

Измерение параметров осцилляций трех типов нейтрино в эксперименте NOvA



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THREE-FLAVOR NEUTRINO OSCILLATIONS

$$\begin{array}{c}
 \text{ATMOSPHERIC} \\
 \text{ACCELERATOR}
 \end{array}
 \begin{array}{c}
 \text{SHORT BASELINE REACTOR} \\
 \text{ACCELERATOR}
 \end{array}
 \begin{array}{c}
 \text{SOLAR} \\
 \text{LONG BASELINE REACTOR}
 \end{array}
 \begin{array}{c}
 \nu_e \\
 \nu_\mu \\
 \nu_\tau
 \end{array}
 =
 \begin{pmatrix}
 1 & & \\
 & c_{23} & s_{23} \\
 & -s_{23} & c_{23}
 \end{pmatrix}
 \begin{pmatrix}
 c_{13} & & s_{13}e^{-i\delta} \\
 & 1 & \\
 -s_{13}e^{i\delta} & & c_{13}
 \end{pmatrix}
 \begin{pmatrix}
 c_{12} & s_{12} & \\
 -s_{12} & c_{12} & \\
 & & 1
 \end{pmatrix}
 \begin{array}{c}
 \nu_1 \\
 \nu_2 \\
 \nu_3
 \end{array}$$

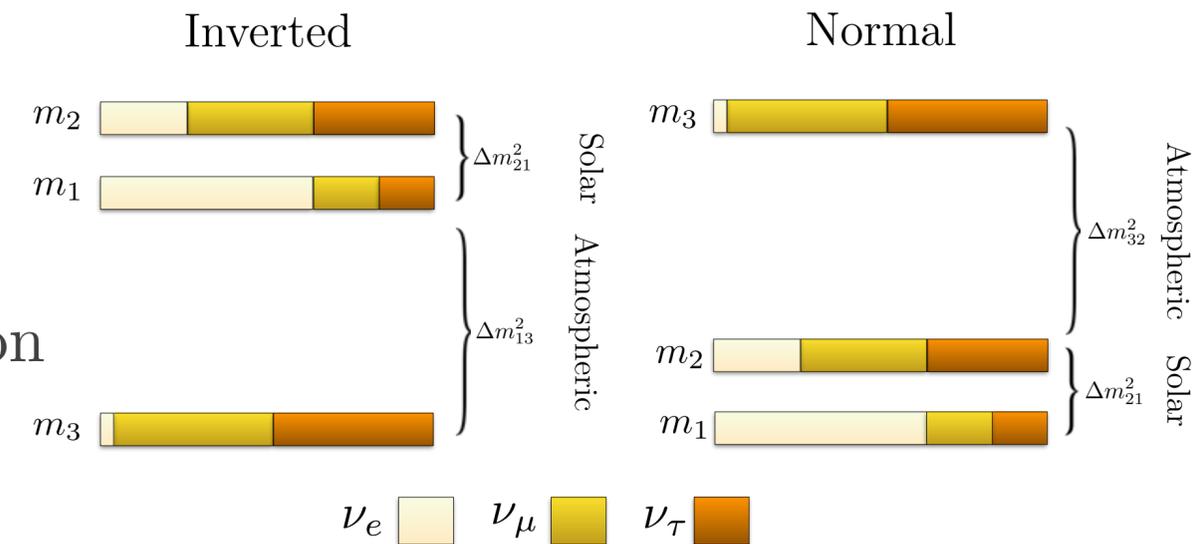
OSCILLATION PARAMETERS AND HOW PRECISELY DO WE KNOW THEM:

$$\begin{aligned}
 \theta_{12} &\approx 34^\circ \quad (4.2\%) \\
 \theta_{23} &\approx 49^\circ \quad (5.2\%) \\
 \theta_{13} &\approx 9^\circ \quad (3.1\%) \\
 \Delta m_{21}^2 &\approx 7.4 \times 10^{-5} \text{ eV}^2 \quad (2.2\%) \\
 \Delta m_{32}^2 &\approx +2.5 \times 10^{-3} \text{ eV}^2 \quad (1.2\%)
 \end{aligned}$$



OPEN QUESTIONS:

- * Is $\theta_{23} 45^\circ$? (possible ν_μ and ν_τ symmetry in ν_3)
- * Is there CP violation in lepton sector? (matter-antimatter asymmetry of the Universe (leptogenesis))
- * Neutrino mass hierarchy (ordering) is Normal or Inverted? (neutrinoless double beta-decay searches, supernova simulations, relic neutrinos searches, absolute ν mass measurements etc)



THE NO_νA EXPERIMENT

The NuMI Off-Axis ν_e Appearance Experiment

Experiment goals:

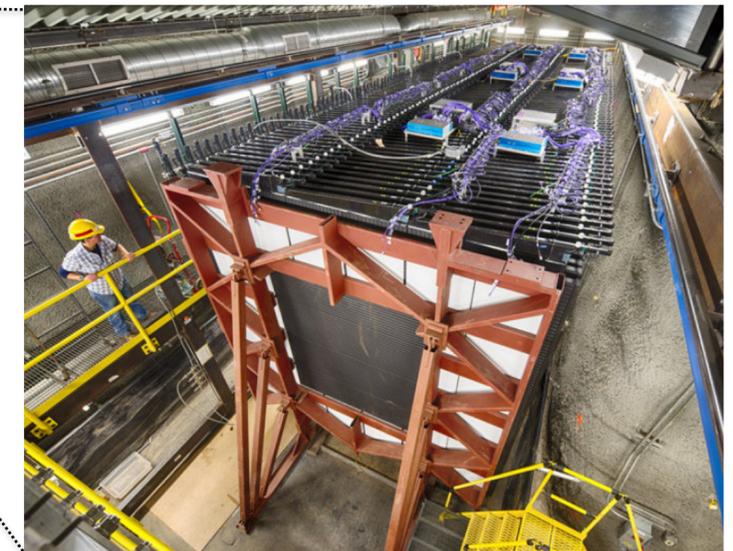
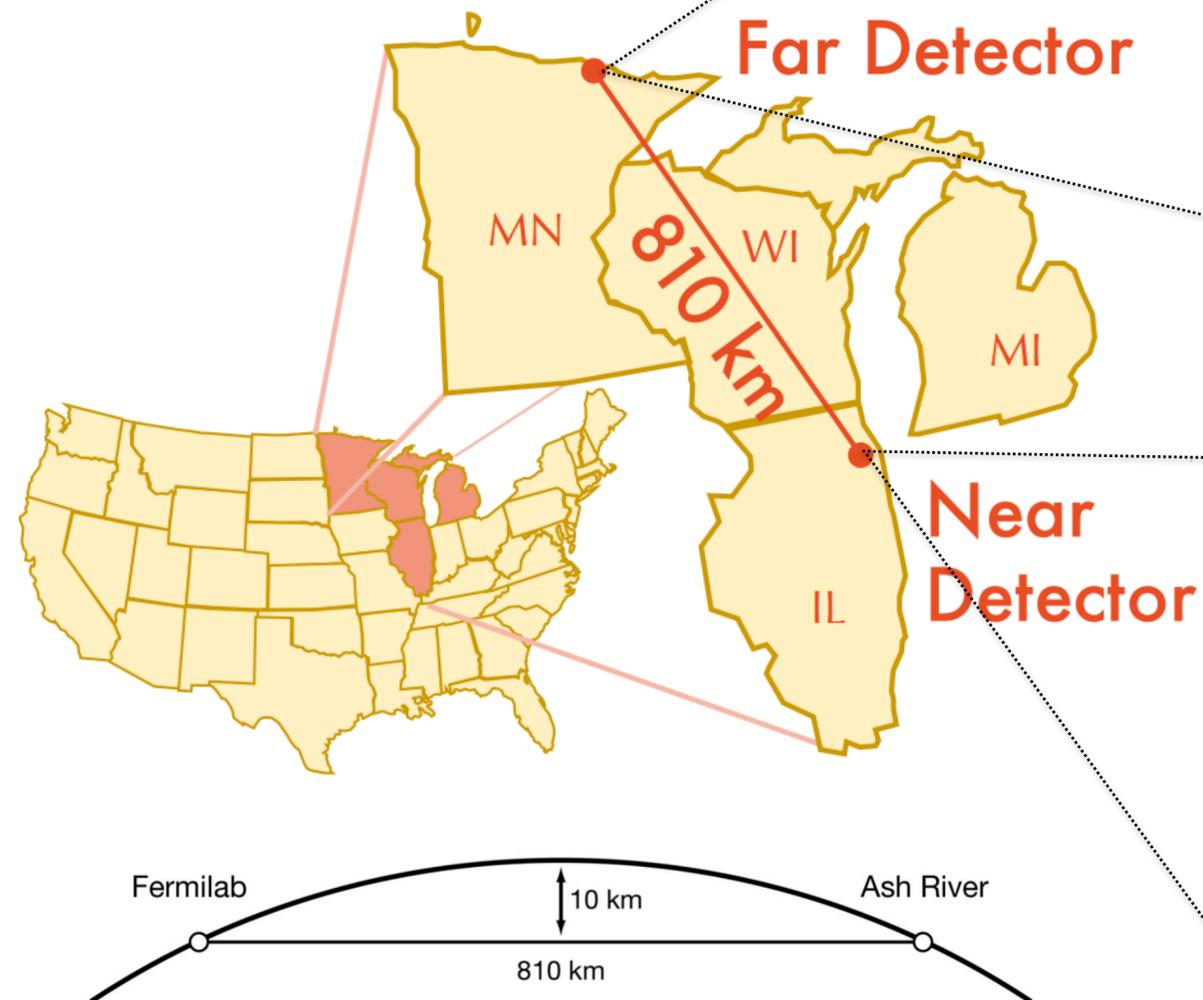
Using $\nu_\mu \rightarrow \nu_\mu$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

- * Precise measurement of Δm_{32}^2
- * Mixing angle θ_{23}

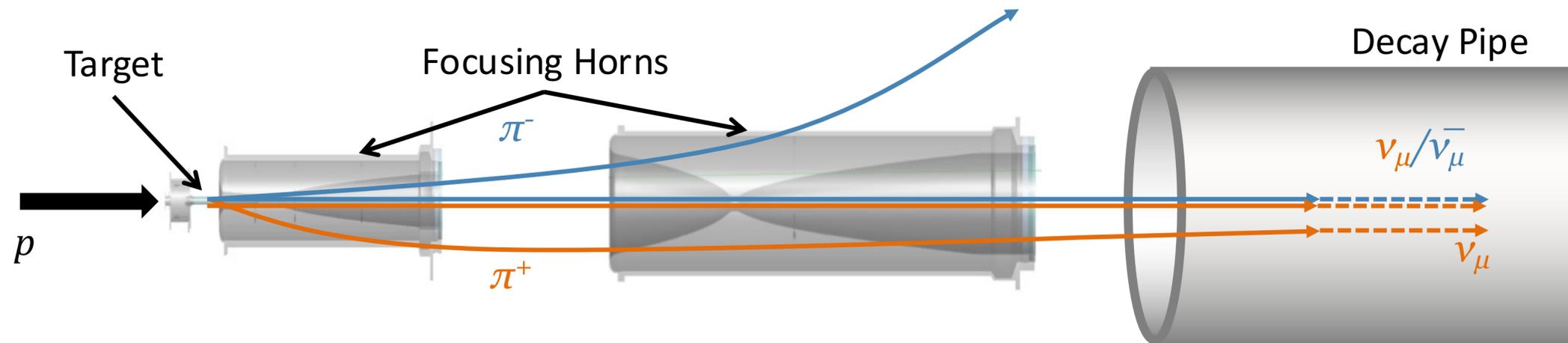
Using $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

- * Neutrino mass hierarchy
- * CP violating phase
- * Octant of θ_{23}

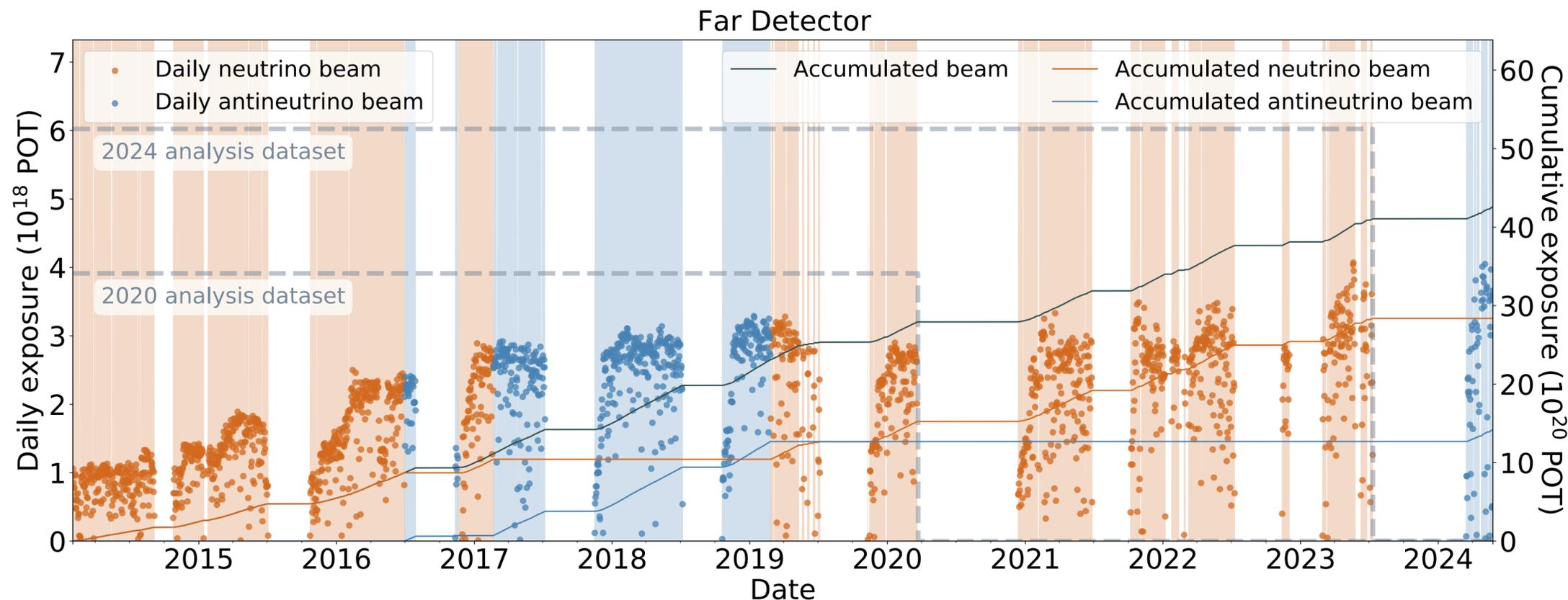
Long-baseline,
beam from Fermilab (USA),
two detectors sit at
14 mrad off-axis



NEUTRINO BEAM



- * 120 GeV protons on a carbon target, produce mesons which yield neutrinos.
Beam purity with $\nu(\bar{\nu})$: 95% ν_μ , 4% $\bar{\nu}_\mu$, 1% $\nu_e/\bar{\nu}_e$ (93% $\bar{\nu}_\mu$, 6% ν_μ , 1% $\nu_e/\bar{\nu}_e$).
- * Typically run at ~ 900 kW, power record 1018 kW.



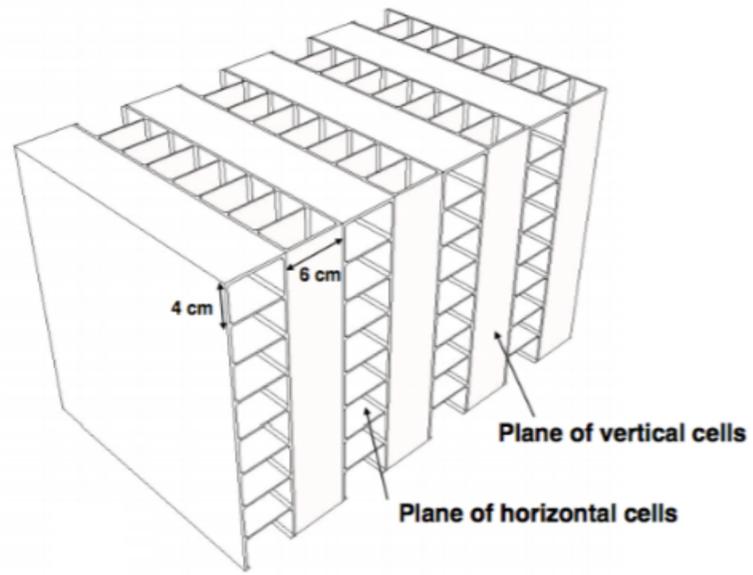
+96% to ν exposure:
 $13.6 \times 10^{20} \rightarrow 26.61 \times 10^{20}$
 (2020 \rightarrow 2024)

26.61×10^{20} POT
 neutrino beam

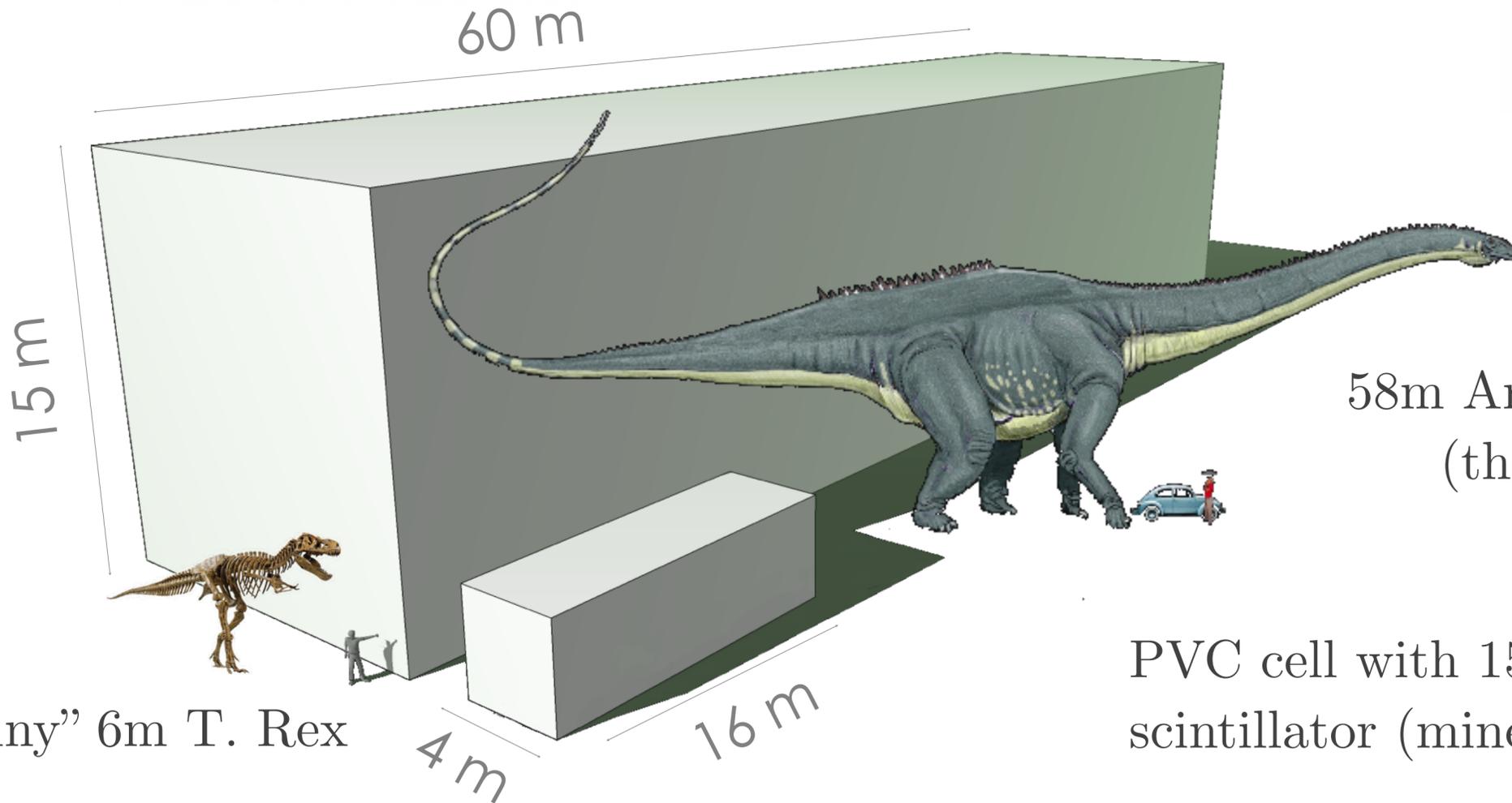
+

12.5×10^{20} POT
 antineutrino beam

NOvA DETECTORS

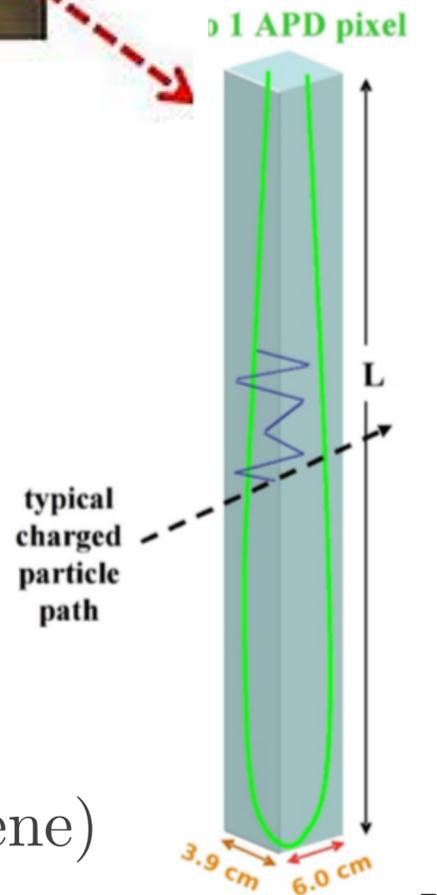


FD: 344 064 cells
 ND: 20 192 cells



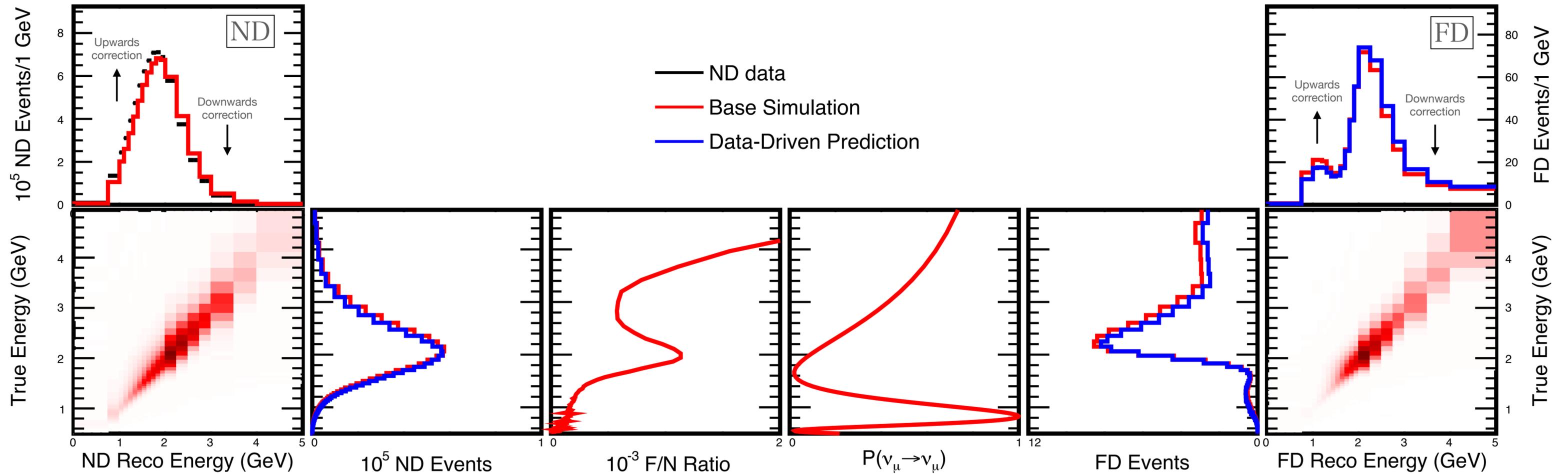
58m *Amphicoelias fragillimus*
 (the largest estimate)

PVC cell with 15% TiO₂ with liquid scintillator (mineral oil with 5% pseudocumene)



EXTRAPOLATION

Far Detector predictions are constrained by high-stat unoscillated Near Detector data:

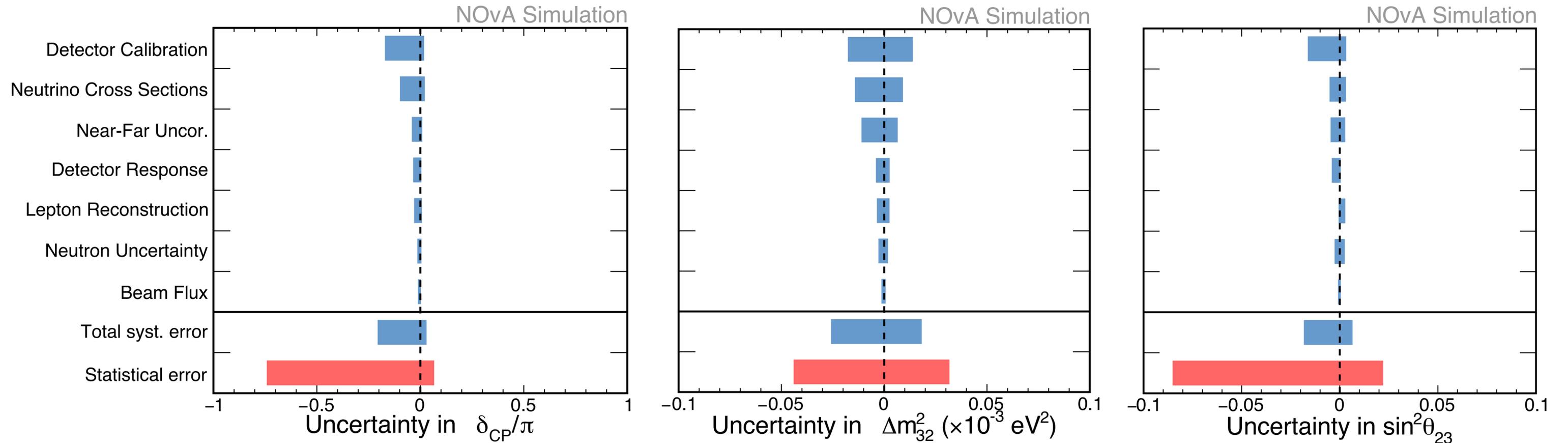


Correcting ND simulation to agree with data in reco E_ν ...

... via Far/Near transformation that comprises well understood effects (beam divergence, detector acceptance) + oscillations

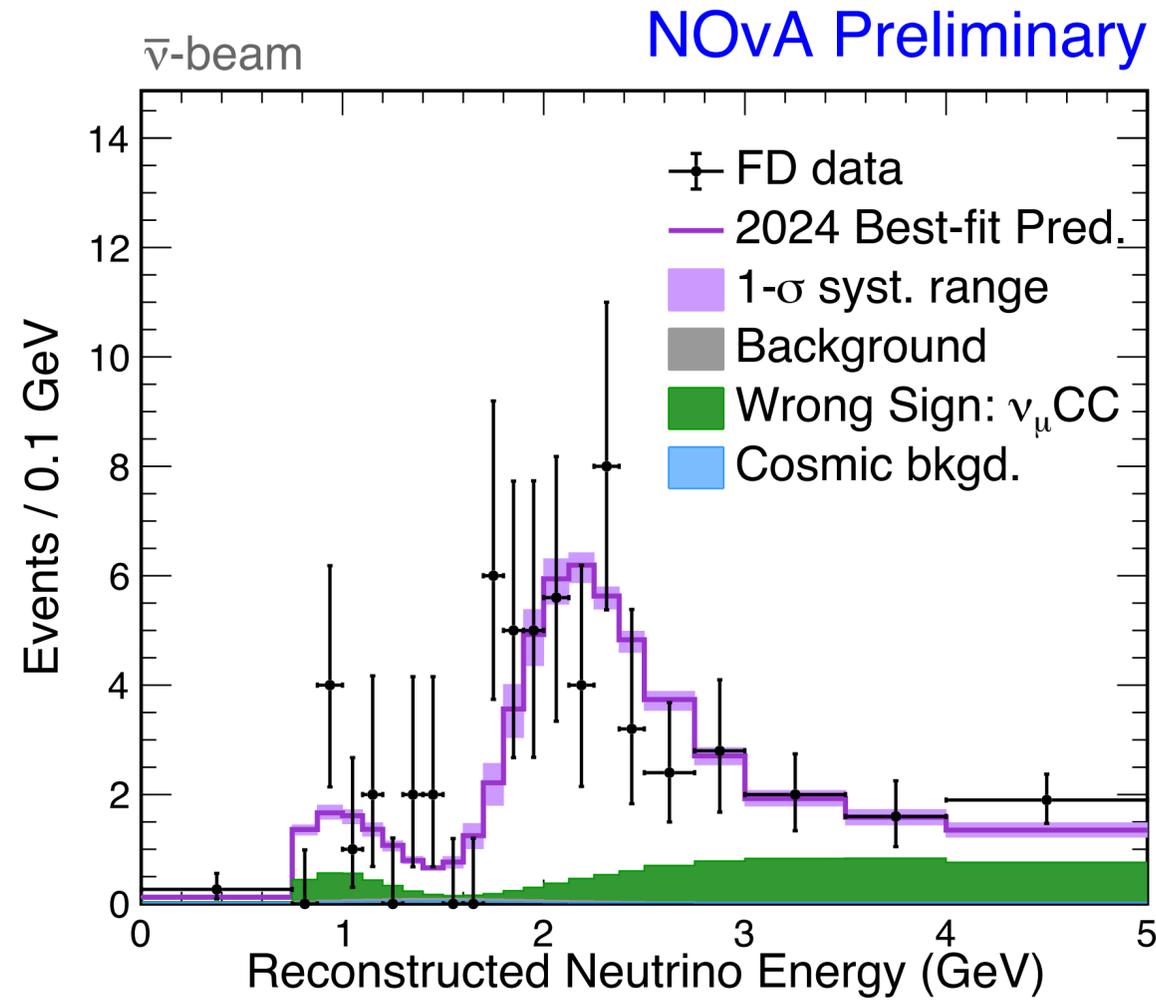
... results in constrained FD E_ν prediction highly correlated with ND correction

SYSTEMATIC UNCERTAINTIES

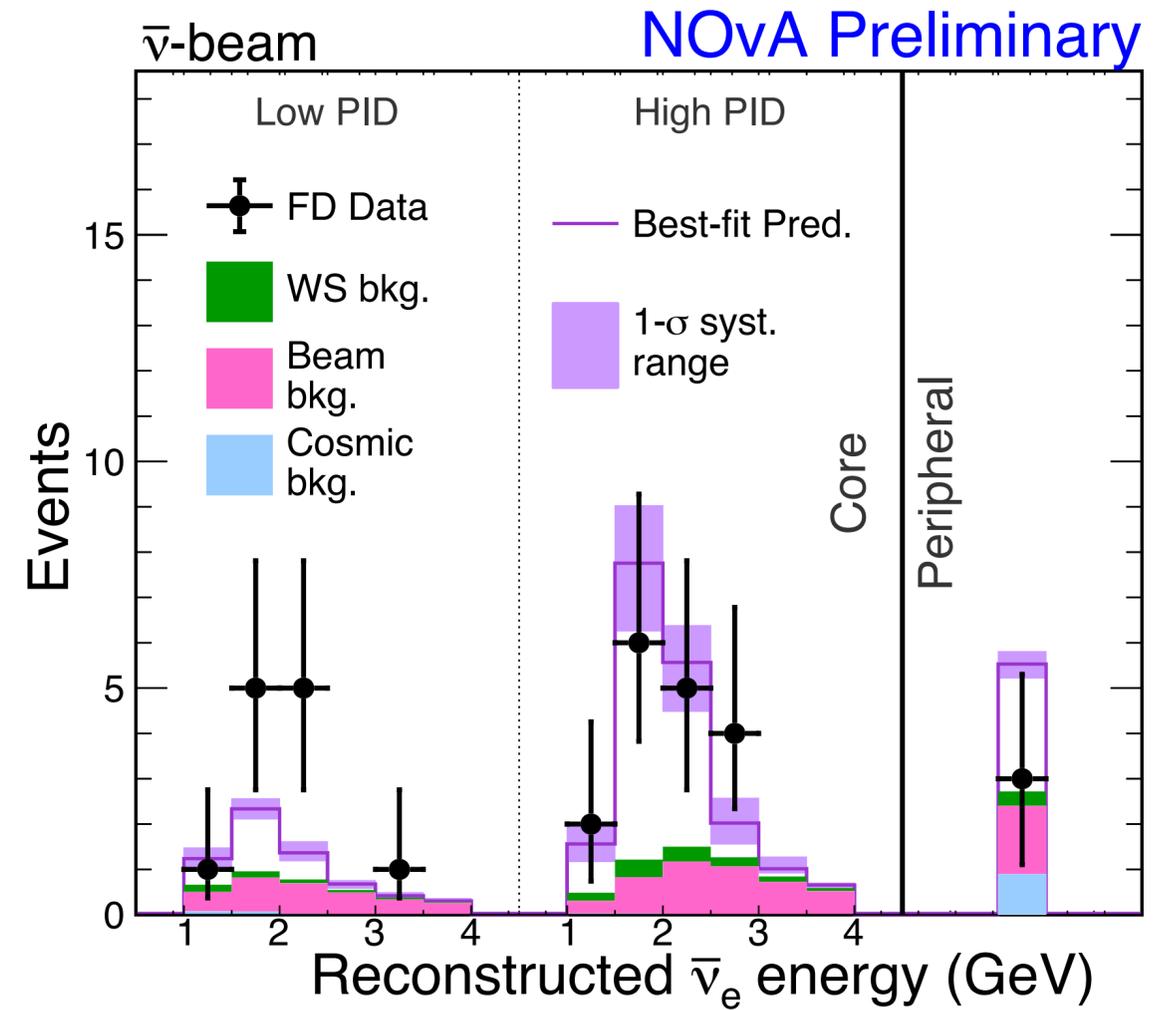


- *The most important systematics: neutrino cross sections; detector calibration (will be improved by test beam program); neutron uncertainty - with $\bar{\nu}$.
- * ND constraints reduce the systematic uncertainties in the FD predictions from $\sim 15\%$ to 4-5%.
Statistical uncertainties are dominant in the oscillation measurement.

FD DATA: ANTINEUTRINO BEAM

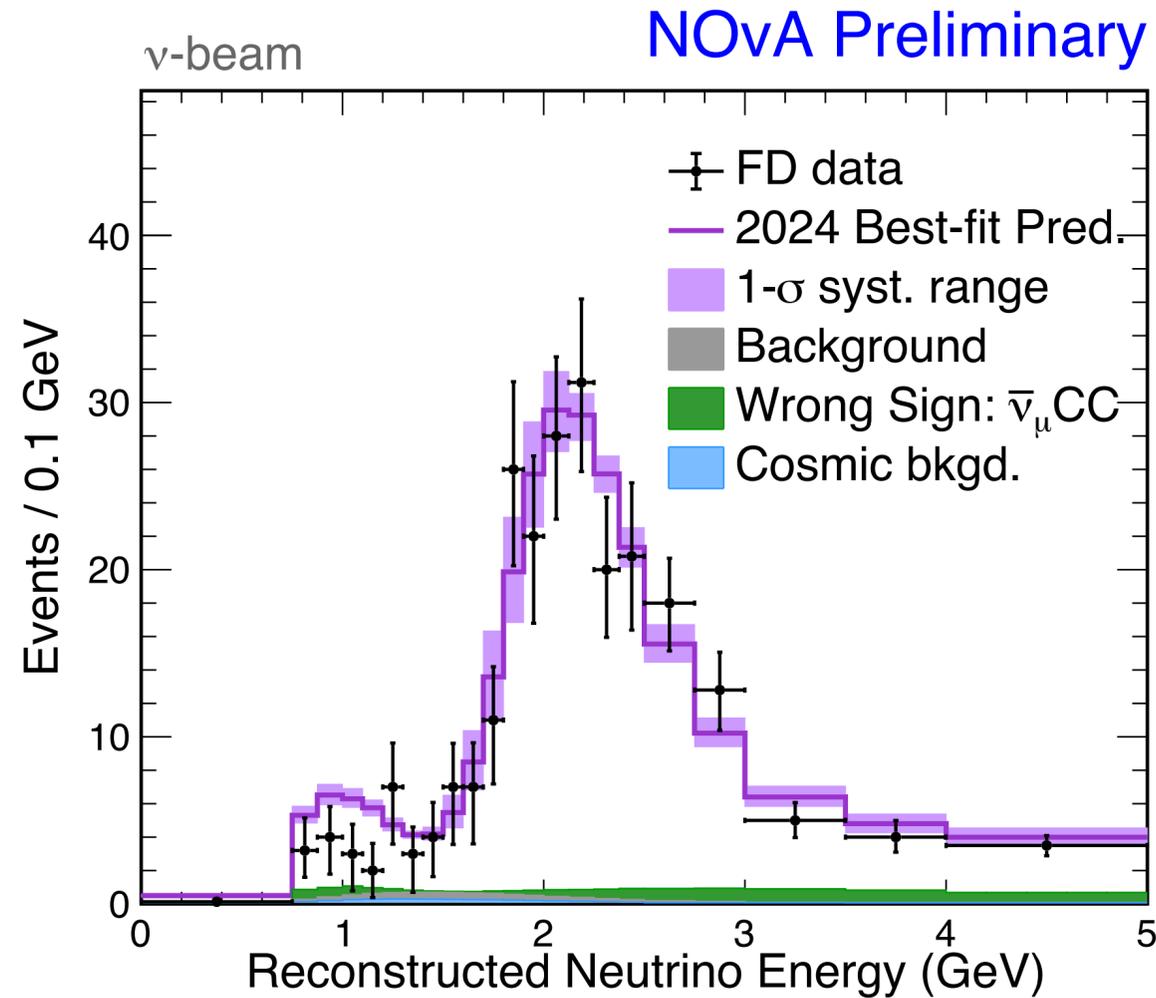


106 $\bar{\nu}_{\mu}$ candidates
 (expected total bkg 1.7)

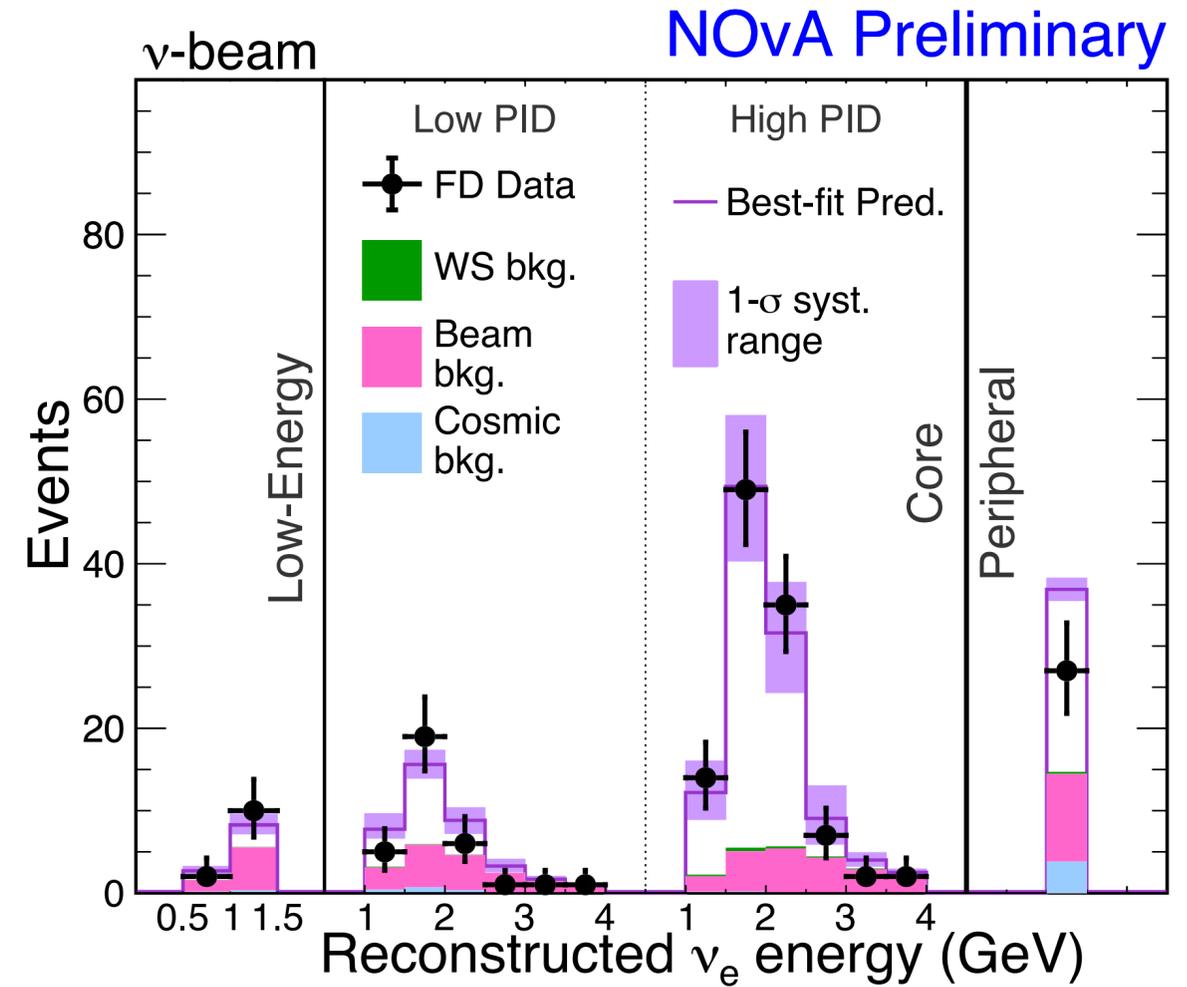


32 $\bar{\nu}_e$ candidates
 (expected total bkg 12.2)

FD DATA: NEUTRINO BEAM



384 ν_μ candidates
 (expected total bkg 11.3)



181 ν_e candidates
 (expected total bkg 61.7)

FIT

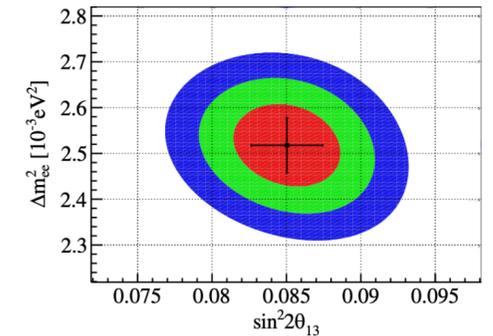
We perform a simultaneous fit of all samples, using Bayesian or frequentist techniques. External constraints are used for the solar parameters and optionally reactor constraint on θ_{13} .

4 $\{\nu_\mu, \bar{\nu}_\mu\}$ quartiles + $\{\nu_e, \bar{\nu}_e\}$ low PID, high PID, Peripheral samples + ν_e low E sample

+

Three possibilities for reactor constraint:

θ_{13} unconstrained (NOvA only) **OR** Daya Bay 1D θ_{13} constraint $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ **OR** Daya Bay 2D $(\Delta m_{32}^2, \theta_{13})$ constraint PRL 130, 161802



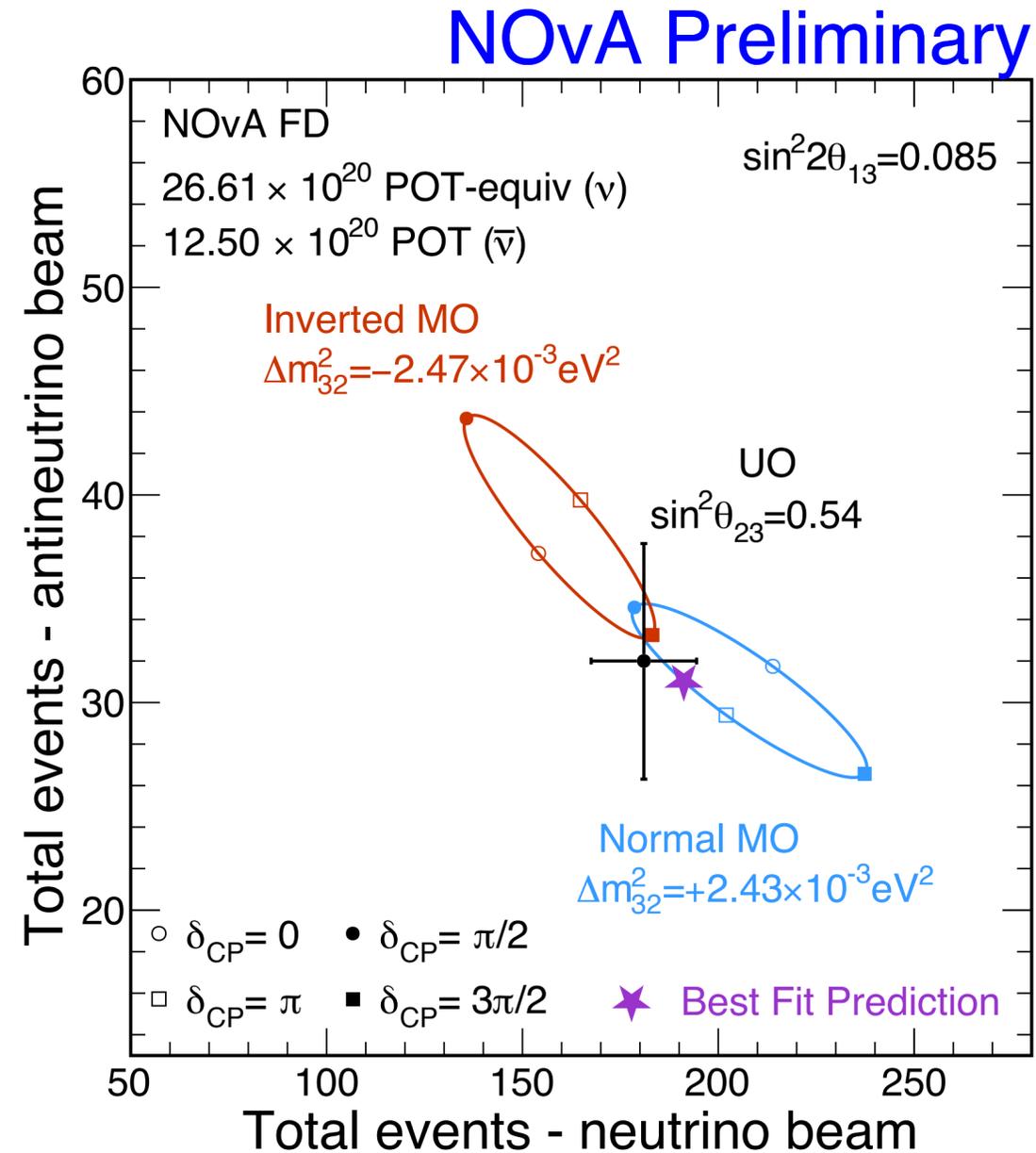
Bayesian Markov Chain Monte Carlo (marginalization) (technique described in arXiv:2311.07835) Bayesian credible regions **OR** Frequentist χ^2 minimization (profiled Feldman-Cousins) (technique described in arXiv:2207.14353) Frequentist confidence regions

$\Delta m_{32}^2, \sin^2 \theta_{23}, \sin^2 2\theta_{13}, \delta_{CP}$

Octant, Hierarchy, CP-violation

Other mixing parameters:
 $\sin^2 \theta_{12} = 0.307$ (PDG 2023)
 $\Delta m_{21}^2 = 7.53 \times 10^{-5} \text{ eV}^2$ (PDG 2023)
 $\rho = 2.74 \text{ g/cm}^3$ (CRUST 1.0)

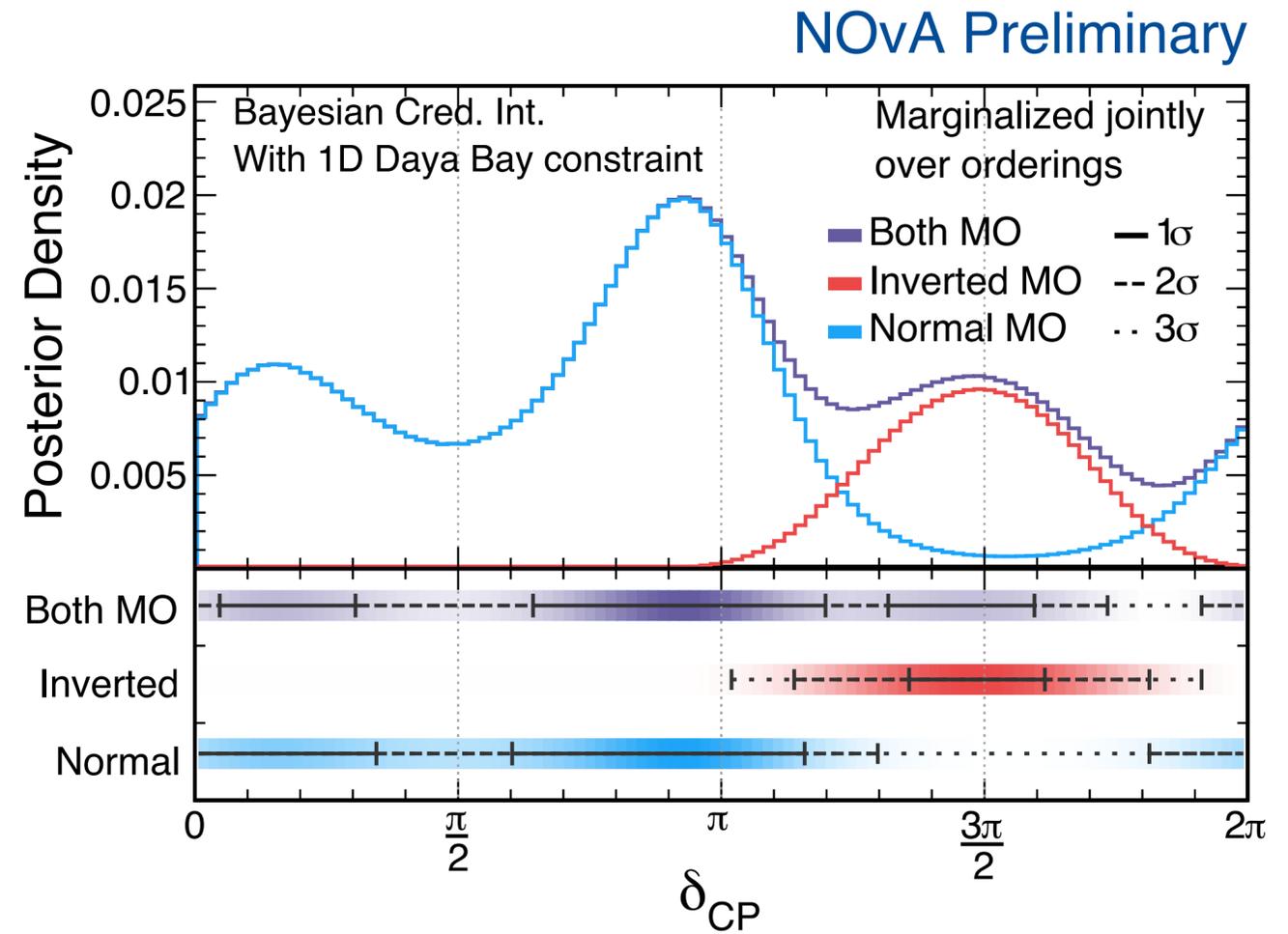
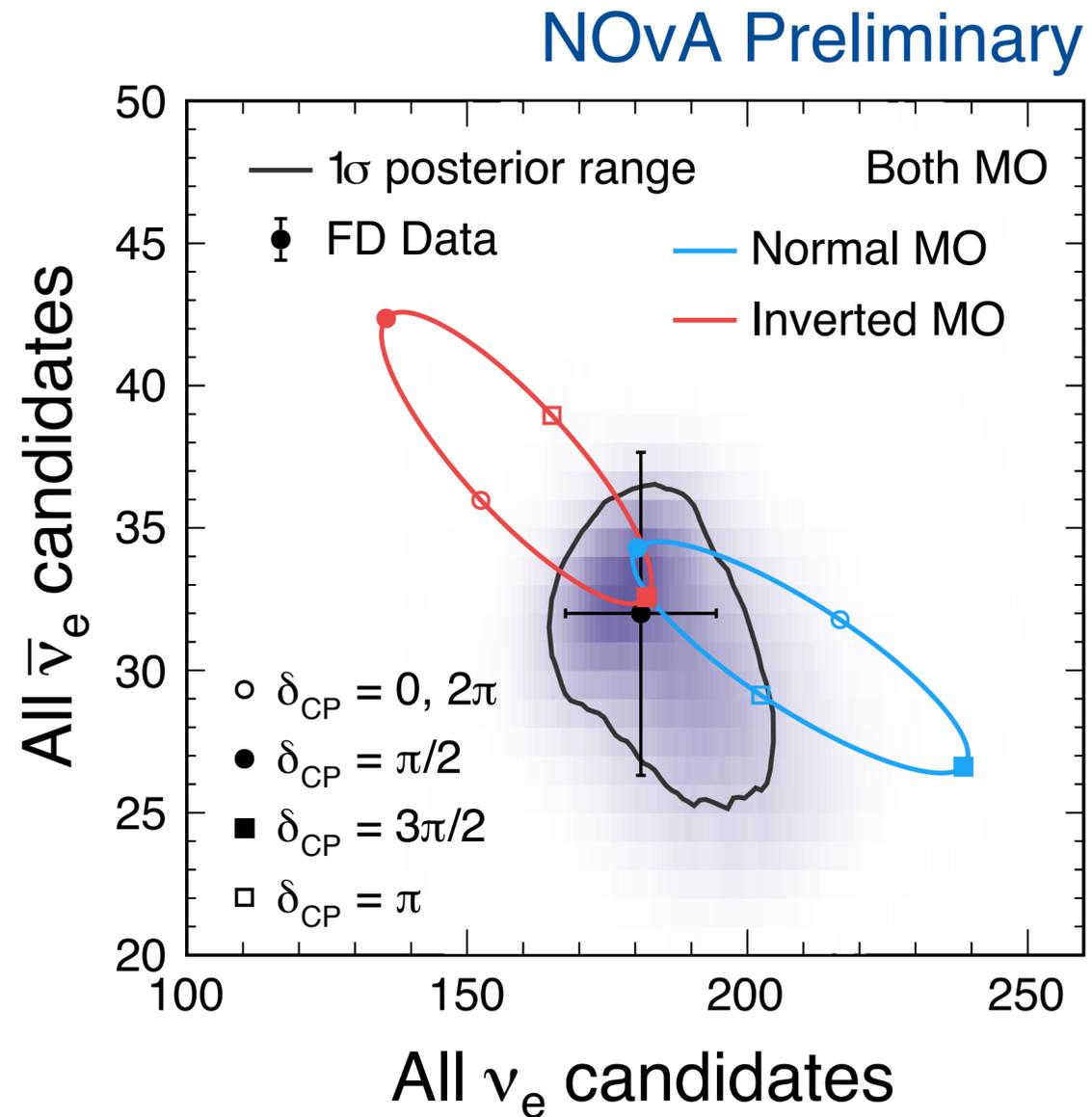
FD DATA AND BEST FIT



	Frequentist results (w/ Daya Bay 1D ϑ_{13} constraint)	
	Normal MO	Inverted MO
$\Delta m_{32}^2 / 10^{-3} \text{ eV}^2$	+2.433	-2.473
$\sin^2 \theta_{23}$	0.546	0.539
δ_{CP}	0.88π	1.51 π
Rejection significance (σ)	1.36	

The appearance data favor a region where matter and CP violation effects are highly degenerate

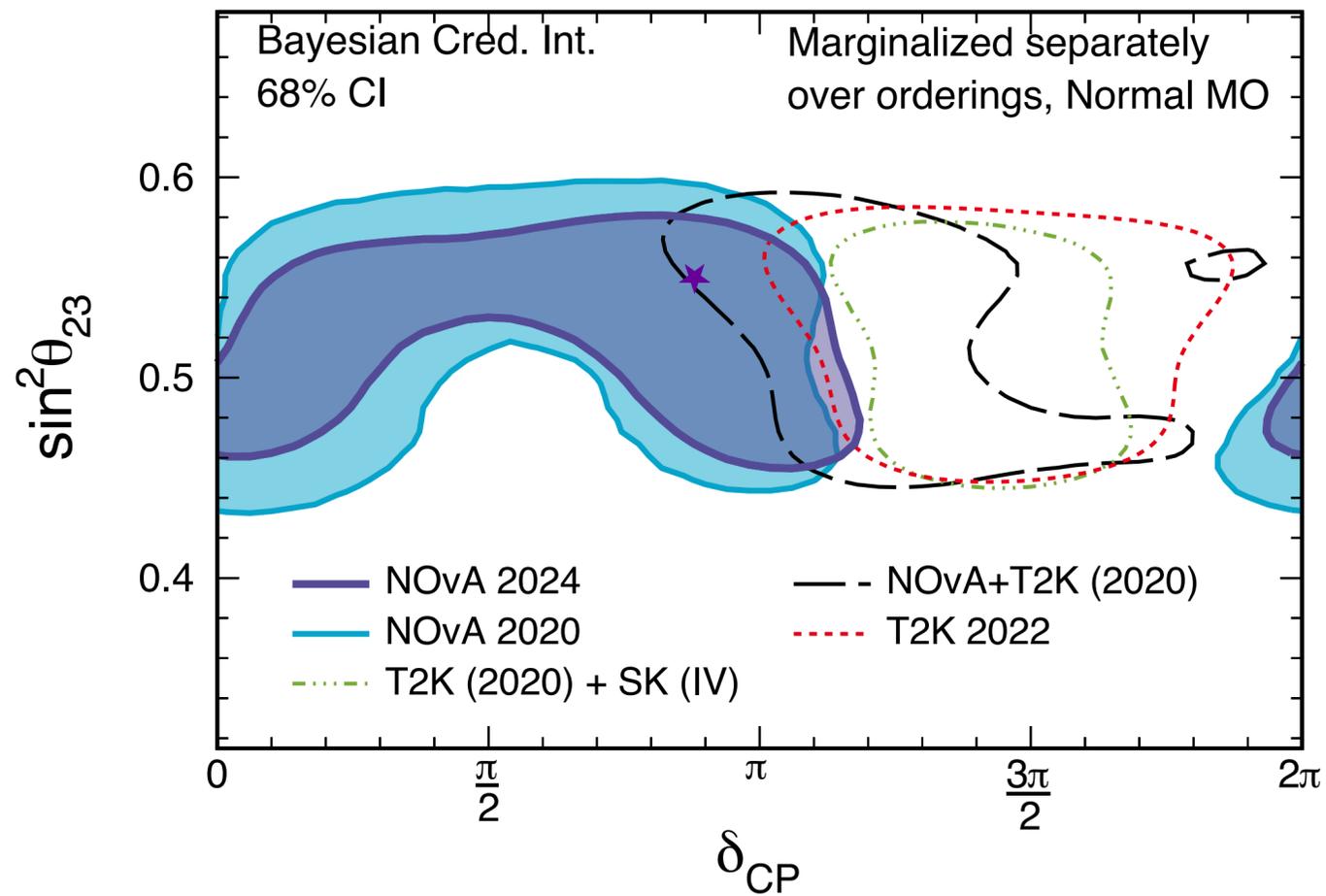
RESULTS



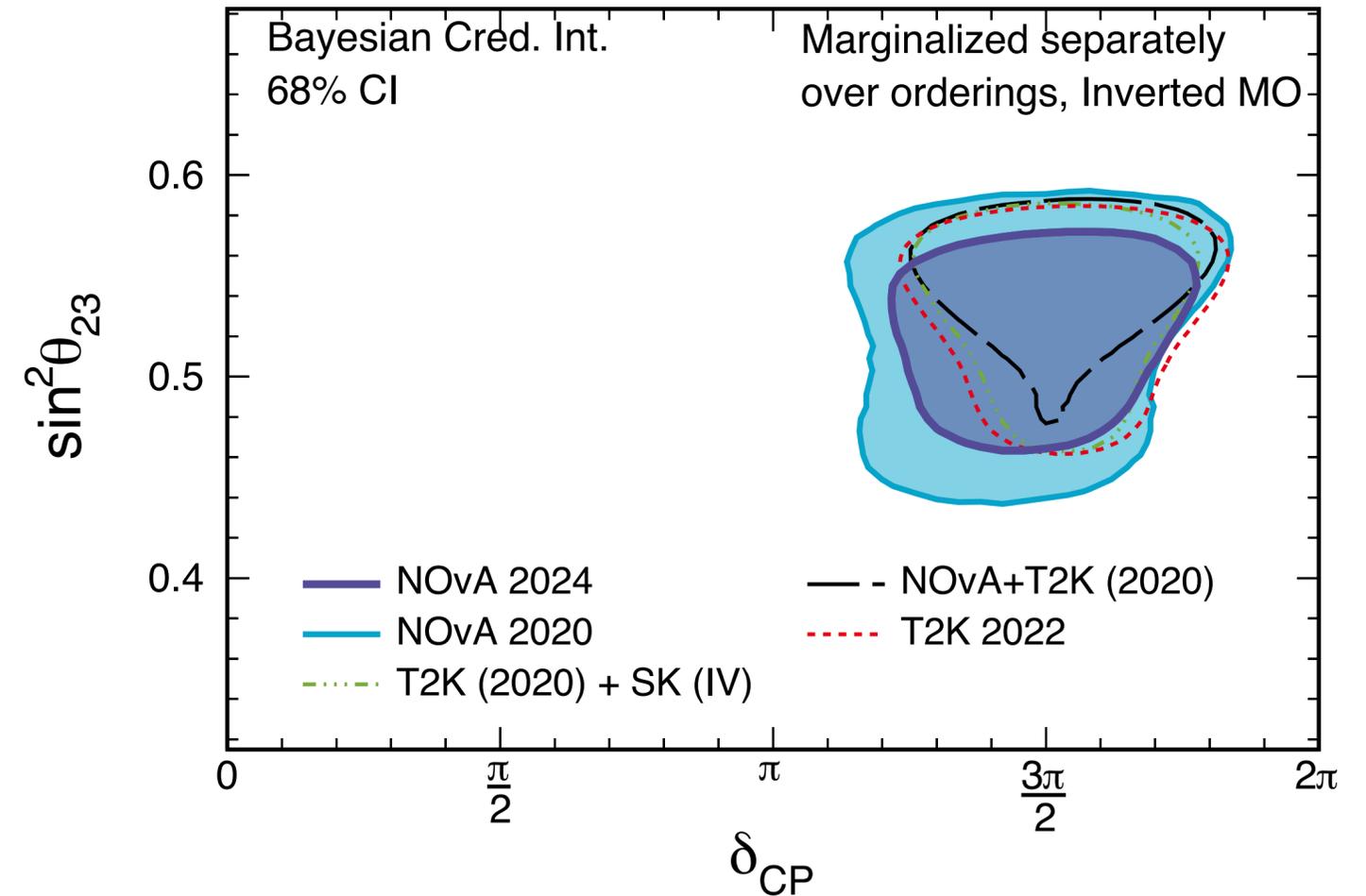
- * The data disfavor “extreme” asymmetry combinations: (IO, $\delta = \pi/2$) and (NO, $\delta = 3\pi/2$).
- * CP-conserving points outside 3σ interval in IO.

RESULTS

NOvA Preliminary

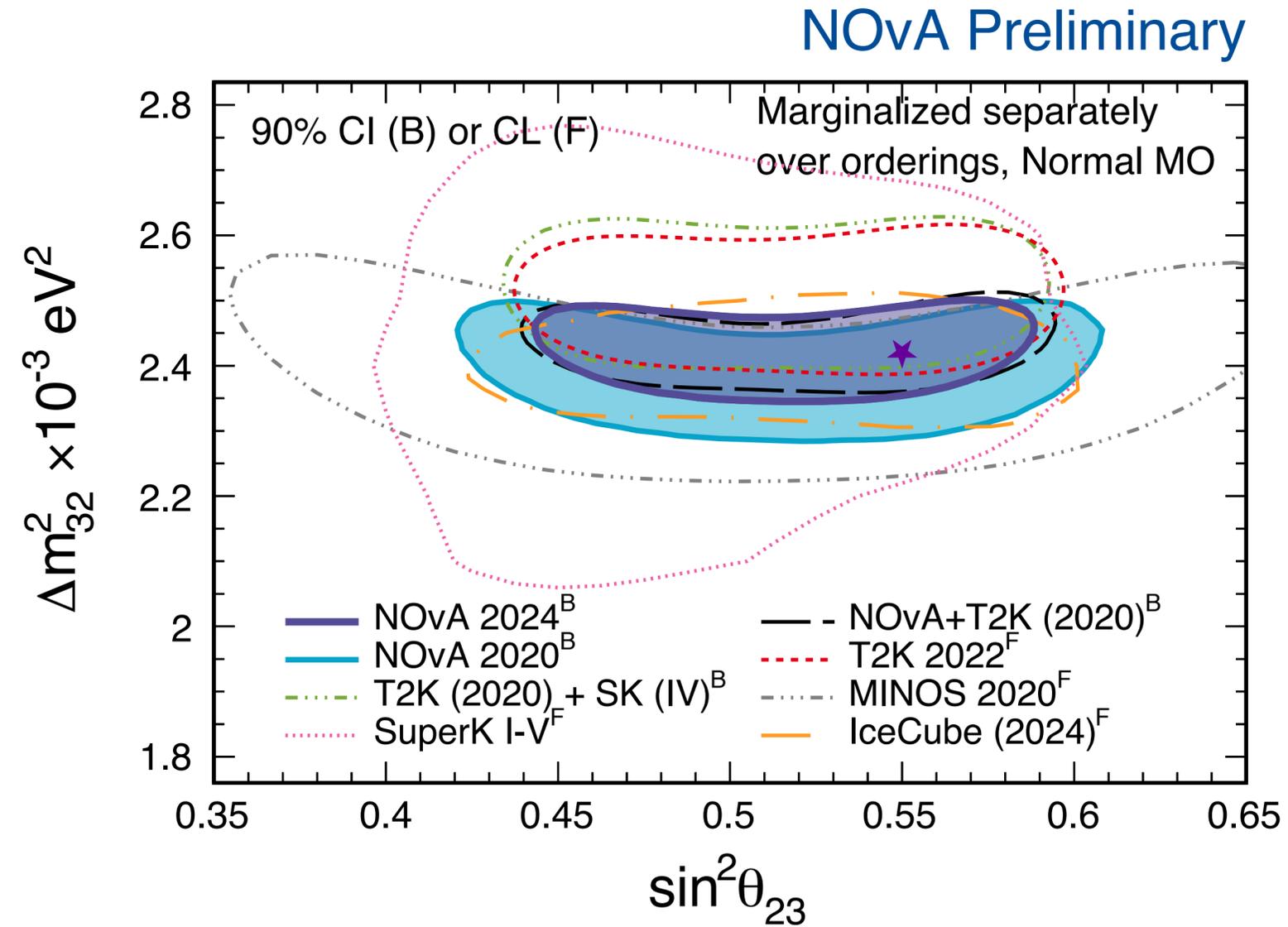


NOvA Preliminary



- * The new NOvA result is consistent with its previous analysis.
- * T2K, joint fits, favor different regions in NO, same region in IO.
- * NB: different choices of reactor constraint.

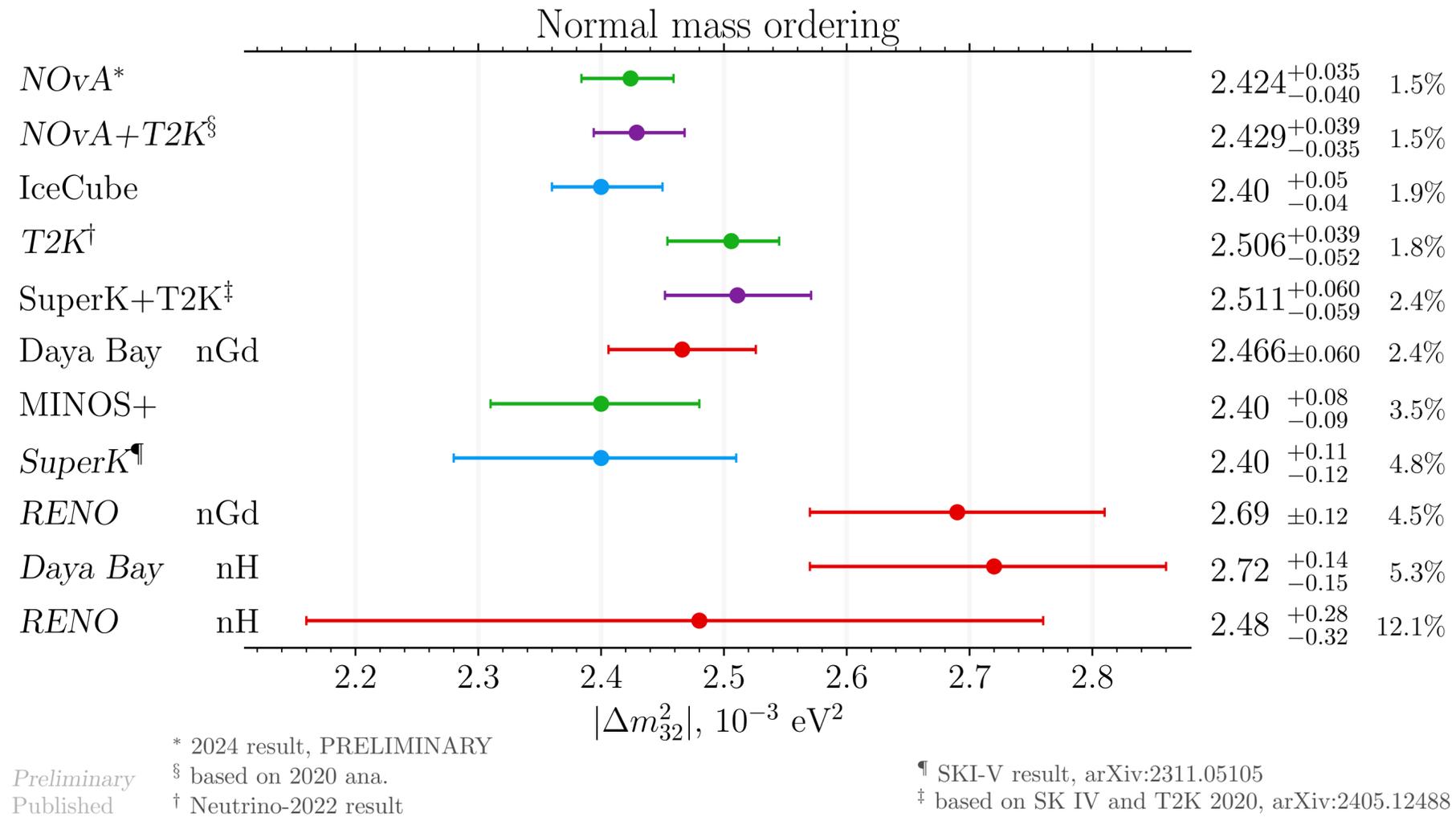
RESULTS



* The new NOvA result is consistent with its previous analysis.

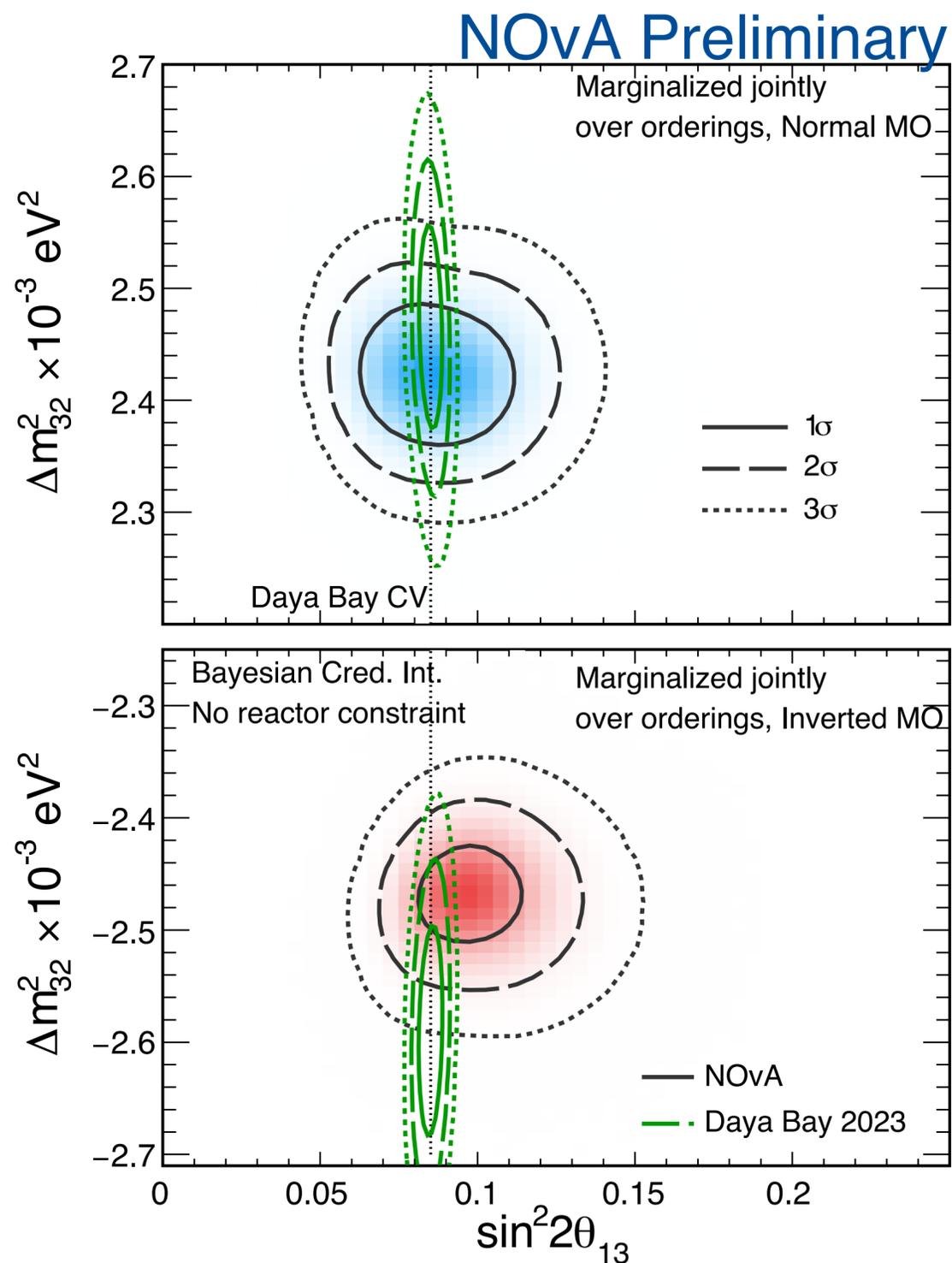
* Overall consistency between all experiments in $\nu_2 - \nu_3$ sector.

RESULTS



- * The new NOvA result gives the most precise single experiment measurement of Δm_{32}^2 .
- * Δm_{32}^2 is now the most precisely know PMNS parameter.

RESULTS



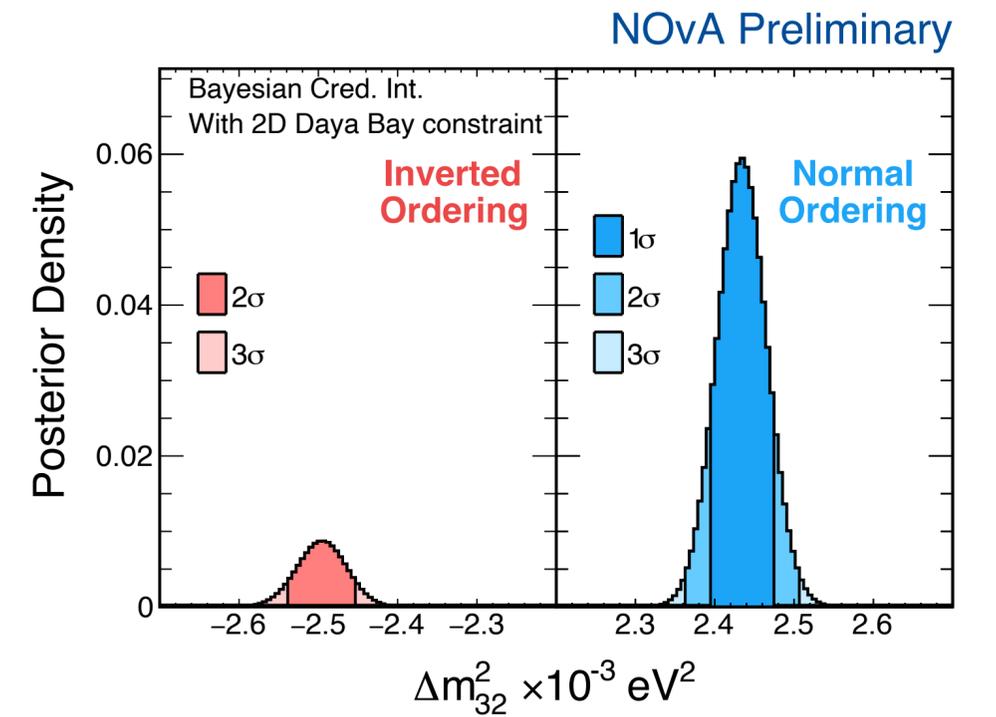
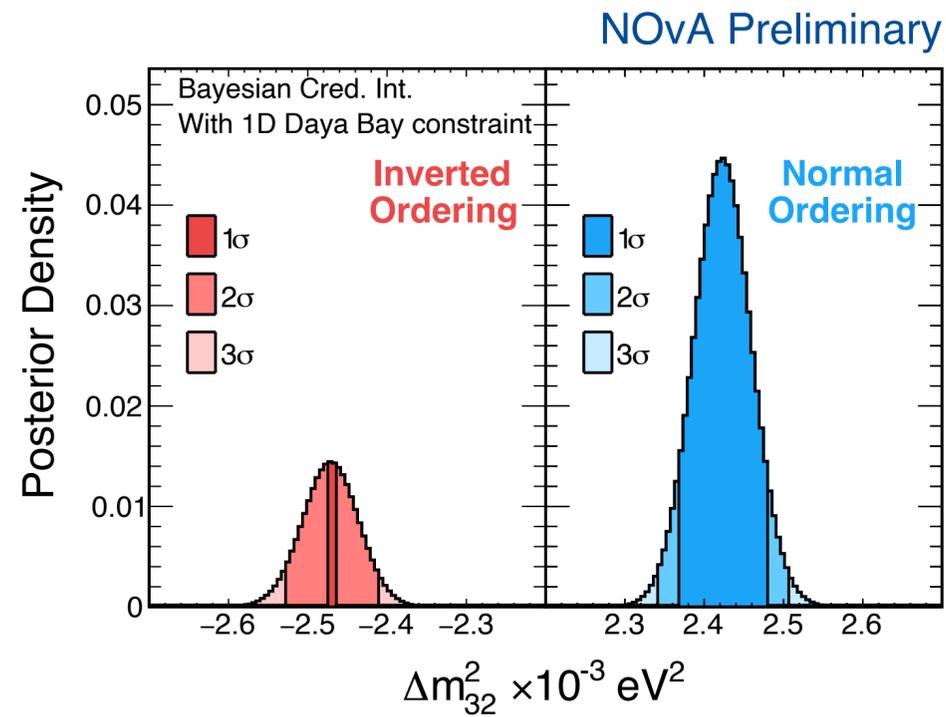
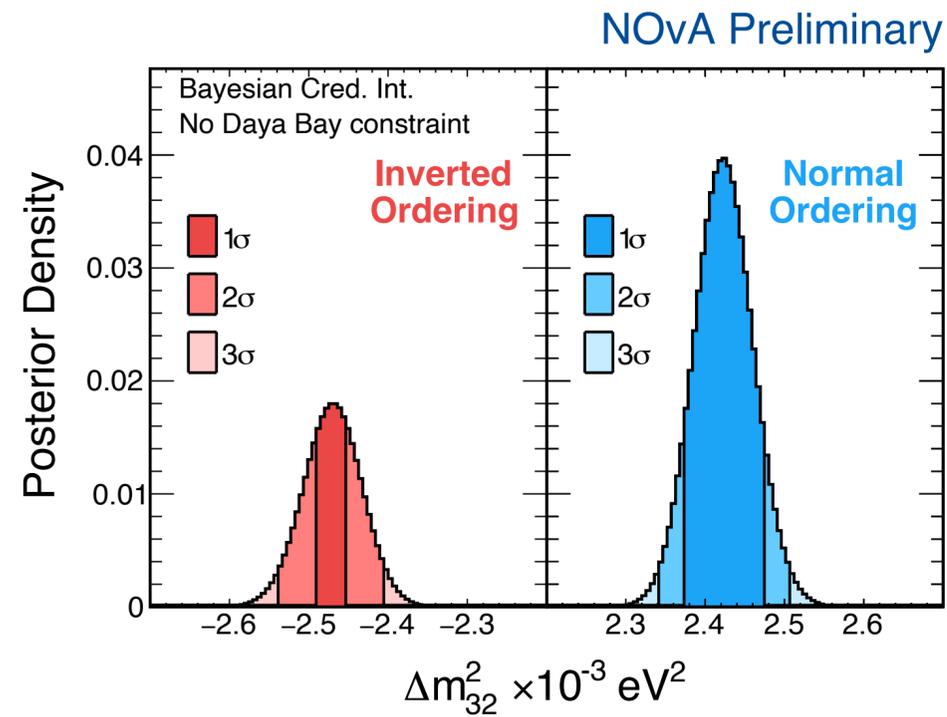
- * Precision measurements of Δm_{32}^2 in both accelerator and reactor experiments offer more ways to resolve degeneracies
- * Use 2D reactor constraint to boost sensitivity to the Mass ordering.
 - * In the true mass ordering reactor LBL measurements of Δm_{32}^2 would be consistent but in incorrect MO would be wrong by different amounts.

See: [Stephen Parke W&C, 2023](#) *[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‡}

RESULTS



* NOvA data prefer the normal mass ordering. This preference is enhanced by applying reactor constraints (1D and 2D).

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

SUMMARY

- * The NOvA 2024 analysis is the first large update since 2020
 - * Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data.
 - * Various remarkable updates to the analysis.
- * NOvA's most recent oscillation analysis results:
 - * Most precise single-experiment measurement of Δm_{32}^2 (1.5%).
 - * Results are consistent with previous analysis.
 - * Data favors region where matter, CP violation effects are degenerate.
- * Strong synergy with reactor measurements
 - * Constraint on θ_{13} enhances Upper Octant preference (69% odds).
 - * Constraint on Δm_{32}^2 enhances Normal Ordering preference (87% odds).
- * Future prospects:
 - * Goal of doubling antineutrino dataset → Increased precision measurements of the osc. parameters, disentangle mass ordering / CPV?
 - * Test beam results could address some of the largest systematic uncertainties in NOvA.
 - * Sterile searches, NSI, cross section measurements, cosmic ray physics, exotics... and more!