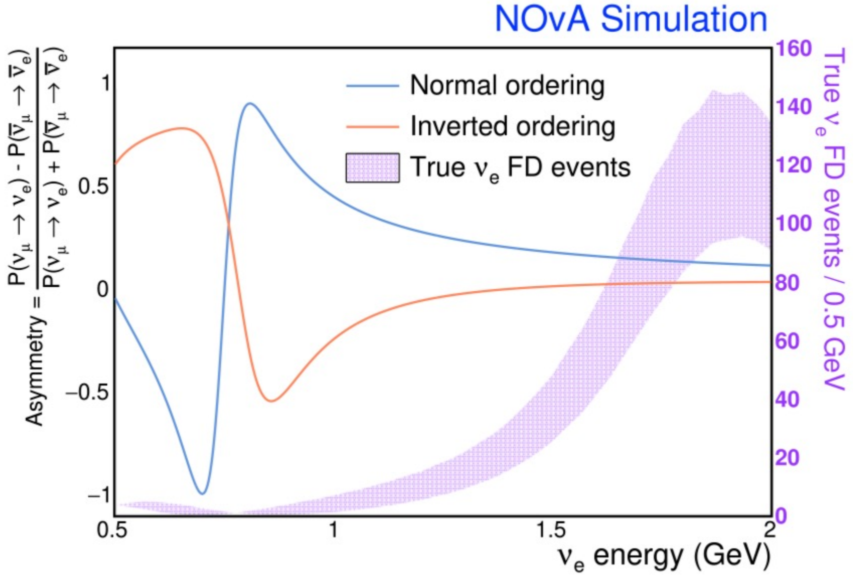
Improved neutron systematic uncertainty informed by n-^{12}C inelastic scattering model in MENATE_R*

*P. Désesquelles, et al., NIM A307 366-373 (1991), Z. Kohley, et al., NIM A682 59-65 (2012)

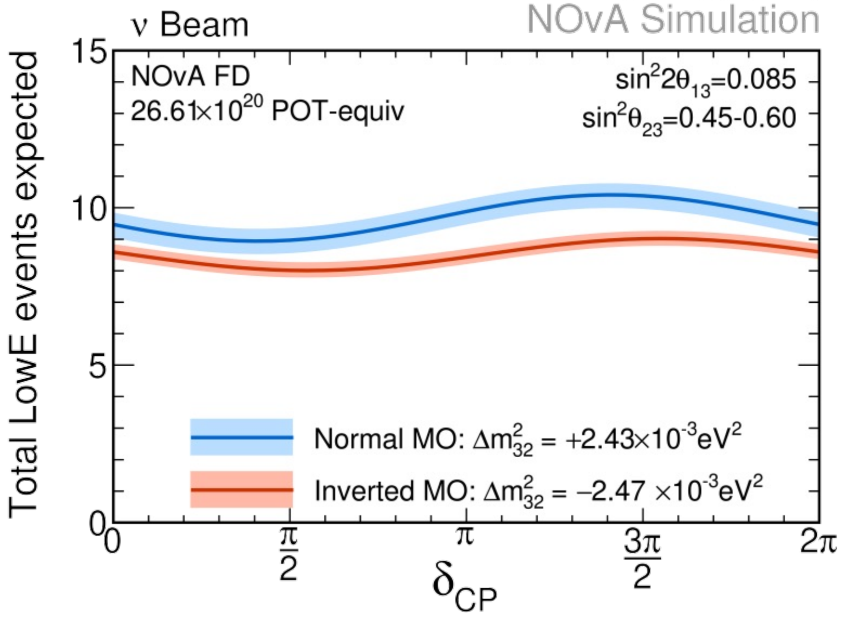
New cross-section systematics targeting the relative ratio of Delta vs. non-Delta resonance and rates of charged vs neutral hadron productions

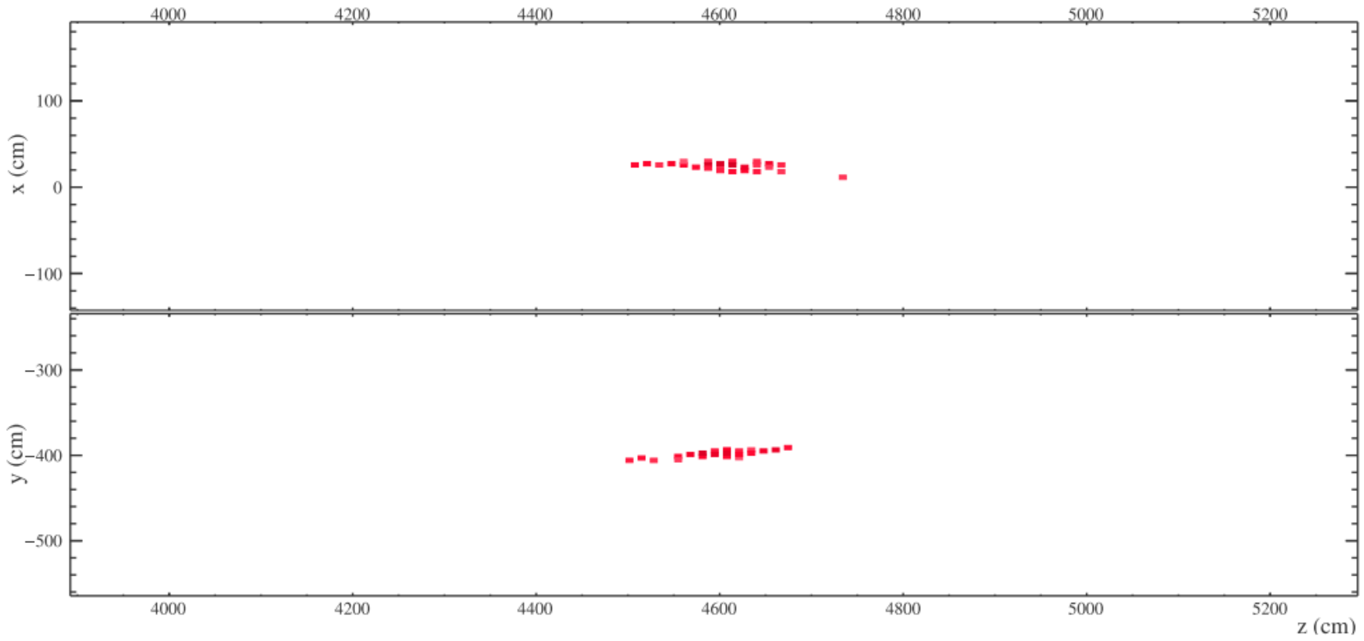
Expanding ν_e selections

New for this analysis



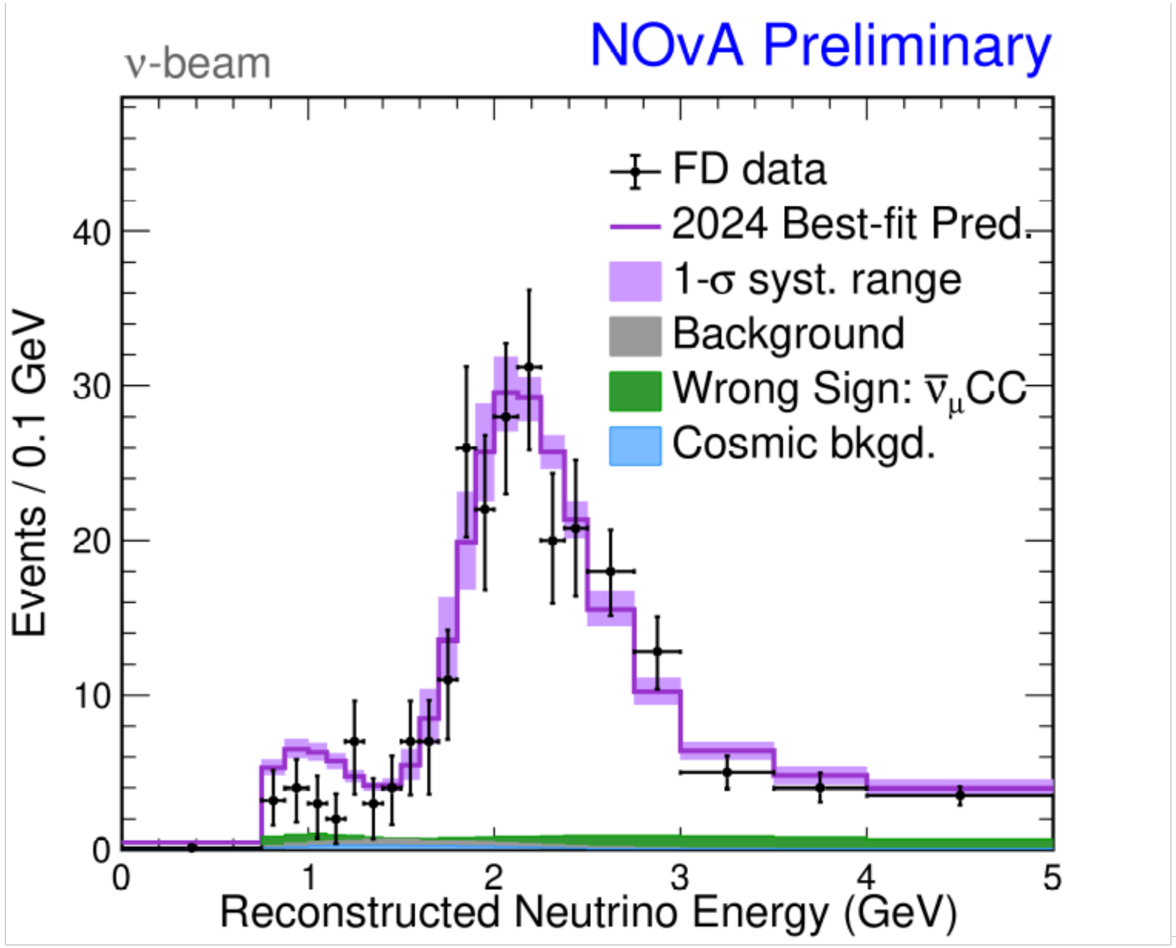
- Low energy ν_e are very sensitive to mass ordering due to large asymmetry between ν_e and $\bar{\nu}_e$ appearance.
- New selection targeting these ν_e candidates using BDT to reject background

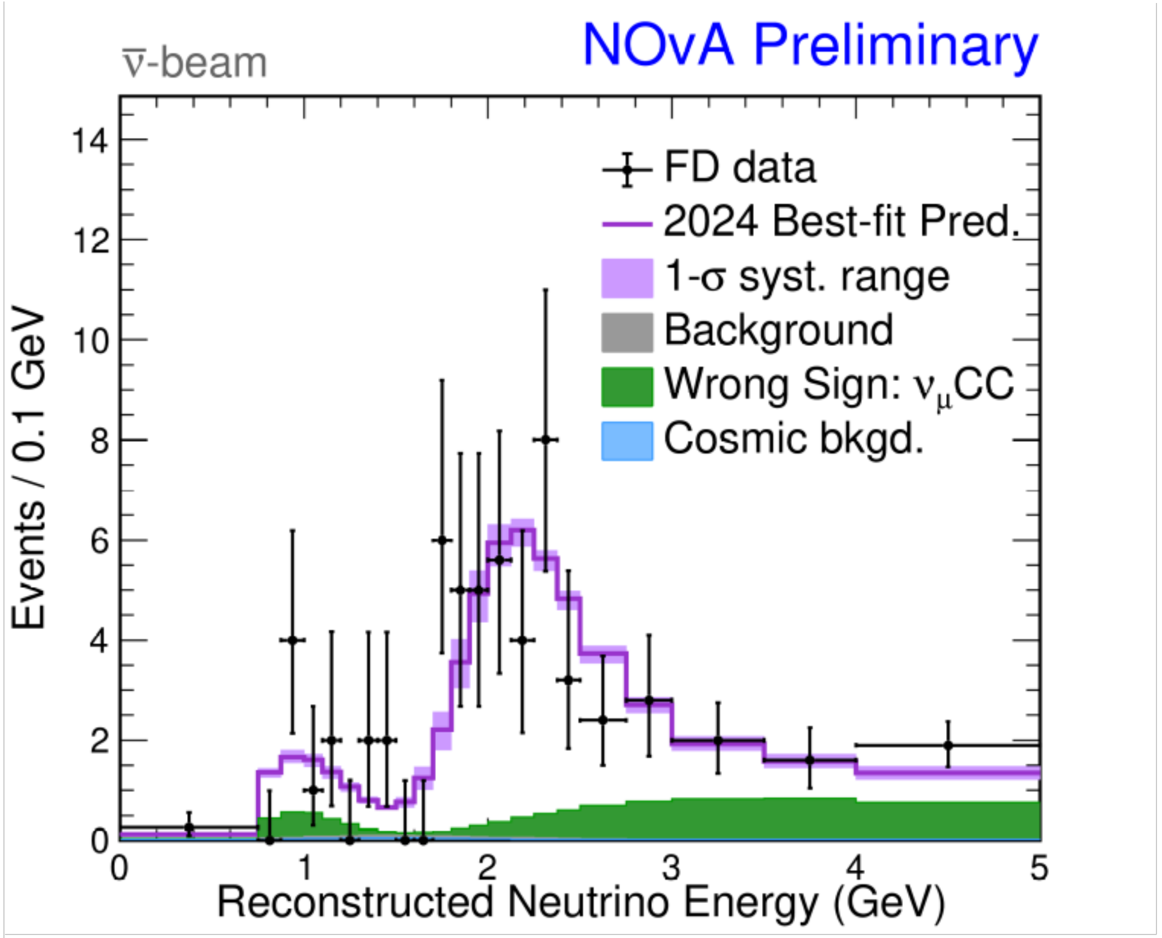




FD Samples: ν_μ

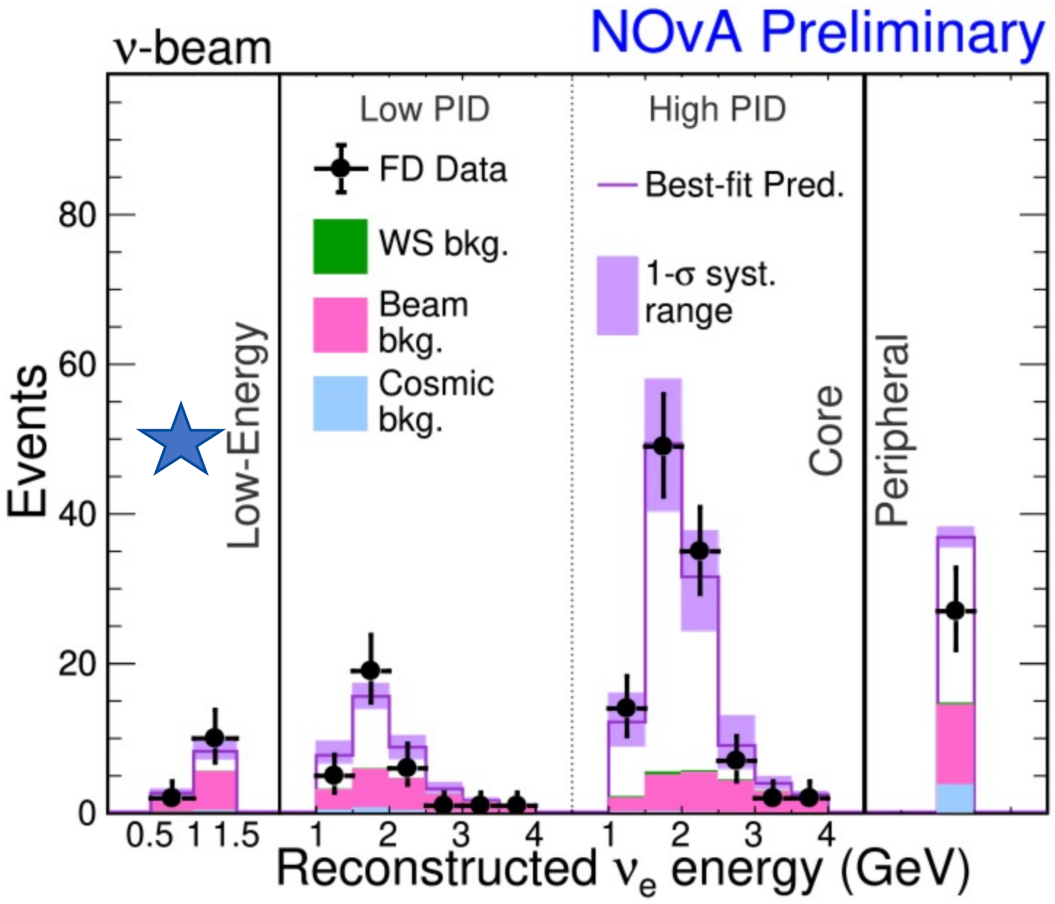
Bayesian posterior predictive p-value: 0.54

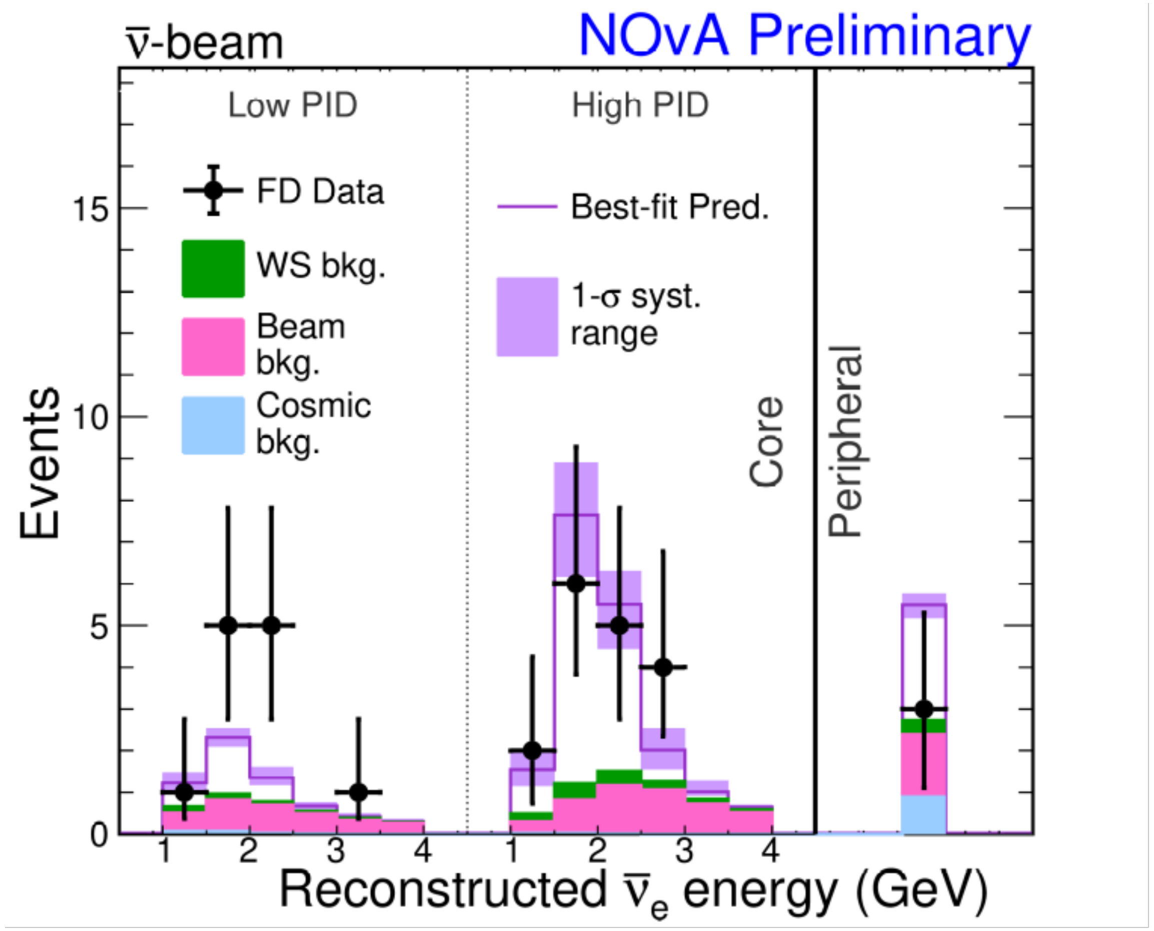




- Observe 384 ν_μ and 106 $\bar{\nu}_\mu$ candidates in the FD. In the absence of oscillations, we'd expect ~2100 and ~500.

FD Samples: ν_e

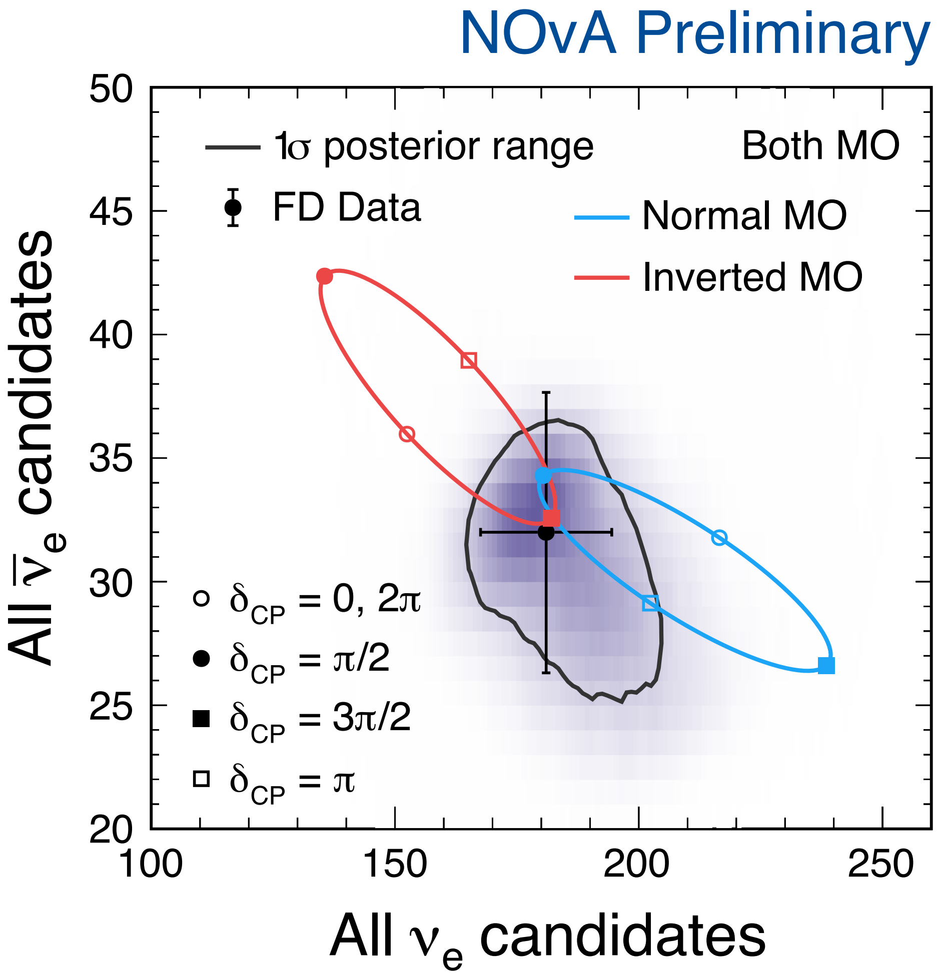


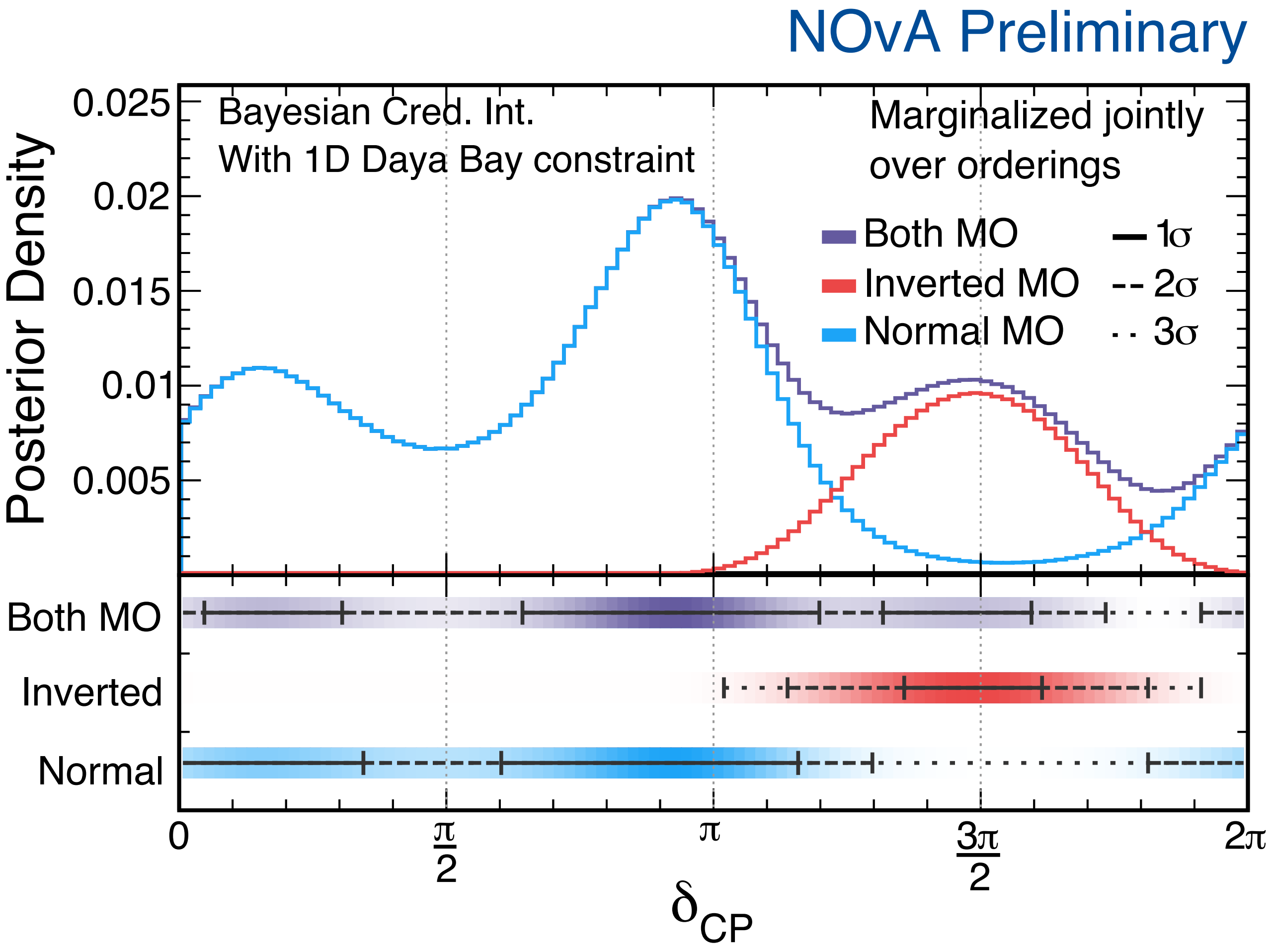


- We observe 181 $\boldsymbol{\nu}_{\mathbf{e}}$ and 32 $\bar{\boldsymbol{\nu}}_{\mathbf{e}}$ appearance candidates in the FD. The predicted backgrounds are 62 and 12 respectively.

CP Phase: δ_{CP}

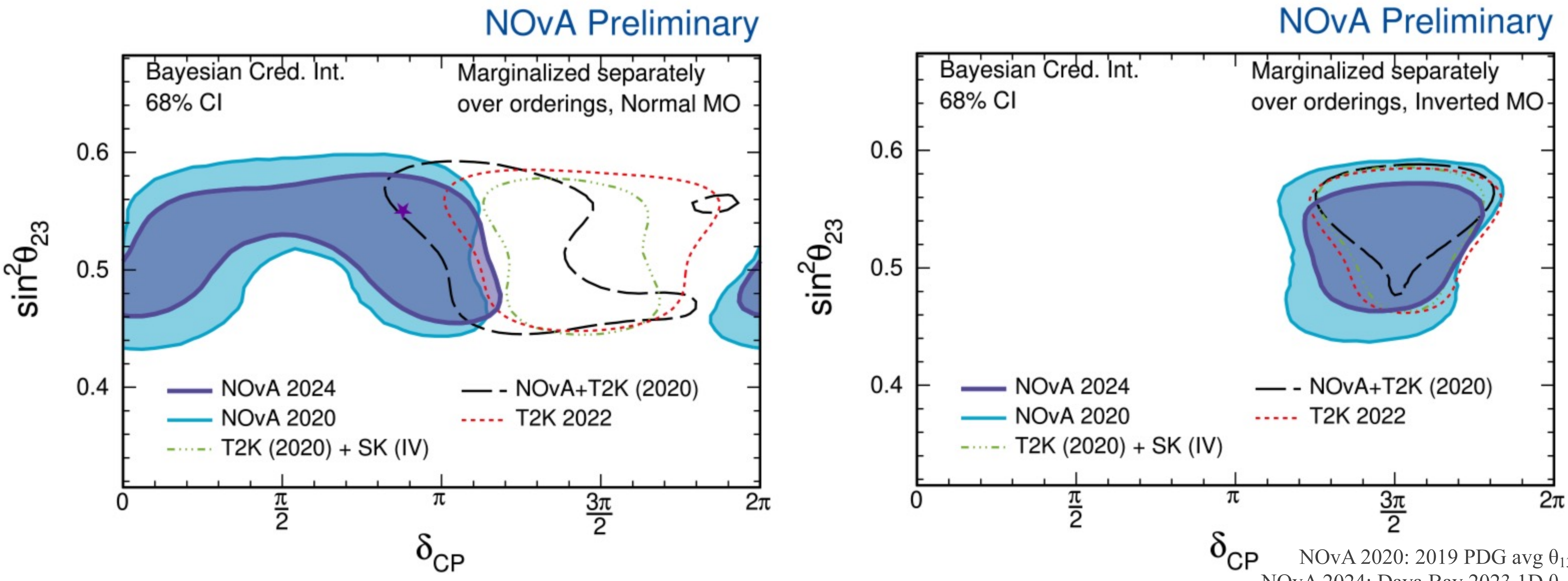
- The data disfavors large asymmetry combinations: (IO, $\delta_{CP} = \pi/2$) and (NO, $\delta_{CP} = 3\pi/2$).





CP Phase: δ_{CP}

- New NOvA result is consistent with its previous analysis. T2K, joint fits, favor different regions in Normal Ordering, same region in Inverted Ordering.



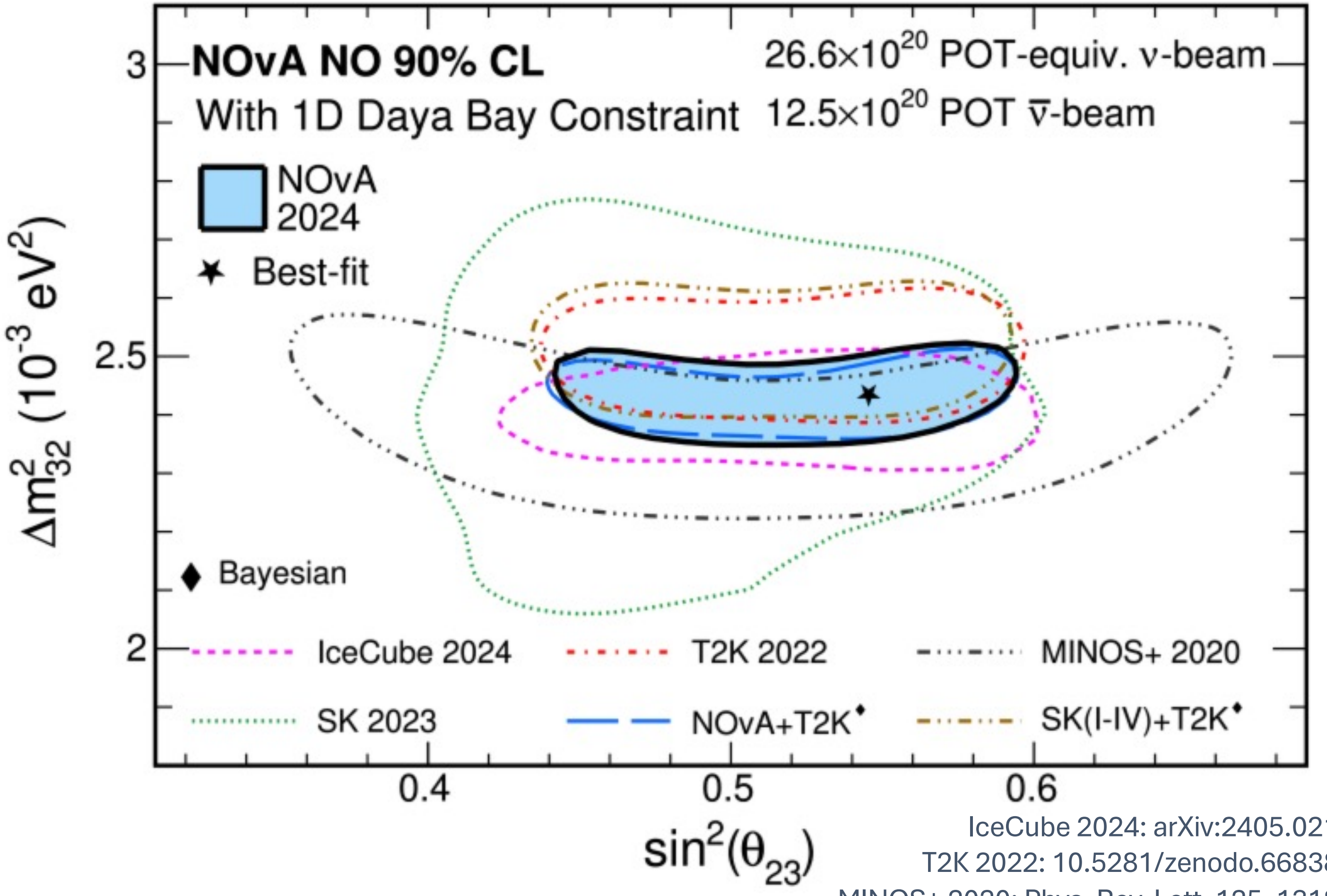
Note: results use slightly different choices of reactor constraint

NOvA 2020: 2019 PDG avg θ_{13}
NOvA 2024: Daya Bay 2023 1D θ_{13}
T2K: 2019 PDG avg θ_{13}
NOvA+T2K: Daya Bay 2023 1D θ_{13}
T2K+SK: 2019 PDG avg θ_{13}

Δm^2_{32} and θ_{23}

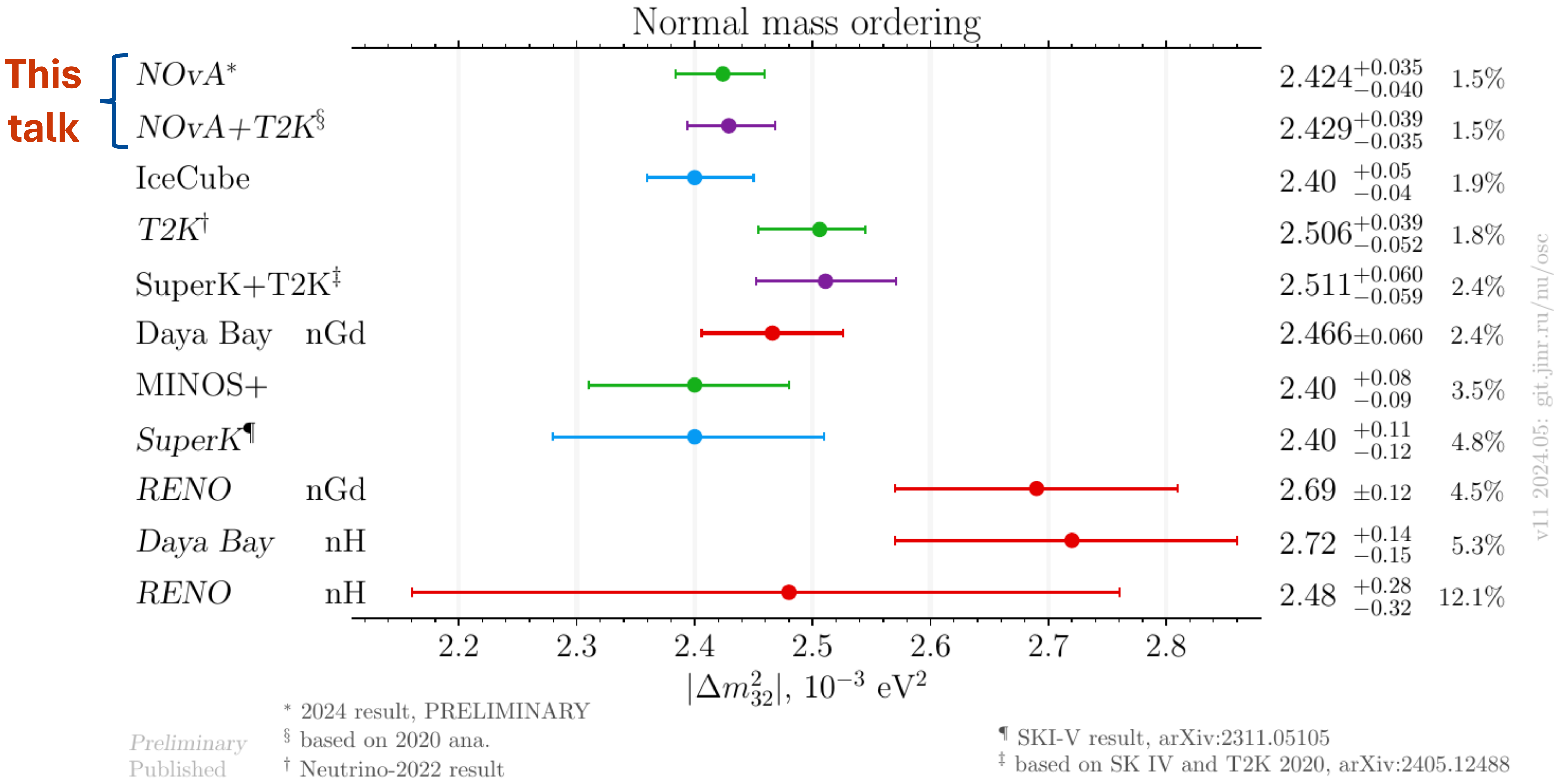
- Global consistency across accelerator, atmospheric and joint-fit results.
- All data is **consistent with maximal mixing** hypothesis for θ_{23}

NOvA Preliminary

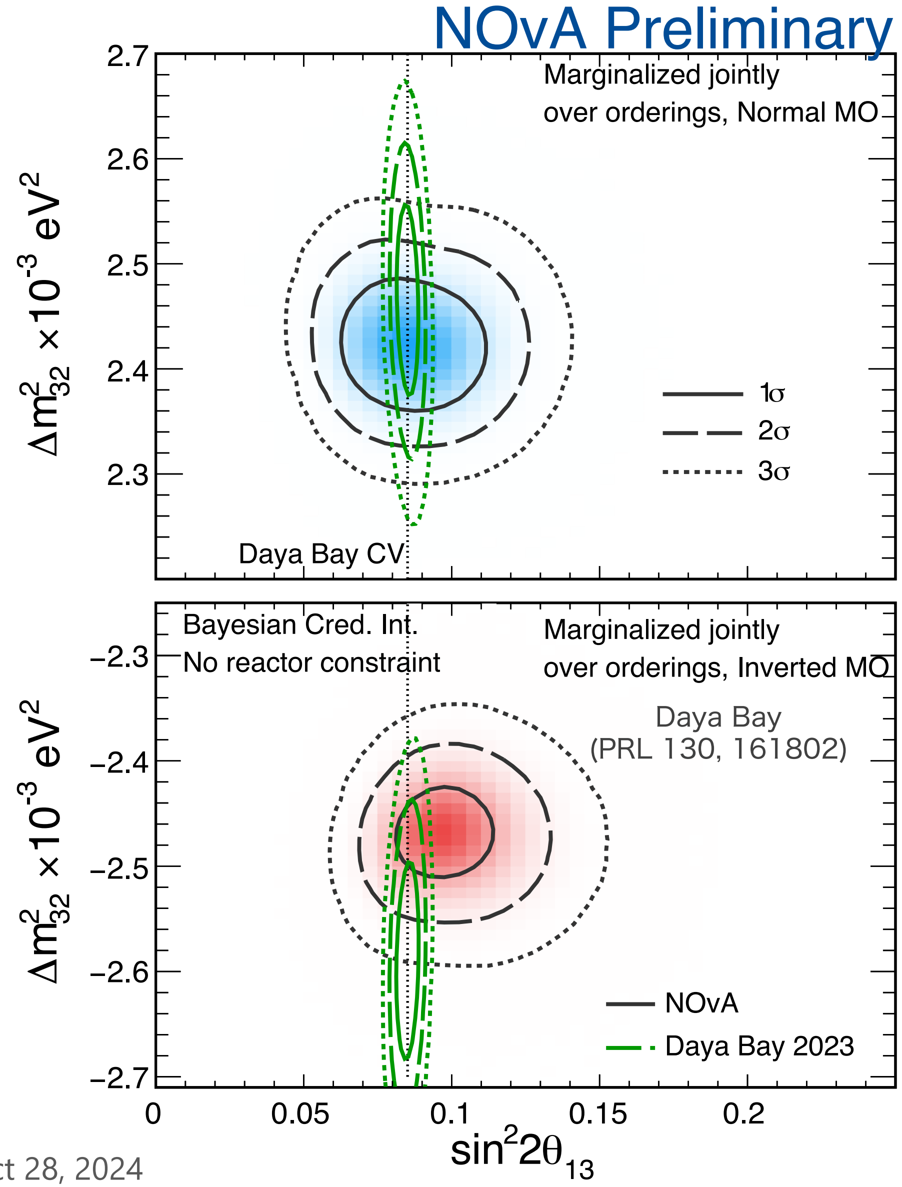


IceCube 2024: arXiv:2405.02163
T2K 2022: 10.5281/zenodo.6683821
MINOS+ 2020: Phys. Rev. Lett. 125, 131802
SK 2023: Phys. Rev. D109, 072014
NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar
T2K+SK 2024: arXiv:2405.12488

Precision on Δm^2_{32}



Mass Ordering

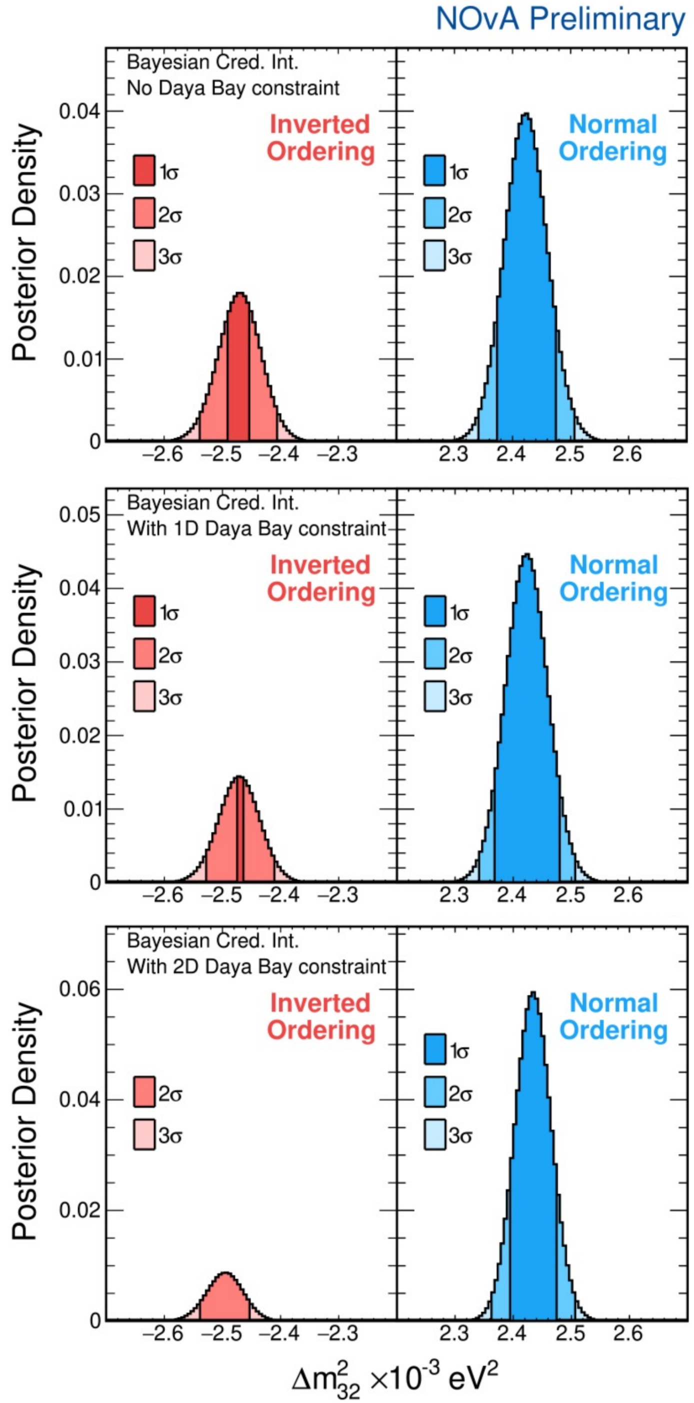


Normal Ordering preference (Bayes factor)

69% (2.2)
no Daya Bay constraint

76% (6.2)
θ_{13} Daya Bay constraint

87% (6.8)
θ_{13} & Δm^2_{32} Daya Bay constraint



Summary

Celebrating the 10 years of data-taking, NOvA released two prominent oscillation analysis results this year.

NOvA + T2K analysis

- Joint fit is useful to break degeneracy in the mass ordering and δ_{CP} parameter space. Fit demonstrates compatibility of the datasets.
- Excellent precision on Δm^2_{32}. No strong mass ordering preference.
- $\delta_{CP} = \pi/2$ (and vicinity) lies outside 3σ C.I. for both orderings. If inverted ordering, CP conserving points lie outside 3σ C.I.
- Both experiments continue to collect data.

Celebrating the 10 years of data-taking, NOvA released two prominent oscillation analysis results this year.

New NOvA analysis

- Doubled neutrino data set. New samples, simulation and systematics update featured in this analysis.
- Leading single experiment precision on Δm^2_{32}. 87% preference for Normal Mass Ordering with 2D constraints from Daya Bay.
- Data favors "degenerate" mass ordering and δ_{CP} combinations.
- Aim to double antineutrino data set for the next analysis.

NOvA

Thank you!

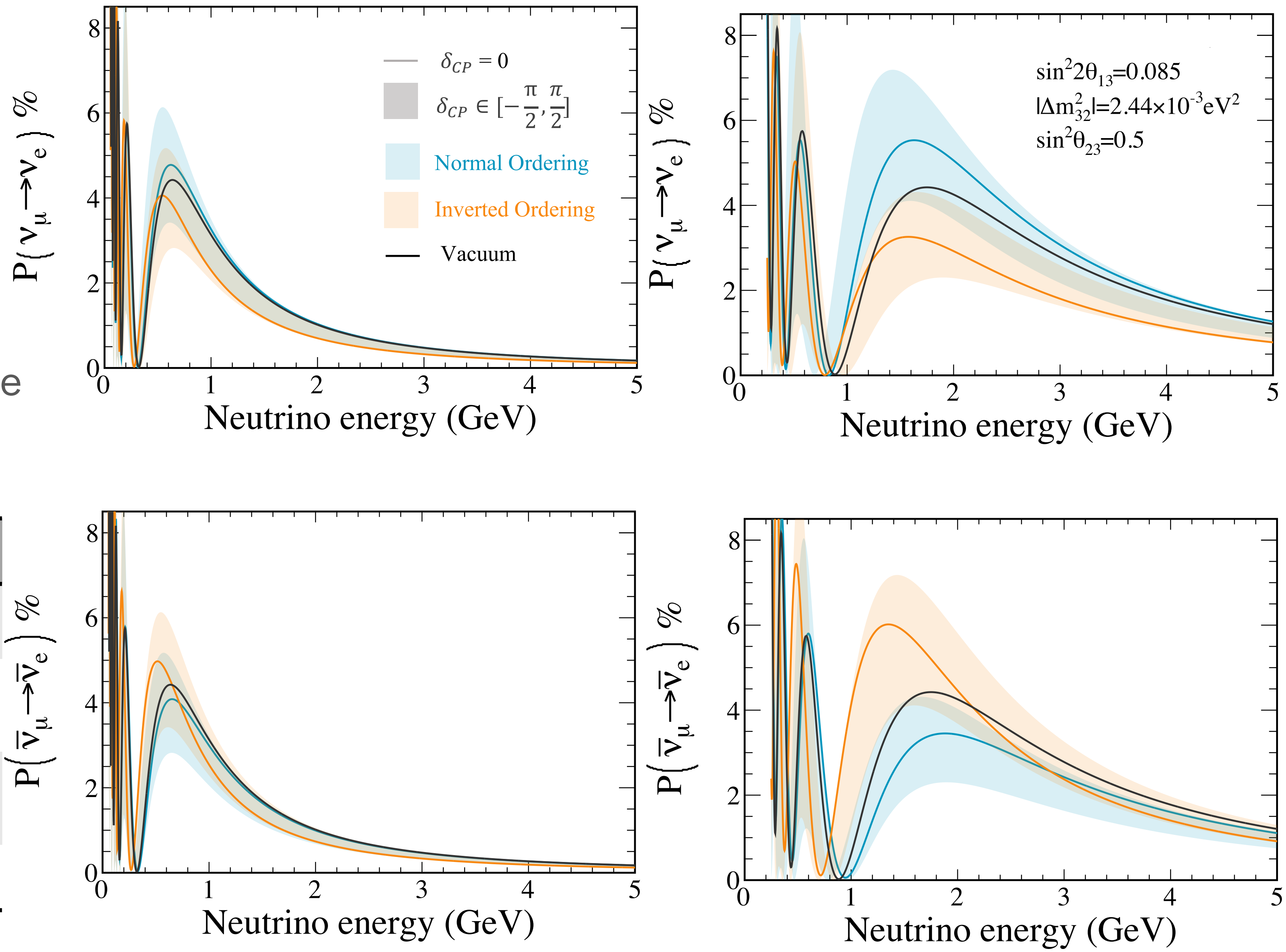
Baselines

- Larger matter effect for higher neutrino energy → higher sensitivity to mass ordering.
  - Therefore, associated asymmetry is higher for the longer baseline.

	T2K	NOvA
L (baseline)	295 km	810 km
Energy (beam peak)	0.6 GeV	2 GeV
Matter effect*	~ ±9%	~ ±19%
CP effect*	~ ±30%	~ ±25%

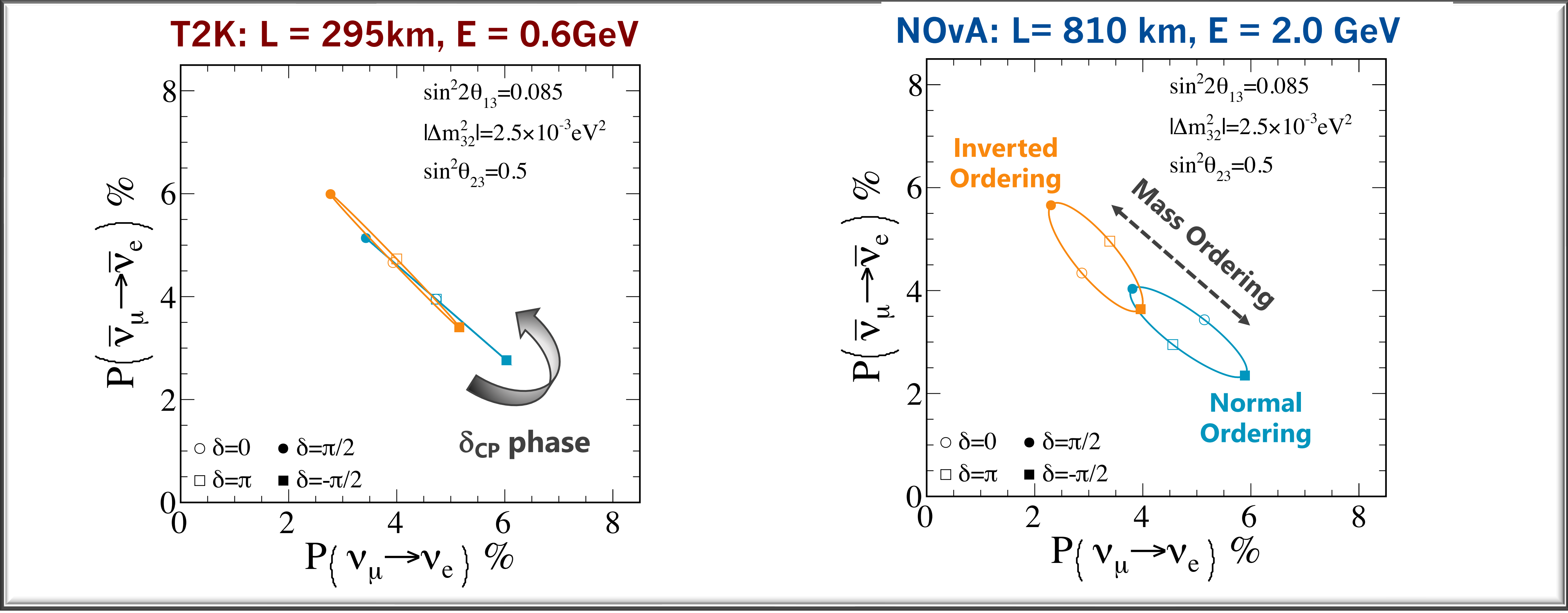
*calculated at beam peak energy

T2K: L = 295km **NOvA: L= 810 km**



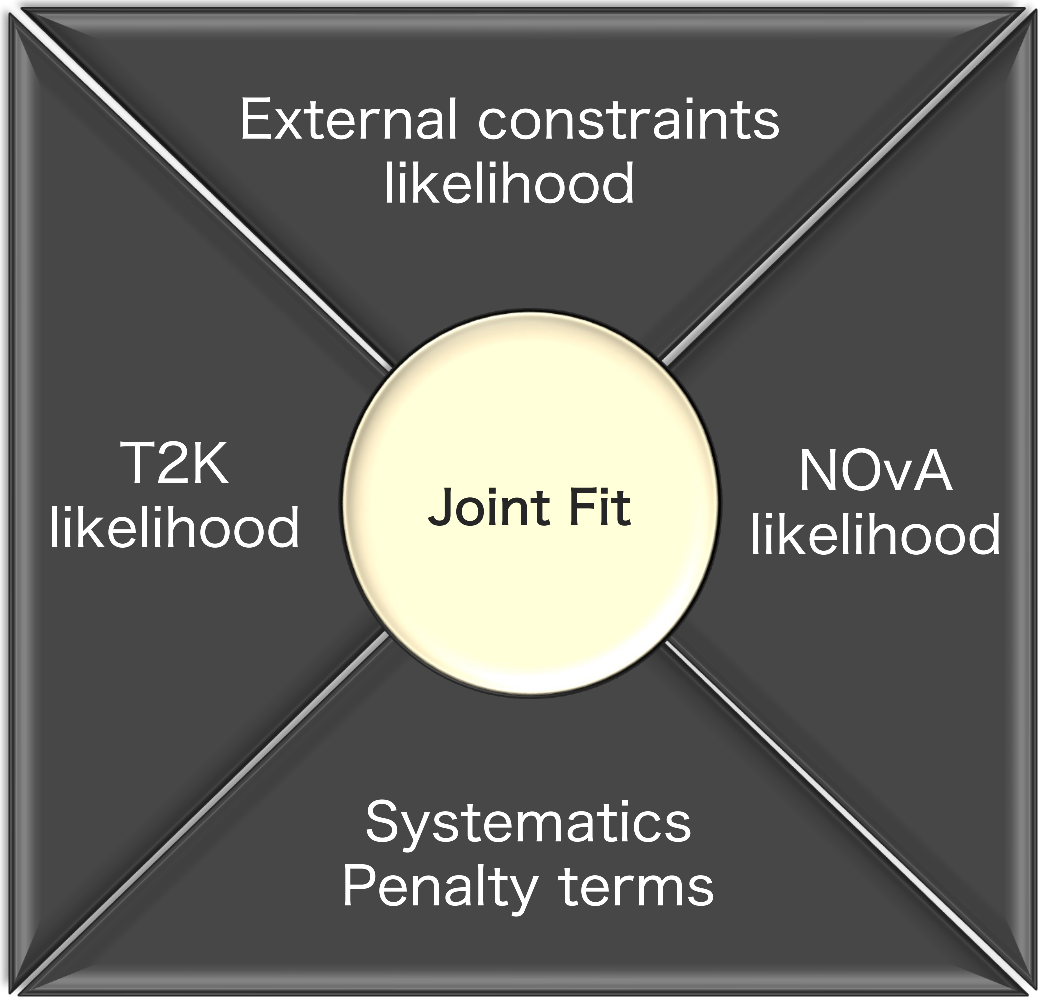
Resolving degeneracies

- **T2K** measurements isolate impact of **CP violation** while **NOvA** has significant **sensitivity to mass ordering.**
- **Joint analysis probes both spaces lifting degeneracies of individual experiments.**



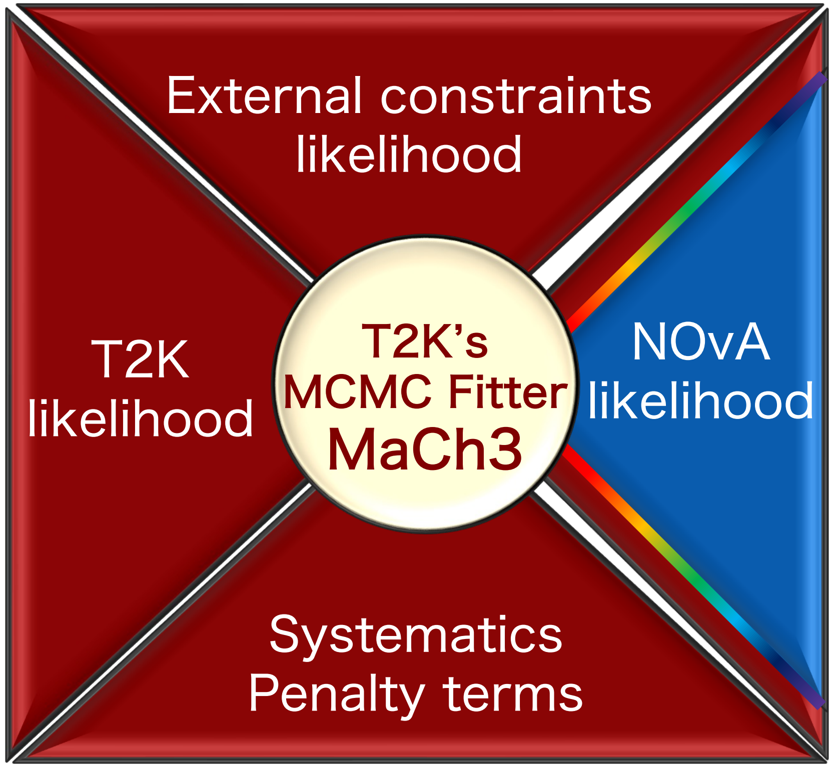
Constructing the joint-analysis

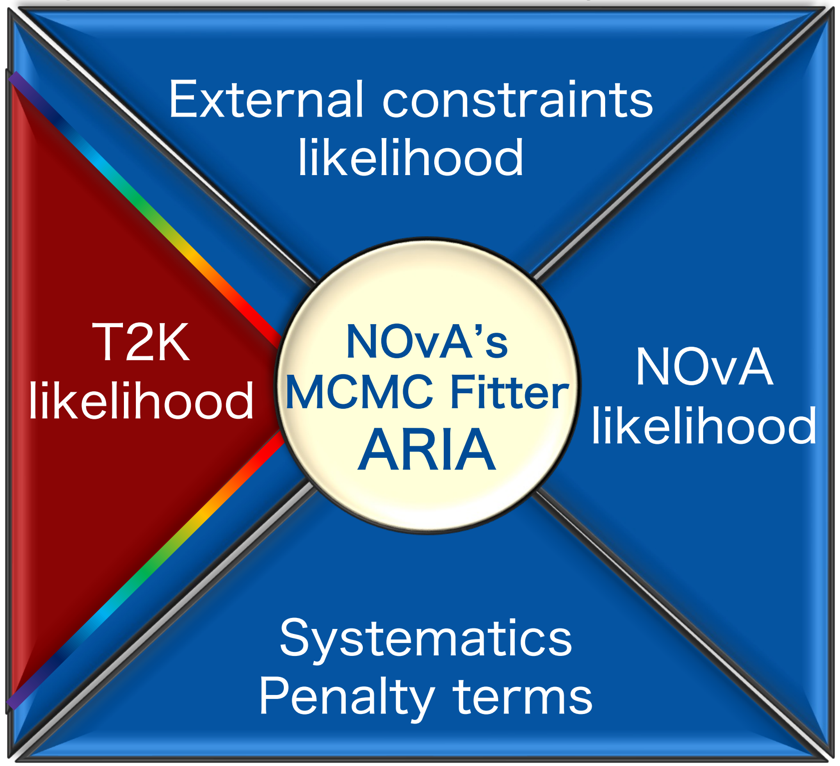
- The joint-fit is constructed using:
  - Poisson likelihood from each experiment
  - Penalty terms from the systematics pull
  - External constraints on θ_{13}, θ_{12}, Δm^2_{21} from solar and reactor neutrino experiments
- The other experiment's likelihoods are integrated via a containerized environment.
  - Both experiments can run each other's analysis through these containers.
  - Full access to Monte-Carlo and data.



Constructing the joint-analysis

- Both T2K and NOvA have used their Bayesian Markov Chain Monte Carlo (MCMC) fitters.
- Both produce same output format:
  - Posterior densities and credible intervals for parameters-of-interest.
  - Bayes factor for discrete model preferences (ordering and octant).
- Independent implementation of the framework provided rigorous validation of the joint fit.



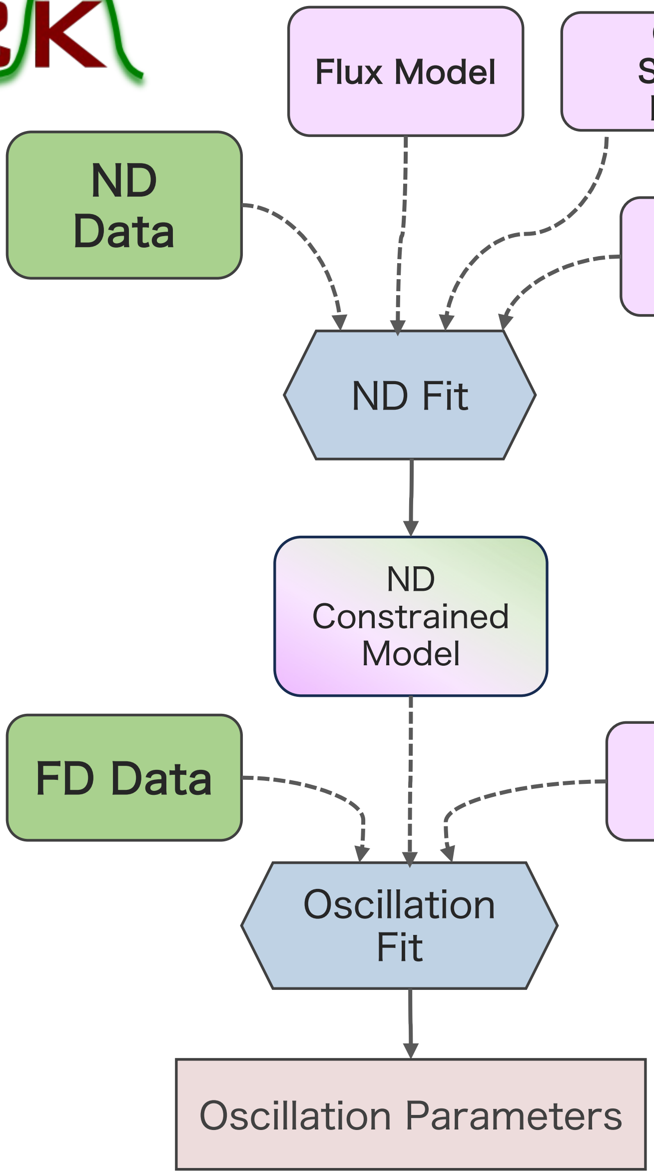


Red represents T2K codebase & blue shows NOvA codebase.

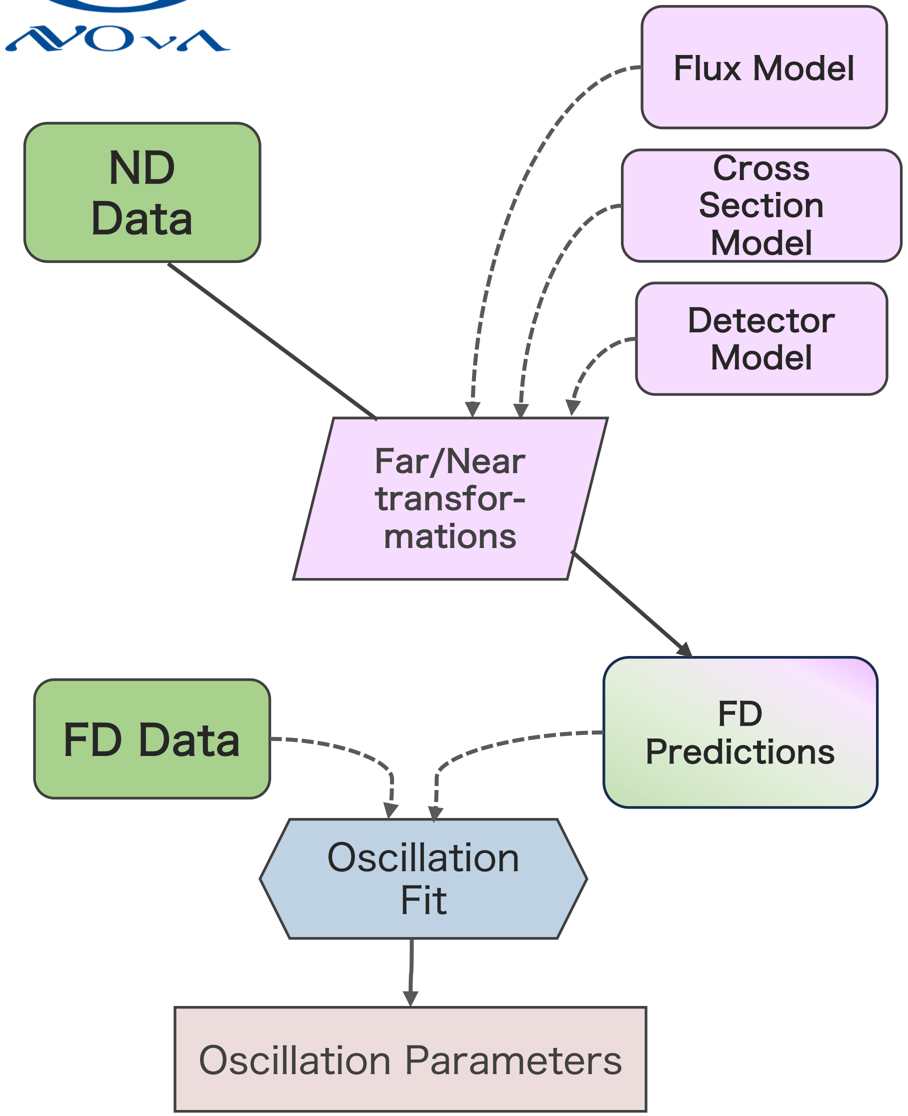
Analysis Strategy

- The experiments have different analysis approaches driven by contrasting detector designs.

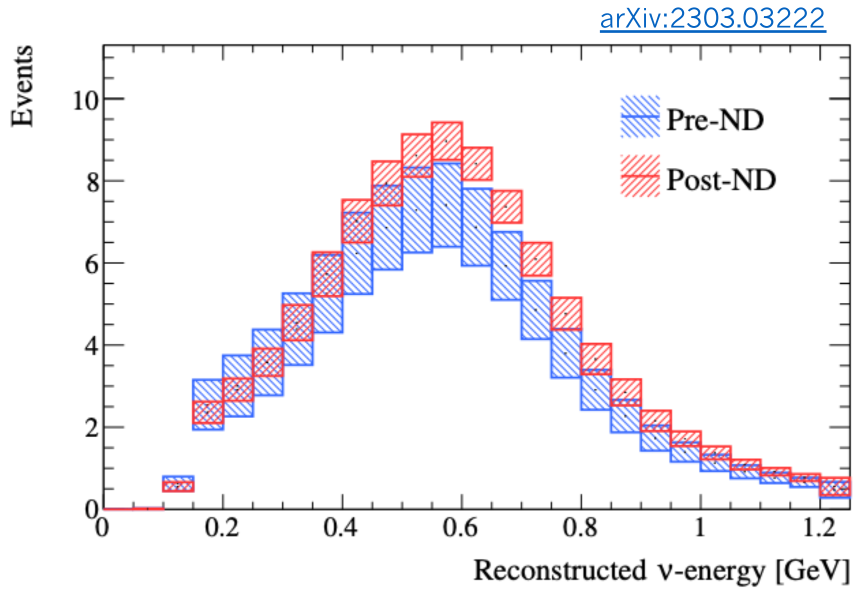
T2K

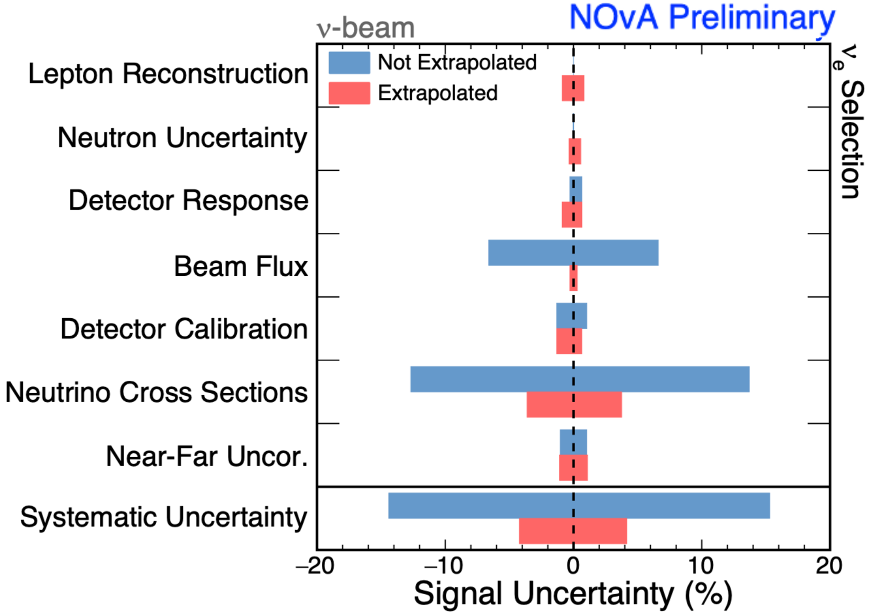


NOvA



Impact on systematics



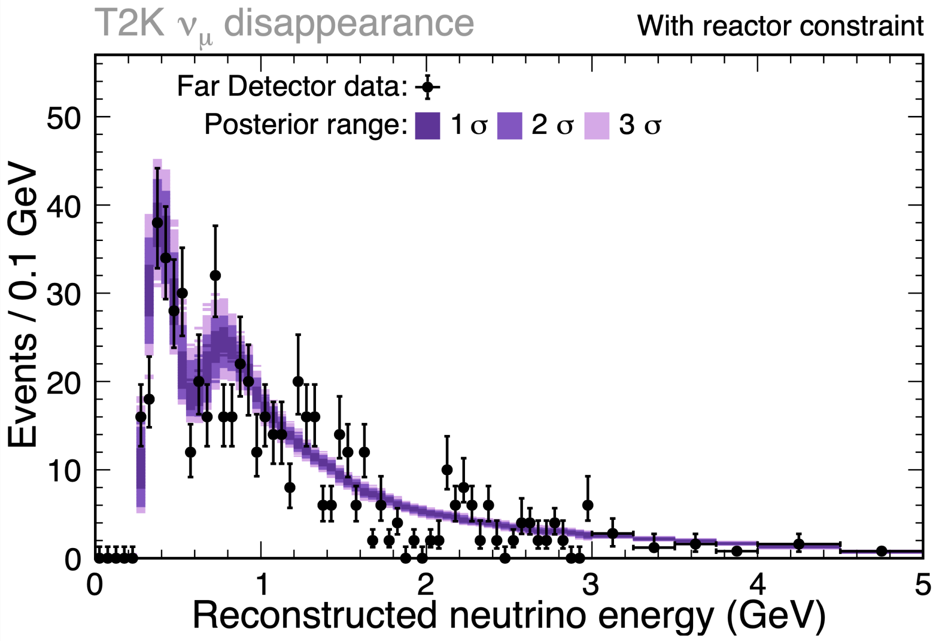


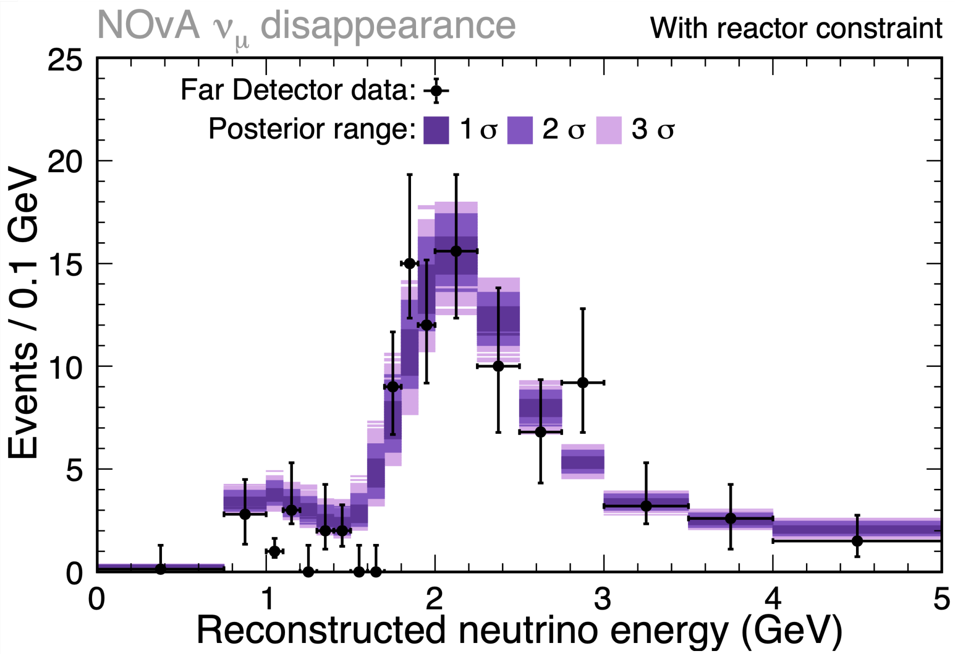
- NOvA: Systematic uncertainties in the FD ν_e prediction from ~15% to ~5%
- T2K: Uncertainty on FD 1e-like ring ν_e event rate goes from 13.0% to 4.7% after applying constraints from ND data fit

FD Data Samples

- The joint-fit uses the data collected by each experiment up until 2020.
- Using both experiments data roughly doubles the total statistics at the far detectors.

Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137





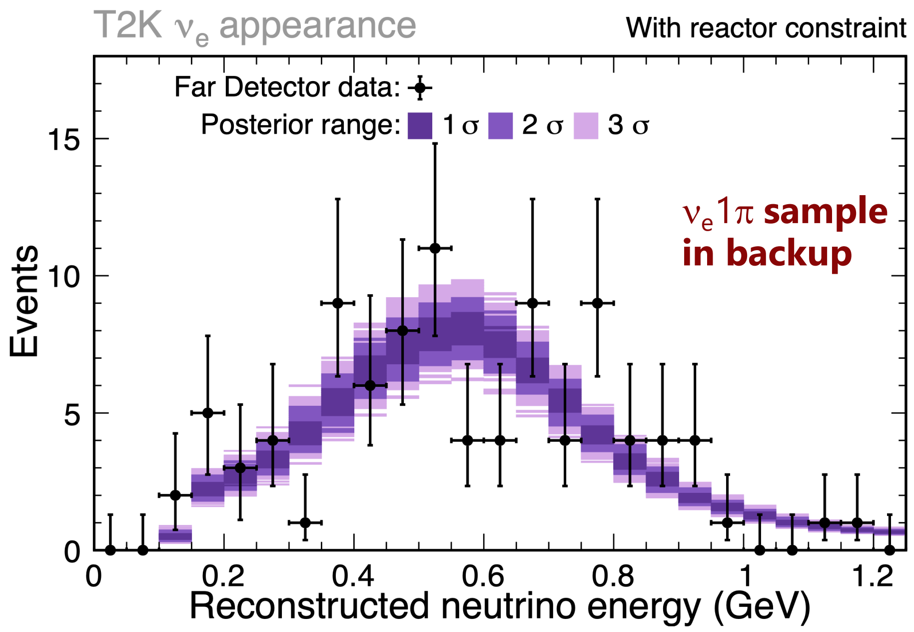
$\bar{\nu}_\mu$ samples in backup

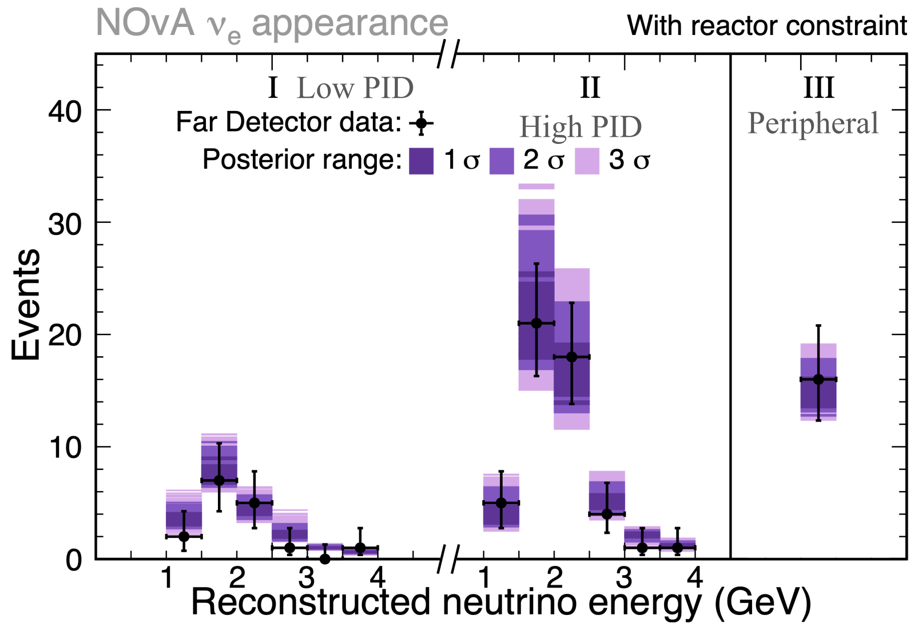
Compatibility of datasets

- Posterior predictive p-values (PPP)*
  - Compare likelihood best fit to data and fluctuated predictions
  - A good PPP is around 0.5
- **The data from both experiments is described well by the joint fit.**

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

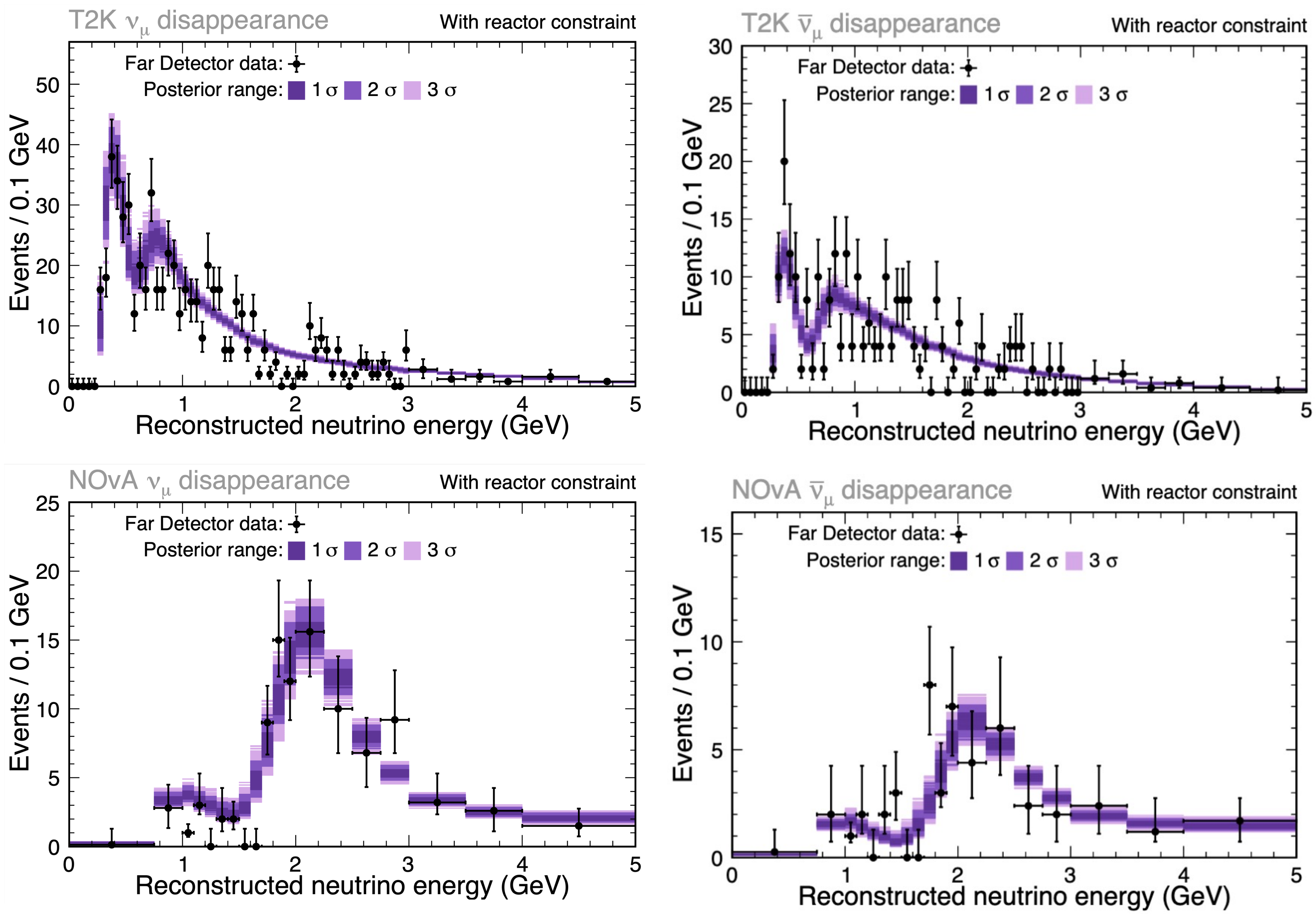
posterior predictive p-value



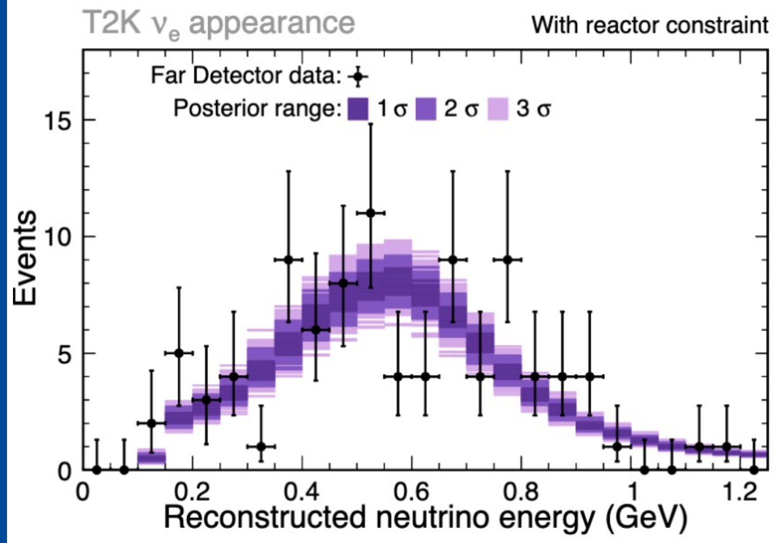


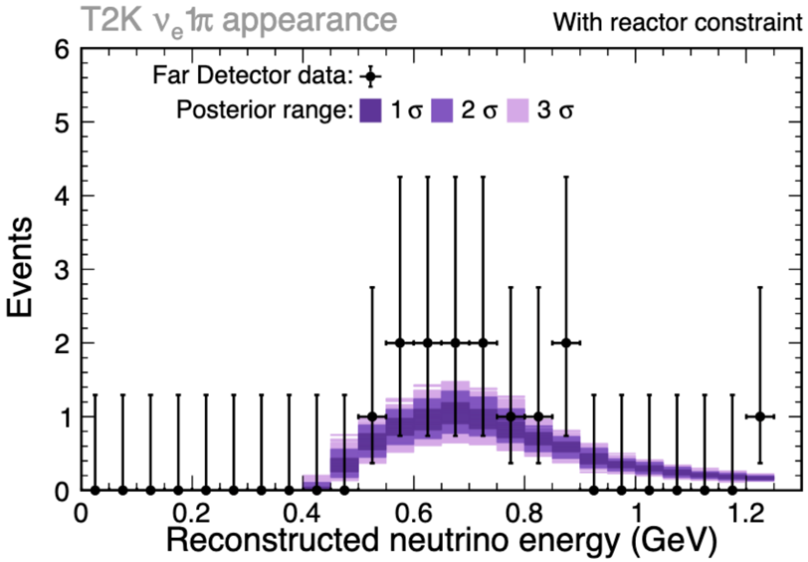
*Statistica Sinica, vol. 6, no. 4, 1996, pp. 733–60. JSTOR

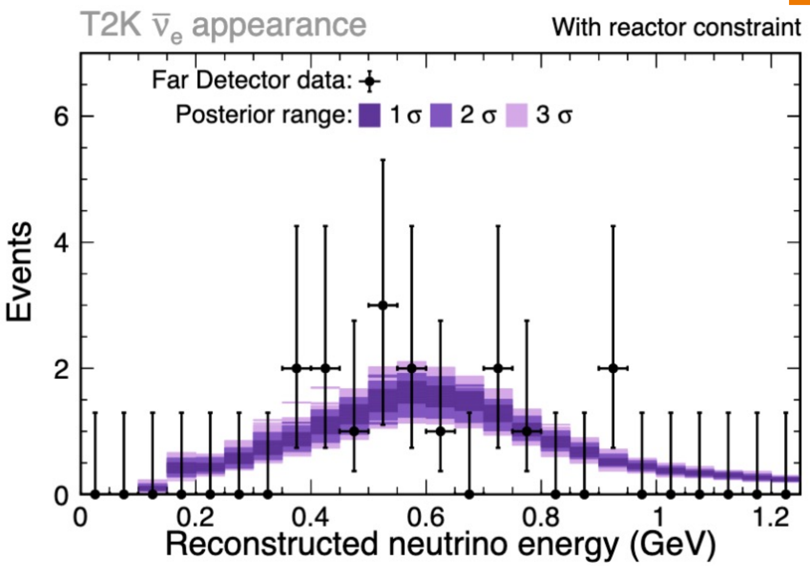
NOvA+T2K Disappearance Data samples:

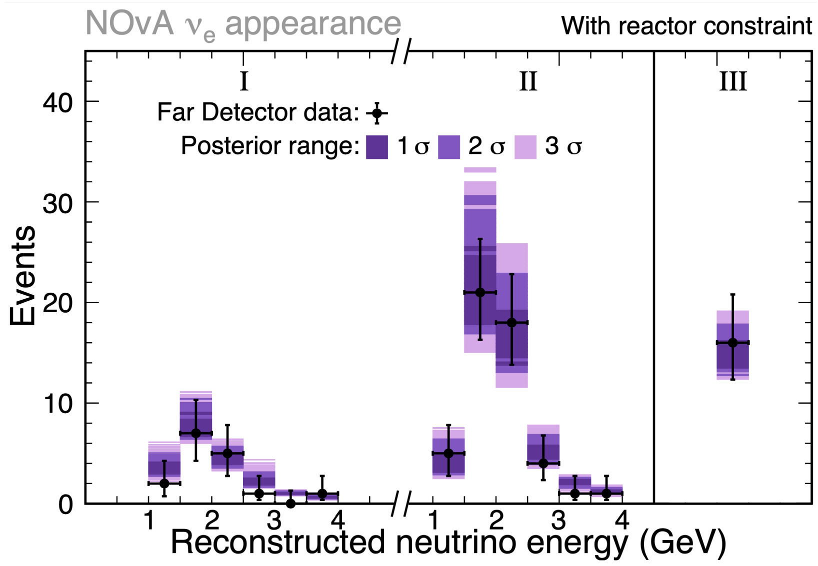


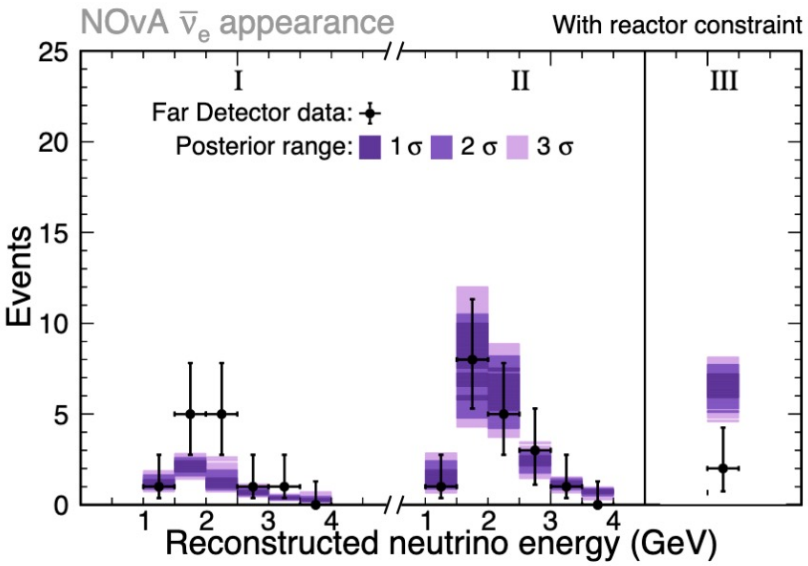
NOvA+T2K Appearance Data samples:





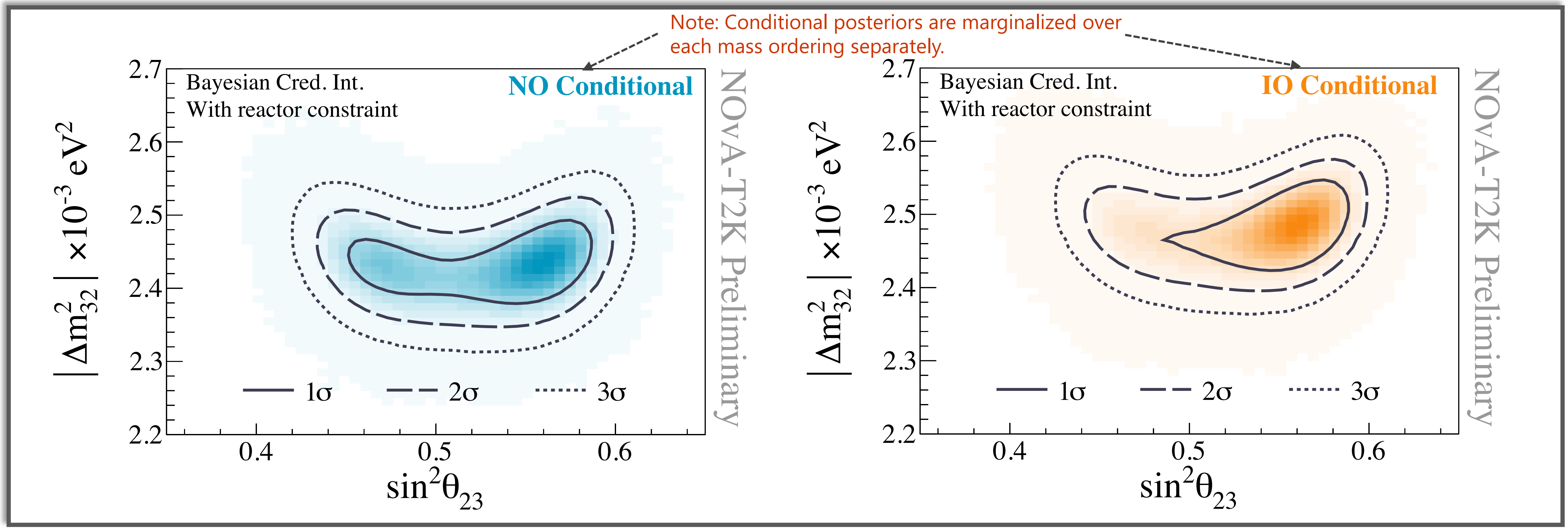






Δm^2_{32} and $\sin^2\theta_{23}$

- Marginalizing over each mass ordering, we note a small but distinct difference in the $\sin^2\theta_{23}$ and Δm^2_{32} phase space.
- Measurements remain consistent with the maximal mixing hypothesis for θ_{23} mixing angle.



CP Violation: Jarlskog

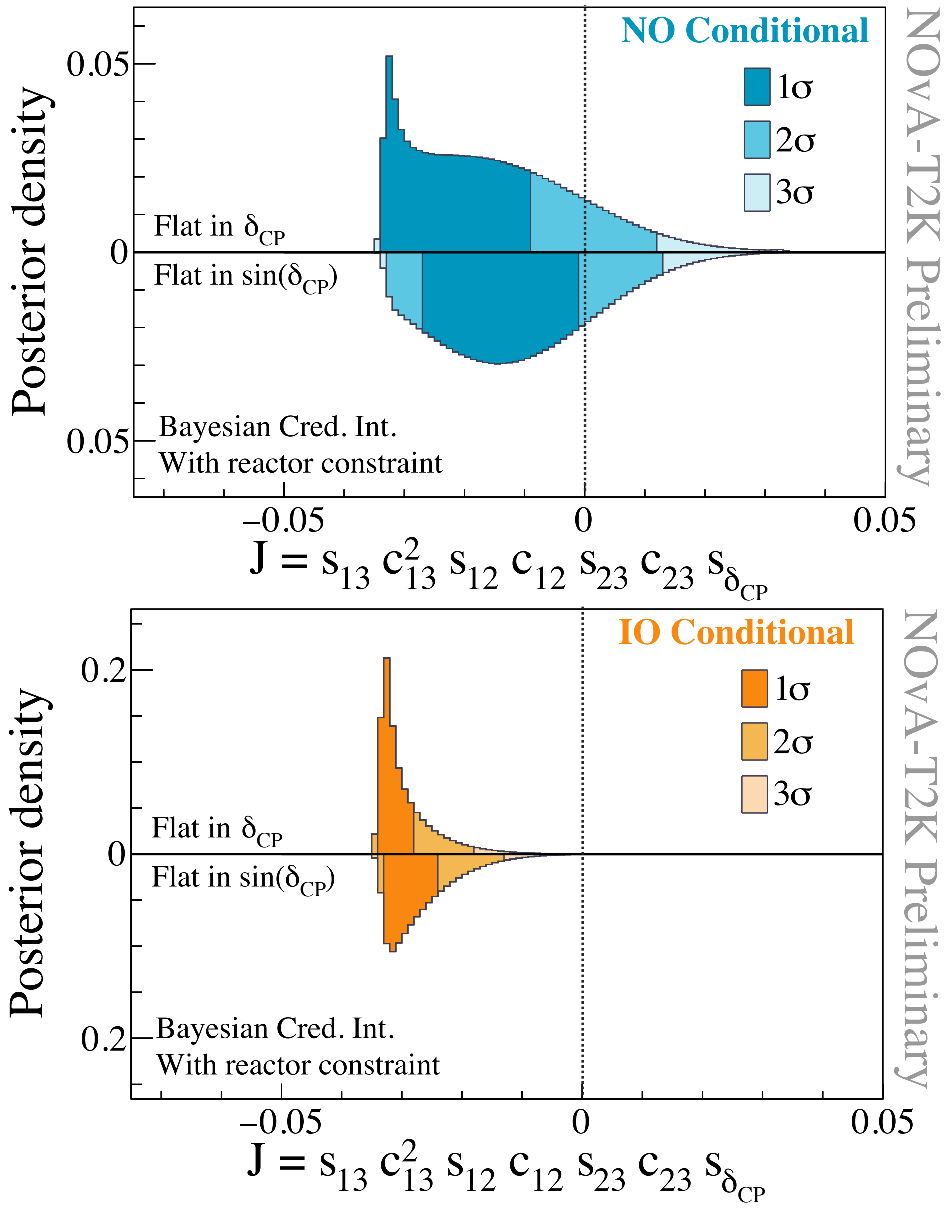
- Jarlskog-invariant is a parameterization independent way* to measure CP violation.

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

J=0: CP-Conservation J ≠ 0: CP-Violation

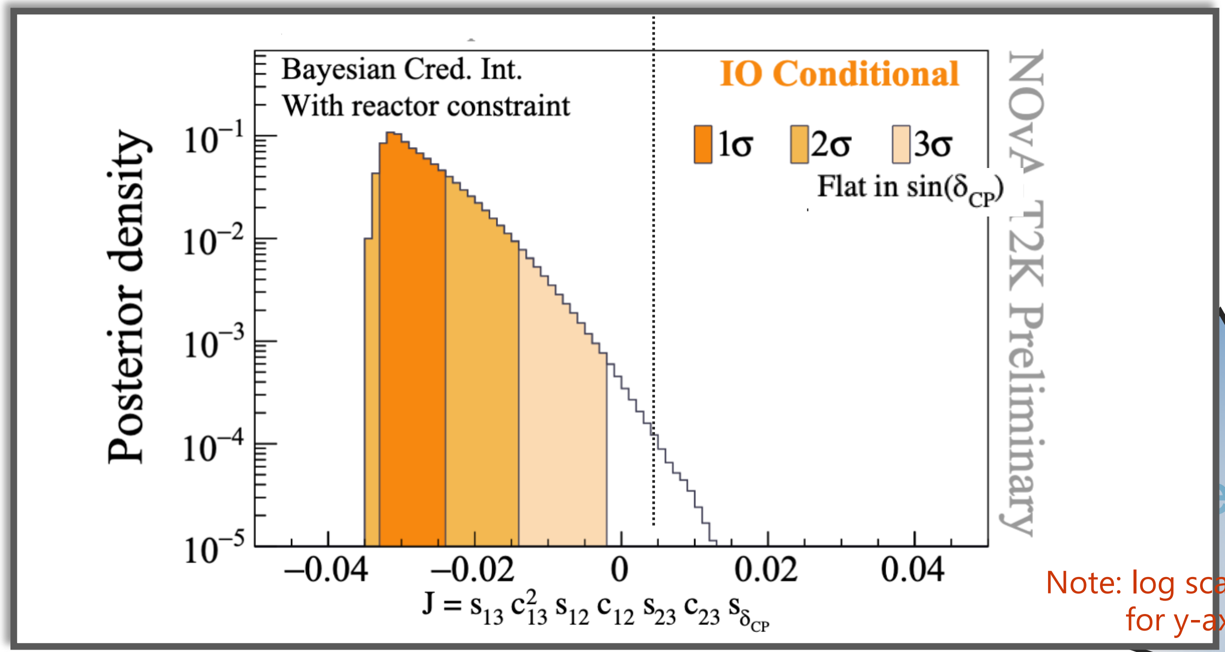
- For Normal Ordering, a considerably wider range of probable values for J
- J = 0 lies outside the 3σ interval for the Inverted Ordering
  - for priors that are both uniform in δ_{CP} and uniform in sin δ_{CP}

*Phys. Rev. D 100, 053004 (2019)



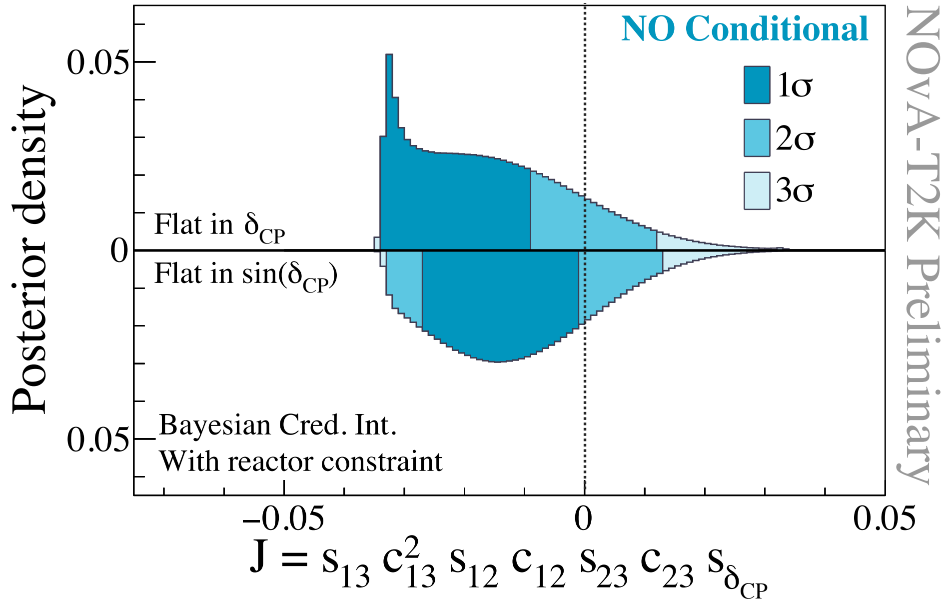
$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$s_{\delta_{CP}} = \sin\delta_{CP}$

CP Violation: Jarlskog

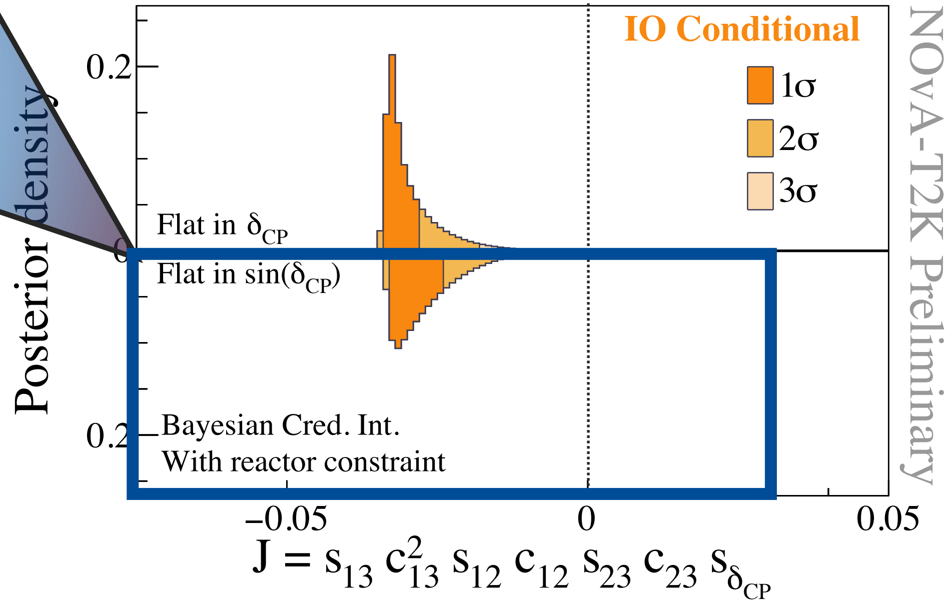


Note: log scale for y-axis

- J = 0 lies outside the 3σ interval for the Inverted Ordering
  - for priors that are both uniform in δ_{CP} and uniform in sin δ_{CP}



$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$s_{\delta_{CP}} = \sin\delta_{CP}$

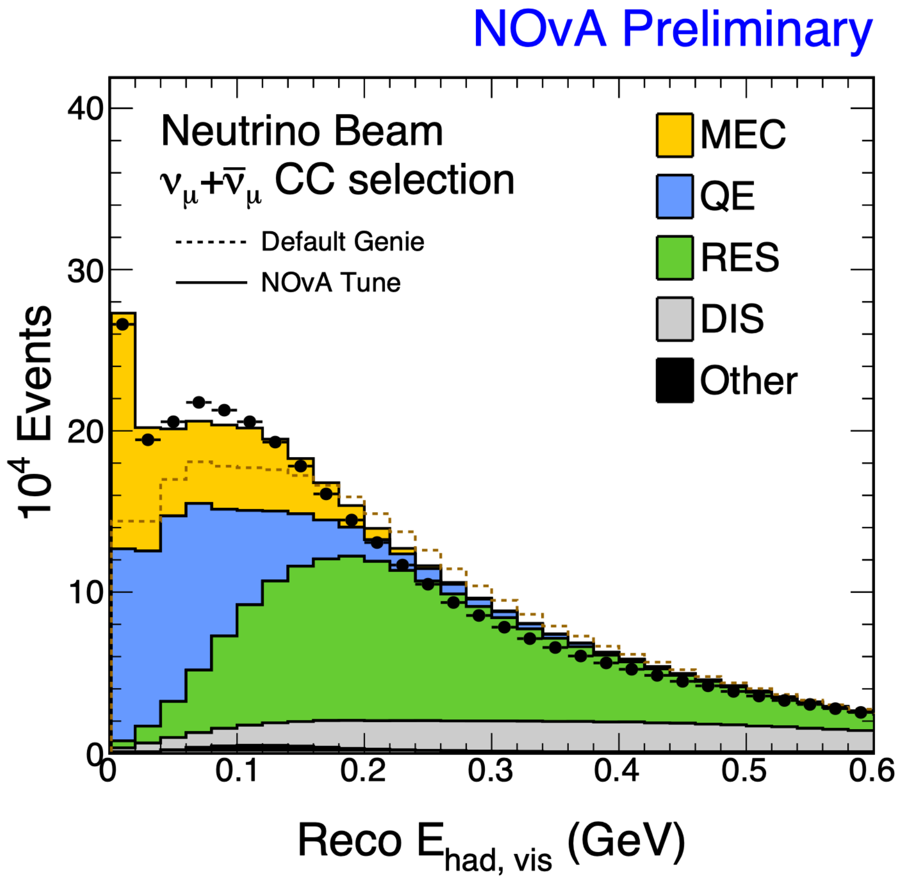


*Phys. Rev. D 100, 053004 (2019)

GENIE model

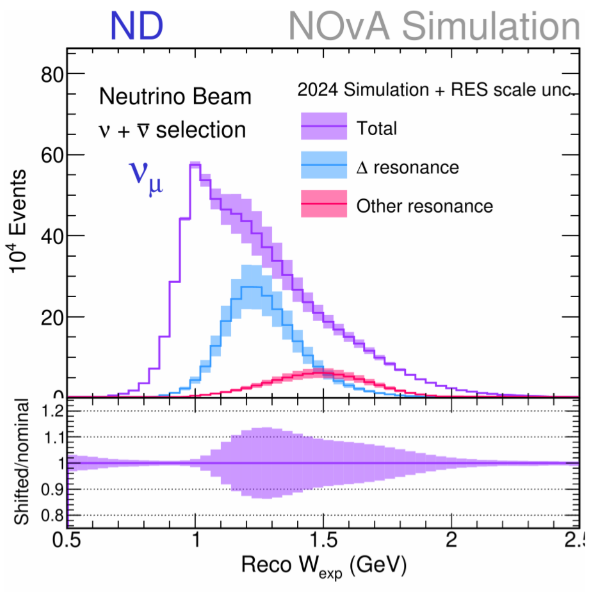
- The cross-section model is largely unchanged from previous analysis: GENIE 3.0.6 Custom configuration and tuned to external data and NOvA ND Data.

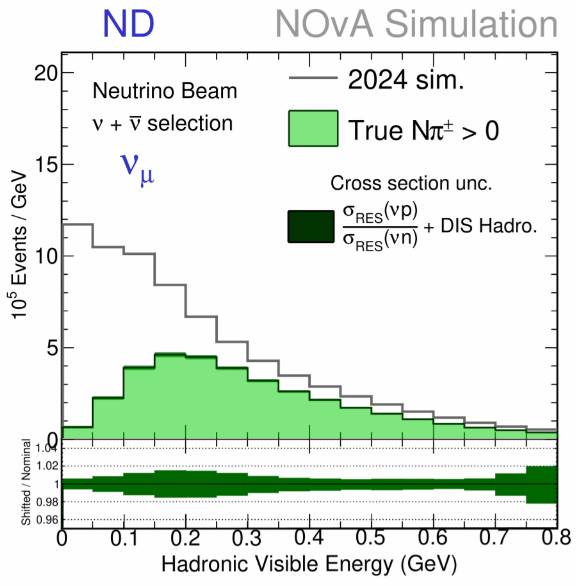
Neutrino - free nucleon interactions	
Quasi-Elastic (QE)	Valencia 1p1h Z-expansion axial form facror
Resonance (RES)	Berger-Sehgal
Deep inelastic Scattering (DIS)	Bodek-Yang
Multinucleon interactions	
Meson exchange current (MEC)	Valencia MEC custom adjustment to NOvA data for 2p2h
Interactions with the nuclear environment	
Final State Interactions (FSI)	hN Semi Classical Cascade Custom fit to external pion scattering data.

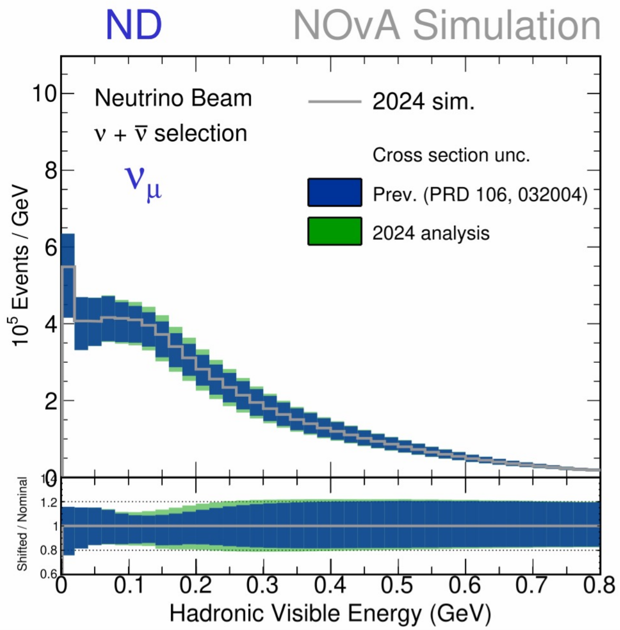


New Pion Production Uncertainties

- Relative strength of Δ vs non-Δ resonant production (1 uncertainty)
  → Shift Δ and non-Δ resonances ±20% independently
  - Default GENIE: all resonances affected together
  - Overcounts Δ-specific uncertainty somewhat with other GENIE knobs, but "conservative"
- Charged vs. neutral hadron production in RES, DIS (2 uncertainties)
  - Shift ratio of RES Δ-channel proton/neutron final states by ±5%
  - Shift composition of proton/neutron final states in DIS
- Moderate impacts on pion-rich subsamples, but overall effect on uncertainty budget is minor

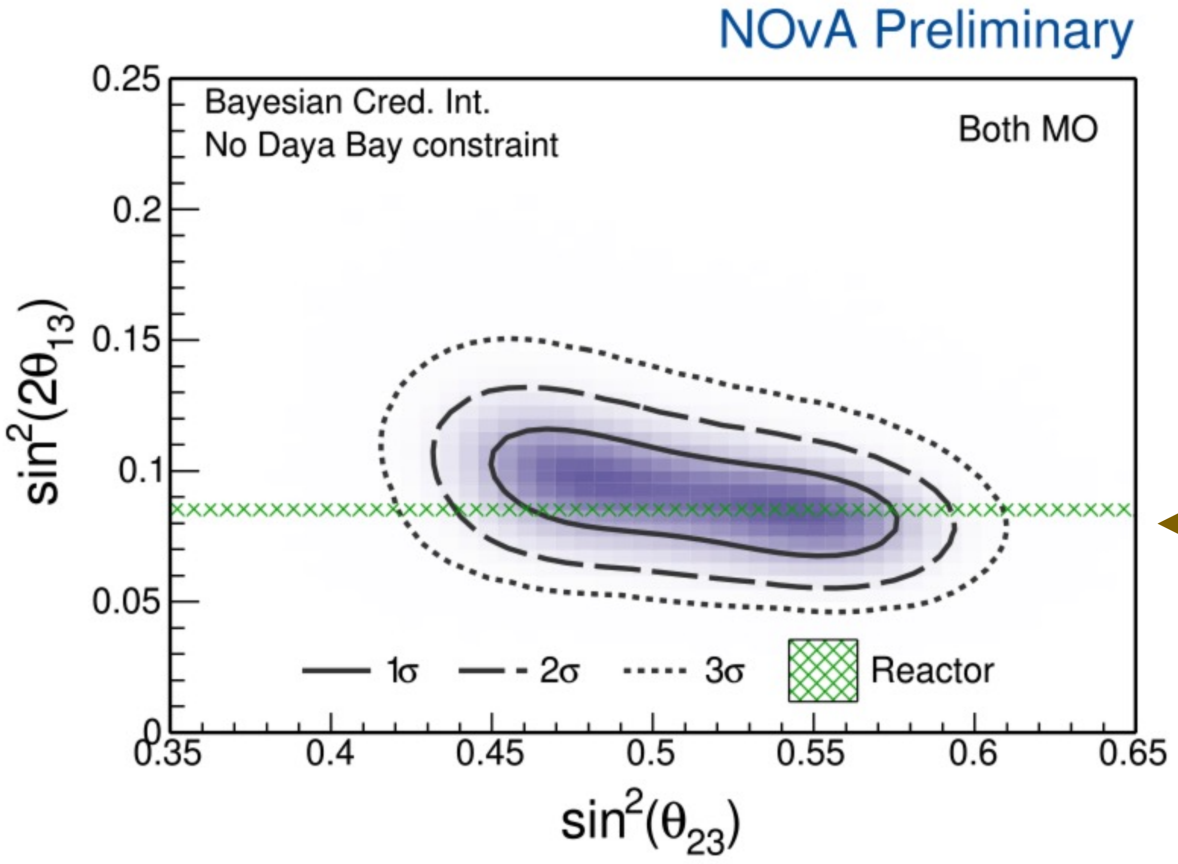






Mixing Angles

- Without any external constraint from reactor experiments, there's a degeneracy between $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$

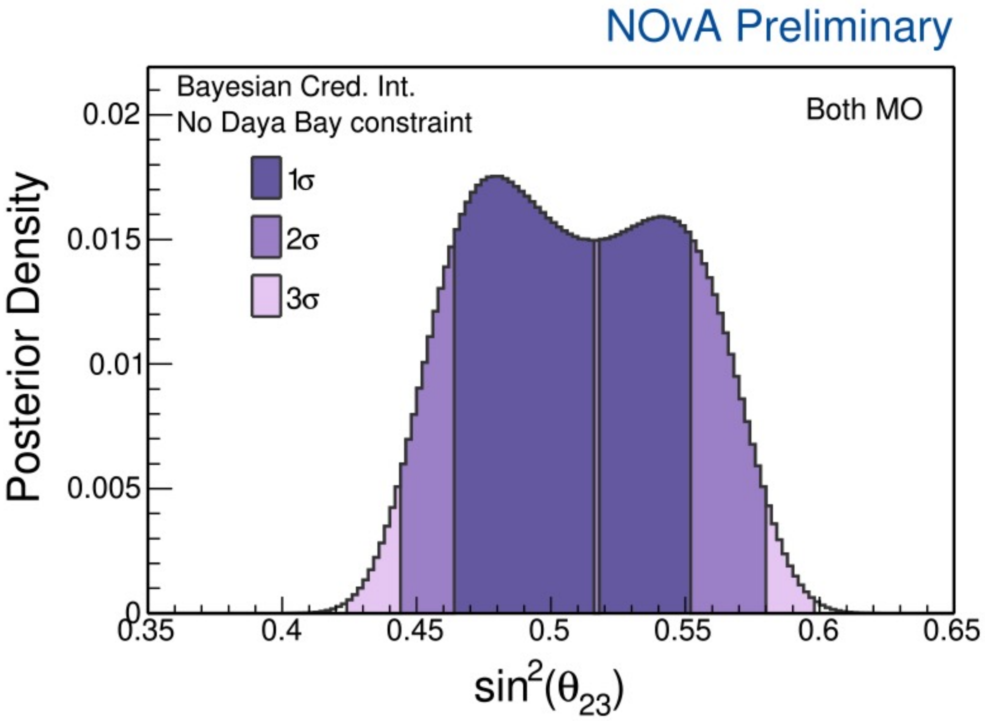


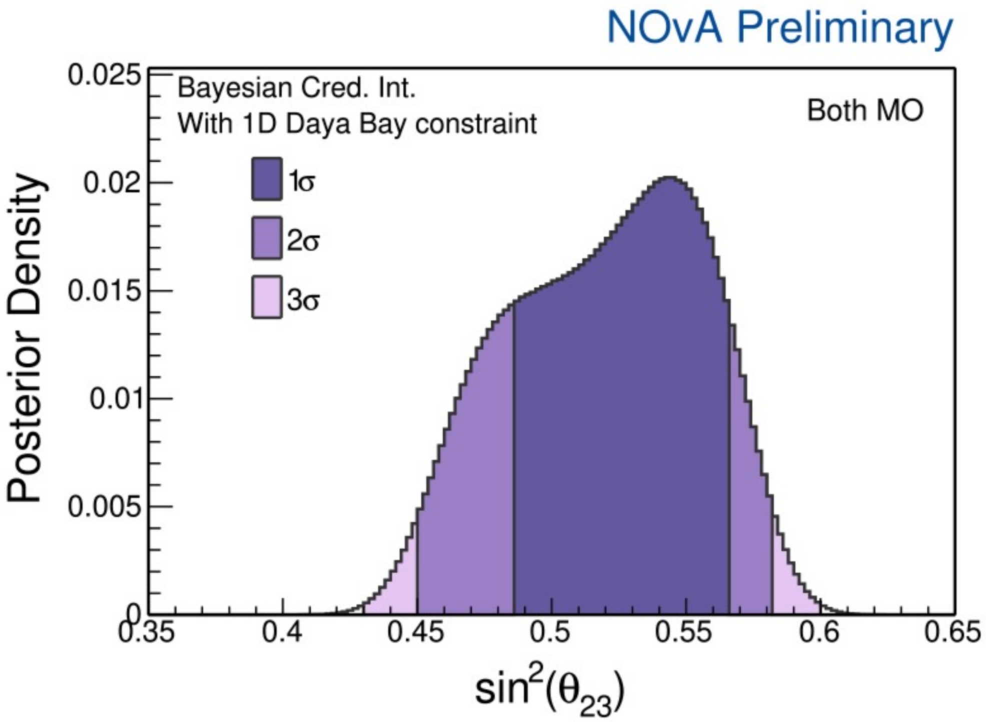
θ_{13} unconstrained (NOvA only)

Daya Bay 1D θ_{13} constraint
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

Mixing angle: $\sin^2\theta_{23}$

- The NOvA results show a mild preference for the upper octant that emerges from applying the reactor constraint. Maximal mixing is allowed at <1 σ





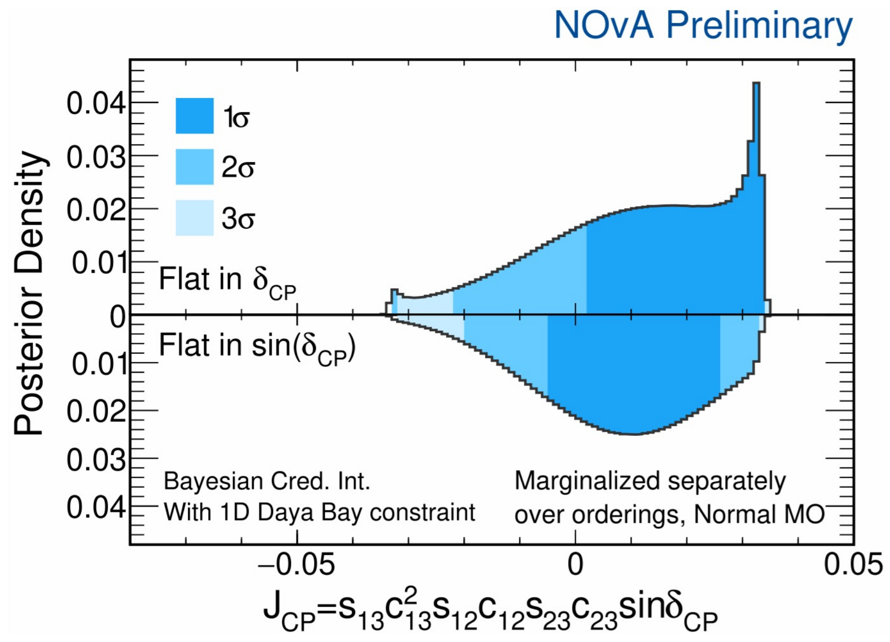
	No constraint		Daya Bay 2023 1Dθ_{13}	
	Probability	Bayes Factor	Probability	Bayes Factor
Upper Octant preference	57%	1.3	69%	2.2

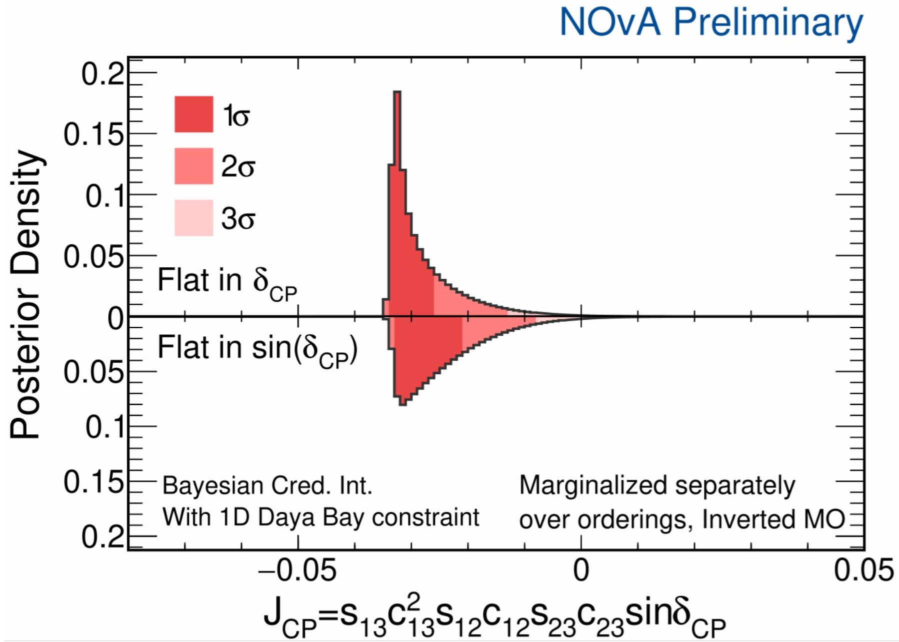
Jarlskog Invariant

- Jarlskog-invariant is a parameterization independent way to measure CP violation.

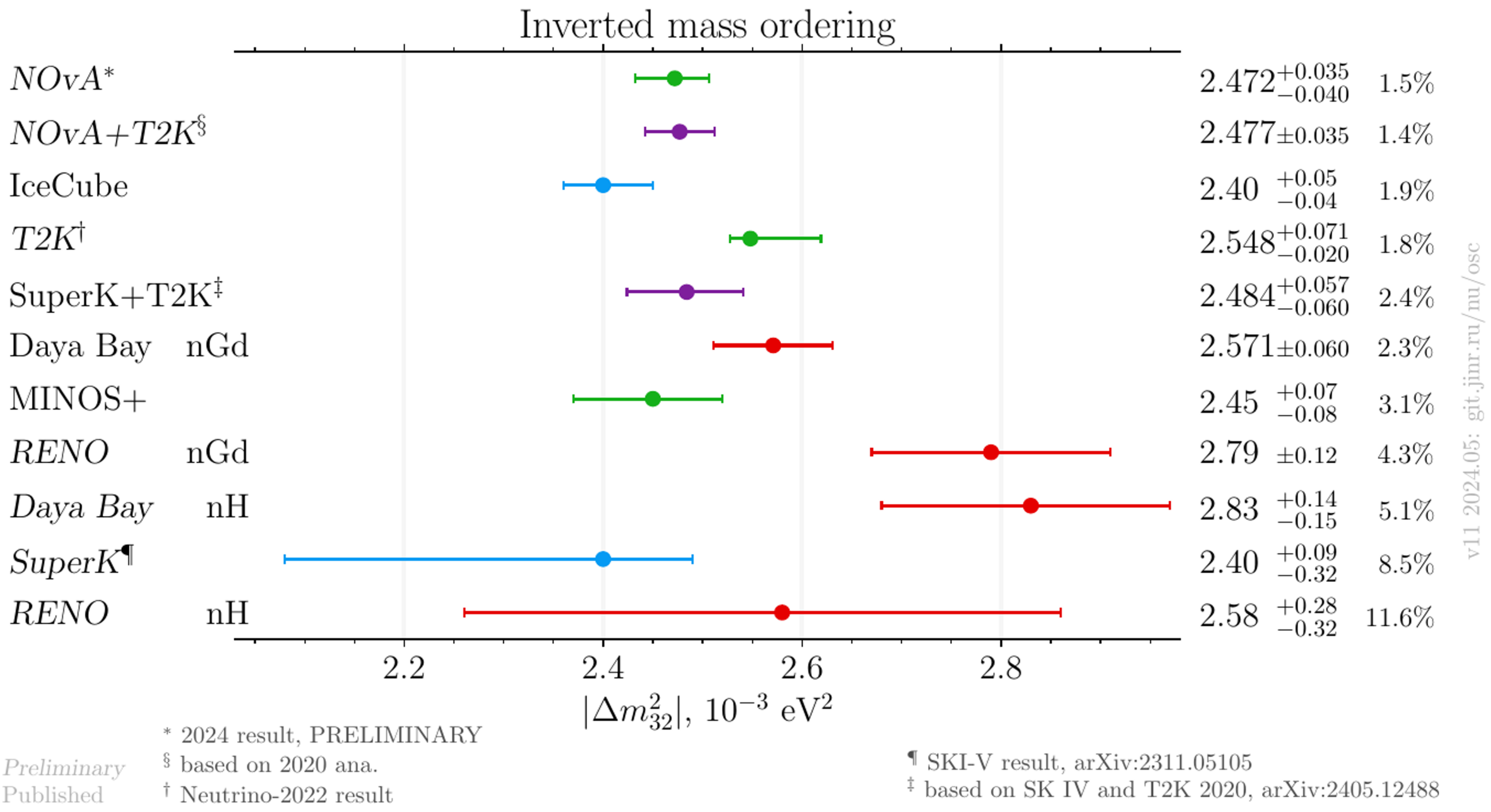
  J=0: CP-Conservation J ≠ 0: CP-Violation

- For Normal Ordering, wide range of probable values for J. Fully compatible with J=0.
- In Inverted Ordering, J=0 is in tension w/ posterior, but only "uniform in δ_{CP}" prior has J=0 outside 3σ interval.





Precision on Δm^2_{32}



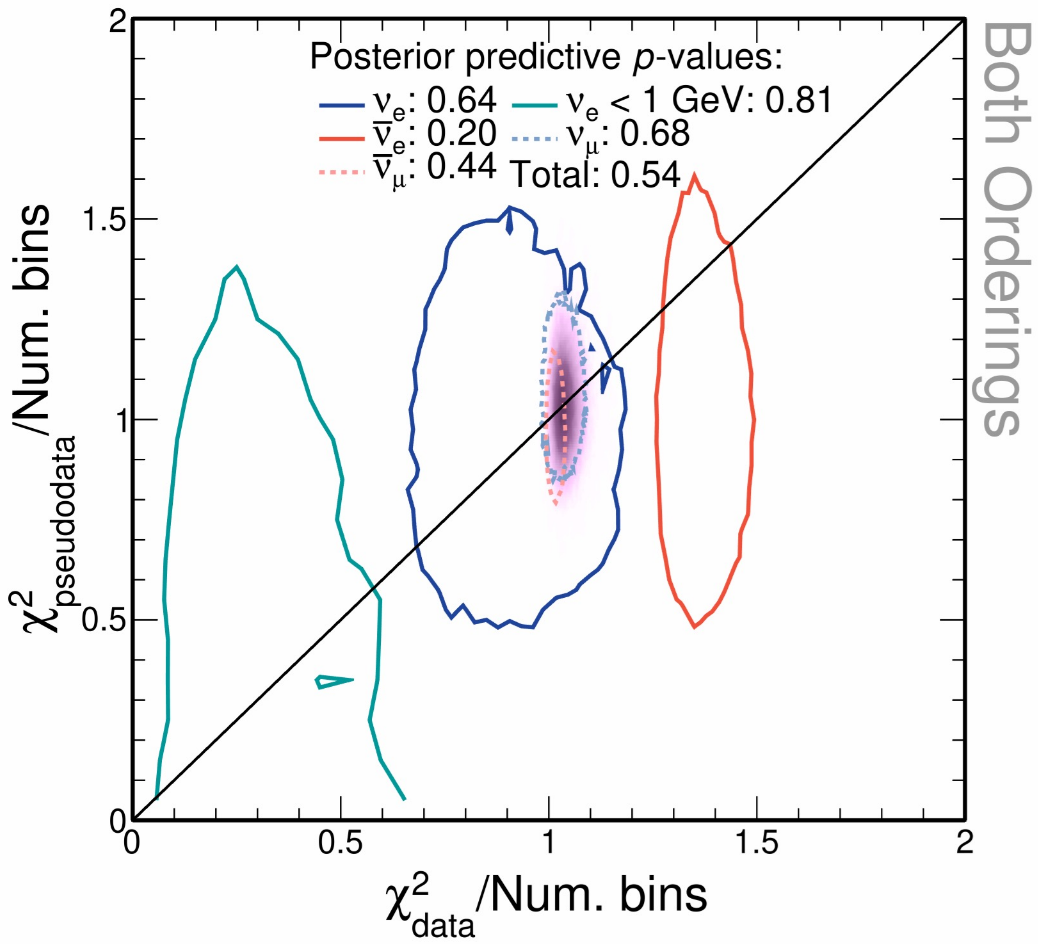
Goodness of fit

Bayesian posterior predictive *p*-values

Asymptotic expectation is *p* = 0.5

Deviations from 0.5 can indicate insufficient or excessive model freedom can push higher or lower

Large fluctuations can also push away from 0.5 (as in lowE ν_e, $\bar{\nu}_e$ samples here)



NOvA numerical results

Bayesian results	NOvA only		Daya Bay 1D		Daya Bay 2D	
	Prob.	BF	Prob.	BF	Prob.	BF
$\theta_{23} > 0.5$ preference	57%	1.3	69%	2.2	67%	2.0
N.O. preference	69%	2.2	76%	3.2	87%	6.8

Frequentist results (w/ Daya Bay 1D θ_{13} constraint)	N.O.	I.O.
Δm^2_{32} / 10^{-3} eV^2	$+2.433^{+0.035}_{-0.036}$	$-2.473^{+0.035}_{-0.035}$
$\sin^2\theta_{23}$	$0.546^{+0.032}_{-0.075}$	$0.539^{+0.028}_{-0.075}$
δ_{CP} / π	0.88	1.51
Rejection significance (σ)	—	1.36