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Latest Three-Flavor Neutrino Oscillation Results from NOvA

Brajesh Choudhary, **Ishwar Singh**, University of Delhi, Delhi, India

Louise Suter, Fermi National Accelerator Laboratory, US

On behalf of the NOvA Collaboration

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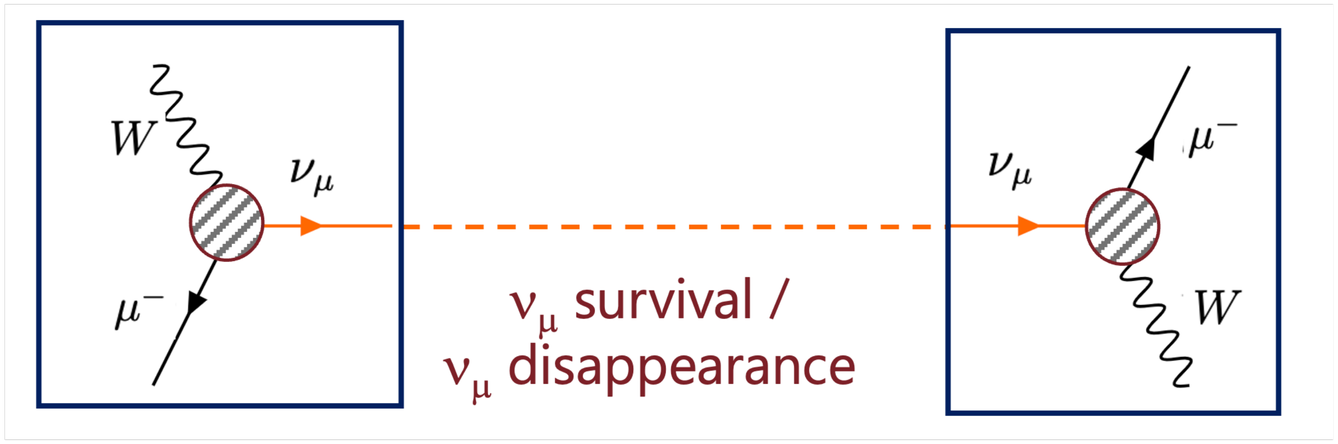
Neutrino Mixing and Oscillations

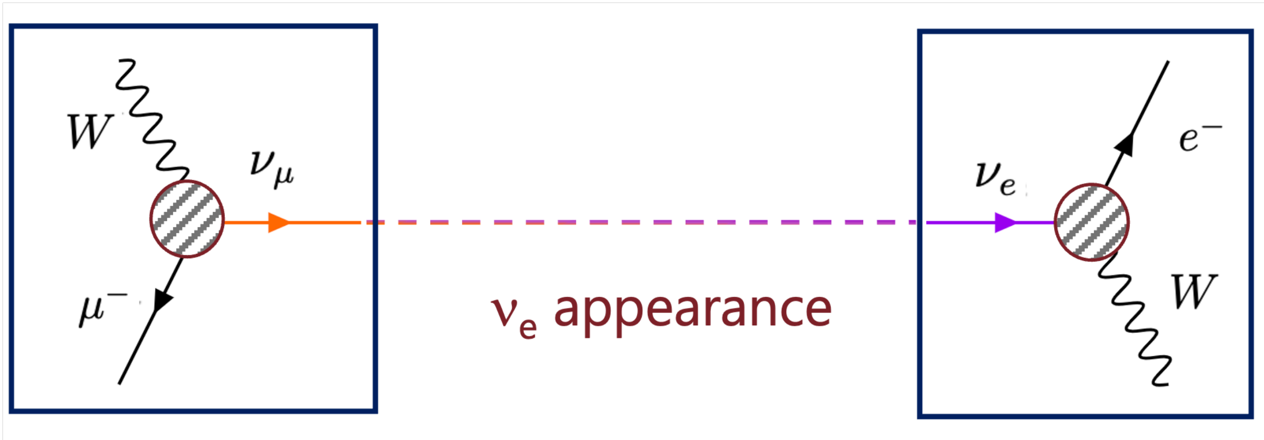
- Neutrinos are fundamental particles
  - ✳ tiny non-zero masses
  - ✳ comes in three flavors ν_e, ν_μ, ν_τ
- Flavor eigenstates are mixed with the mass eigenstates by a unitary matrix
- Neutrinos oscillate between flavor eigenstates
- The oscillation probability is given by

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

- Neutrino oscillations let us probe the elements of the mixing matrix



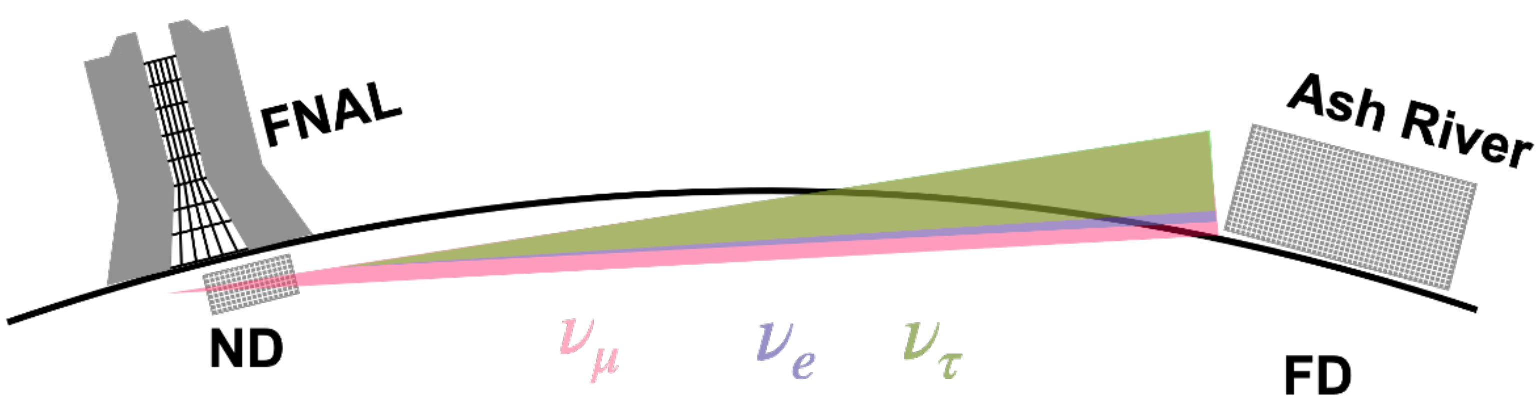
Sensitive to Δm^2_{32} and mixing angle θ_{23} (resolution of octant degeneracy)



Sensitive to the CP-violating phase δ_{CP}, mixing angle θ_{13} (although mild) and mass ordering

The NOvA Experiment

- **N**uMI **O**ff-axis ν_e **A**ppearance Experiment
  - NuMI**:** Neutrinos at the Main Injector
  - Off-axis: Detectors situated 14.6 mrad off-axis to beam direction
  - $\nu_\mu(\bar{\nu}_\mu)$ dis-appearance and $\nu_e(\bar{\nu}_e)$ appearance
  - Functionally identical liquid scintillation detectors. ND and FD located at 1km and 810km from the beam source
- **Primary Goals**:
  - Measure neutrino oscillation parameters
  - Resolve neutrino mass ordering
  - Resolve octant degeneracy
  - Measure δ_{CP}, the CP-violating phase



Check out Prof. Bipul Bhuyan's talk from Plenary-I for the details

Beyond Neutrino Oscillations

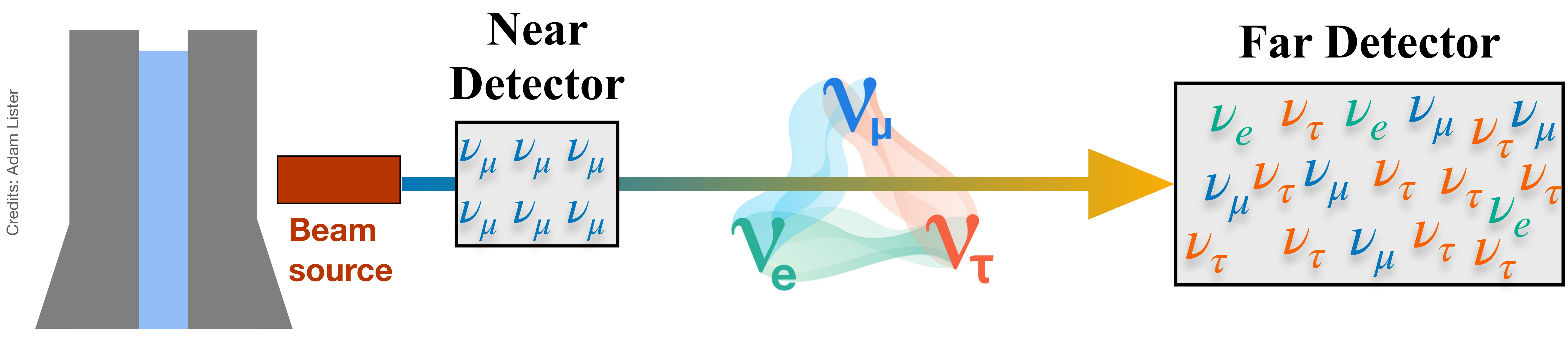
- Non-standard interactions
- Neutrino cross-sections
- Sterile neutrinos
- Magnetic monopoles
- Dark matter
- And many more!

The NuMI beam line at Fermilab provides an intense $\nu/\bar{\nu}$ beam

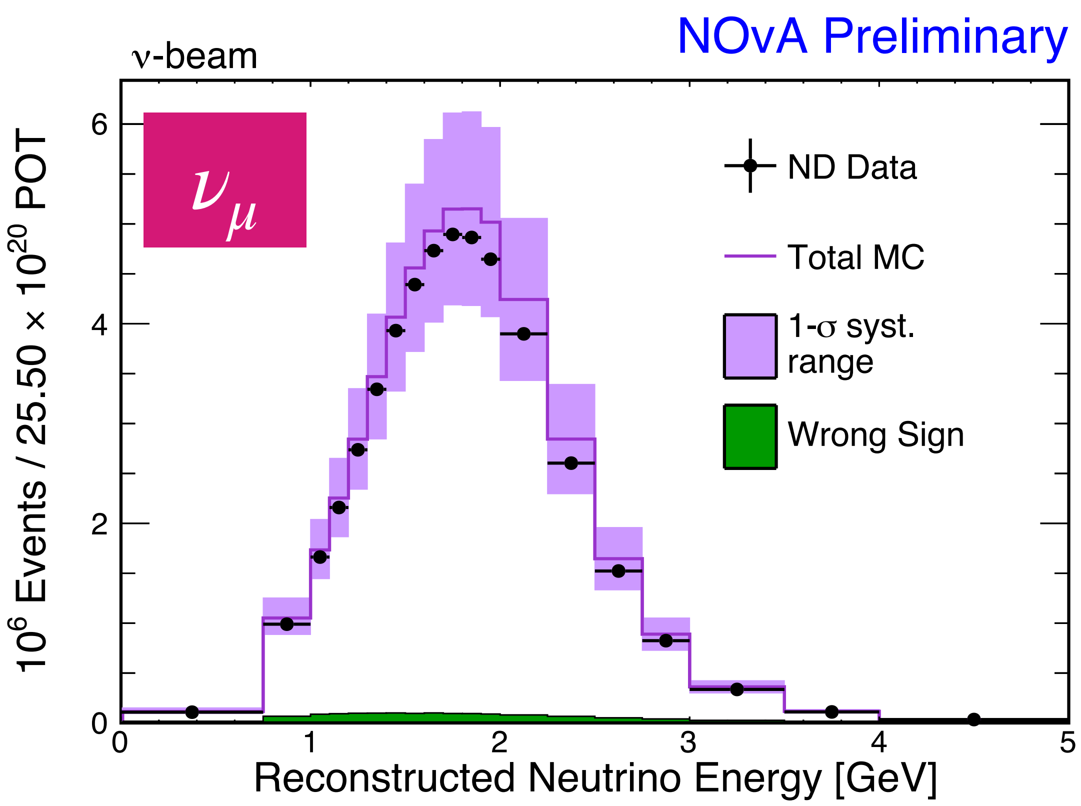
How to Measure Neutrino Oscillations?

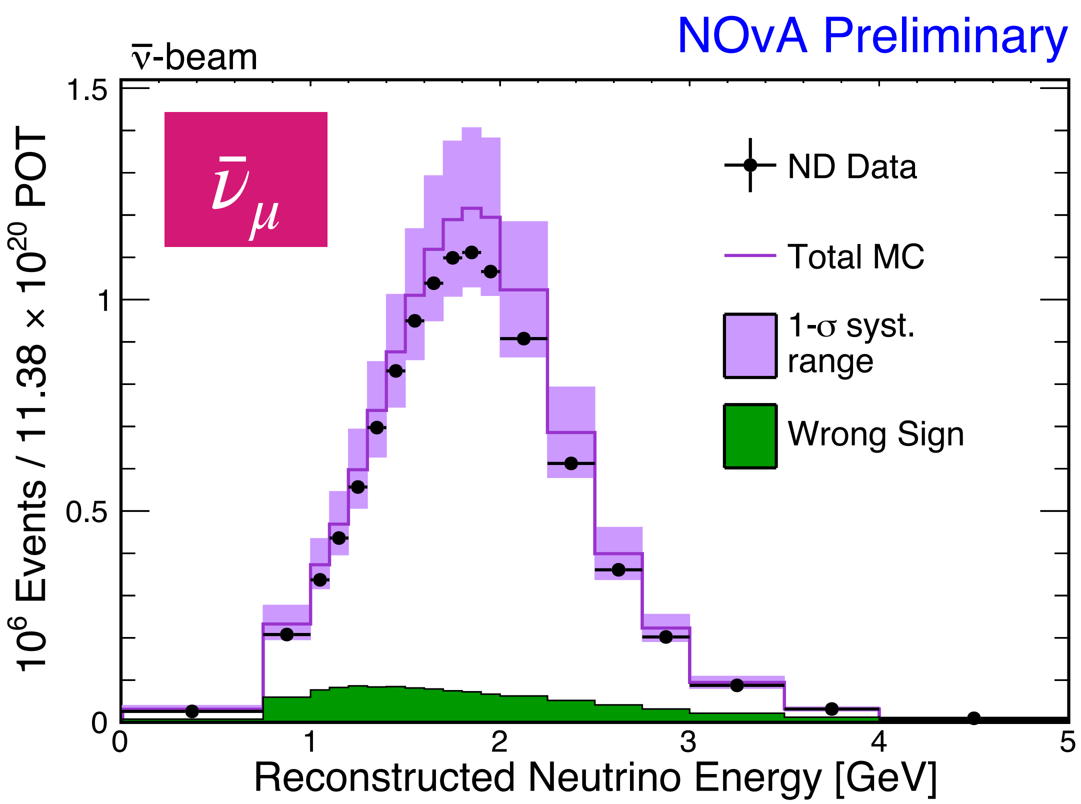
Credits: Alex Himmel

Observe how flavor changes with energy over a long distance, while mitigating uncertainties related to neutrino flux, interaction cross sections, and detector performance.



Near Detector Spectra

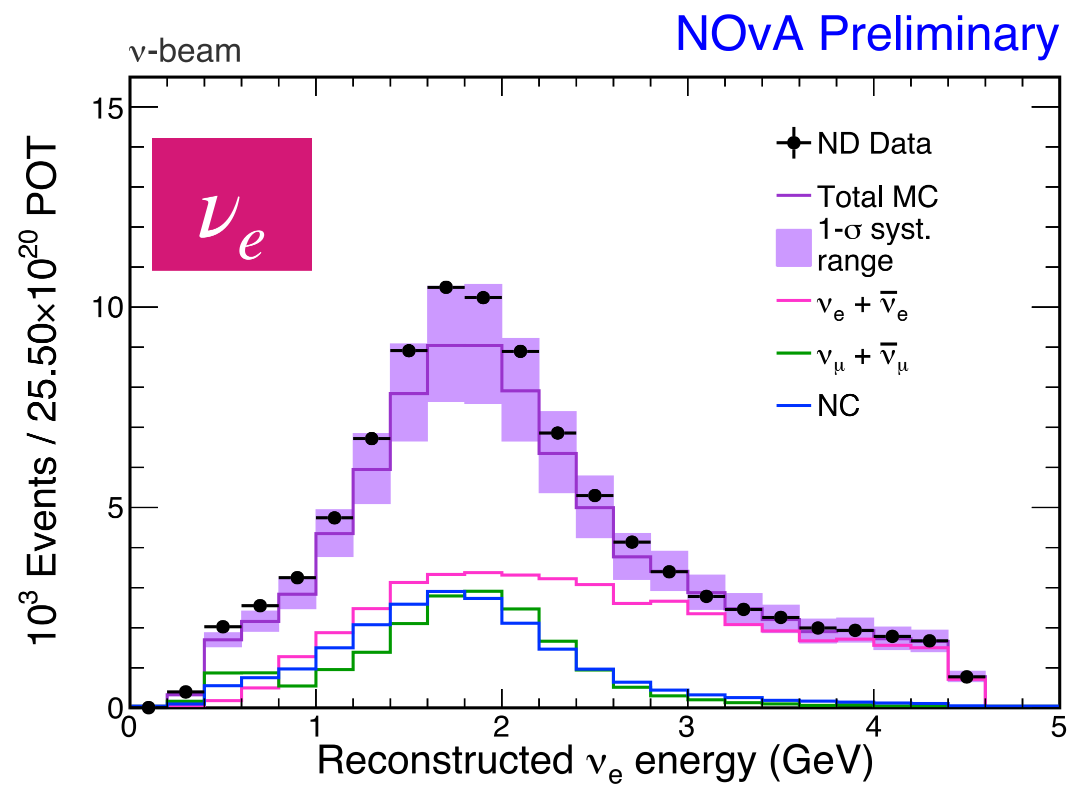


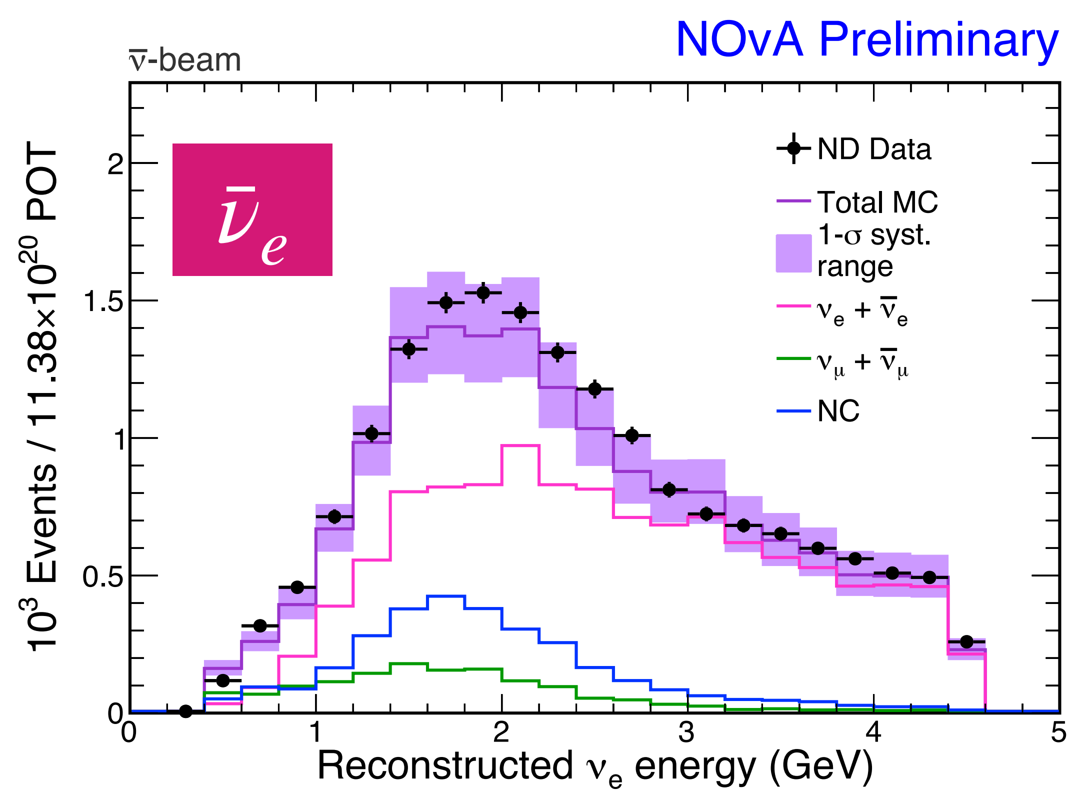


- The observed un-oscillated $\nu_\mu/\bar{\nu}_\mu$ candidates at the Near Detector
- We use this sample in predicting both the ν_μ and ν_e signal events at the Far Detector

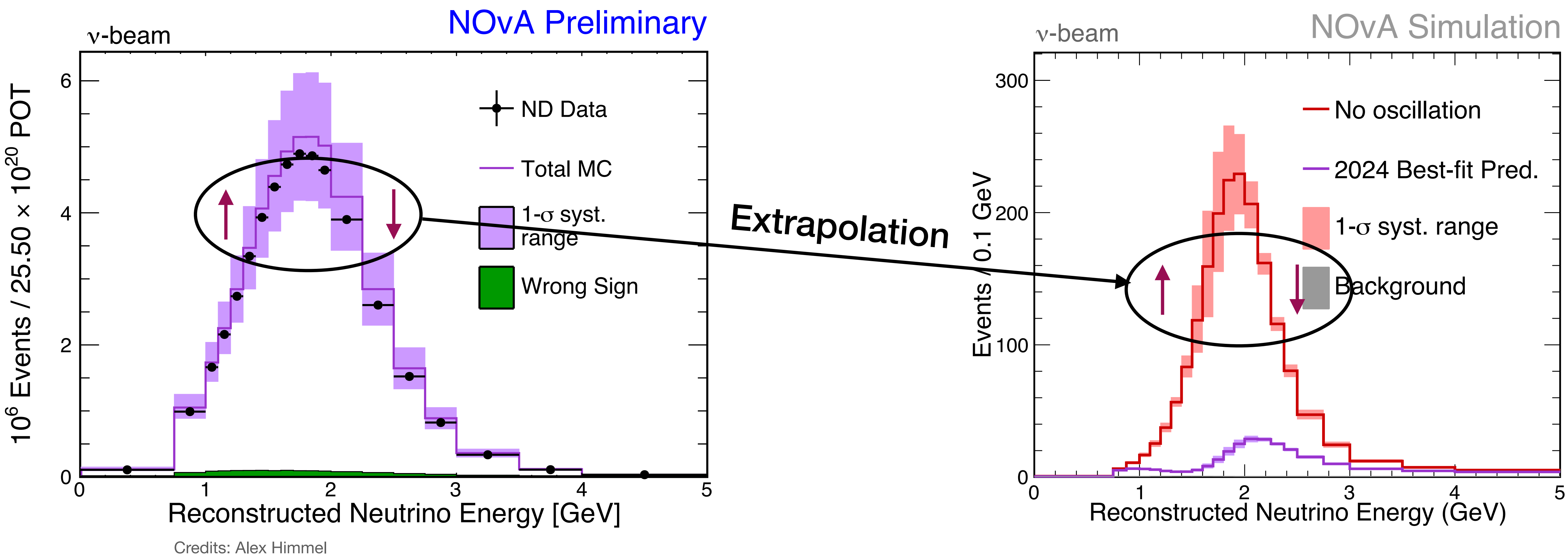
Near Detector Spectra

- The observed $\nu_e/\bar{\nu}_e$ events at the Near Detector
- Dominant background: beam $\nu_e/\bar{\nu}_e$ events
- We use these samples in predicting the background events for the ν_e appearance analysis





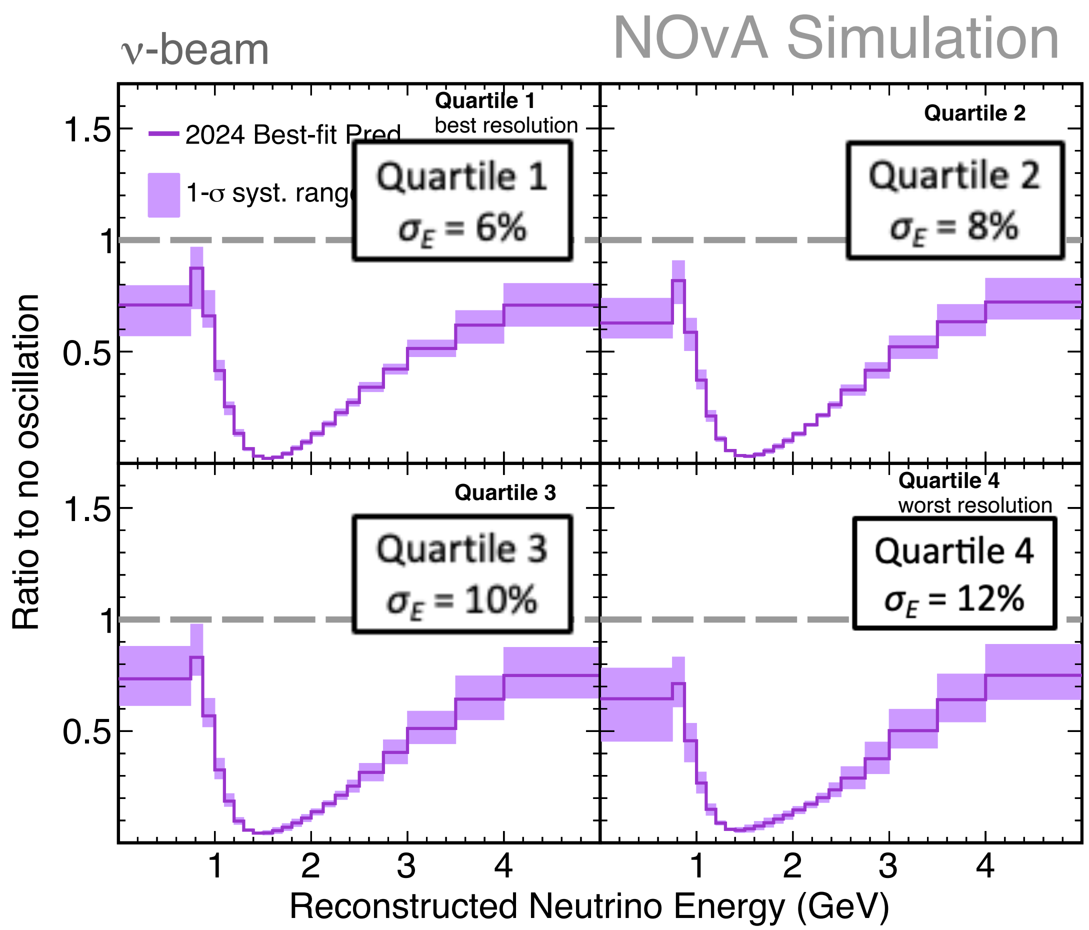
Extrapolation: Mitigating Corrections



- Correct FD simulations by observing the differences in the ND data and simulations
  - Takes into account Far/Near transformation, oscillations, and detector acceptance
- Significantly reduces the impact of systematic uncertainties
  - e.g. uncertainty on neutrino cross-sections goes down from ~15% to ~4-5%

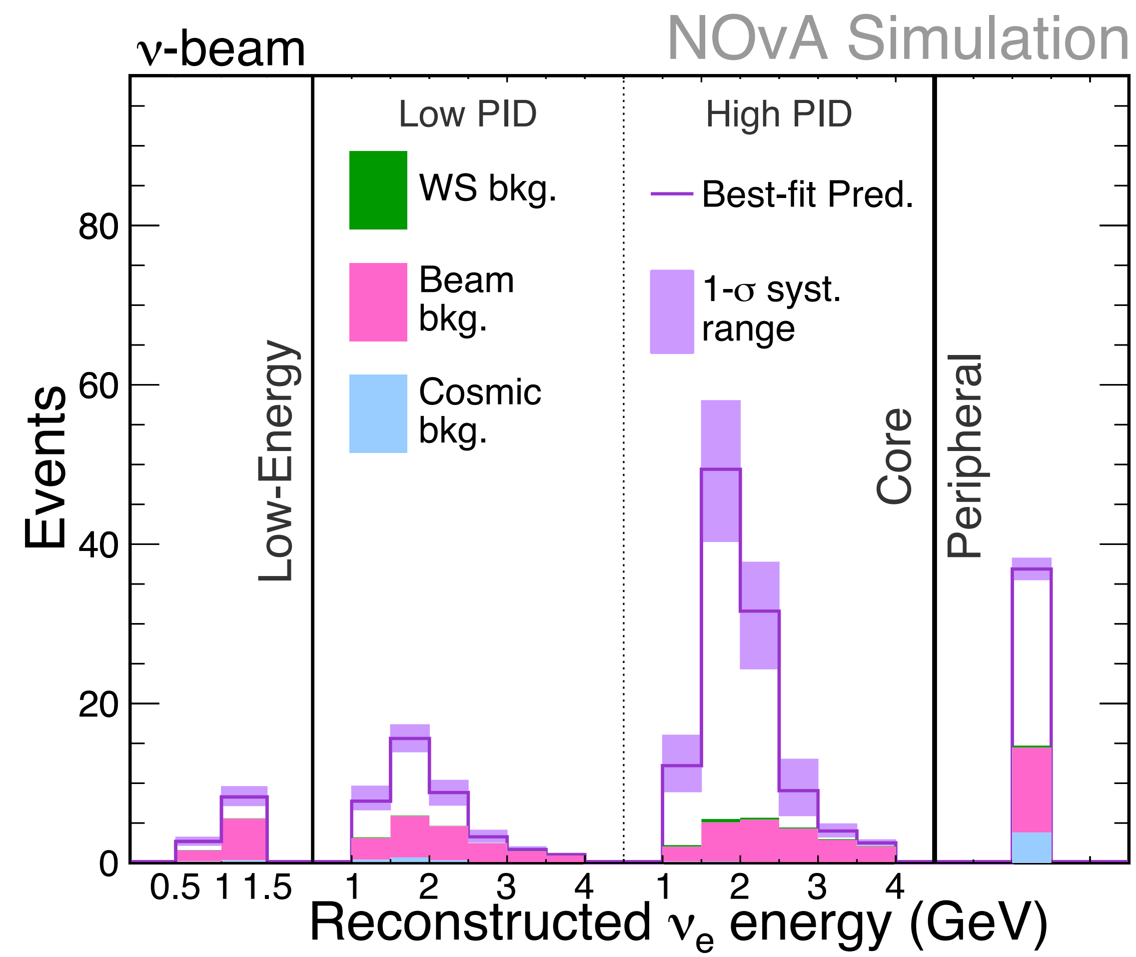
Enhancing Sensitivity to Oscillations

$\nu_\mu/\bar{\nu}_\mu$ Sample



- Sensitivity depends on the location of the oscillation dip
- Divide ν_μ and $\bar{\nu}_\mu$ samples in the bins of hadronic energy fraction (i.e. by *energy resolution*)

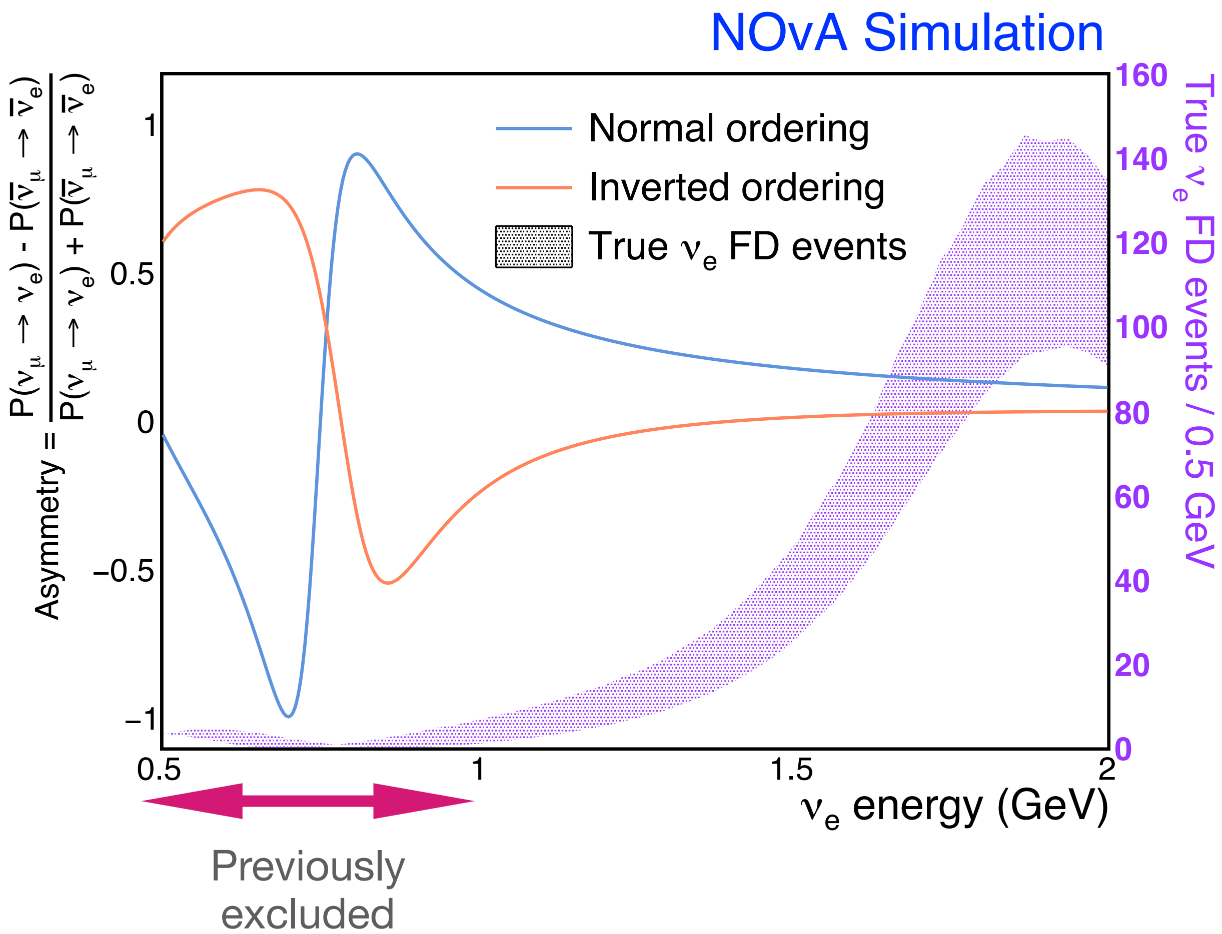
$\nu_e/\bar{\nu}_e$ Sample

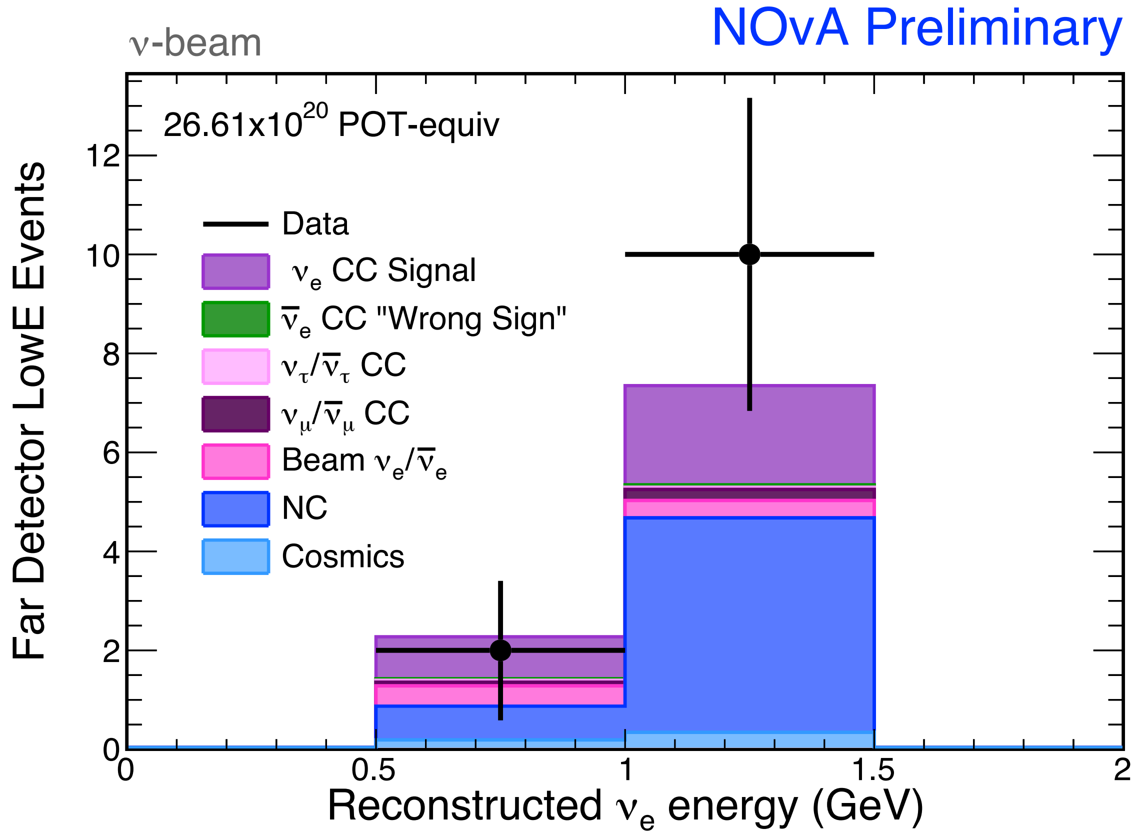


- Sensitivity depends on signal-background separation
- Divide ν_e and $\bar{\nu}_e$ samples in the bins of *purity (low PID and high PID)*

New Low Energy ν_e Sample

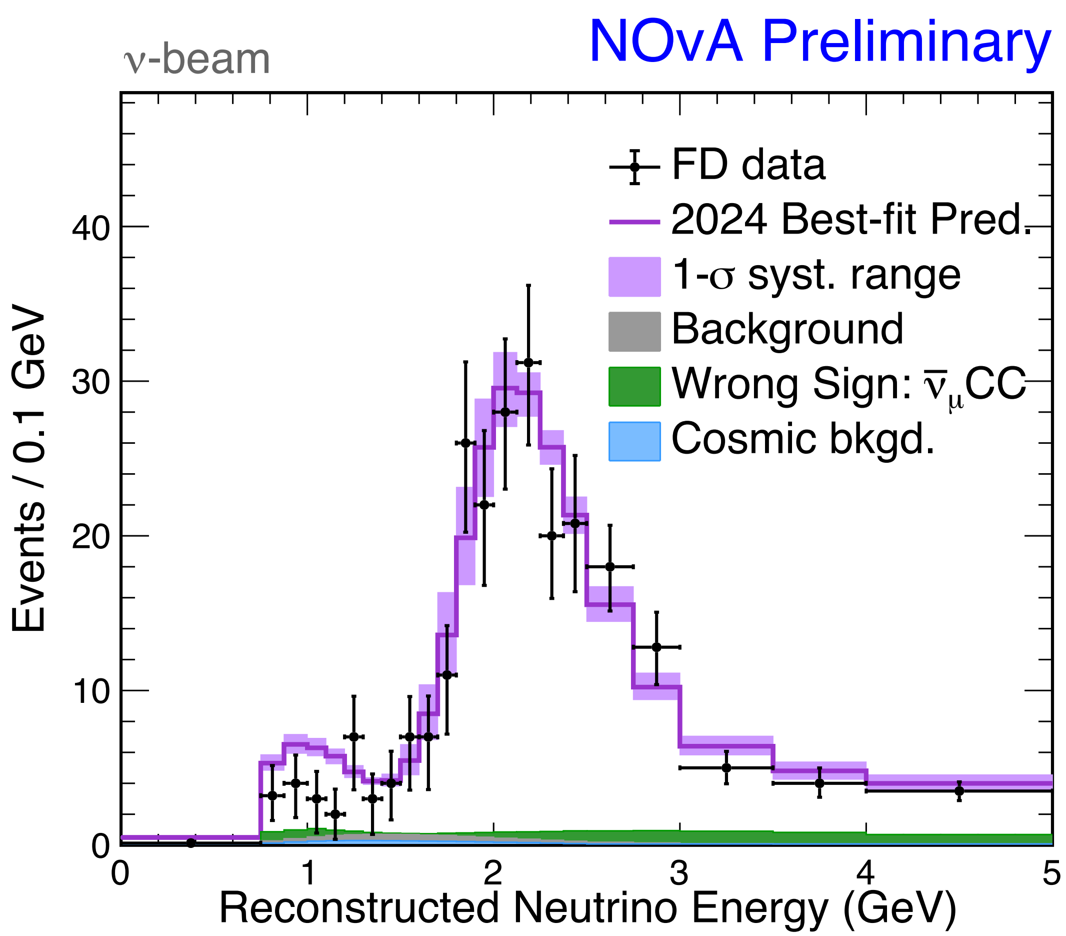
- **Developed a new selection to retain ν_e events in the low energy region** where neutrino-anti neutrino asymmetry is maximal
- Improves sensitivity to mass orderings by ~few percent (depending on the oscillation parameters)
- No low energy events for the anti-neutrino beam mode

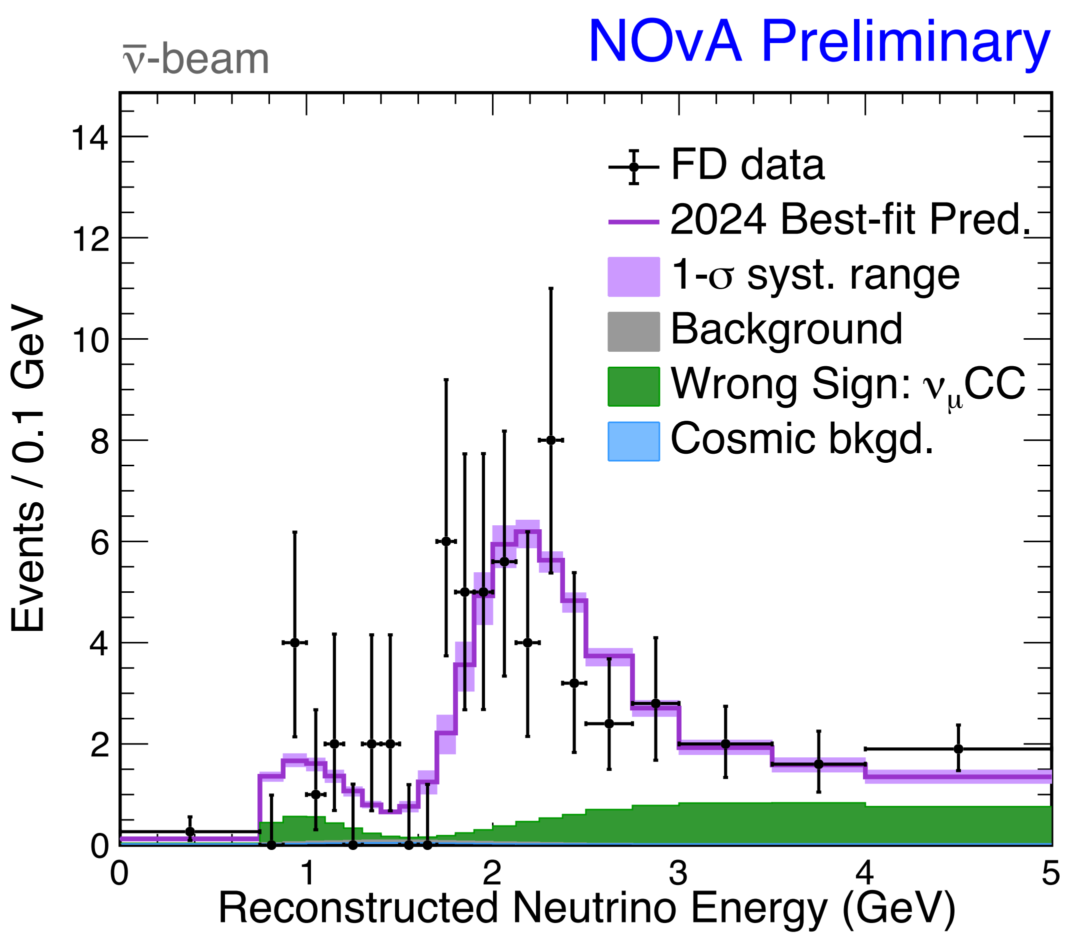




Far Detector $\nu_\mu(\bar{\nu}_\mu)$ Observations

- Observed $\nu_\mu(\bar{\nu}_\mu)$ candidates from 10 years of NOvA Data (neutrino beam exposure of 26.6×10^{20} POT and anti-neutrino beam exposure of 12.5×10^{20} POT)



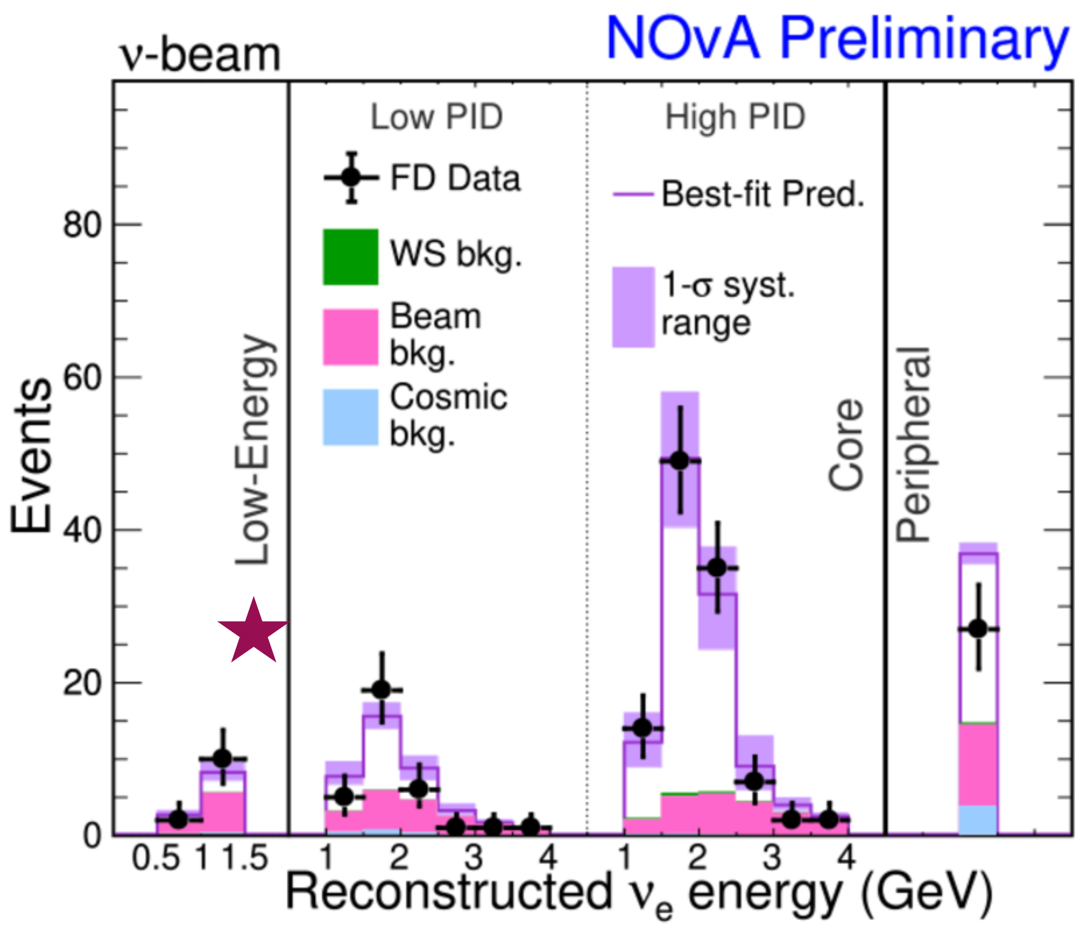


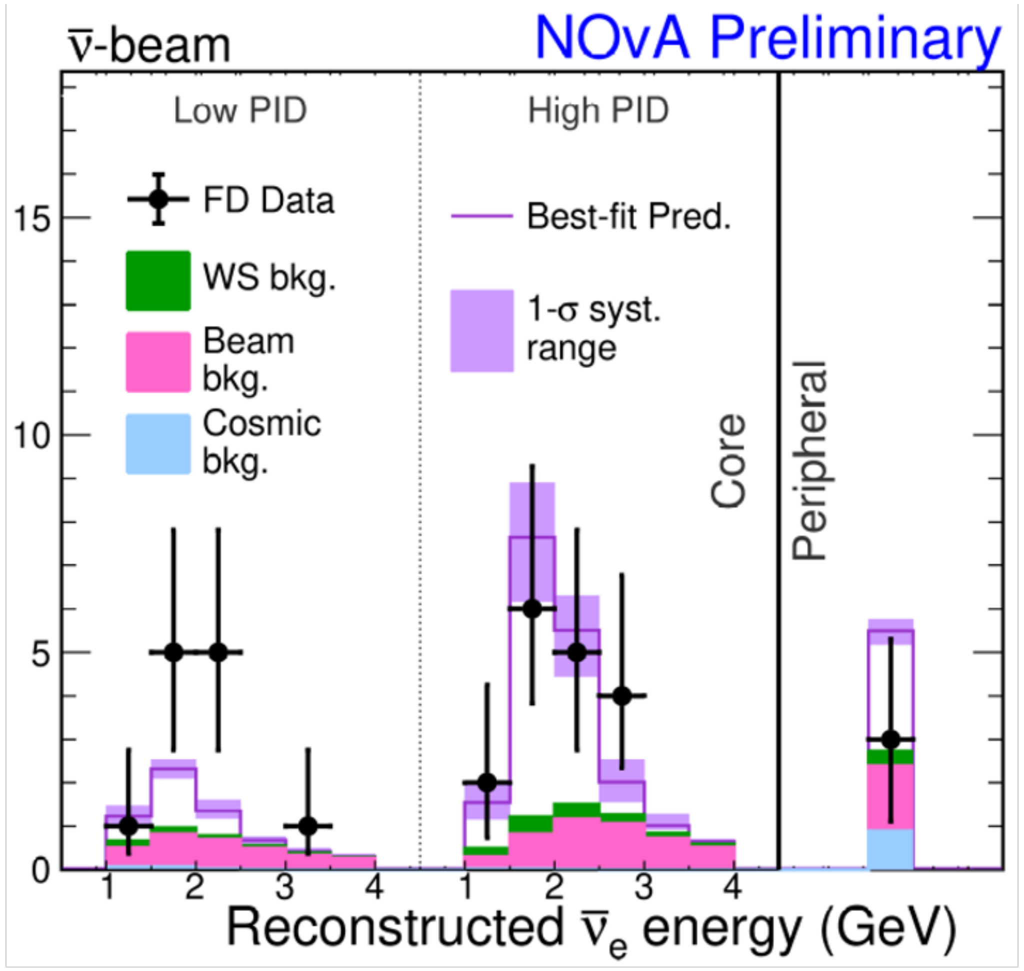
384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

Far Detector $\nu_e(\bar{\nu}_e)$ Observations

- Observed $\nu_e(\bar{\nu}_e)$ candidates from 10 years of NOvA Data (neutrino beam exposure of 26.6×10^{20} POT and anti-neutrino beam exposure of 12.5×10^{20} POT)



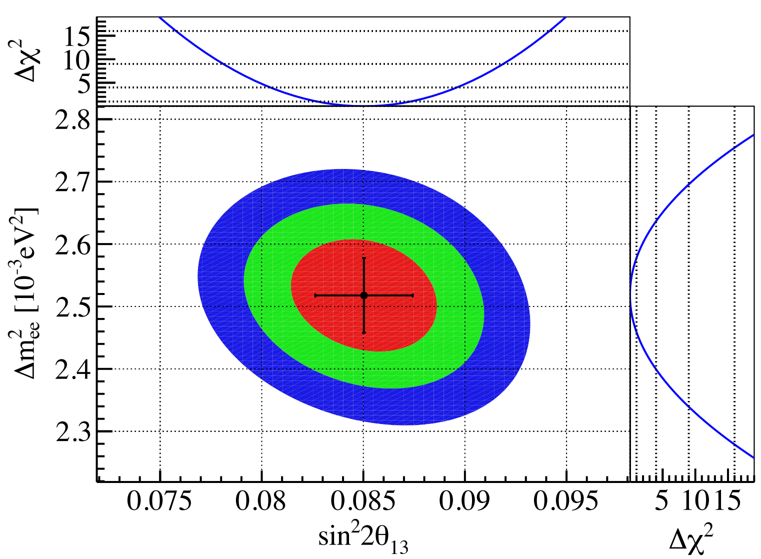


181 ν_e data candidates
(61.7 background)

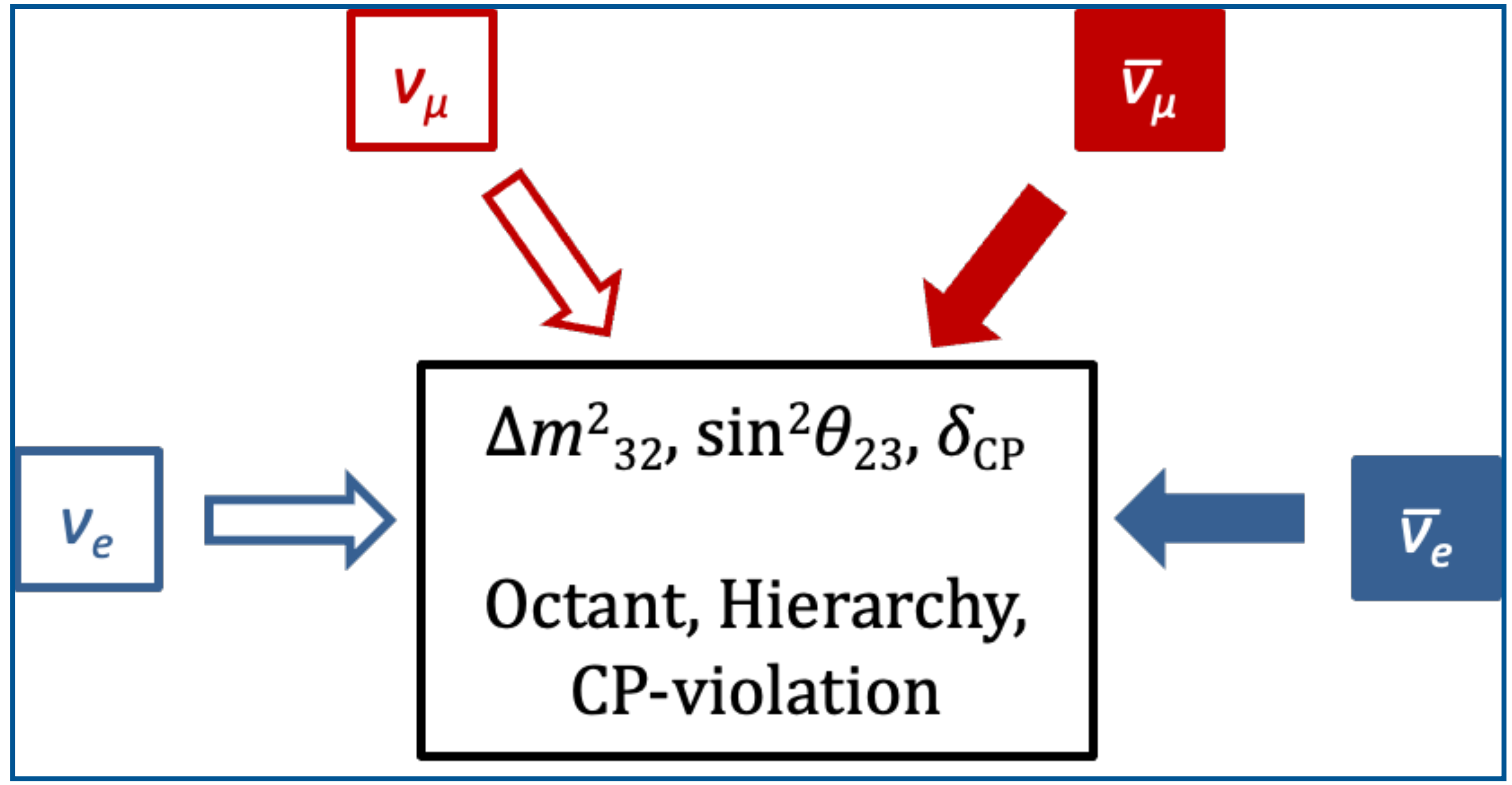
32 $\bar{\nu}_e$ data candidates
(12.2 background)

Fitting Procedure

- We perform a joint fit to $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance data to extract oscillation parameters
- External constraints on solar parameters
- Reactor constraints on θ_{13}:
  - Unconstrained
  - Daya Bay 1D reactor constraint: $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$
  - Daya Bay 2D $(\Delta m^2_{32}, \theta_{13})$ constraint



Phys. Rev. Lett. 130, 161802



Credits: Alex Himmel

Bayesian

Markov Chain Monte Carlo
(marginalization)

Bayesian Credible Intervals

(technique described in arXiv:2311.07835)

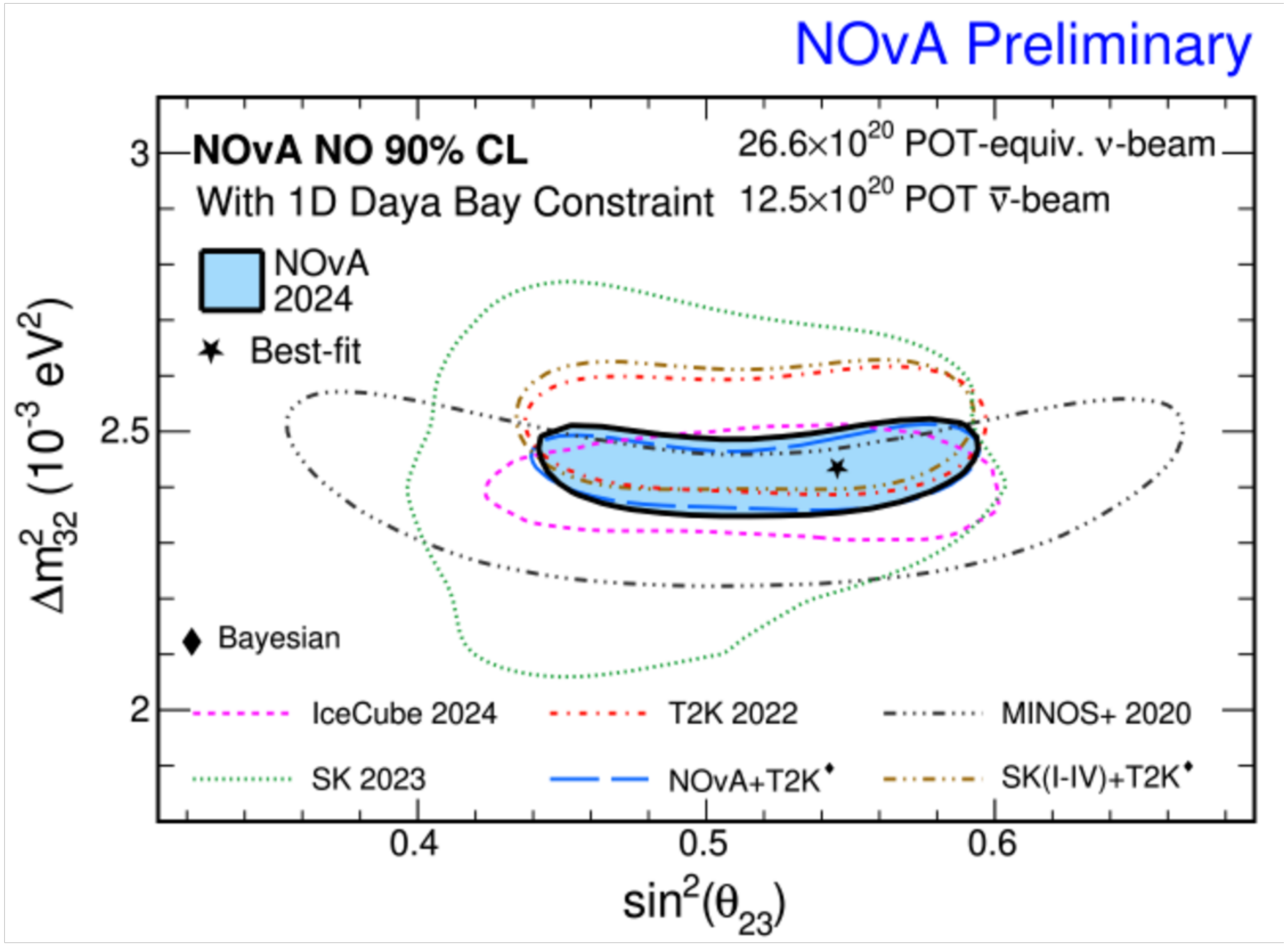
Frequentist

χ^2 Minimization
(profiled Feldman-Cousins)

Frequentist Confidence Regions

(technique described in arXiv:2207.14353)

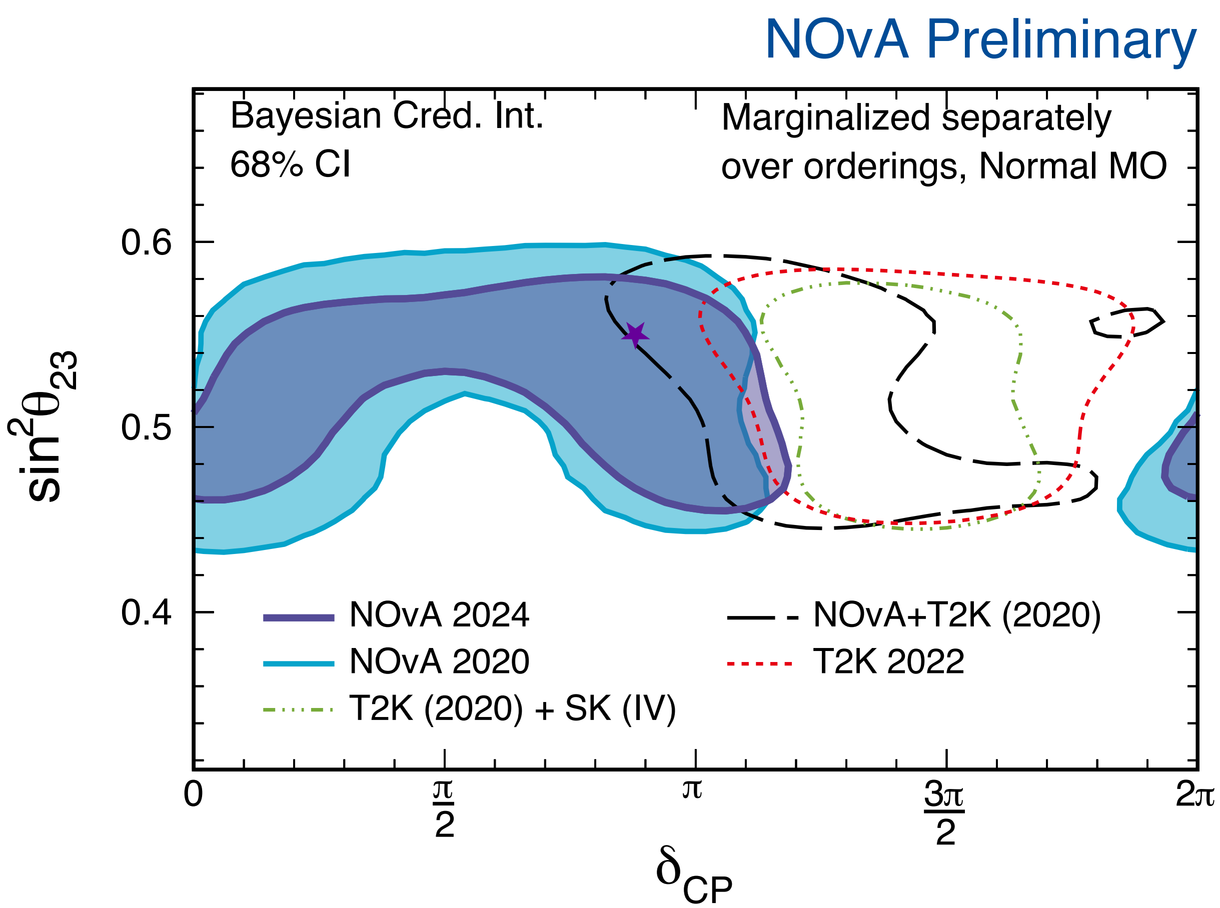
Results: I

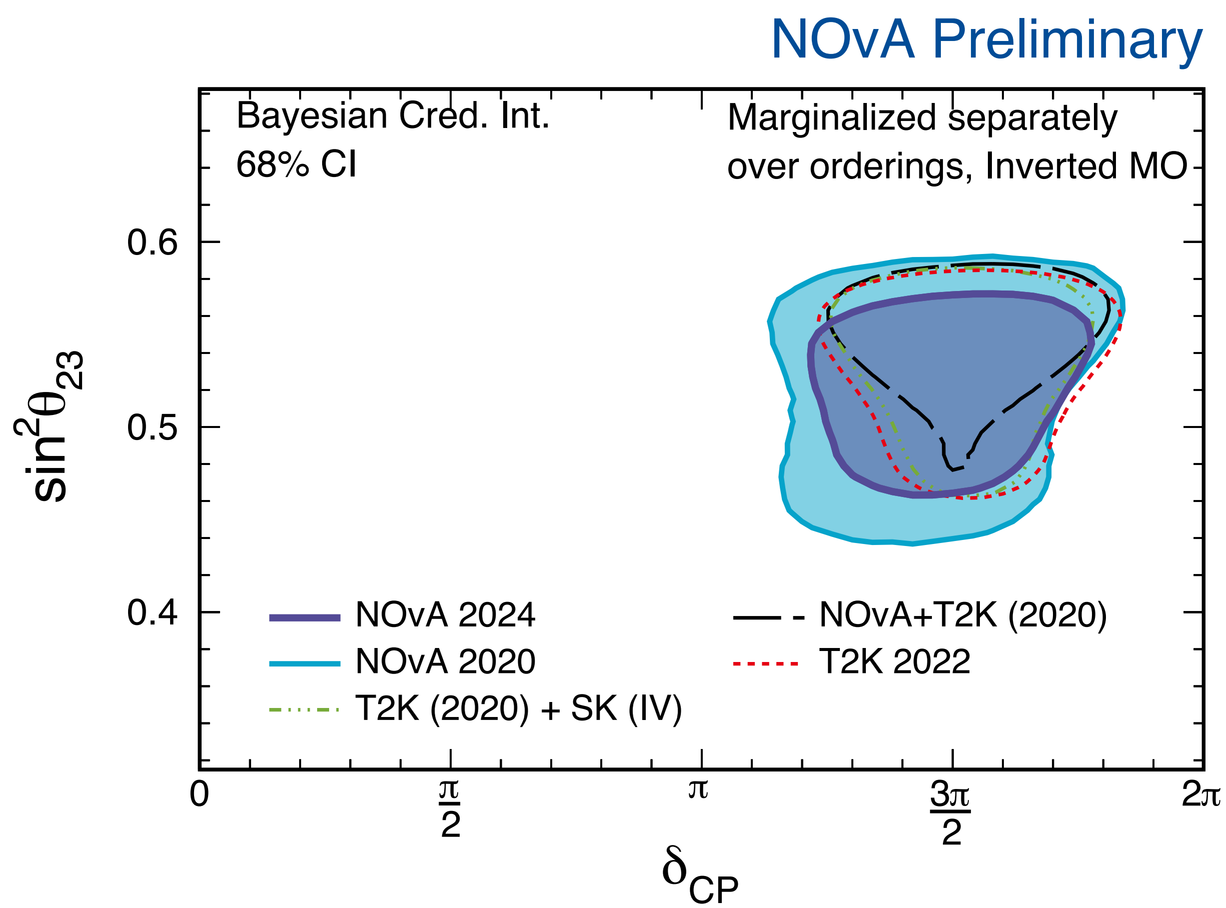


	Frequentist results (w/ Daya Bay 1D θ_{13} constraint)			
	Normal MO		Inverted MO	
Δm^2_{32} / 10^{-3} eV^2	+2.433	+0.035 −0.036	−2.473	+0.035 −0.035
$\sin^2\theta_{23}$	**0.546**	+0.032 −0.075	0.539	+0.028 −0.075
δ_{CP}	**0.88 π**		1.51 π	
Rejection significance (σ)			1.36	

- NOvA's measurements consistent with the rest of the accelerator and atmospheric experiments
- Δm^2_{32} best-fit lies in the normal mass ordering (NO)
- $\sin^2(\theta_{23})$ best-fit value lies in the upper octant

Results: II

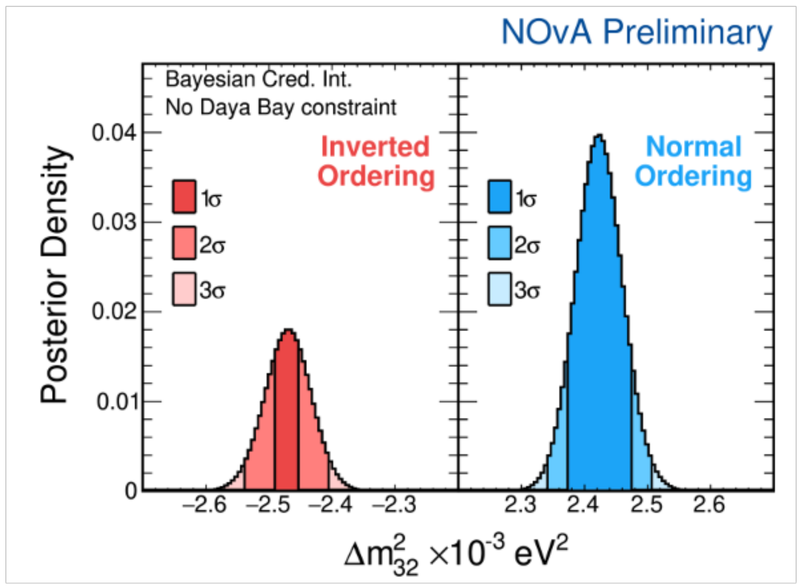




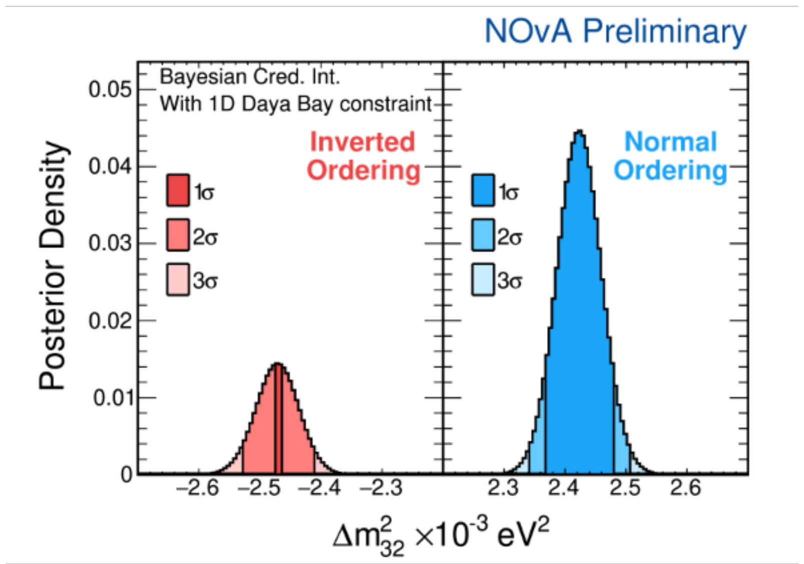
- NOvA data disfavors $\delta_{CP} = 3\pi/2$ in NO and $\delta_{CP} = \pi/2$ in IO
- The new NOvA measurements of δ_{CP} are consistent with our previous (2020) analysis
- The T2K, joint NOvA+T2K results favor different δ_{CP} regions in NO, same in IO

Synergy With Reactor Measurements

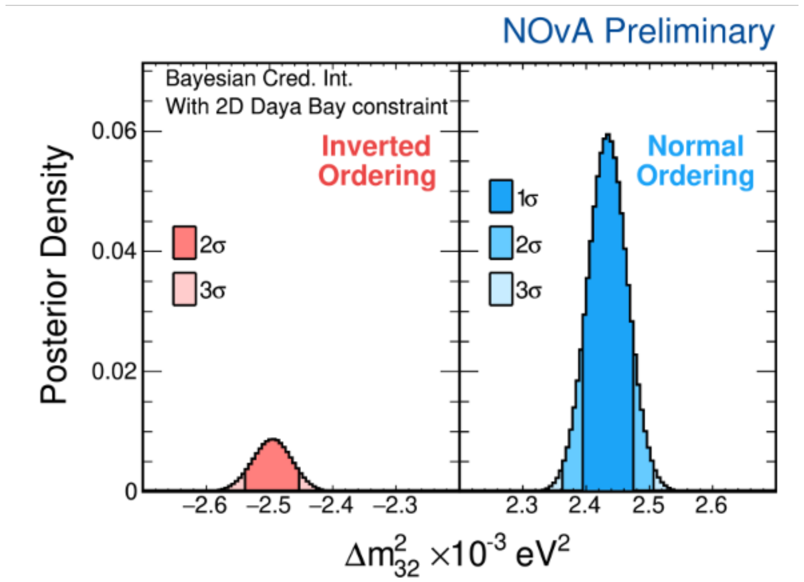
- **NOvA data has a mild preference for the normal mass ordering**
- **Preference enhances with 1D and 2D reactor constraints**



No reactor constrains



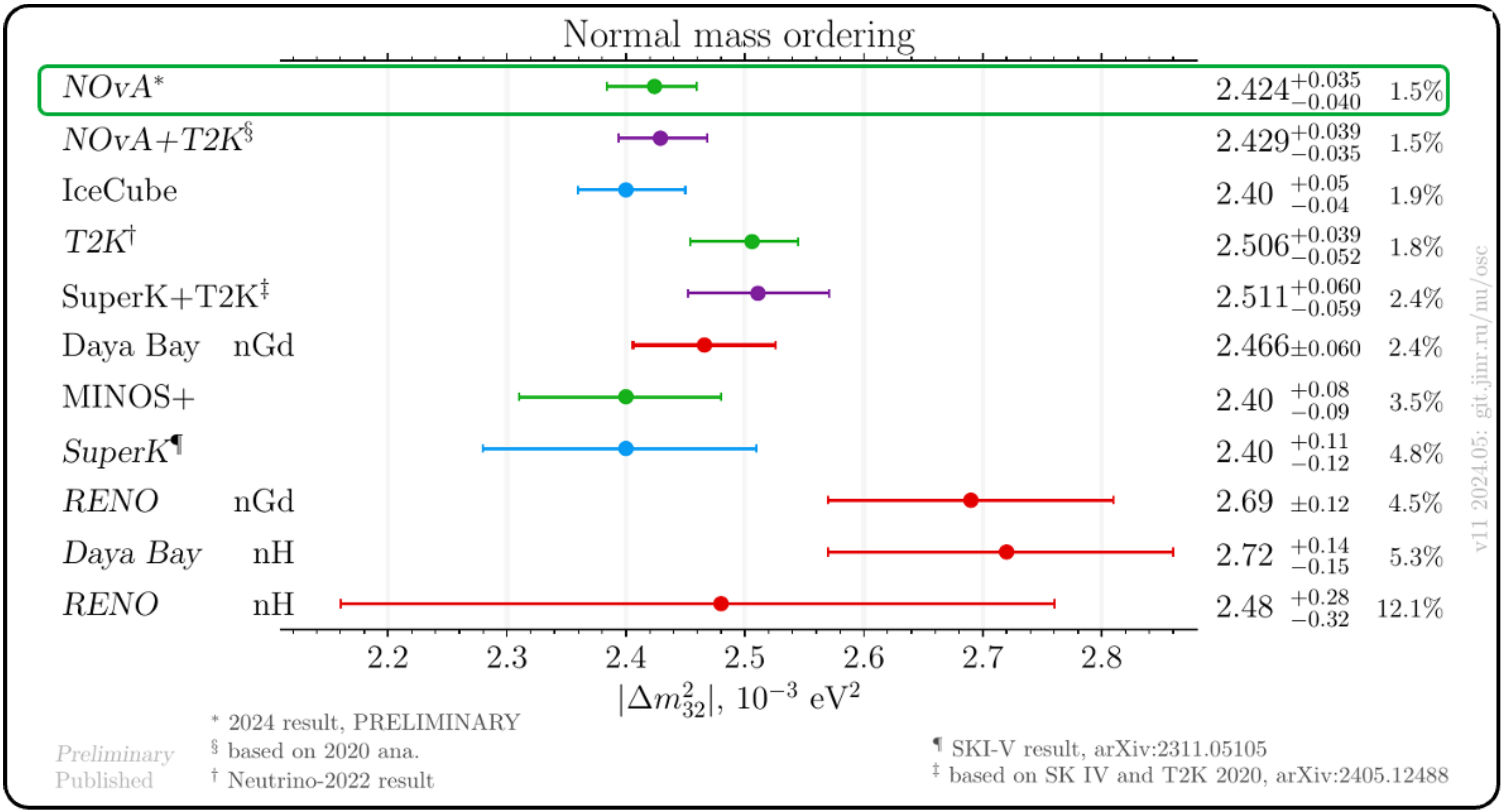
Daya Bay 1D constraint



Daya Bay 2D constraint

	No Constraint		1D Constraint		2D Constraint	
	Prob	BF	Prob	BF	Prob	BF
Normal Ordering Preference	69%	2.2	76%	3.2	87%	6.8

Results Contd.



NOvA produced the most precise (~1.5%) measurement of Δm^2_{32}.

Conclusions

- Latest three-flavor neutrino oscillation results from 10 years of NOvA data with doubled neutrino beam dataset (compared to 2020)
- NOvA data prefers upper octant with reactor constraints on θ_{13} (prob=69%)
- Mild preference to normal mass ordering (posterior prob. = 87%)
- The most precise single experiment measurement of Δm^2_{32} (precision=1.5%)
- Frequentist best-fit values

	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	

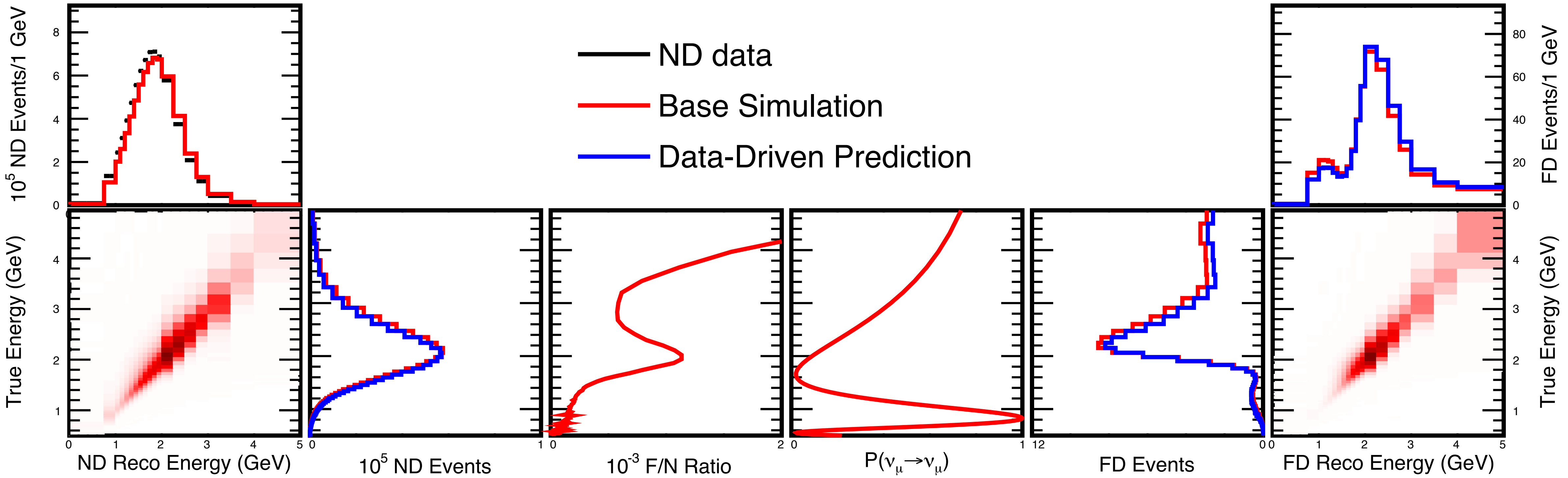
The NOvA Collaboration

Thank you for your attention!

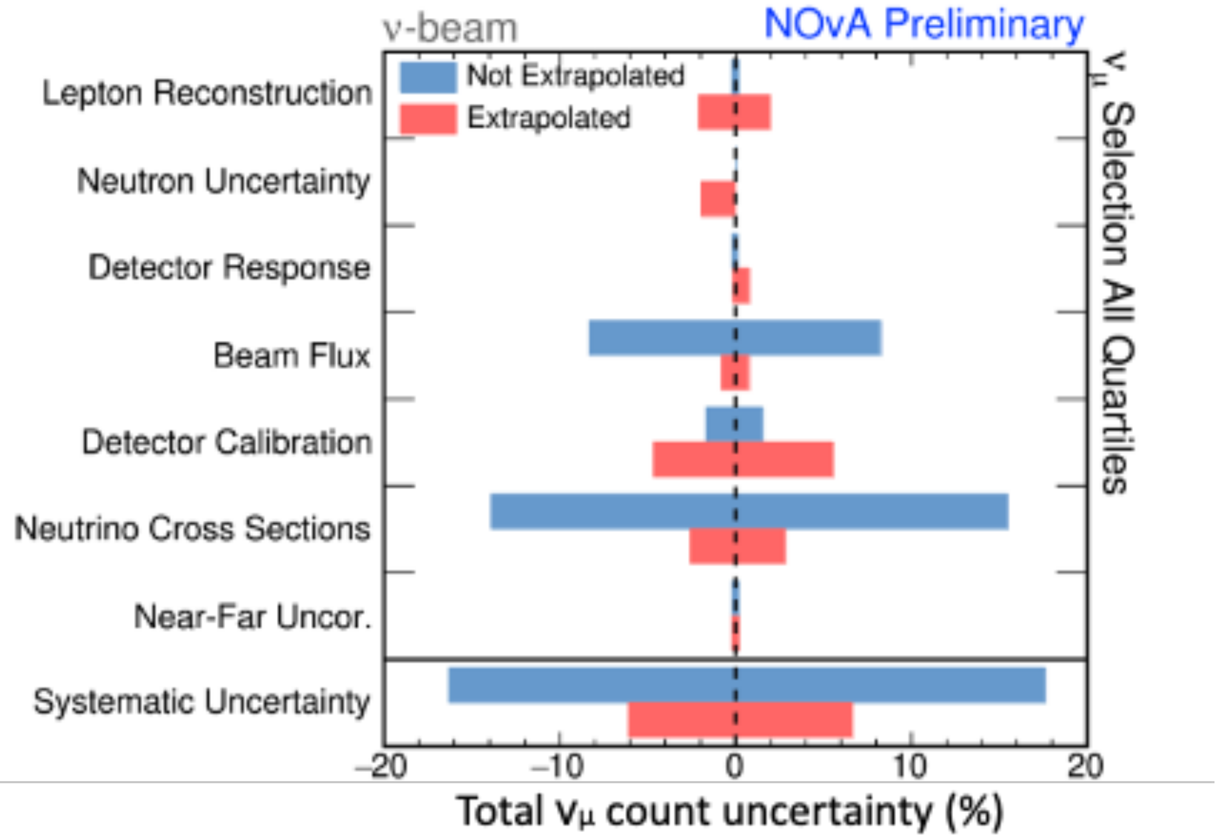
Back Up

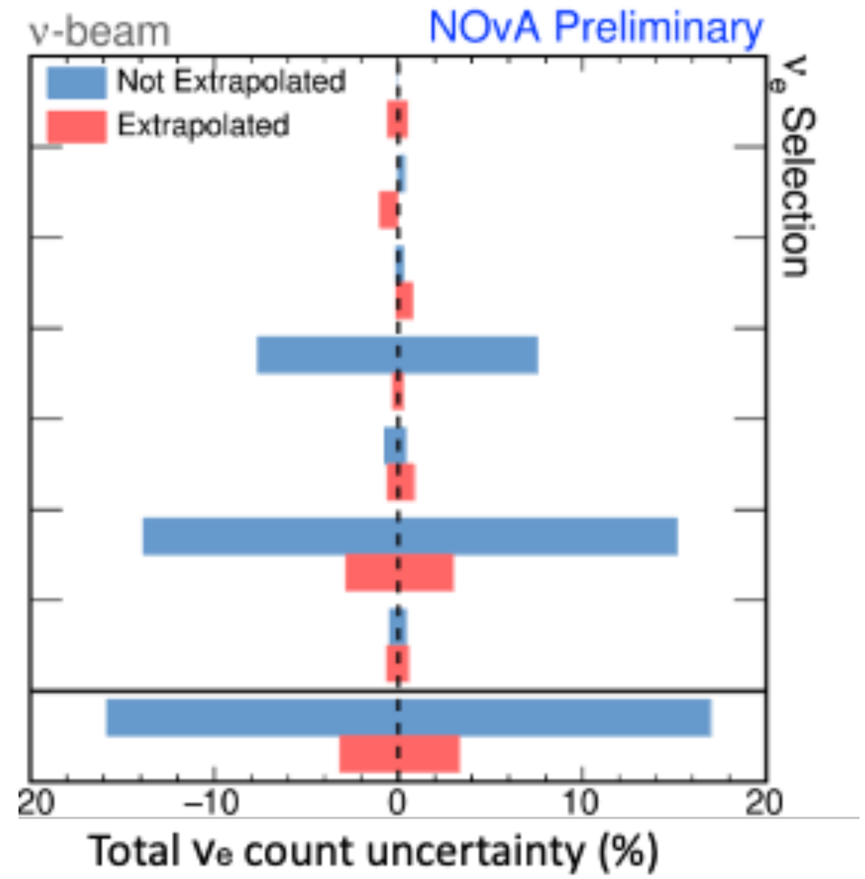
Near-to-Far Extrapolation

- Functionally identical detectors cancel out systematic uncertainties on the best fit neutrino oscillation parameters
- The near detector (ND) data-MC differences are extrapolated in true energy bins to provide data-driven predictions of un-oscillated ν_μ ($\bar{\nu}_\mu$) and oscillated ν_e ($\bar{\nu}_e$) events at the far detector (FD)
- The ν_μ ($\bar{\nu}_\mu$) extrapolation is divided into 4 hadronic energy fraction quartiles to improve the sensitivity of the experiment
- Extrapolation is further divided into 3 bins of final state lepton transverse momentum (p_t) which takes into account the neutrino interaction mis-modeling and the differences in ND and FD

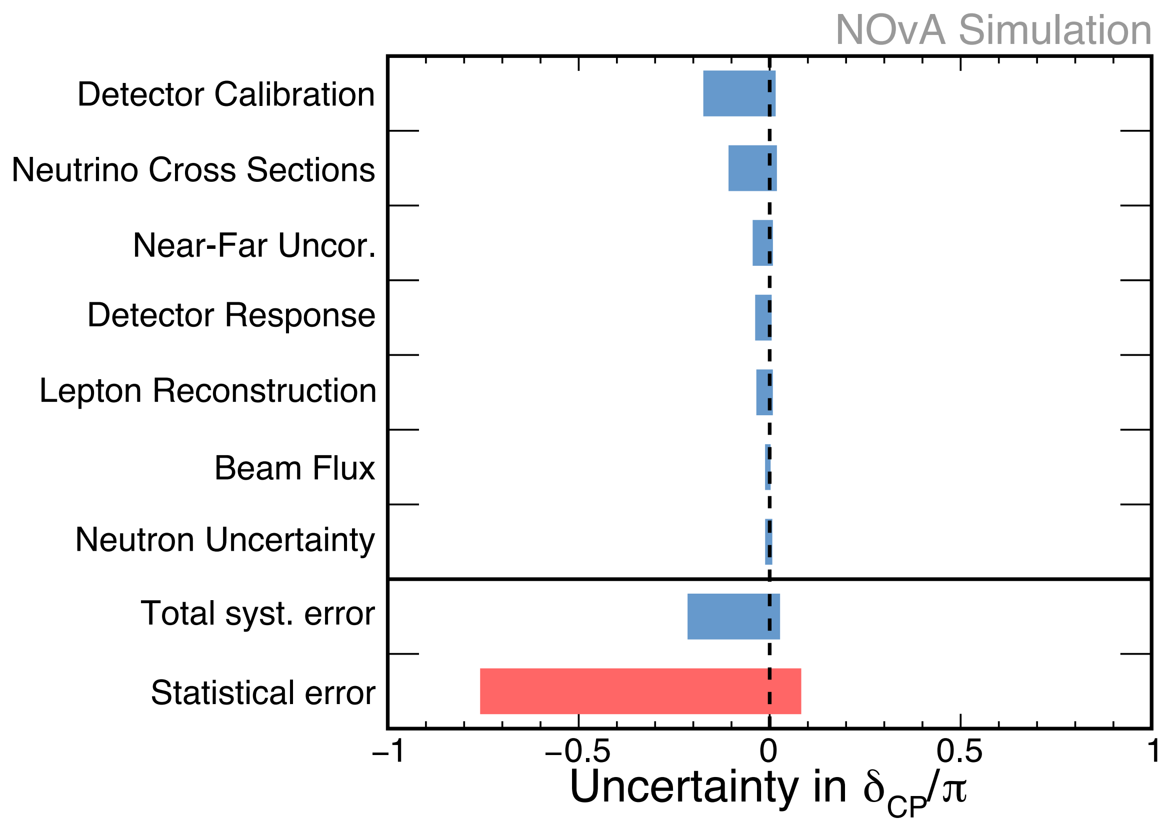


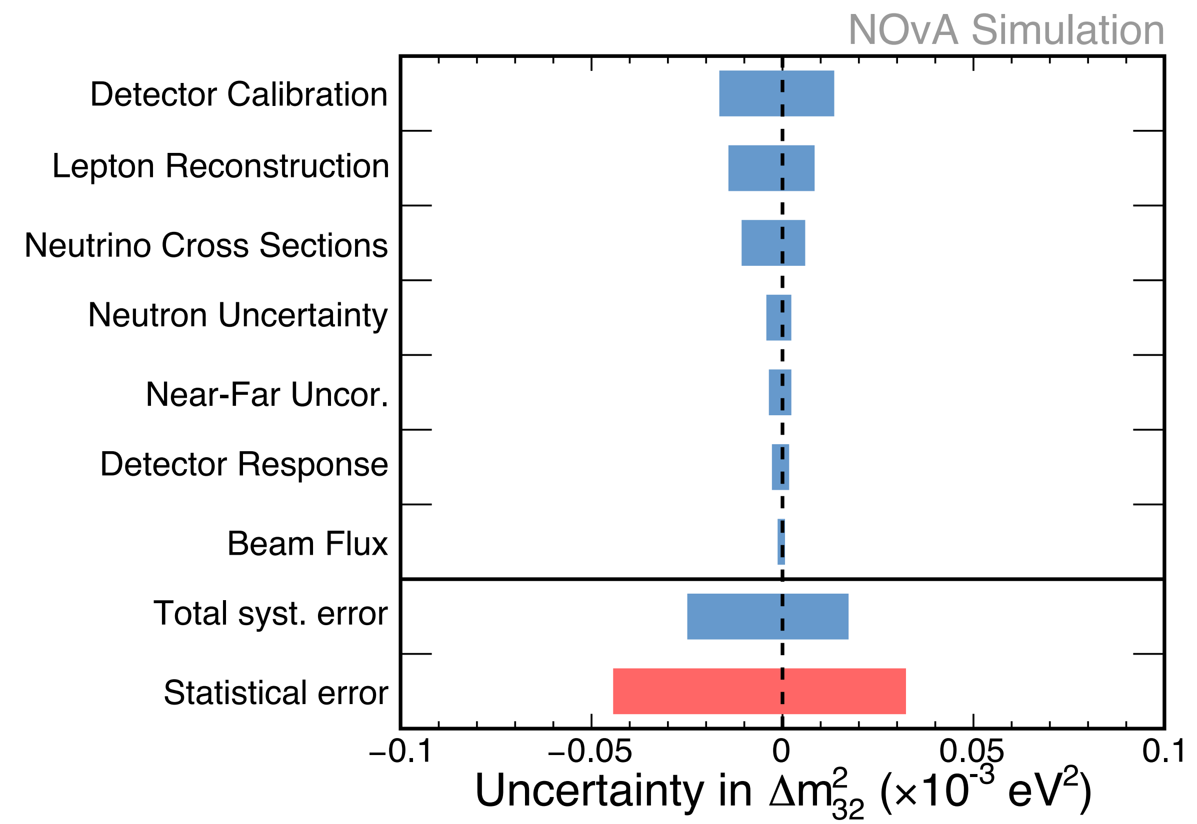
Uncertainties on FD Predictions

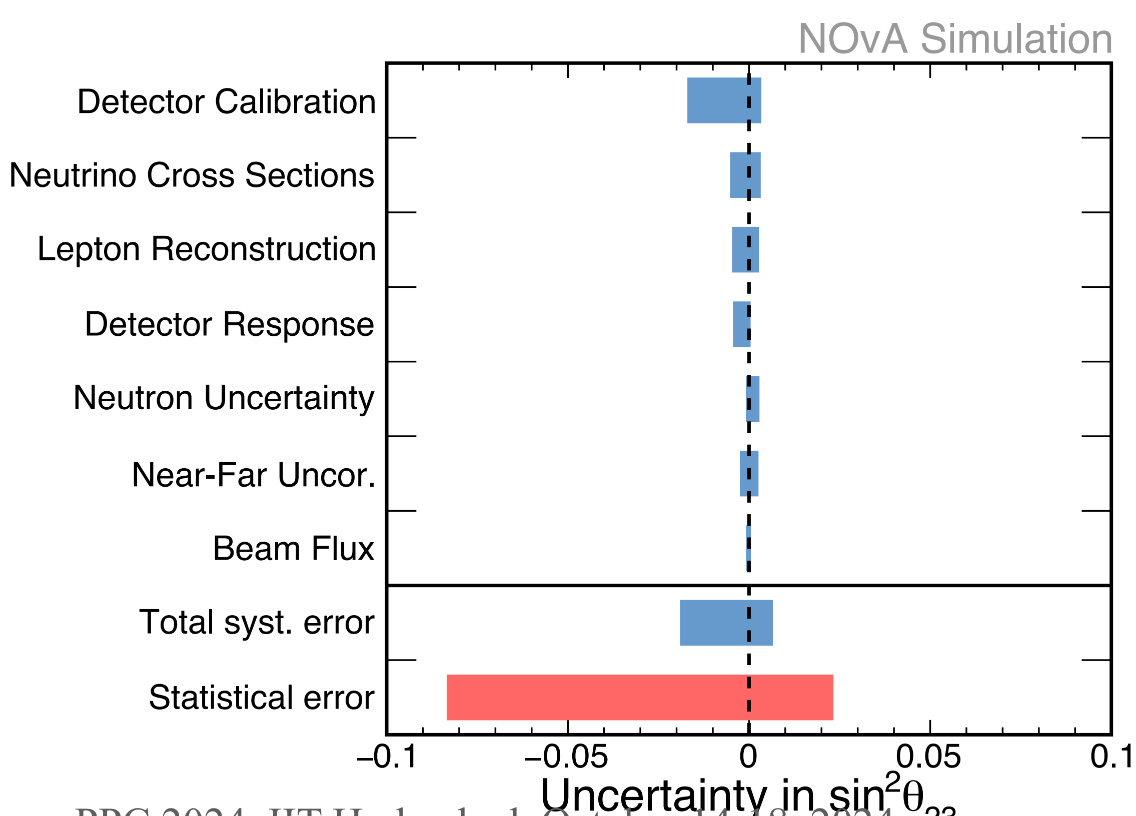




Uncertainties on Oscillation Parameters



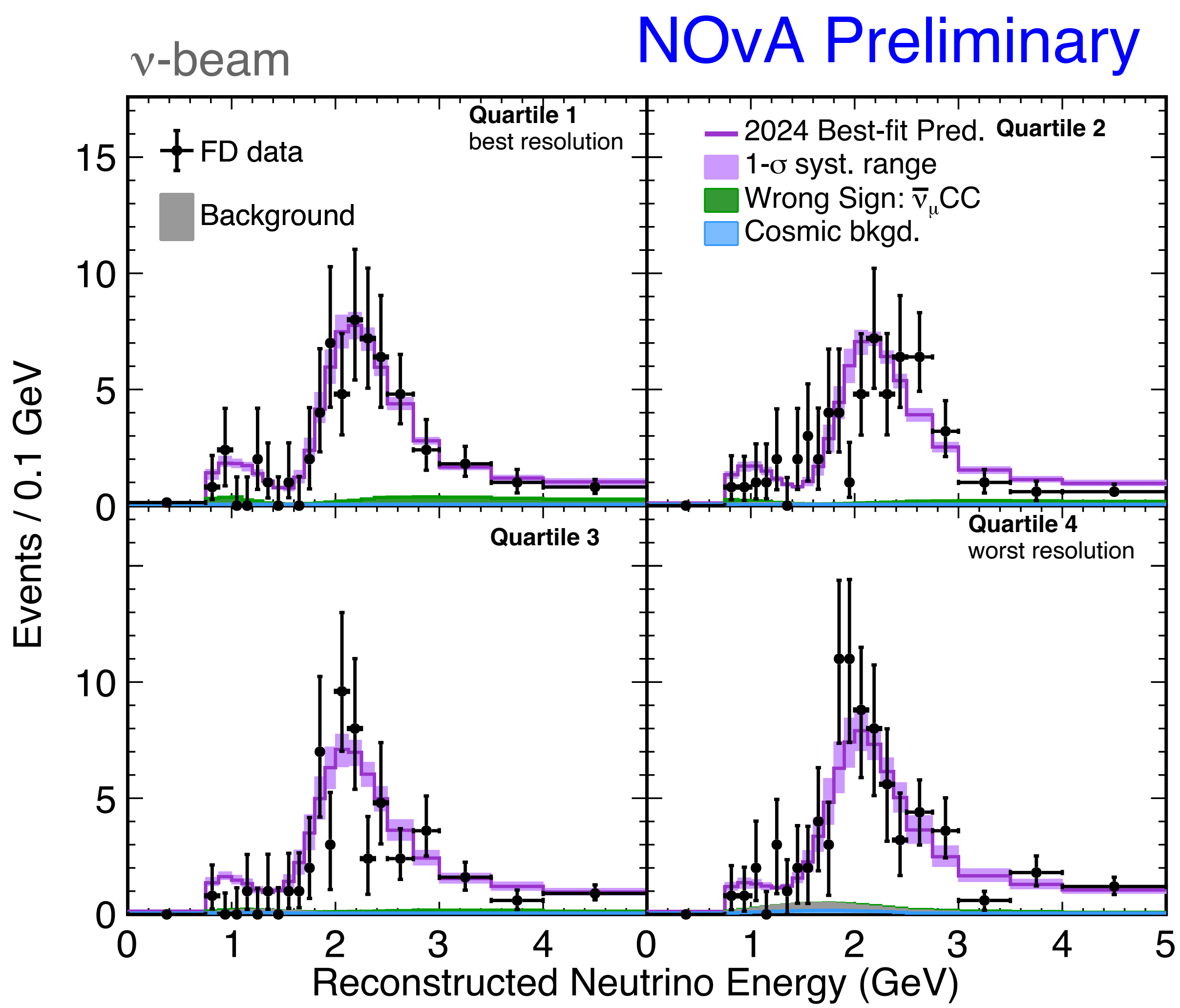


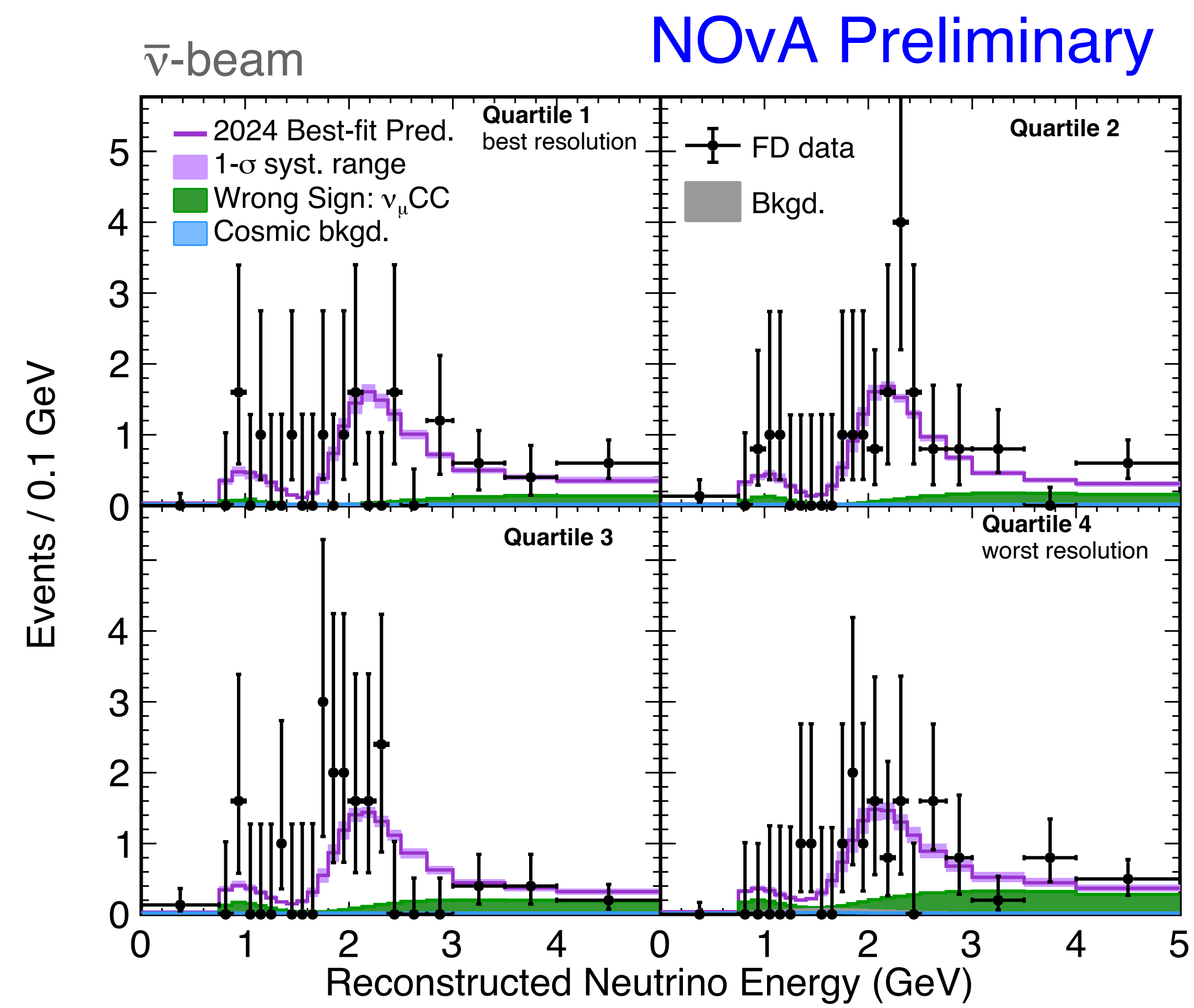


Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ $(\times 10^{-3}\ \mathrm{eV}^2)$
Beam Flux	+0.00042 / -0.00069	+0.0012 / -0.011	+0.00053 / -0.0012
Detector Calibration	+0.0033 / -0.017	+0.014 / -0.17	+0.013 / -0.016
Detector Response	+0.00031 / -0.0043	+0.004 / -0.037	+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 $\lvert\Delta m^2_{32}\rvert$ $(\times 10^{-3}\ \mathrm{eV}^2) = 2.43$.

FD $\nu_\mu(\bar{\nu}_\mu)$ Events By Quartiles





Ratios to No Oscillations