# NOVA AND T2K JOINT RESULTS

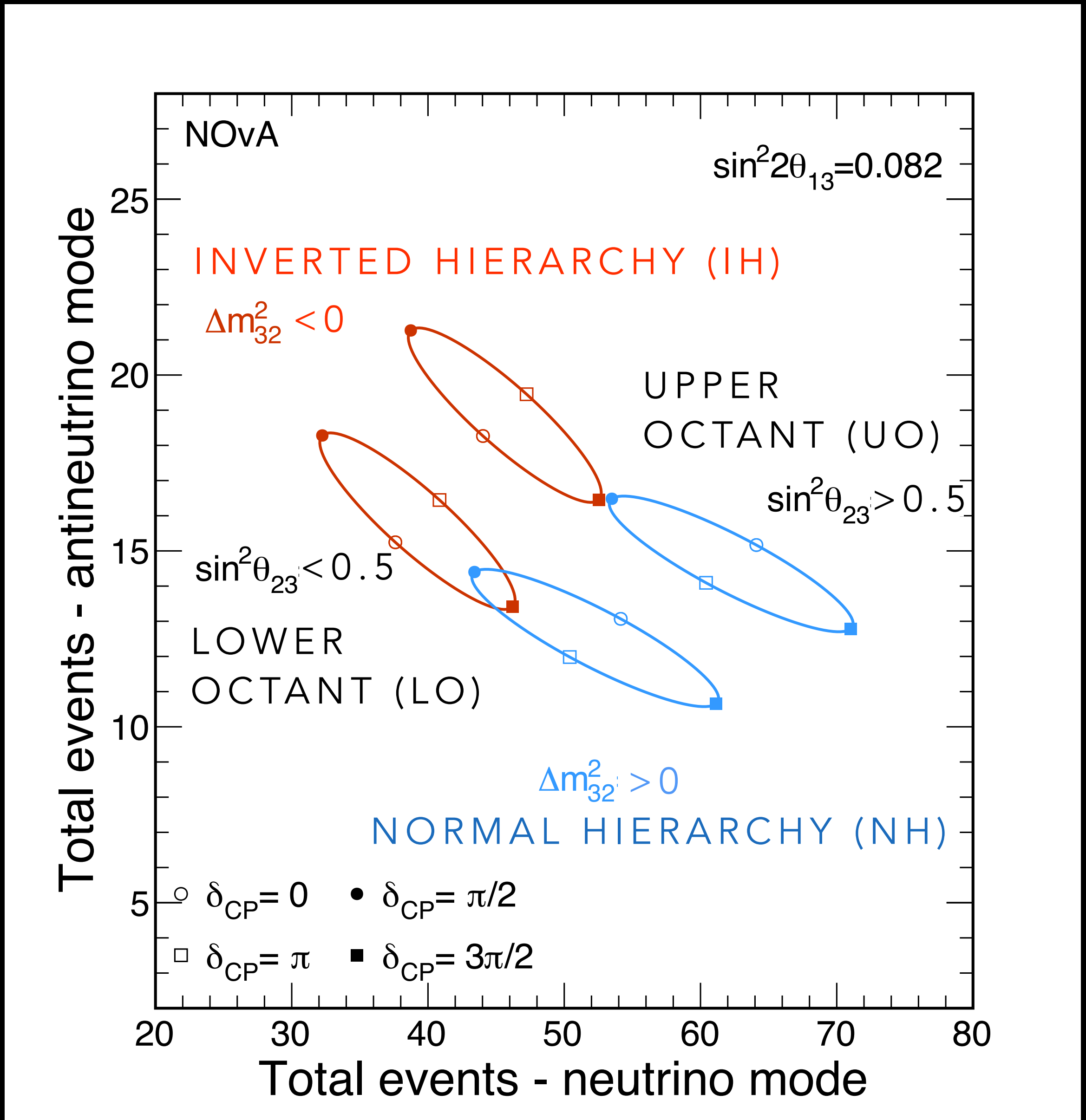
MAYLY SANCHEZ
FLORIDA STATE UNIVERSITY

Recontres de Moriond 2024 - March 29,  2024

# STUDYING NEUTRINO OSCILLATIONS

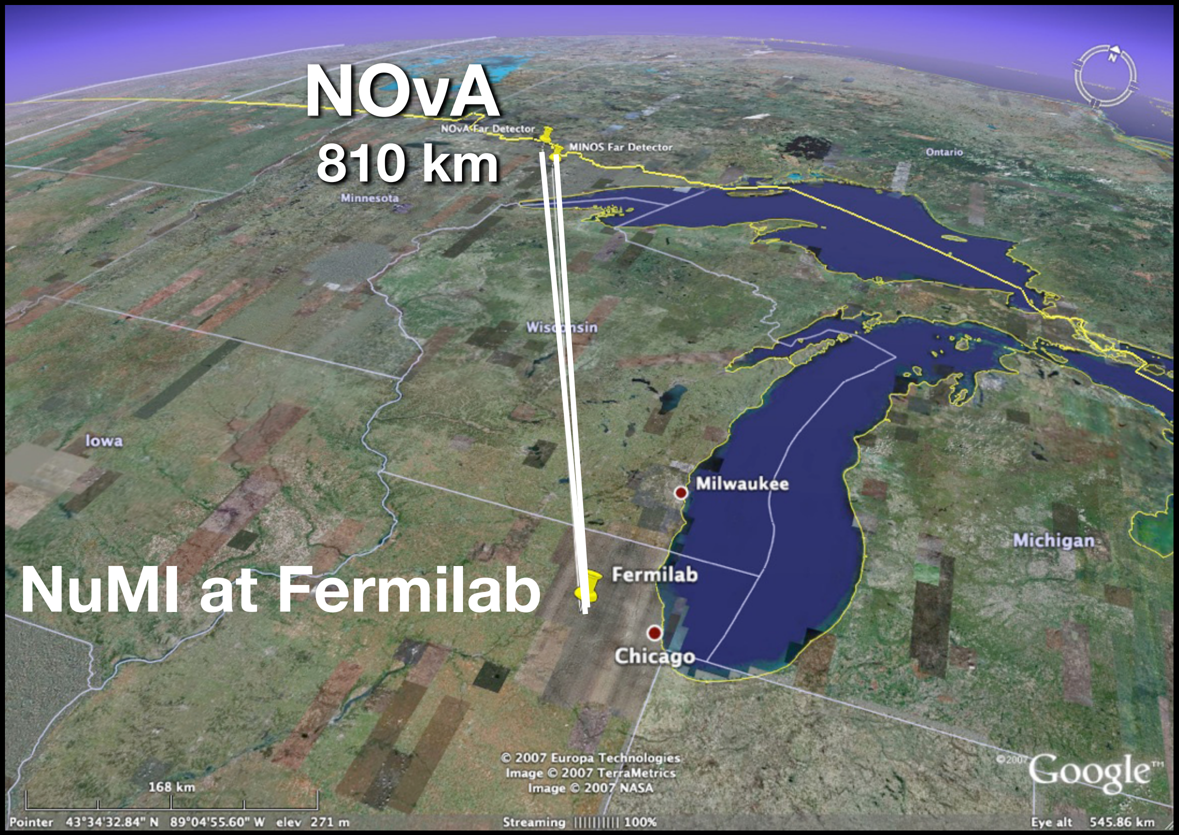
## NEUTRINO AND ANTINEUTRINO DATA ARE REQUIRED

- What is the mass hierarchy or ordering for atmospheric neutrinos ie sign of $\Delta m^2_{32}$?
- Is there a $\nu_\mu$ - $\nu_\tau$ symmetry (is the large mixing angle $\theta_{23}$ maximal; if not, what is the octant)?
- Is CP violated in the lepton sector?
- Are there other neutrinos beyond the three known active flavors?




**LONG-BASELINE ACCELERATOR NEUTRINOS ARE ABLE TO DISENTANGLE THESE!**

# NOVA AND T2K: LONG-BASELINE NEUTRINO EXPERIMENTS IN A NUTSHELL




- These LBL experiments use neutrino beams produced by accelerators: **NuMI** and **JPARC**
- Precision is achieved by placing a detector close to the source (Near Detector) and one at or close to the oscillation maximum (Far Detector).

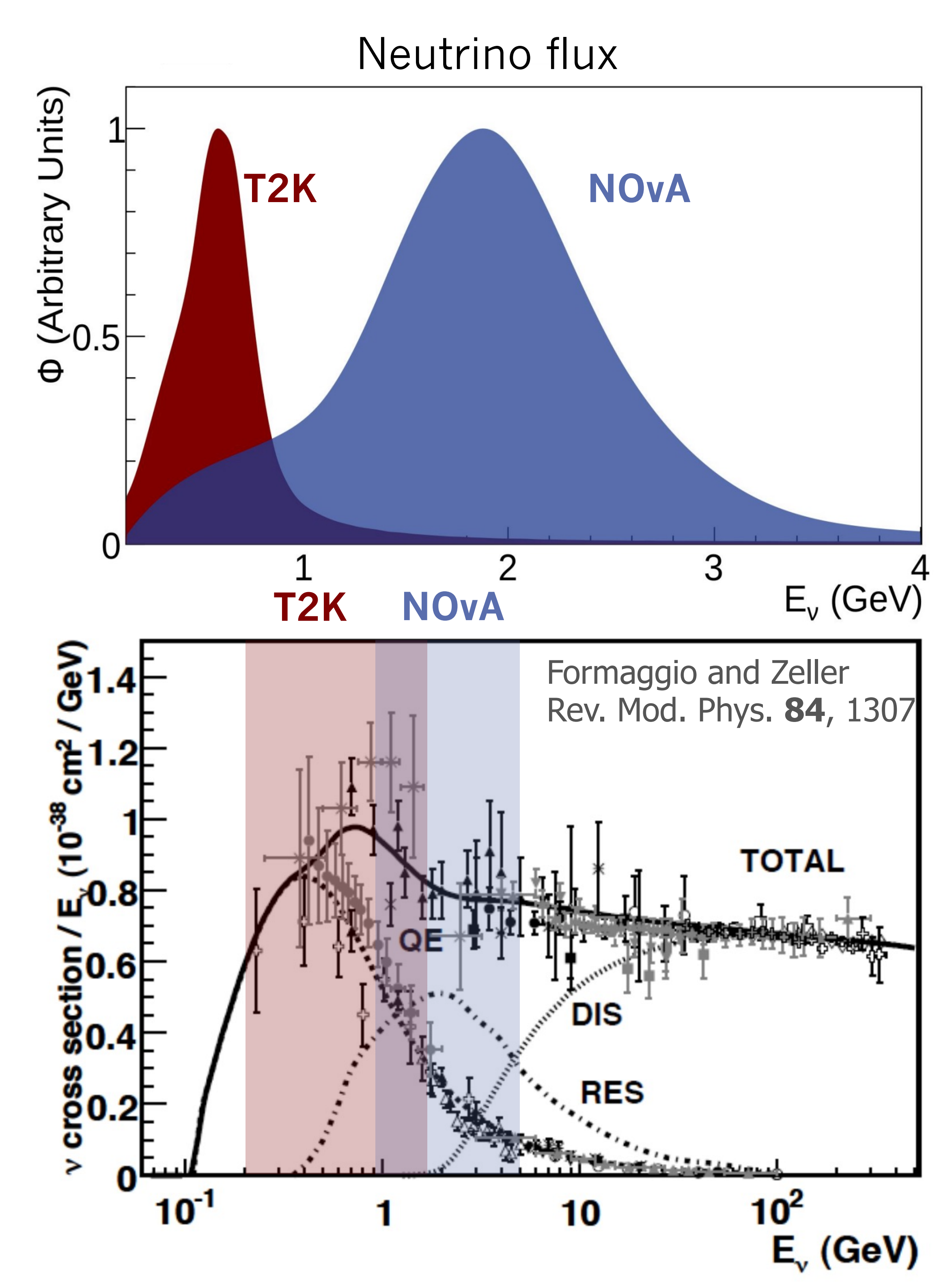
$$ND(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{ND}$$
$$FD(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{FD} \times P_{osc}$$


- The measured spectrum in the ND is used to make a prediction of the expectation at the FD before considering oscillations.

**Muon neutrino disappearance and electron neutrino appearance is the signature of oscillations**

# NOVA AND T2K BEAM NEUTRINOS

- Experiments are located off-axis for narrow-band, highly pure muon (anti-) neutrino beam:
  - T2K: from J-PARC at 0.6 GeV beam neutrino energy.
  - NOvA: from Fermilab NuMI at 2 GeV beam neutrino energy.
- Different neutrino energy leads to qualitatively different neutrino interactions:
  - T2K: primarily quasi-elastic interactions.
  - NOvA: mix of quasi-elastic, 2p2h, resonant and DIS interactions.

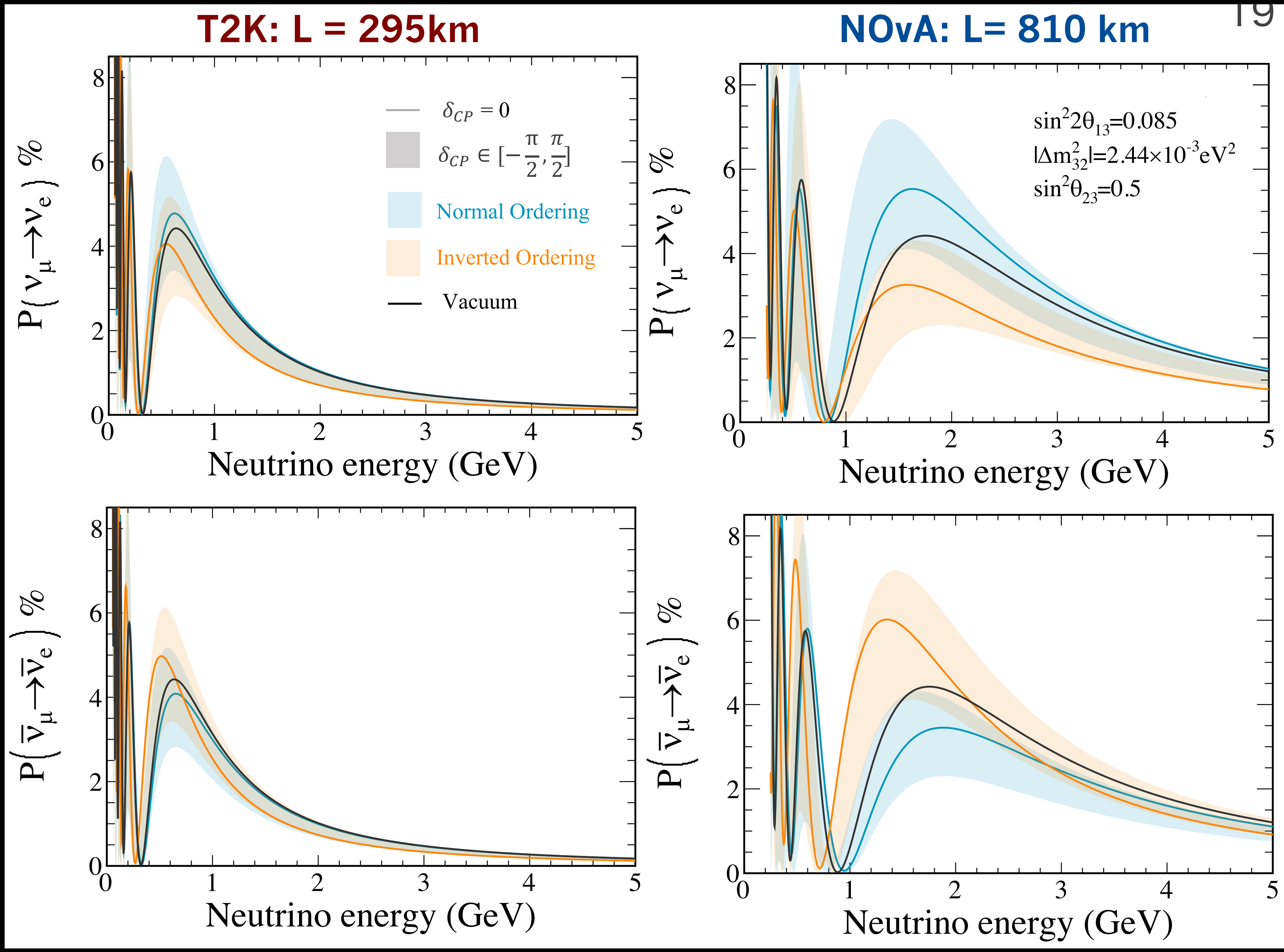


# NOVA AND T2K BASELINES

- Matter effects modify the spectrum depending on mass ordering, neutrino/ anti-neutrino.
- Effect is larger for longer baseline.

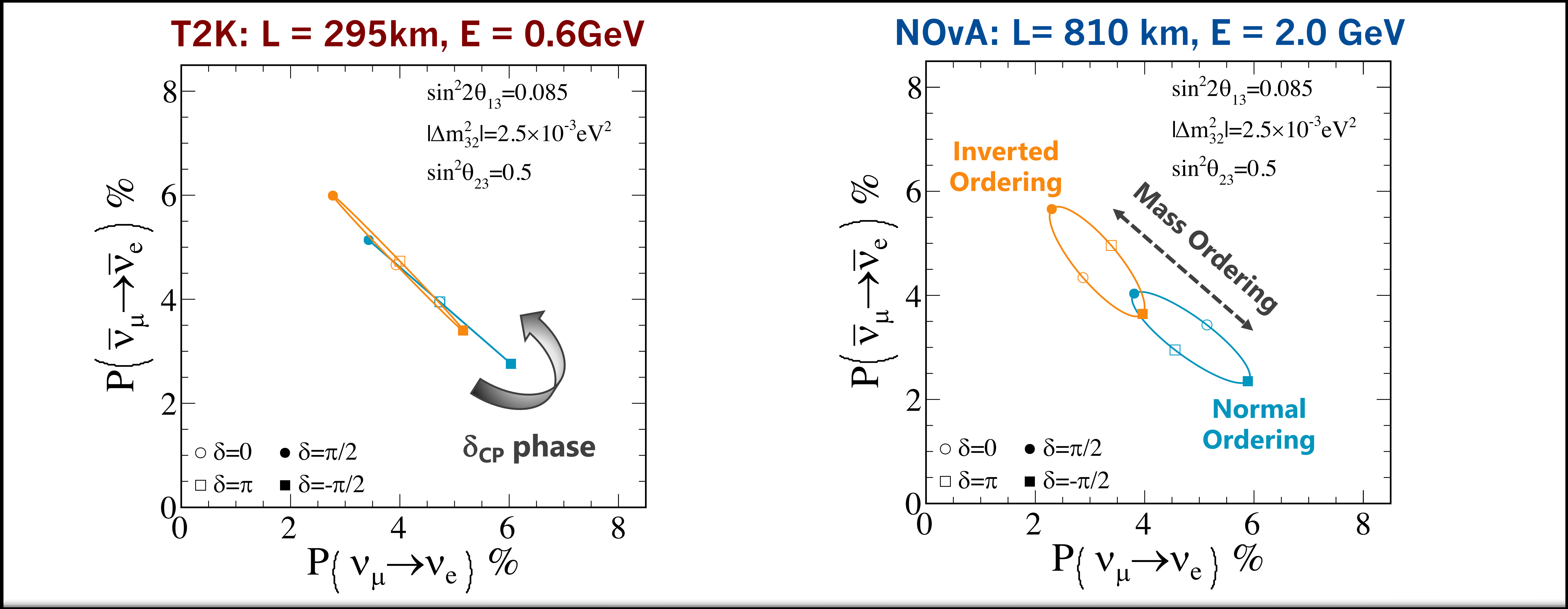
| | T2K | NOvA |
|---|---|---|
| L (baseline) | 295 km | 810 km |
| Energy (beam peak) | 0.6 GeV | 2 GeV |
| Matter effect* | ~ ±9% | ~ ±19% |
| CP effect* | ~ ±30% | ~ ±25% |

*calculated at beam peak energy



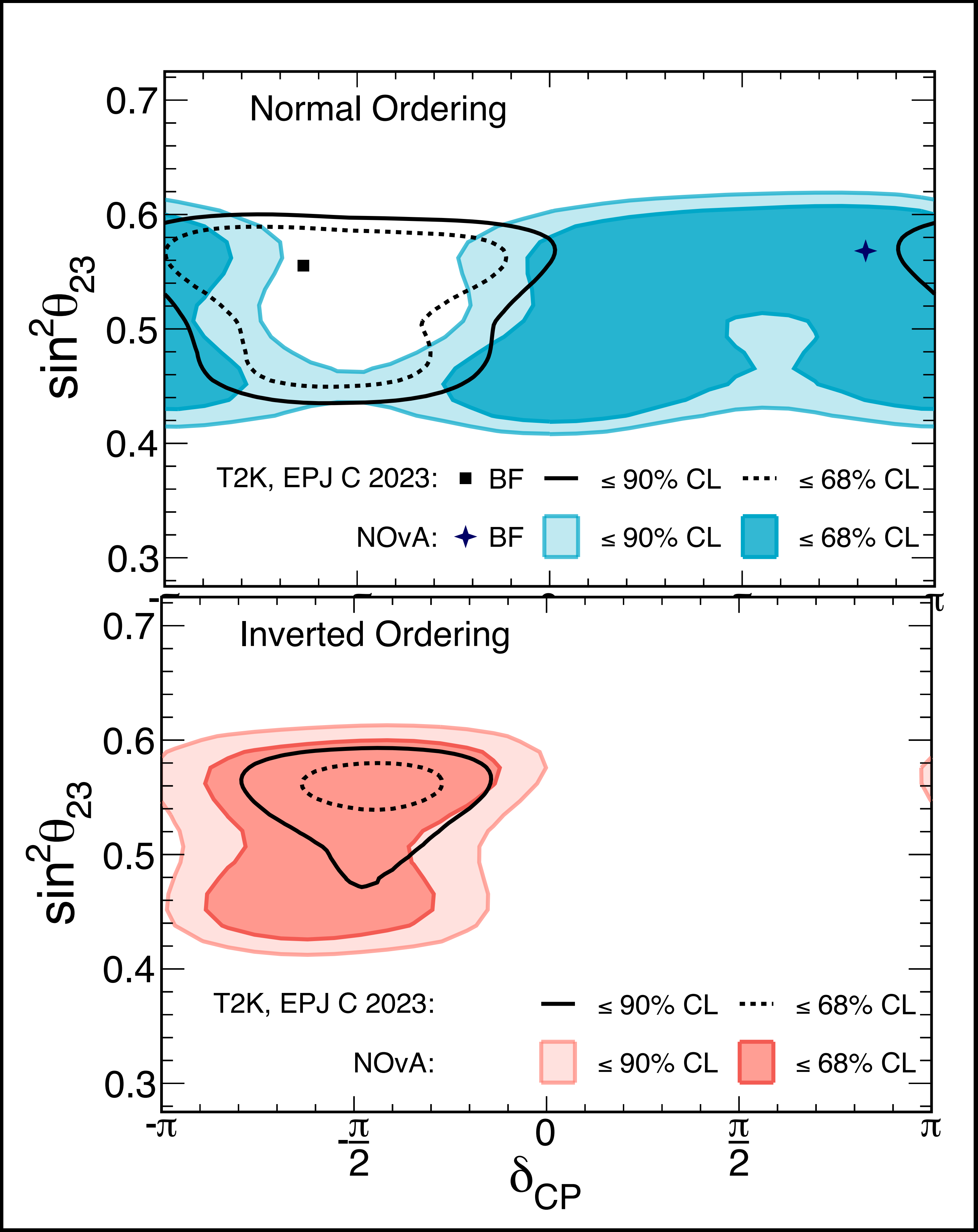
# NOVA AND T2K RESOLVING DEGENERACIES

- T2K measurements isolate the impact of CP violation whereas NOvA has significant mass ordering sensitivity.
- The complementarity between the experiments has the power to break degeneracies.



# WHY COMBINE NOVA AND T2K?

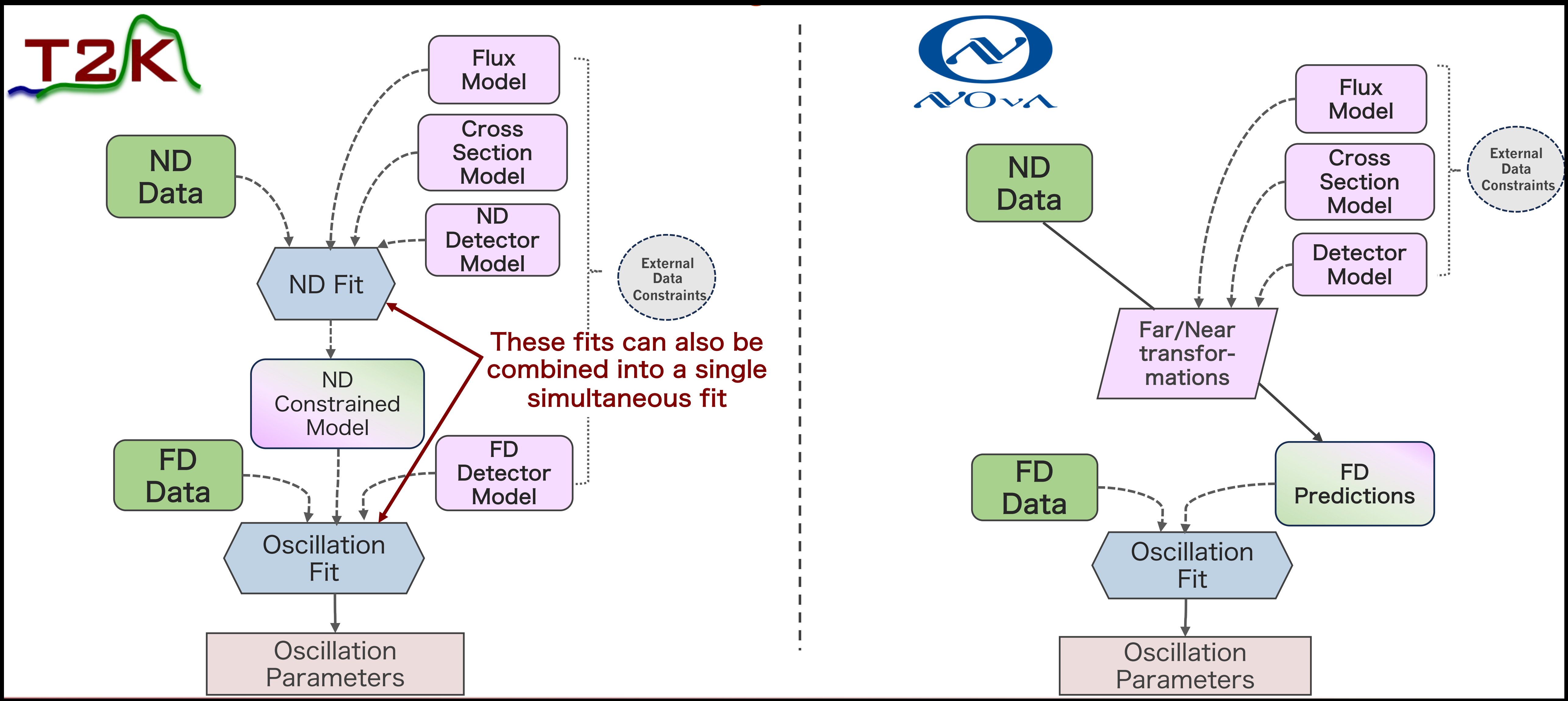
- Mild disagreement (at 90% CL) on allowed CP values in Normal Ordering
- Good agreement on allowed values for Inverted Ordering.




**Results from NOvA and T2K with 2020 data**

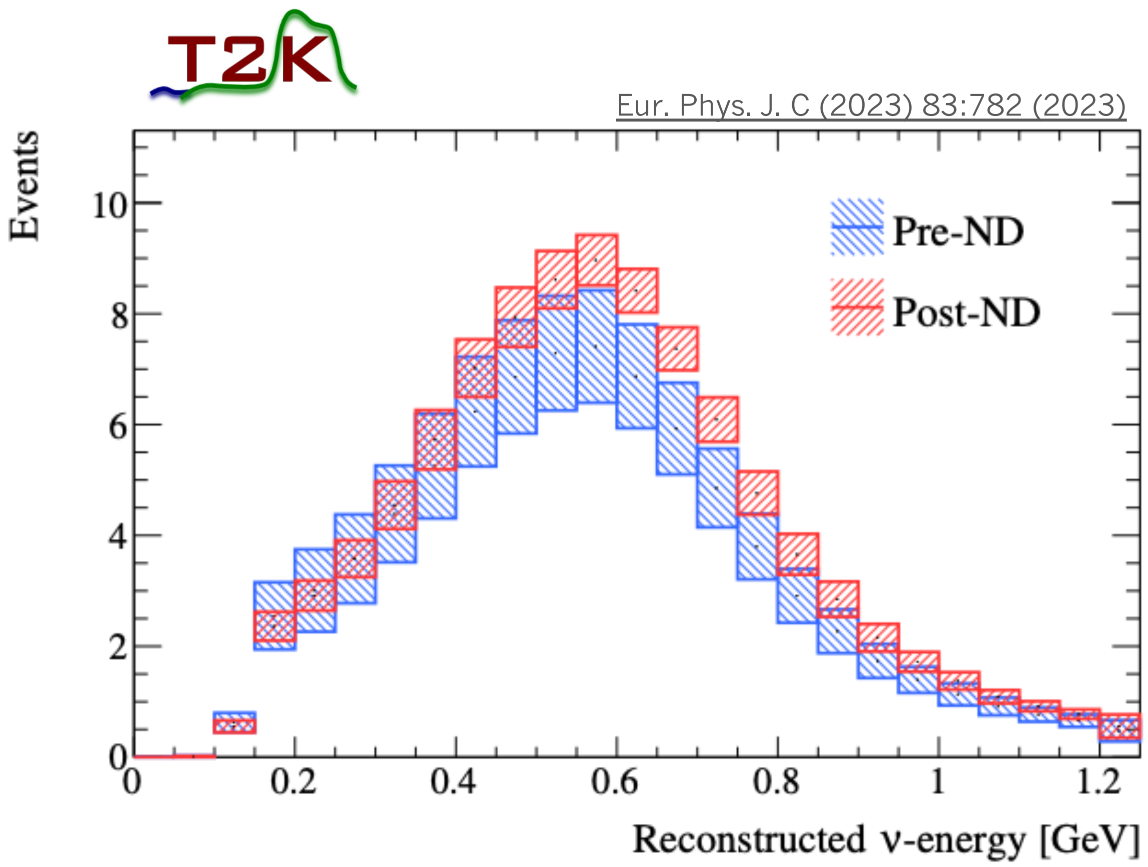
# NOVA AND T2K ANALYSES

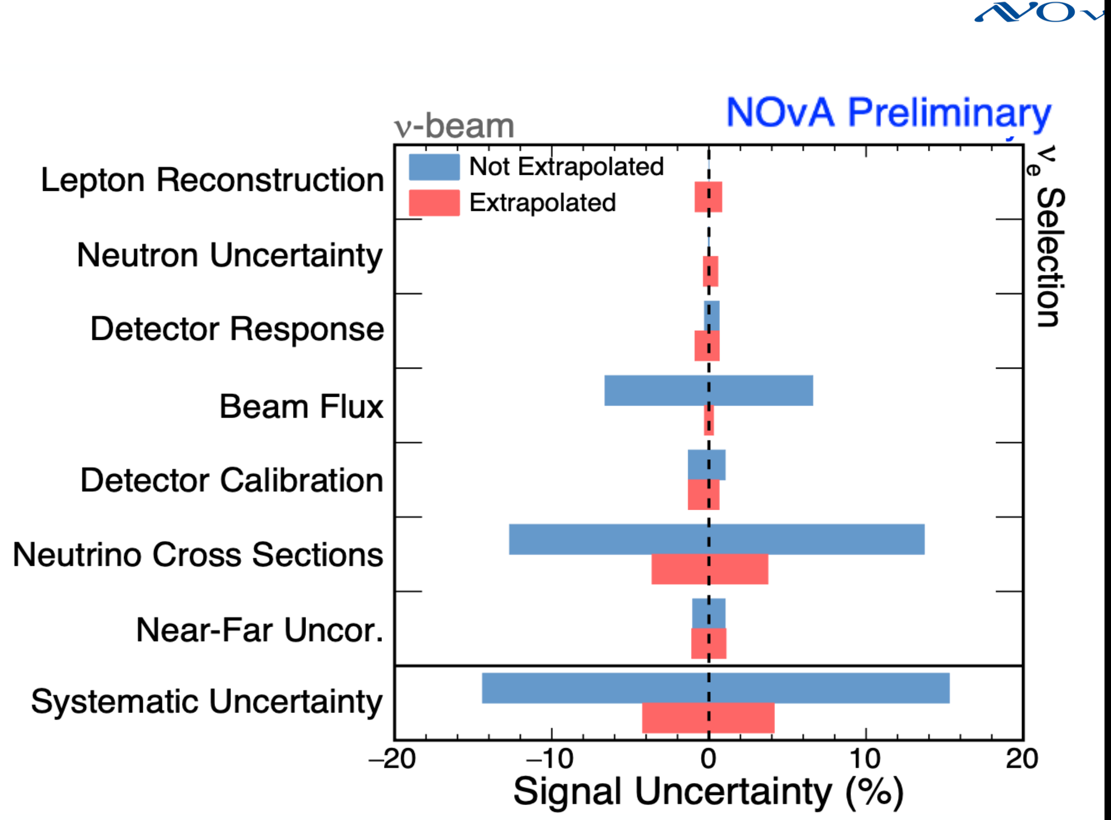
- The experiments have different analyses approaches driven by contrasting experimental design.
- Both T2K and NOvA have used Bayesian Markov Chain Monte Carlo (MCMC) fitters.



# NOVA AND T2K SYSTEMATIC UNCERTAINTIES

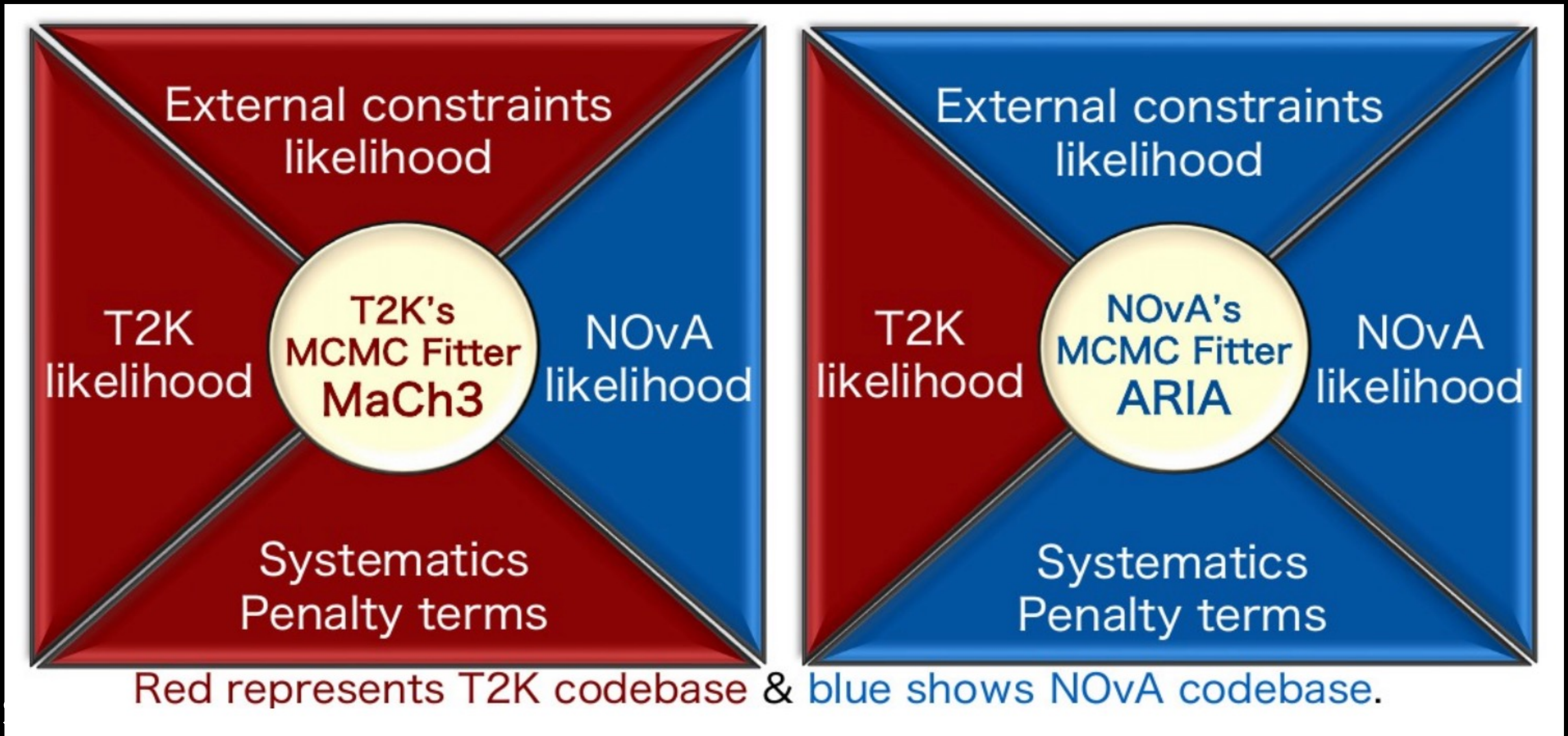
- Both analyses approaches reduce systematic uncertainties from over 10% to ~4-5%.
- The joint analysis thus seeks to respect each approach throughout.



# CONSTRUCTING A JOINT ANALYSIS

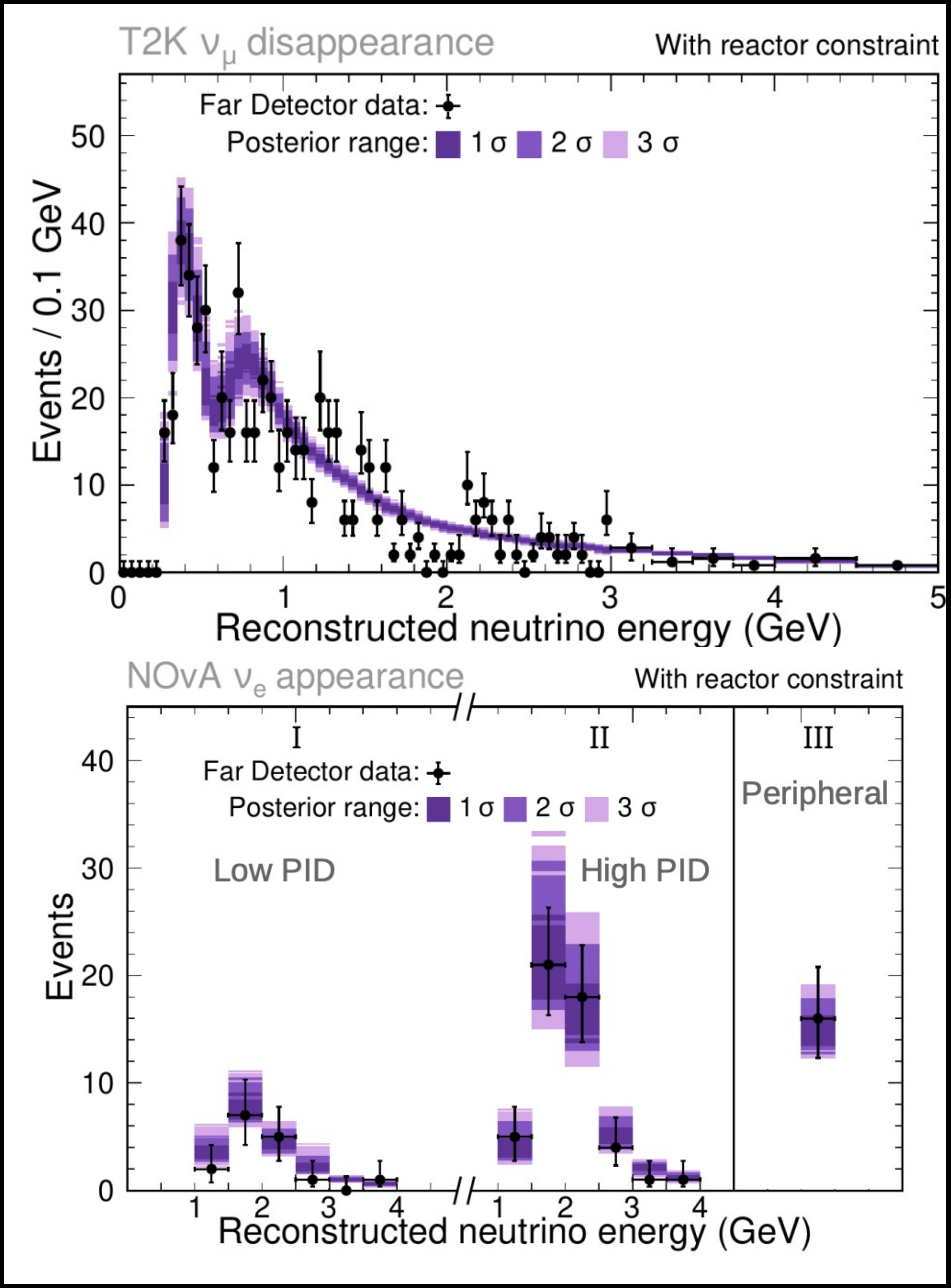
- The joint-fit is constructed using: Poisson likelihood from each experiment, penalty terms from the systematics pull and external constraints on $\theta_{13}$ and $\theta_{12}$, , $\Delta m^2_{21}$ from solar and reactor neutrino experiments.
  - The other experiment's likelihoods are integrated via a containerized environment. Both experiments can run each other's analysis through these containers. Independent implementation of the framework provided rigorous validation of the joint fit.
- No significant correlations between the experiments in flux and detector models. For neutrino interaction models instead we expect correlations and experiments use different underlying models.
  - Significant work to demonstrate robustness to no-correlations except for uncertainty in $\nu_e/\nu_\mu$.



# THE DATA

- The joint-fit uses the data collected by each experiment up until 2020.
- Using both experiments data roughly doubles the total statistics at the far detectors.
- The data from both experiments is described well by the joint fit, posterior predictive p-value of 0.75.

| Channel | NOvA | T2K |
|---|---|---|
| $\nu_e$ | 82 | 94 ($\nu_e$)<br>14 ($\nu_e 1\pi$) |
| $\bar{\nu}_e$ | 33 | 16 |
| $\nu_\mu$ | 211 | 318 |
| $\bar{\nu}_\mu$ | 105 | 137 |

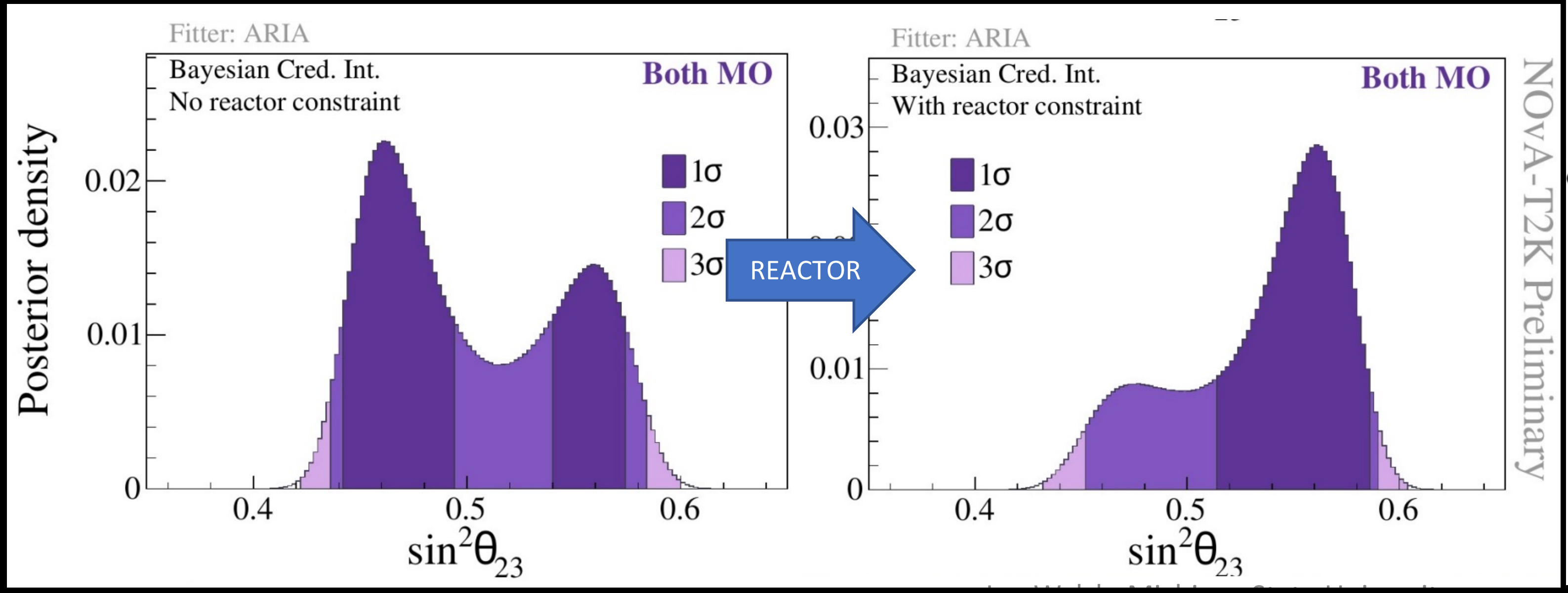


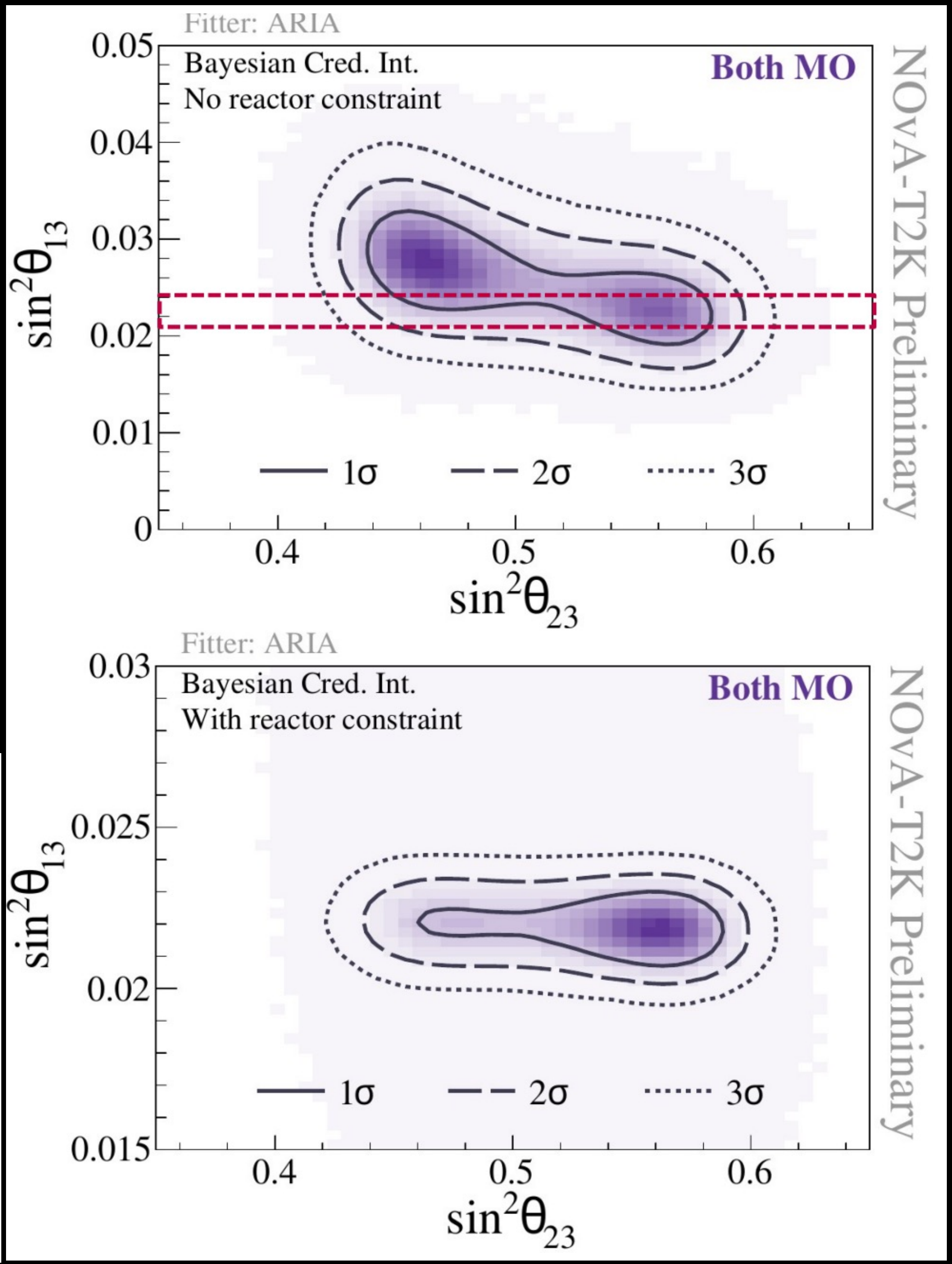

Complete sets in backup

T2K: Eur. Phys. J. C (2023) 83: 782
NOvA: Phys. Rev. D 106, 032004 (2022)

# RESULTS: MIXING ANGLES

- Joint fit result is consistent in $\theta_{13}$ with reactor experiment results but has degeneracy in $\theta_{23}$.
- Using the PDG average from the reactor experiments lifts degeneracy and provides small preference for the upper octant.

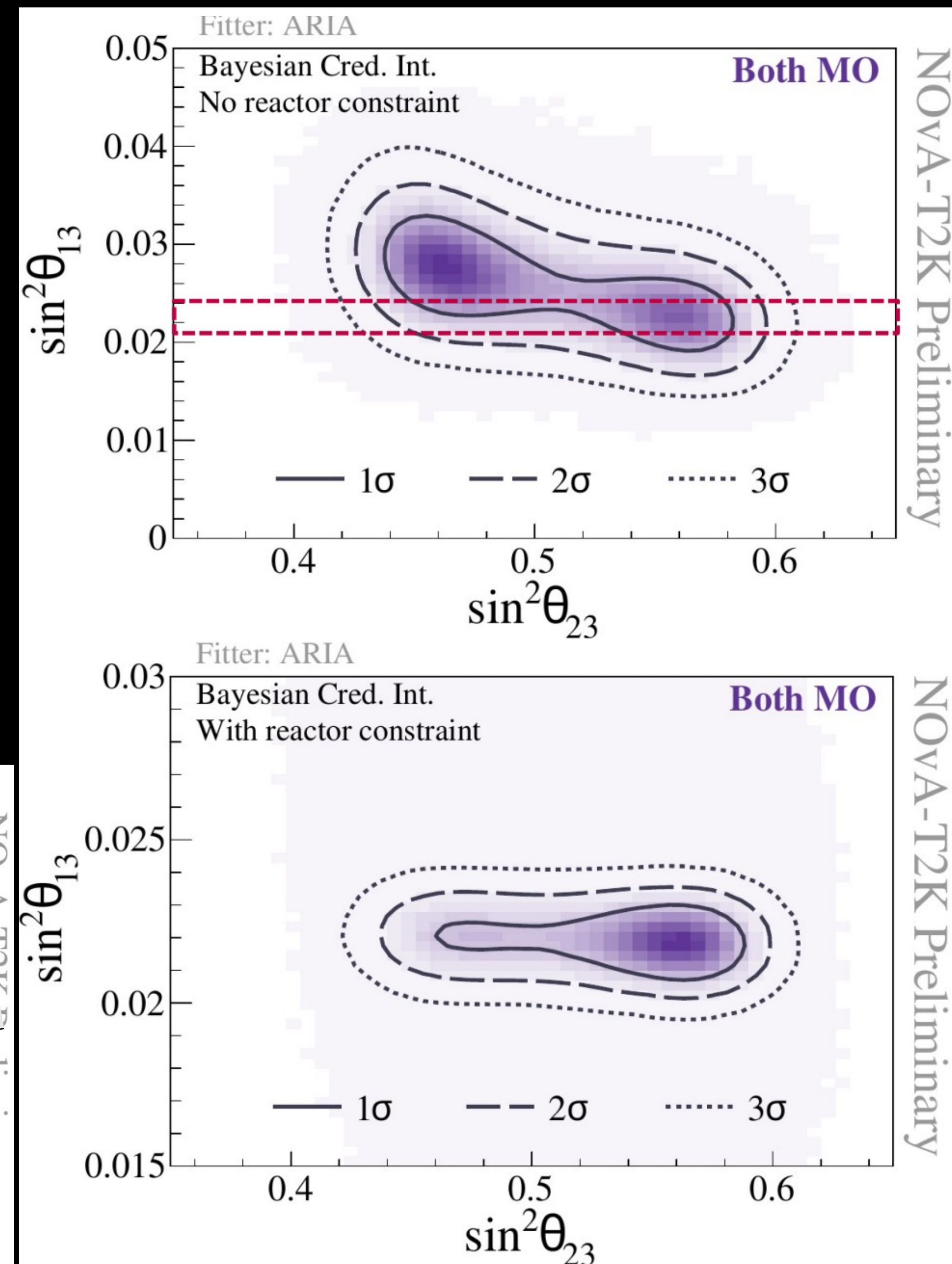


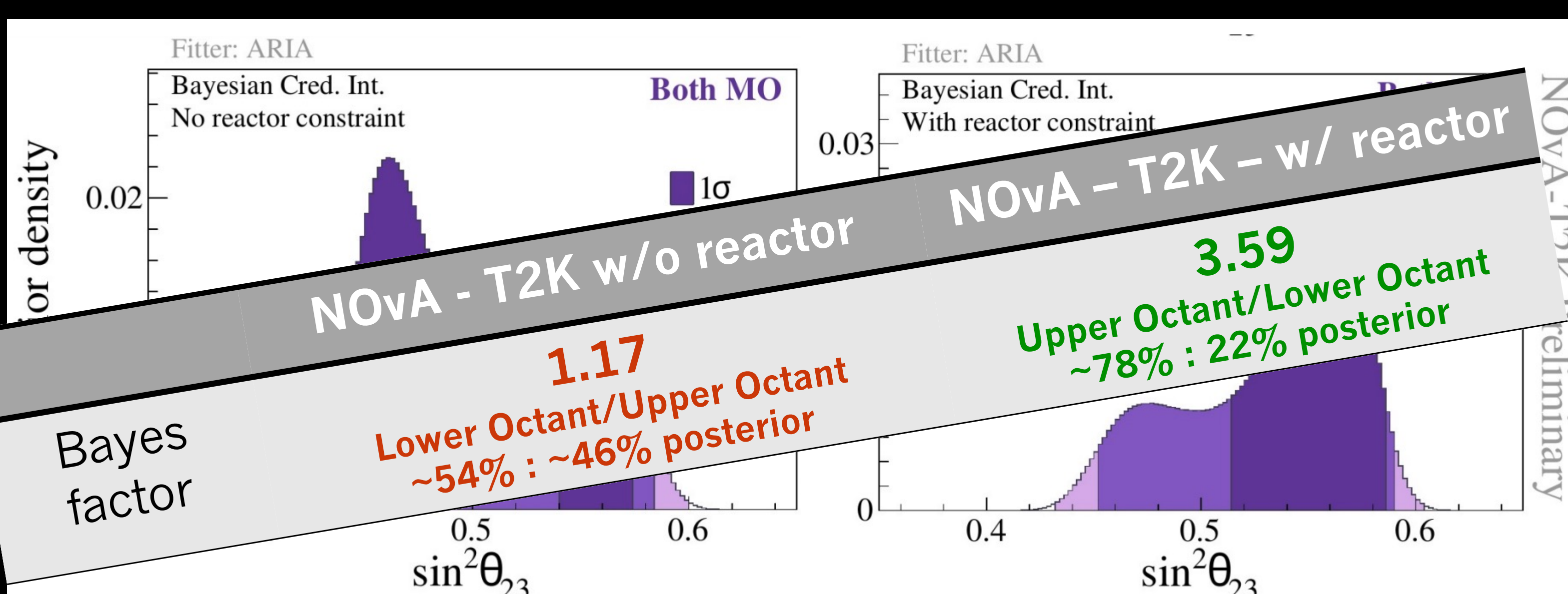




**Using reactor constraint in all other results**

# RESULTS: MIXING ANGLES

- Joint fit result is consistent in $\theta_{13}$ with reactor experiment results but has degeneracy in $\theta_{23}$.
- Using the PDG average from the reactor experiments lifts degeneracy and provides small preference for the upper octant.



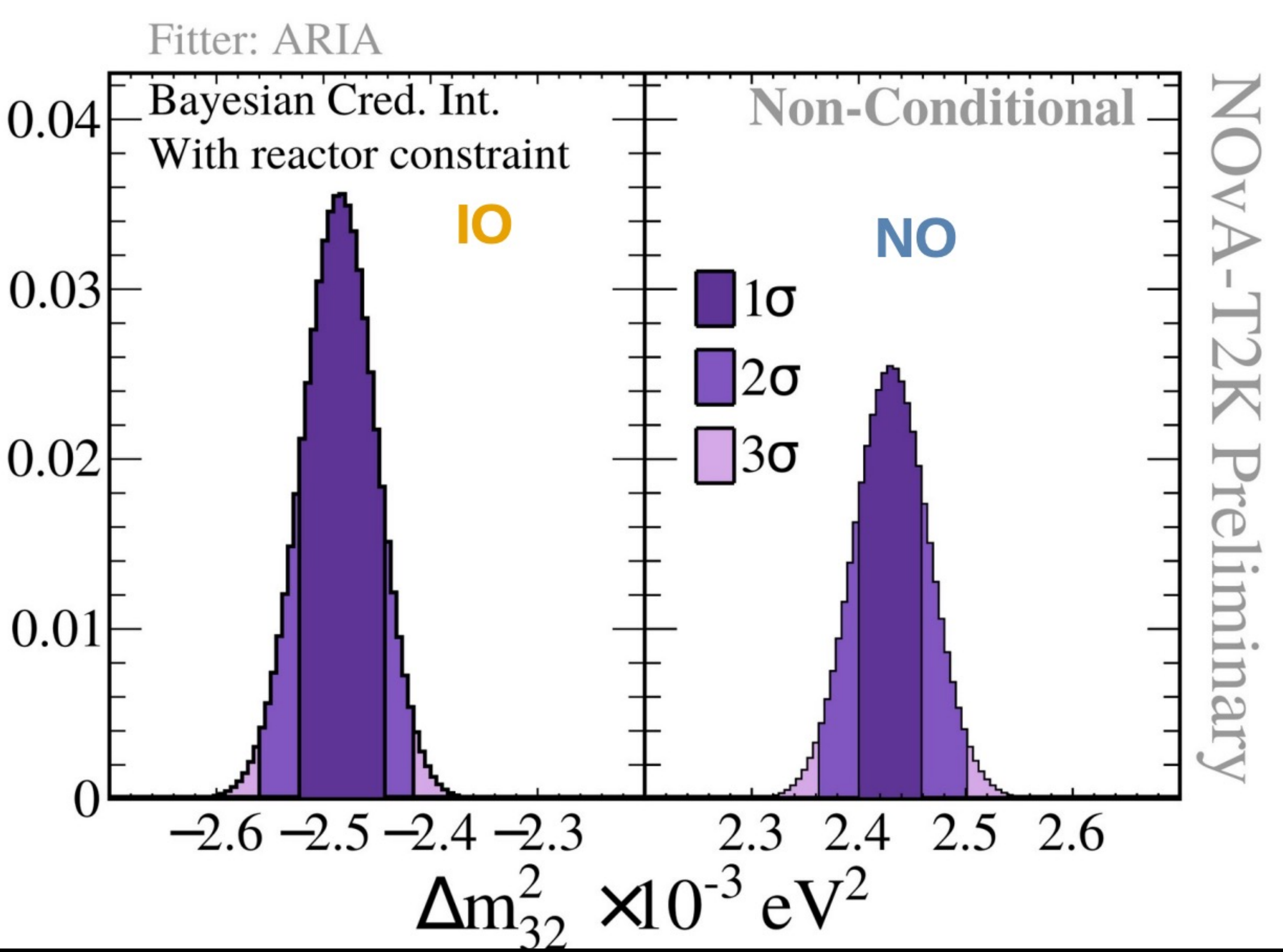




| | NOvA - T2K w/o reactor | NOvA – T2K – w/ reactor |
|---|---|---|
| Bayes factor | 1.17<br>Lower Octant/Upper Octant<br>~54% : ~46% posterior | 3.59<br>Upper Octant/Lower Octant<br>~78% : 22% posterior |

**Using reactor constraint in all other results**

# RESULTS: MASS ORDERING

- The experiments individually have preferences for normal ordering.
- The NOvA-T2K joint fit has a weak preference for the Inverted Ordering.

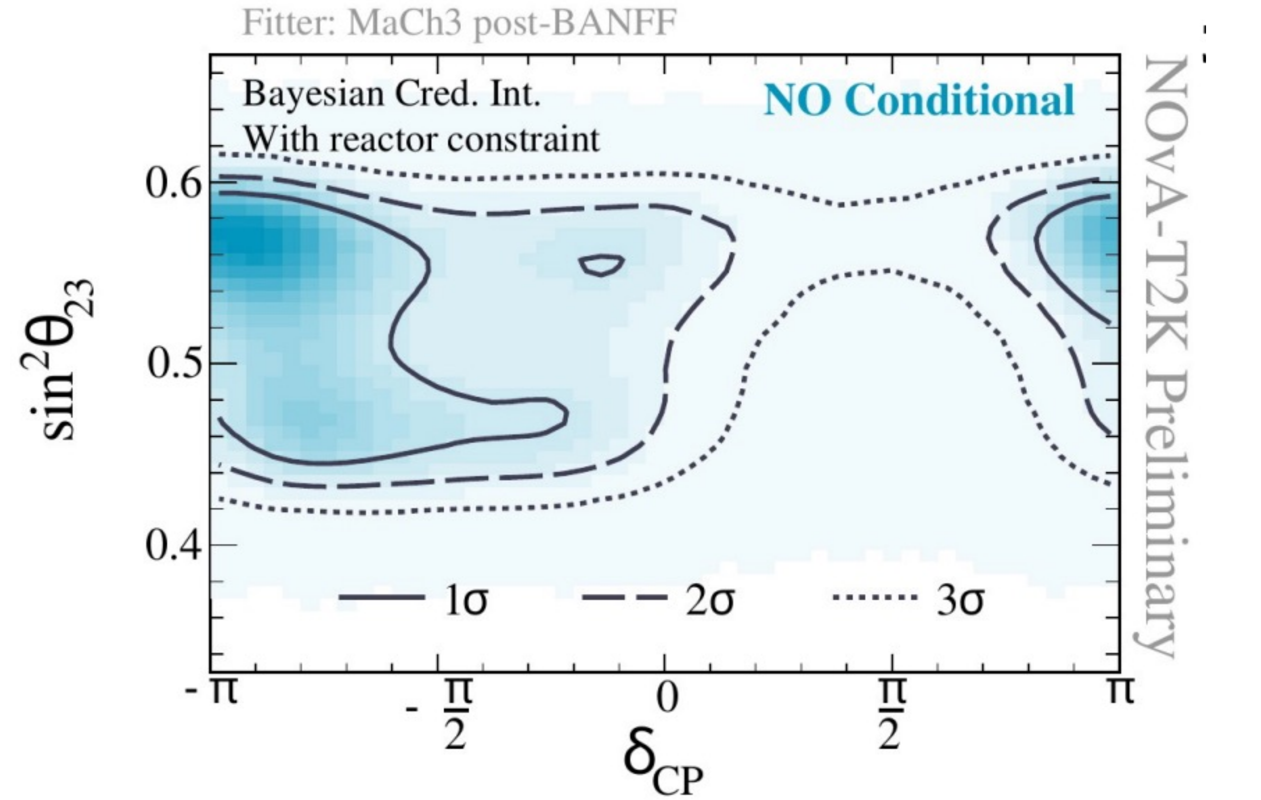


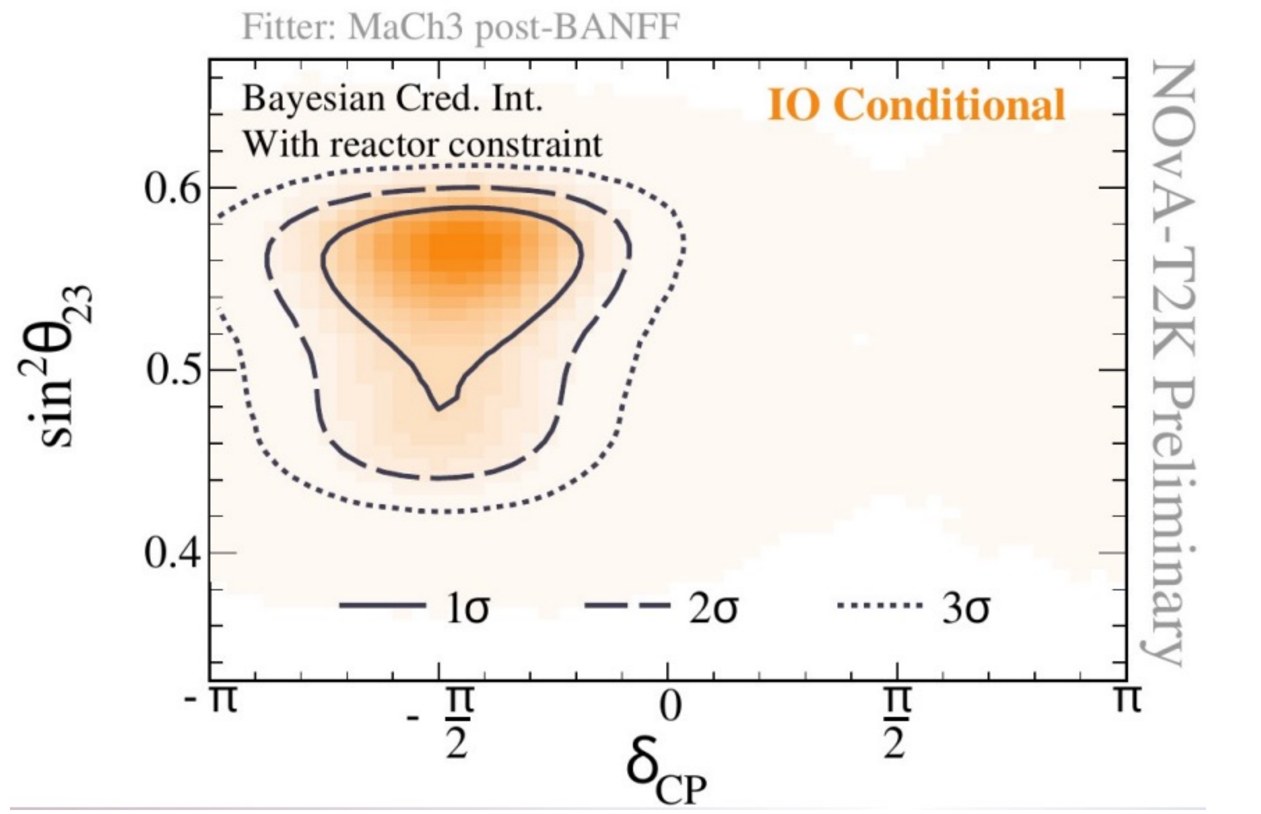

| | NOvA – T2K – w/ reactor |
|---|---|
| Bayes factor | **1.36** Inverted Ordering/Normal Ordering ~58% : ~42% posterior |

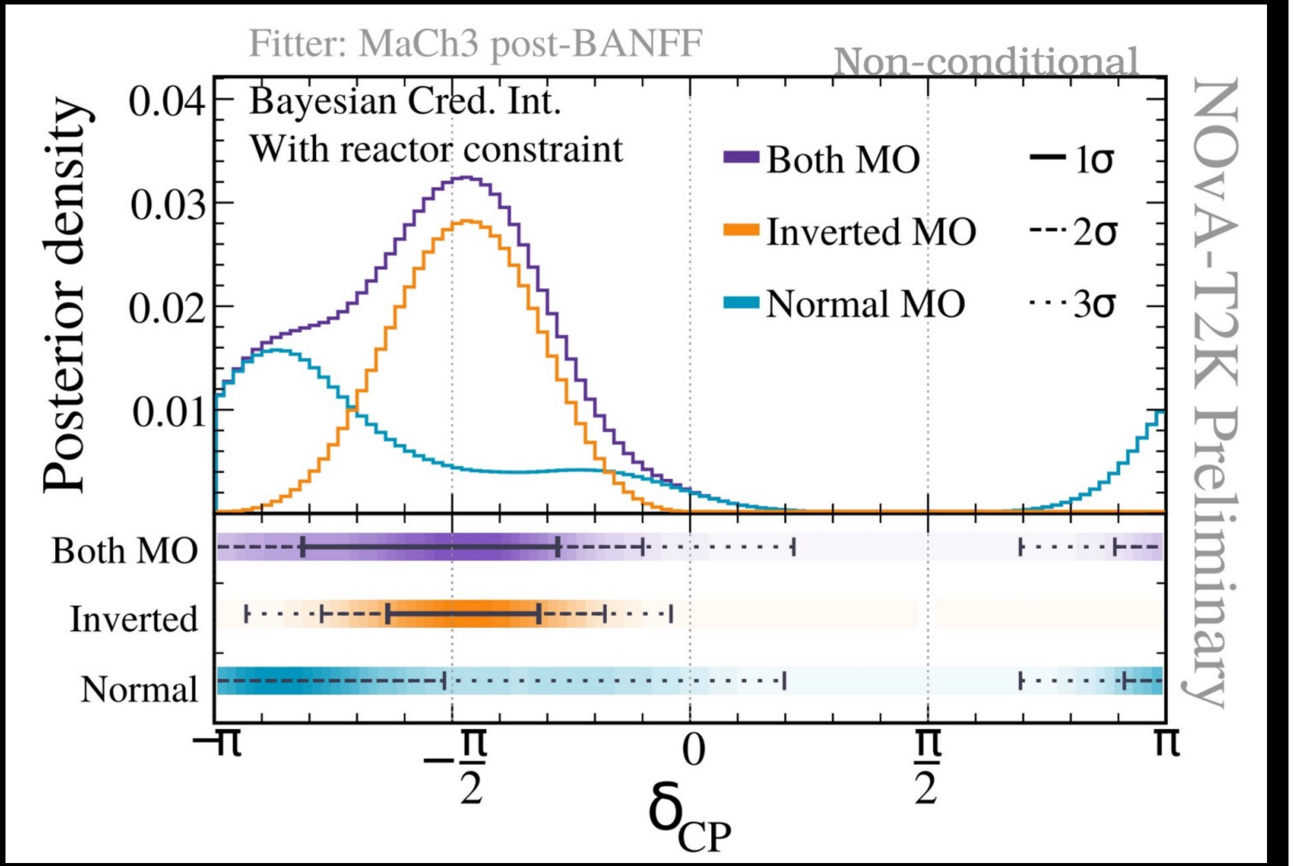
- Ask me more: Including the $\Delta m^2_{32}$ constraint from the Daya Bay reverses the mass ordering preference back to the Normal Ordering.

# RESULTS: CP VIOLATION

- Normal Ordering allows for a broad range of $\delta_{CP}$.
- Inverted Ordering, CP conserving values lie outside the 3-sigma credible interval.
- $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval for both mass orderings.

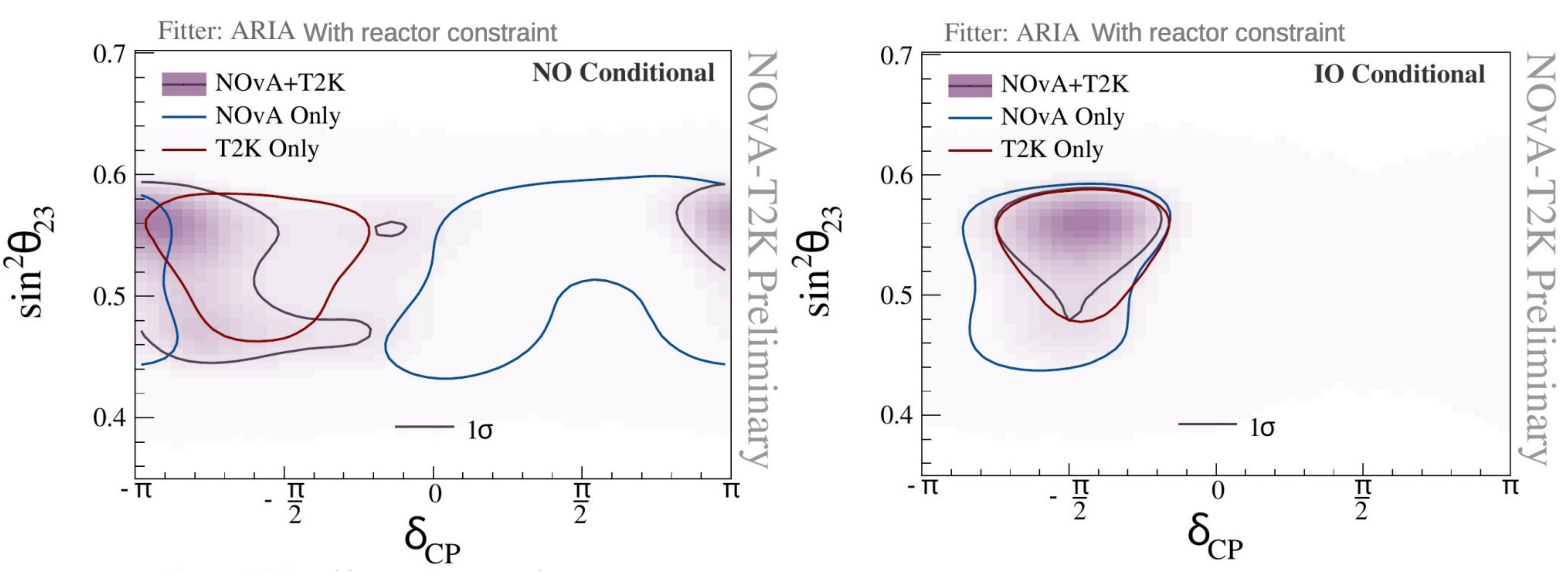


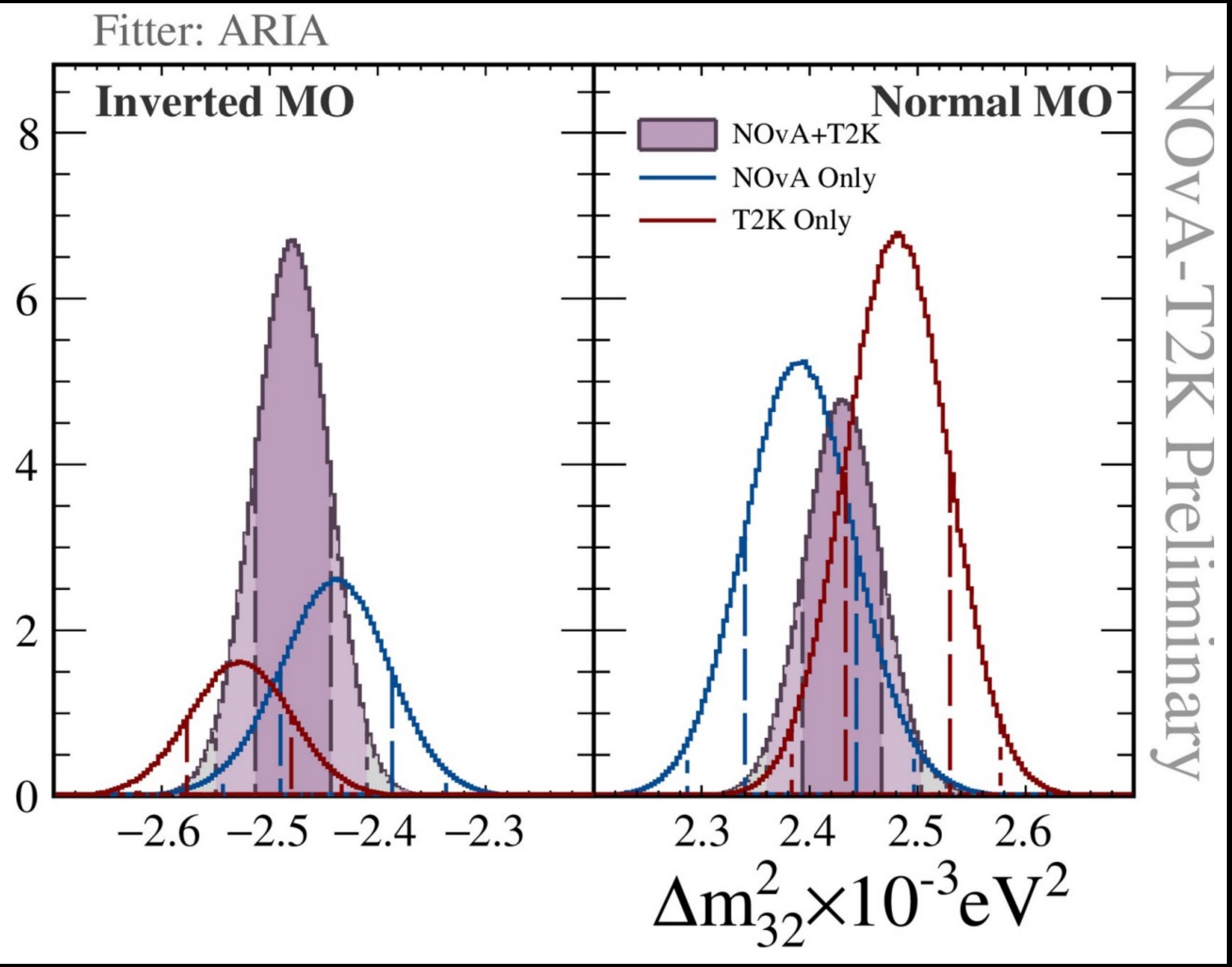
# RESULT: COMPARISON WITH INDIVIDUAL EXPERIMENTS

- The joint result disfavors (slightly) the Normal Ordering where the individual experiments preferred differing phase-spaces in $\delta_{CP}$.
- Provides tighter constraint in the Inverted Ordering where there was good agreement between NOvA-only and T2K-only fits.



# RESULT: COMPARISON WITH INDIVIDUAL EXPERIMENTS

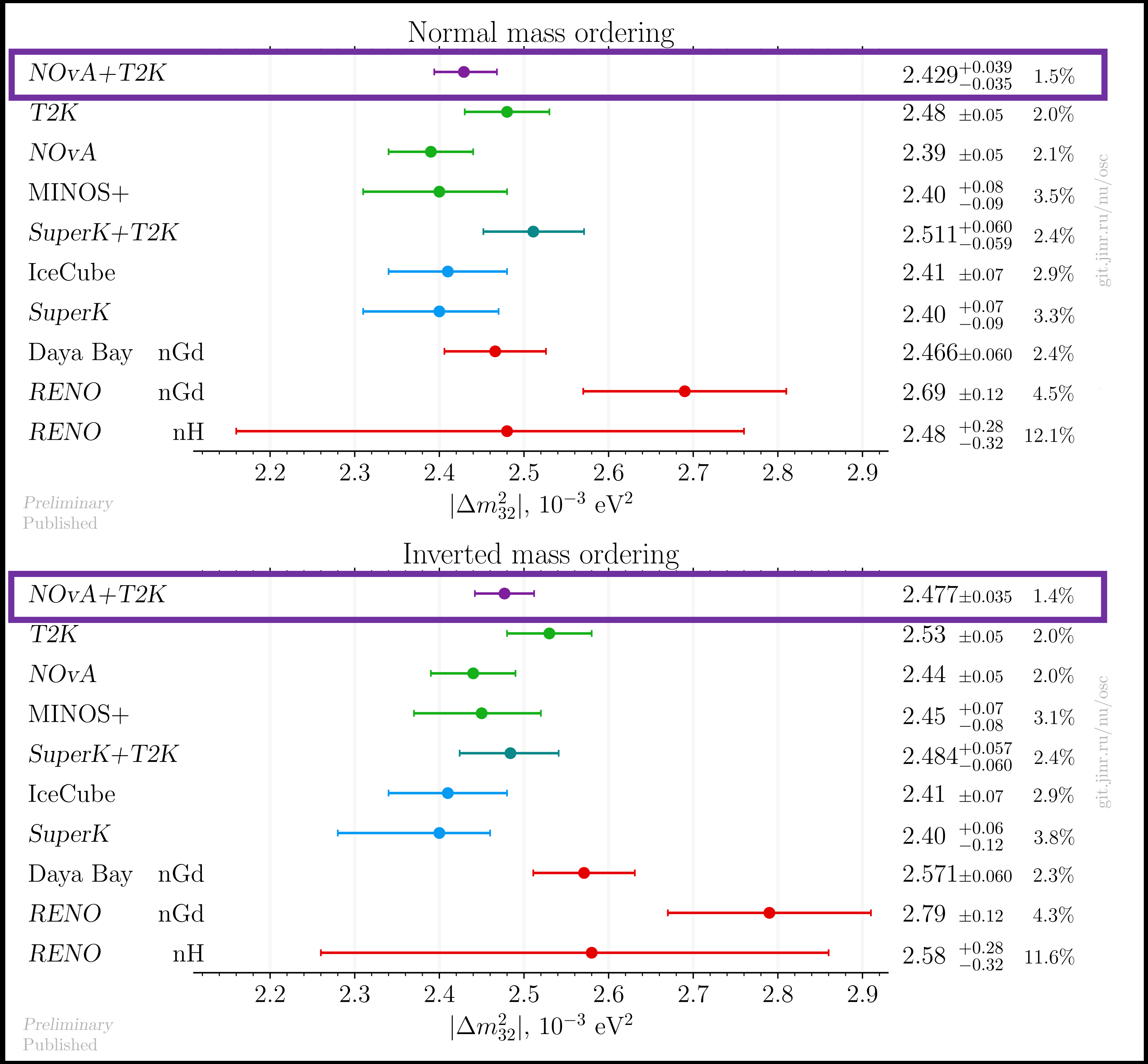
- The 1D posterior in $\Delta m^2_{32}$ highlights the switch in the mass ordering preference when NOvA and T2K are combined.
- The joint-fit enhances the precision of $|\Delta m^2_{32}|$ over individual experiments.




| | NOvA only | T2K only | NOvA+T2K |
|---|---|---|---|
| Bayes factor | **2.07** Normal/Inverted ~67% : ~33% posterior | **4.24** Normal/Inverted ~81% : ~19% posterior | **1.36** Inverted/Normal ~58% : ~42% posterior |

# COMPARISON WITH OTHER RESULTS

- This analysis has the smallest uncertainty on $|\Delta m^2_{32}|$ as compared to other previous measurements.



# SUMMARY AND OUTLOOK

- The joint analysis of NOvA and T2K is the first combination of these two long-baseline experiments.
  - It is a combination of two very different analysis approaches.
- The joint analysis shows:
  - **A strong constraint on $|\Delta m^2_{32}|$.**
  - Mass Ordering remains inconclusive. Mild preference for upper octant.
  - $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval for both mass orderings.
  - CP conserving values for the Inverted Ordering fall outside the 3-sigma range.
- NOvA and T2K continue data taking and analysis.
  - We look forward to future work together.

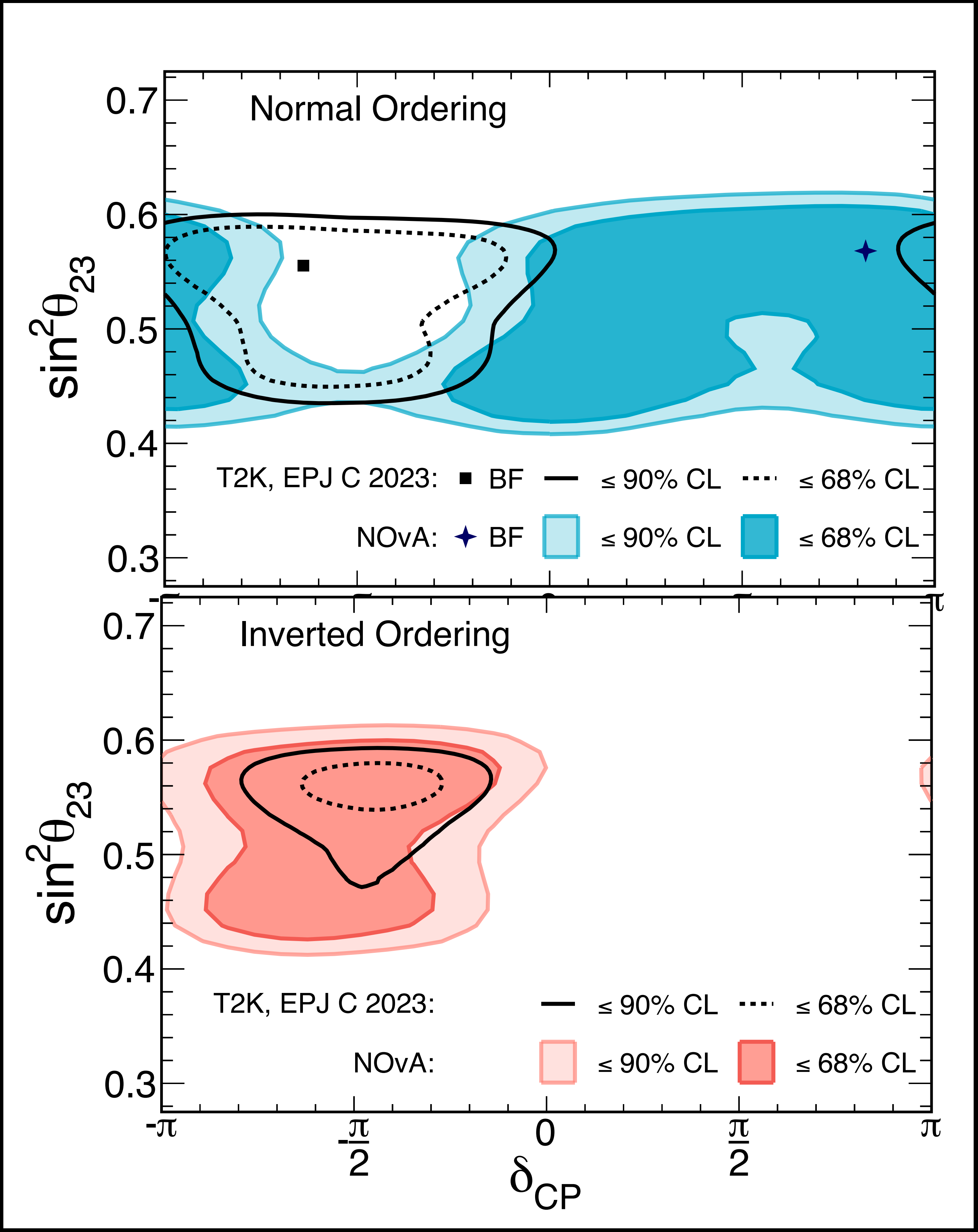
# Backup

# NOvA and T2K similarities and differences

| | T2K | NOvA |
|---|---|---|
| Baseline | 295 km | 810 km |
| Beam spectrum peak | 0.6 GeV | 2 GeV |
| Interactions | Mostly QE, 2p2h and RES backgrounds | Mixture of QE, 2p2h, RES, DIS etc |
| Near Detector target | Plastic scintillator with some water | Organic liquid scintillator |
| Far Detector Target | Water | Organic liquid scintillator |
| Near Detector principle | Magnetized<br>Plastic Scintillator and<br>Gaseous Argon TPC tracker | Segmented Liquid Scintillator Tracker |
| Far Detector principle | Water Cherenkov | Segmented Liquid Scintillator Tracker |
| Near-to-far extrapolation | Fit model to ND data and propagate best-fit model parameters and uncertainties | Large overlap in systematics allows for direct cancellation and use of ND-tuned model to build FD predictions |
| Neutrino energy estimator | Lepton Kinematics<br>(Assume elasticity) | Sum of lepton and hadronic energy<br>(Momentum by range and calorimetry) |

# WHY COMBINE NOVA AND T2K?

- Full implementation of:
  - Energy reconstruction and detector response
  - Detailed likelihood from each experiment
  - Consistent statistical inference across the full dimensionality
- In-depth review of:
  - Models, systematic uncertainties and possible correlations
  - Different analysis approaches driven by contrasting detector designs

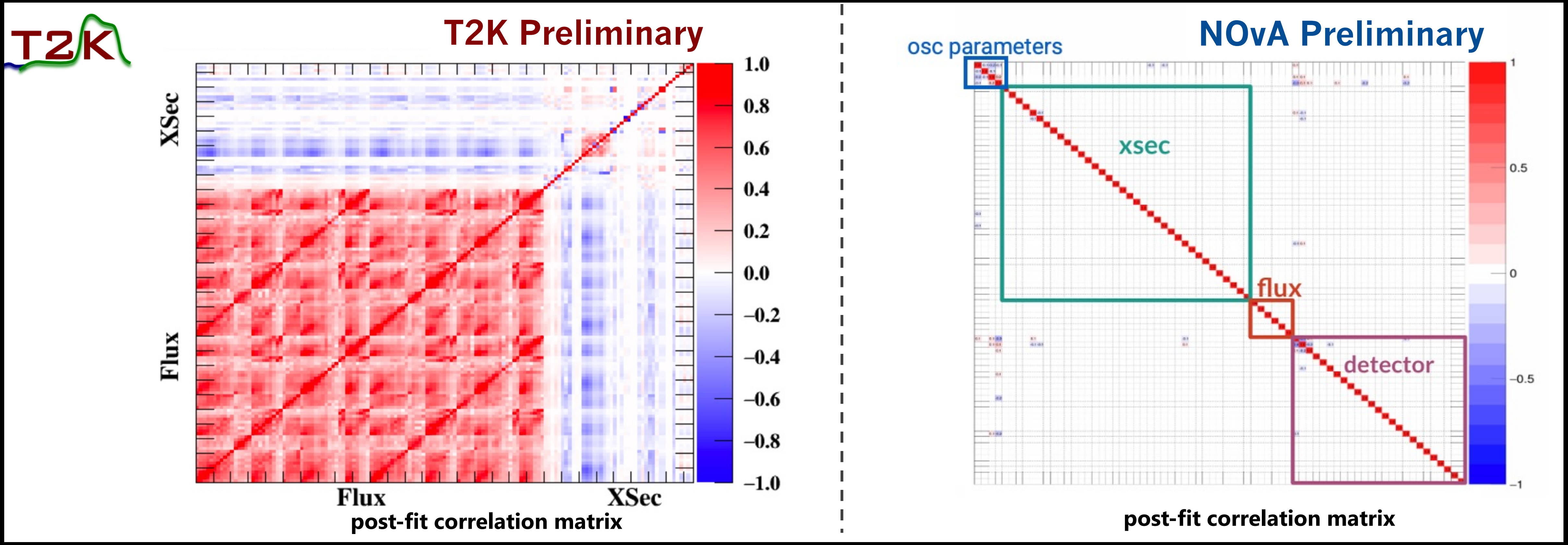



**Results from NOvA and T2K with 2020 data**

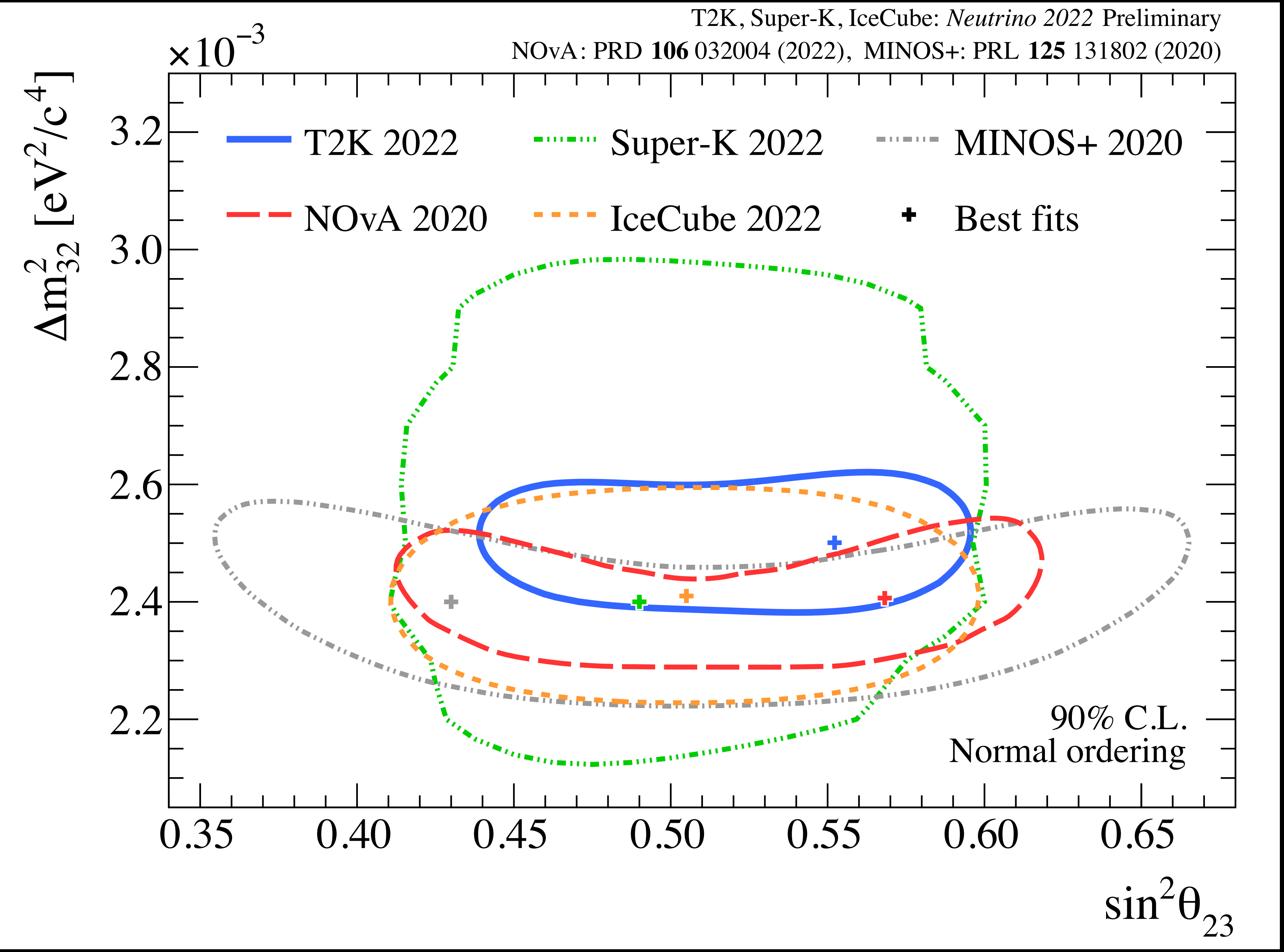
# NOVA AND T2K SYSTEMATIC UNCERTAINTIES

- T2K: Leverages high-statistics ND data to constrain model parameters and uncertainties prior to oscillations, leading to significant anti-correlations between flux and cross-section.

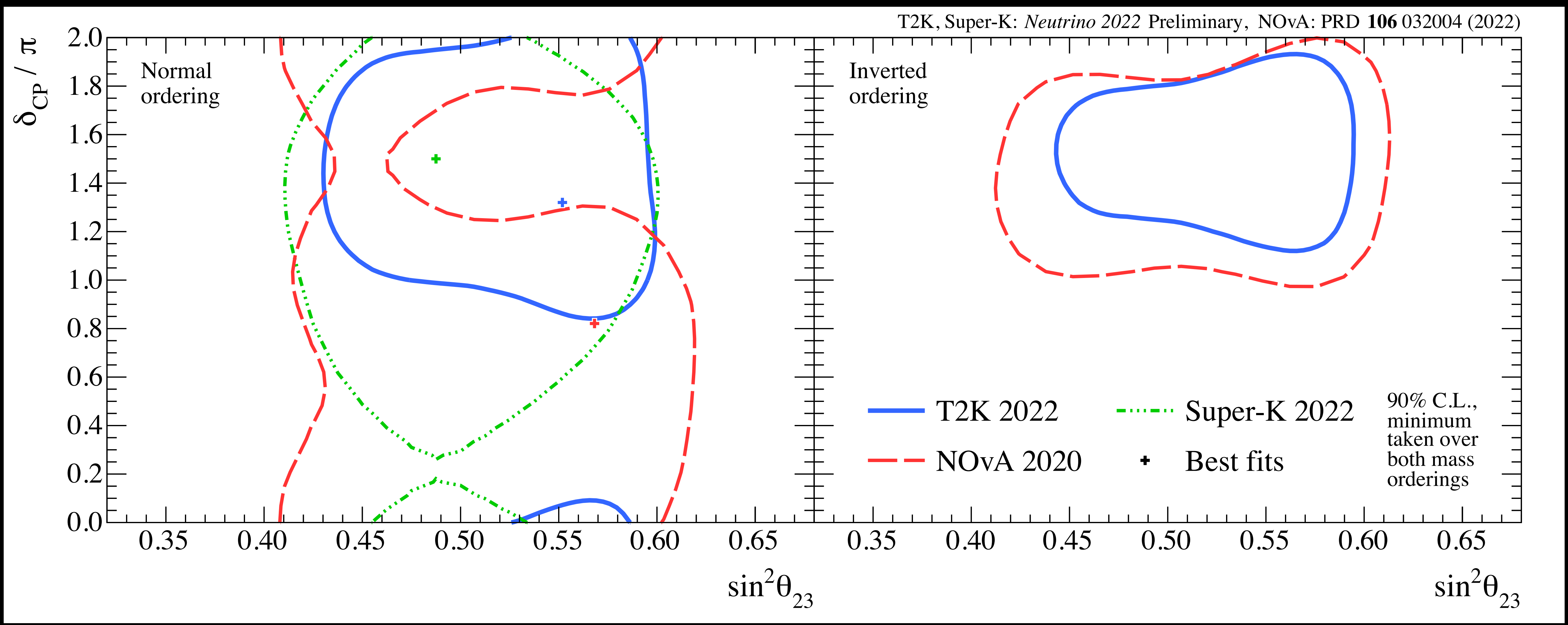
- NOvA: Model and systematic parameters enter as a ratio of how they impact near vs far detector. This cancelation constrains the variations allowed by systematics, minimizing their correlations with oscillations and nuisance parameters.



# MOST RECENT INDIVIDUAL EXPERIMENT RESULTS

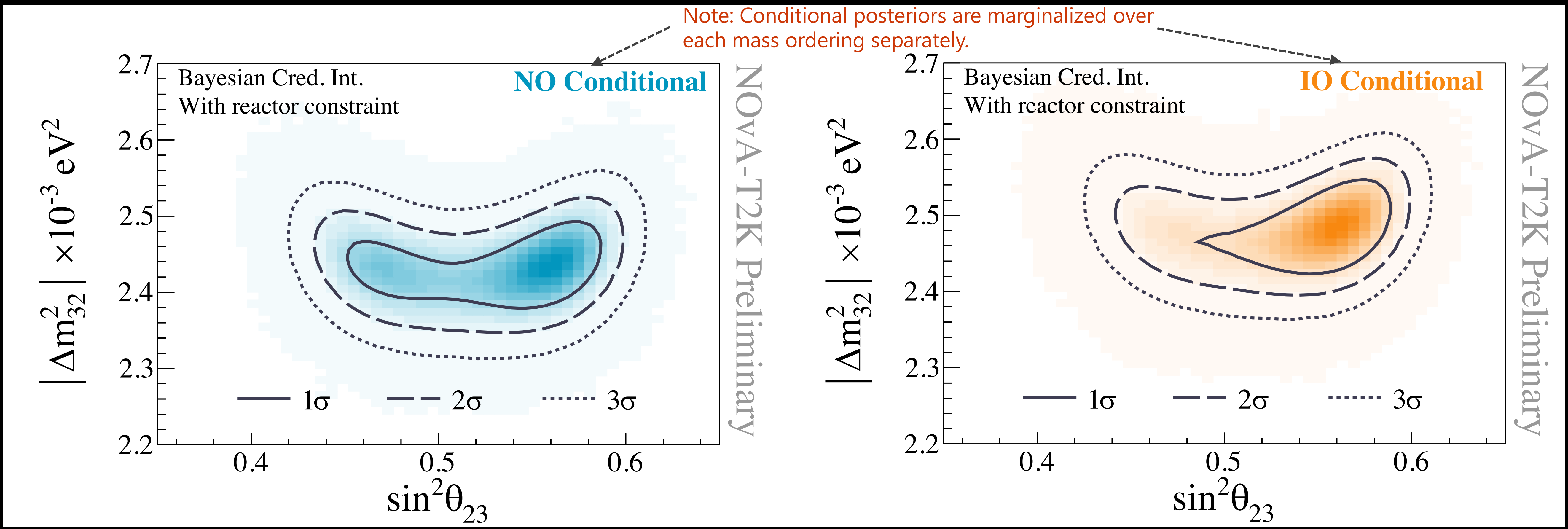


# MOST RECENT INDIVIDUAL EXPERIMENT RESULTS



# RESULTS: MASS DIFFERENCE AND OCTANT

- Marginalizing over each mass ordering, measurements remain consistent with an upper octant preference but also with a maximal mixing angle.

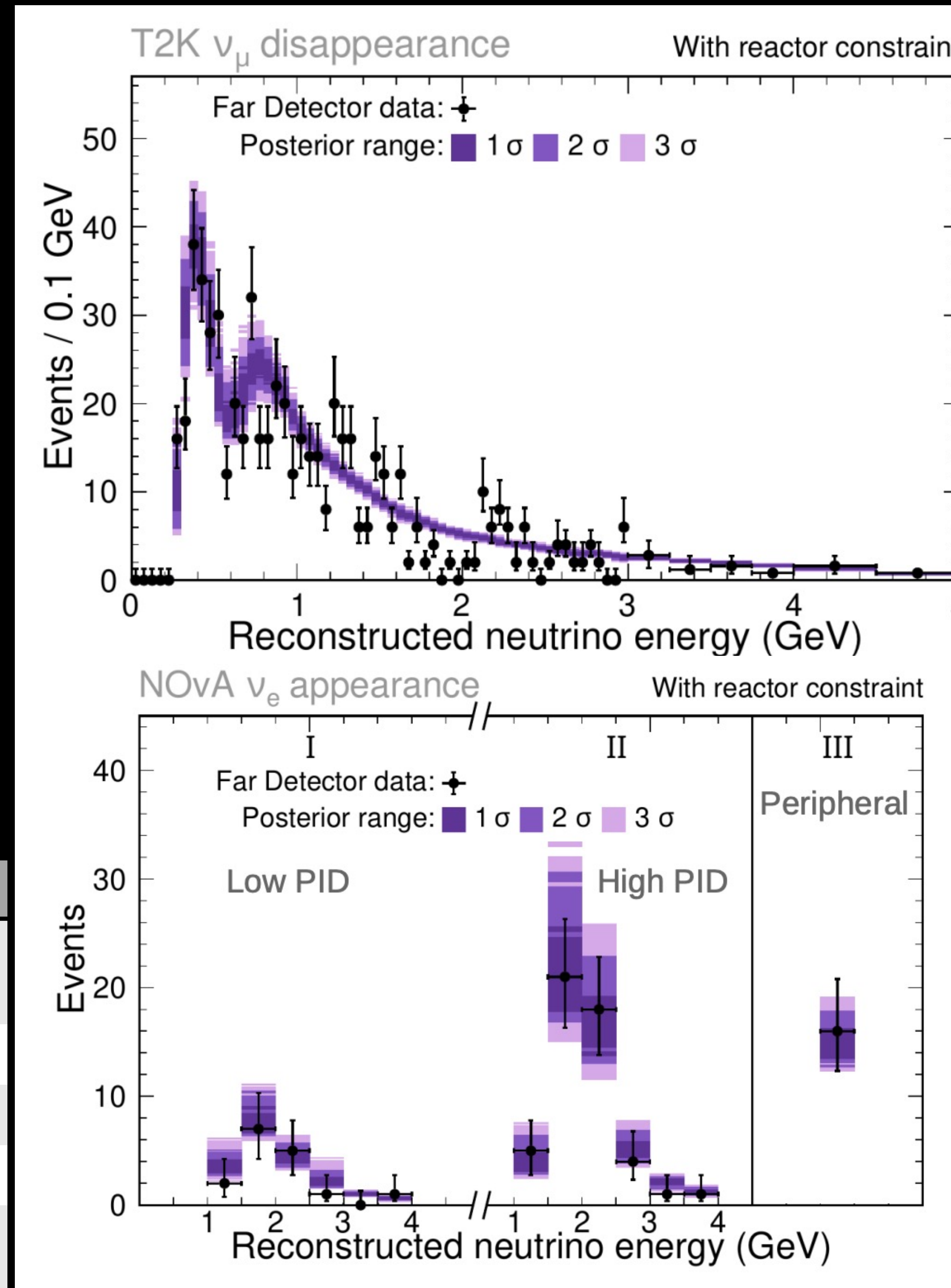


# THE DATA

- The joint-fit uses the data collected by each experiment up until 2020.
- Using both experiments data roughly doubles the total statistics at the far detectors.
- The data from both experiments is described well by the joint fit.

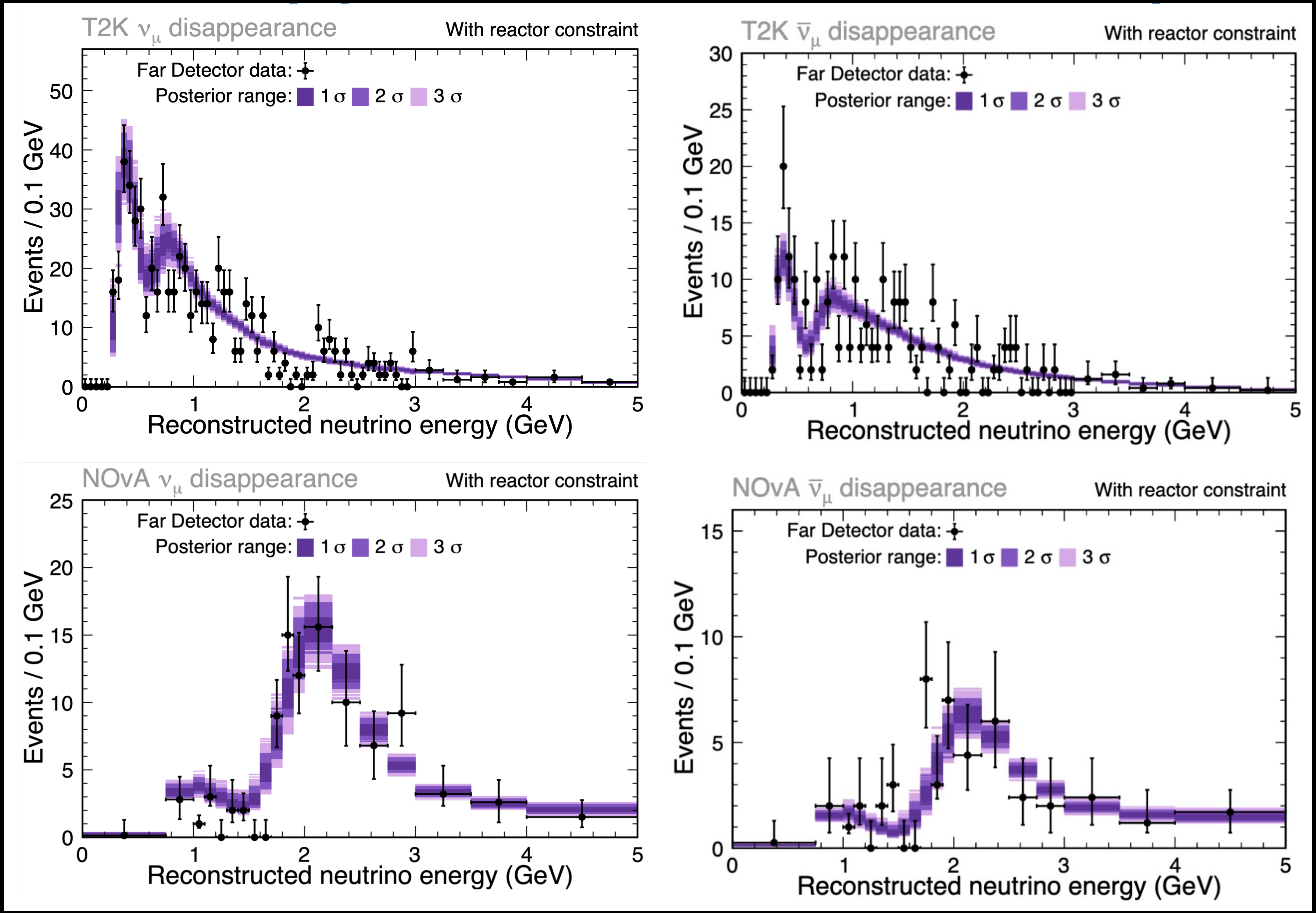
| Channel | NOvA | T2K | Combined |
|---|---|---|---|
| $\nu_e$ | 0.90 | 0.19 ($\nu_e$)<br>0.79 ($\nu_e 1\pi$) | 0.62 |
| $\bar{\nu}_e$ | 0.21 | 0.67 | 0.40 |
| $\nu_\mu$ | 0.68 | 0.48 | 0.62 |
| $\bar{\nu}_\mu$ | 0.38 | 0.87 | 0.72 |
| Total | 0.64 | 0.72 | 0.75 |

**posterior predictive p-value**

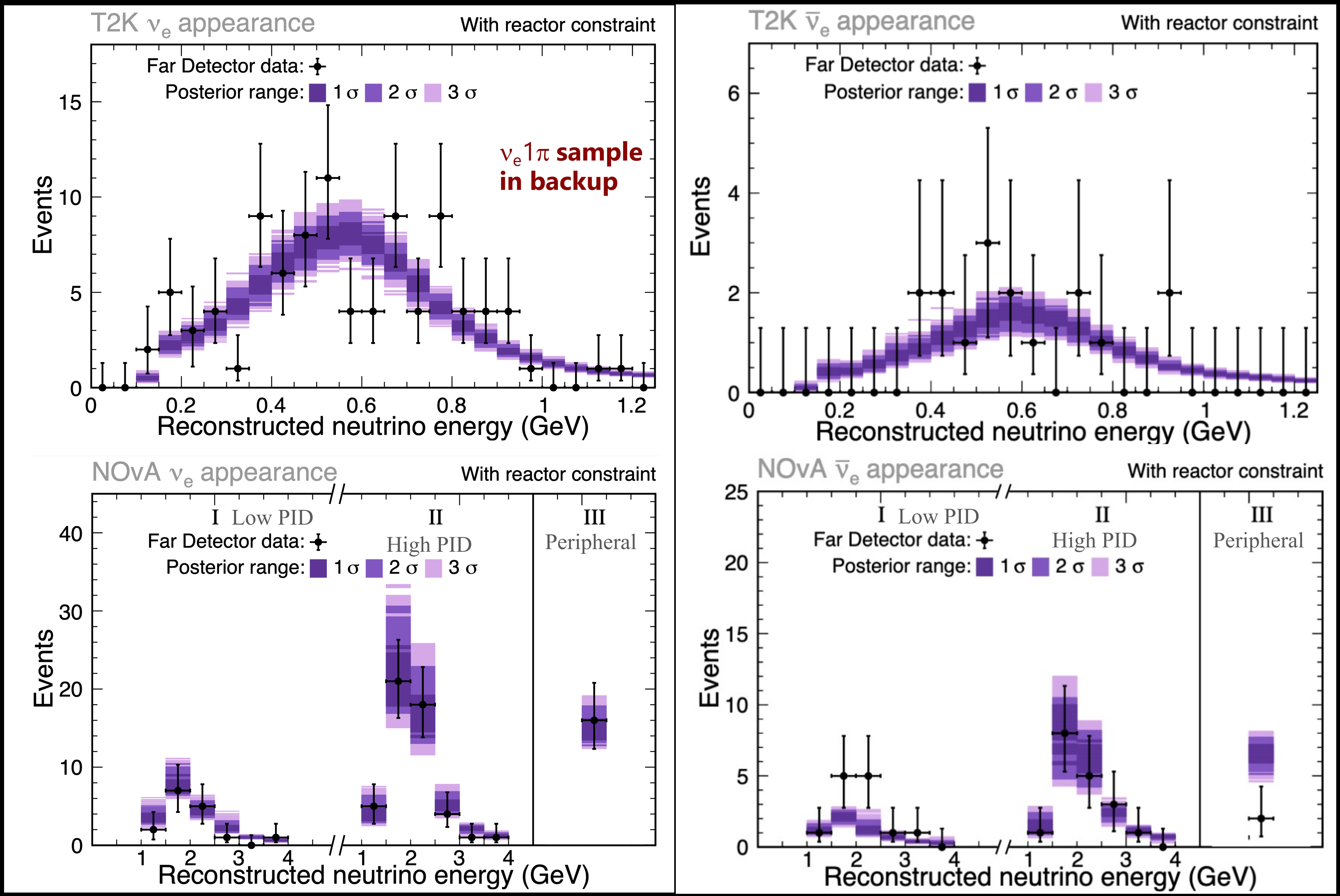



**Complete sets in backup**

# MUON (ANTI-)NEUTRINO DISAPPEARANCE FOR NOVA AND T2K

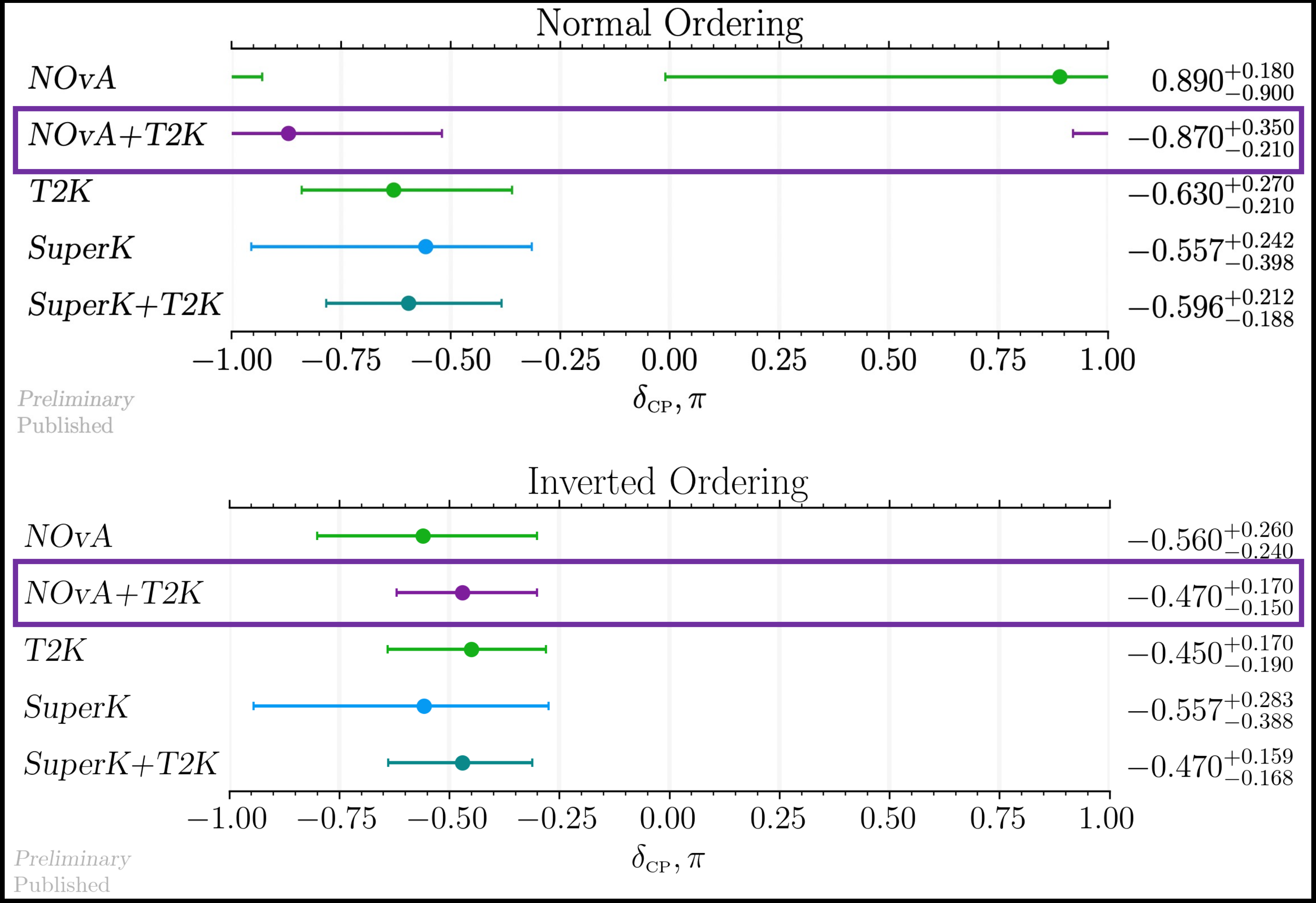


# ELECTRON (ANTI-)NEUTRINO APPEARANCE FOR NOVA AND T2K



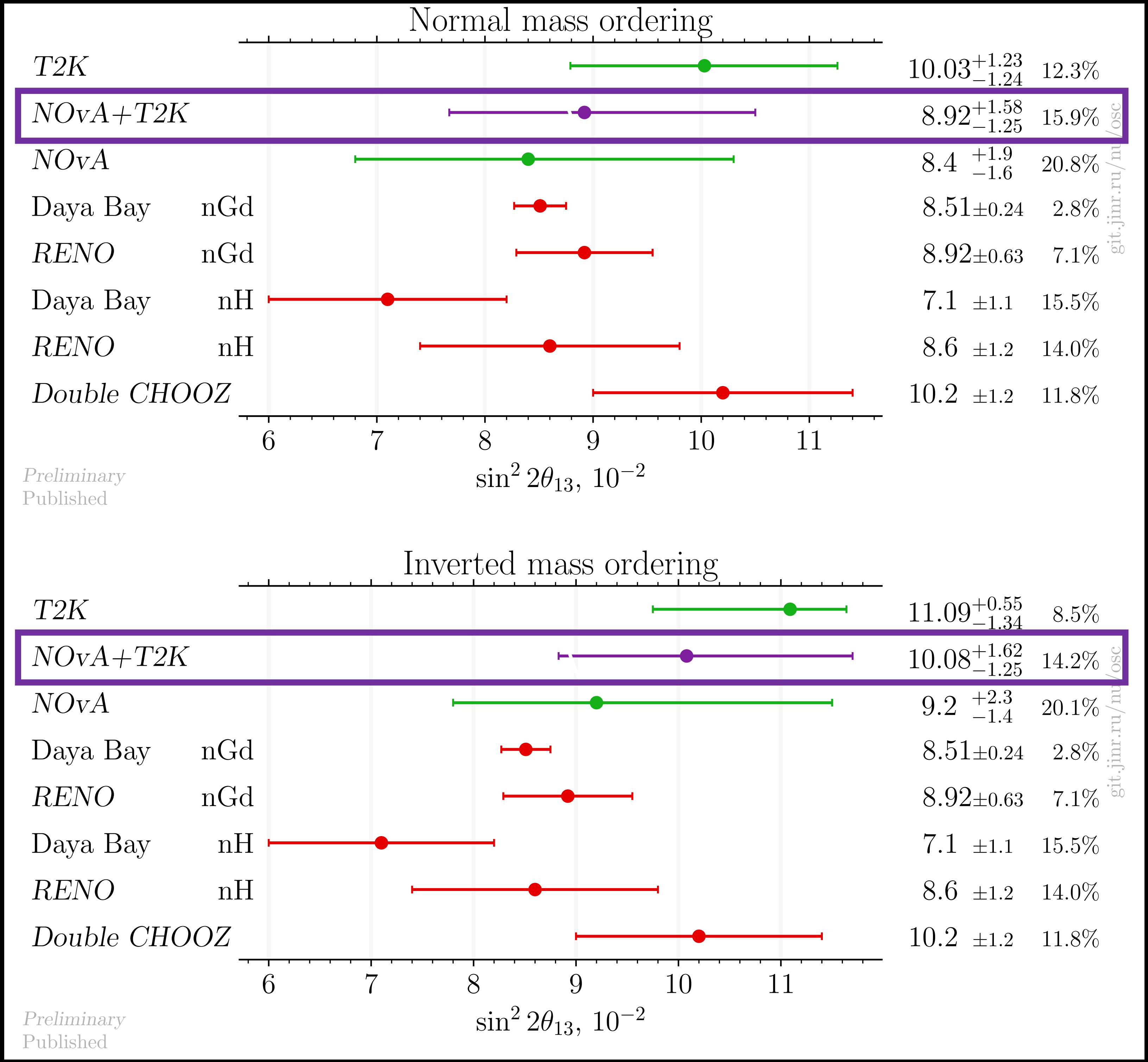
# RESULT: COMPARISON WITH OTHER RESULTS

- The $\delta_{CP}$ measurements are consistent across all experiments and their combinations.
- The uncertainty on $\delta_{CP}$ remains large.



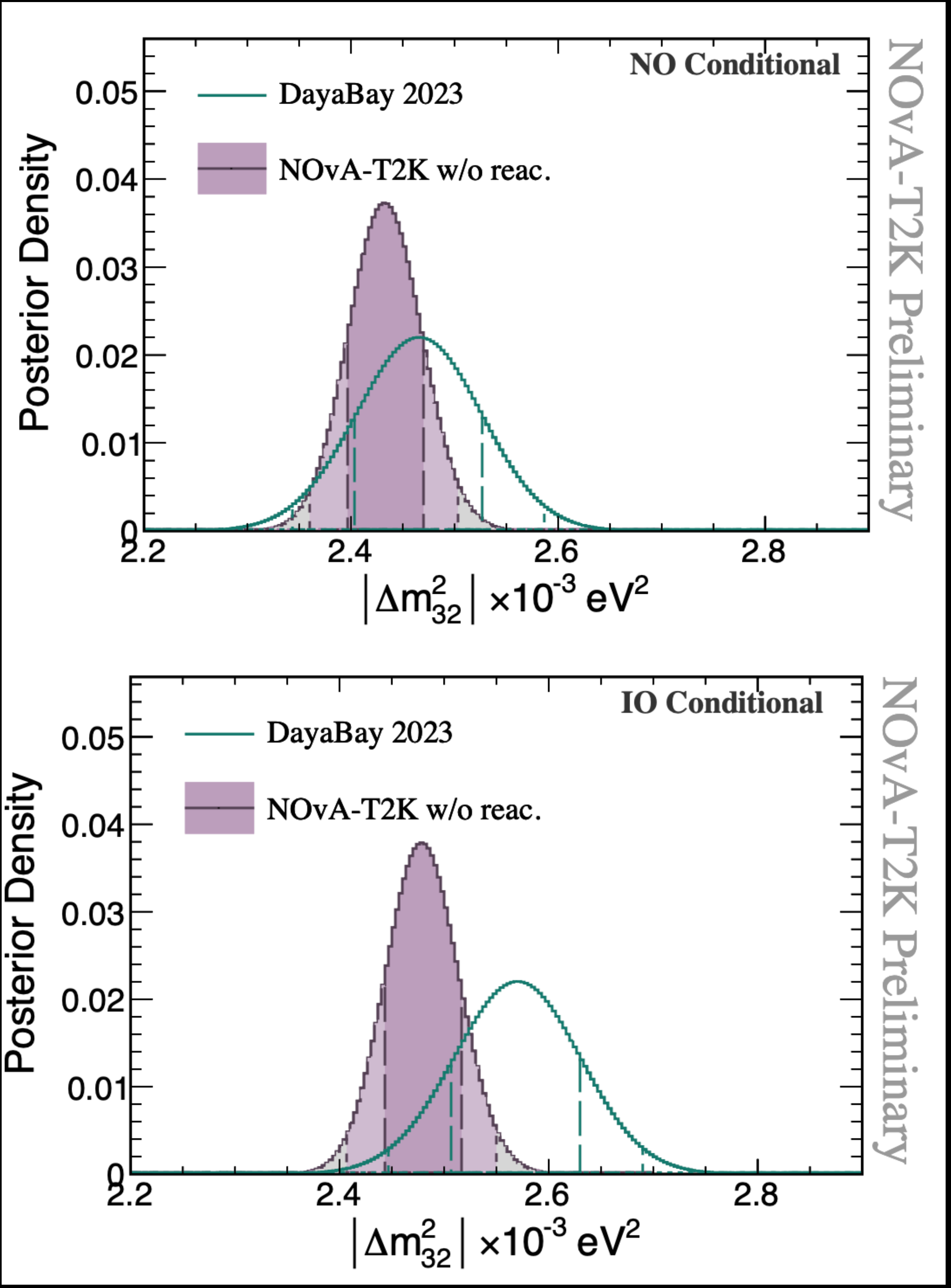
# RESULT: COMPARISON WITH OTHER RESULTS

- Daya Bay leads the precision on the measurement of $\theta_{13}$ with 2.8% uncertainty.
- Overall, the long-baseline measurements are consistent with reactor experiments, with larger consistency in the normal ordering than the inverted ordering.



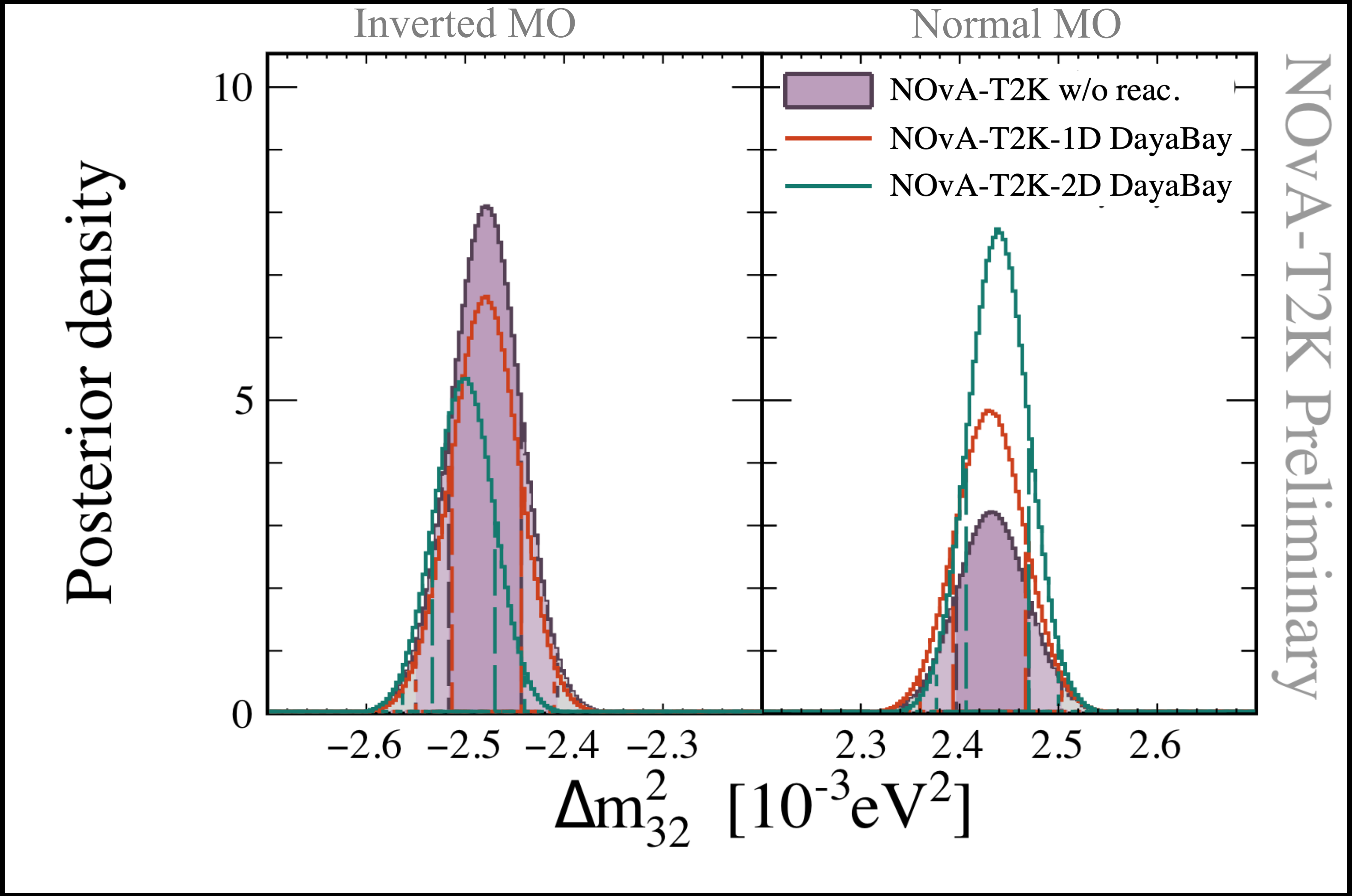
# COMBINING WITH DAYA BAY IN MASS DIFFERENCE AND MIXING ANGLE

- Enhanced precision in $\Delta m^2_{32}$ is a new handle when combining reactor and long-baseline results.
- In the true mass ordering, reactor and long-baseline measurements of $\Delta m^2_{32}$ would be consistent but in the incorrect mass ordering would be wrong by different amounts.
- More info: Nunokawa, Parke and Zukanovich Funchal. Phys. Rev. D 72: 013009, 2005.



# COMBINING WITH DAYA BAY IN MASS DIFFERENCE AND MIXING ANGLE

- Including the $\Delta m^2_{32}$ constraint from the Daya Bay (Phys. Rev. Lett. **130**, 161802, 2023), reverses the mass ordering preference back to the Normal Ordering.
- Overall, this analysis does not show a significant preference for either mass ordering.

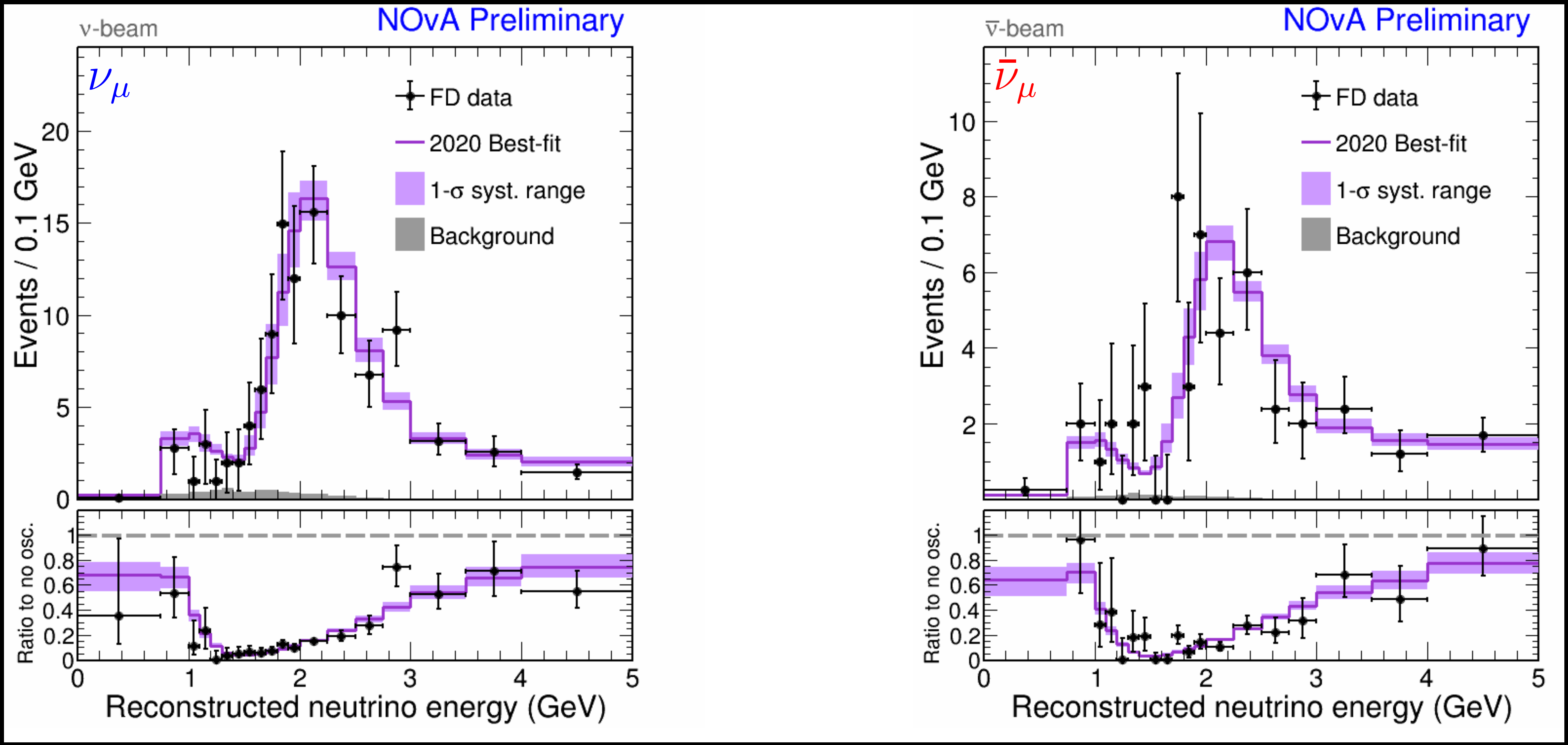



| | NOvA - T2K w/o reactor | NOvA – T2K – 1D Daya Bay | NOvA - T2K - 2D Daya Bay |
|---|---|---|---|
| Bayes factor | **2.47** Inverted/Normal ~71% : ~29% posterior | **1.34** Inverted/Normal ~57% : ~43% posterior | **1.44** Normal/Inverted ~59% : ~41% posterior |

Backup old

# NOVA'S DISAPPEARANCE SPECTRA

- NOvA uses an off-axis beam (2.5º) with large segmented scintillator detector in a 810 km baseline.

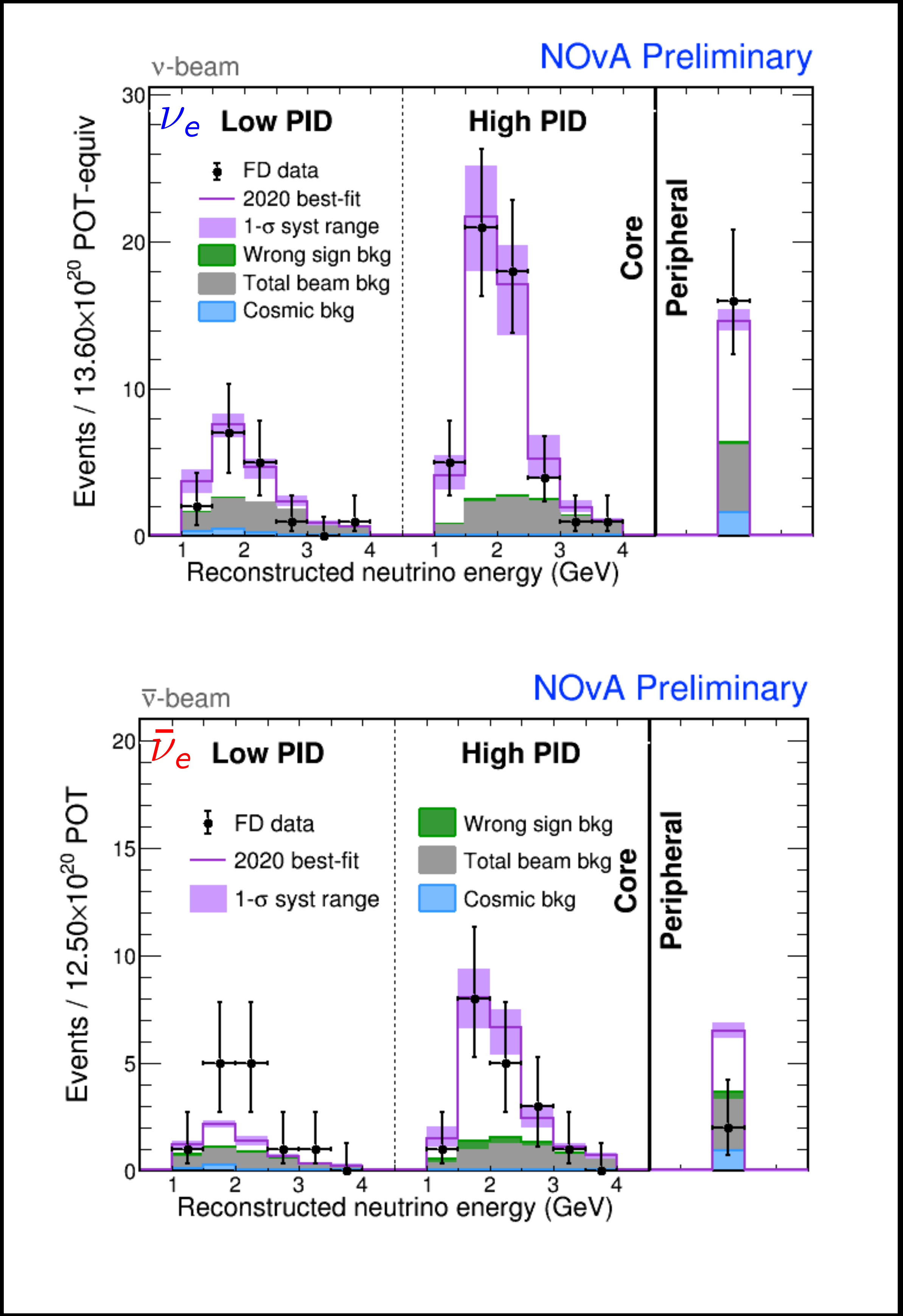



- Observe 221 events in neutrino mode and 105 events in antineutrino mode.

# NOVA'S ELECTRON NEUTRINO AND ANTINEUTRINO APPEARANCE

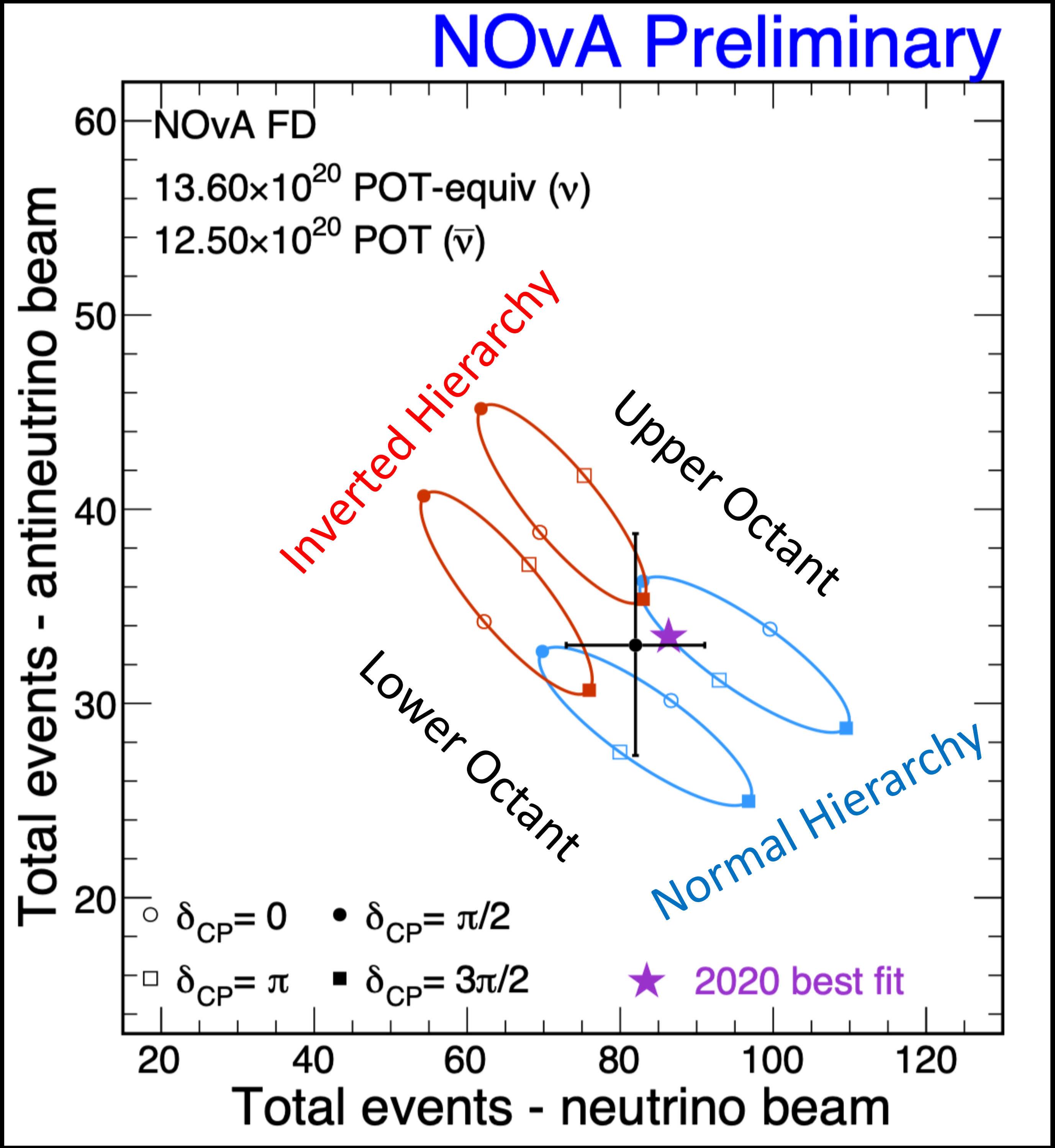
- On the neutrino beam we observe 82 events and expect 26.8 background interactions.
- For the antineutrino beam we observe 33 and expect 14 background interactions.

**> 4σ evidence of electron antineutrino appearance**



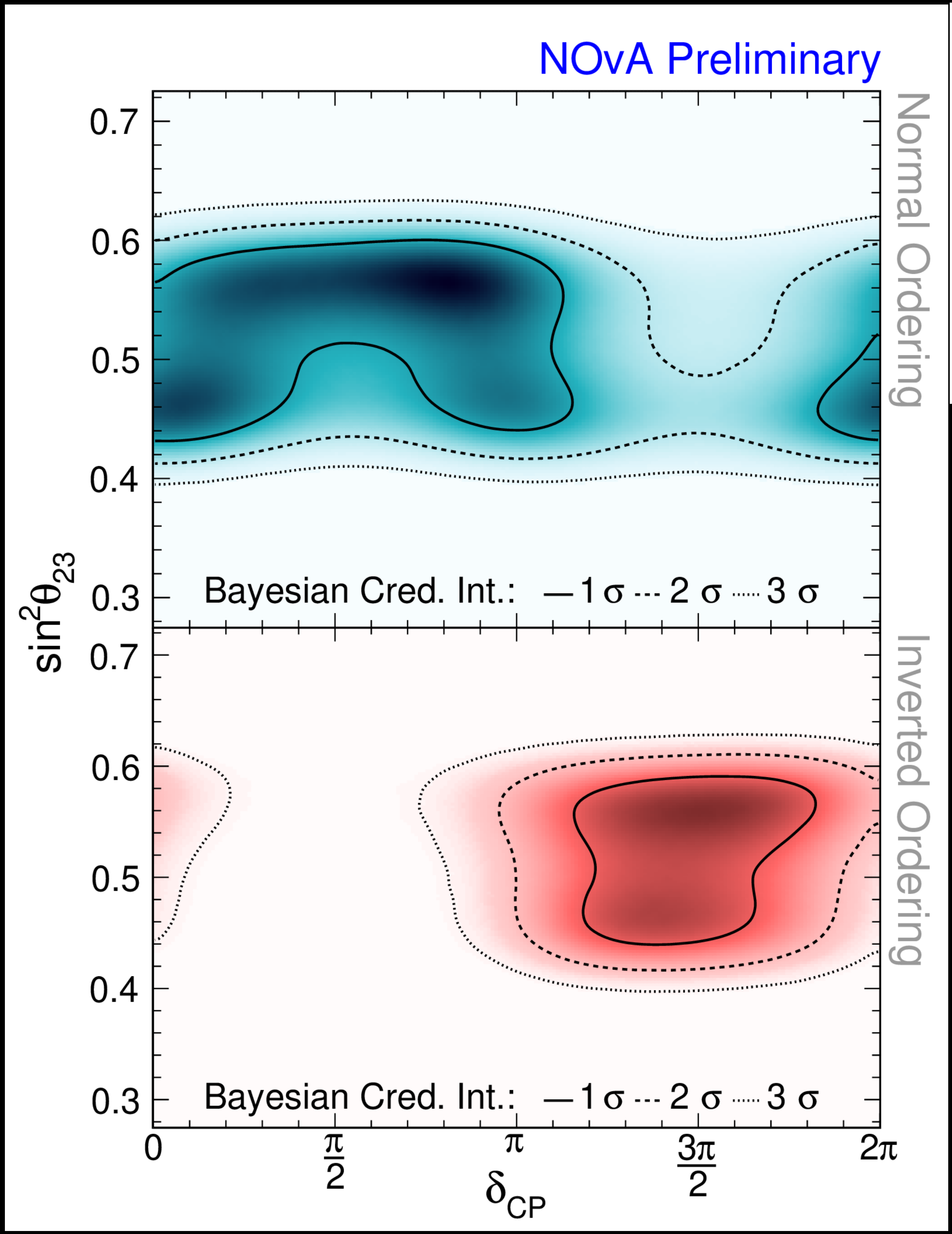
# ELECTRON NEUTRINO APPEARANCE EXPECTATIONS

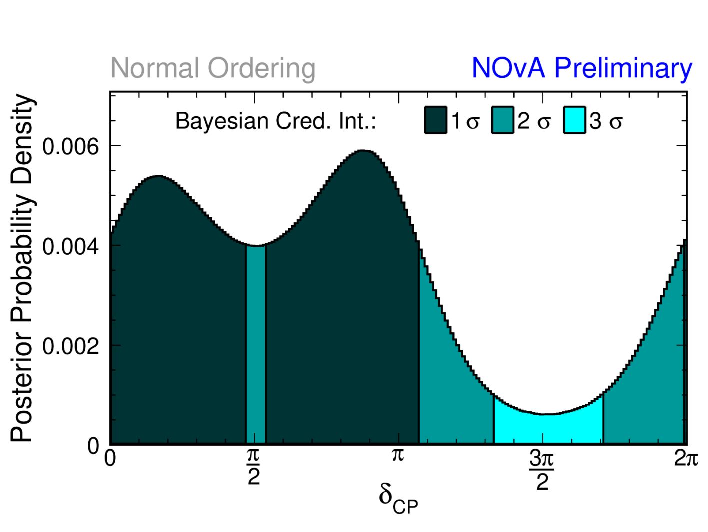
- Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.
- Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).

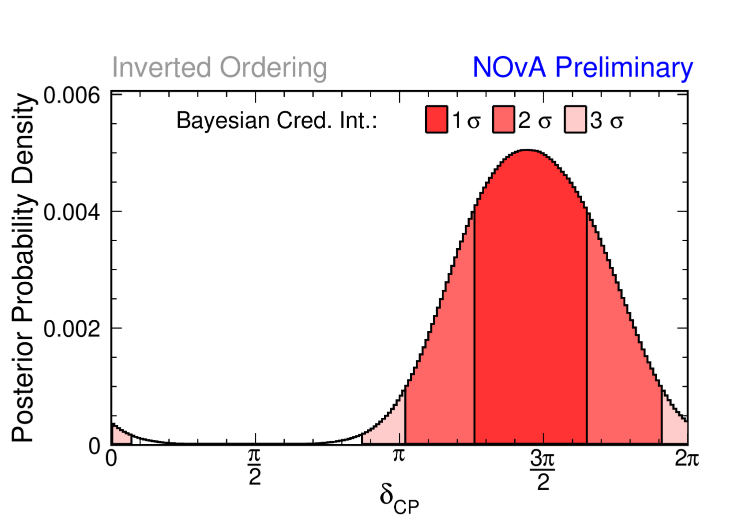



**OBSERVE 82 EVENTS FOR NEUTRINO MODE AND 33 FOR ANTINEUTRINO MODE**

# NOVA'S RESULTS: $\delta_{CP}$ VS. $\sin^2\theta_{23}$



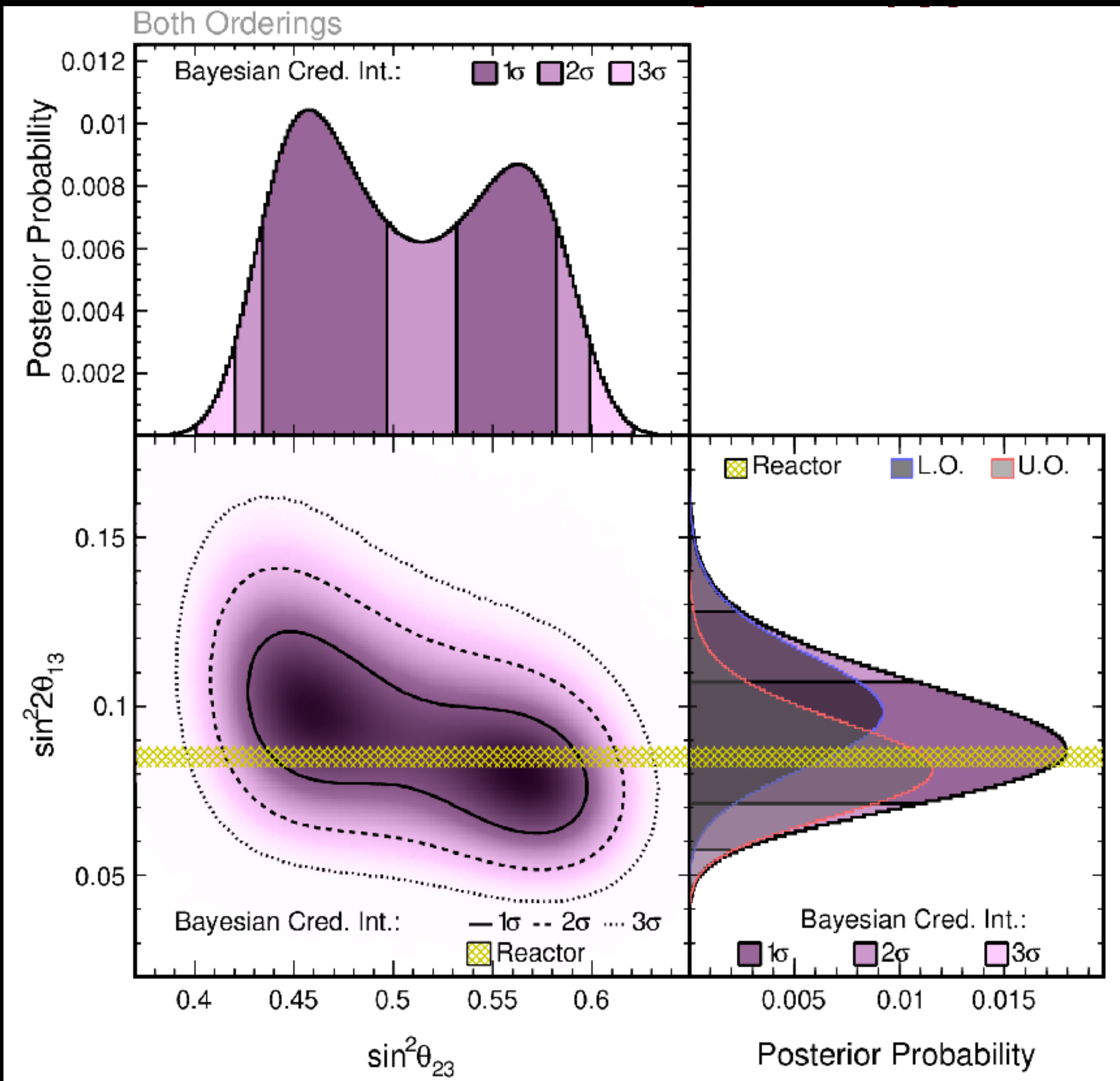




- No asymmetry in electron neutrino vs antineutrino rates of appearance. Disfavoring points that would produce that asymmetry.

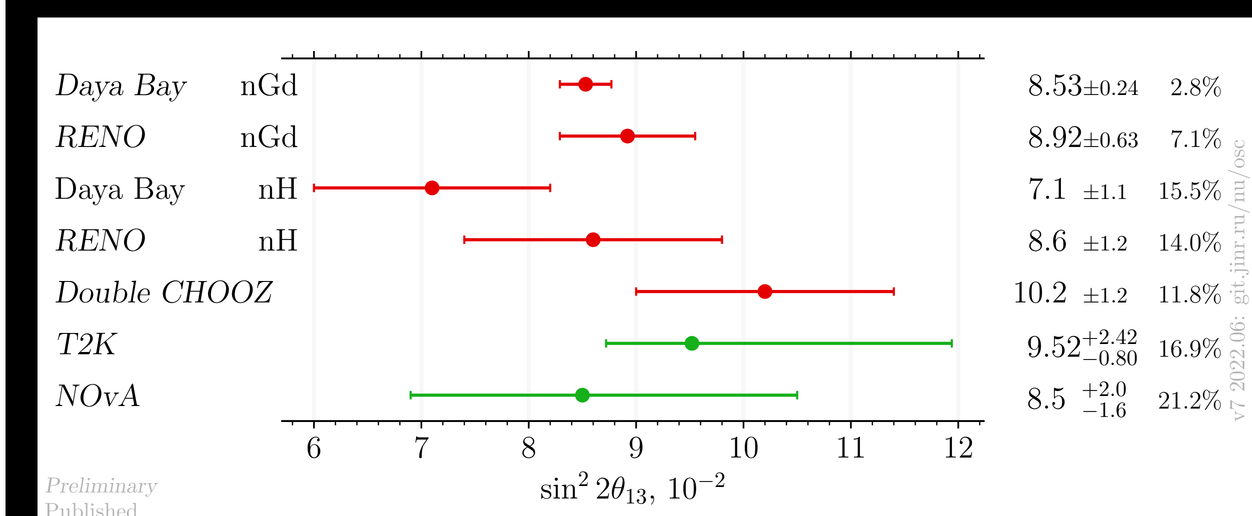
**Bayesian reanalysis consistent with**

**Disfavor NH $\delta=3\pi/2$ at ~2σ**
**Exclude IH $\delta=\pi/2$ at > 3σ**

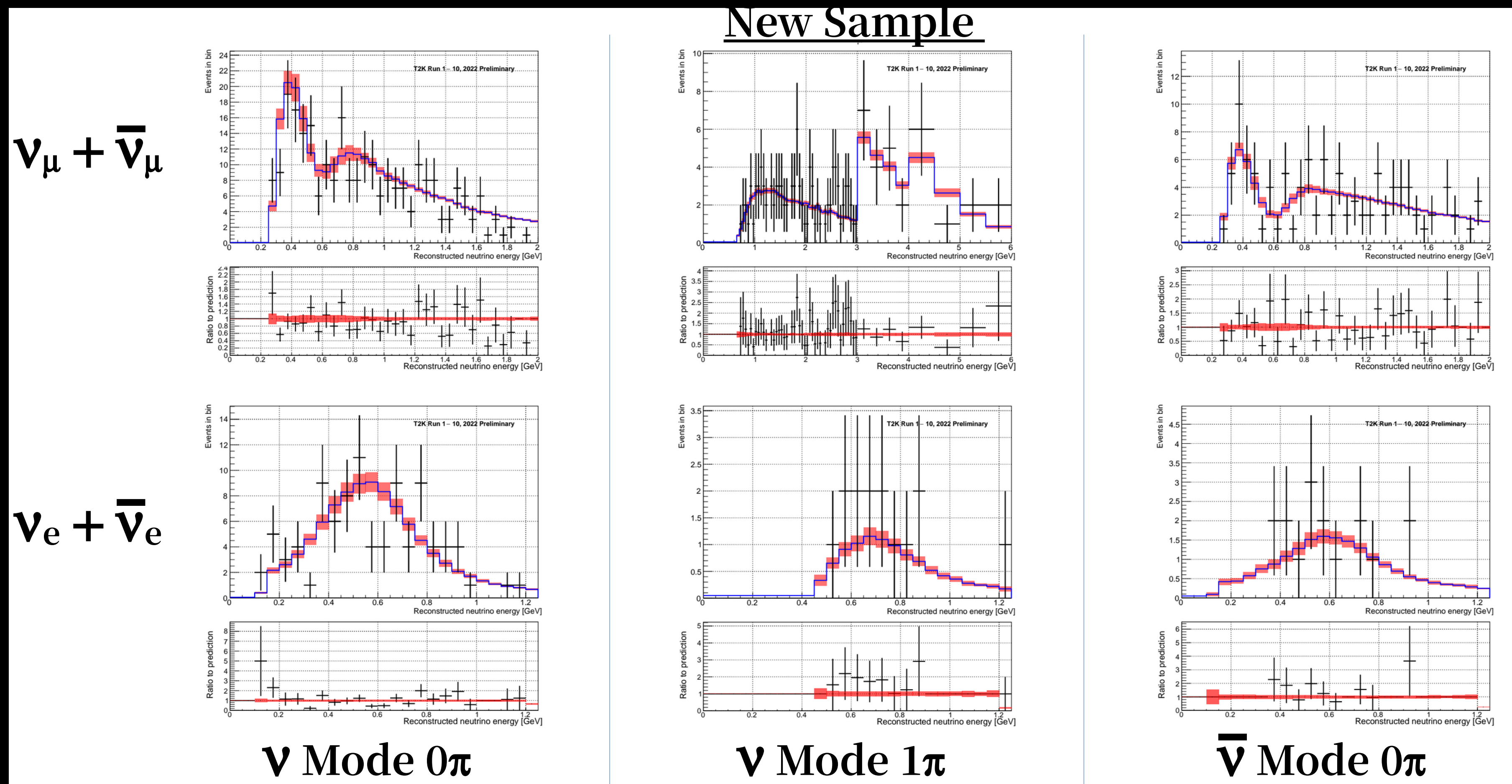
# NOVA'S RESULTS WITH AND WITHOUT REACTOR CONSTRAINT




- NOvA uses the reactor constraint for the value of $\theta_{13}$. If instead we allow it to float the value is consistent with the PDG value.
- Note that the slight (upper) octant preference is driven by the reactor constraint.



# T2K: AN OFF-AXIS NEUTRINO EXPERIMENT IN THE JPARC BEAM




- T2K uses an off-axis beam (2.5°) with large water Cherenkov detector of SuperK in a 295 km baseline.
  - It has run in both neutrino and anti-neutrino modes.