

Neutrino Oscillations at the NOvA experiment

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for the NOvA collaboration



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THE NOvA EXPERIMENT

The NuMI Off-Axis ν_e Appearance Experiment

Experiment goals:

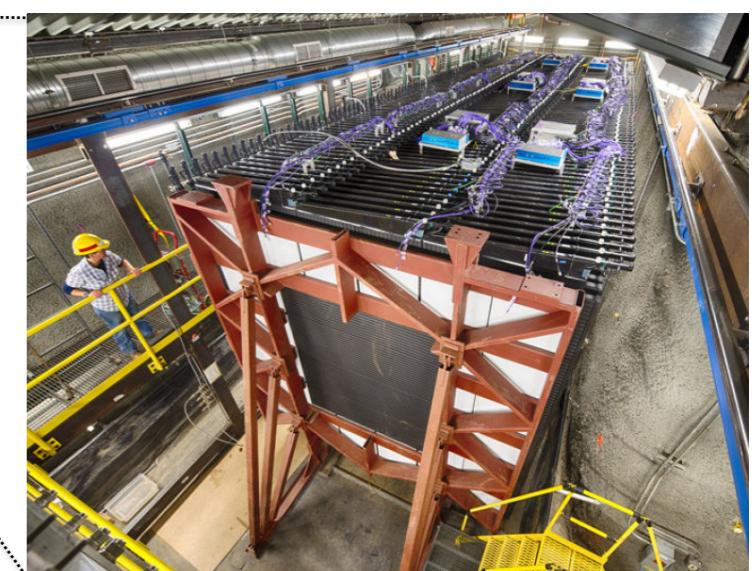
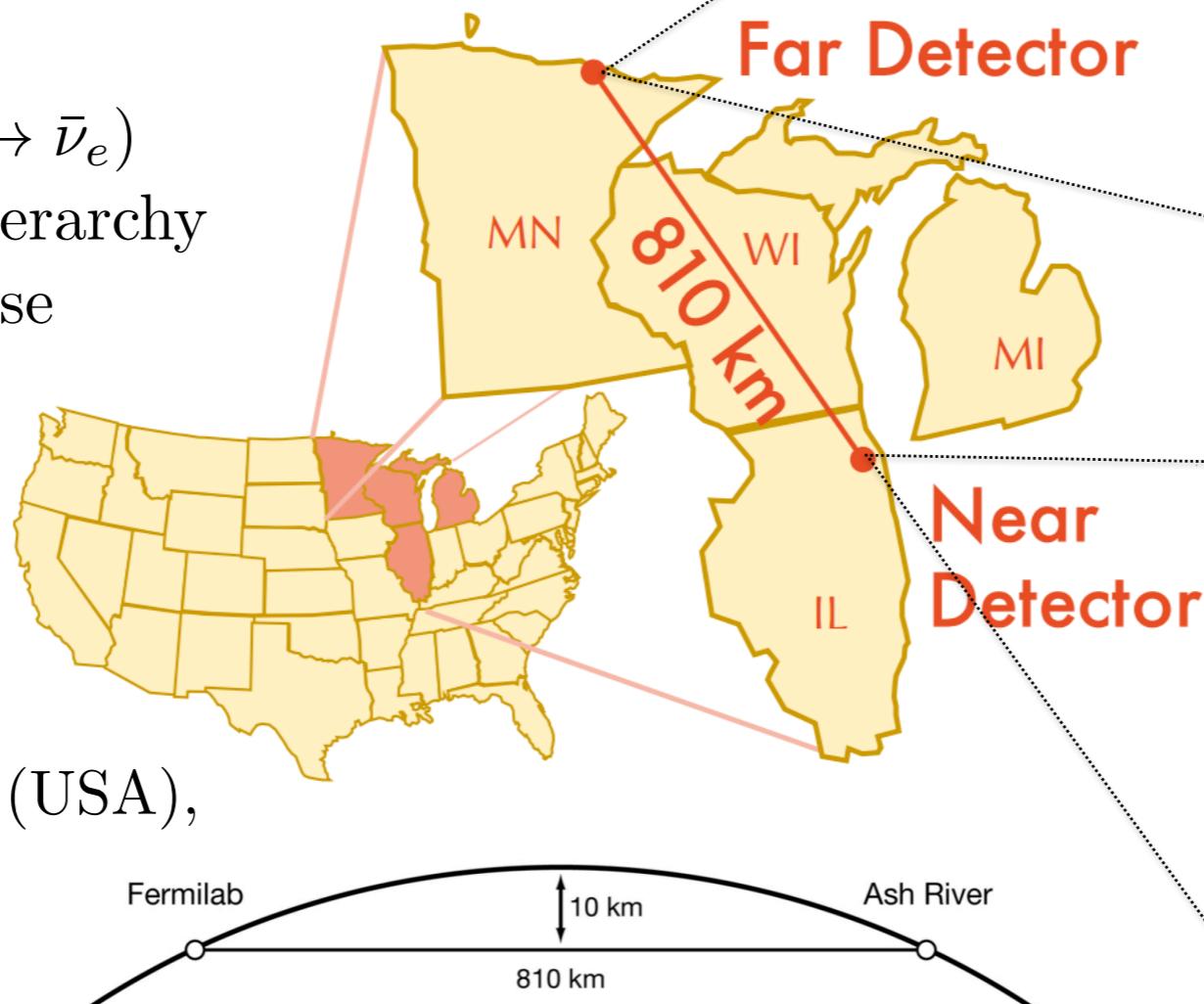
Using $\nu_\mu \rightarrow \nu_\mu$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

- * Precise measurement 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
- * Mixing angle θ_{23}

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



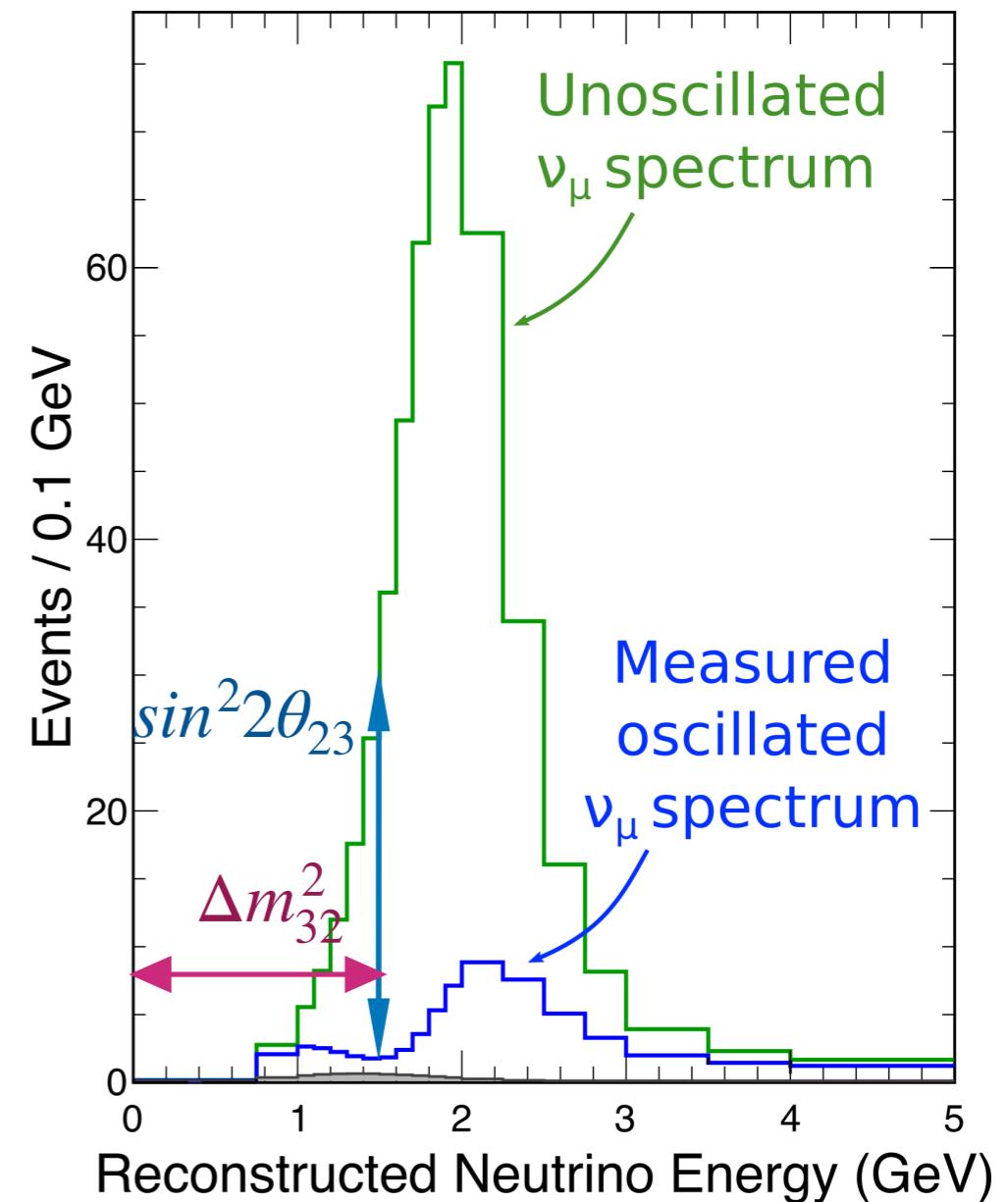
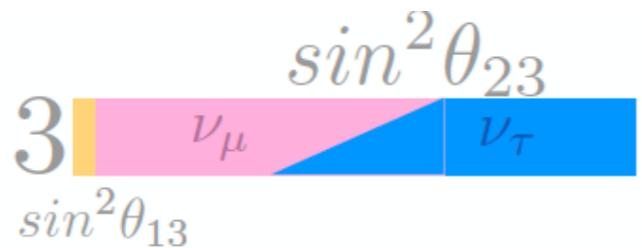
STRATEGY: ν_μ DISAPPEARANCE

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E} \right)$$

Precise measurement of the following parameters:

Location of dip $\rightarrow \Delta m_{32}^2$

Amplitude $\rightarrow \sin^2 2\theta_{23}$



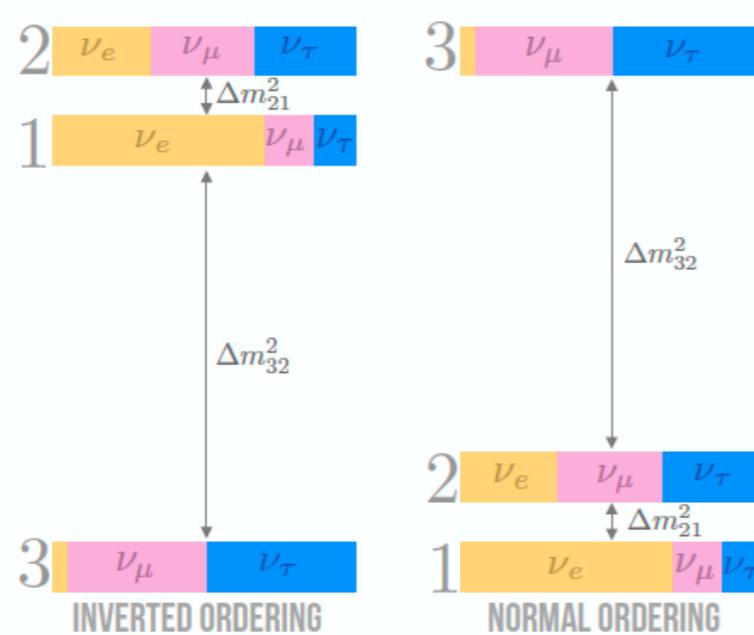
STRATEGY: ν_e APPEARANCE

$$\Delta P_{\nu\bar{\nu}} \sim \sin \delta_{CP}$$

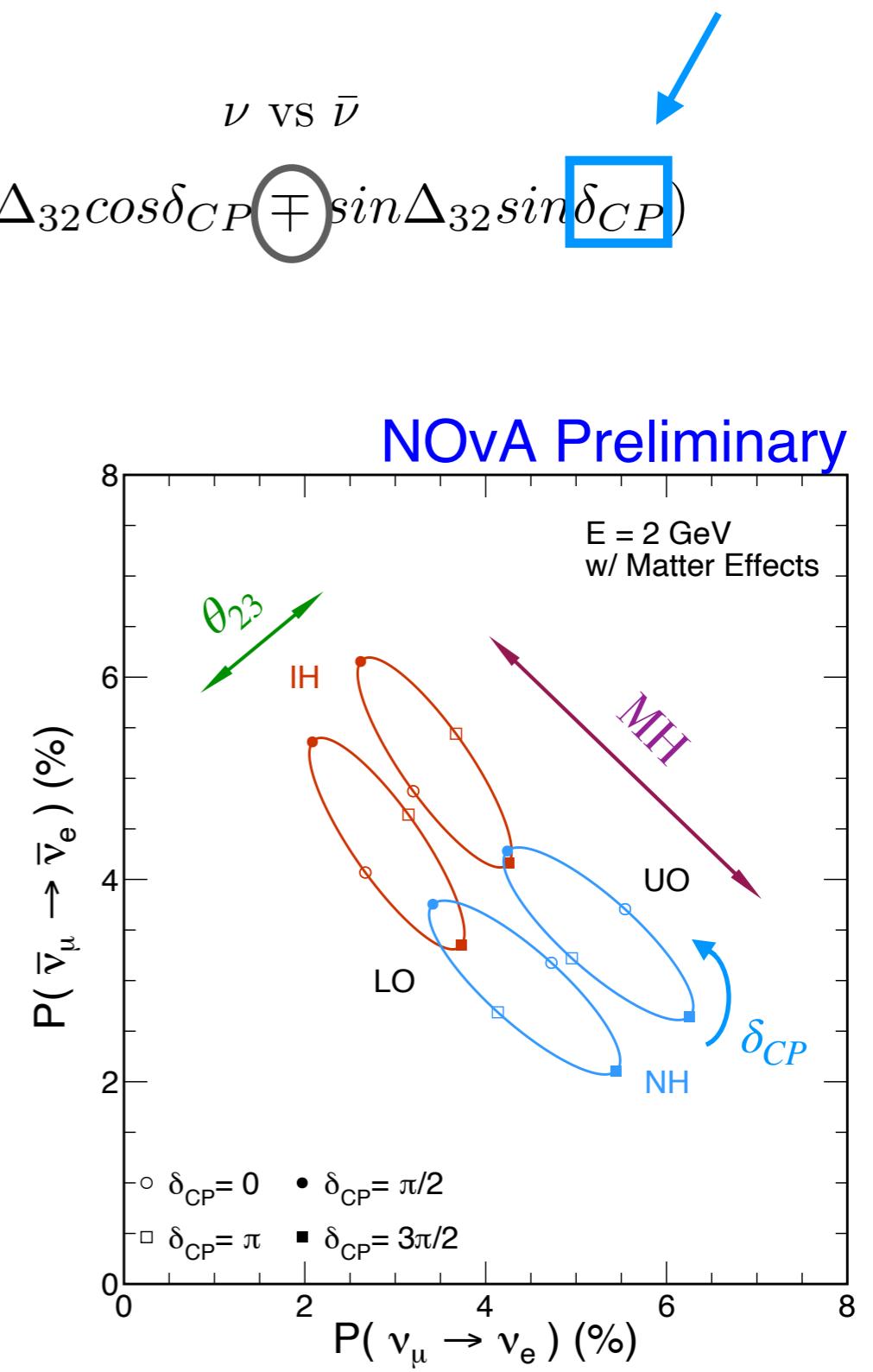
In presence of matter:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP})$$

$$\sqrt{P_{atm}} = \sin(\theta_{23})\sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}$$



Degeneracy "θ₂₃ - mass hierarchy - δ_{CP}"

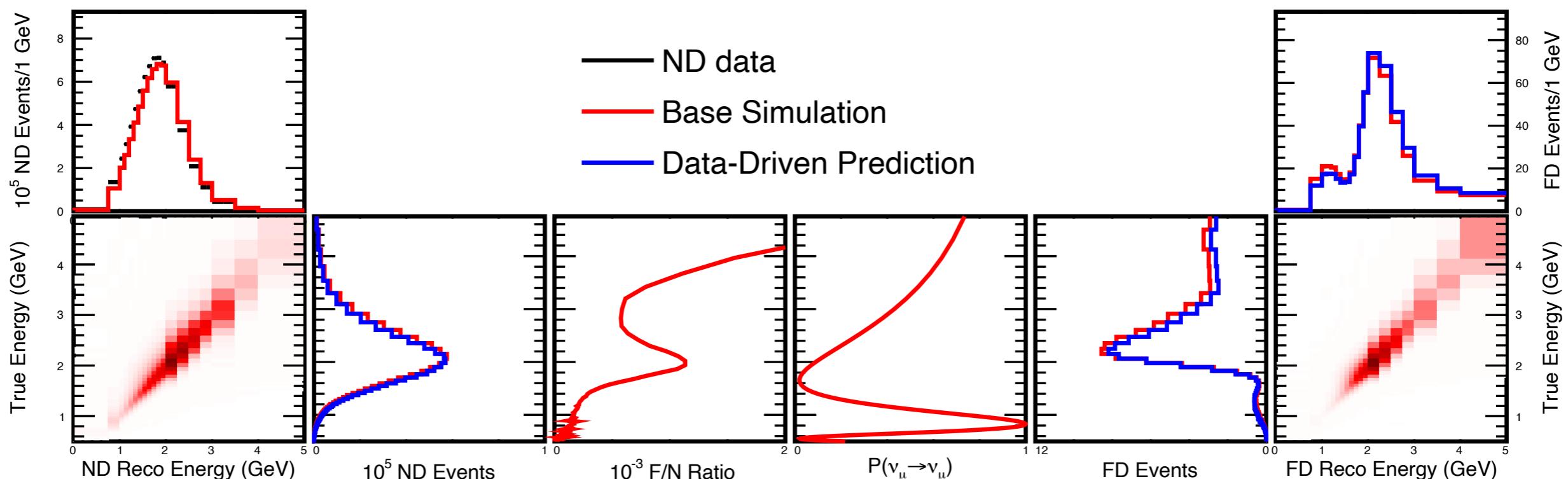


SIMULATION AND PREDICTIONS

Basic Monte-Carlo simulation chain:

- * Beam hadron production, propagation; neutrino flux: **GEANT4/External Data**;
- * Neutrino interactions and FSI modeling: **GENIE v3.0.6**;
- * Detector simulation: **GEANT4**;
- * Readout electronics and DAQ: Custom simulation routines;
- * Cosmic ray flux: Cosmic Triggers.

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

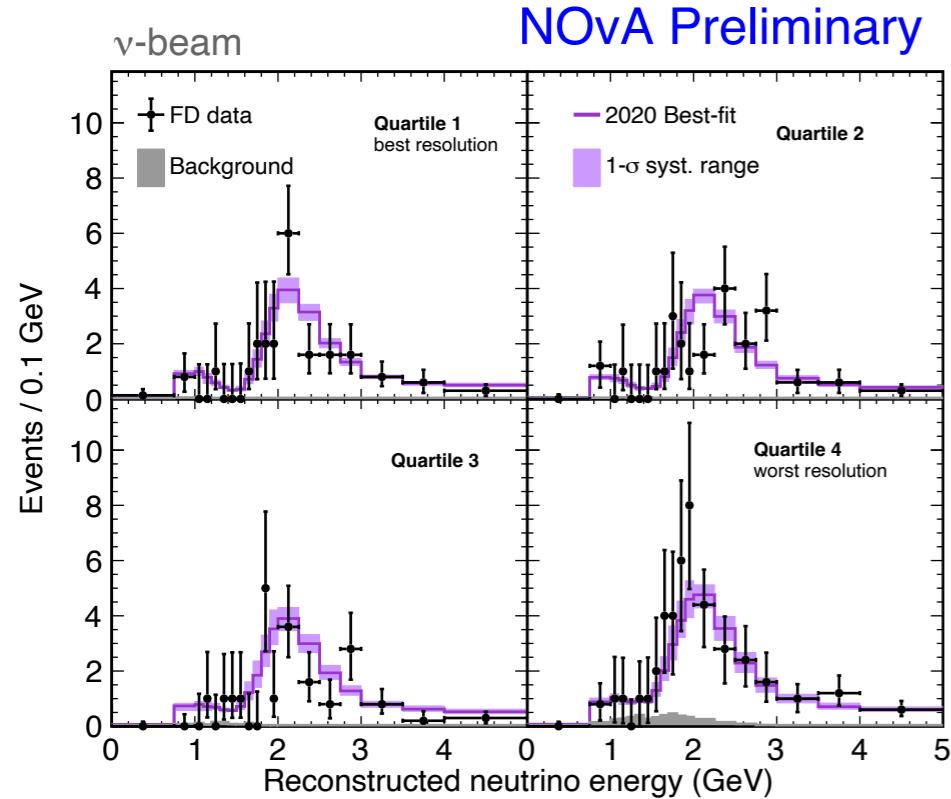


Constrain predictions
with ND data

Apply oscillations and
FD/ND ratio

Compare to
FD data

FD DATA. INPUTS FOR FIT

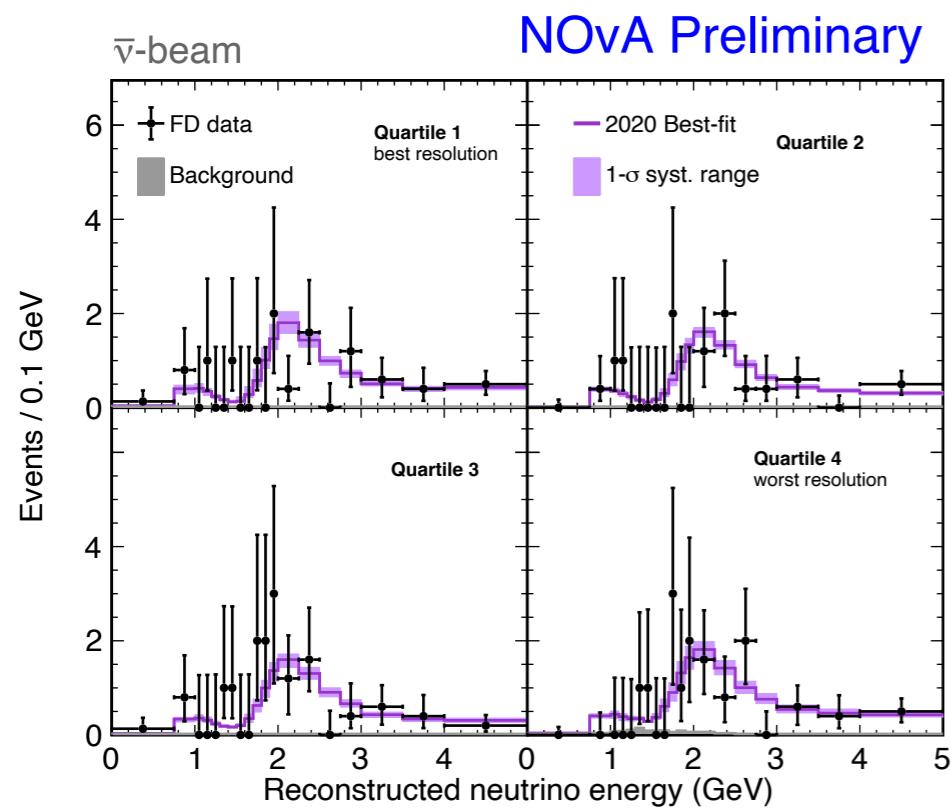
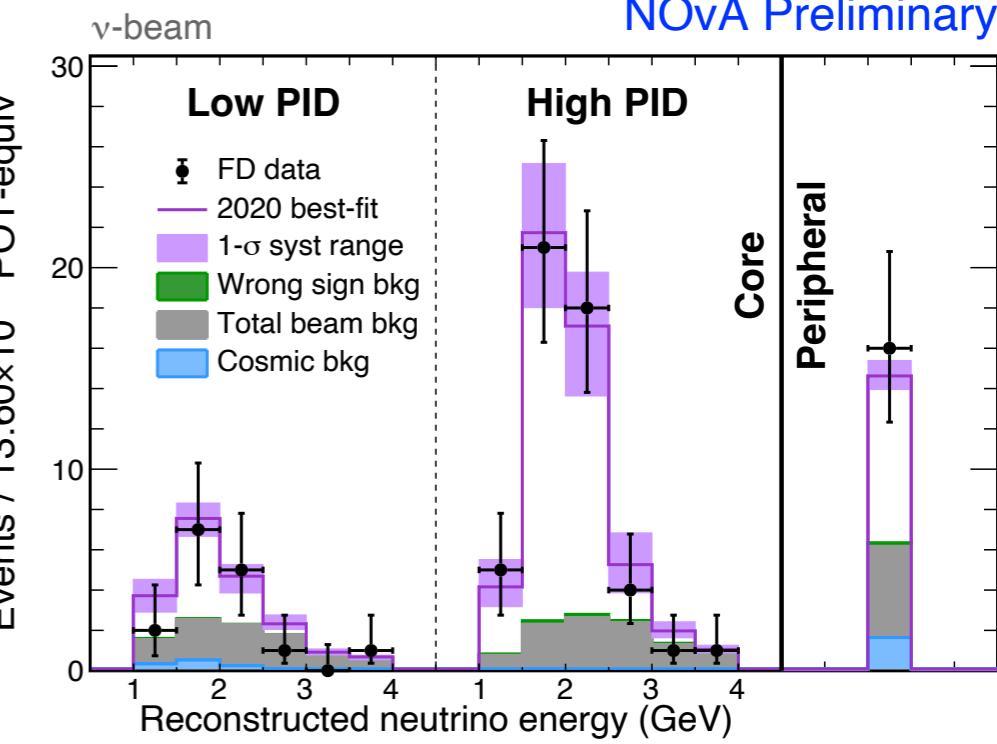


NEUTRINO BEAM

$(13.6 \times 10^{20} \text{ POT})$

211 ν_μ candidates
(bkg: 8.2)

82 ν_e candidates
(bkg: 26.8)

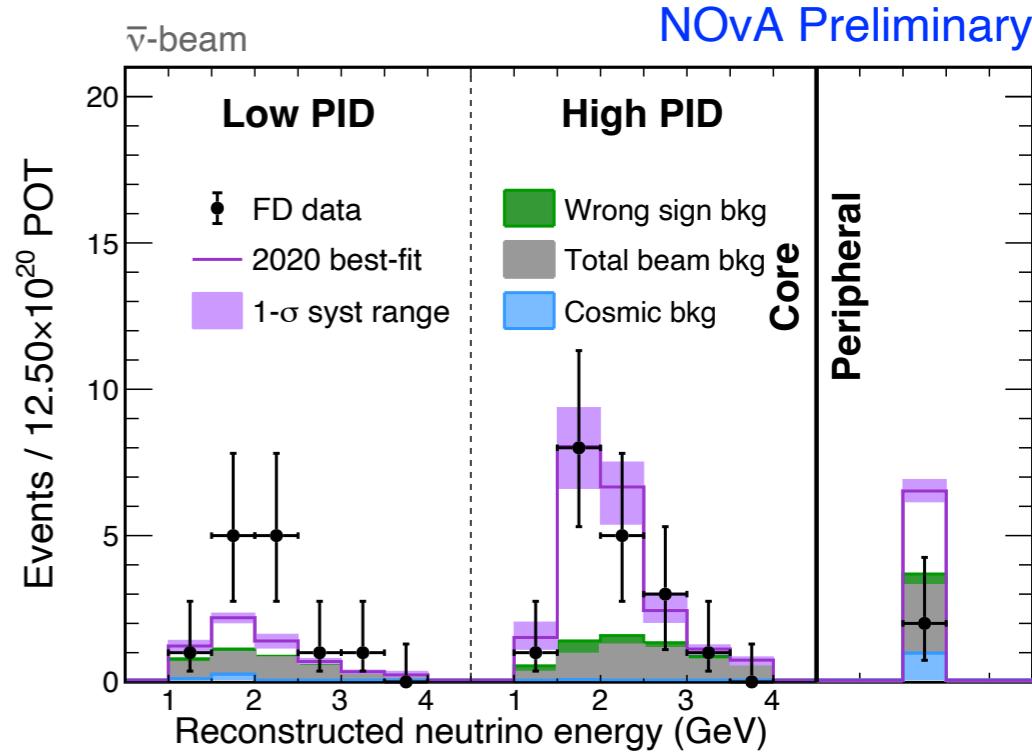


ANTINEUTRINO BEAM

$(12.5 \times 10^{20} \text{ POT})$

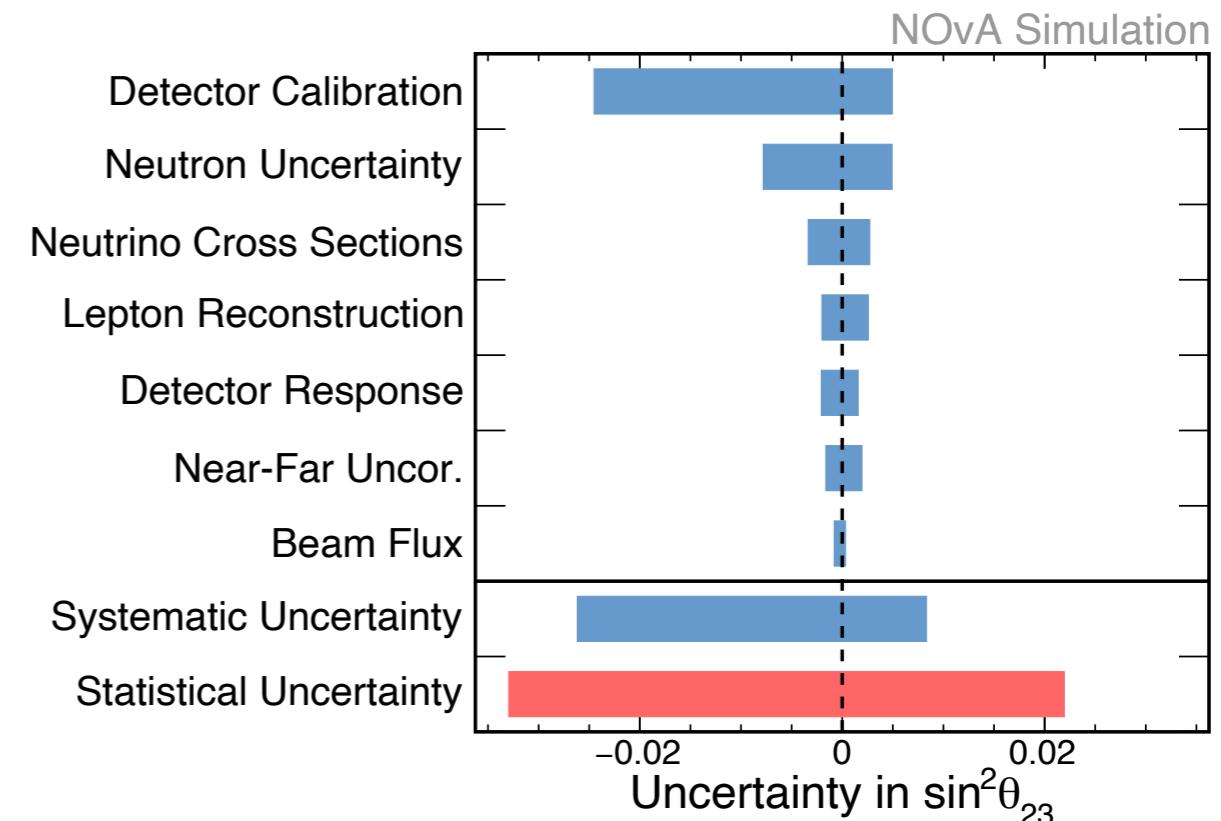
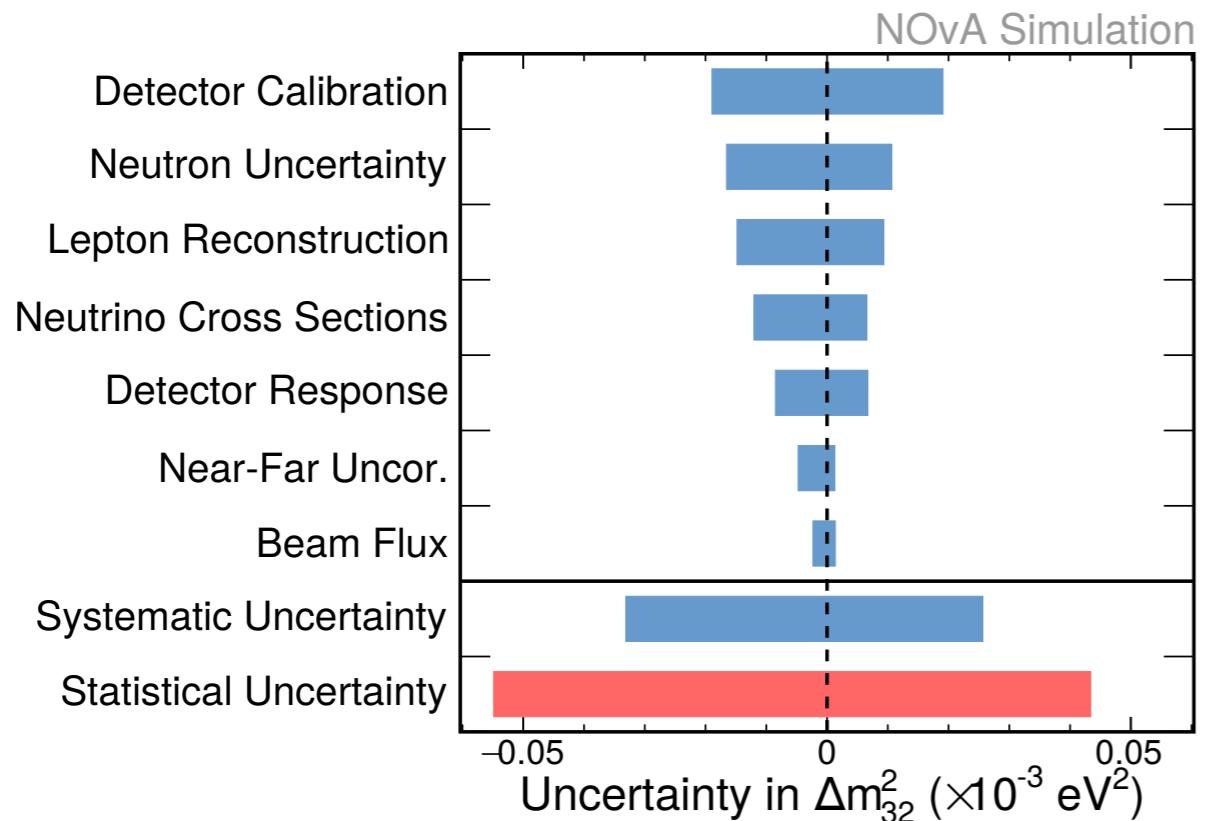
105 $\bar{\nu}_\mu$ candidates
(bkg: 2.1)

33 $\bar{\nu}_e$ candidates
(bkg: 14.0)
 $>4\sigma$ $\bar{\nu}_e$ appearance

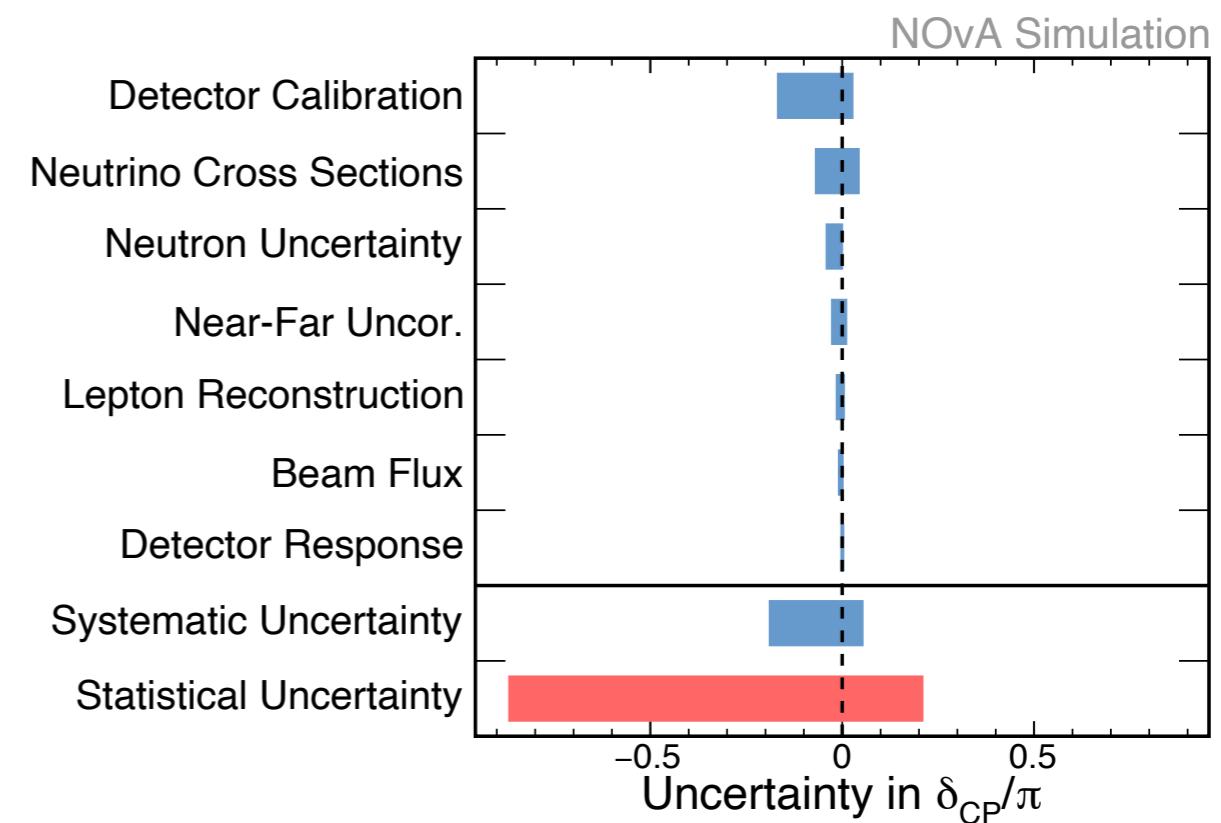


3-flavor oscillations describe data well
(goodness-of-fit $p = 0.705$)

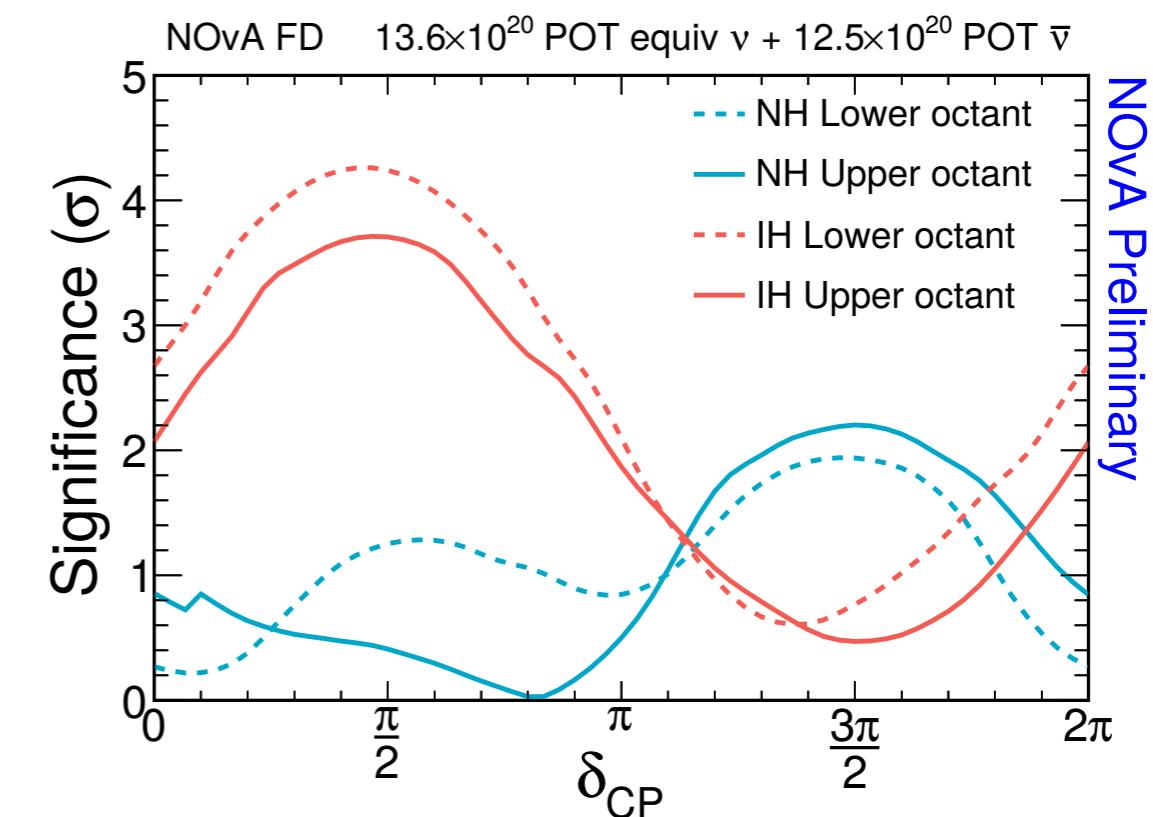
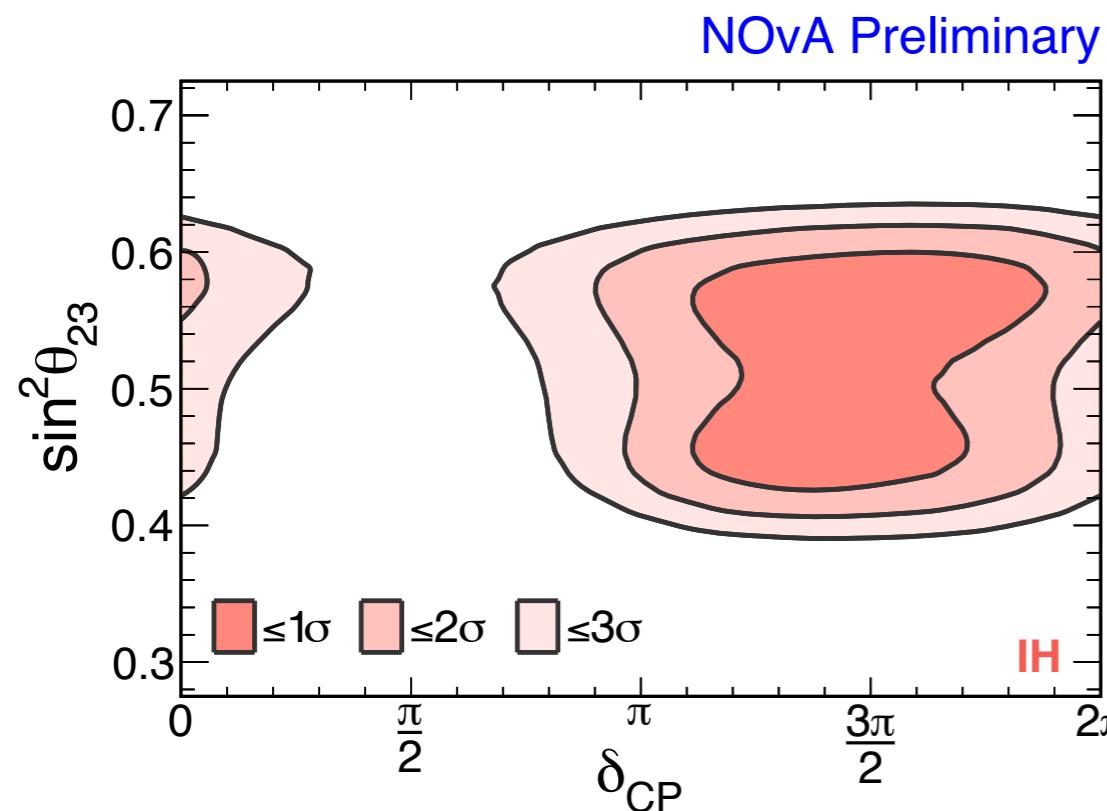
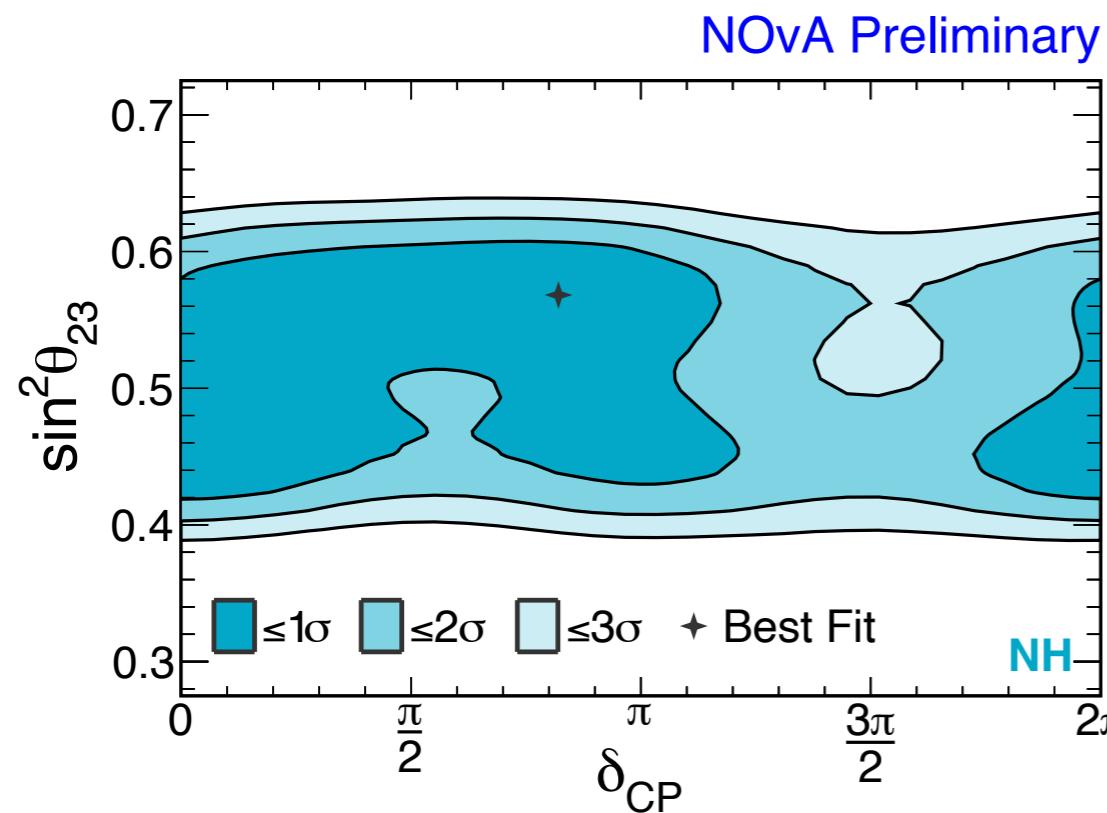
SYSTEMATICS



- * Still **statistically limited**.
- * The most important systematics:
 - * neutrino cross sections;
 - * detector calibration
(will be improved by test beam program);
 - * neutron uncertainty - with $\bar{\nu}$.



OSCILLATION RESULTS: JOINT $\nu_\mu + \nu_e$ FIT



- * All systematic uncertainties, Feldman - Cousins corrections are applied.
- * Best fit:

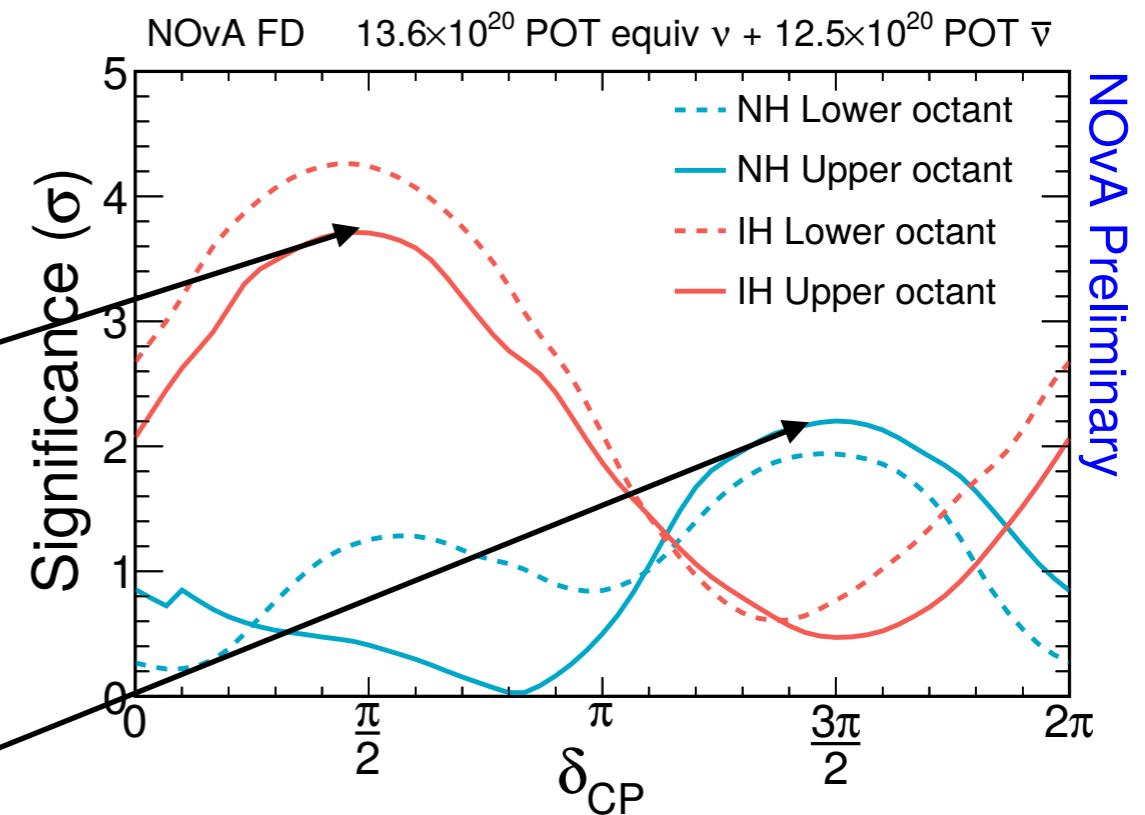
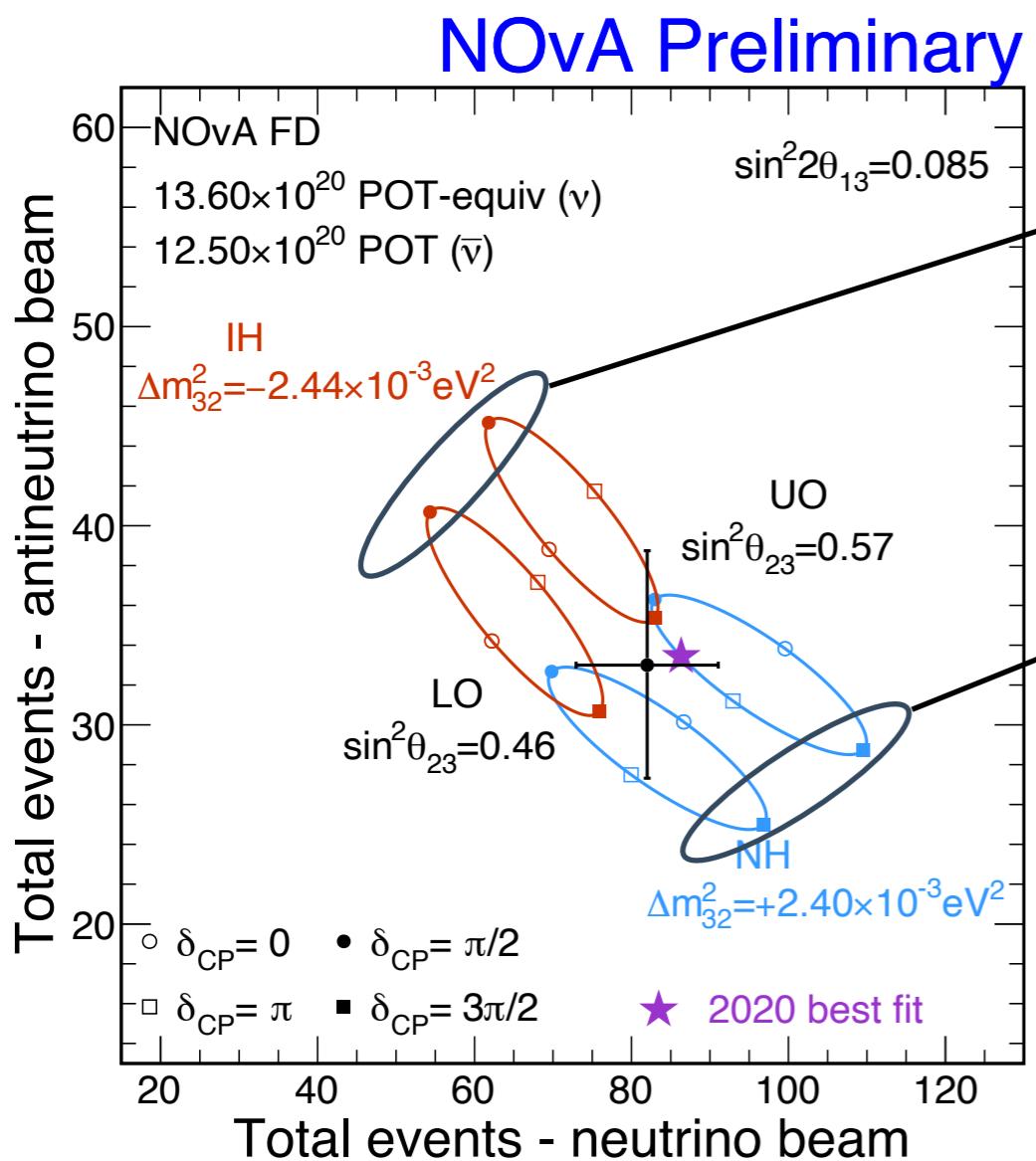
$$\sin^2 \theta_{23} = 0.57^{+0.03}_{-0.04}$$

$$\Delta m_{32}^2 = (+2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2 \text{ (NO)}$$

$$\delta_{CP} = 0.82\pi.$$
- * Disfavor IO at 1σ

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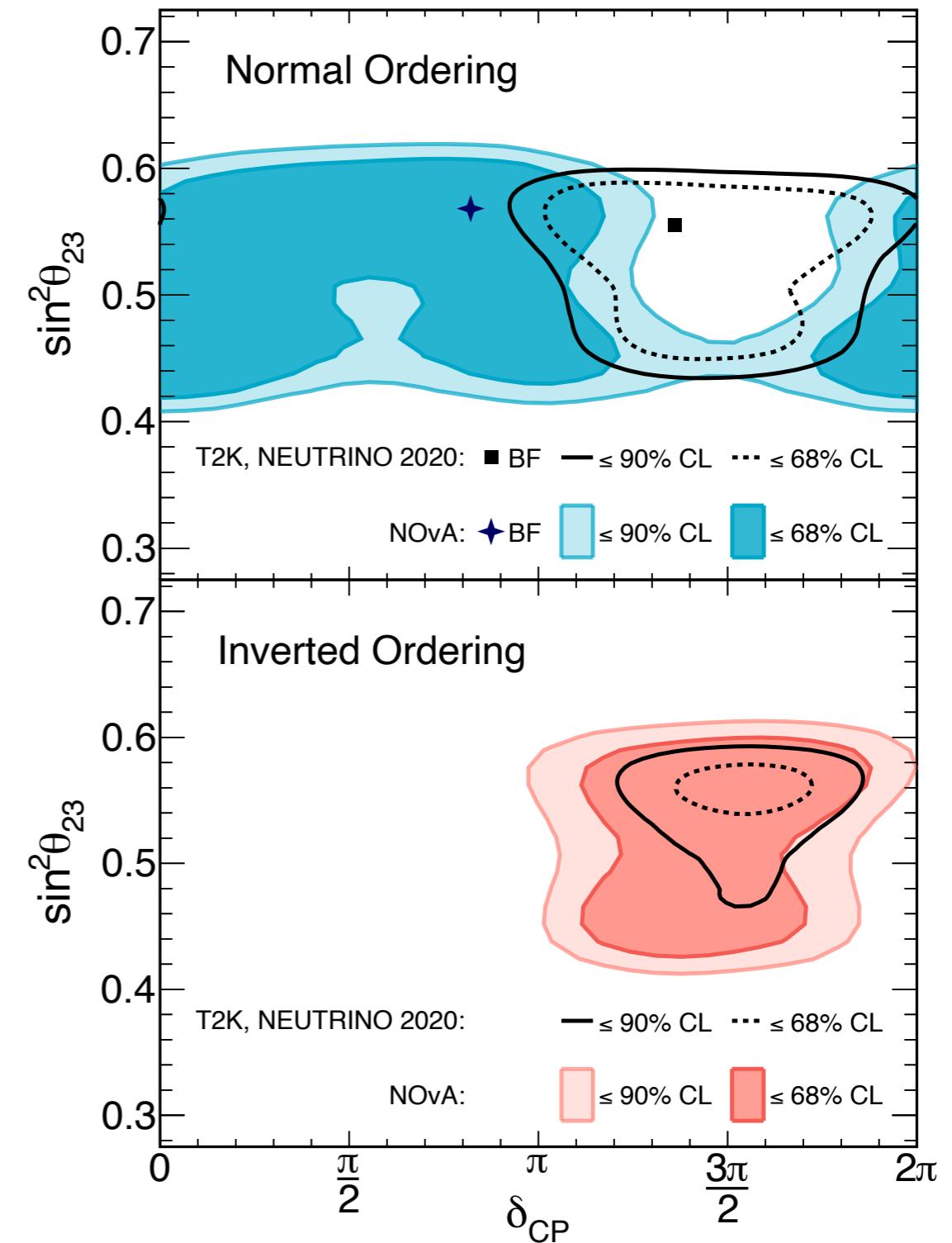
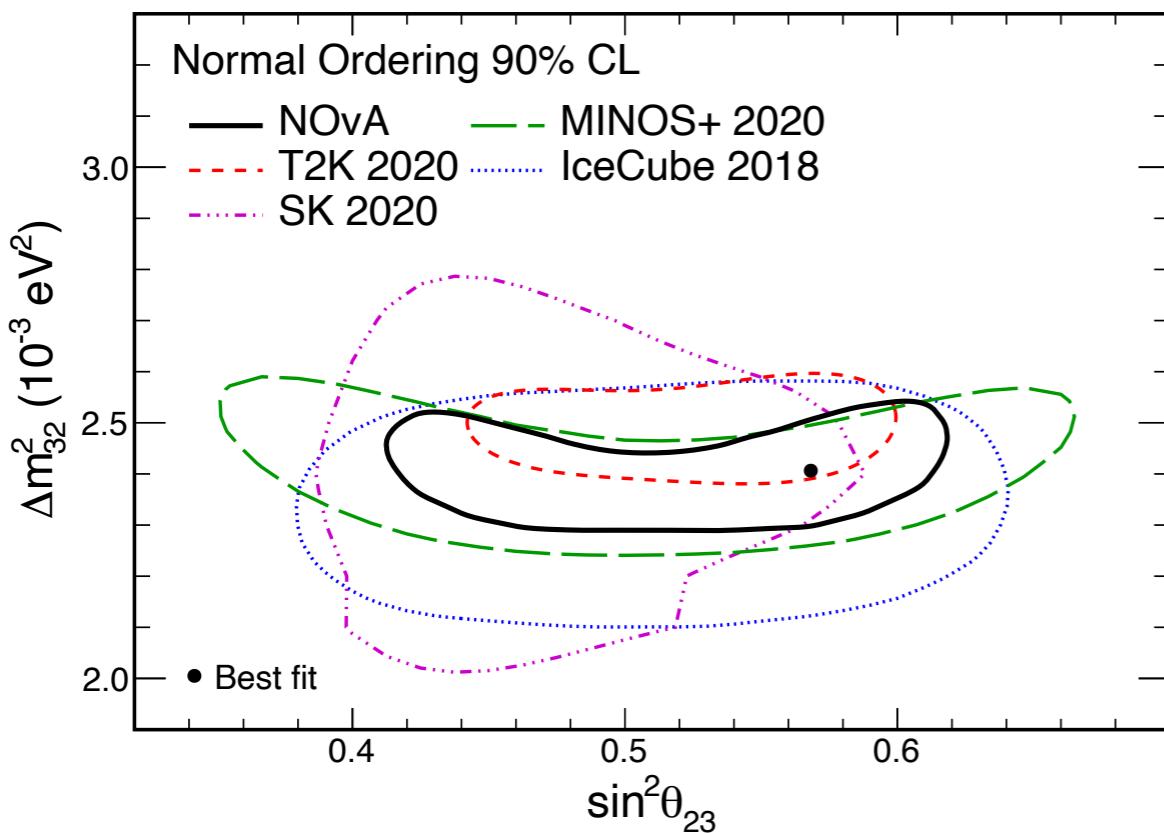
OSCILLATION RESULTS: JOINT $\nu_\mu + \nu_e$ FIT



- * No strong asymmetry in the rates of ν_e and $\bar{\nu}_e$ appearance.
- * Disfavor NO, $\delta = 3\pi/2$ at $\sim 2\sigma$.
- * Exclude IO, $\delta = \pi/2$ at $> 3\sigma$.
- * Combinations that include effect “cancellation” are preferred:
 - * since such options exist for both octants and hierarchies, results show no strong preferences.

OSCILLATION RESULTS: GLOBAL PICTURE

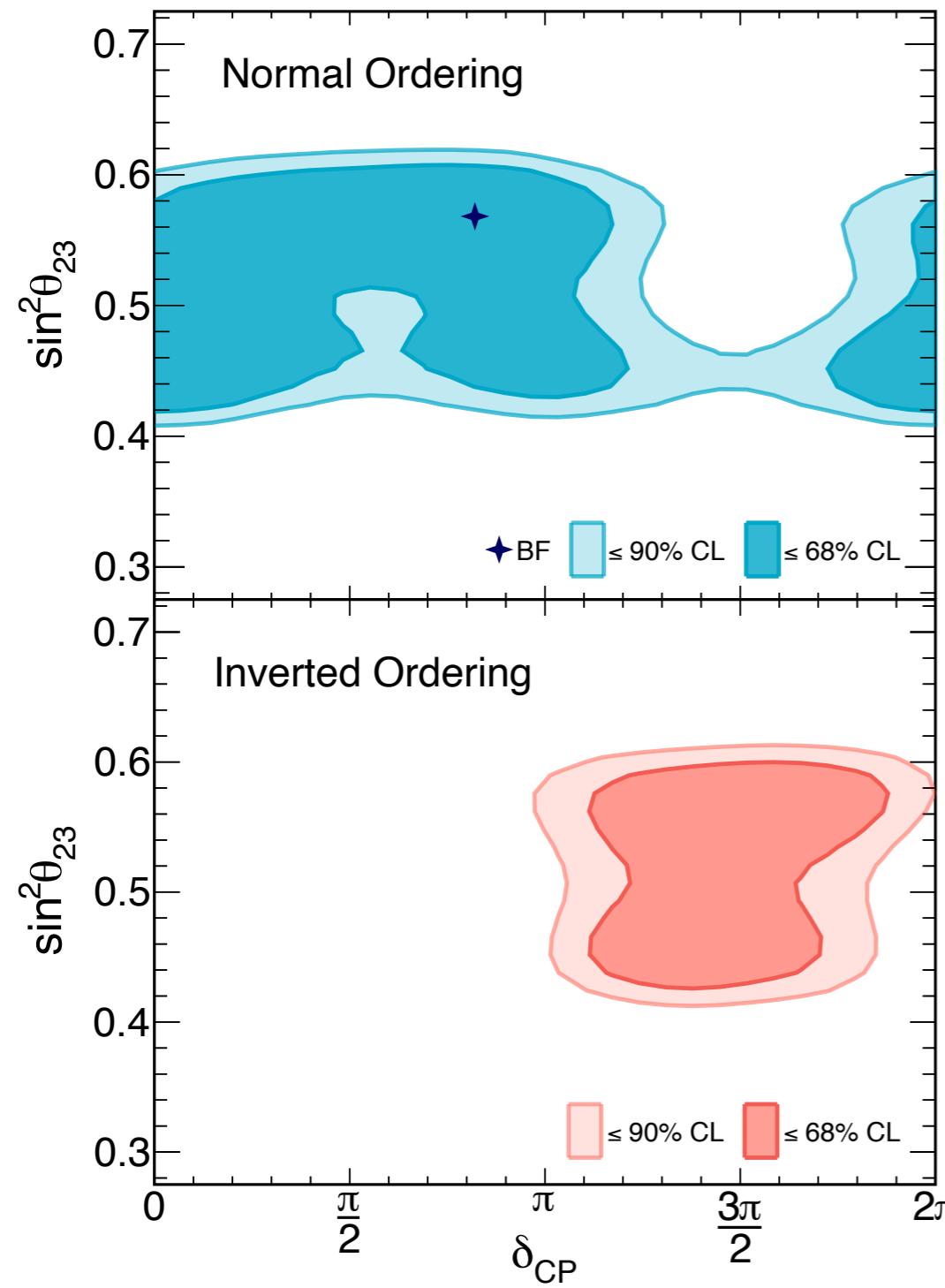
- * Consistent with other long-baseline and atmospheric experiments for “atmospheric parameters”.
- * Apparent tension in allowed values of δ_{CP} for T2K and NOvA in NO (agreement in IO).



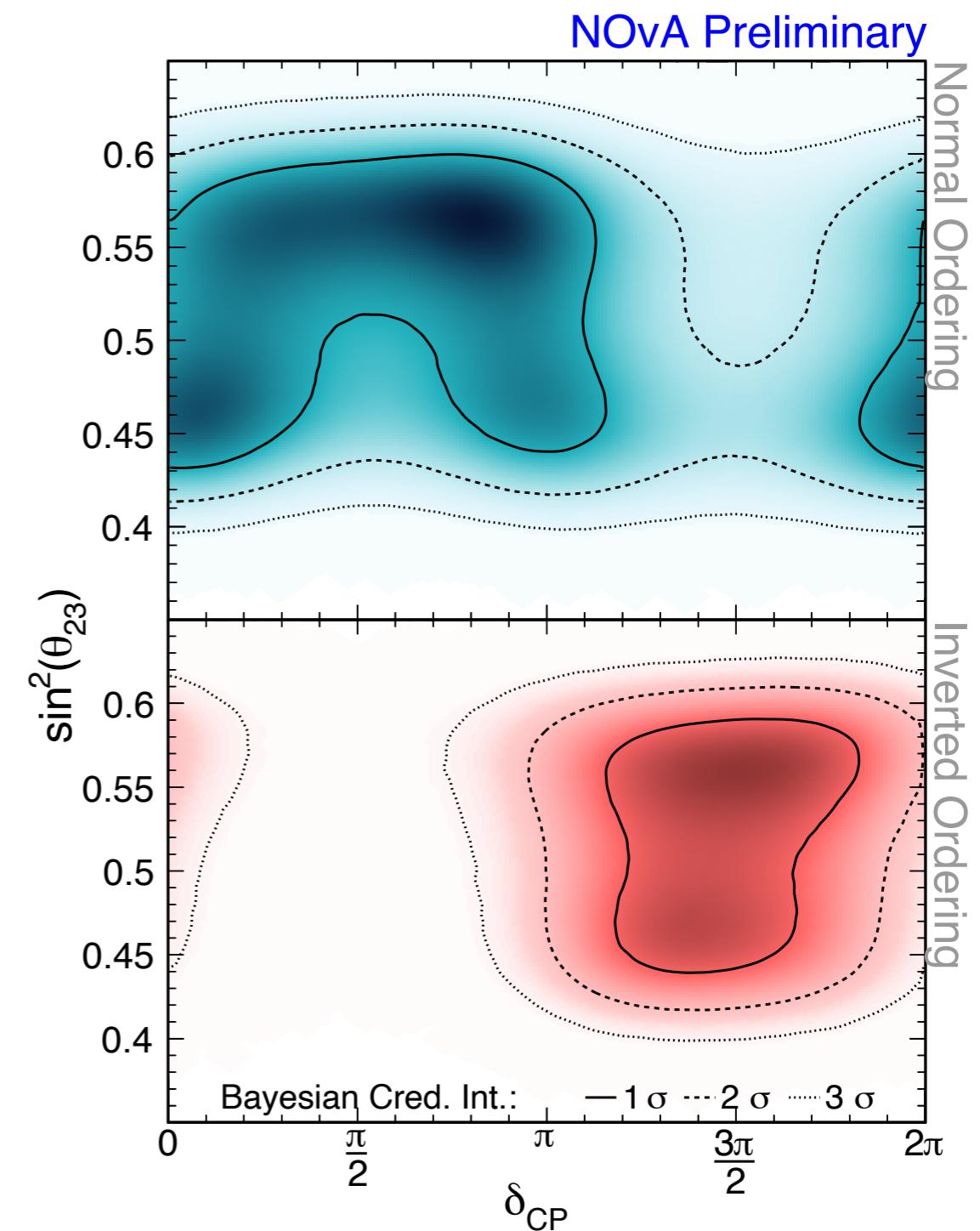
T2K and NOvA are working together on joint fit including systematics
(first results very soon!)

TWO FITTING METHODS

Frequentist result



Bayesian result

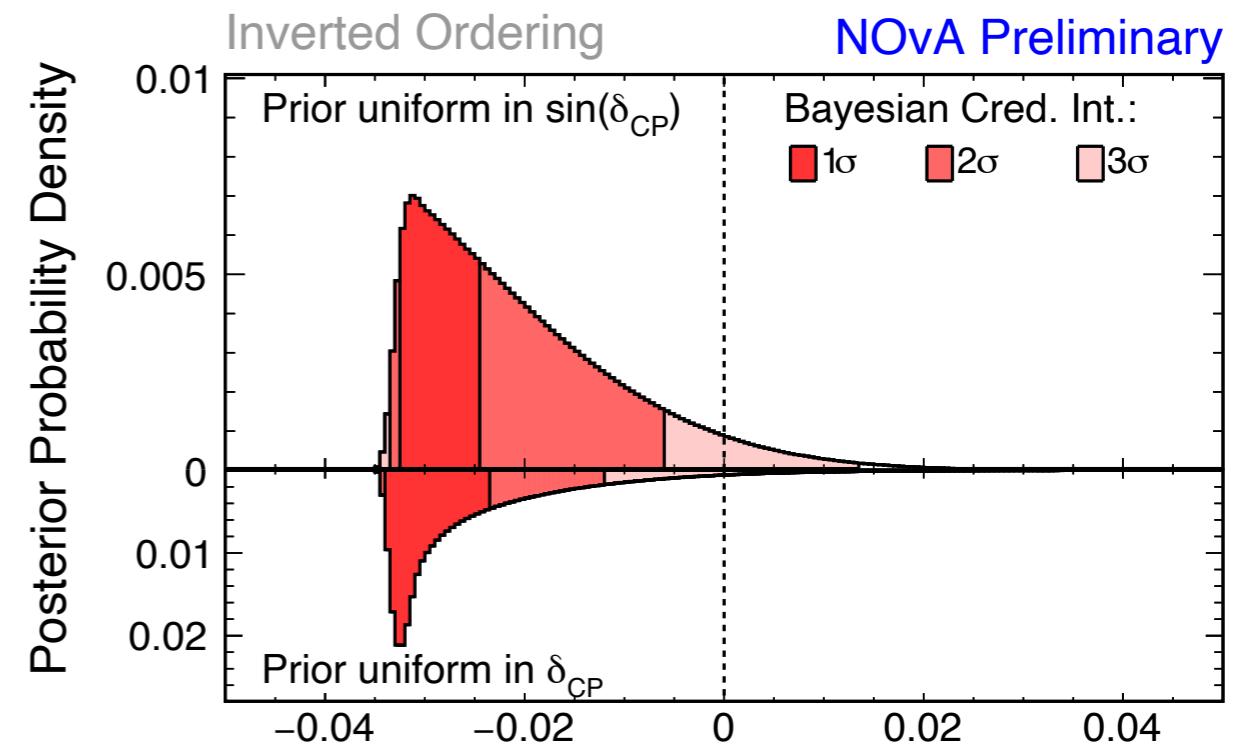
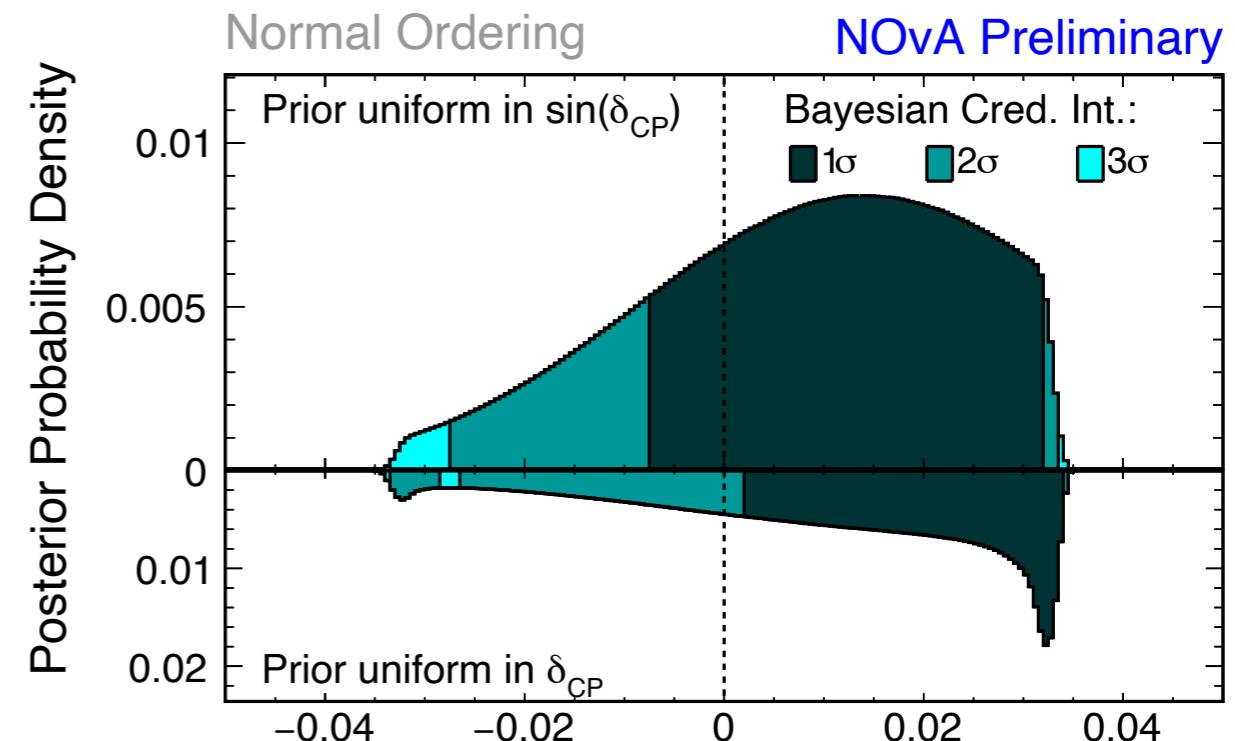


JARLSCOG INVARIANT MEASUREMENT

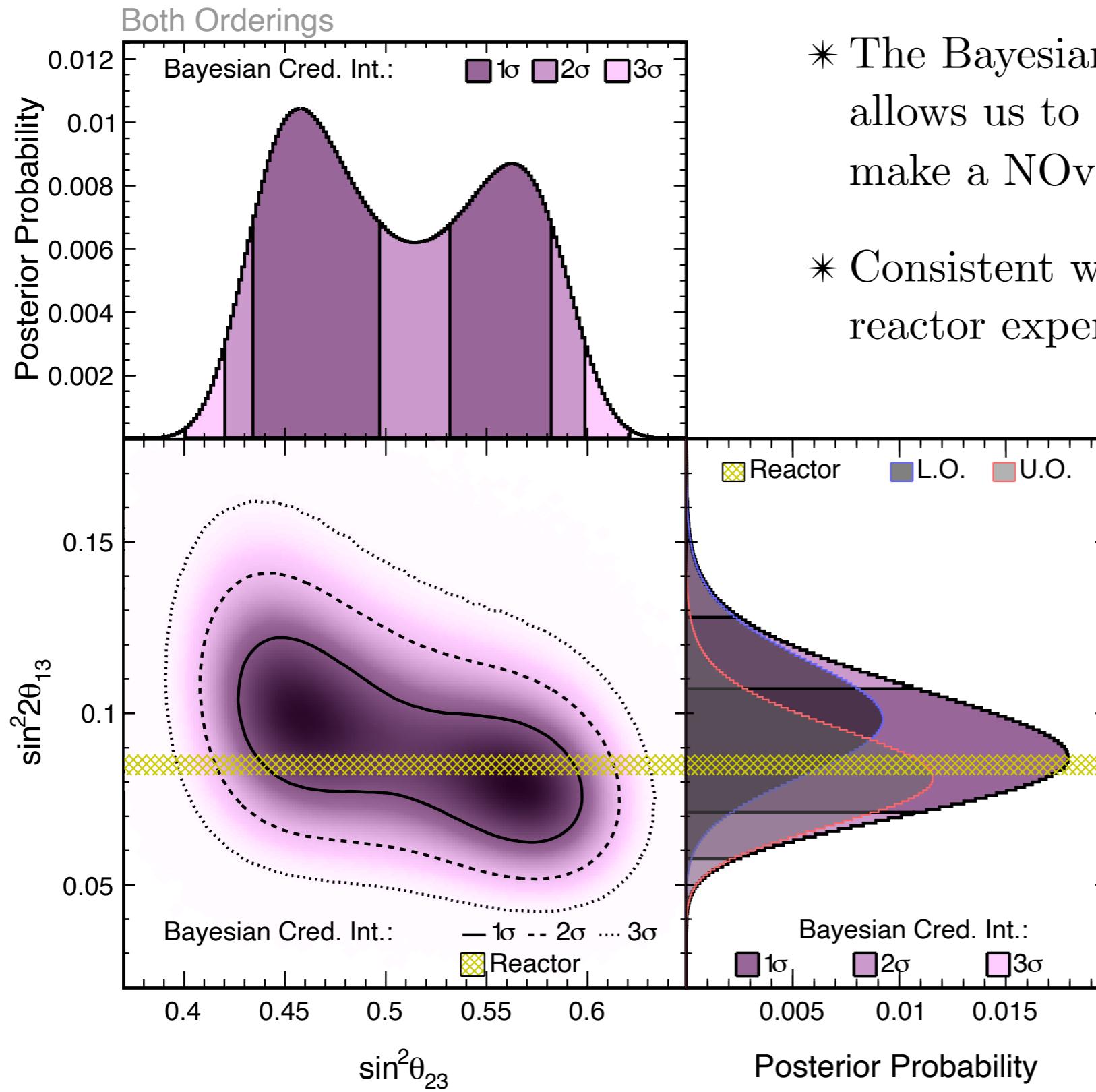
- * Jarlskog-Invariant is a measure of CP-violation independent of parametrization.

$$J \equiv s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

- * $J=0$: CP-Conservation.
 $J \neq 0$: CP-Violation
- * CP-Conservation ($J=0$) within 1σ interval in NO, within 3σ in IO
- * Slight, but not significant preference for CP-violation.



θ_{13} MEASUREMENT



- * The Bayesian interpretation of our data allows us to drop this constraint and make a NOvA measurement of θ_{13} .

- * Consistent with the measurements from reactor experiments.

$$\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$$

- * θ_{13} is strongly linked with θ_{23}

FUTURE

Currently running with neutrino beam.

- * Plan is to run 50:50% $\nu : \bar{\nu}$;
- * NOvA is expected to run until **2026**.

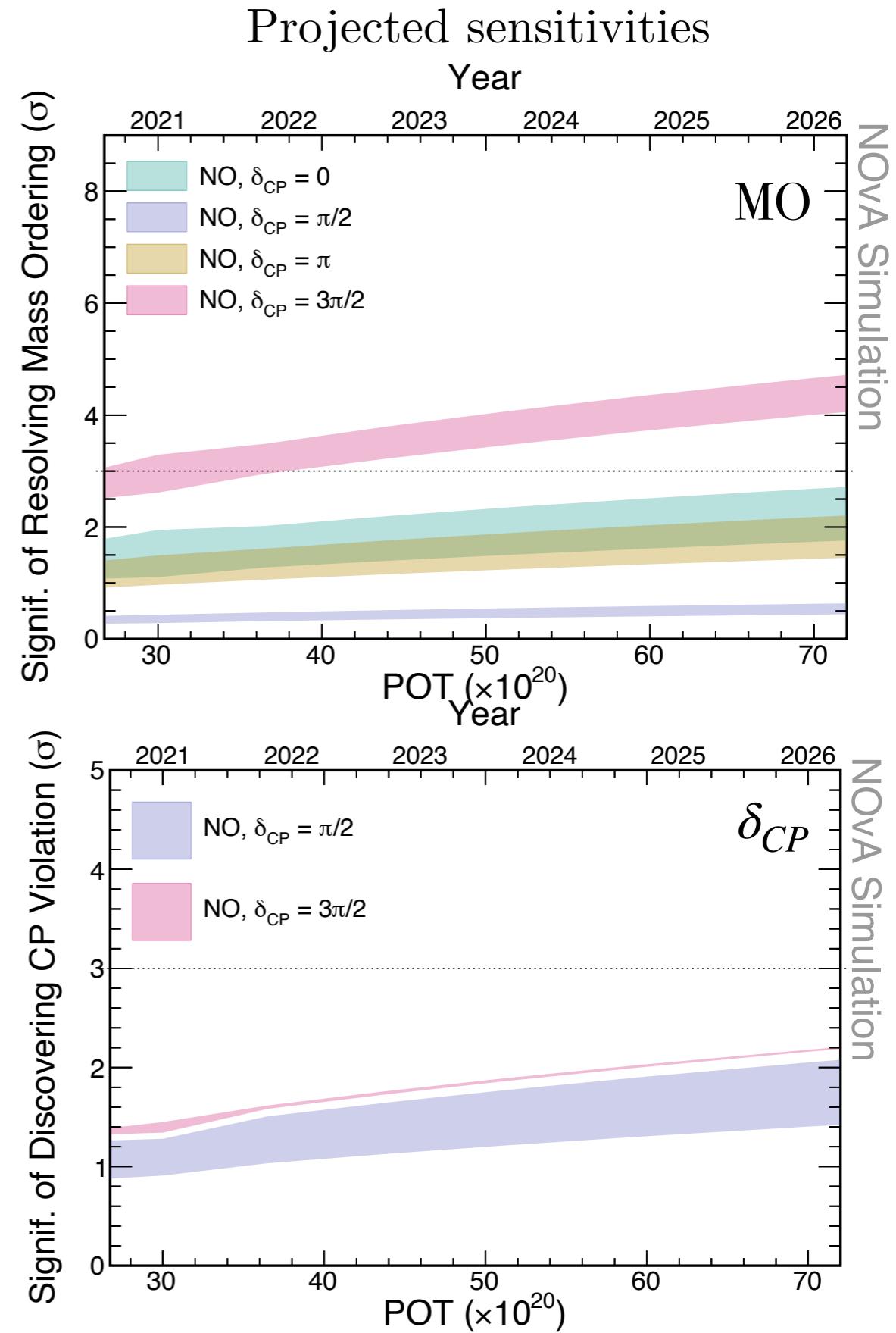
With current analysis, expect:

- * potential **3σ** sensitivity to hierarchy with favorable parameters;
- * possible **2σ** sensitivity to CP violation.

Note: sensitivity depends strongly on the true values in nature.

Expected improvements for upcoming analyses:

- * accelerator $\rightarrow \nu/\bar{\nu}$ beam intensity;
- * test beam \rightarrow improved det. response model.



CONCLUSIONS

With 13.6×10^{20} (ν) + 12.5×10^{20} ($\bar{\nu}$) POT exposure NOvA got the following results.

- * Our best fit is in the Normal Hierarchy,
 $\delta_{CP} = 0.82\pi$, $\sin^2 \theta_{23} = 0.57$, $\Delta m_{32}^2 = +2.41 \times 10^{-3}$ eV².
- * Constraints on strongly asymmetric $\nu_e - \bar{\nu}_e$ appearance PMNS solutions:
 - * disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$;
 - * exclude IH, $\delta = \pi/2$ at $> 3\sigma$.

With operation through 2026 NOvA expects:

- * possible $3 - 4\sigma$ sensitivity to mass hierarchy for some values of δ_{CP} ;
- * potential sensitivity to CP violation phase 2σ .

We're waiting for the test beam results, analysis and accelerator improvements.

Stay tuned!