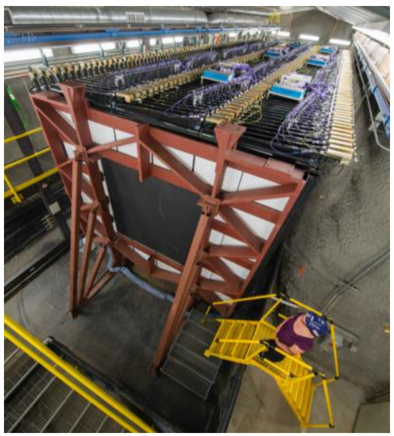
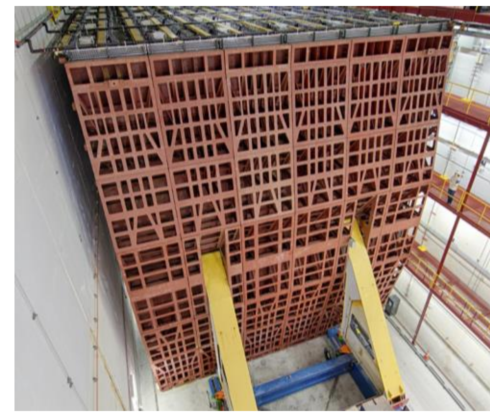
Latest NOvA 3-Flavor Neutrino Oscillation Results



Jozef Trokan-Tenorio
On Behalf of the NOvA Collaboration

NuFact 2024
Working Group 1
September 16th, 2024



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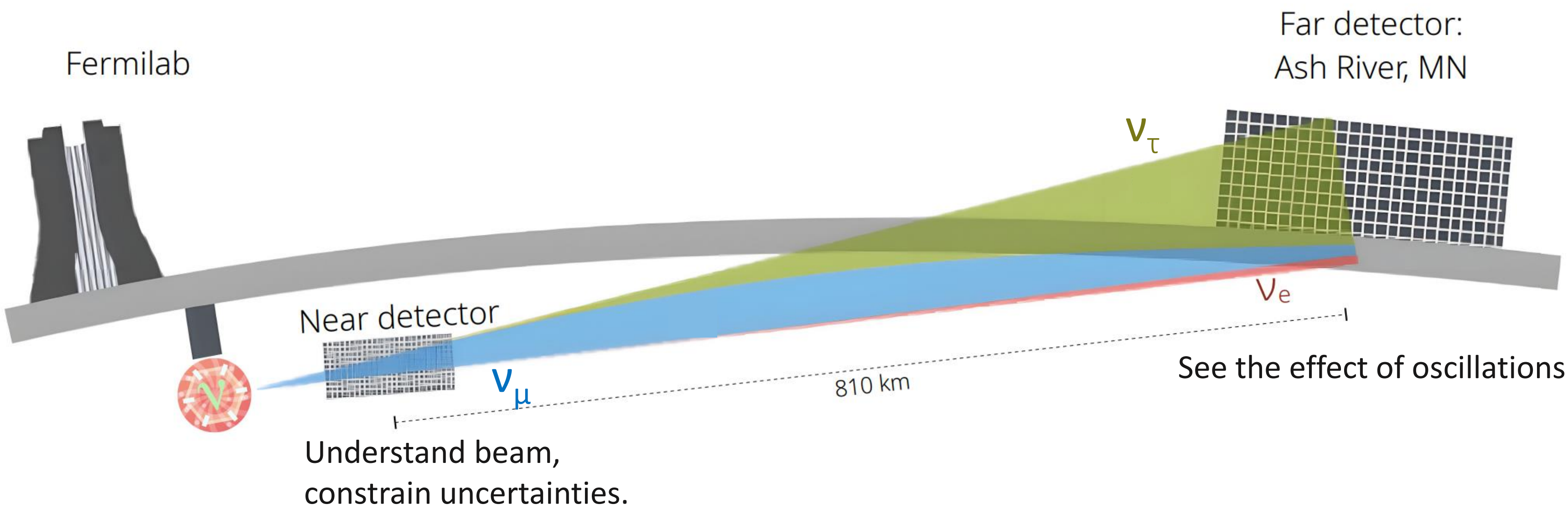
The NOvA Experiment



NuMI Off-axis ν_e Appearance Experiment (NOvA)

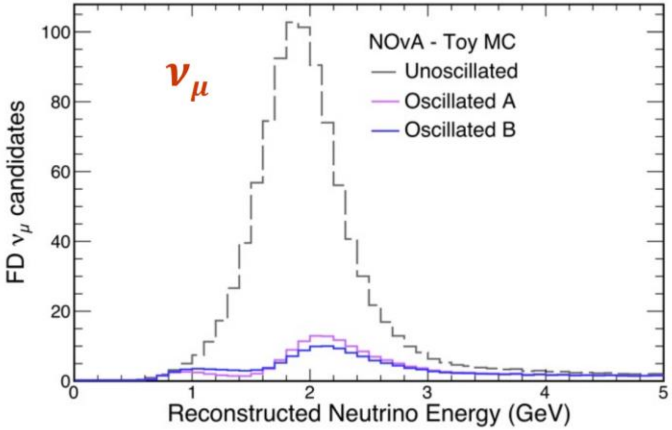
Primary Goals:

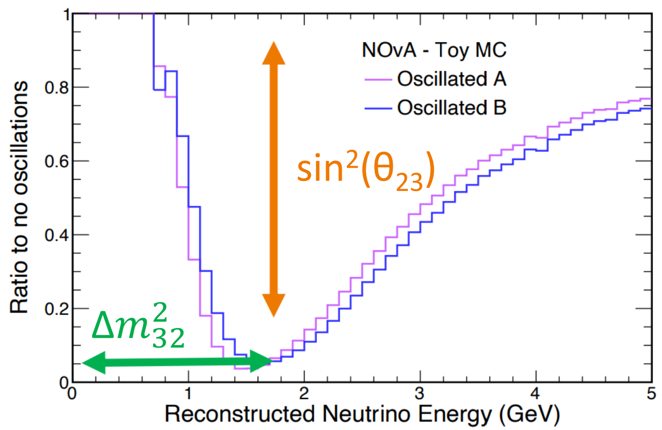
ν_μ Disappearance
- Measure $|\Delta m^2_{32}|$
- Measure θ_{23}

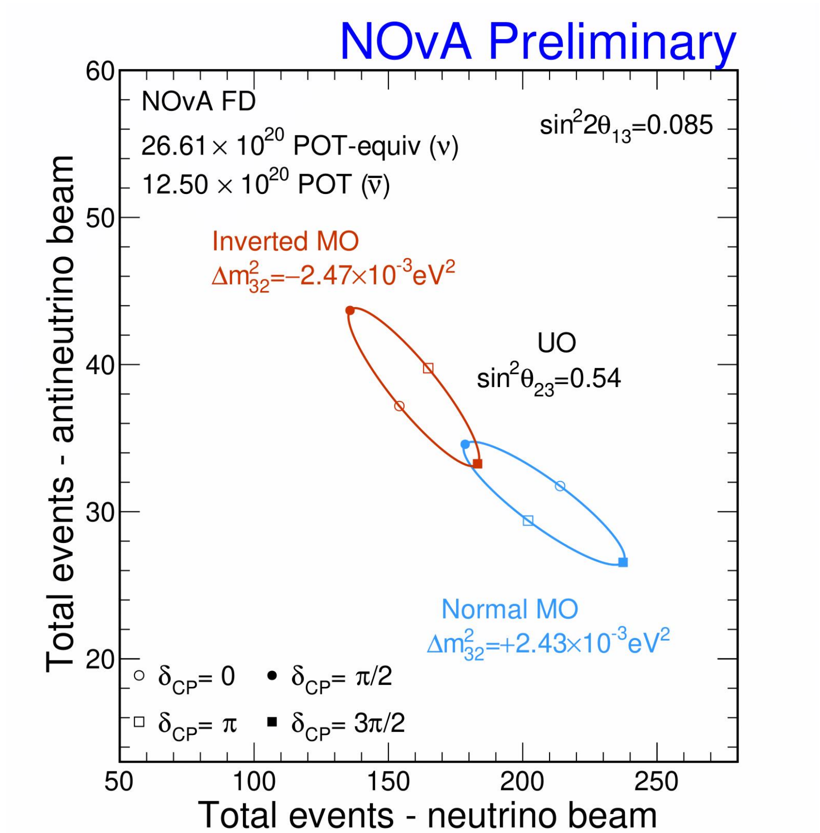
ν_e Appearance
- Resolve Mass Ordering
- Resolve CP Violation
- θ_{23} octant

How We Measure Oscillation Parameters

- The shape of the muon neutrino energy spectrum in the FD tells us about the ν2-ν3 parameters
- Asymmetry in the rate of electron neutrinos vs antineutrinos tells us about mass ordering and $\boldsymbol{\delta_{CP}}$
- The mass ordering and value of $\boldsymbol{\delta_{CP}}$ will serve to either enhance neutrinos and suppress antineutrinos, or vice versa. The effects can add up or cancel each other out.

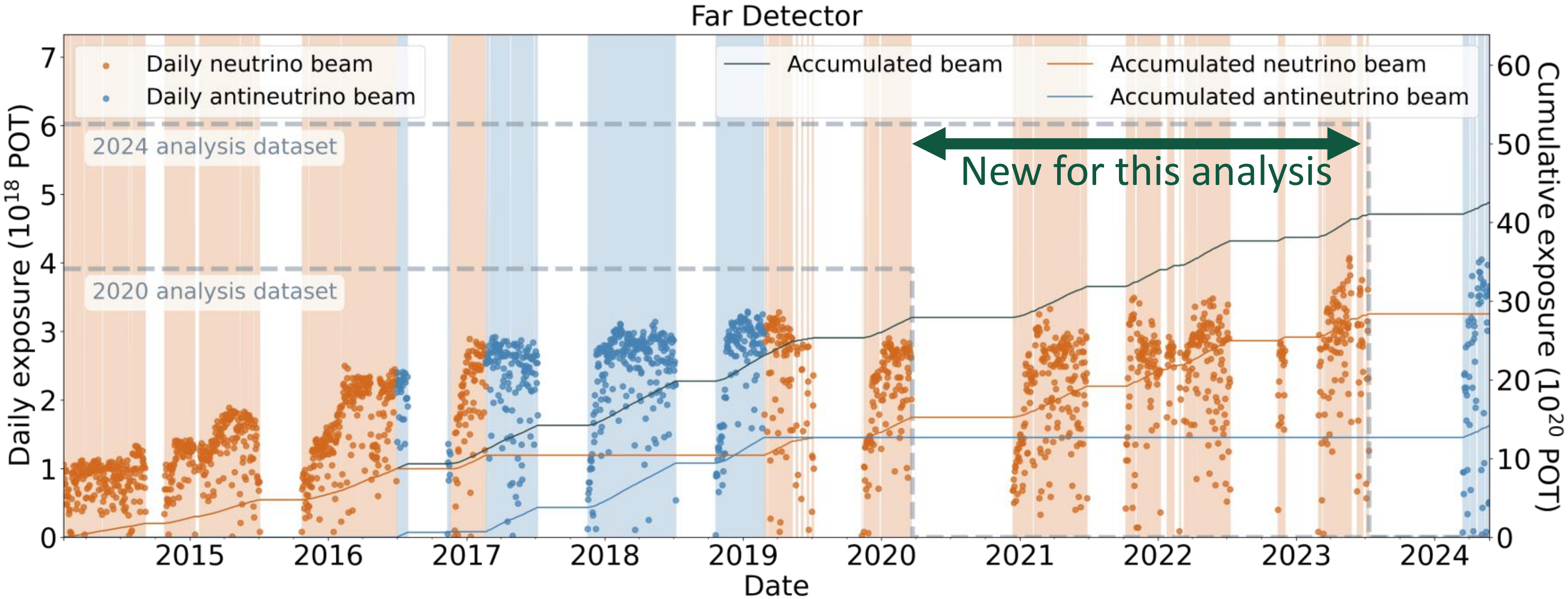






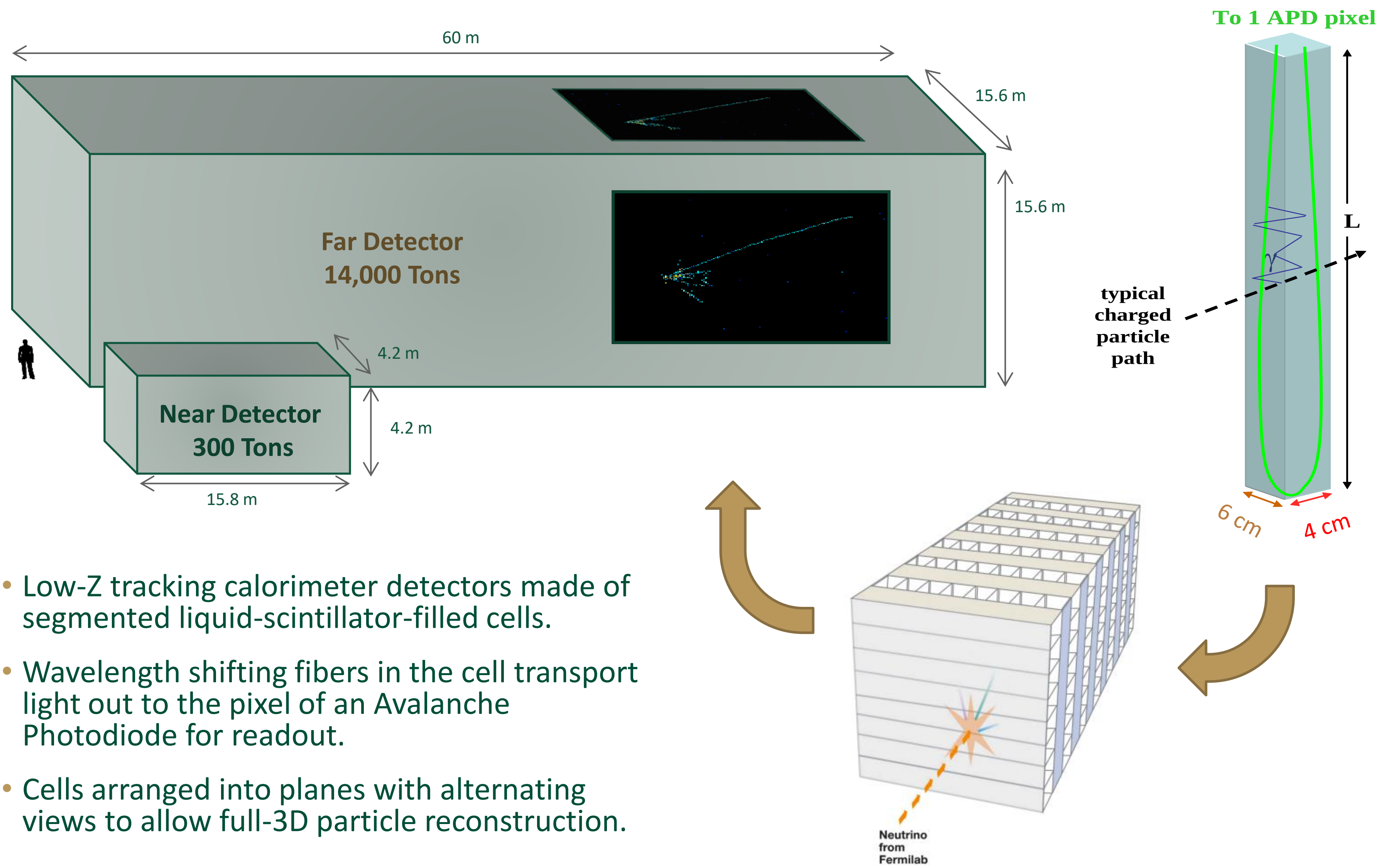
The NuMI Beam

- Fermilab's NuMI beam is a horn-focused neutrino beam, with the NOvA detectors situated 14 mrad off-axis to provide a narrow-band beam with energy peaked at 2GeV
- 26.61×10^{20} POT neutrino mode (doubled from previous analysis in 2020)
- 12.50×10^{20} POT antineutrino mode
- Typical beam power of ~900kw
- New beam power record of 1.018 MW in June 2024



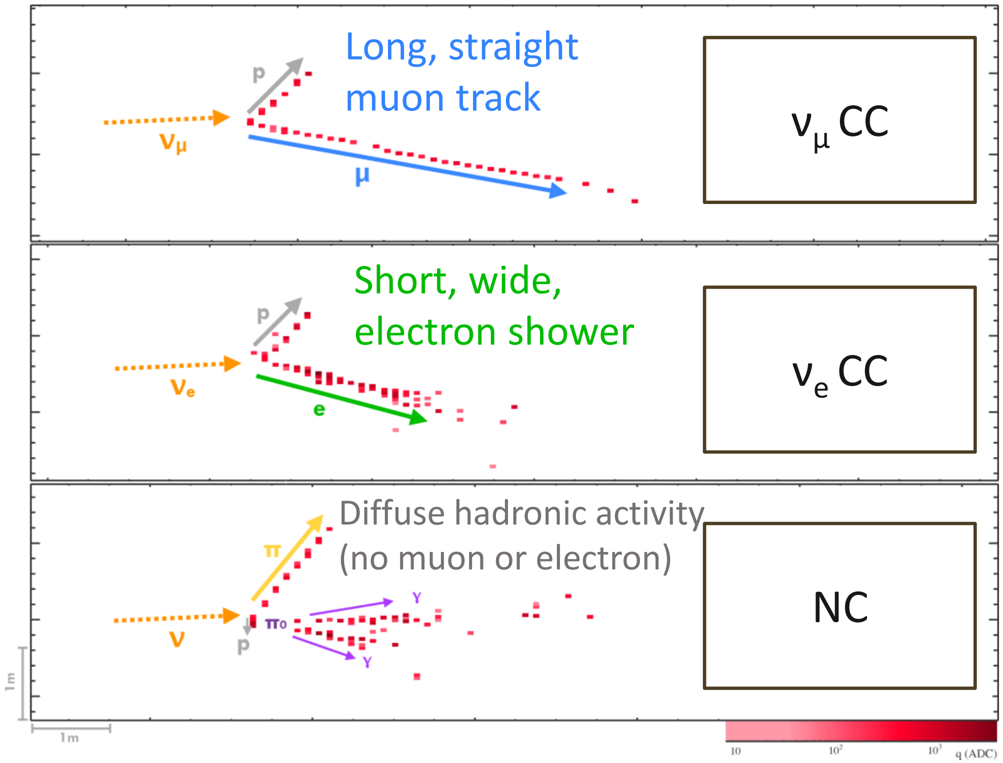
These results comprise 10 Years of NOvA data (2014 -2023)!

The NOvA Detectors



- Low-Z tracking calorimeter detectors made of segmented liquid-scintillator-filled cells.
- Wavelength shifting fibers in the cell transport light out to the pixel of an Avalanche Photodiode for readout.
- Cells arranged into planes with alternating views to allow full-3D particle reconstruction.

Event Topologies For Selection & Energy Estimation



E_μ ~4% Resolution

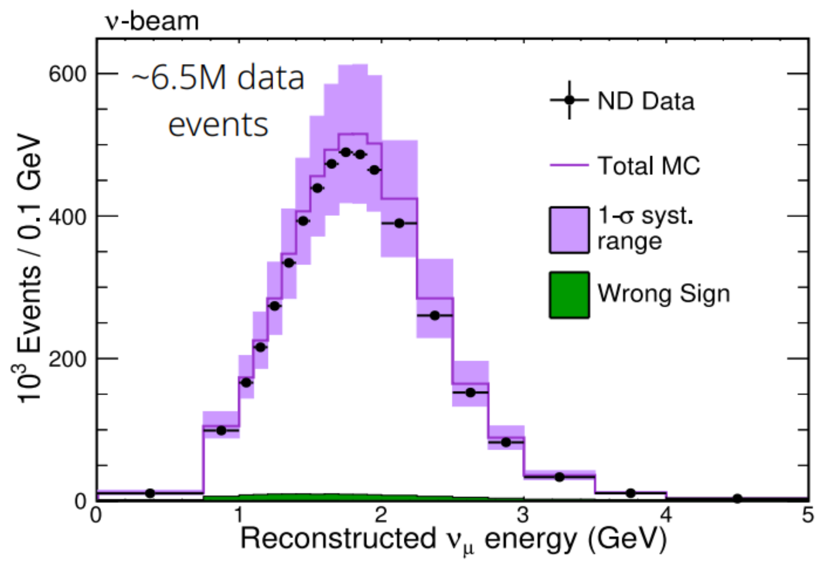
E_{EM}~10% Resolution

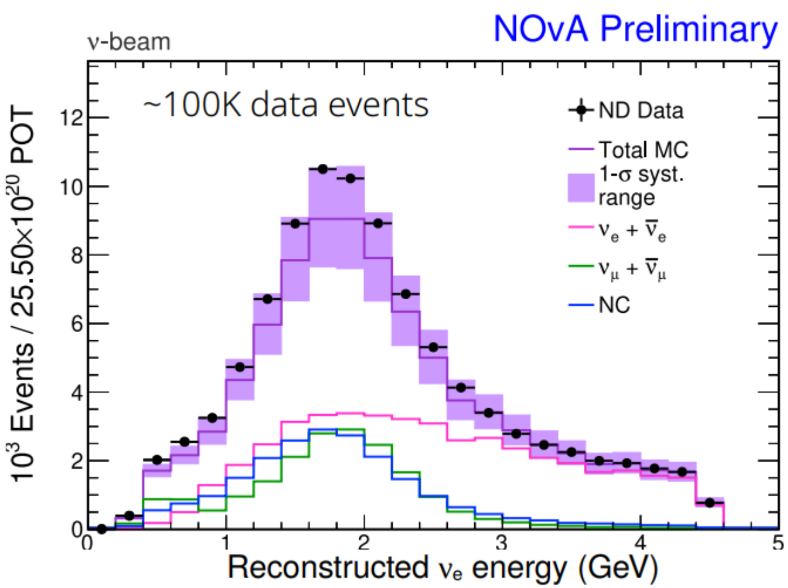
E_{Had} ~30% Resolution

- Convolutional Neural Networks (CNNs) are used for interaction flavor identification, particle ID, and cosmic rejection. (JINST 11 (2016) P09001).
- Energy estimation is done via tracking for muons, and calorimetry for electromagnetic and hadronic components.

Near Detector Events

- Using this process, we select millions of ν_μ , and thousands of ν_e candidate events in our near detector.
- With such a large dataset we can understand these unoscillated events well, make corrections, and use them to improve predictions of our far detector events.

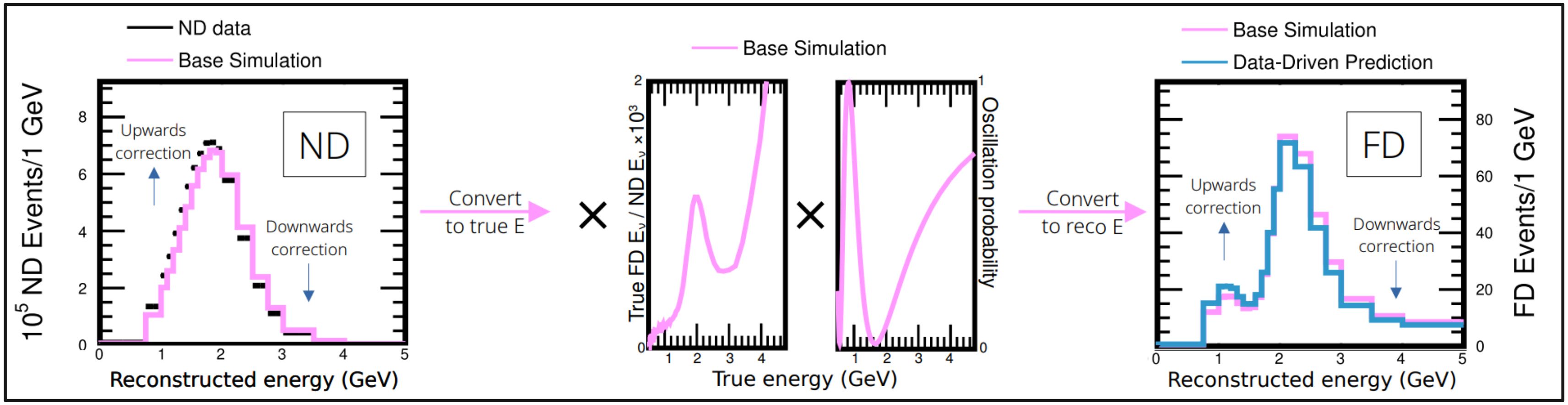




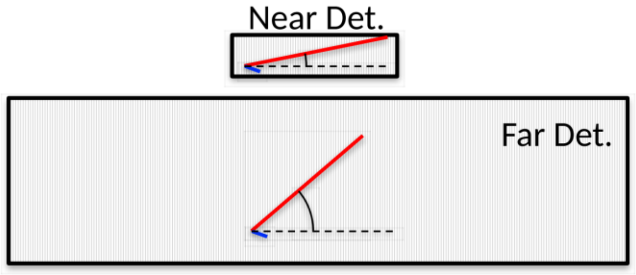
<u>Near Detector ν_μ Candidates</u>
Used for constraining ν_e and ν_μ signal events in the FD

<u>Near Detector ν_e Candidates</u>
Used for constraining ν_e background in the FD

Making Far Detector Predictions

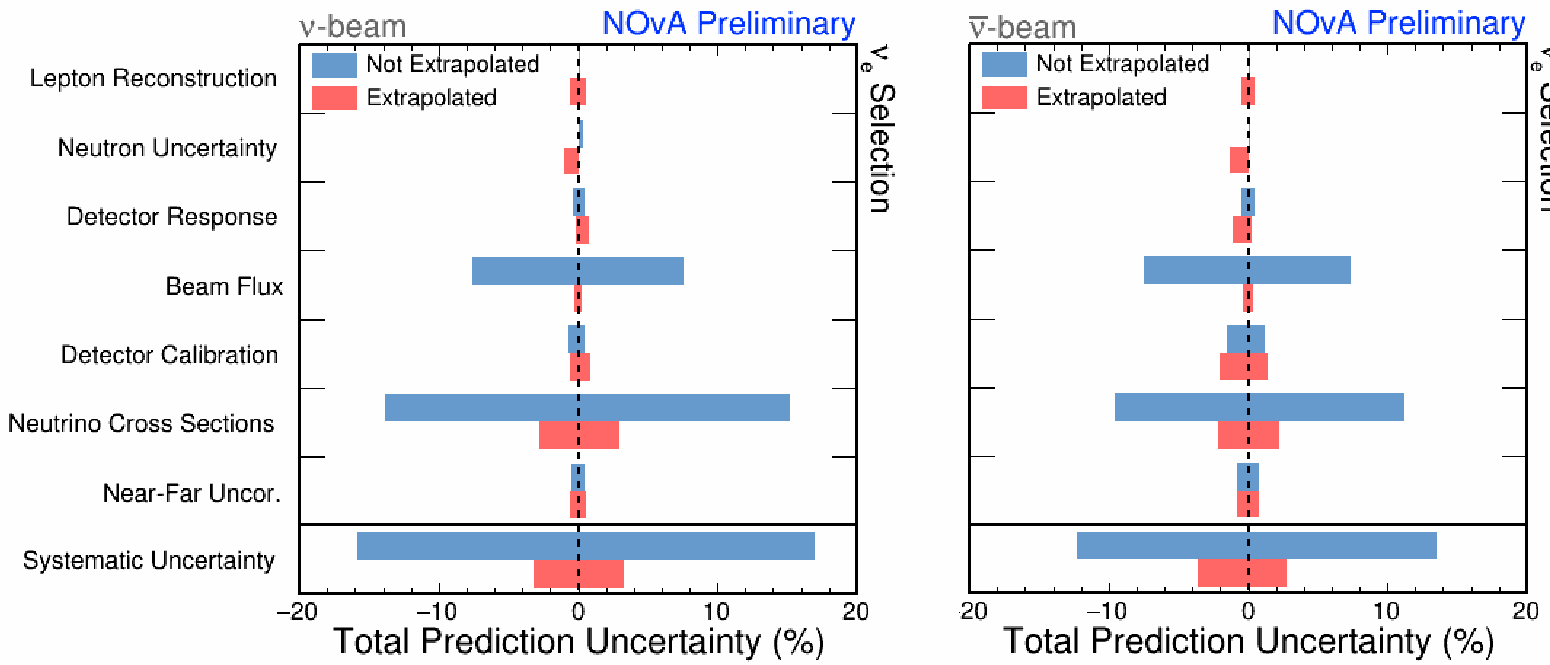


- We use the far-to-near ratio as well as Near Detector Data/MC ratios to correct the Far Detector predictions.
- This accounts for well-understood effects like beam divergence, and detector acceptance differences.
- We then apply the effects of oscillations.
- The resulting constrained FD predictions are highly correlated with the ND corrections.



Extrapolation Reduces Systematic Uncertainty

The result is a significant reduction in systematic uncertainties, particularly ones that are correlated between detectors such as flux and cross-section (due to the detectors being functionally similar).



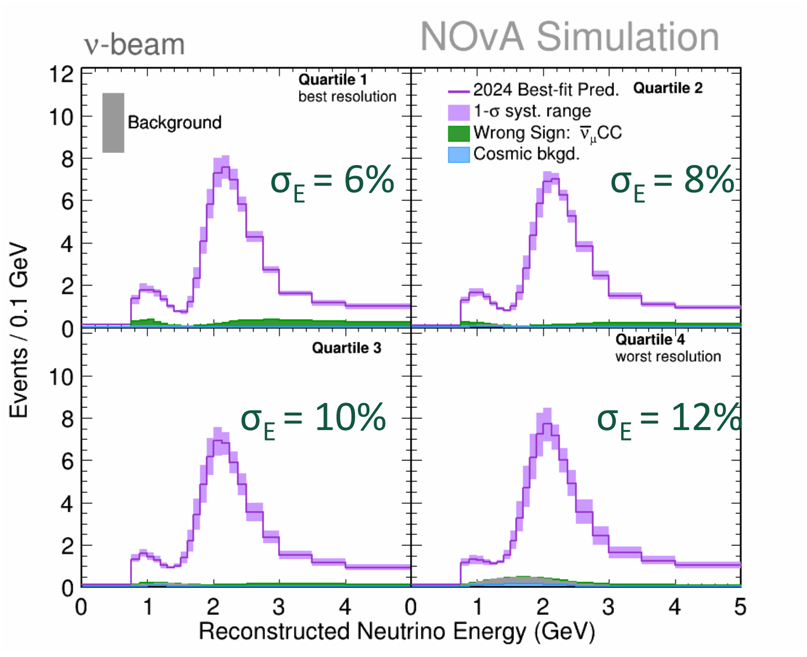
ν_e Prediction $\bar{\nu}_e$ Prediction

Total Systematic Uncertainty Drops ~18% → ~4%

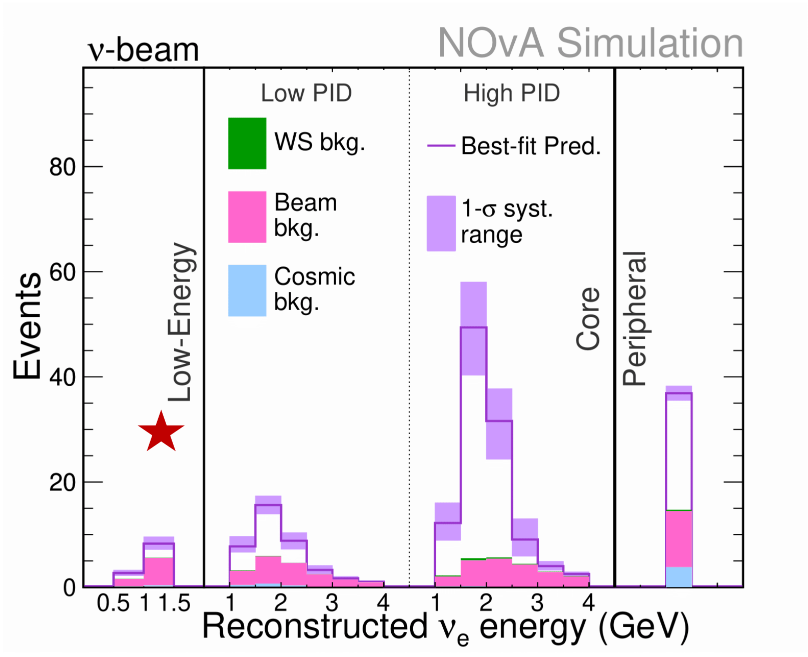
Binning To Improve Sensitivity

- Bin ν_μ events in 4 quartiles of increasing hadronic energy fraction (proxy for energy resolution).
- Bin ν_e events by purity, with additional peripheral and low-energy samples.

Binning ν_μ by Hadronic Energy Fraction



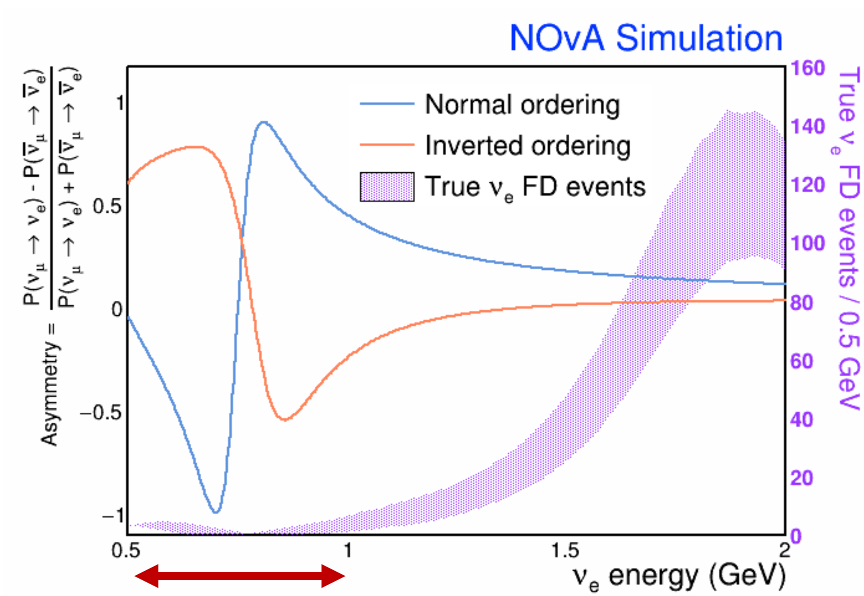
Binning ν_e by Purity



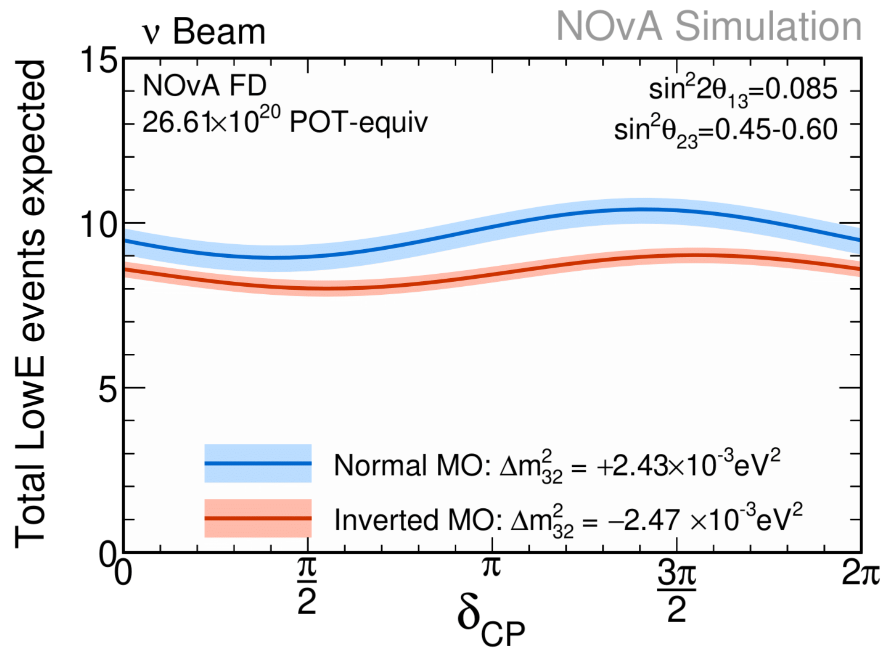
New for this analysis!

New Low-Energy ν_e Sample

LowE is neutrino-mode only for this analysis

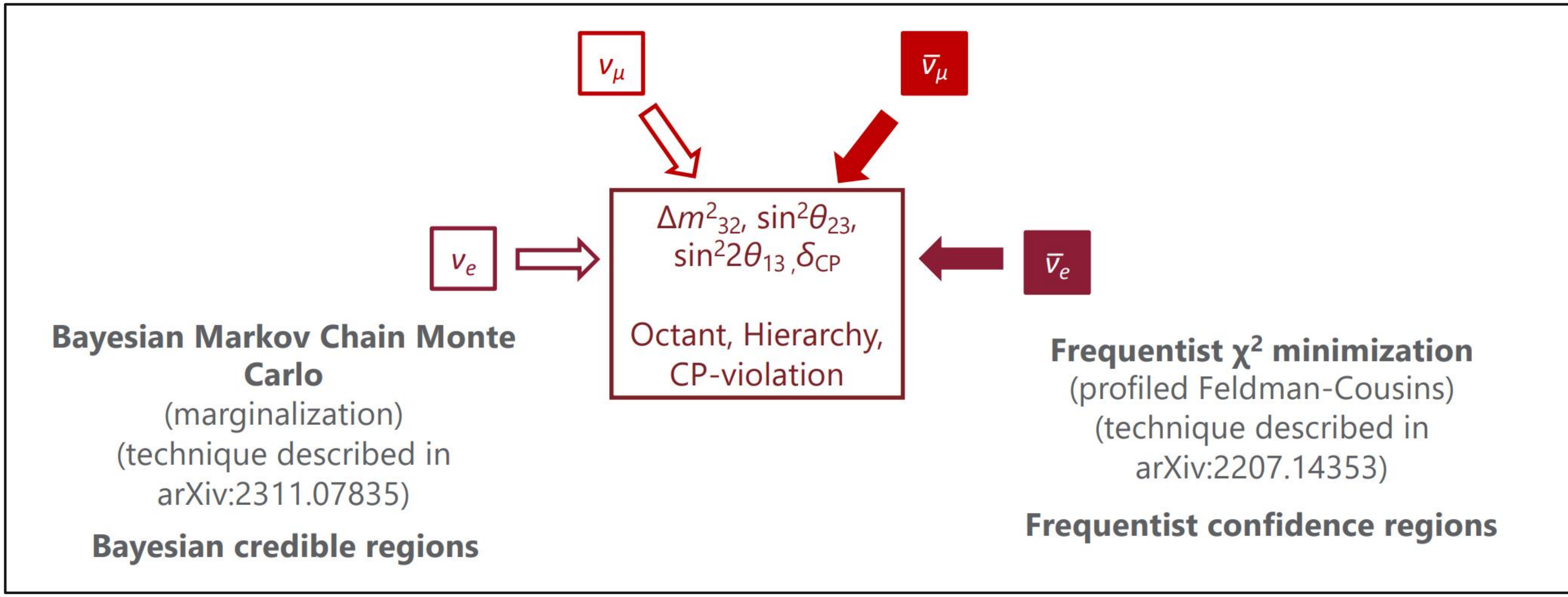


Energy region excluded in previous analysis



- We have developed a new selection to retain low-energy ν_e events.
- High asymmetry in ν_e / $\bar{\nu}_e$ appearance at lower energies can improve our mass ordering sensitivity by a few % depending on oscillation parameters.

Two Ways to Analyze our Data



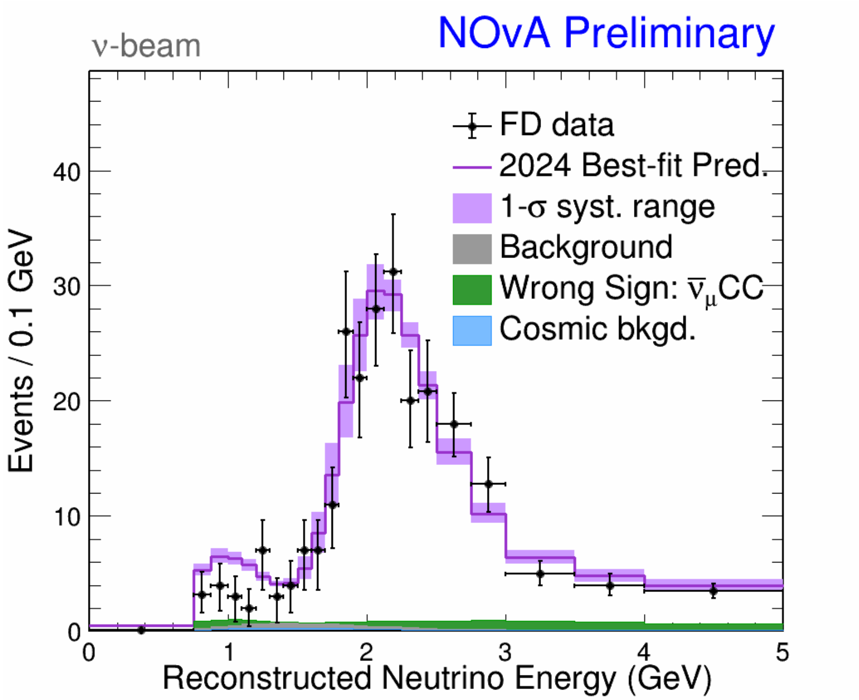
- We fit all our samples simultaneously, using either Bayesian or Frequentist techniques.
- We use external constraints on the solar oscillation parameters and consider optional reactor constraints on θ_{13}.

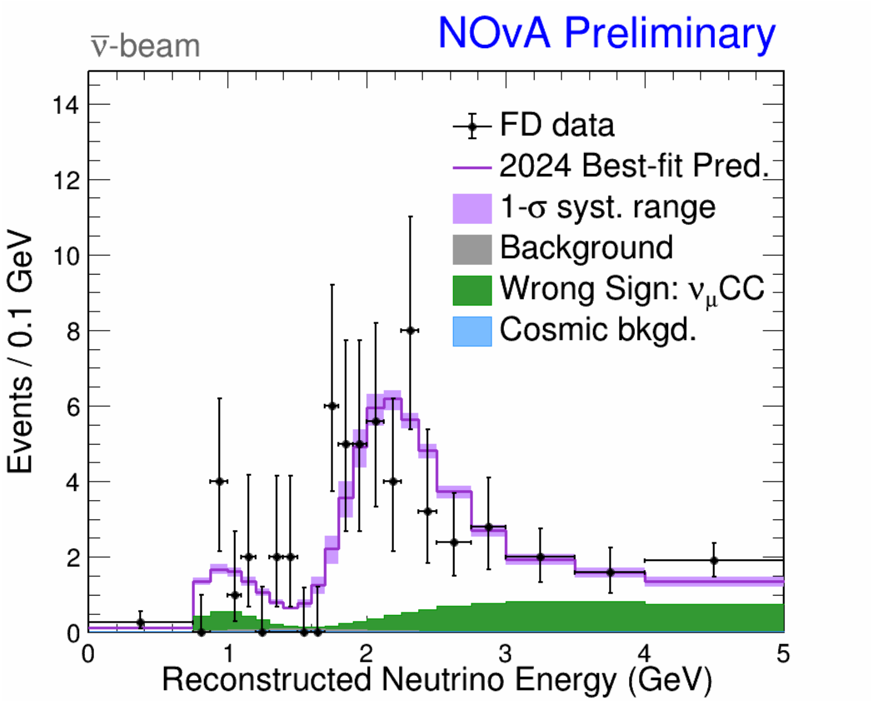
Daya Bay Constraint (PRL 130, 161802)
1D: $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$
2D: $(\Delta m^2_{32}, \theta_{13})$

Other mixing parameters:

$\sin^2\theta_{12}$	$= 0.307$	(PDG 2023)
Δm^2_{21}	$= 7.53\times10^{-5}\,\text{eV}^2$	(PDG 2023)
ρ	$= 2.74\ \text{g/cm}^3$	(CRUST1.0)

Our Data: ν_μ Disappearance

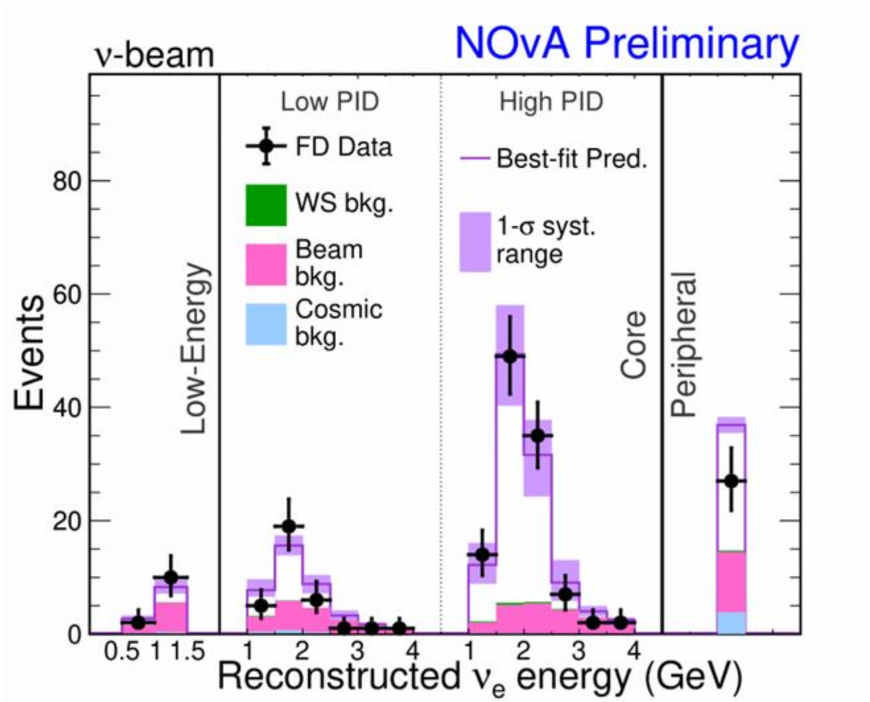


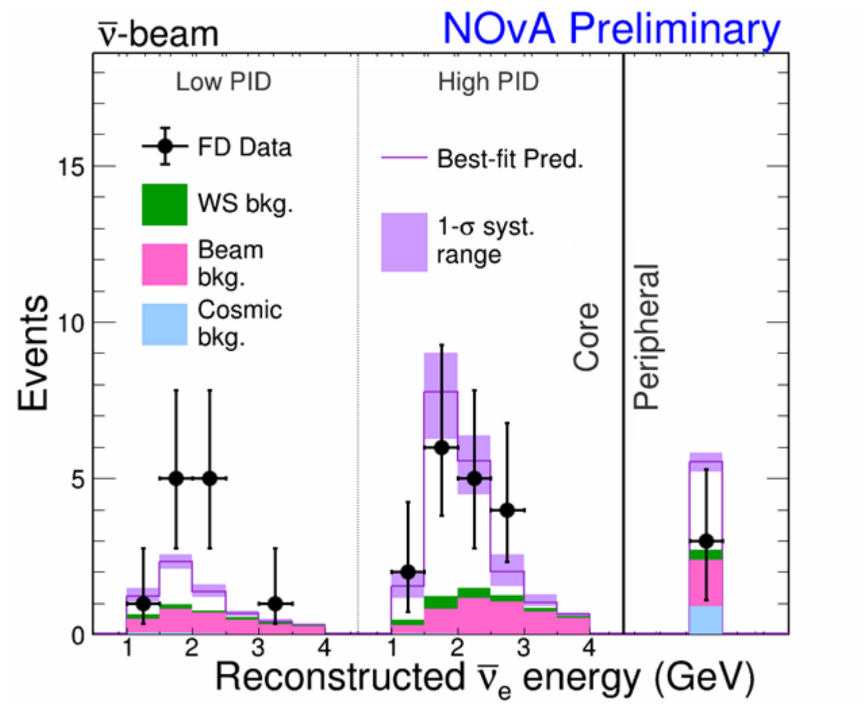


384 ν_μ Events
(2100 expected w/o oscillations)

106 $\bar{\nu}_\mu$ Events
(500 expected w/o oscillations)

Our Data: ν_e Appearance



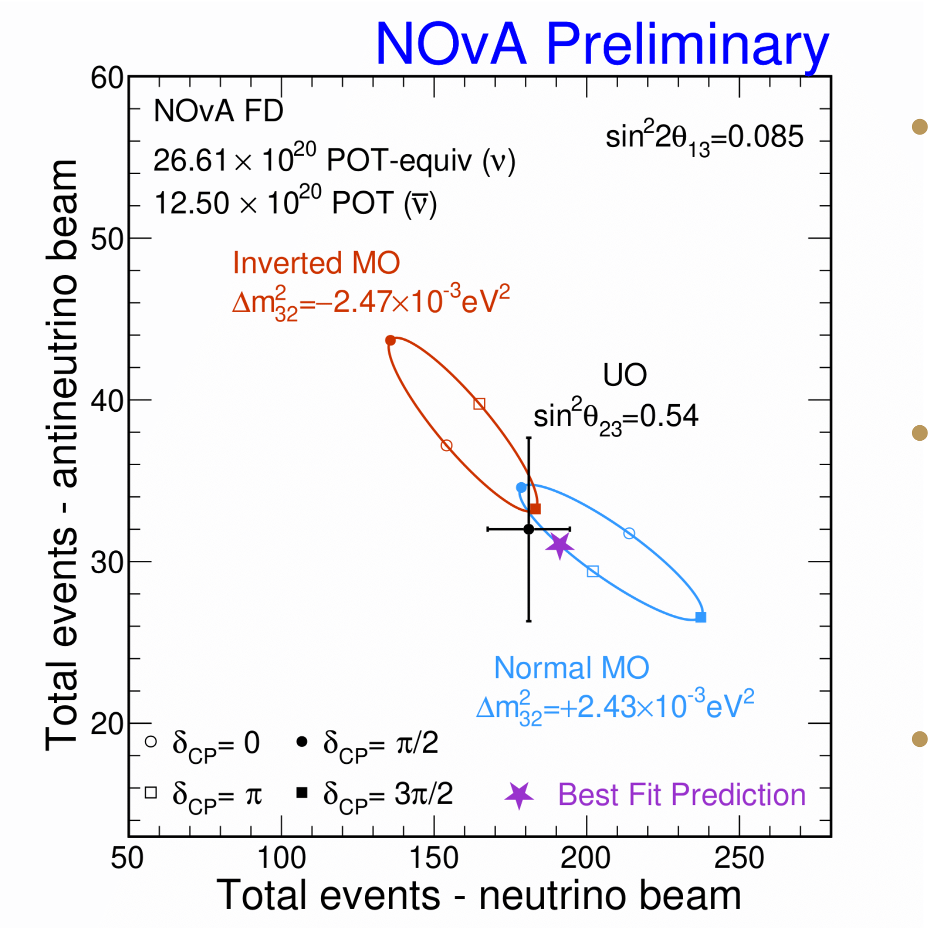


181 ν_e Events
(62 predicted background)

32 $\bar{\nu}_e$ Events
(12 predicted background)

(>4σ signal)

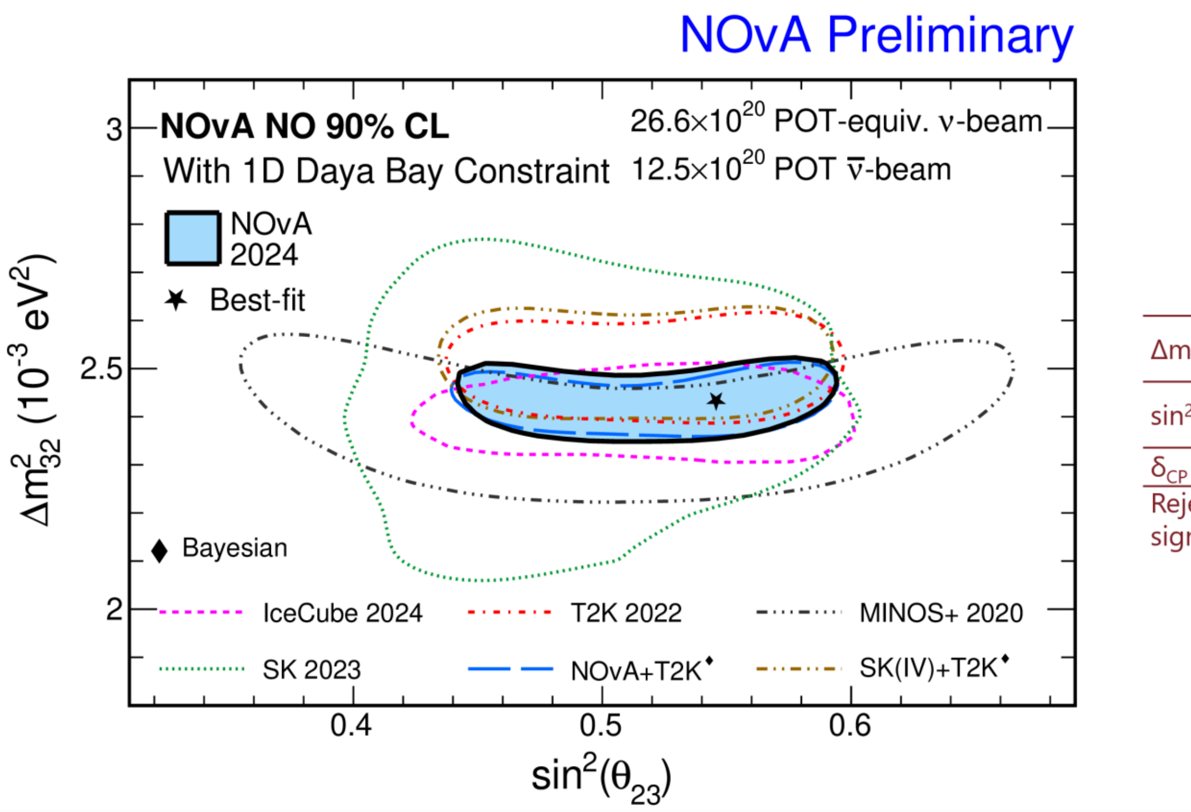
ν_e Appearance Observations



- Ellipses show the predicted total $\bar{\nu}_e$ event vs. ν_e event counts for different combinations of oscillation parameters.
- The appearance data favors a region with degenerate effects from Mass Ordering and CP violation.
- i.e. We don't see a large asymmetry in the rates of electron neutrinos vs. antineutrinos in our data.

$\nu_2 - \nu_3$ Sector Results

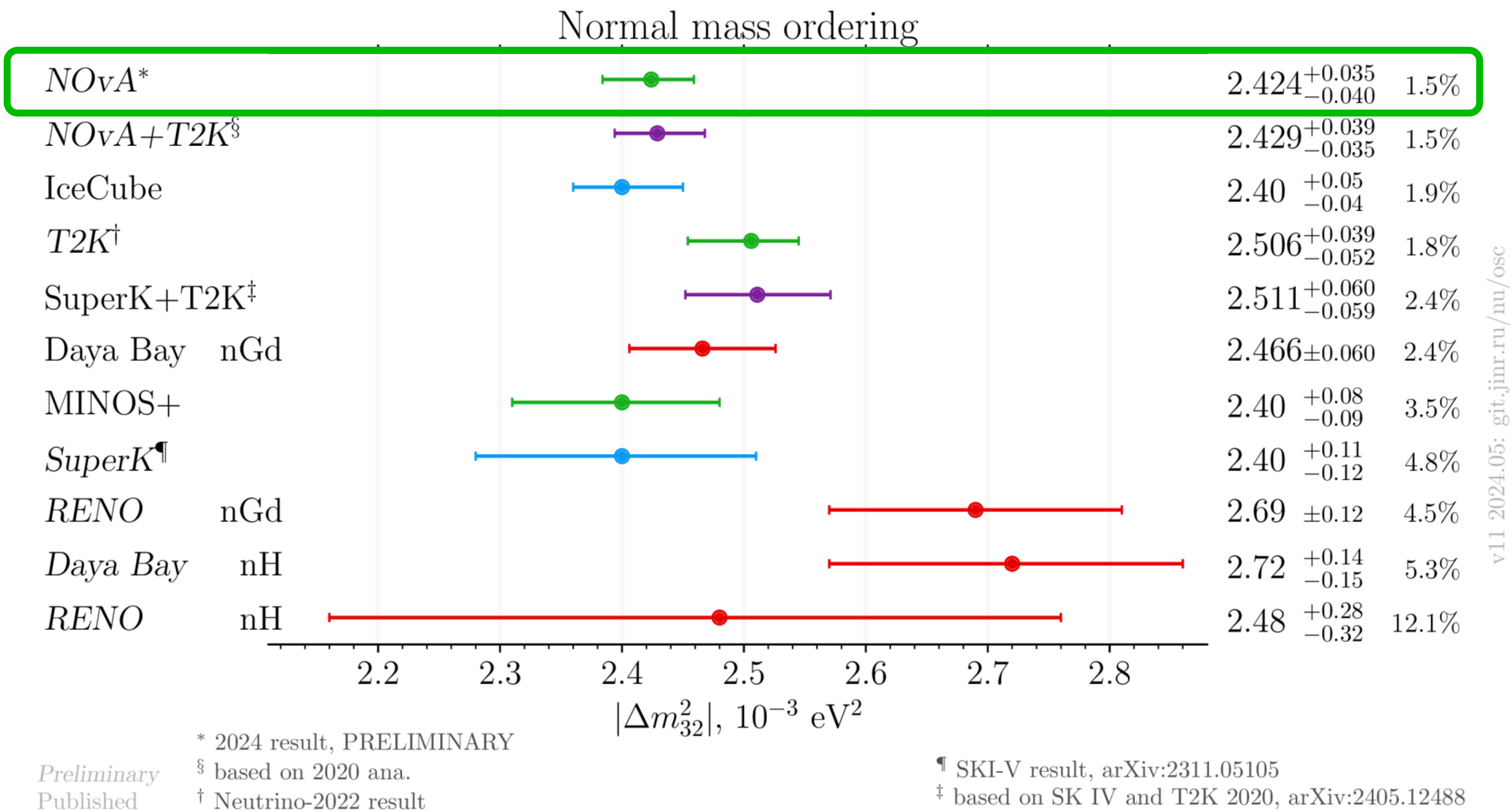
- For the Δm^2_{32} and $\sin^2(\theta_{23})$ measurements, our results are consistent with other experiments and joint results.



	Frequentist results (w/ Daya Bay 1D θ_{13} constraint)			
	Normal MO		Inverted MO	
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}	0.88 π		1.51 π	
Rejection significance (σ)			1.36	

$\nu_2 - \nu_3$ Sector Results

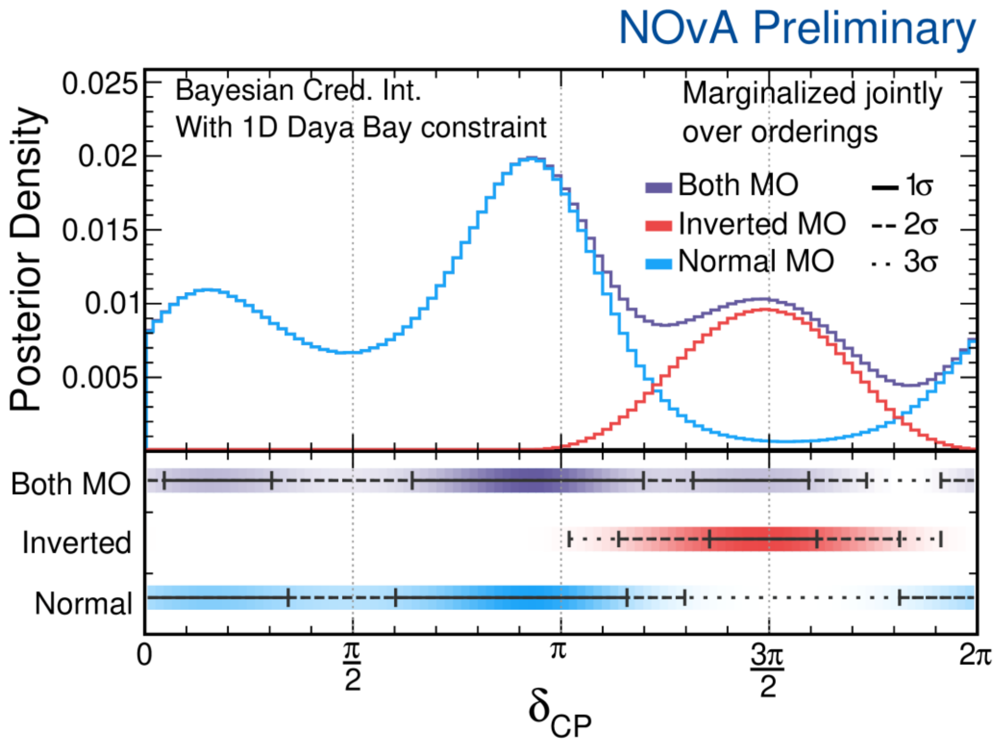
- **Most precise single-experiment measurement of Δm^2_{32}!**



*Note: NOvA 2024 Bayesian range here differs slightly from frequentist one on previous page

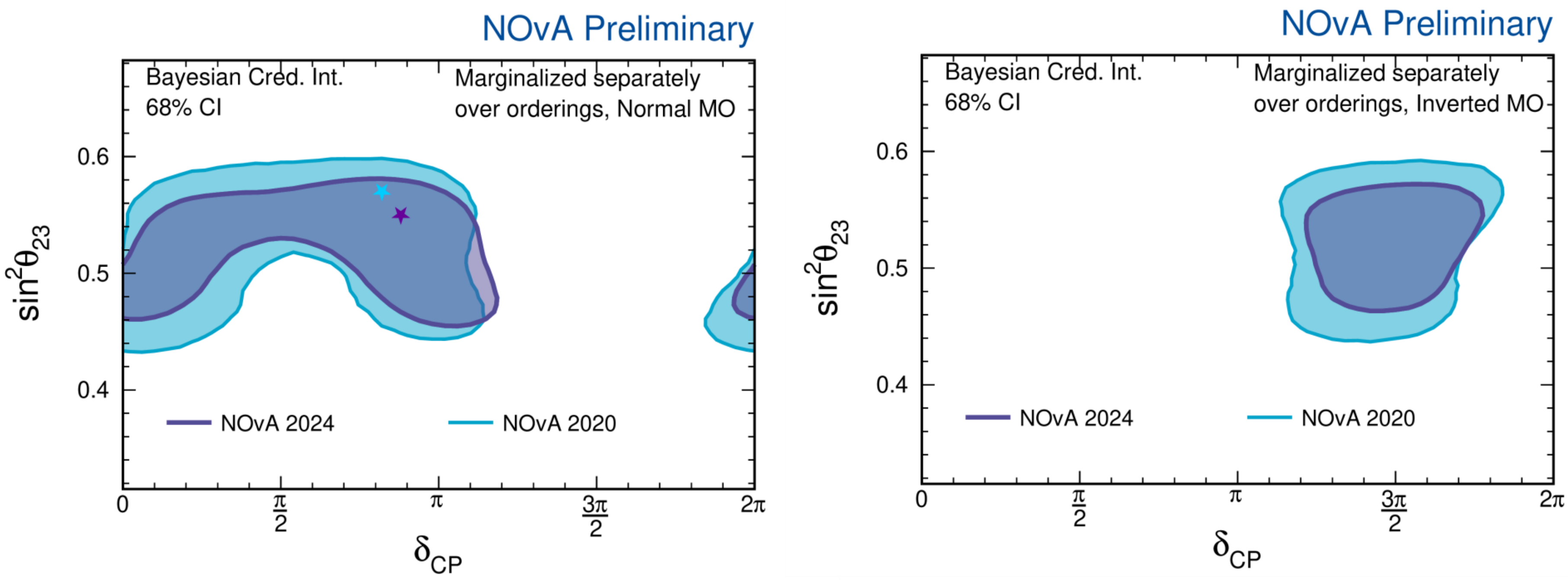
Mass Ordering & CPV Results

- Difficult to disentangle mass ordering and CP violation effects.
- CP Conserving points (π, 2π, 0) are compatible in the Normal MO, but outside the 3-sigma interval in Inverted MO.



Mass Ordering and CPV Results

- Our new results are consistent with our previous analysis.
- Improved constraints occupy approximately the same regions.

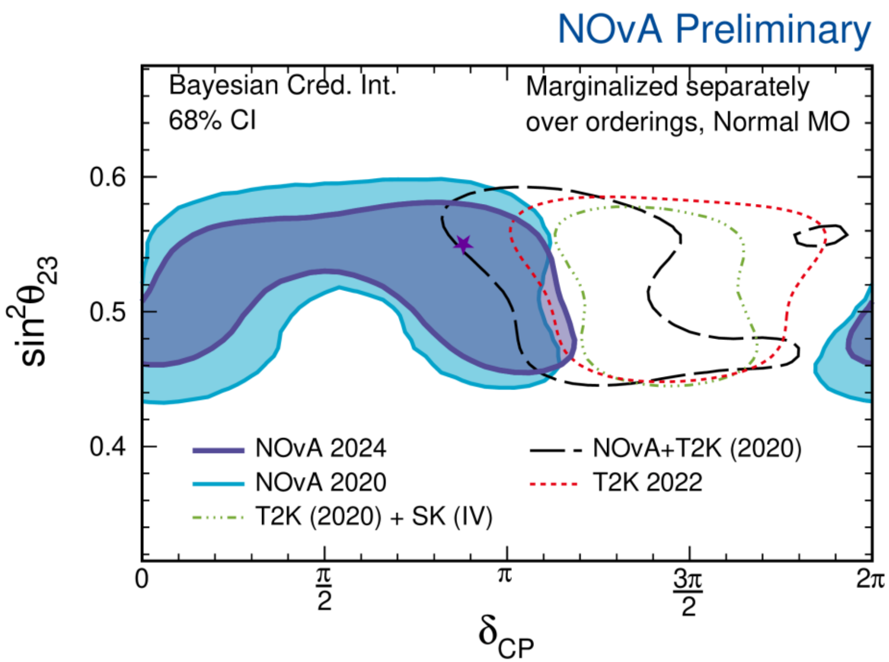


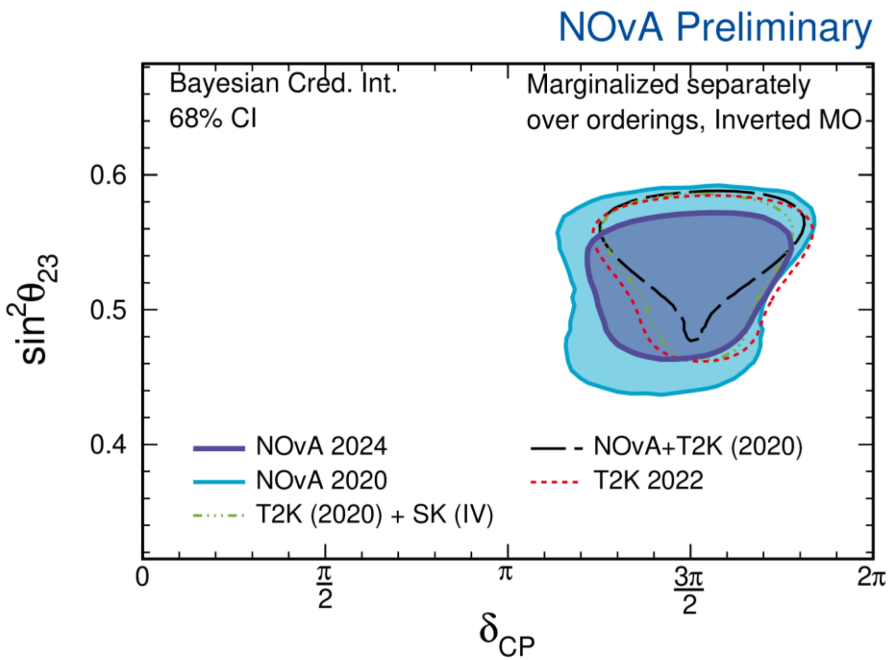
Note: Results use different choices of reactor constraint.

NOvA 2020: 2019 PDG avg θ13
NOvA 2024: Daya Bay 2023 1D θ13

Mass Ordering and CPV Results

- When compared with other experiments results, we prefer similar regions in the Inverted MO, and different regions in the Normal MO.





Note: Results use different choices of reactor constraint.

NOvA 2020: 2019 PDG avg θ13
NOvA 2024: Daya Bay 2023 1D θ13

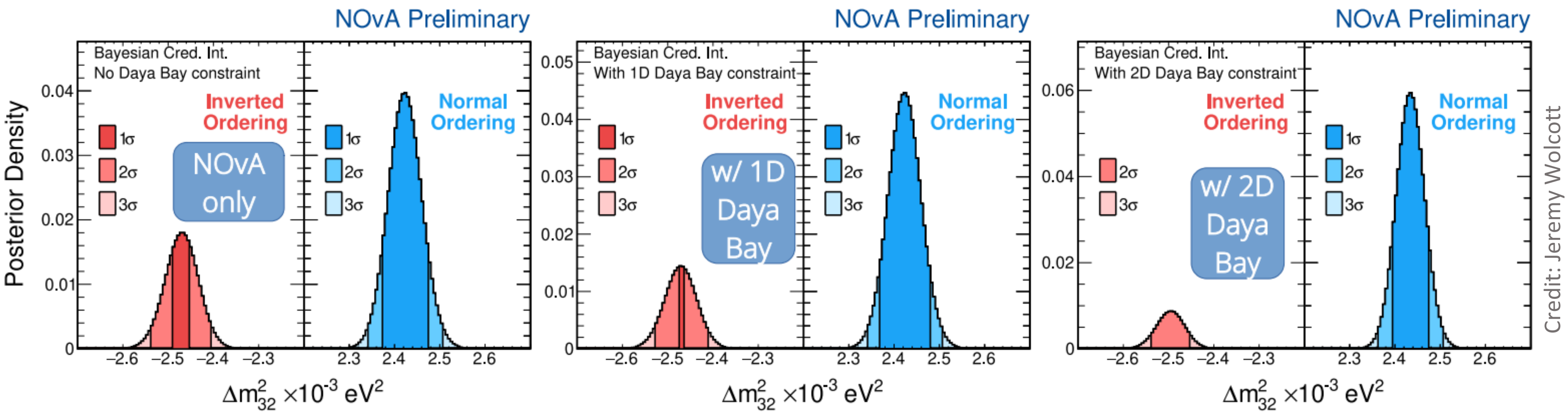
T2K: 2019 PDG avg θ13
NOvA+T2K: Daya Bay 2023 1D θ13
T2K+SK: 2019 PDG avg θ13

Mass Ordering and CPV Results

- Strong synergy with reactor experiment constraints enhance our Normal MO preference.
- Not unexpected, See: Phys. Rev. D 72: 013009, 2005

Another possible way to determine the Neutrino Mass Hierarchy

Hiroshi Nunokawa[1,*] Stephen Parke[2,†] and Renata Zukanovich Funchal[3‡]



No reactor constraint	Daya Bay $\sin^2 2\theta_{13}$ only	Daya Bay ($\sin^2 2\theta_{13}$, Δm^2_{32})
N.O. preference:	N.O. preference:	N.O. preference:
69% prob. (Bayes factor: 2.2)	76% prob. (Bayes factor: 3.2)	87% (Bayes factor: 6.8)
	Frequentist significance*: 1.4σ	Frequentist significance*: 1.6σ

*Frequentist significances computed using Feldman-Cousins procedure thanks to NERSC

NOvA Results Summary

- Both Frequentist and Bayesian analysis of our data yield similar results.
  - Most precise single-experiment measurement of Δm^2_{32} (1.5% uncertainty) .
  - Data disfavor regions with large $\nu_e/\bar{\nu}_e$ asymmetry and favor regions with degeneracy.
  - Slight Preference for Normal MO (6.8 Bayes Factor, 1.6σ), Upper Octant, CP-conserving δ_{CP} values.
  - Reactor experiments provide a strong synergy to enhance sensitivity.
- Future prospects very exciting!
  - Goal of doubling our antineutrino data.
  - Test Beam can provide constraints on energy scales.
  - Lots of other analyses (NSI, Sterile, Cross Sections, …)

Thanks for listening!

172. Neutrino Cross Section Measurements in NOvA
Joshua Barrow (UMN, FNAL visitor)
9/18/24, 12:46 PM

53. Electromagnetic Response Studies in the NOvA Test Beam
Dalton Myers (The University of Te...
9/18/24, 12:10 PM

173. NOvA/T2K joint fit and NOvA
Ryan Patterson (Caltech)
9/19/24, 9:00 AM
Plenary session

116. Constructing confidence intervals with Profiled Feldman-Cousins method for NOvA's neutrino oscillation measurement
Andrew Dye (University of Missis...
9/17/24, 5:15 PM

124. Impact of the HF-CRPA Model on Neutrino Oscillation Parameter Measurements in NOvA
Amit Pal (National Institute of...
9/16/24, 4:05 PM

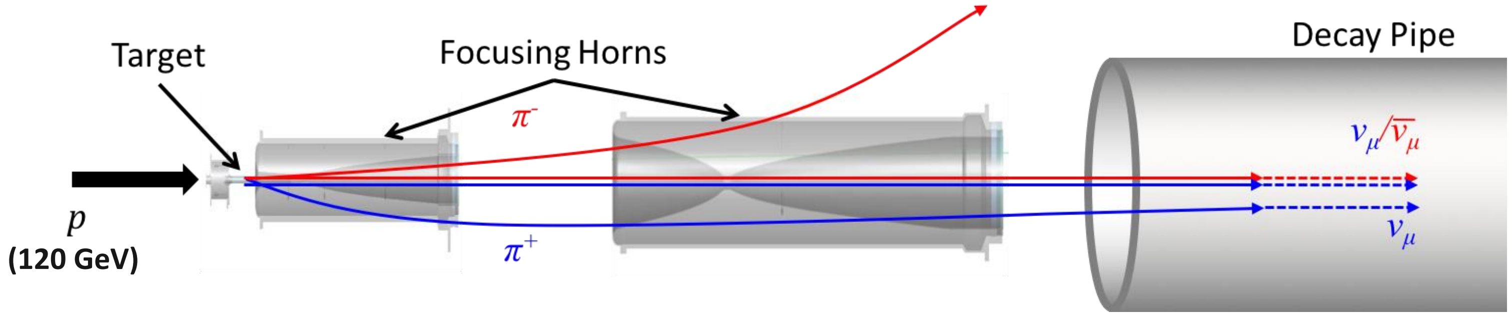
123. Seasonal Variation in Cosmic Muon Rate at the NOvA Experiment
Amit Pal (National Institute of...
9/18/24, 12:30 PM

10. Updates and Lessons Learned from NuMI Beamline at Fermilab
Don Athula Wickremasinghe (Fermilab)
9/16/24, 1:45 PM

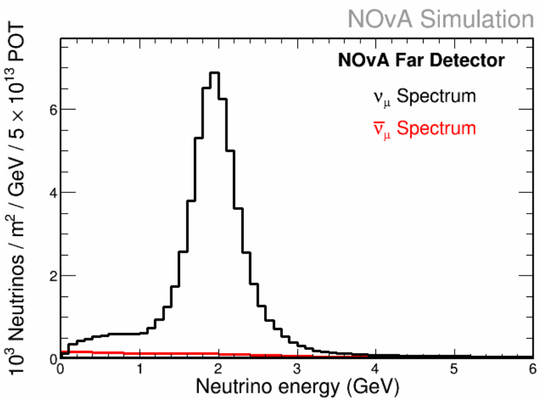
Check out some of the other interesting talks being given by NOvA collaborators at NuFact!

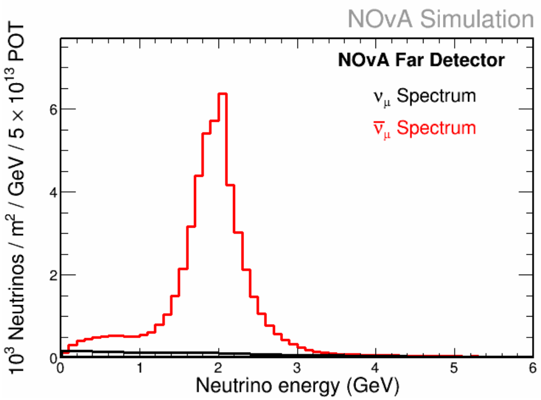
Backup

The NuMI Beam



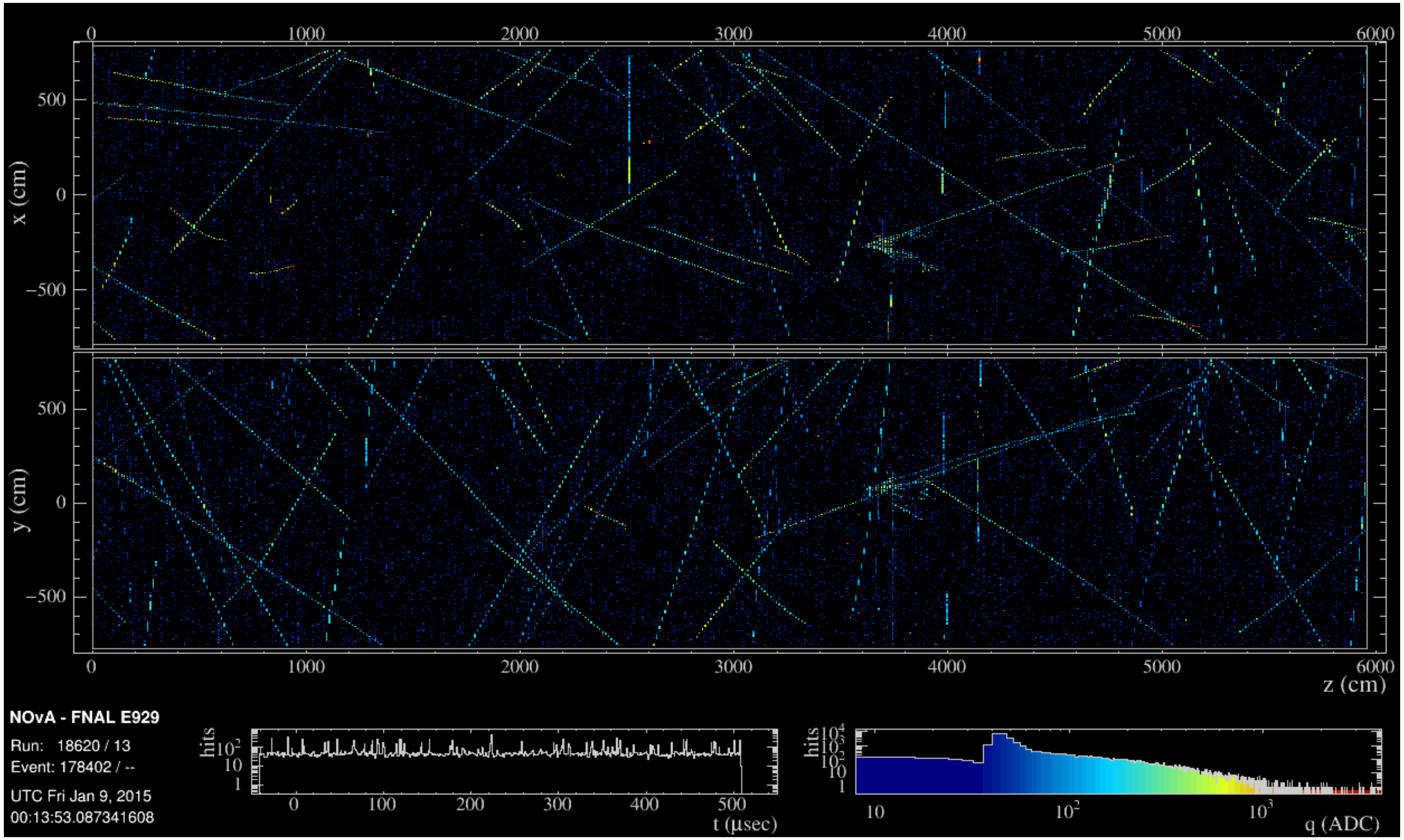
- Neutrinos at the Main Injector (NuMI)
- Beam is 95% (93%) pure when running in neutrino (antineutrino) mode.
  - 4% (6%) wrong-sign and 1% intrinsic beam ν_e
- NOvA detectors are located 14mrad off-axis to provide a narrow-band energy distribution peaked at 2 GeV





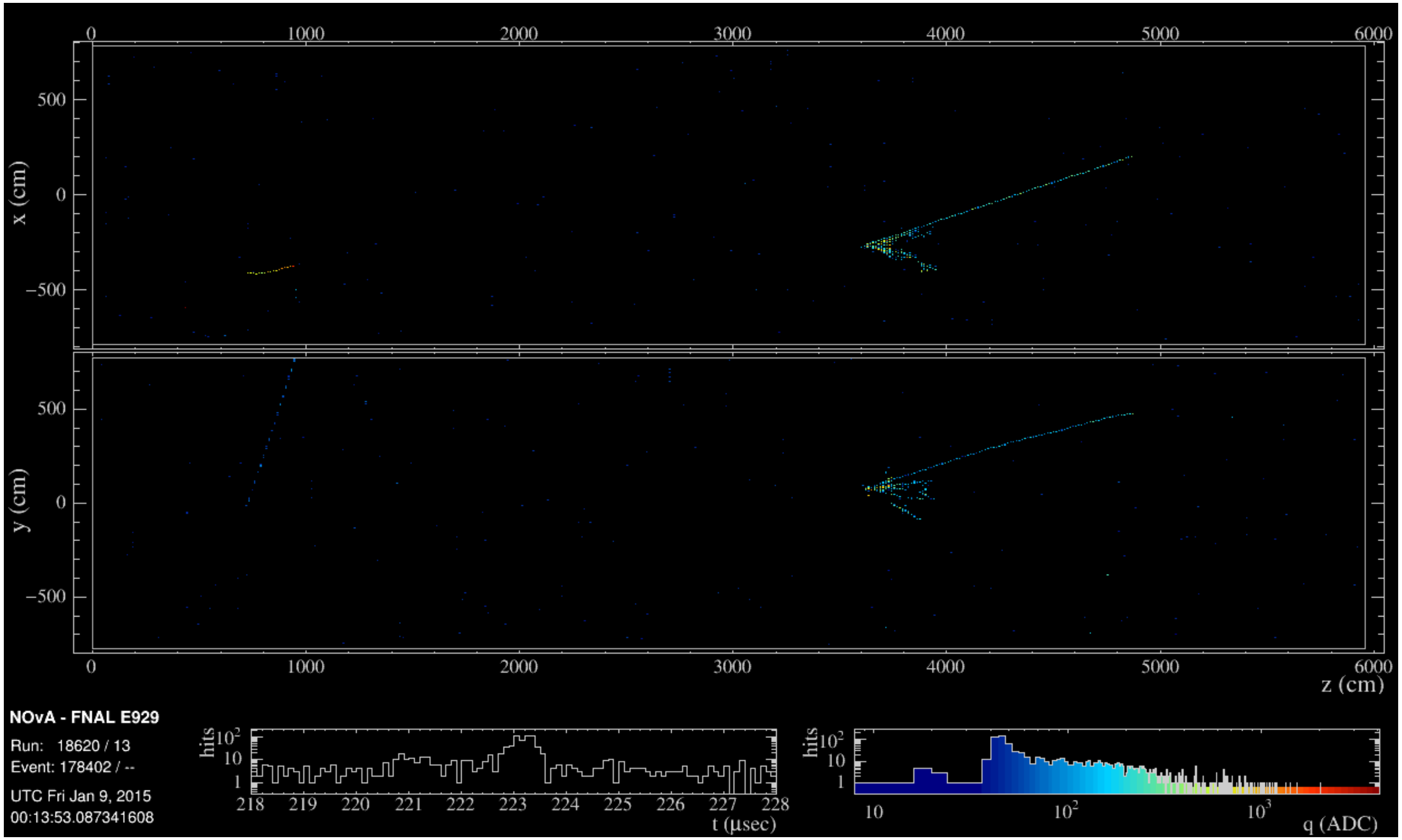
What we see in the detectors

- Example of what we see in the far detector.
- Note the high rate of cosmics due to being on the surface.

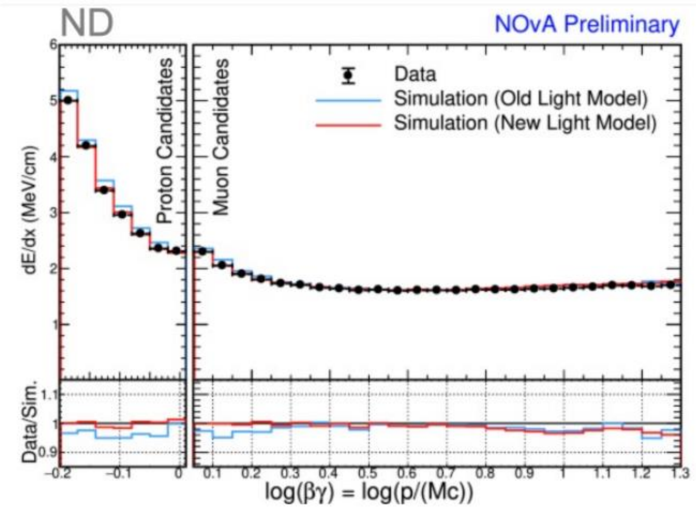


What we see in the detectors

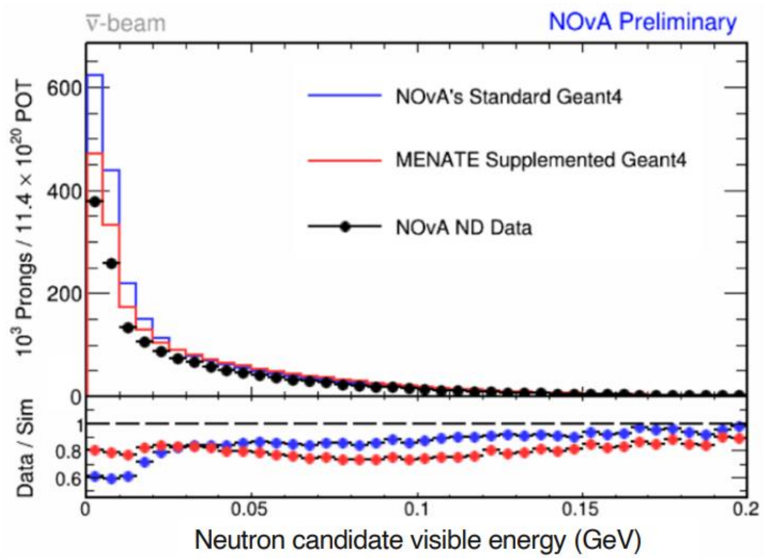
- By cutting out everything not in time with the 10us beam spill, we reduce our cosmic background and can isolate neutrino event candidates.



Simulation Improvements



Improved light production model
(Cherenkov & scintillation)
in both detectors, from dedicated bench measurements & in situ stopping muon and proton tracks

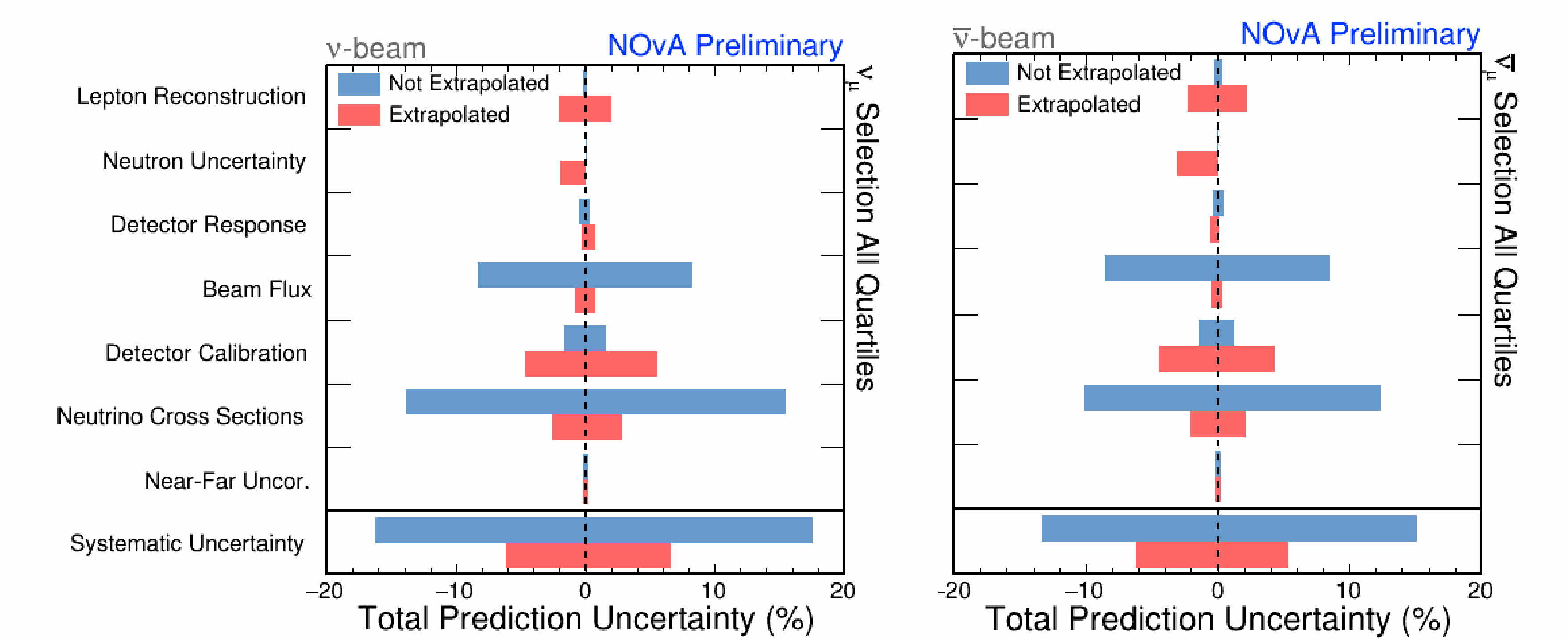


Improved n-^{12}C inelastic scattering model
Difference between MENATE_R* and default Geant4.10.4 informs systematic uncertainty

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

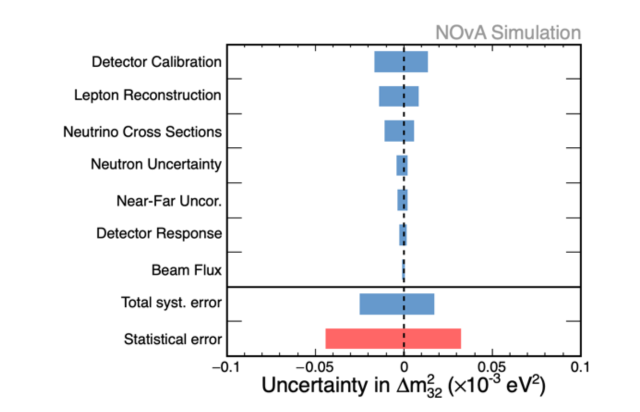
Extrapolation Reduces Systematic Uncertainty

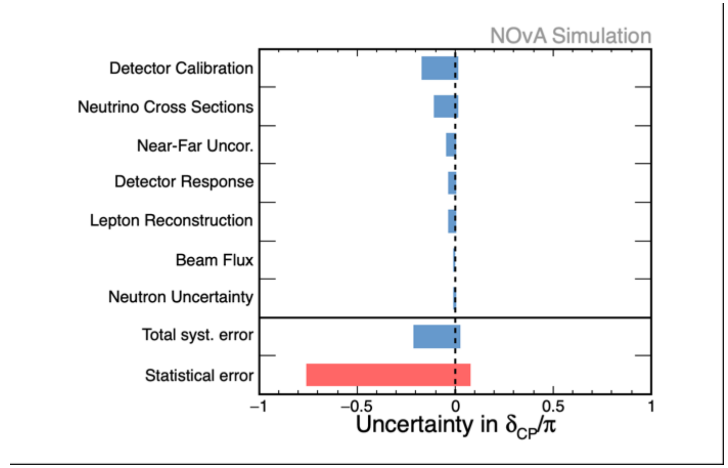
- Numu uncertainties before/after extrapolation

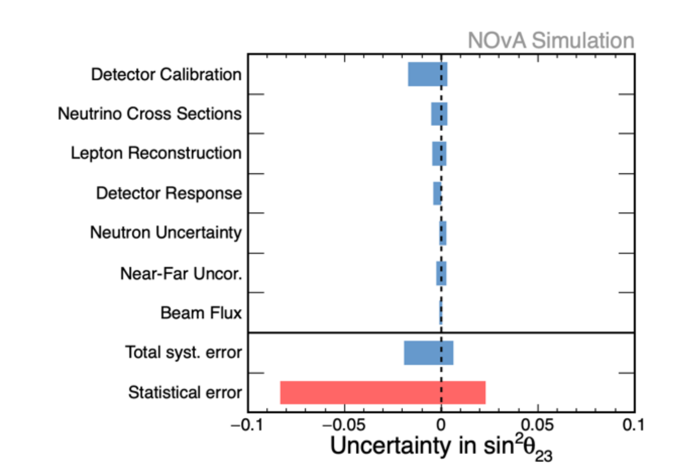


Systematic Uncertainty on Parameters

- Systematic uncertainty breakdown on each of the measured oscillation parameters.







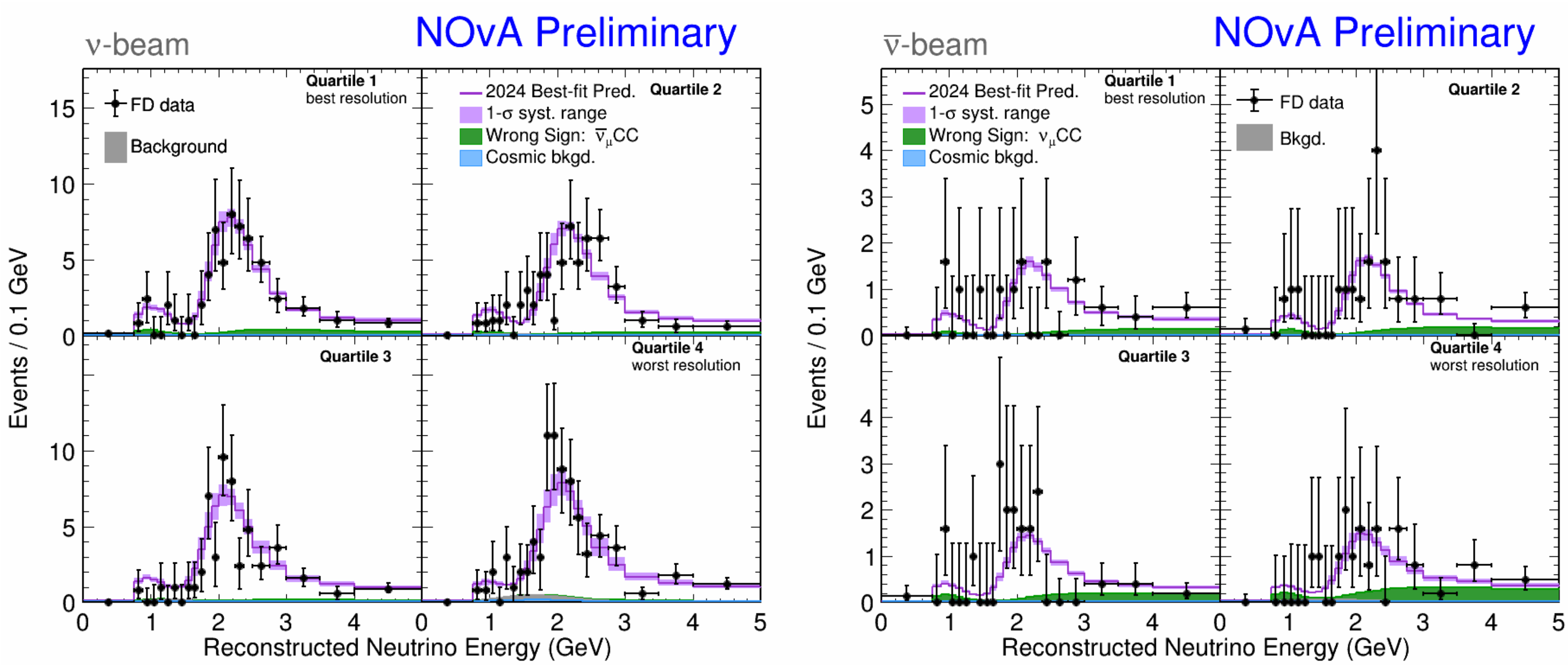
Summary Table

Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)
Beam Flux	+0.00042 / -0.00069	+0.0012 / -0.011	+0.00053 / -0.0012
Detector Calibration	+0.0033 / -0.017	+0.014 / -0.17	+0.013 / -0.016
Detector Response	+0.00031 / -0.0043	+0.004 / -0.037	+0.0016 / -0.0026
Lepton Reconstruction	+0.0027 / -0.0046	+0.007 / -0.034	+0.0083 / -0.014
Near-Far Uncor.	+0.0025 / -0.0024	+0.0072 / -0.043	+0.0022 / -0.0034
Neutrino Cross Sections	+0.0031 / -0.0051	+0.018 / -0.11	+0.0058 / -0.011
Neutron Uncertainty	+0.0028 / -0.00075	+0.0056 / -0.011	+0.0022 / -0.0041
Systematic Uncertainty	+0.0067 / -0.019	+0.027 / -0.21	+0.017 / -0.024
Statistical Uncertainty	+0.023 / -0.083	+0.081 / -0.76	+0.032 / -0.044

Table: Summary of uncertainties on Ana2024 frequentist joint best-fit point, evaluated at the NOUO best-fit values i.e. $\sin^2\theta_{23} = 0.55$, $\delta_{CP}/\pi = 0.88$, and $\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2) $= 2.43$.

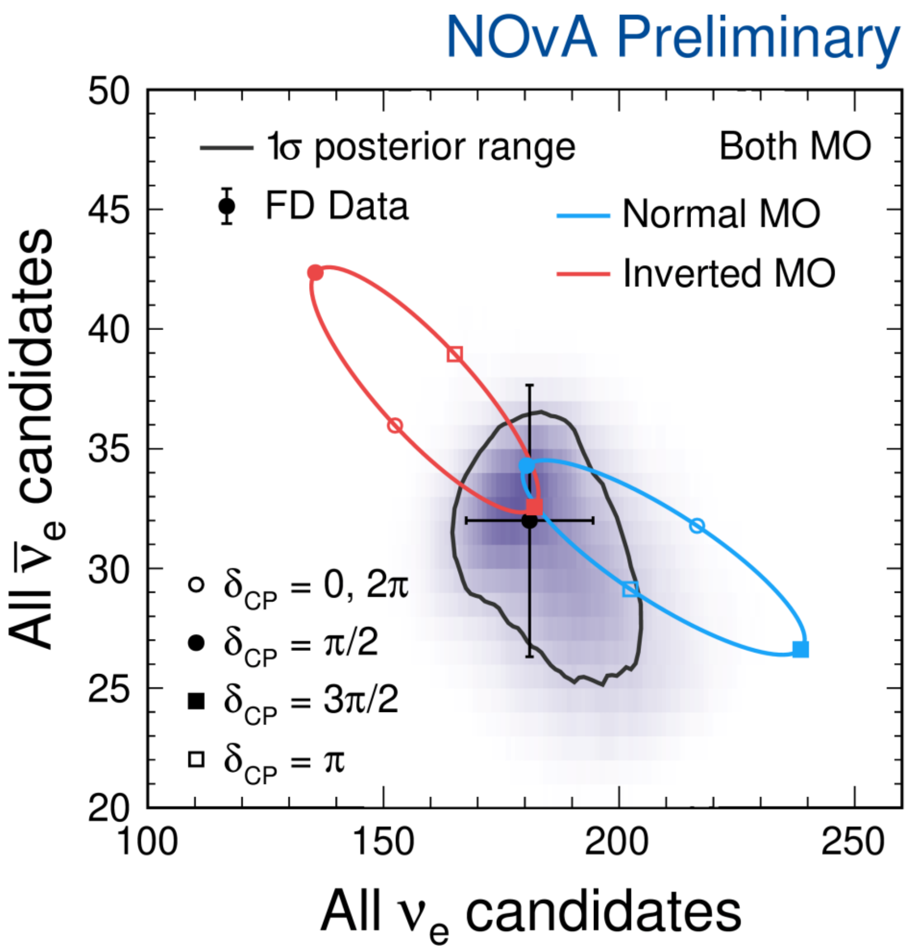
FD Data: Numu energy by E_{had}/E_{ν} quartiles

- Extrapolation procedure is performed in |pt| subpopulations of Ehad/Eν quartiles
- Resolutions range from Q1 6.5% (5.4%) to Q4 12.6% (11.2%) in ν ($\overline{\nu}$) mode



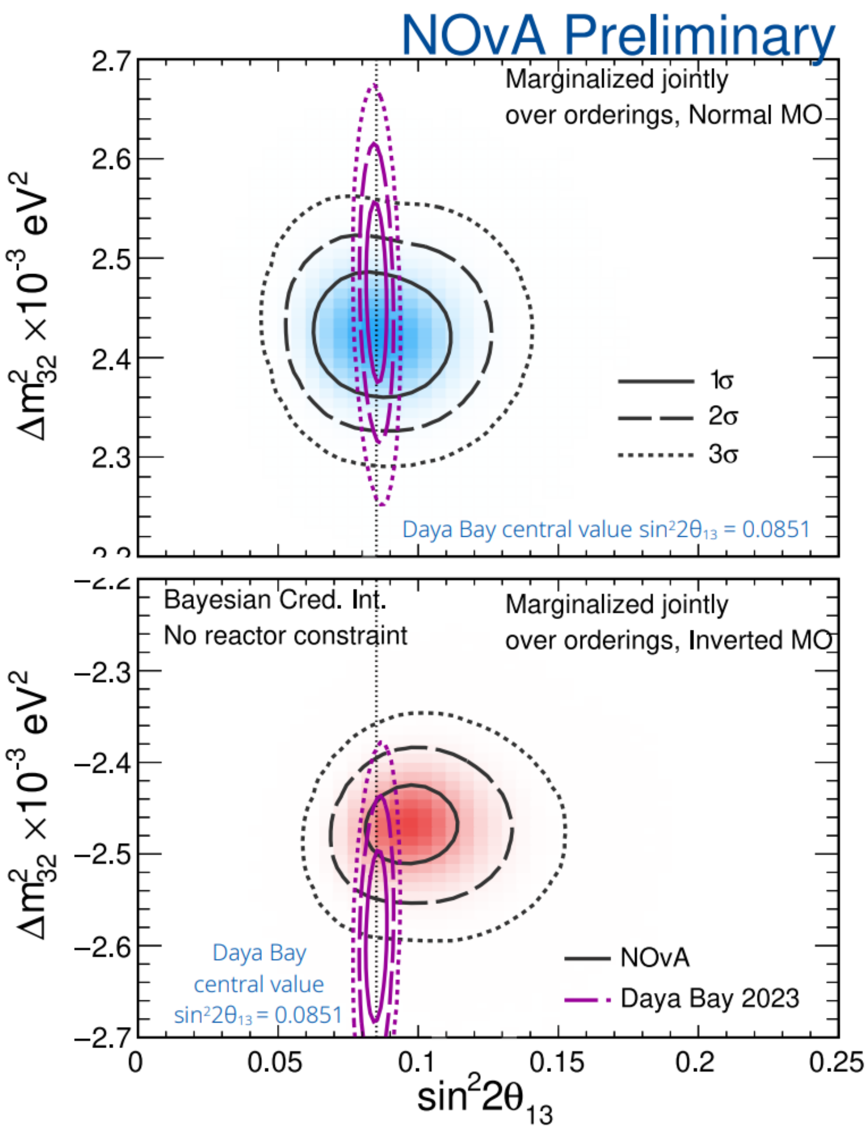
Bayesian Bi-Event Plot

- Bi Event Posterior probability density (violet) for integrals of ν_e and $\bar{\nu}_e$ candidates in FD with one sigma posterior range compared with real data and two sets of hypothesis (Inverted MO and Normal MO ellipses). Each point on ellipse correspond to different value of δ_{CP} , all other oscillation parameters were set to the best fit in corresponding MO.



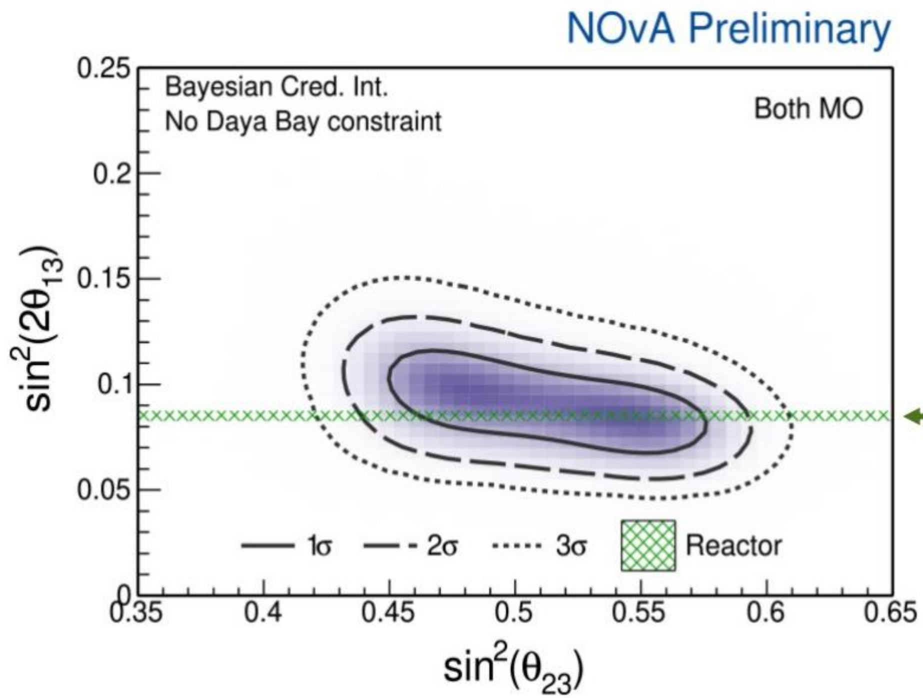
Correlations with Daya Bay

- Daya Bays preferred regions can help us resolve some degeneracies in the NOvA-only measurements



Correlations With Daya Bay

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
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

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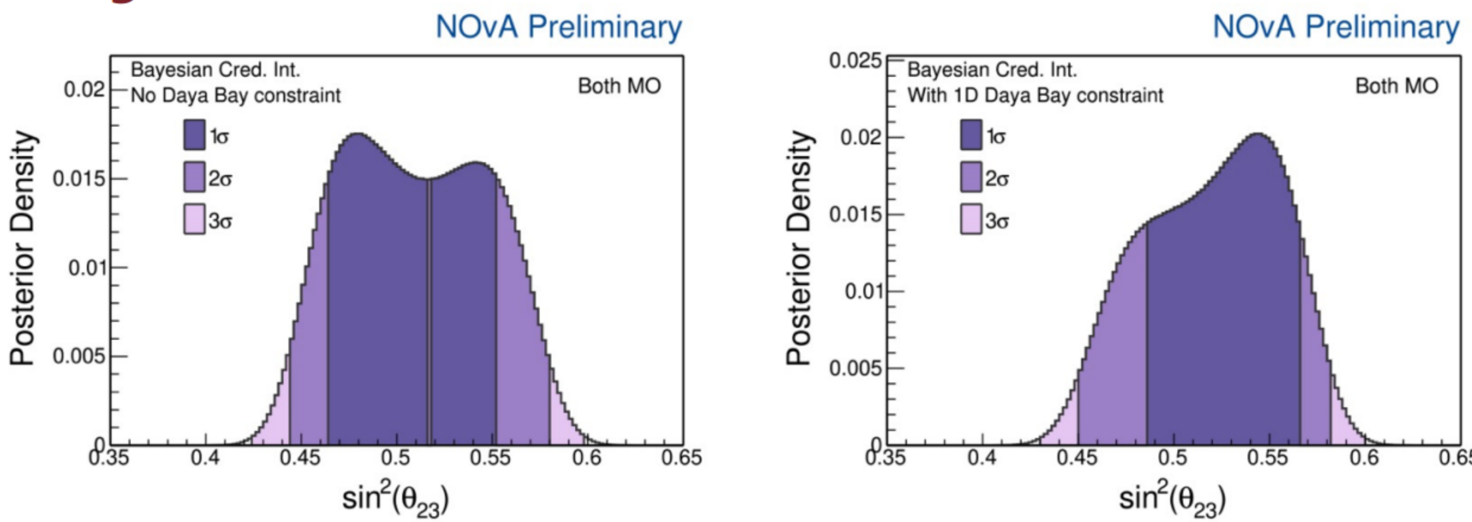
The NOvA results show a mild preference for the upper octant that emerges from applying the reactor constraint. Maximal mixing is allowed at <1σ



	No constraint		Daya Bay 2023 1D θ13	
	Probability	Bayes Factor	Probability	Bayes Factor
Upper Octant preference	**57%**	1.3	**69%**	2.2

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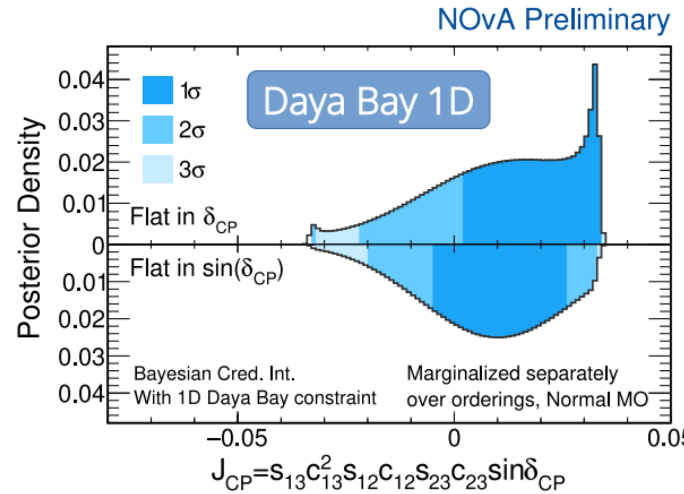
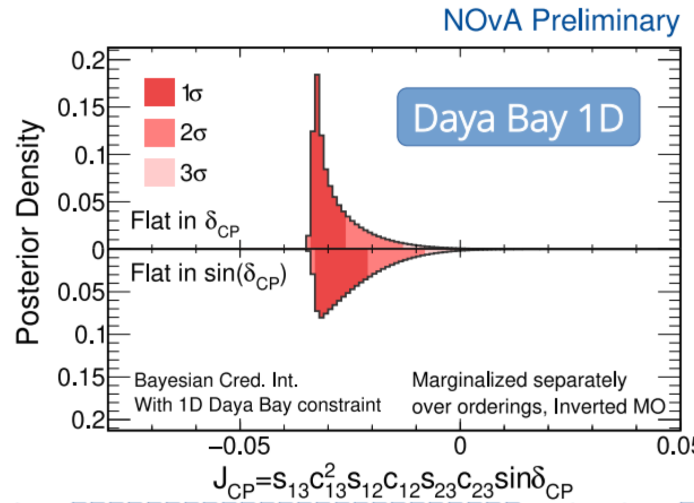
Jarlskog invariant

- Jarlskog* is parameter-independent measure of CP violation
  - J=0 indicates CP conservation regardless of parameterization
  - J≠0 correspondingly indicates CP violation
- Jarlskog posterior shape depends on assumptions
  - Depends on all mixing angles and δ_{CP}
  - Uniform prior on δ_{CP} not uniform in *J* and vice versa → consider both
  - Use 1D θ_{13} constraint from Daya Bay
  - Other parameters constrained sufficiently well to that (reasonable) prior choice does not influence result
- CP conservation (J=0):
  - Strong compatibility w/ posterior in NO, regardless of δ_{CP} prior
  - Strong tension w/ posterior in IO, but only "uniform in δ_{CP}" prior has J=0 outside 3σ interval





*See, e.g., PRD 100, 053004

Slide Credit: Jeremy Wolcott (Neutrino 2024)