FERMILAB-SLIDES-24-0148-PPD

Three-Flavor Neutrino Oscillations at NOvA

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

Louise Suter, Fermi National Accelerator Laboratory, US

On behalf of the NOvA Collaboration

New Perspectives Meeting 2024
Fermi National Accelerator Laboratory
July 8-9, 2024

The NOvA Experiment

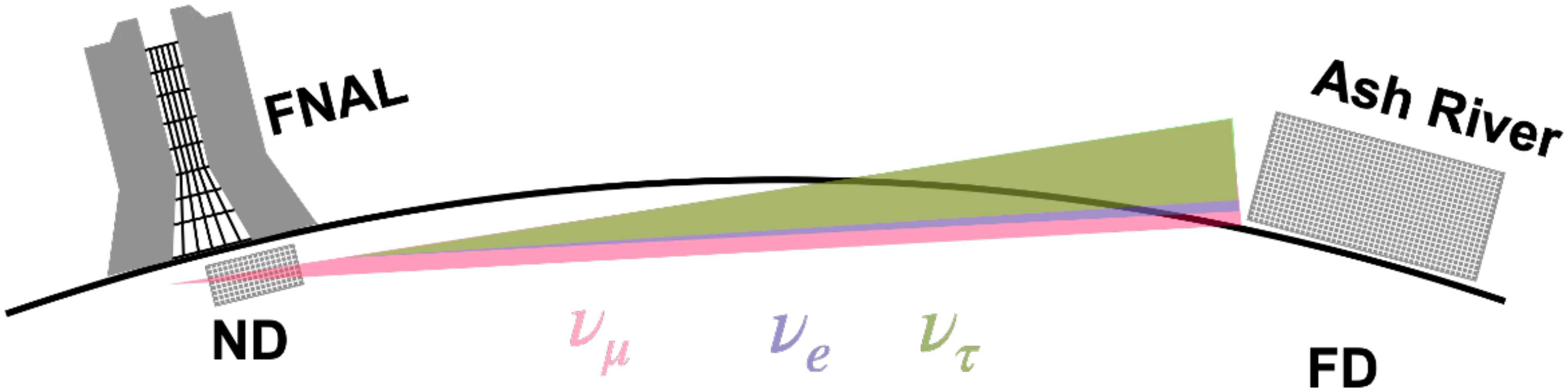
- **N**uMI **O**ff-axis ν_e **A**ppearance Experiment
  - NuMI**:** Neutrinos at the Main Injector
  - Off-axis: Detectors situated 14.6 mrad off-axis to beam direction
  - $\nu_e(\bar{\nu}_e)$ appearance and $\nu_\mu(\bar{\nu}_\mu)$ dis-appearance
  - Functionally identical liquid scintillation detectors, located 809 km apart
- **Primary Goals**:
  - Measure neutrino oscillation parameters
  - Resolve neutrino mass ordering
  - Resolve octant degeneracy
  - Measure δ_{CP}, the CP-violating phase

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

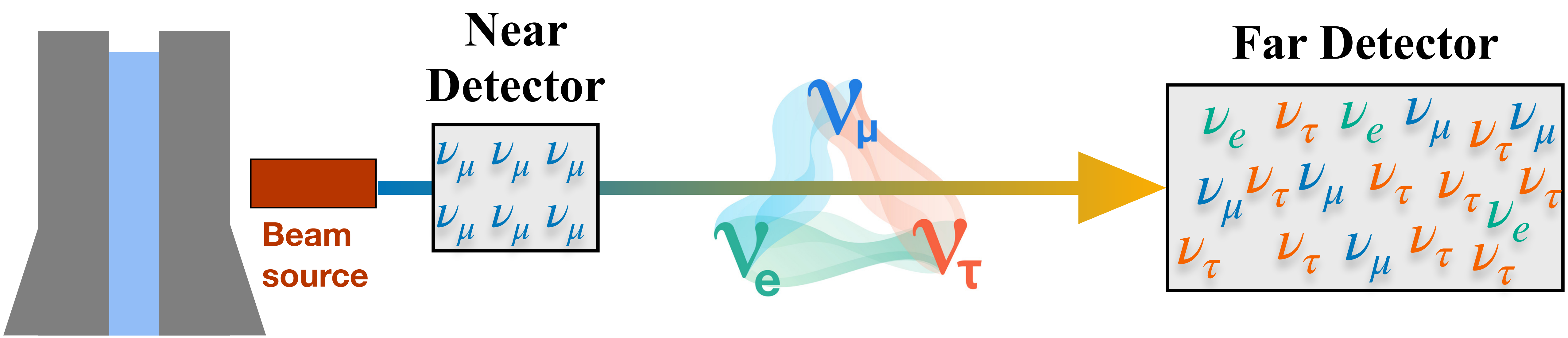
Beyond Neutrino Oscillations

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

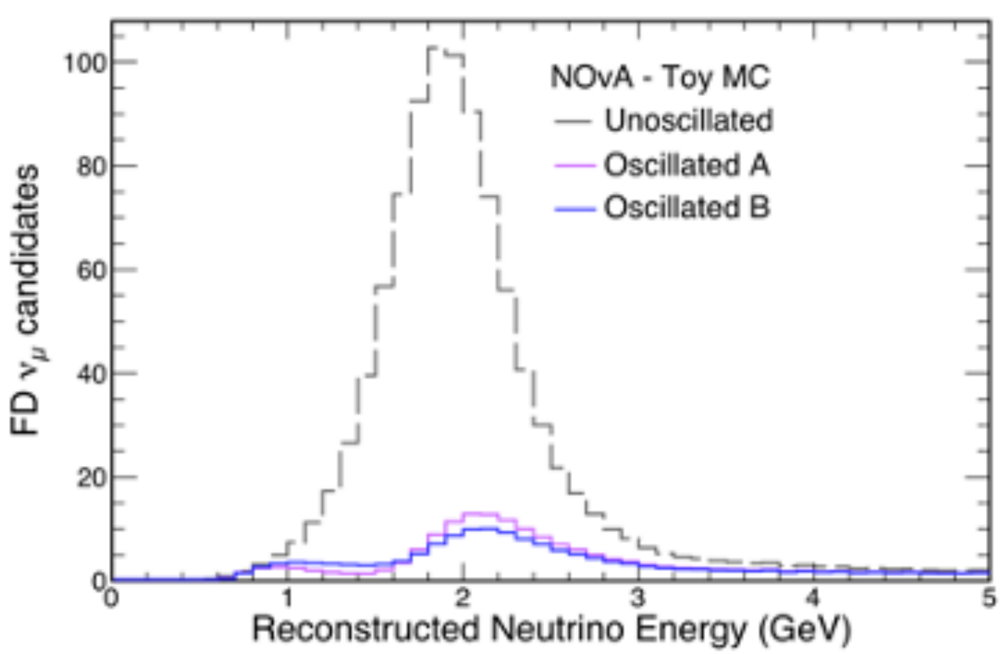
Check out Anna Cooleybeck's talk

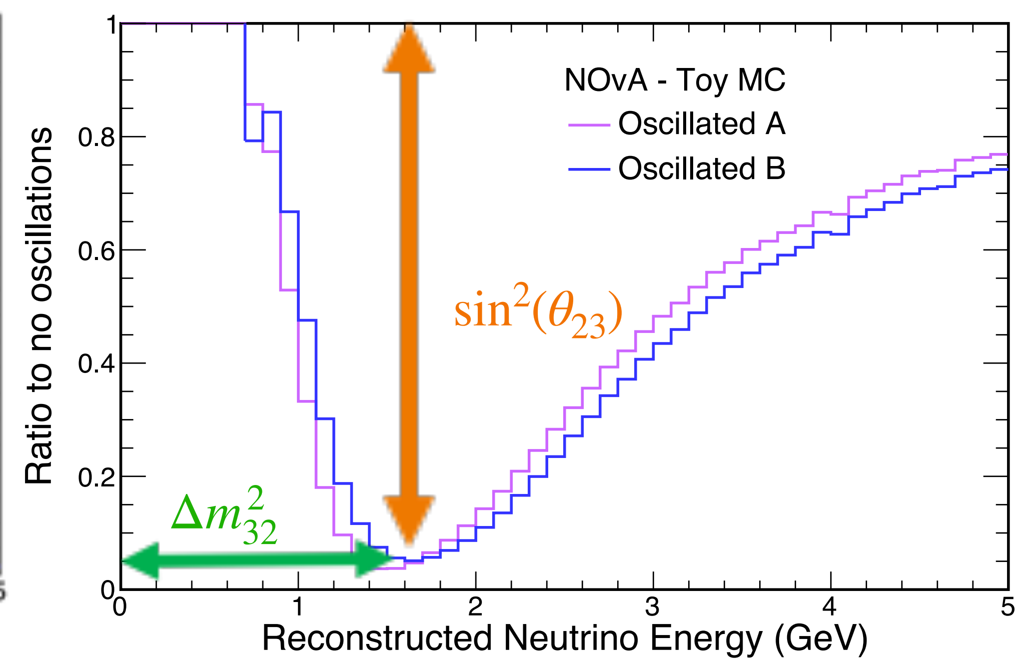


How to Measure Neutrino Oscillations?



- We compare the far detector neutrino candidates with simulated predictions to extract neutrino oscillation parameters

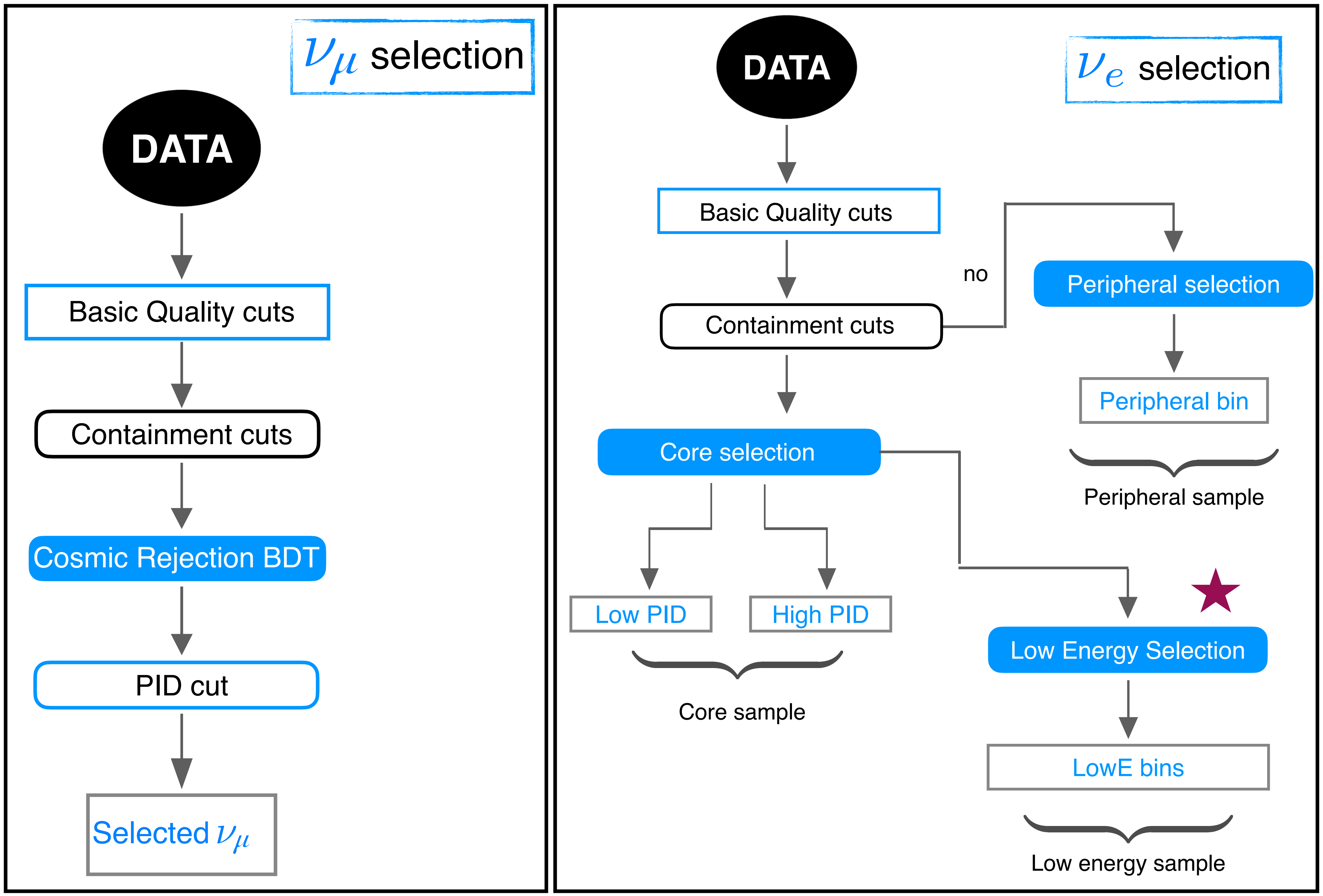




- The oscillation dip: measure of θ_{23}
- The location of oscillation dip (frequency of oscillations): measure of Δm^2_{32}

Oscillating Neutrinos: from https://neutrino.physics.iastate.edu/project/dune

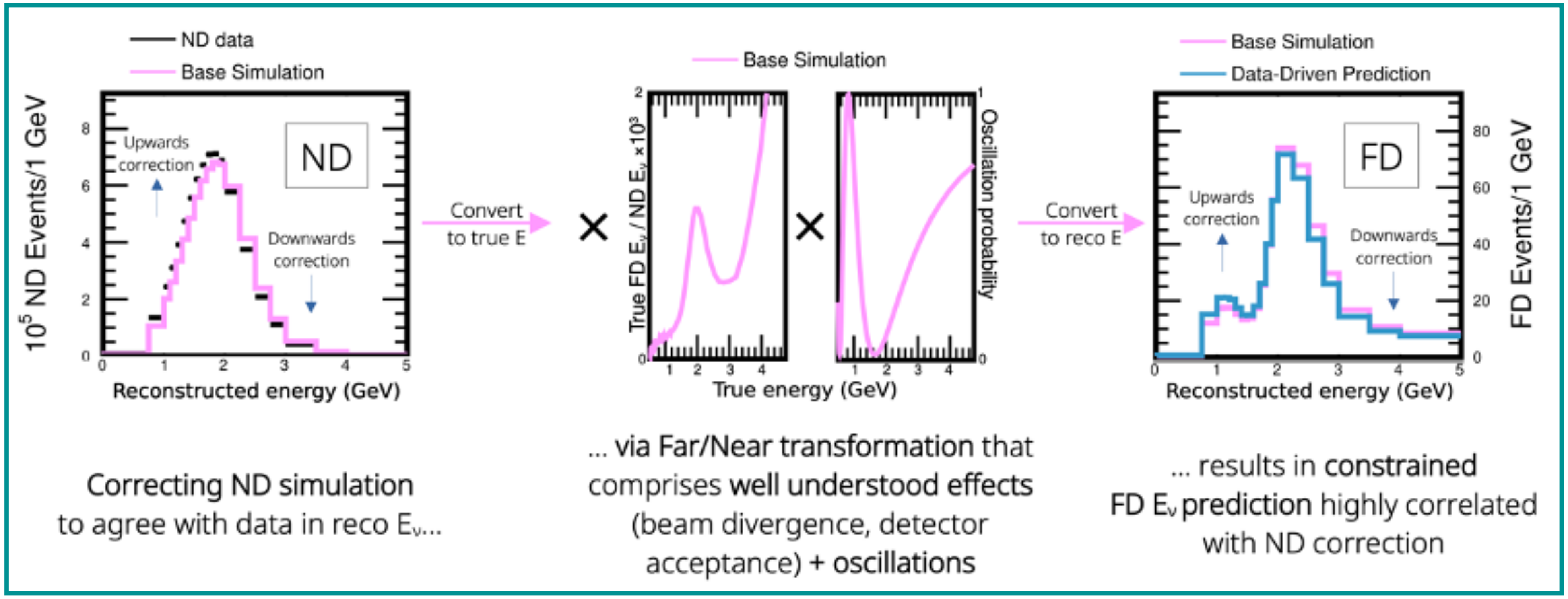
Selecting Neutrino Candidates



- The full far detector selection cut is a combination of quality, containment, cosmic rejection, and the event-classifier (CNN) cuts

Extrapolation

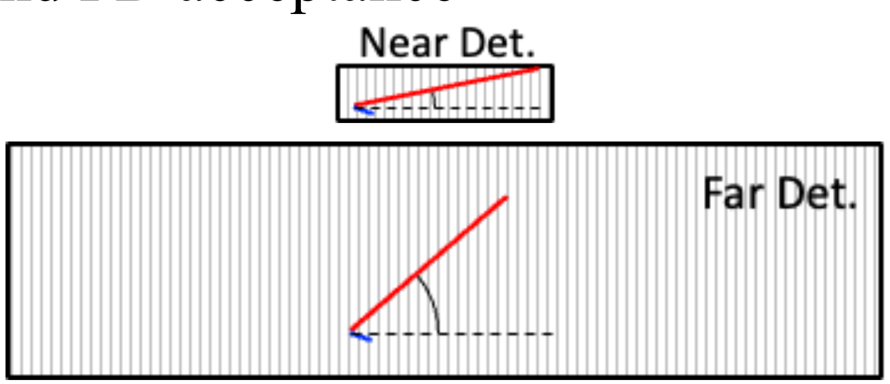
- The Near Detector Data/MC ratios are used to correct the Far Detector predictions

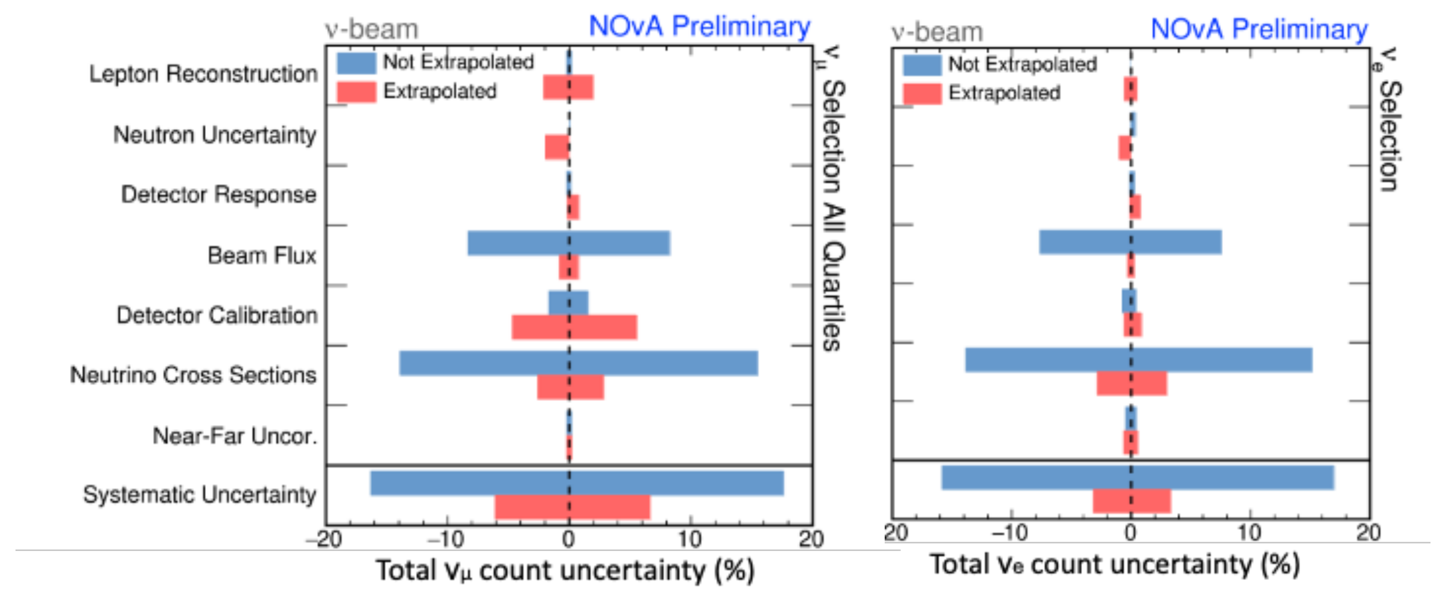


Credits: Jeremy Wolcott

Pt Extrapolation

- Extrapolation is divided further in the bins of lepton transverse momentum, p_t to account for the difference in ND and FD acceptance

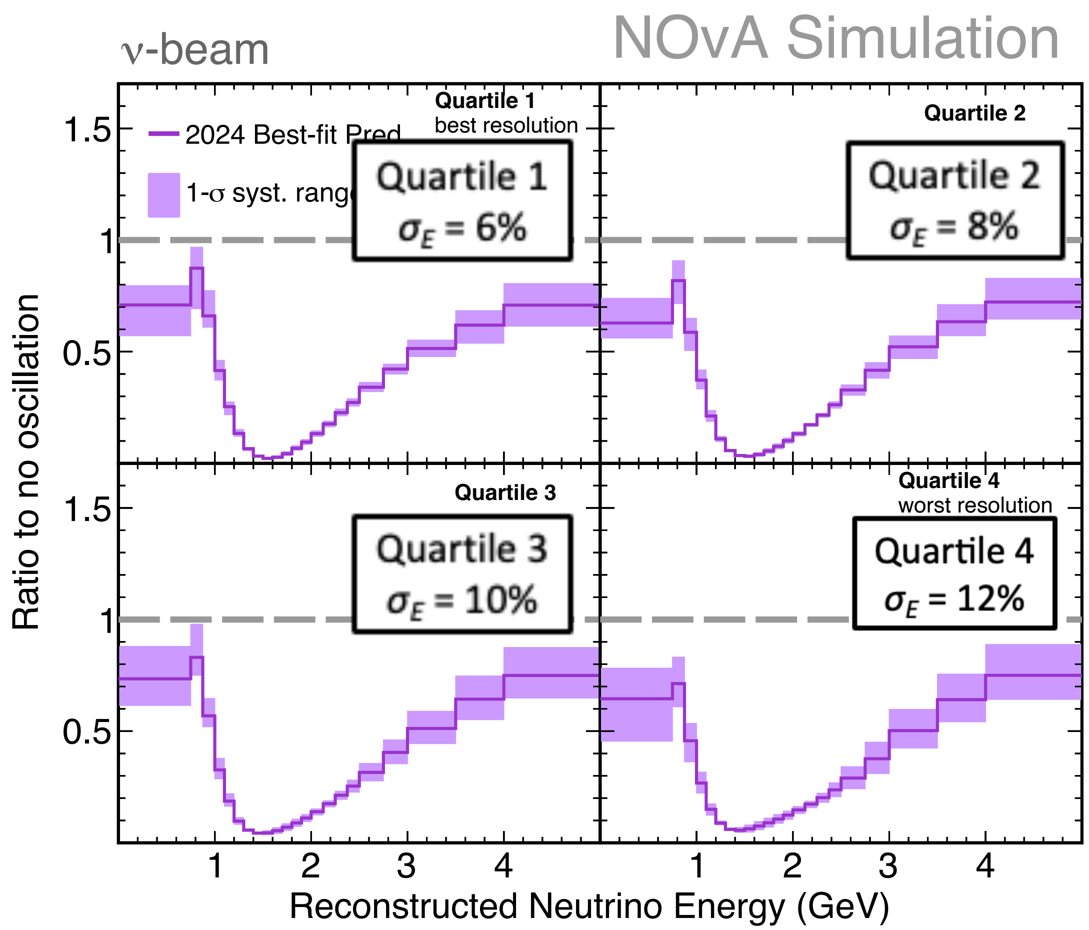




- Extrapolation helps in constraining systematic uncertainties

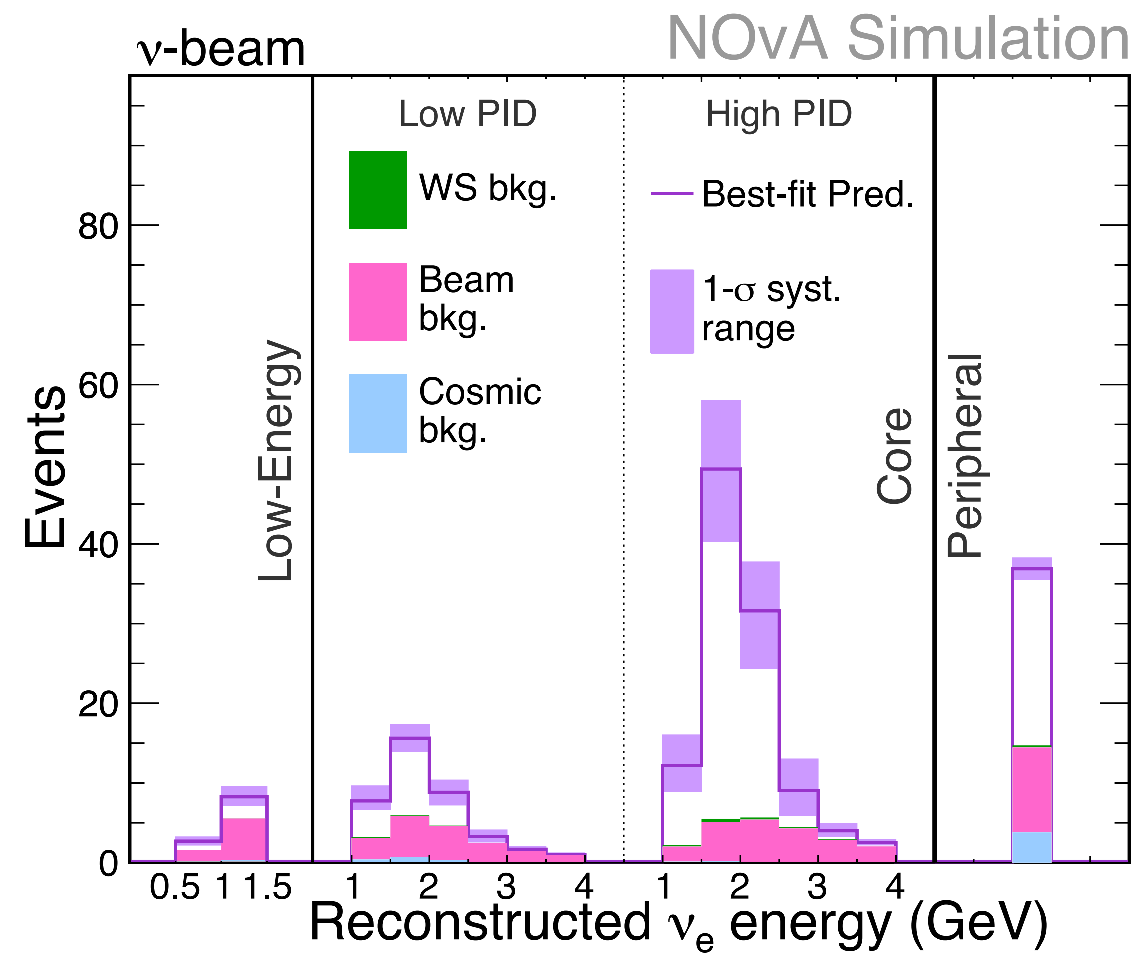
Enhancing Sensitivity to Oscillations

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



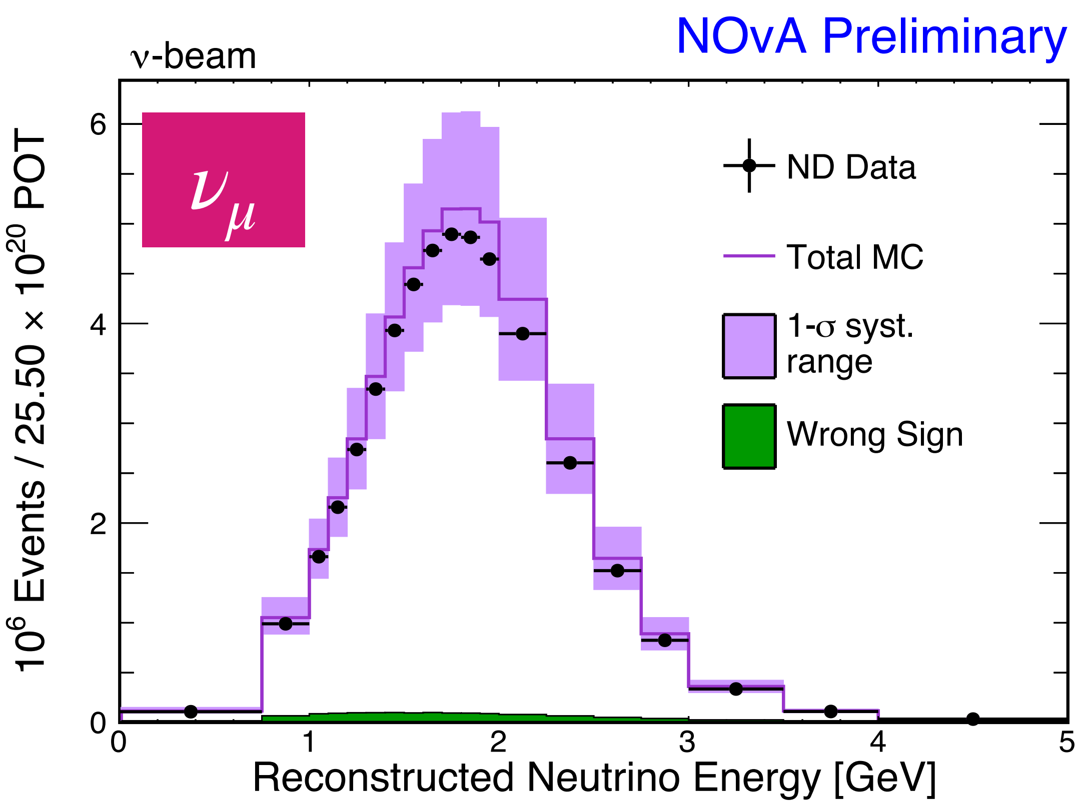
- Divide ν_μ and $\bar{\nu}_\mu$ samples in the bins of hadronic energy fraction (i.e. by *energy resolution*)
- Quartiles enter the fit as individual samples

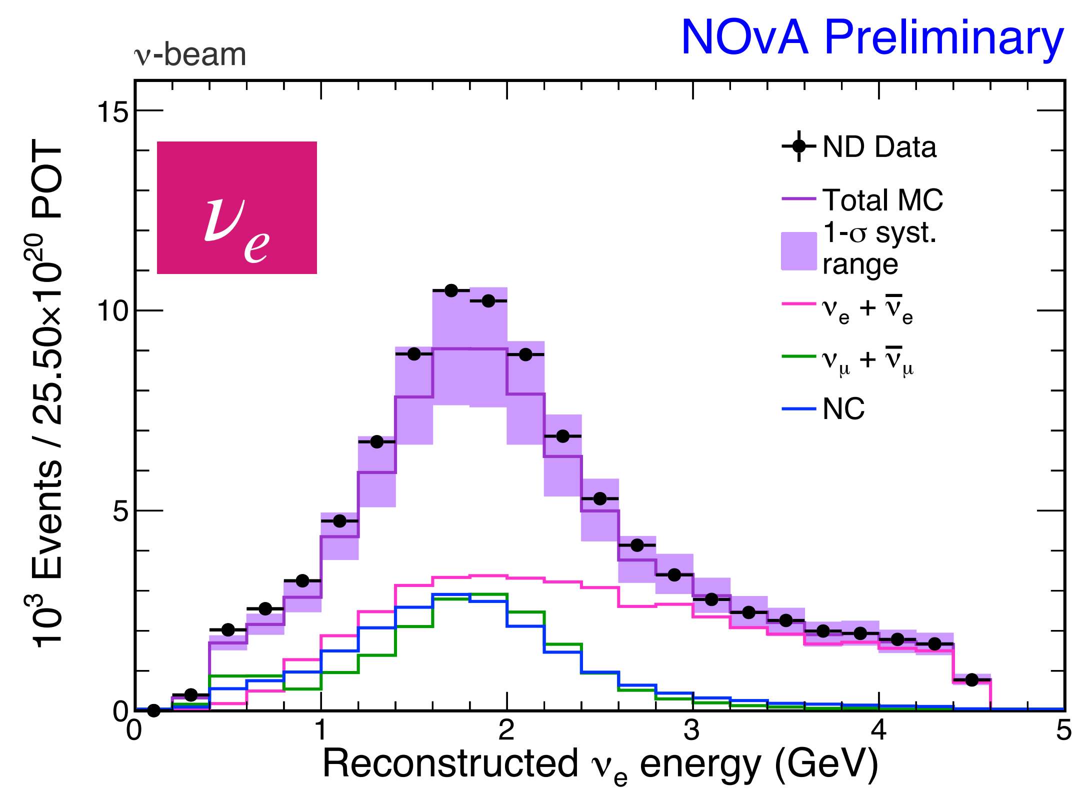
$\nu_e / \bar{\nu}_e$ Sample

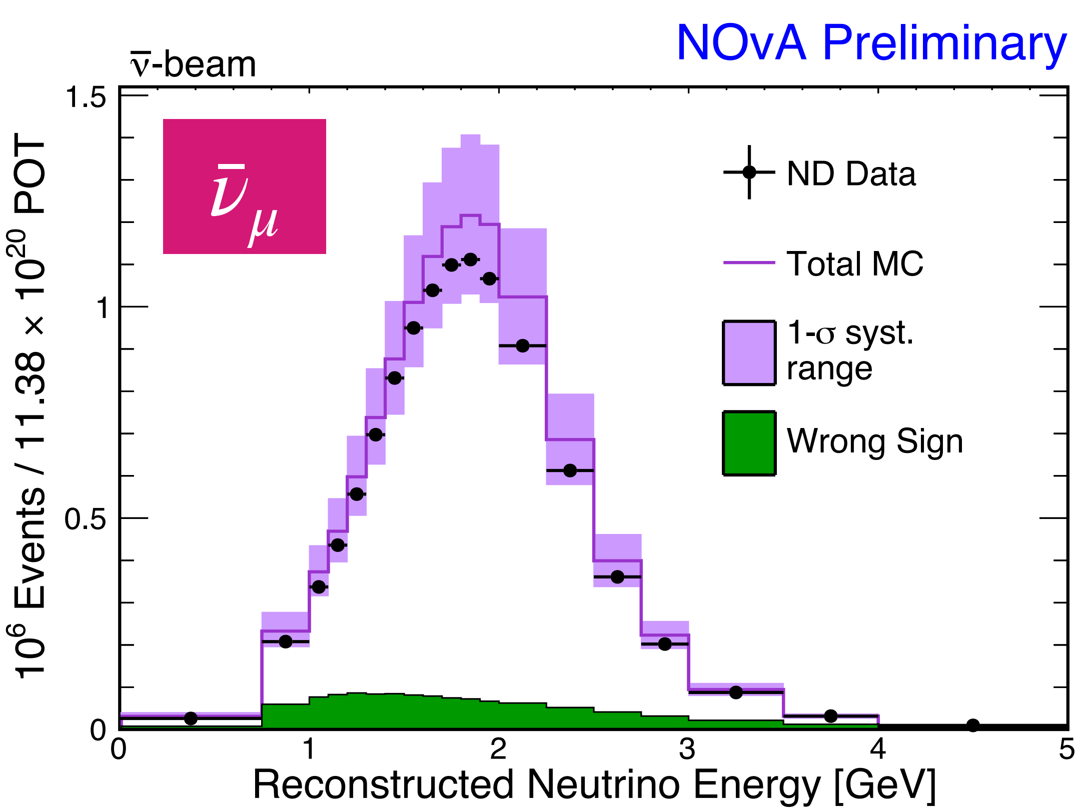


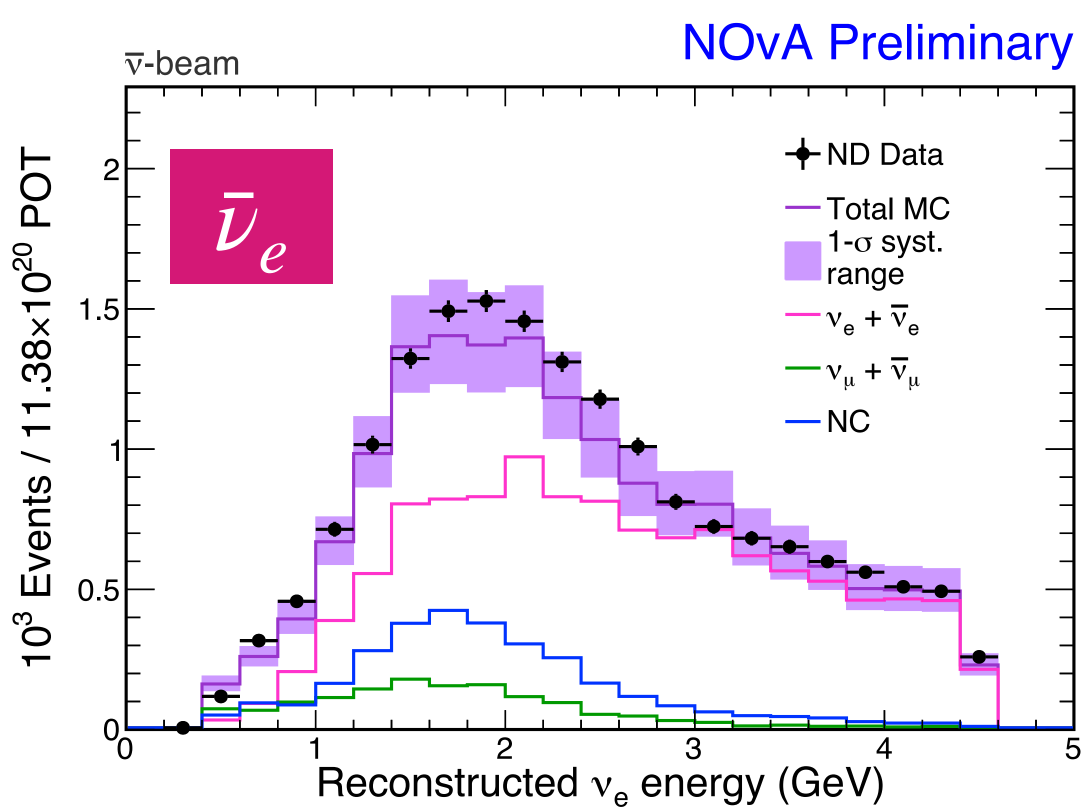
- Divide ν_e and $\bar{\nu}_e$ samples in the bins of *purity* (signal-background separation)
- Included an additional low energy ν_e sample (sensitive to mass ordering)

Near Detector Spectra



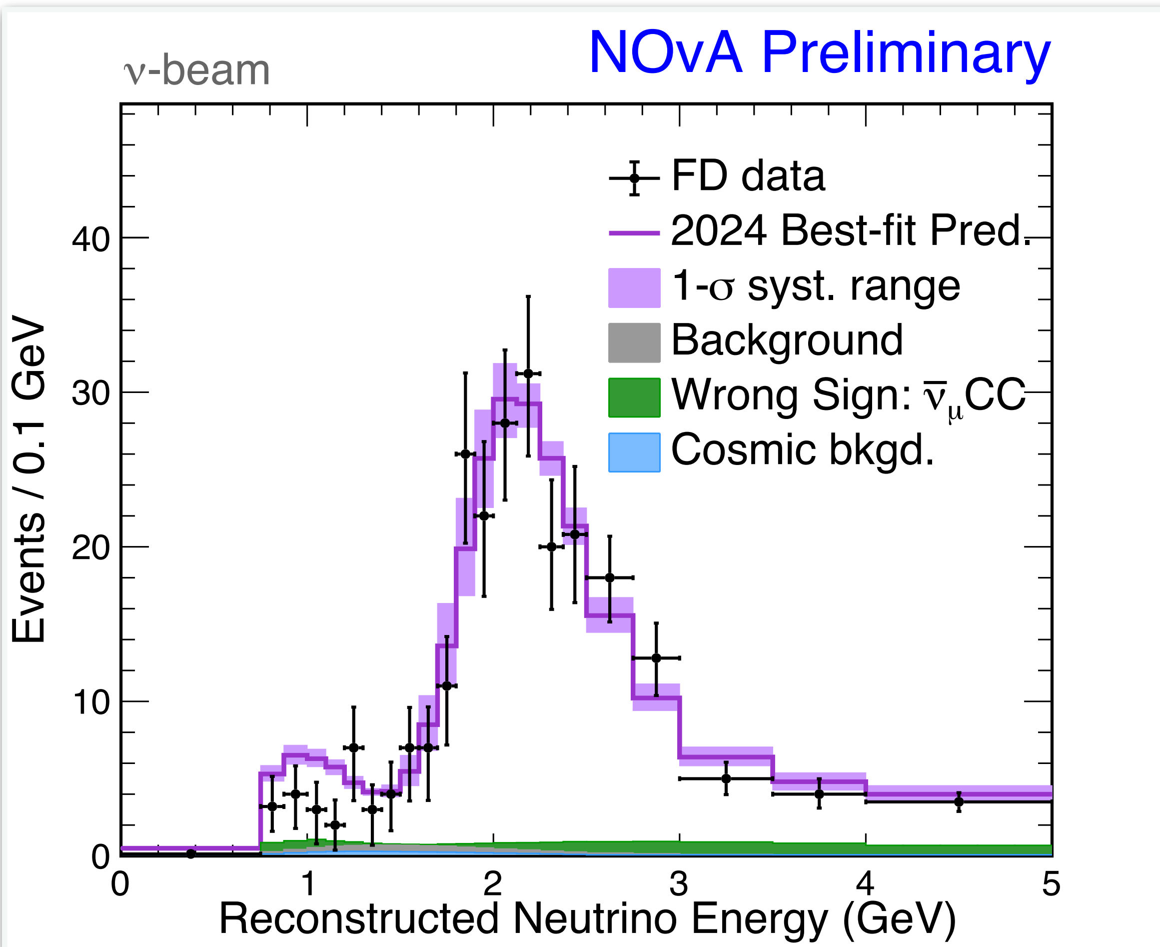




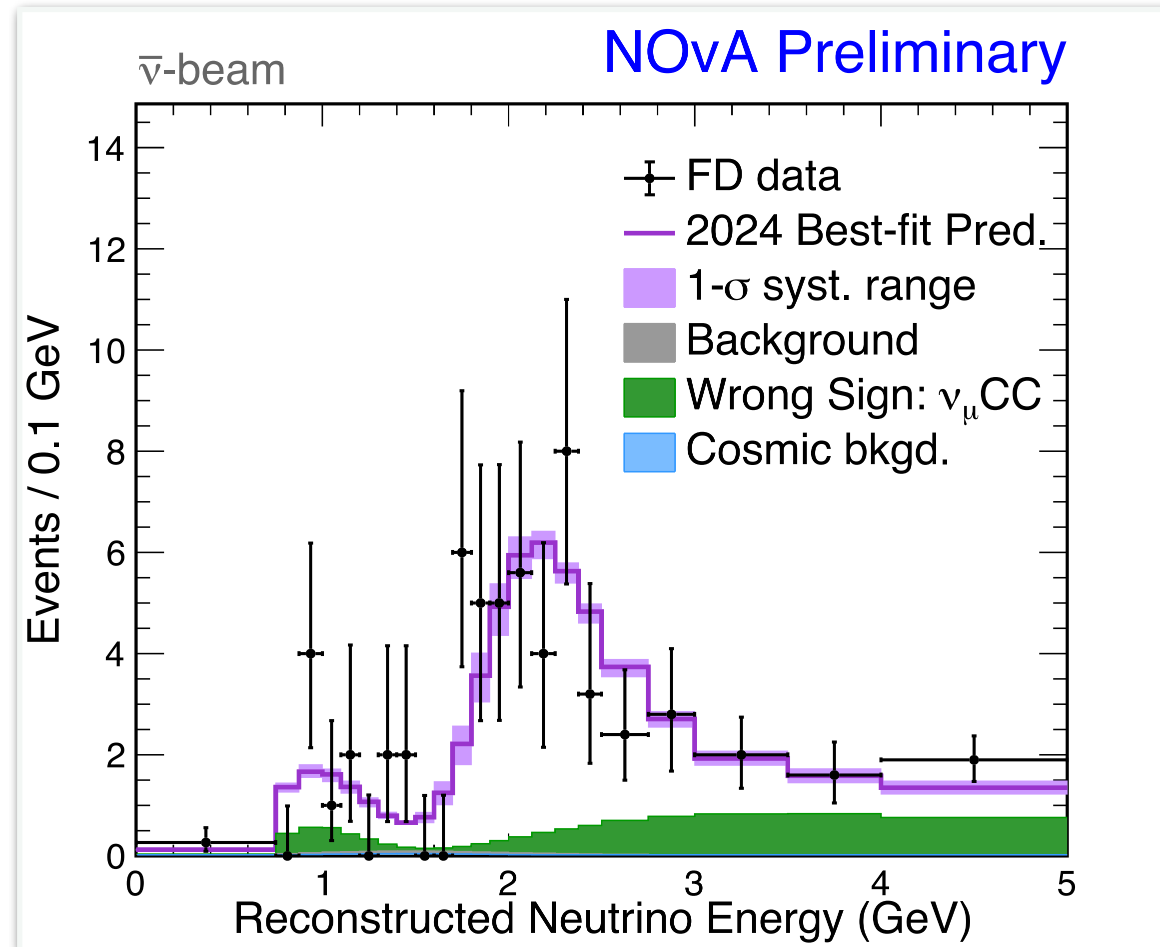


Far Detector $\nu_\mu(\bar{\nu}_\mu)$ Observations

- 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)



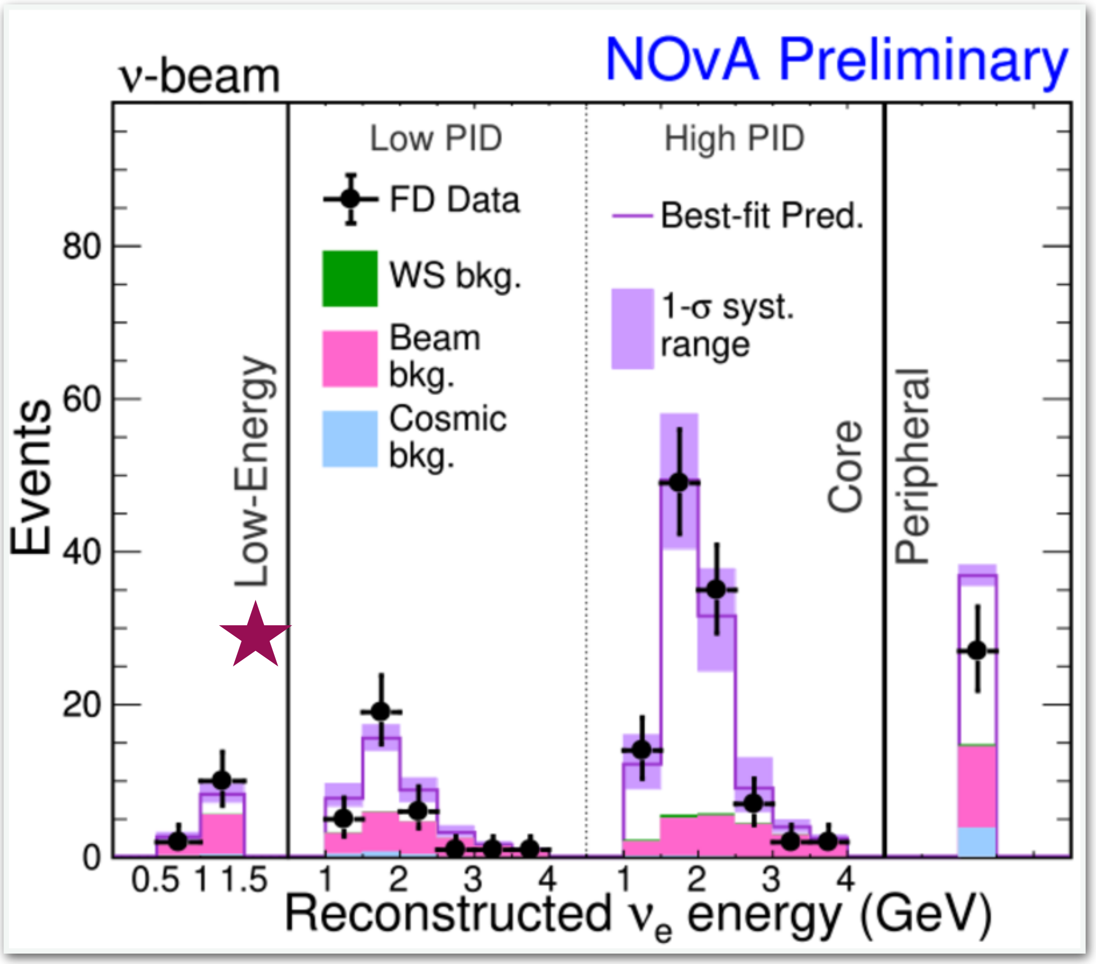
384 ν_μ data candidates
(11.3 background)

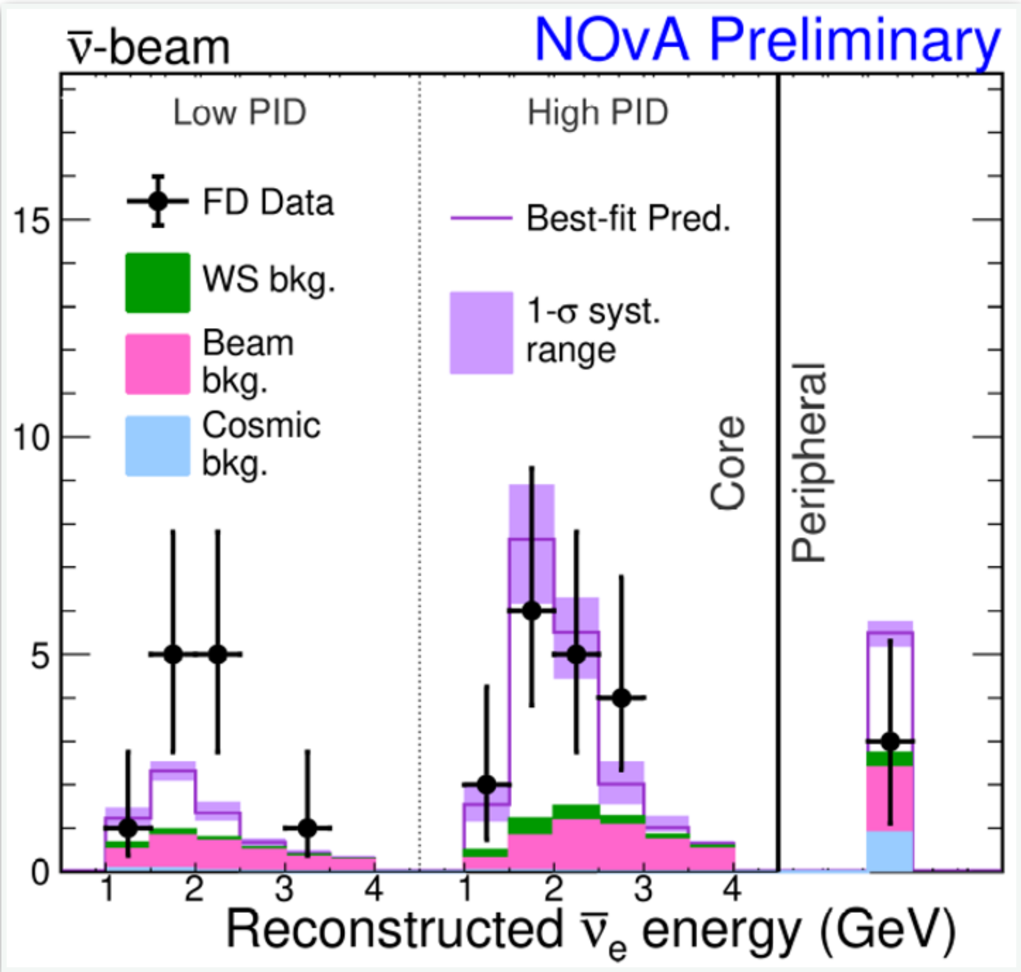


106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

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)



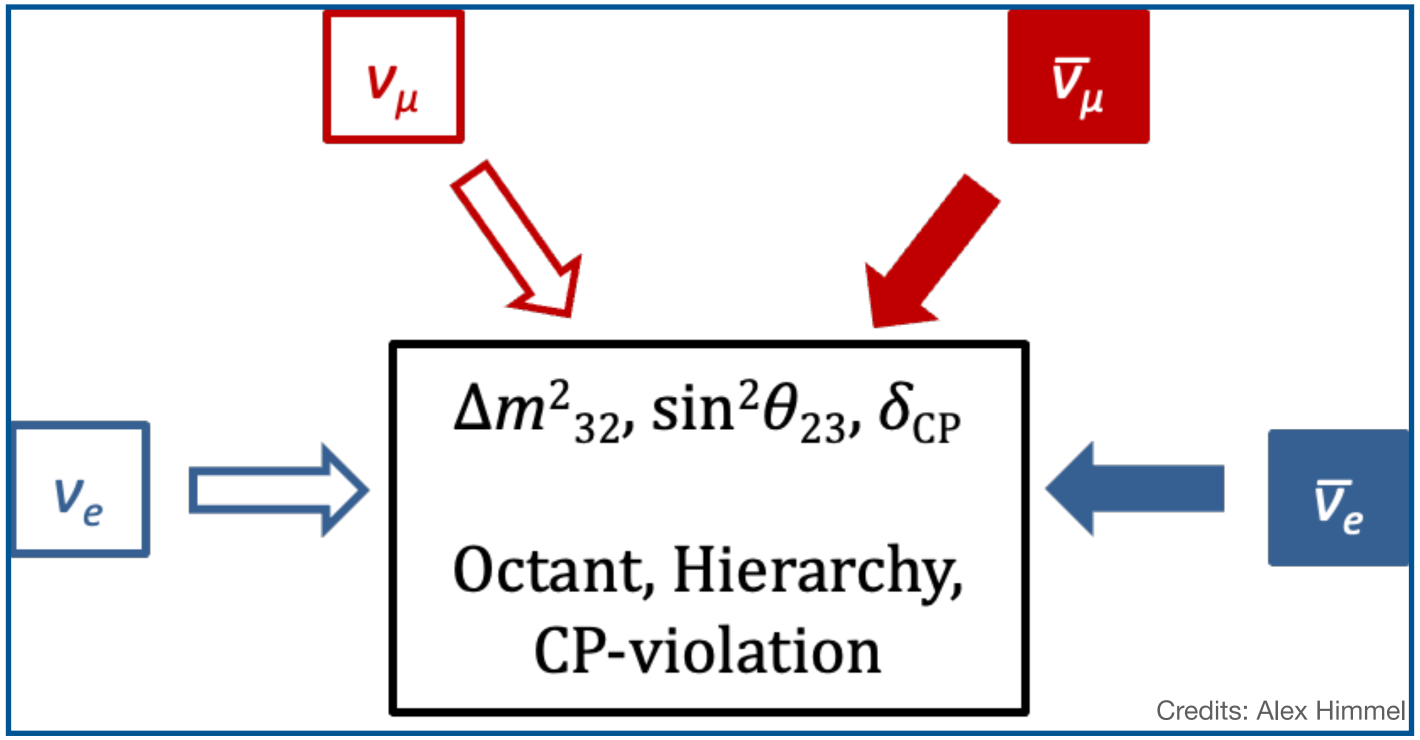


181 ν_e data candidates
(61.7 background)

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 the oscillation parameters



Bayesian

Markov Chain Monte Carlo
(marginalization)

Bayesian Credible Intervals

(technique described in [arXiv:2311.07835])

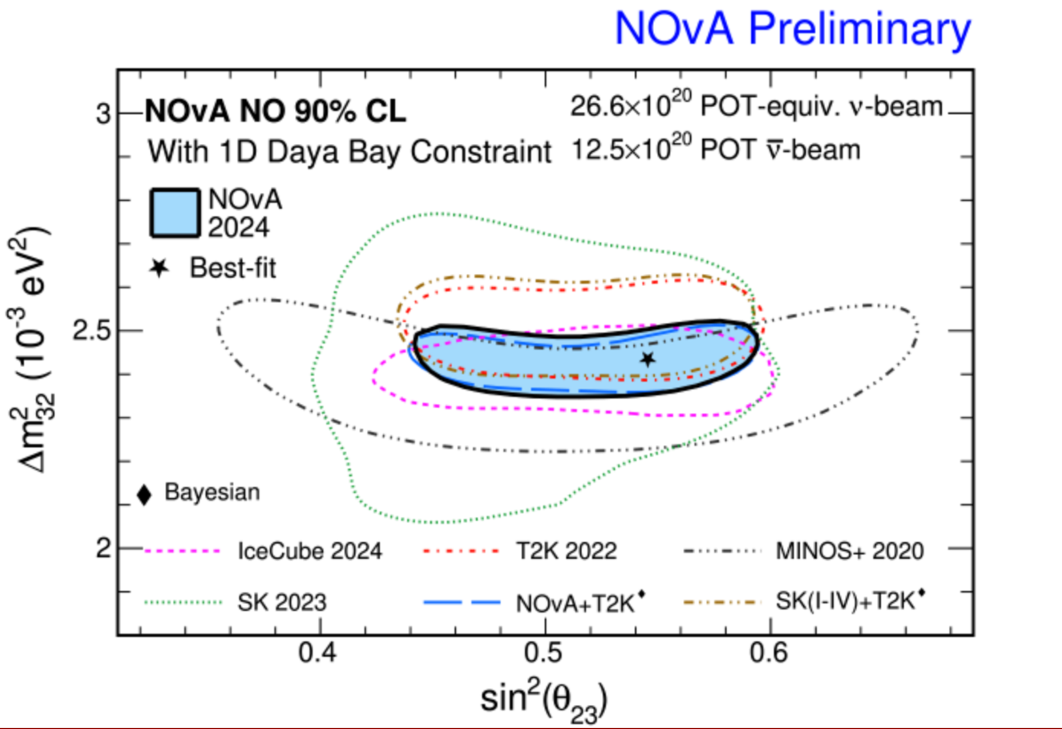
Frequentist

χ^2 Minimization
(profiled Feldman-Cousins)

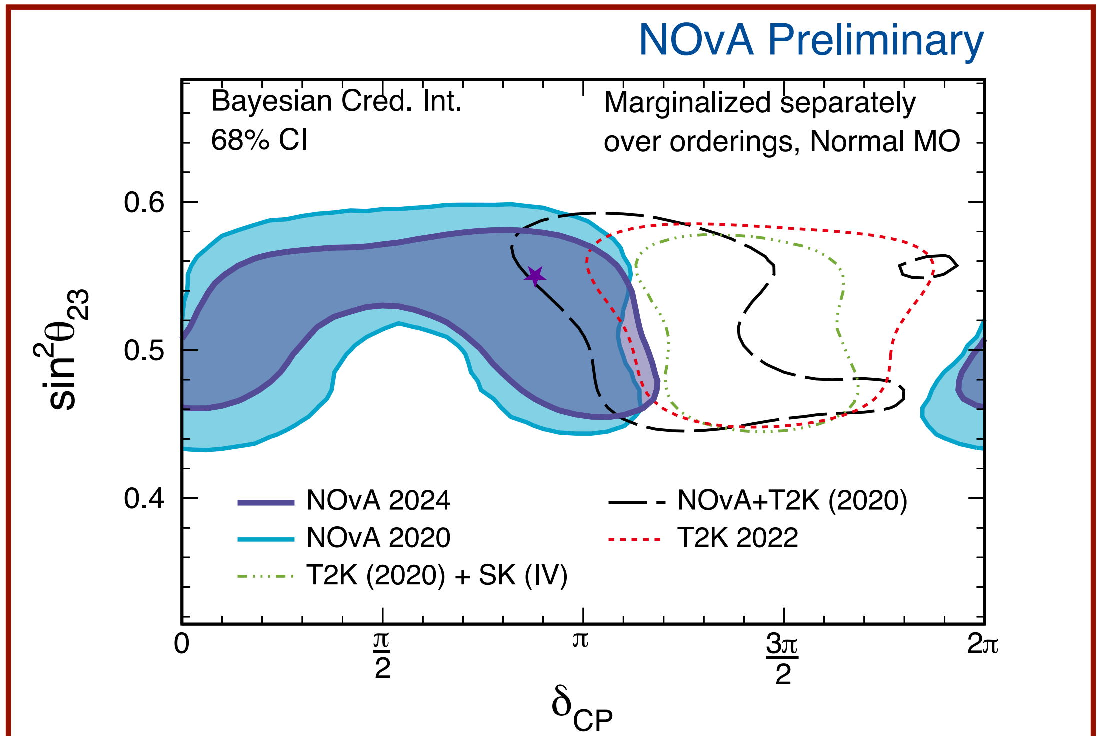
Frequentist Confidence Regions

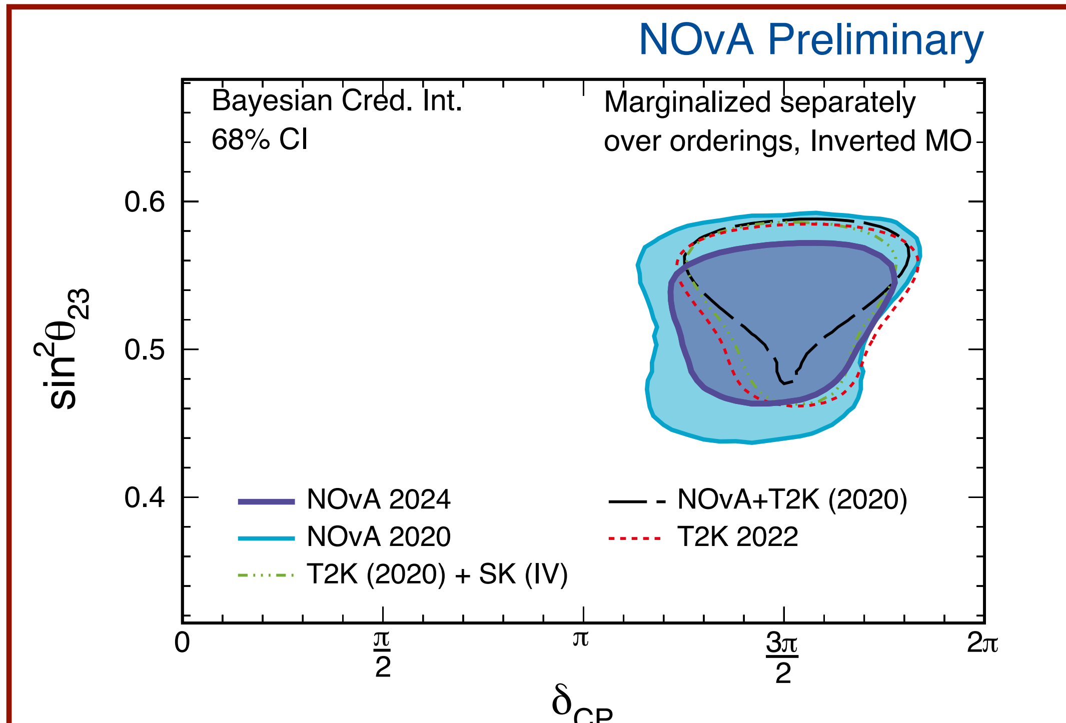
(technique described in [arXiv:2207.14353])

Results

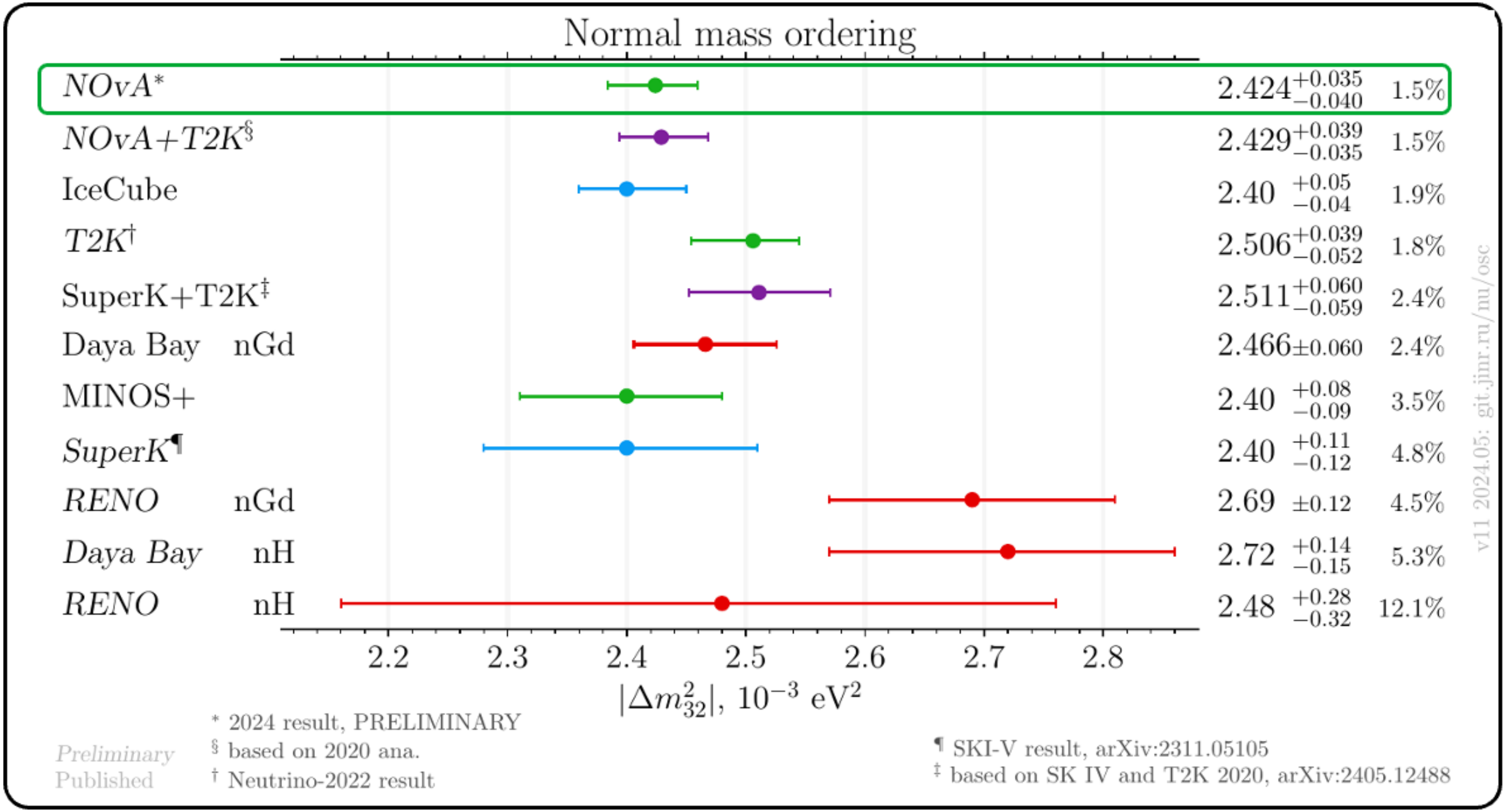


Frequentist results (w/ Daya Bay 1D θ_{13} constraint)	Normal MO		Inverted MO	
Δm^2_{32} / 10^{-3} eV^2	+2.433	+0.035 −0.036	−2.473	+0.035 −0.035
$\sin^2\theta_{23}$	**0.546**	+0.032 −0.075	0.539	+0.028 −0.075
δ_{CP}	**0.88 π**		1.51 π	
Rejection significance (σ)			1.36	





Results Contd.



The most precise measurement of Δm^2_{32}.

Conclusions

- Latest three-flavor neutrino oscillation results from 10 years of NOvA data were presented
- Mild preference (prob=69%) to Upper Octant with reactor constraints on θ_{13}
- 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

$$\Delta m^2_{32} = +2.433^{+0.035}_{-0.036} \times 10^{-3}\ \mathrm{eV}^2$$

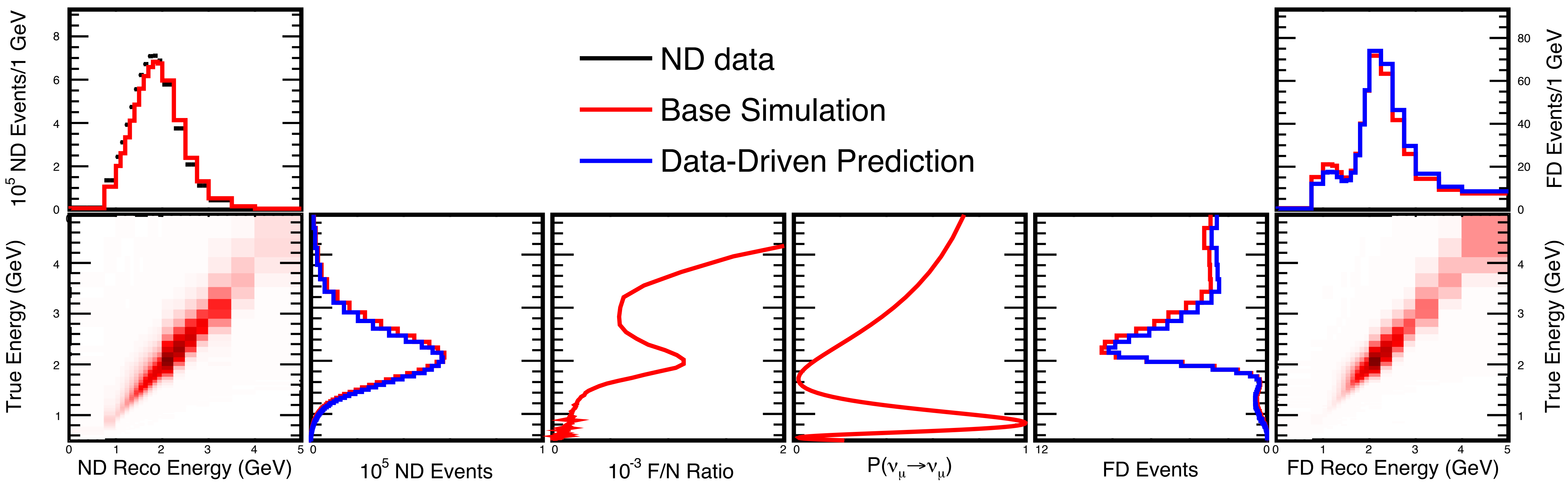
$$\sin^2(\theta_{23}) = 0.546^{+0.032}_{-0.075}$$

The NOvA Collaboration

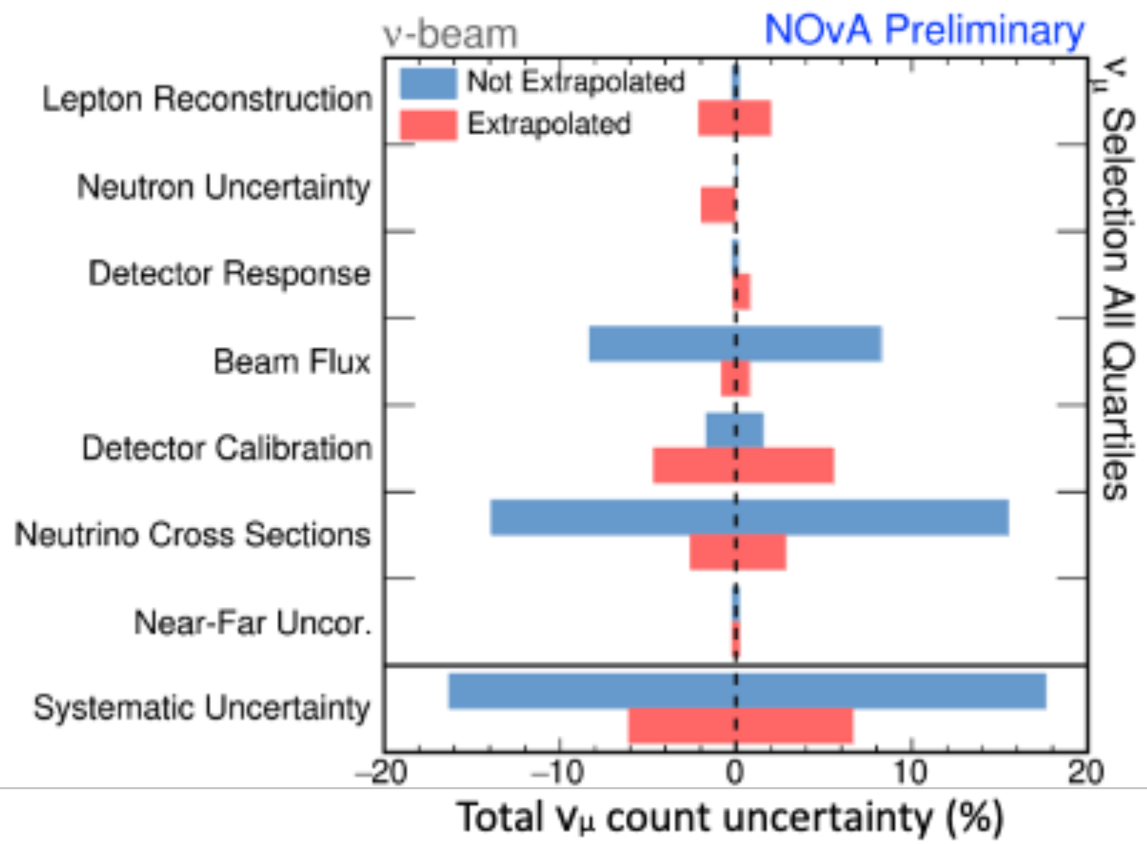
Back Up

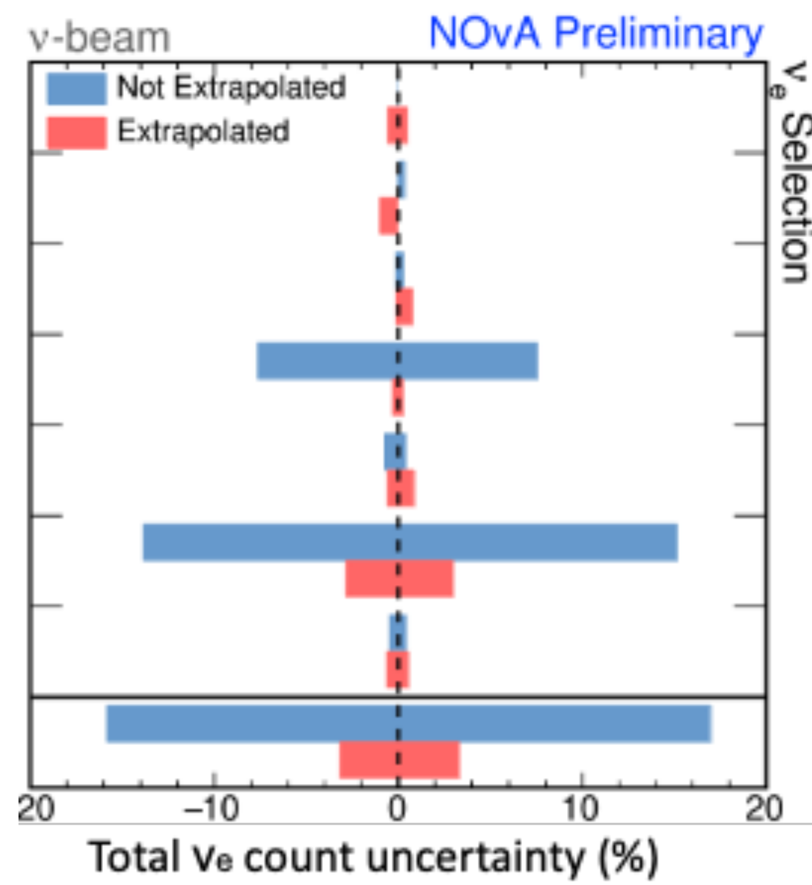
Near-to-Far Extrapolation

- 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

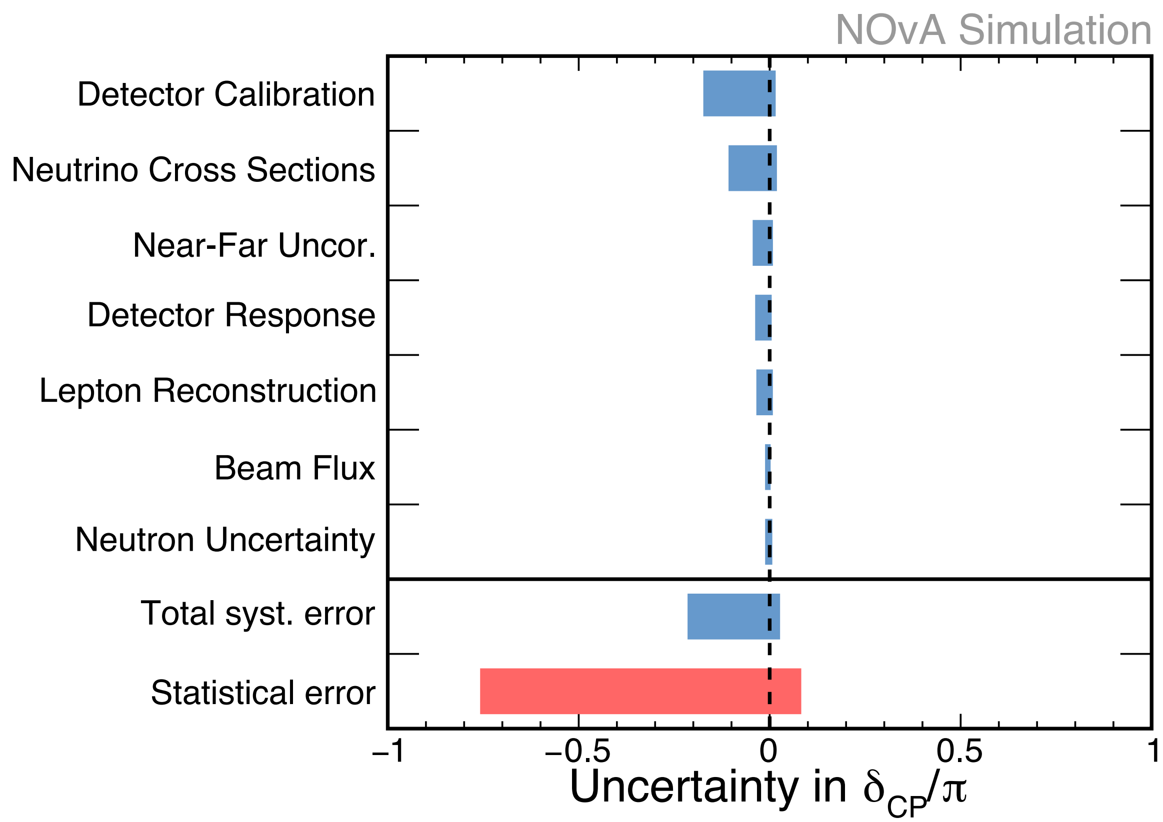


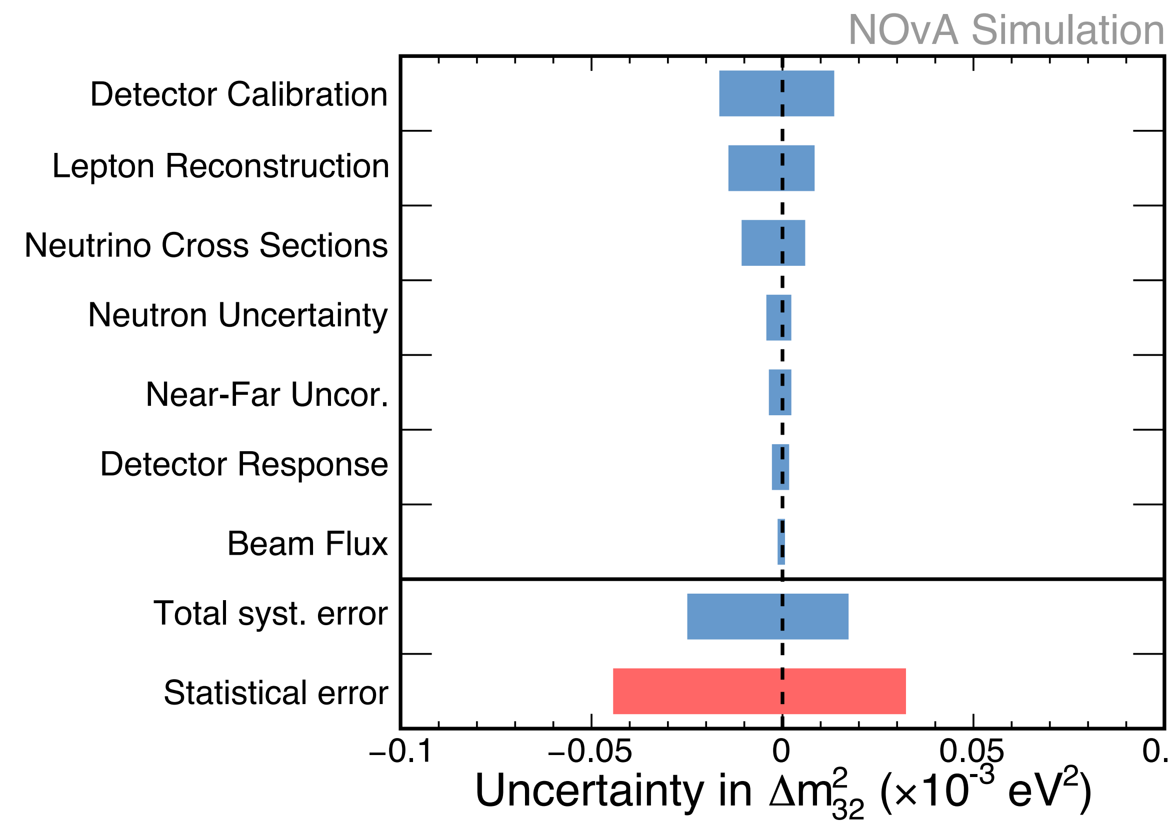
Uncertainties on FD Predictions

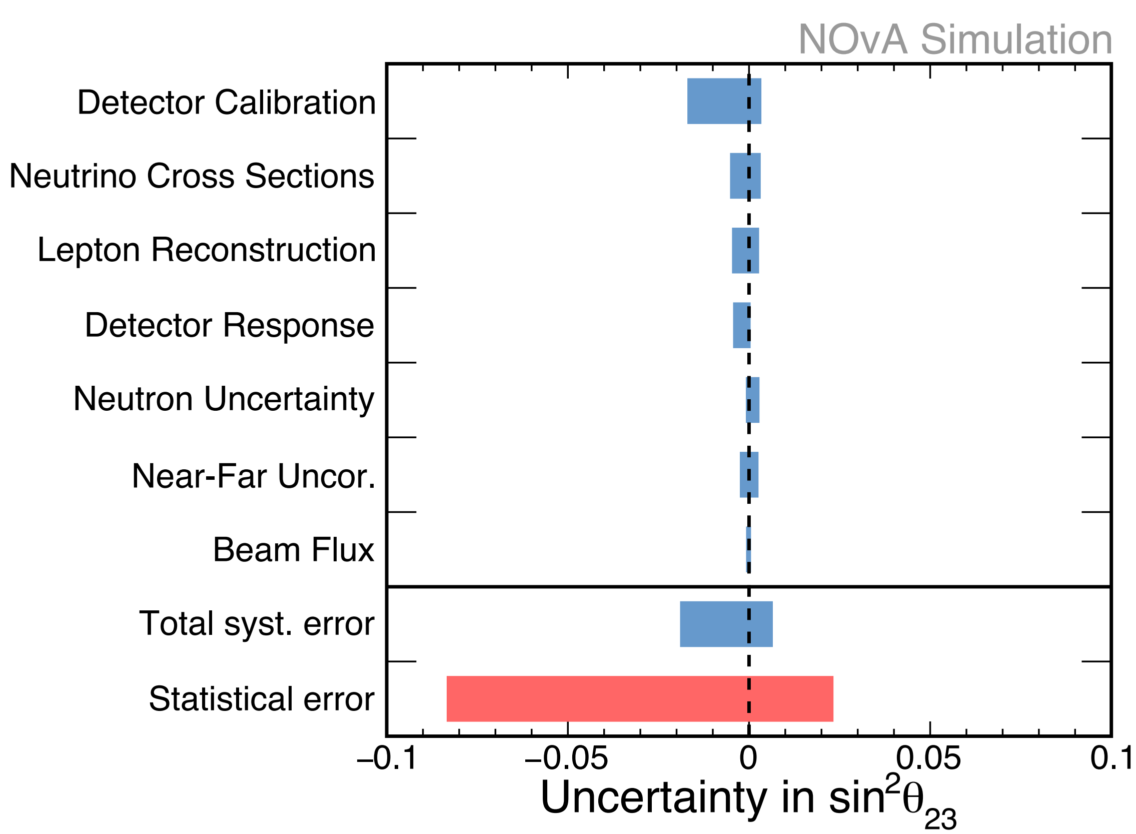




Uncertainties on Oscillation Parameters



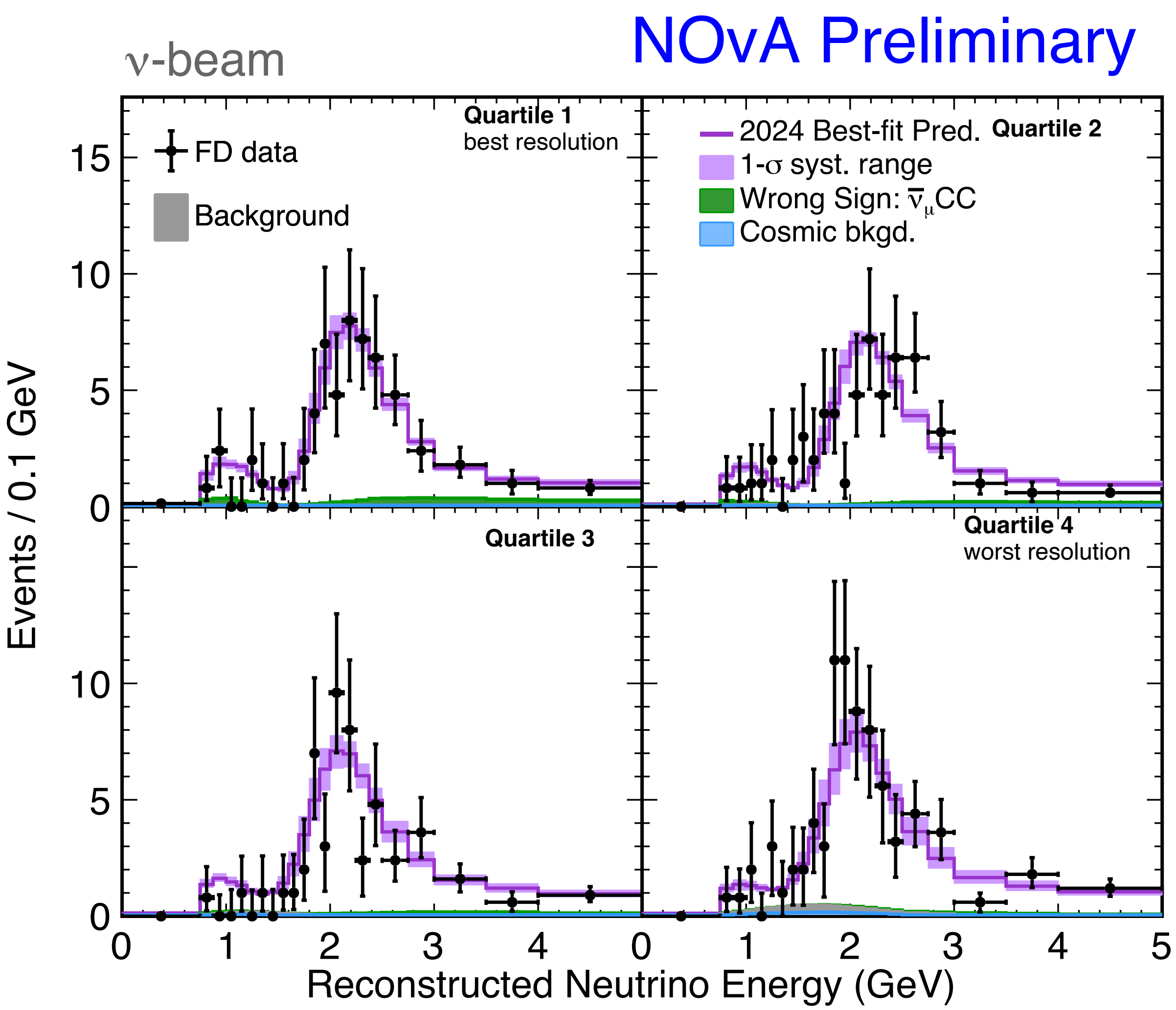


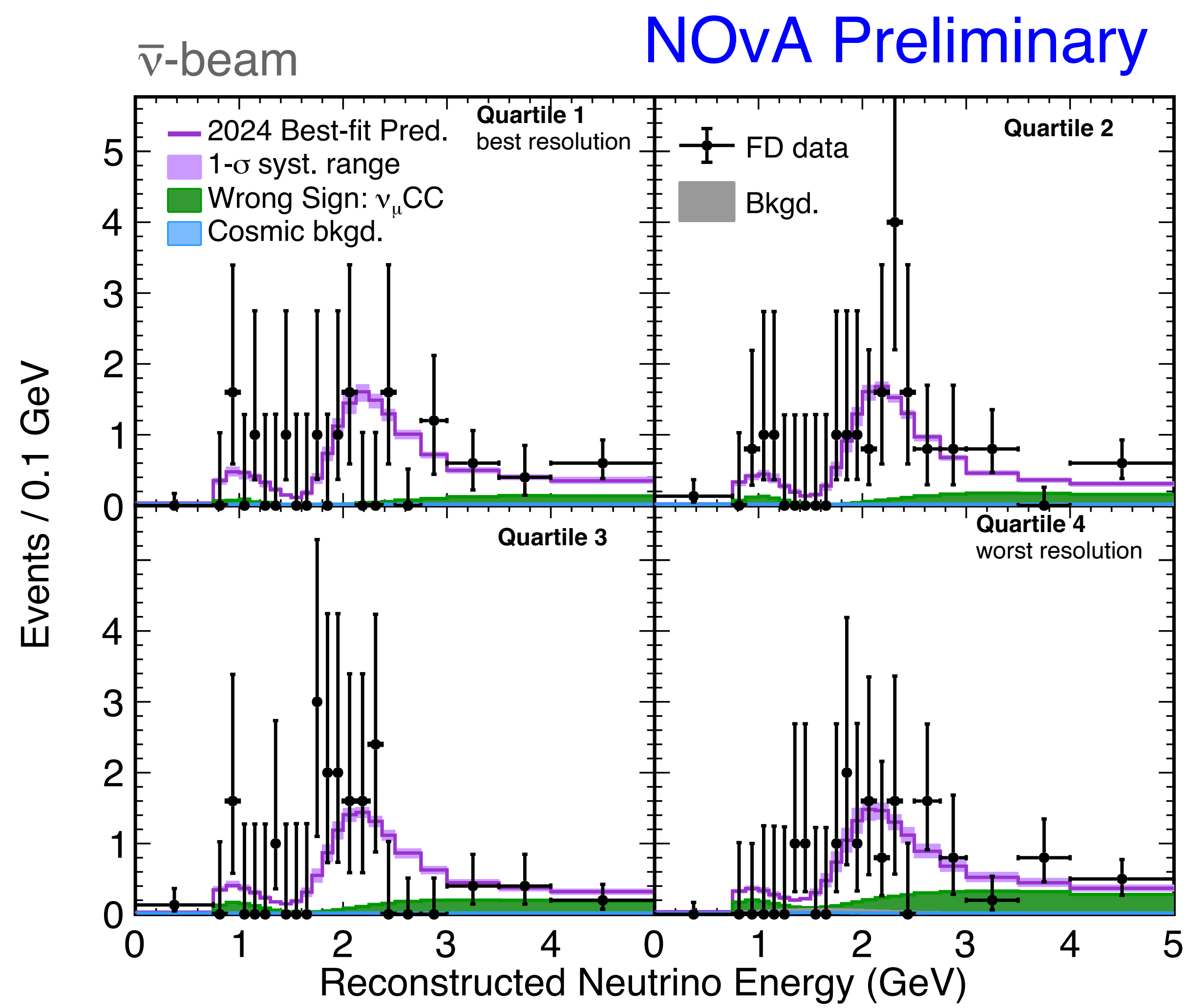


Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ $(\times 10^{-3}\ \mathrm{eV}^2)$
Beam Flux	+0.00042 / -0.00069	+0.0012 / -0.011	+0.00053 / -0.0012
Detector Calibration	+0.0033 / -0.017	+0.014 / -0.17	+0.013 / -0.016
Detector Response	+0.00031 / -0.0043	+0.004 / -0.037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