NOvA and NOvA+T2K results

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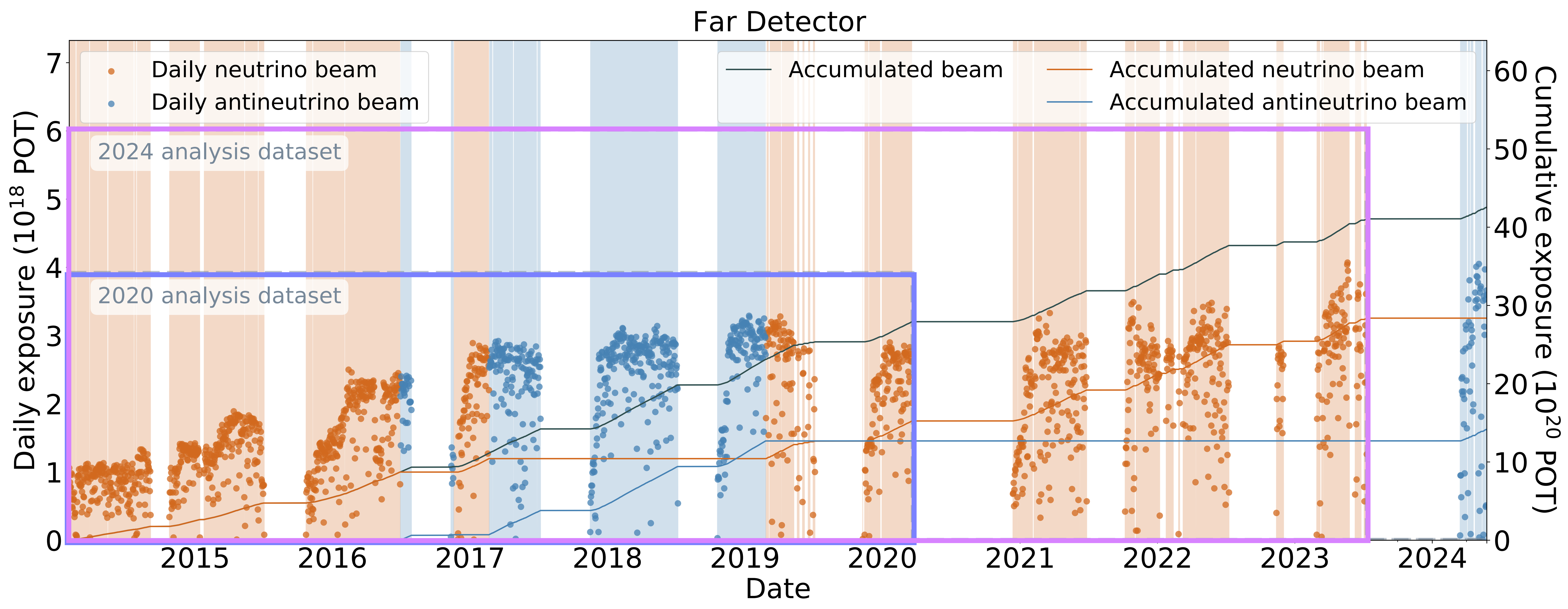
3 Sept, NOW 2024

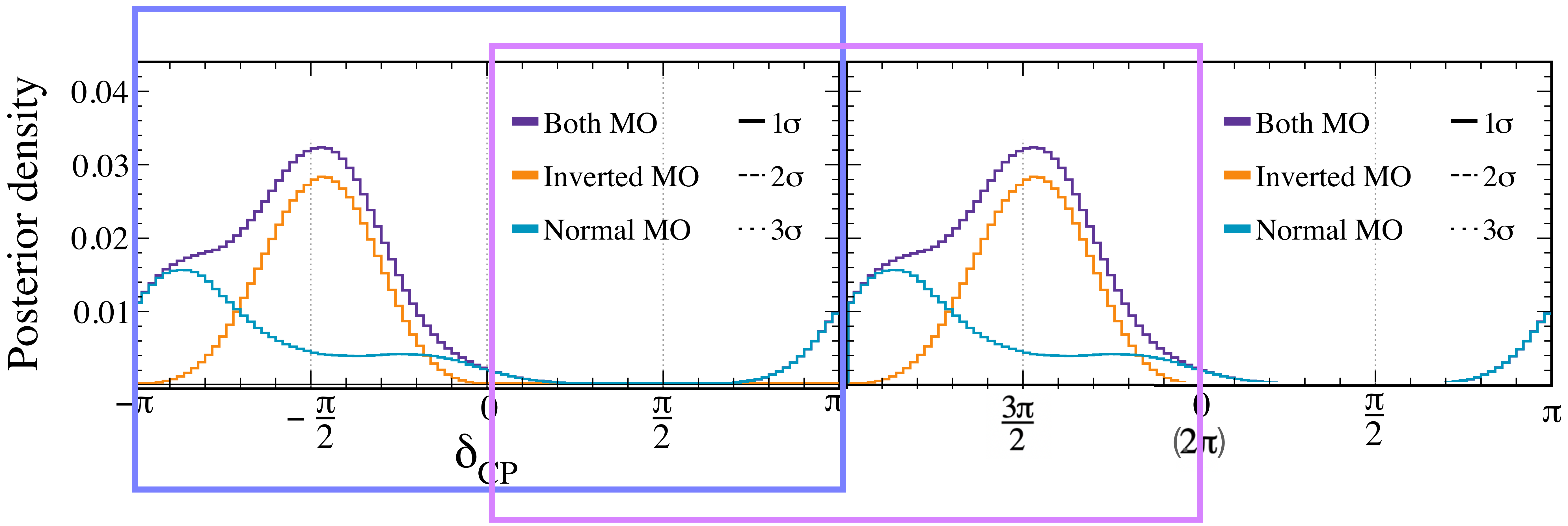
BEFORE WE START



This talk contains two sets of results based on different exposures and analyses.

✳ NOvA + T2K joint analysis based on latest published individual results (2020 state).

✳ The latest NOvA results announced this year with larger exposure and analysis changes.



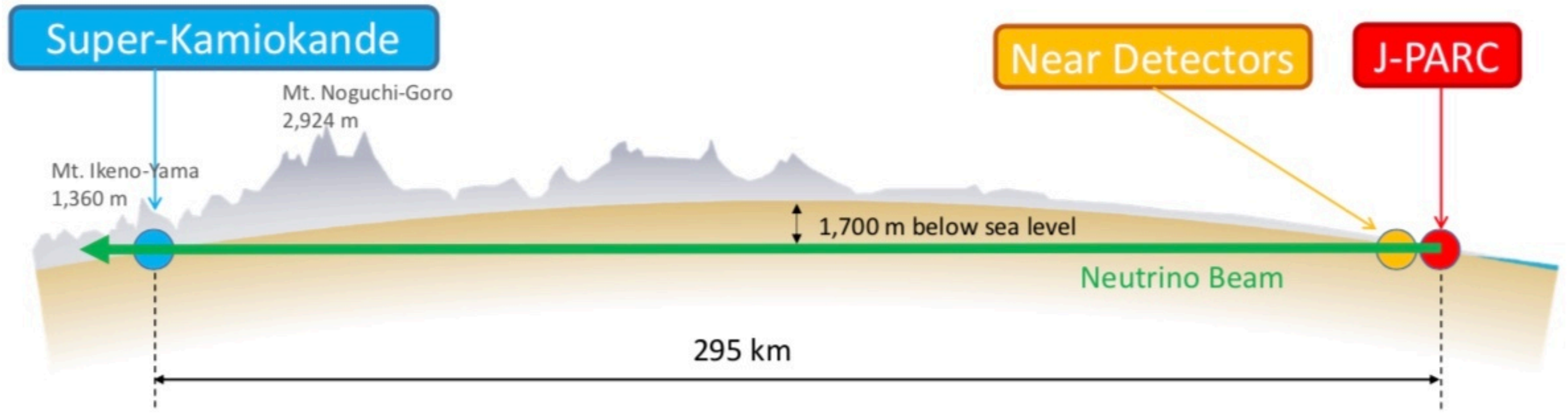
There is also a difference in δ_{CP} axis:

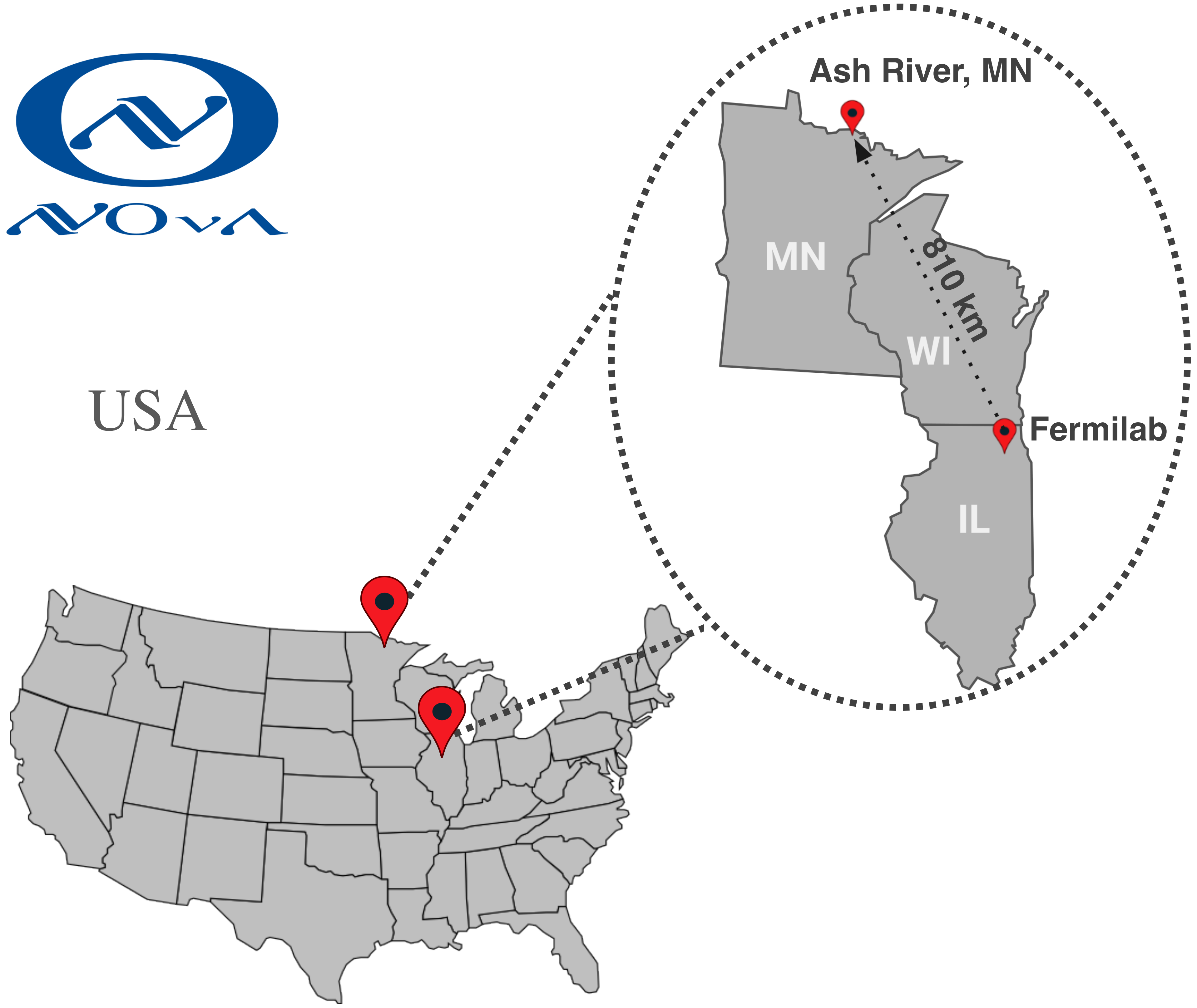
✳ NOvA + T2K uses $[-\pi; \pi]$;

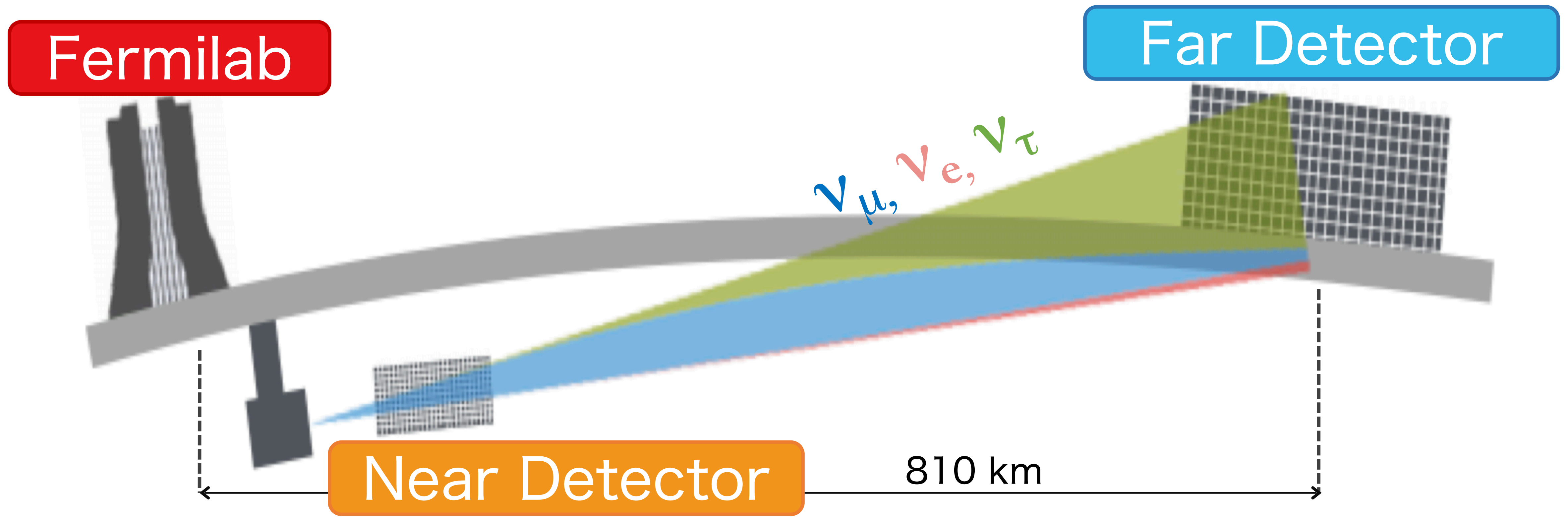
✳ NOvA uses $[0; 2\pi]$.

Part I: NOvA+T2K results

THE EXPERIMENTS

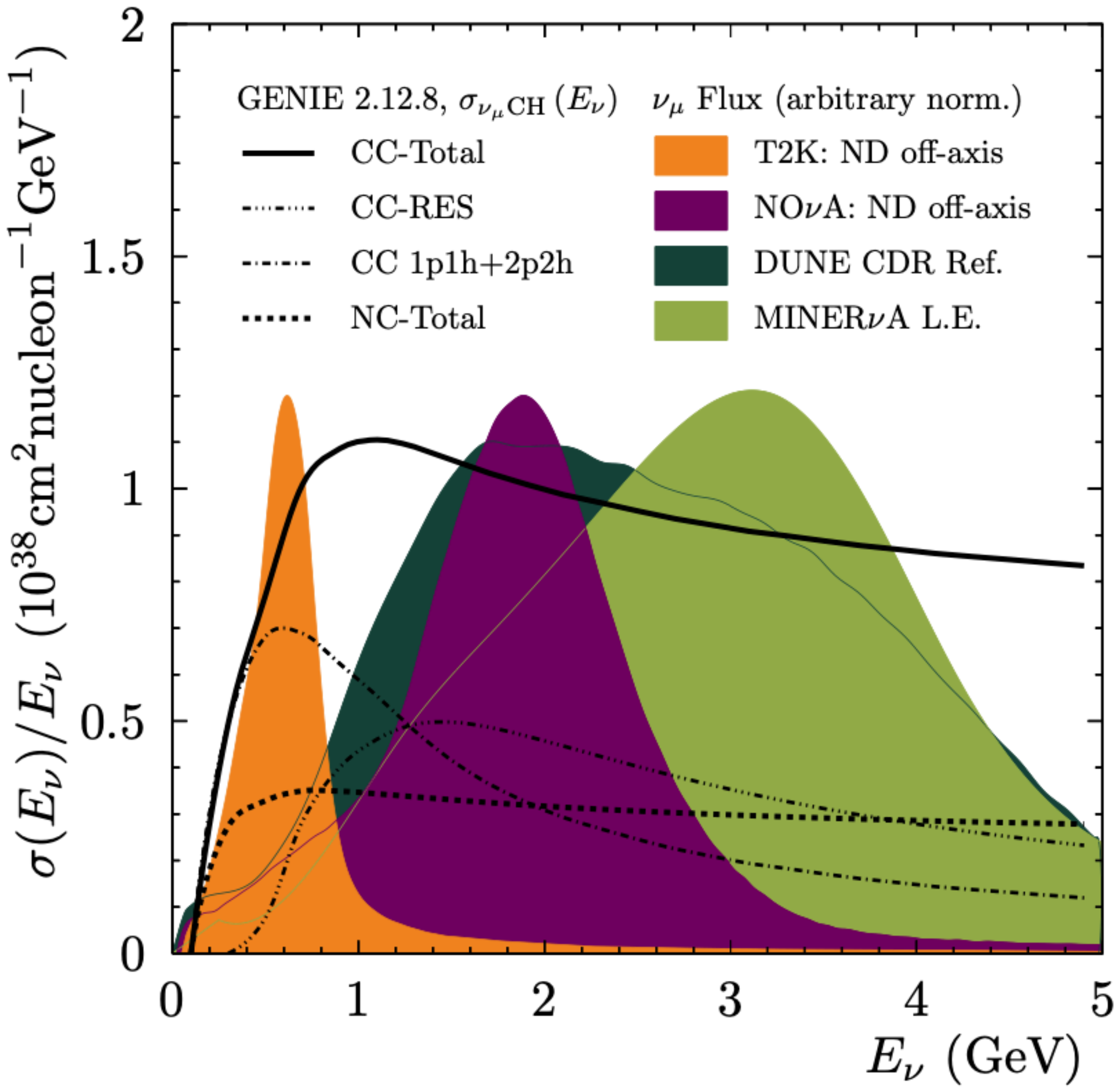






THE EXPERIMENTS

- Both experiments are located off-axis to receive a narrow-band, highly pure muon (anti-)neutrino beam:
  - T2K: beam peaks at 0.6 GeV neutrino energy,
  - NOvA: beam peaks at 2 GeV.
- The difference in neutrino beam energy leads to different neutrino interactions:
  - T2K: primarily Quasi-Elastic and 2p2h interactions,
  - NOvA: mix of Quasi-Elastic, 2p2h, Resonant and DIS interactions.
- Experiments have very different experimental approach:
  - T2K: different detector technologies for Near (magnetized plastic scintillator and gas TPC tracking detector) and Far (water Cherenkov) detectors.
  - NOvA: identical detectors are active scintillator calorimeters.

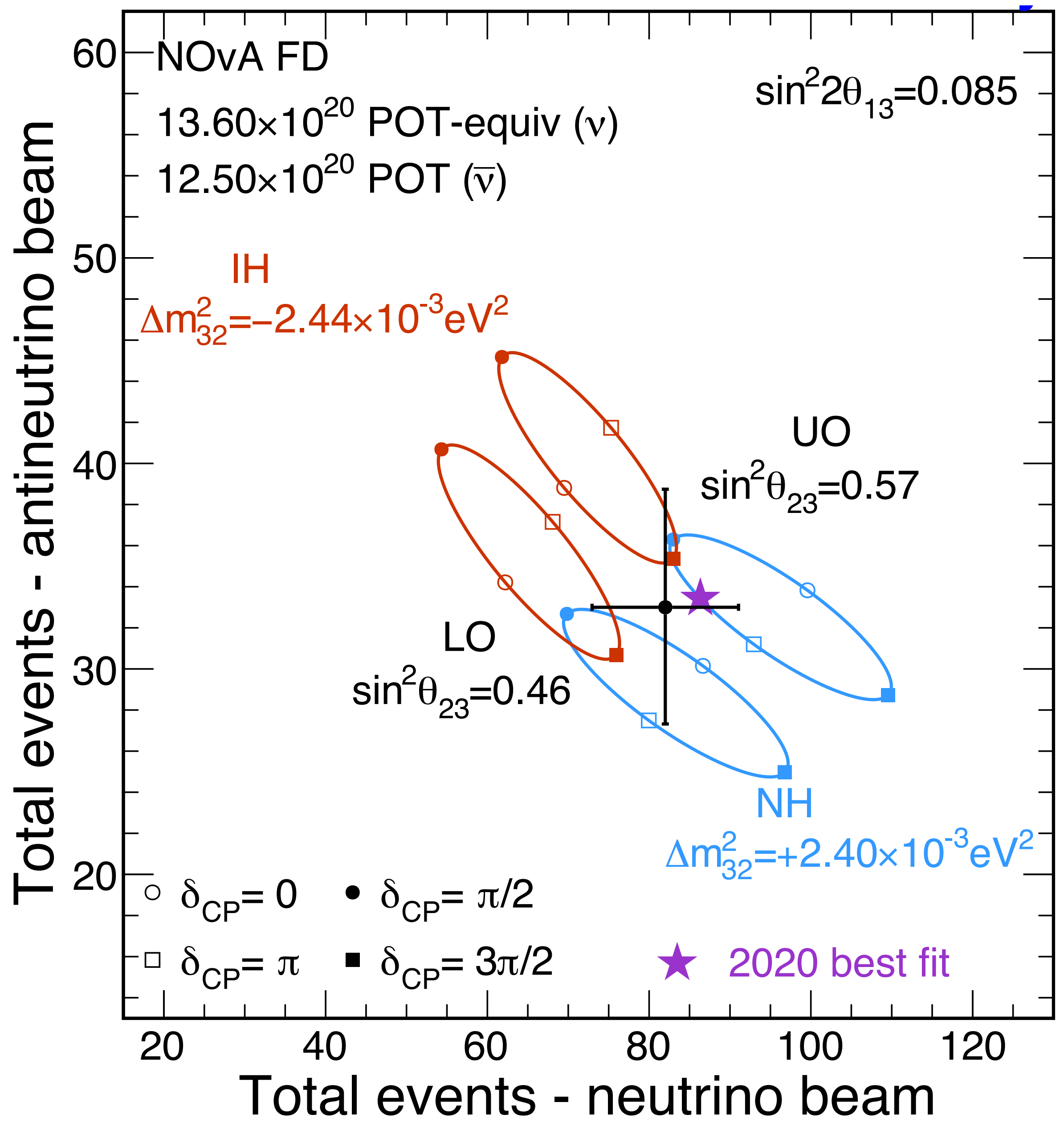


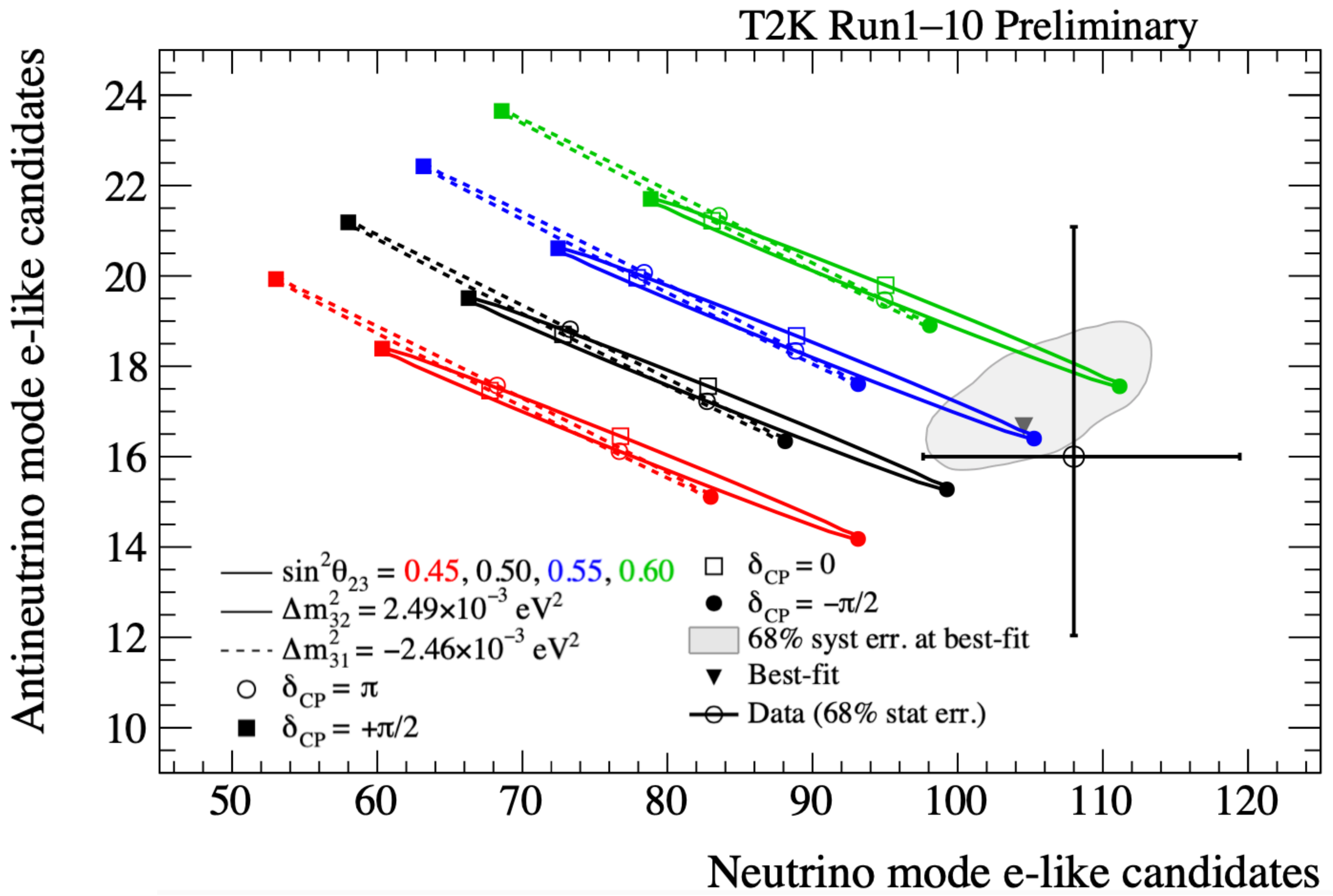
INDIVIDUAL RESULTS IN 2020

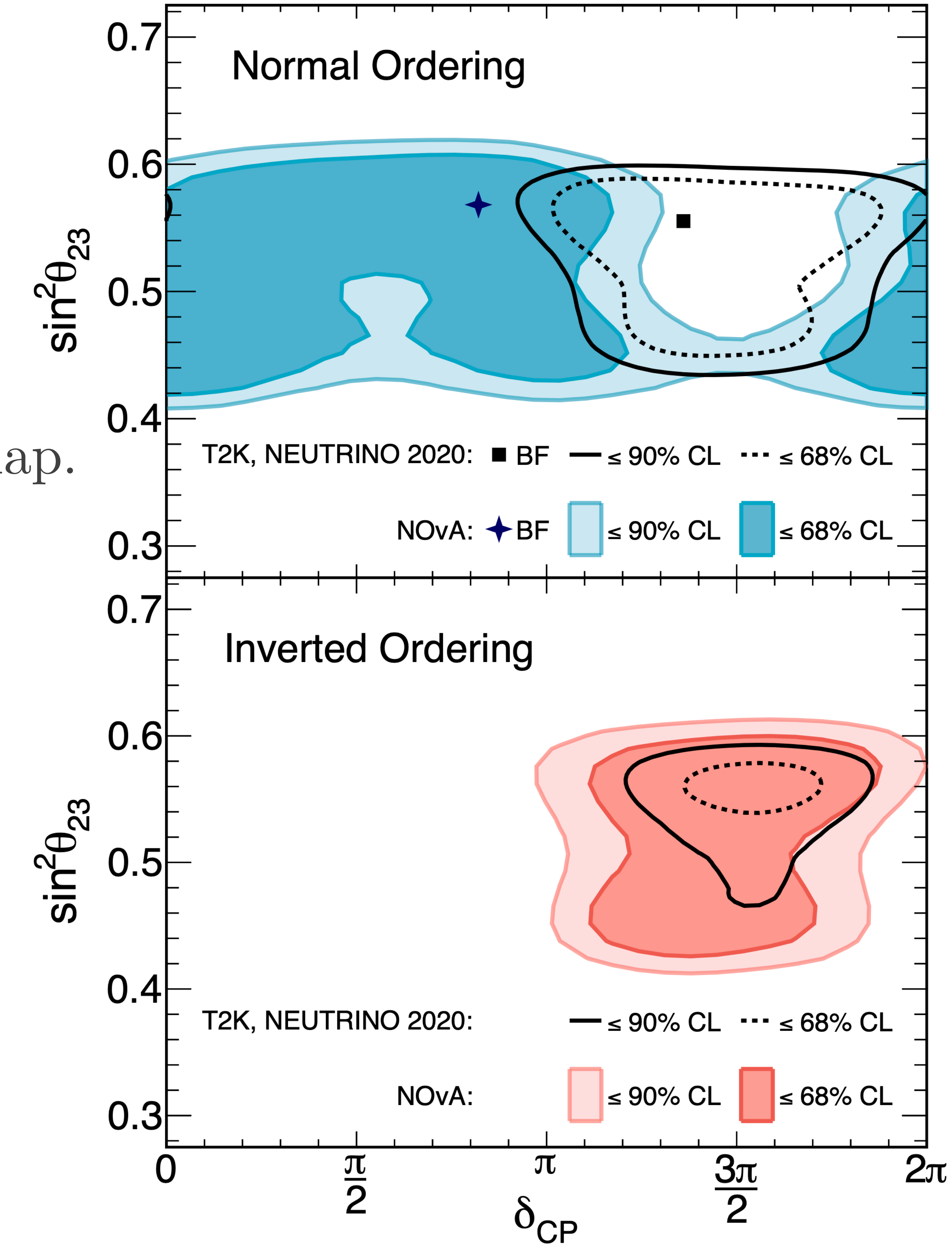
NOvA sees no asymmetry between ν's and $\bar{\nu}$'s.
- $\ast$ Disfavor NO, $\delta = 3\pi/2$ at $\sim 2\sigma$.
- $\ast$ Exclude IO, $\delta = \pi/2$ at $> 3\sigma$.

T2K sees maximum asymmetry effect.
- $\ast$ No CP violation disfavored at $>2\sigma$.
- $\ast$ Disfavour wide range of δ_{CP} values at $>3\sigma$.

As a result, different preferred values of δ_{CP} but 1σ regions have overlap.







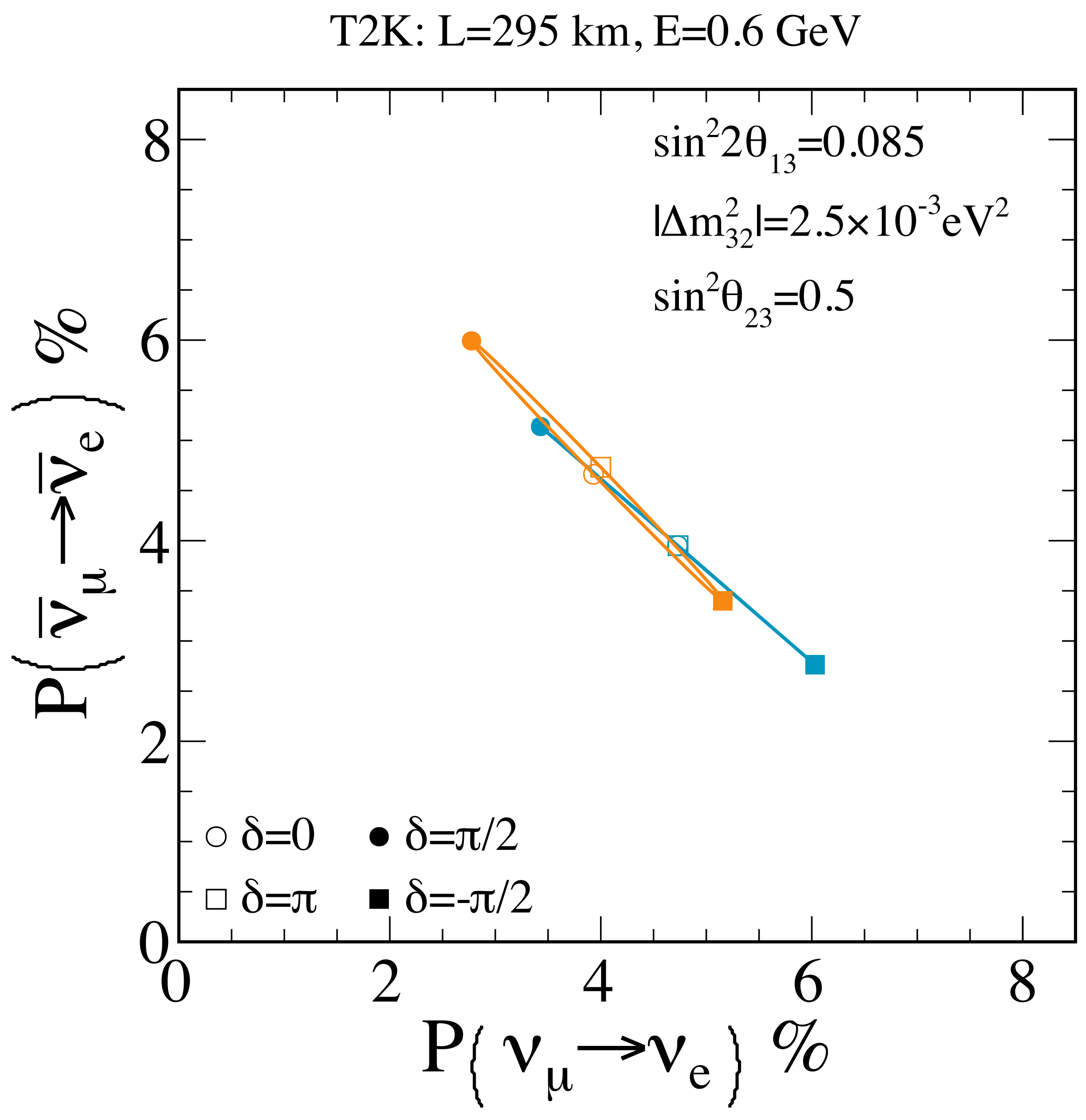
WHY JOINT ANALYSIS?

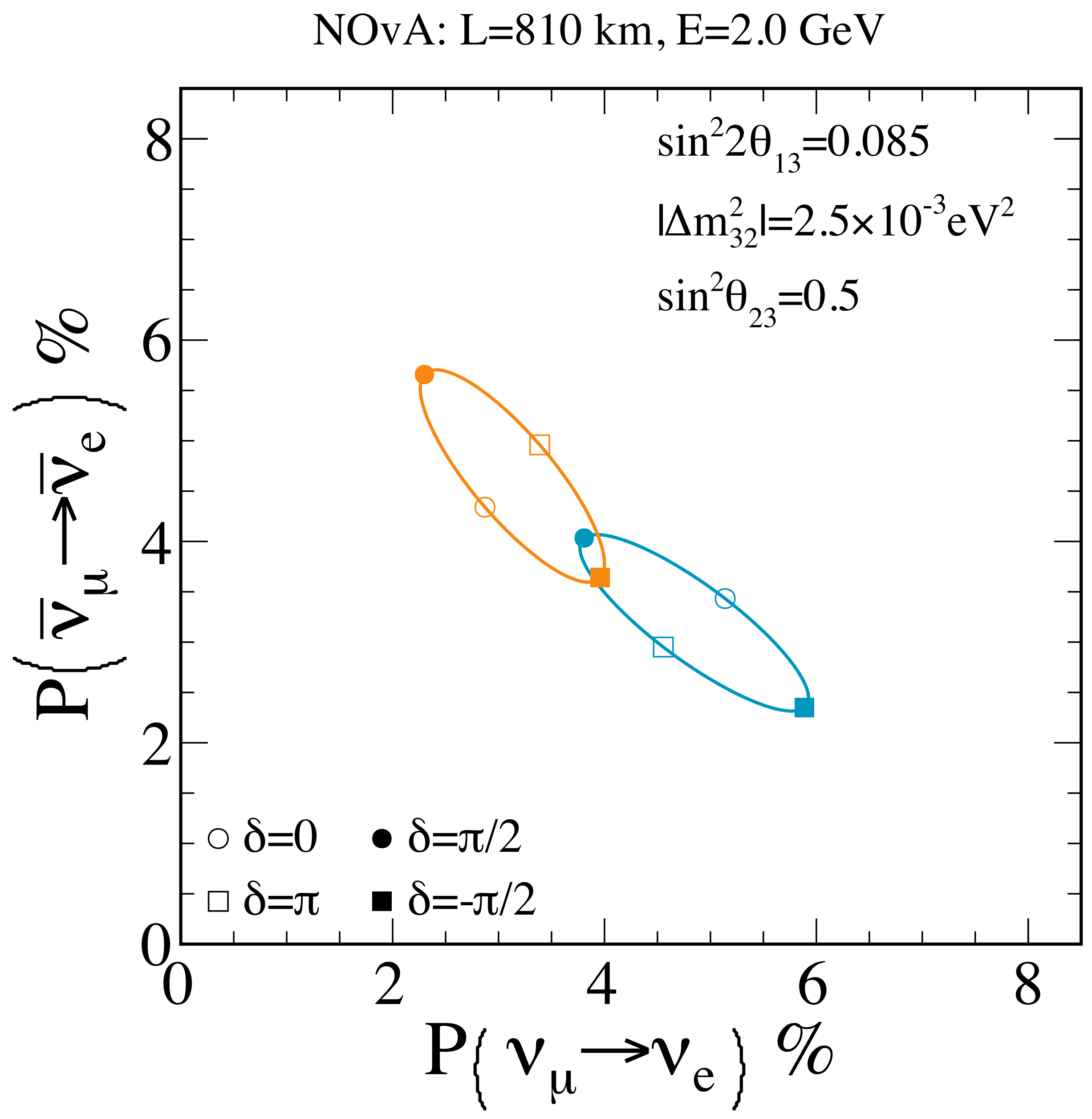
The complementarity between the experiments provides the power to break degeneracies.

- ✳ T2K measurements isolate impact of CP violation while NOvA has significant sensitivity to mass ordering.

How is it different in comparison with global fits:

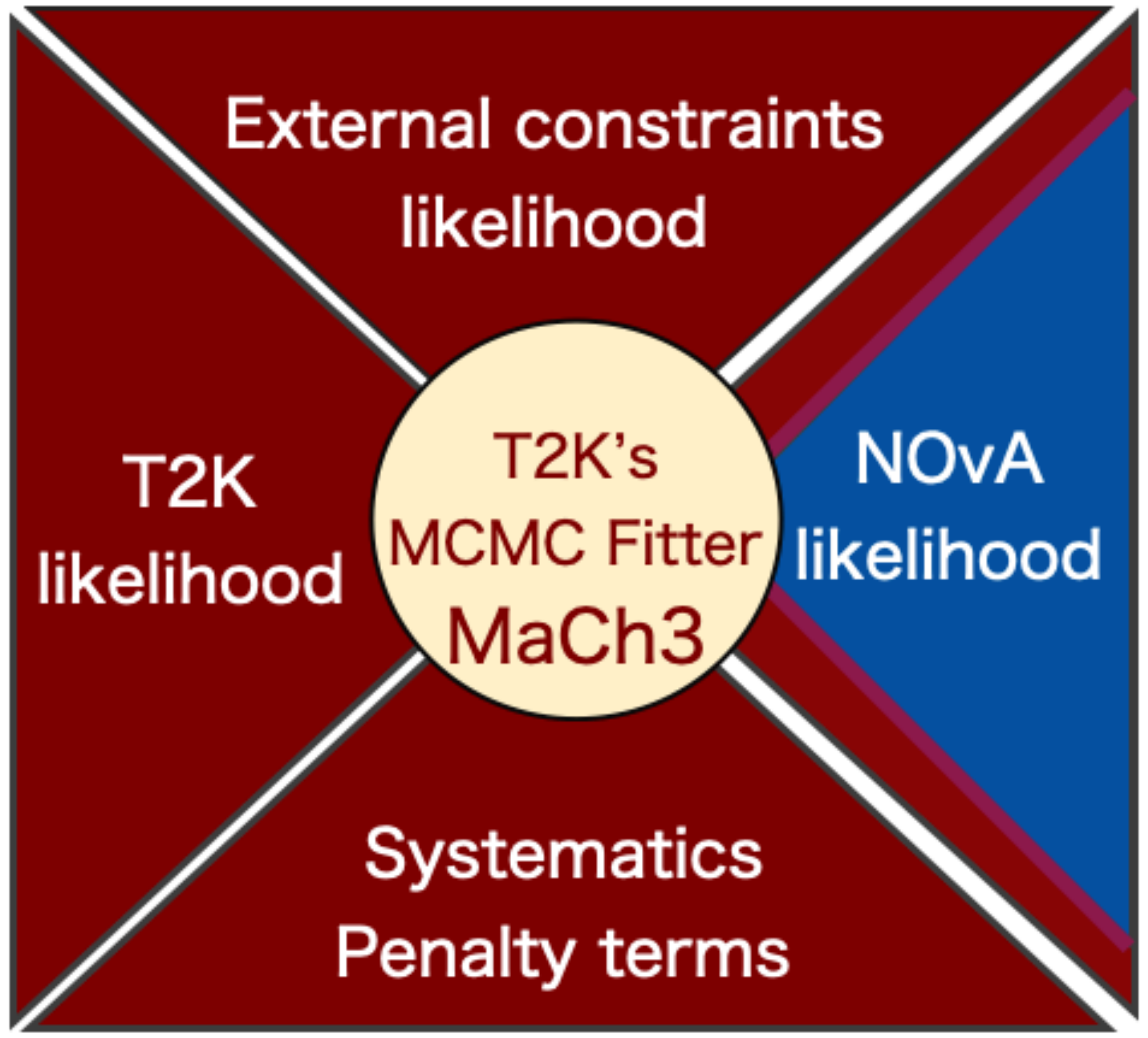
- ✳ Full implementation of:
  - ✳ energy reconstruction and detector response;
  - ✳ detailed likelihood from each experiment;
  - ✳ consistent statistical inference across the full dimensionality.
- ✳ In-depth review of:
  - ✳ models, systematic uncertainties and possible correlations.
  - ✳ different analysis approaches driven by contrasting detector designs.
    - ✳ As a by-product: cross-check and review of each other analyses.

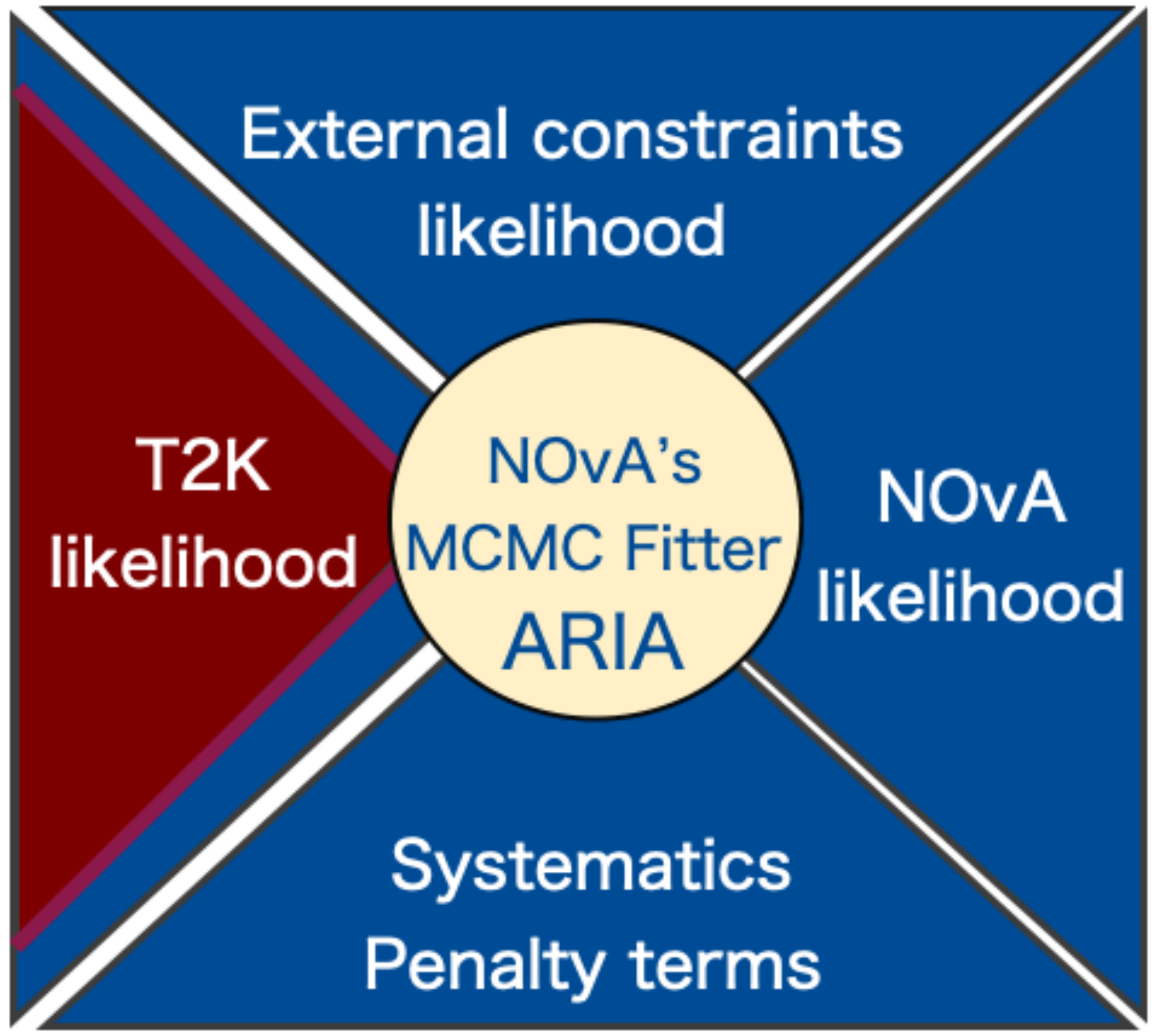




TECHNICAL IMPLEMENTATION

- The joint-fit is constructed using:
  - Poisson likelihood from each experiment;
  - penalty terms from the systematics pull;
  - external constraints on θ_{13}, θ_{12}, Δm^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.
  - Full access to Monte Carlo and data.
  - Safe alternative with full sensitivity to the shared events per bin + systematics details.
  - Containers help to avoid making changes to each experiment's software to resolve dependencies.

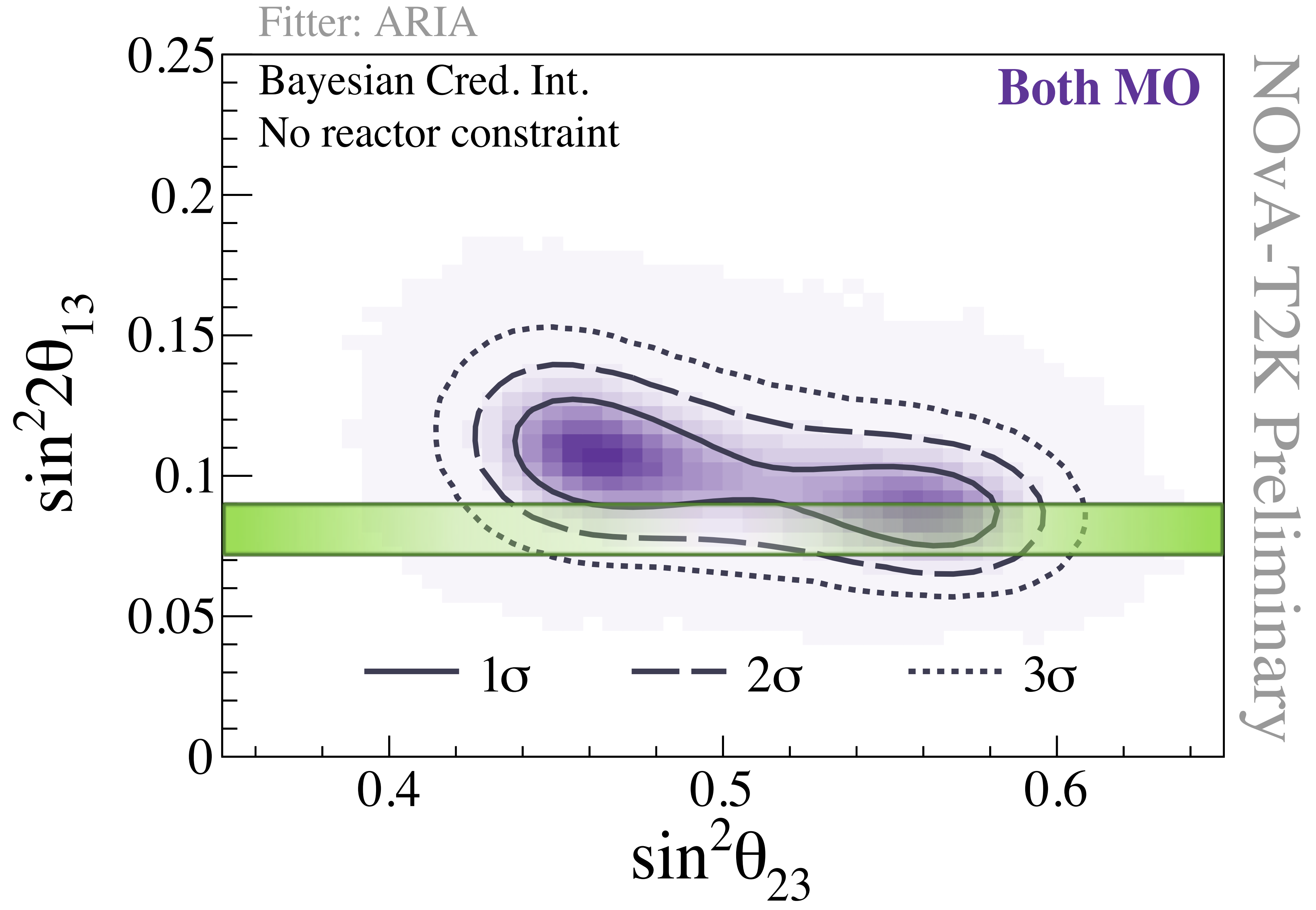


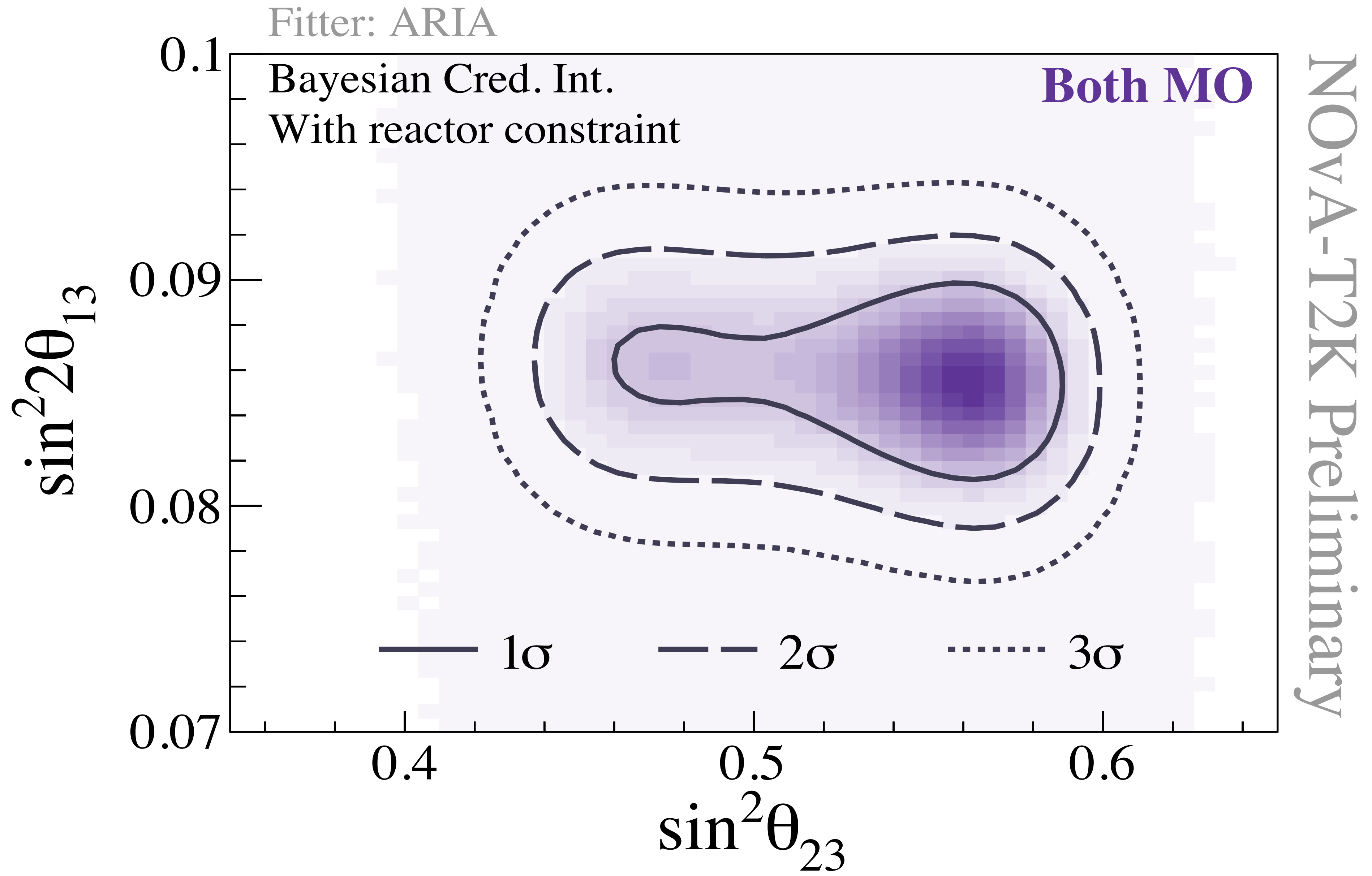


FIT RESULTS: θ_{23} & θ_{13}

- ✶ Without any external constraint from reactor experiments, long-baseline measurements have a degeneracy in $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$ parameters.
- ✶ Using the average constraint on $\sin^2 2\theta_{13} = 0.085 \pm 0.0027$ [PDG 2020], restricts us to a narrow posterior in θ_{13} and lifts this degeneracy.
- ✶ Modest preference for lower octant from the joint-analysis.
- ✶ This preference shifts to a small preference for the upper octant when the reactor constraint on θ_{13} is applied.

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

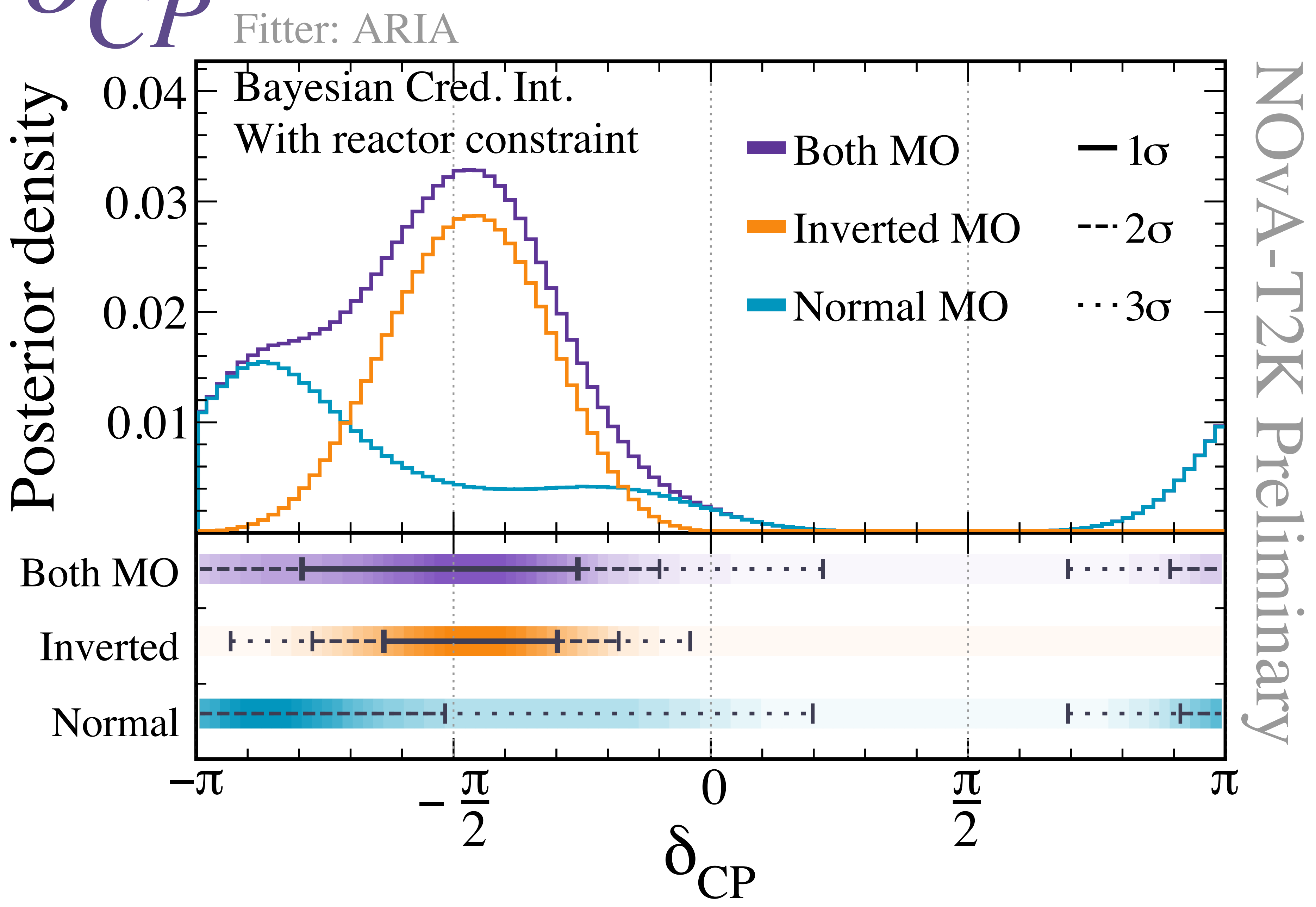


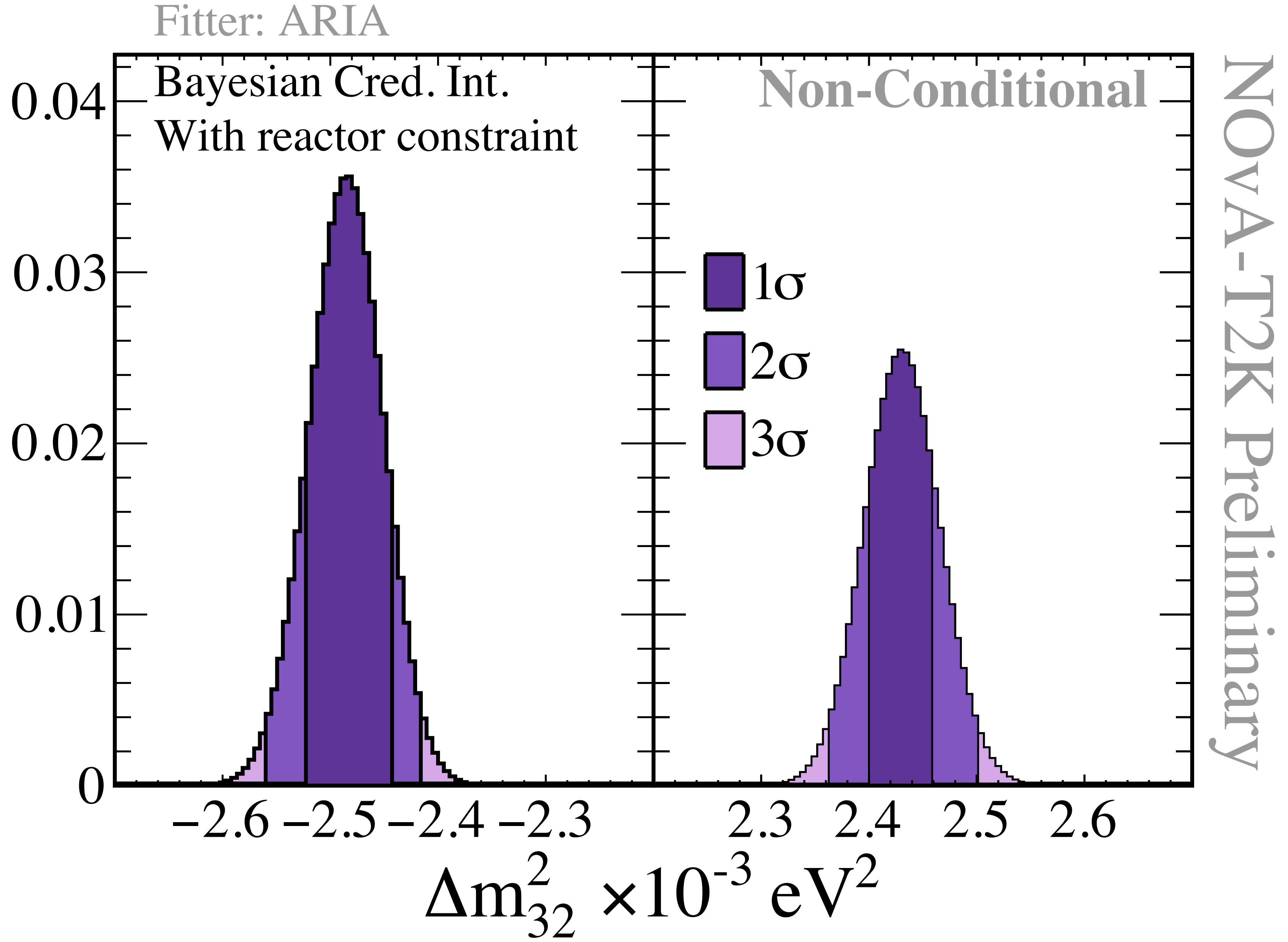


FIT RESULTS: MASS ORDERING AND δ_{CP}

- ✳ For both mass orderings, $\delta_{CP} = \pi/2$ lies outside 3σ credible interval.
- ✳ Normal Ordering allows for a broad range of permissible δ_{CP}.
- ✳ For the Inverted Ordering, CP conserving values of δ_{CP} $(0, \pi)$ lie outside the 3σ credible interval.
- ✳ Comparing the posterior density in each mass ordering, it is evident that the NOvA-T2K joint fit has a modest preference for the Inverted Ordering.

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

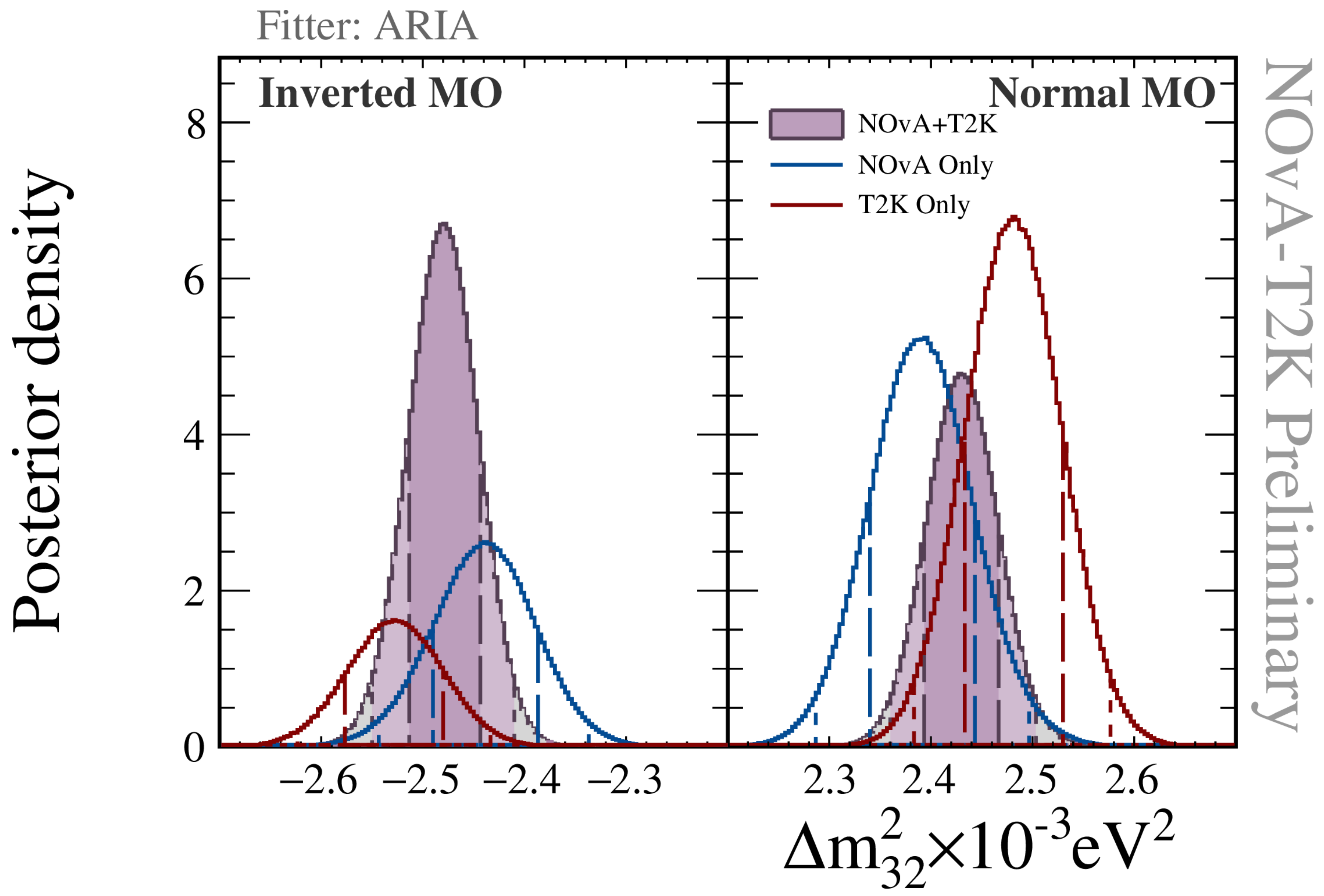




COMPARISONS WITH NOvA-ONLY AND T2K-ONLY

- The 1D posterior in Δm^2_{32} highlights the switch in the mass ordering preference when NOvA and T2K are combined.

- The joint-fit enhances the precision of Δm^2_{32} over individual experiments.

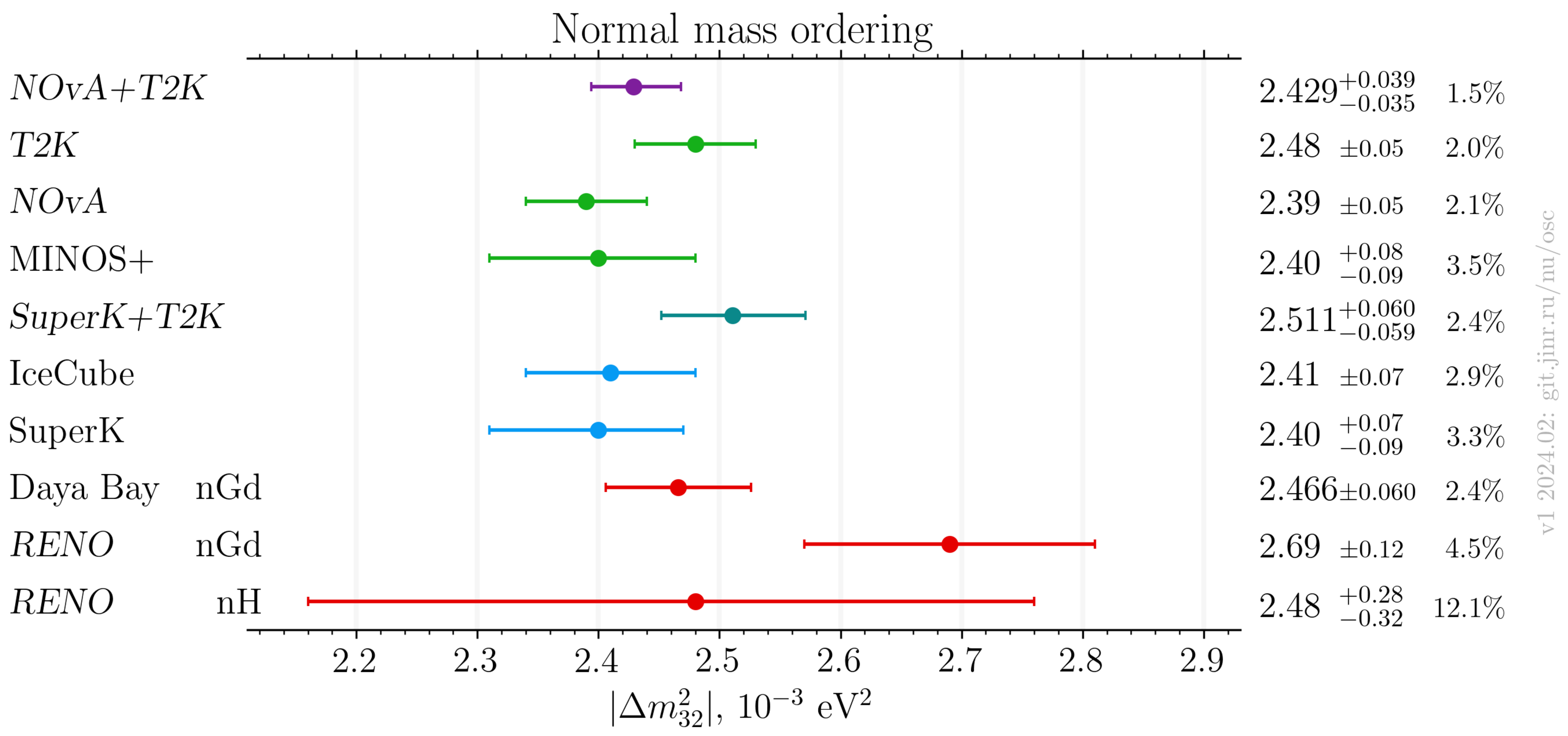


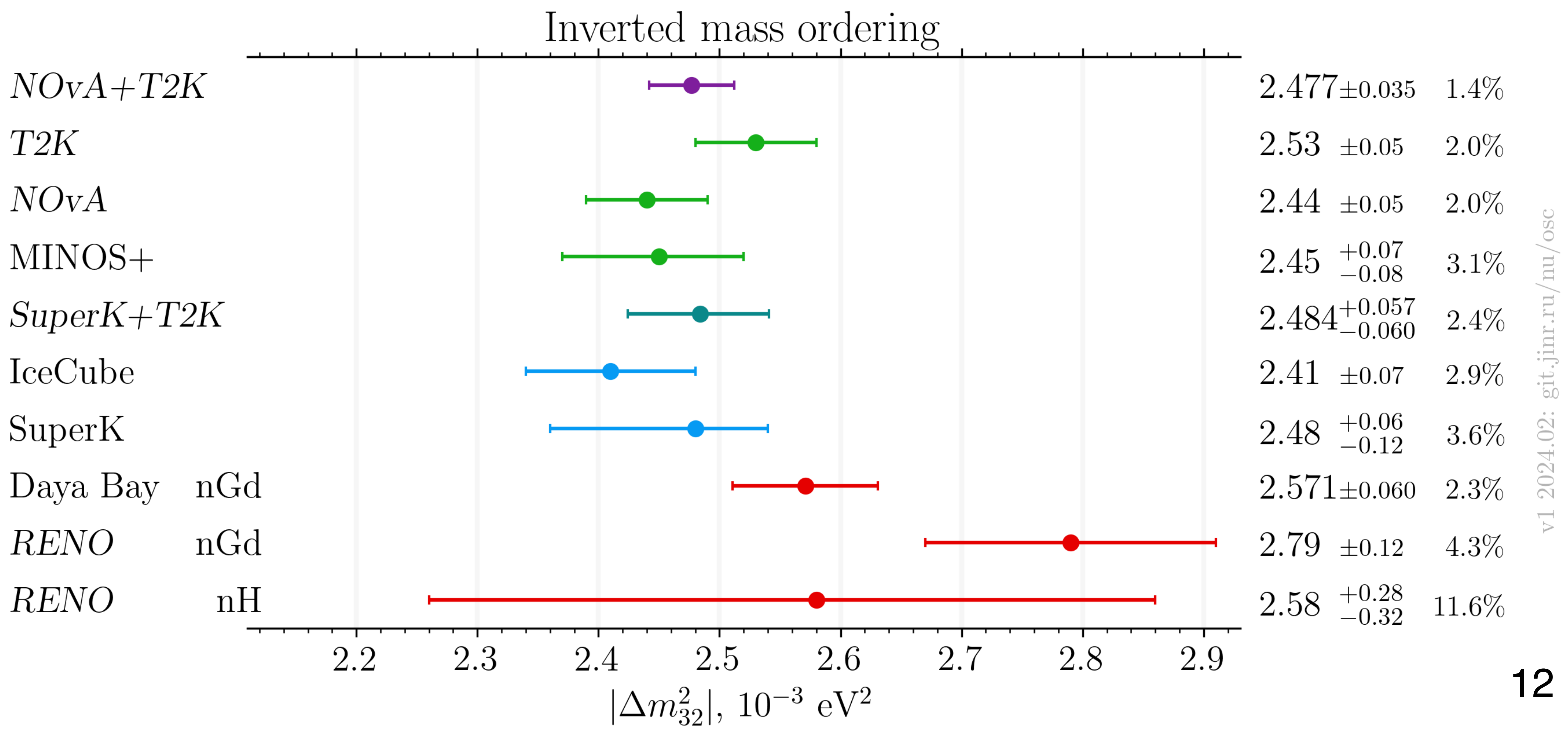
	NOvA only	T2K only	NOvA+T2K
Bayes factor	2.07 Normal/Inverted ~67% : ~33% posterior	4.24 Normal/Inverted ~81% : ~19% posterior	1.36 Inverted/Normal ~58% : ~42% posterior

COMPARISONS WITH OTHER EXPERIMENTS

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

- ✳ Same level of precision with and without reactor constraint.
- ✳ First oscillation parameter measured $<2\%$ precision.

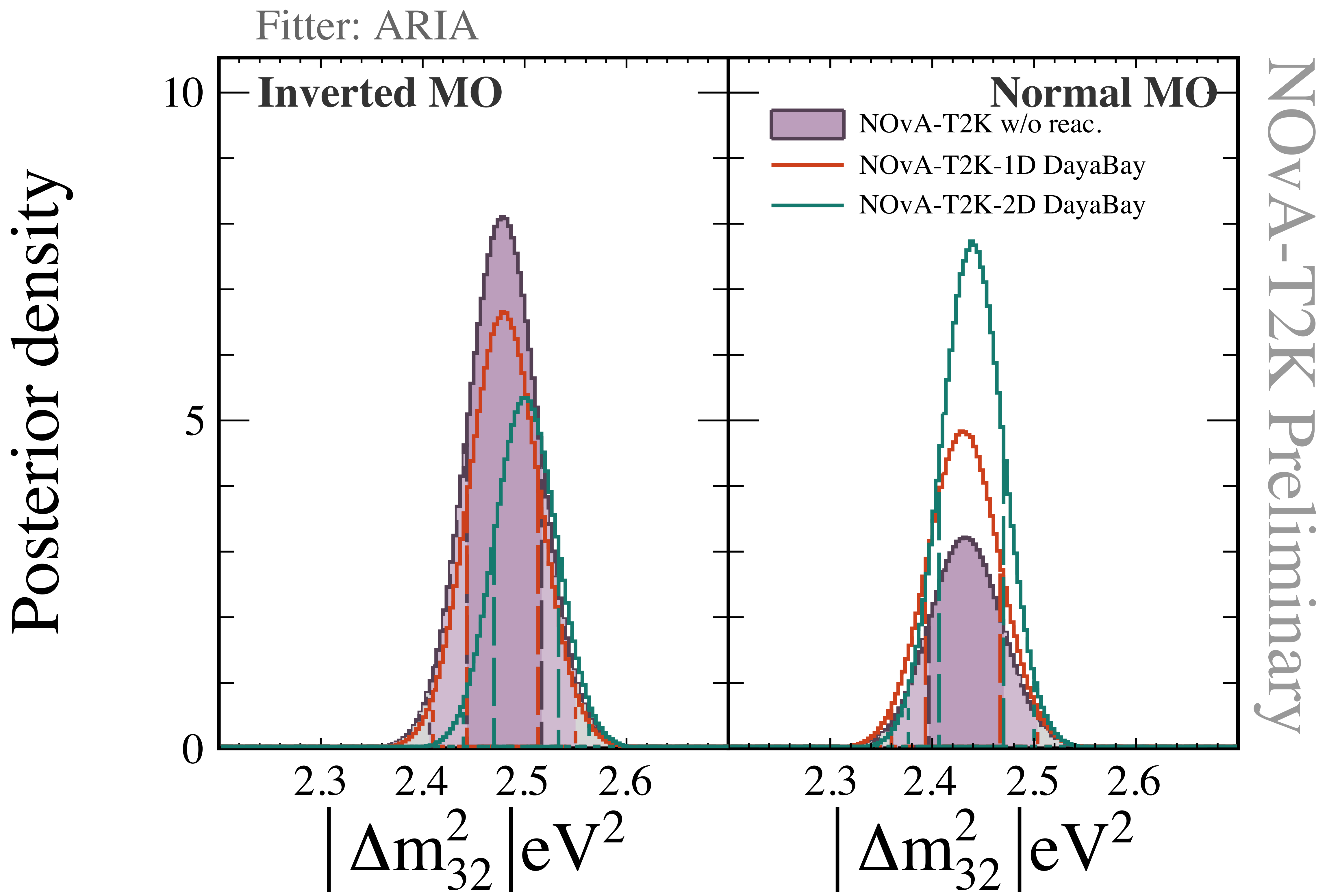




NOvA+T2K+DAYA BAY

* Including the Δm^2_{32} constraint from the Daya Bay, reverse 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

TAKEAWAYS

- ✳ First joint analysis of the NOvA and T2K experiments was performed.
- ✳ Strong constraint on Δm^2_{32}.
- ✳ Weakly prefer IO or NO depending on which reactor constraint is applied.
- ✳ Strongly favour CP violation in IO.
- ✳ Developed a firm foundation for further NOvA+T2K analyses with more statistics.
  - ✳ Results with more data (presumably x2 more than in 2020) at the end of data-taking;
  - ✳ In general can do much more: joint sterile, NSI, cross-section measurement analyses etc.
  - ✳ Further steps are under discussion by both collaborations.

Part II: NOvA 2024 results

THE NOvA EXPERIMENT

Experiment goals:

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

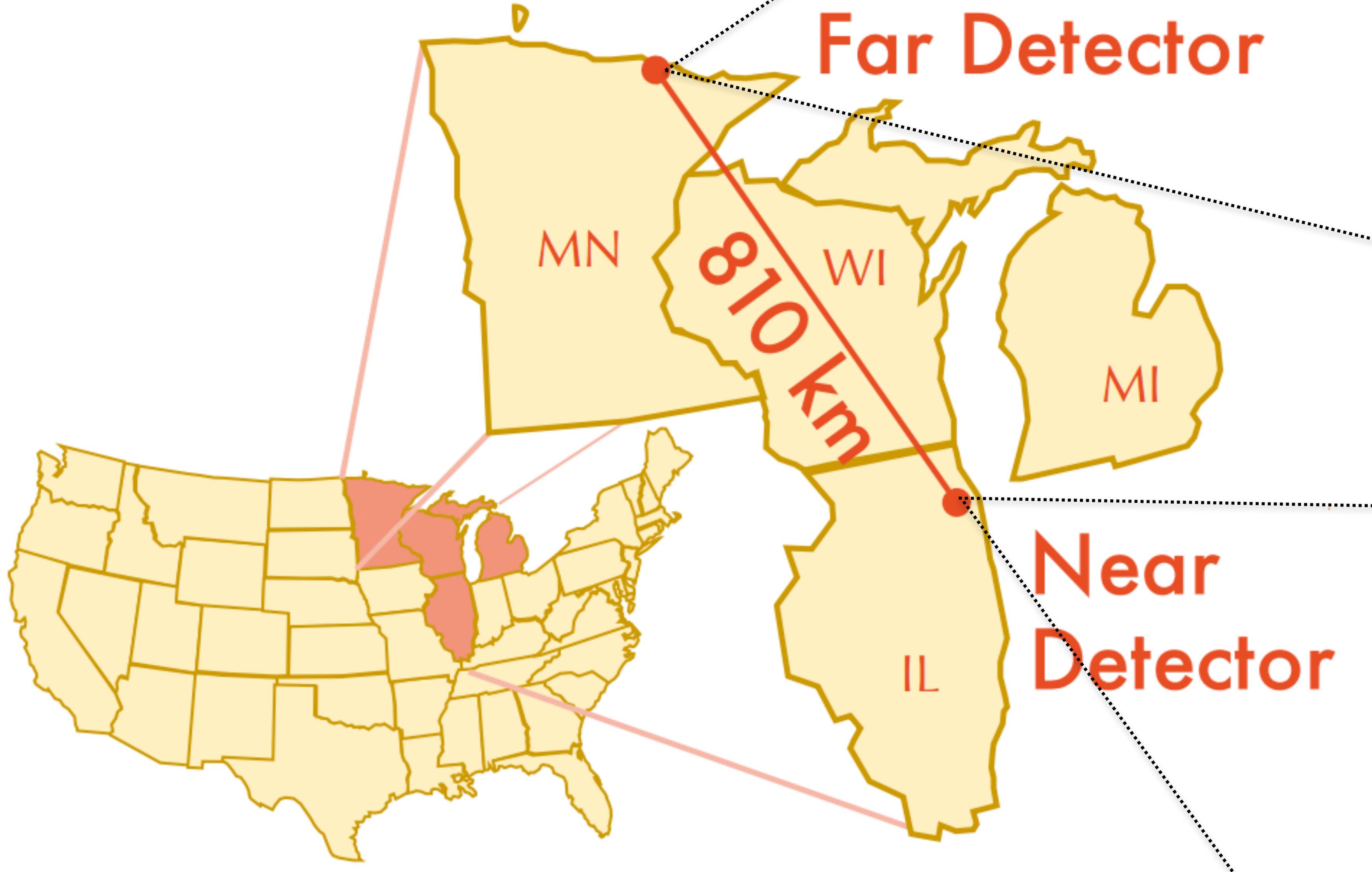
- ✳ Precise measurement of Δm^2_{32}
- ✳ Mixing angle θ_{23}

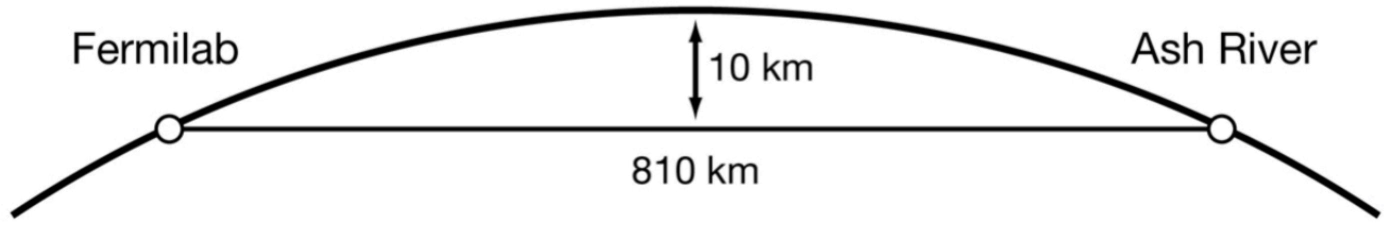
Using $\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$

- ✳ Neutrino mass hierarchy
- ✳ CP violating phase
- ✳ Mixing angle θ_{23}

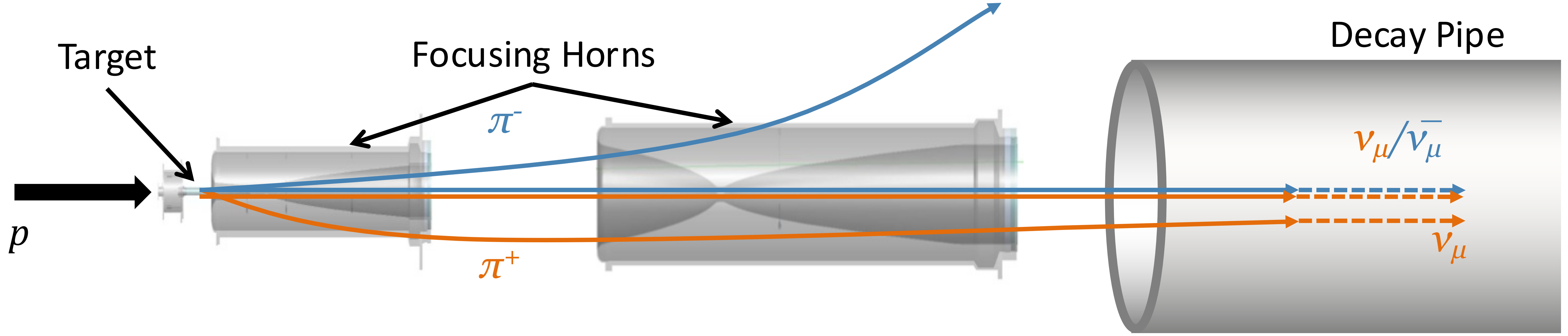
Long-baseline,
beam from Fermilab (USA),
two detectors sit at
14 mrad off-axis

The NuMI Off-Axis ν_e Appearance Experiment

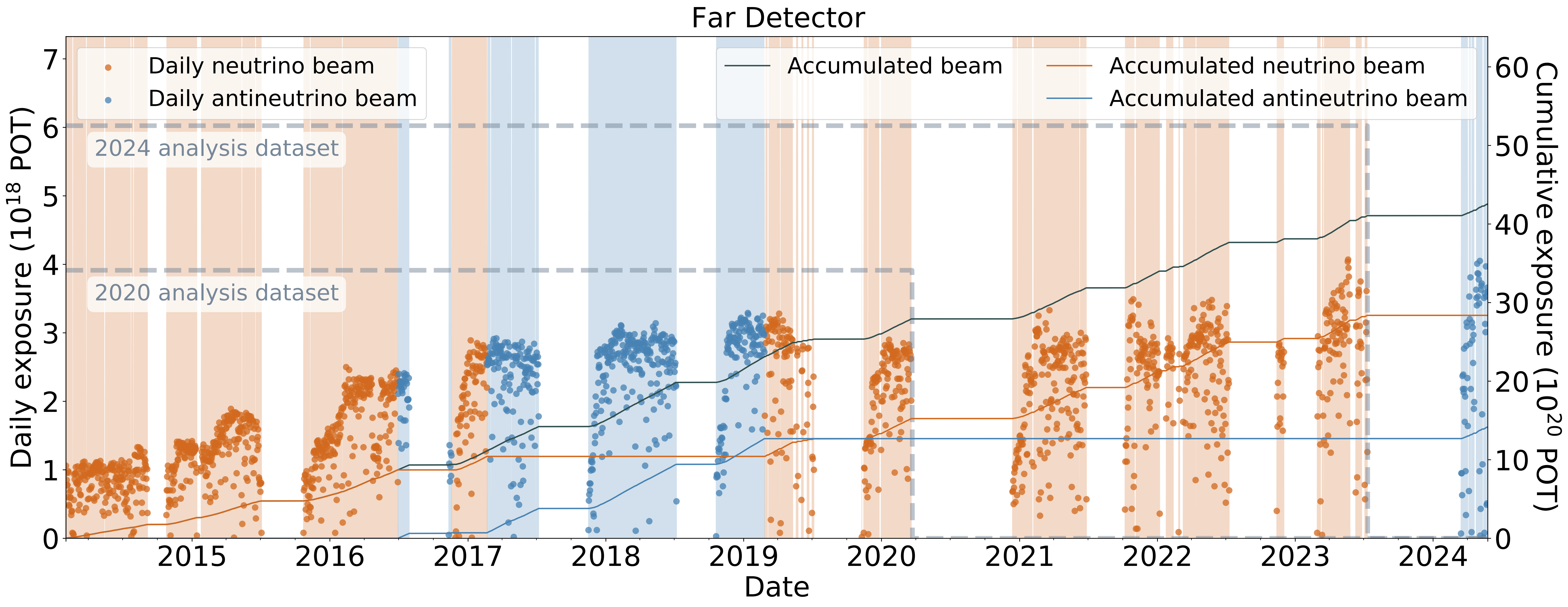




NEUTRINO BEAM



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



$+96\%$ to ν exposure:

$13.6 \times 10^{20} \rightarrow 26.61 \times 10^{20}$

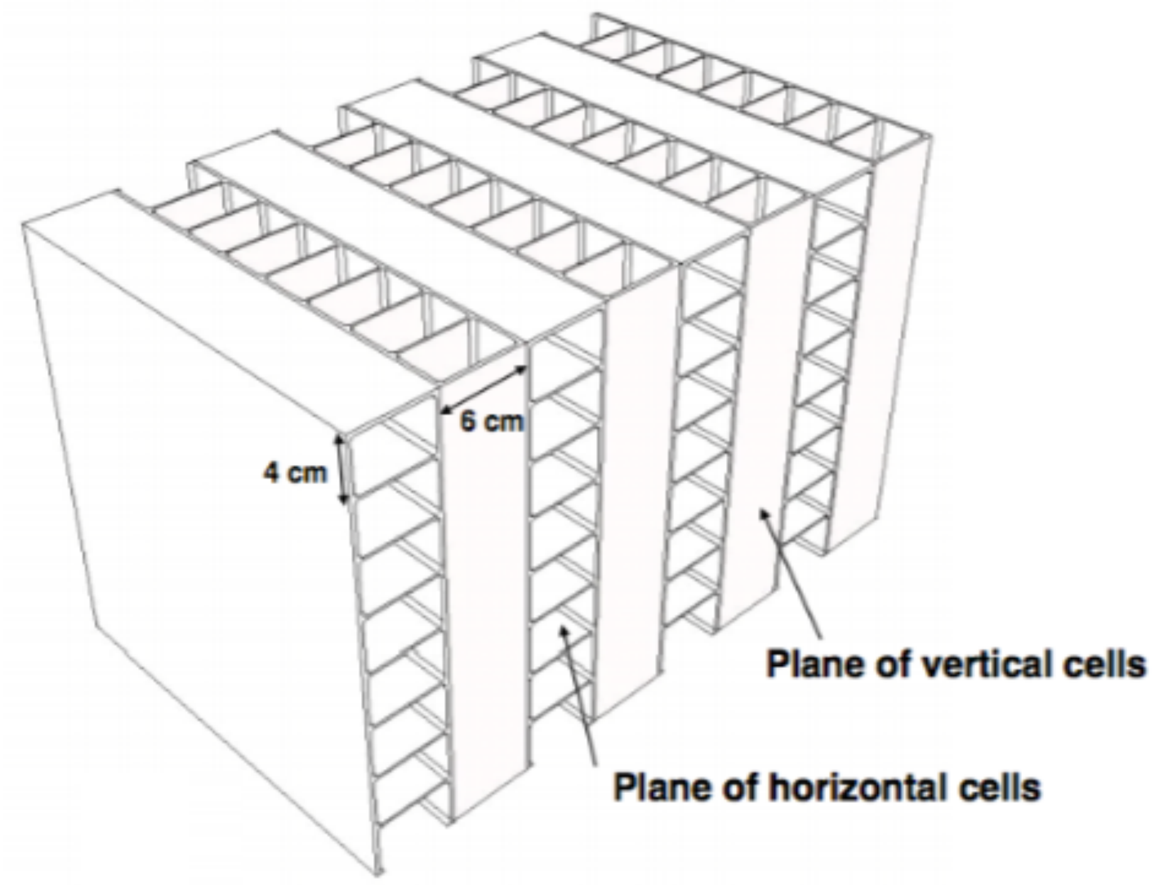
$(2020 \rightarrow 2024)$

26.61×10^{20} POT neutrino beam

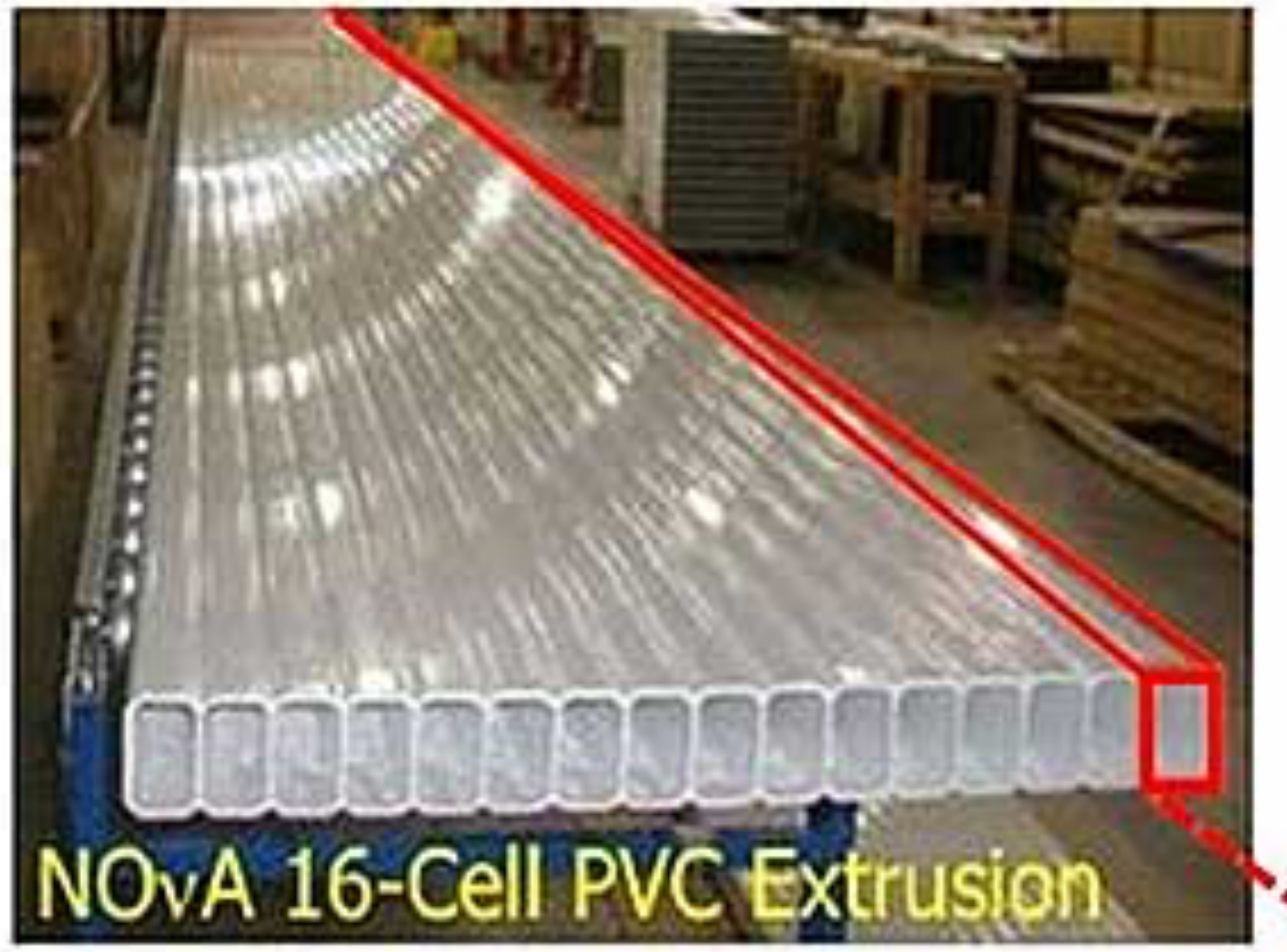
$+$

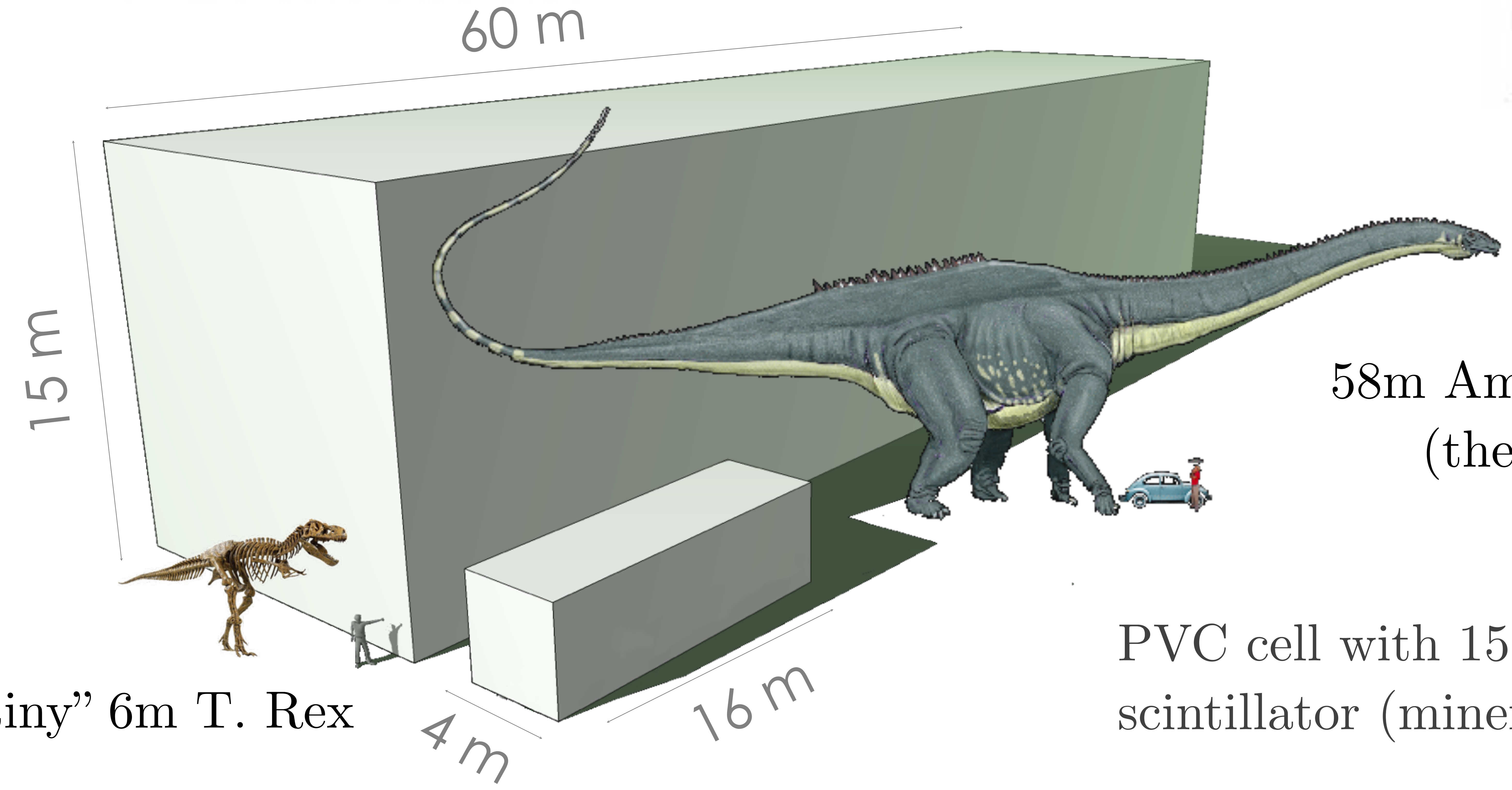
12.5×10^{20} POT antineutrino beam

NOvA DETECTORS



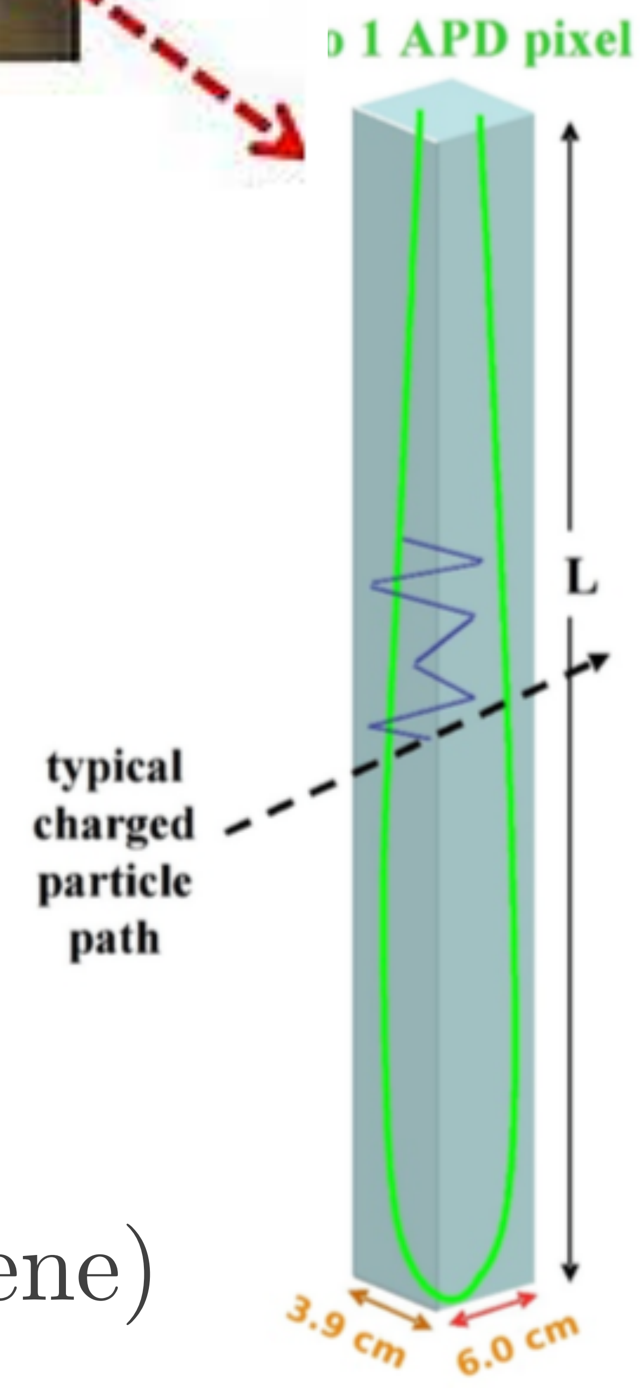
FD: 344 064 cells
ND: 20 192 cells





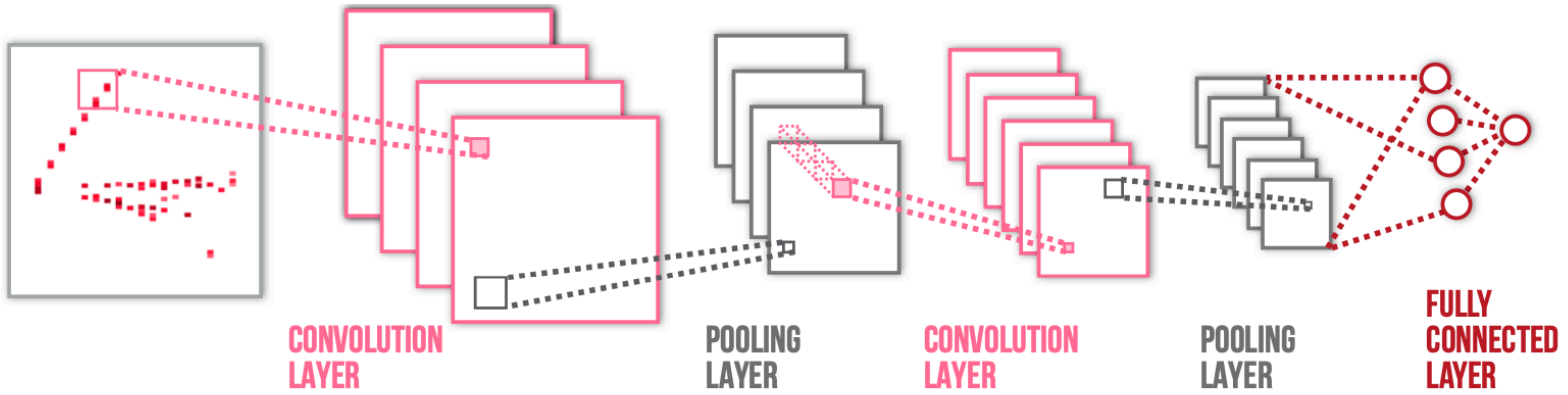
58m Amphicoelias fragillimus
(the largest estimate)

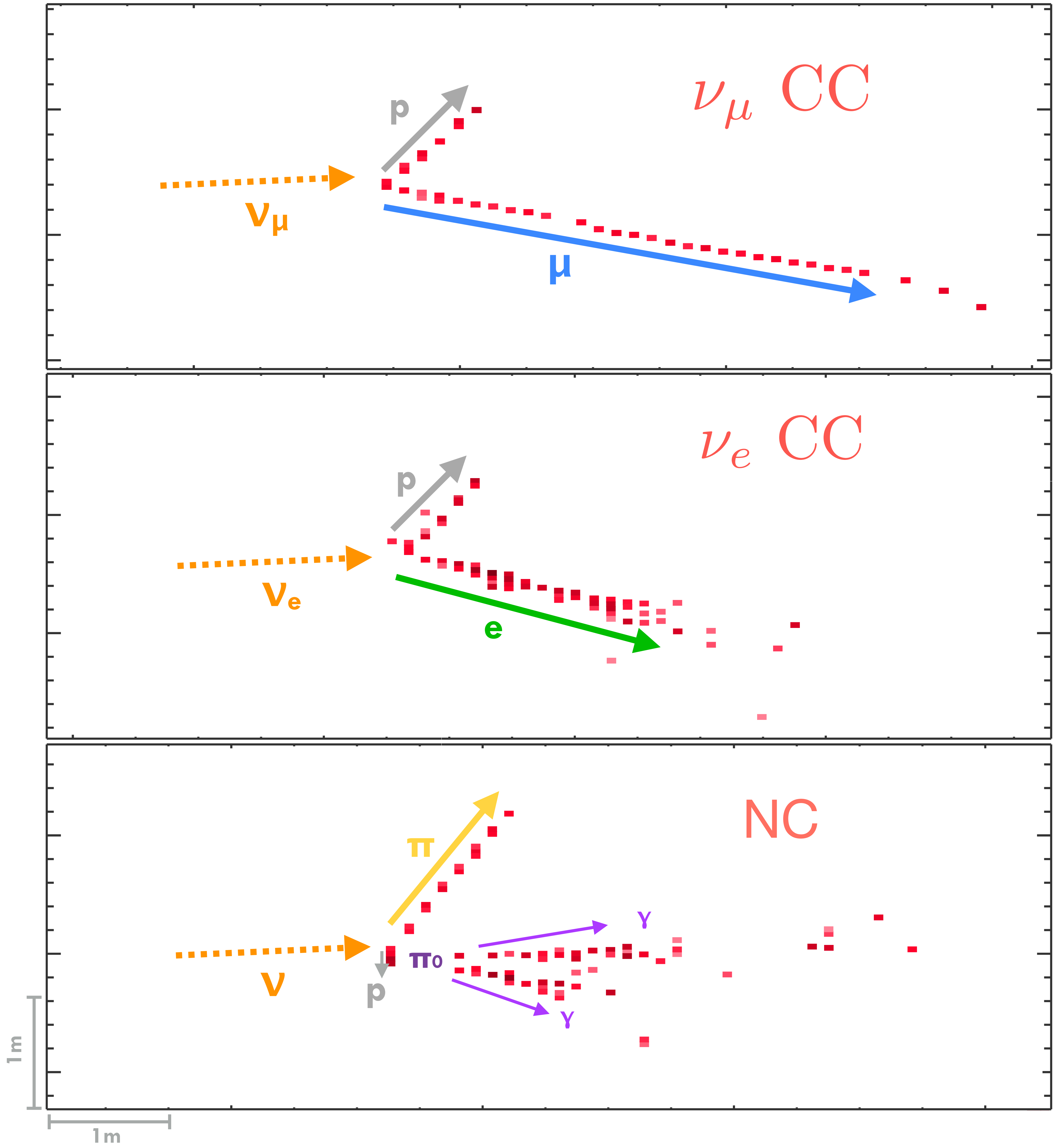
"tiny" 6m T. Rex



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

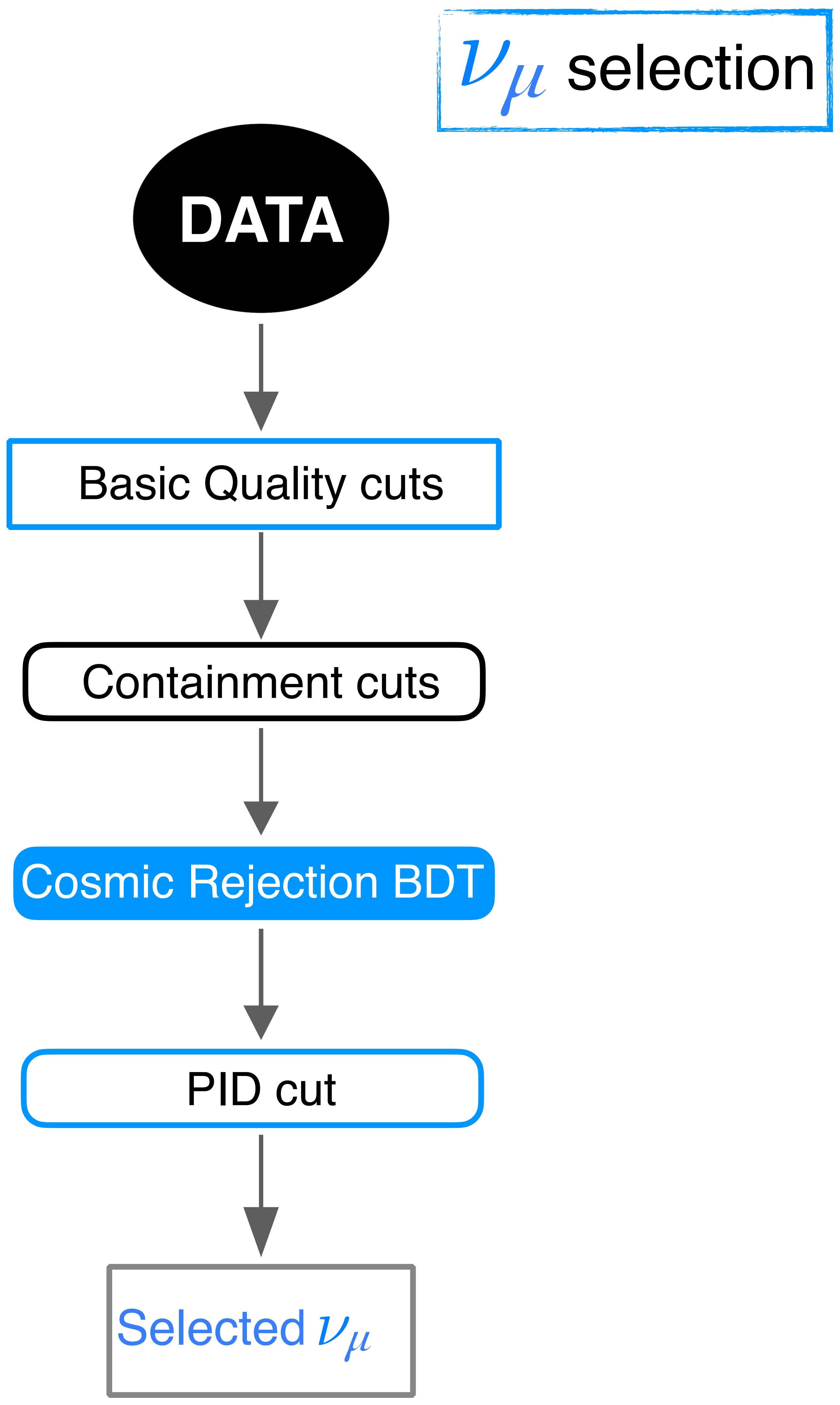
EVENT CLASSIFIER

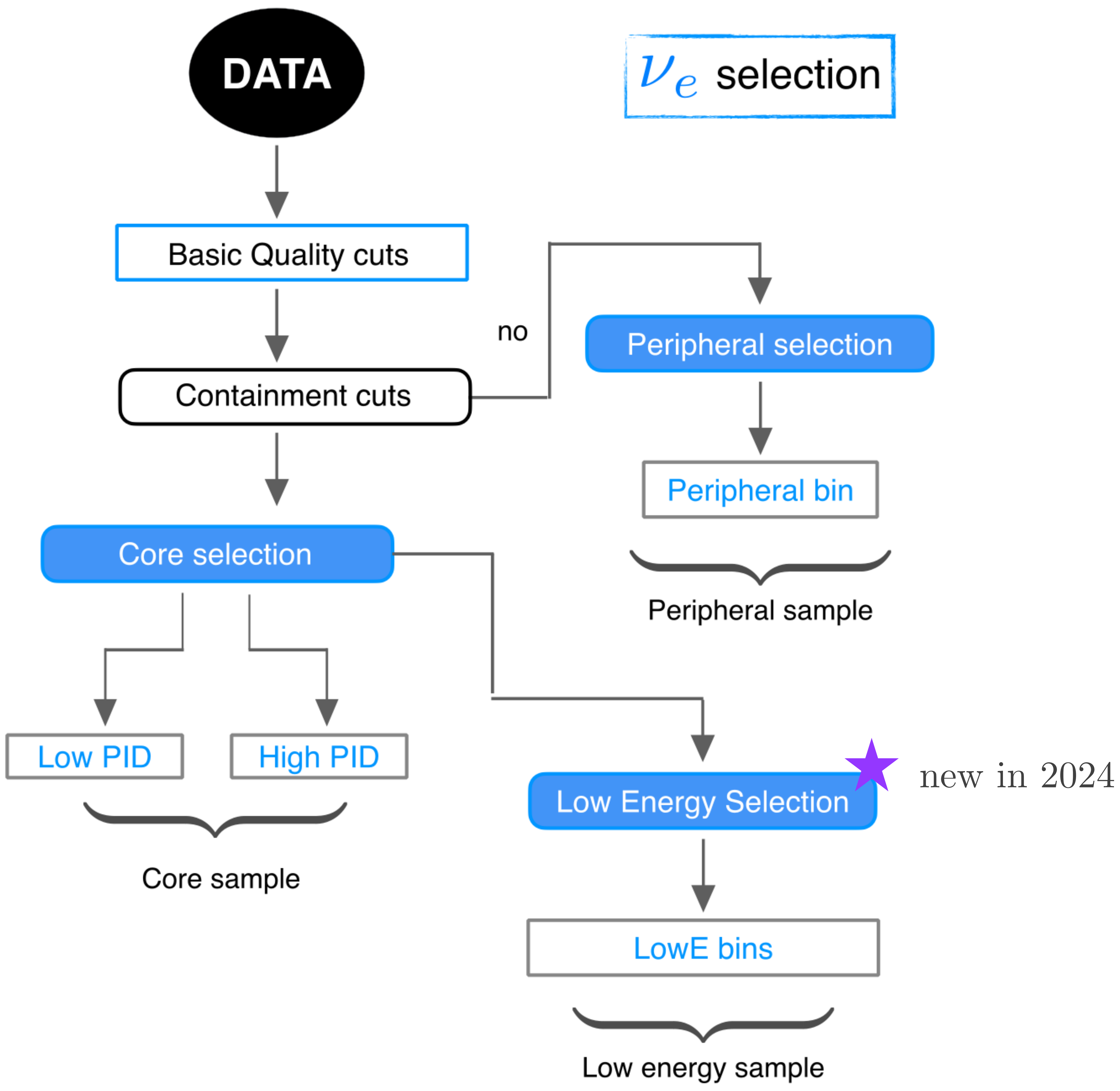




- ✳ We use convolution neural network called CVN (Convolutional Visual Network).
- ✳ Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- ✳ Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ , NC and cosmic.

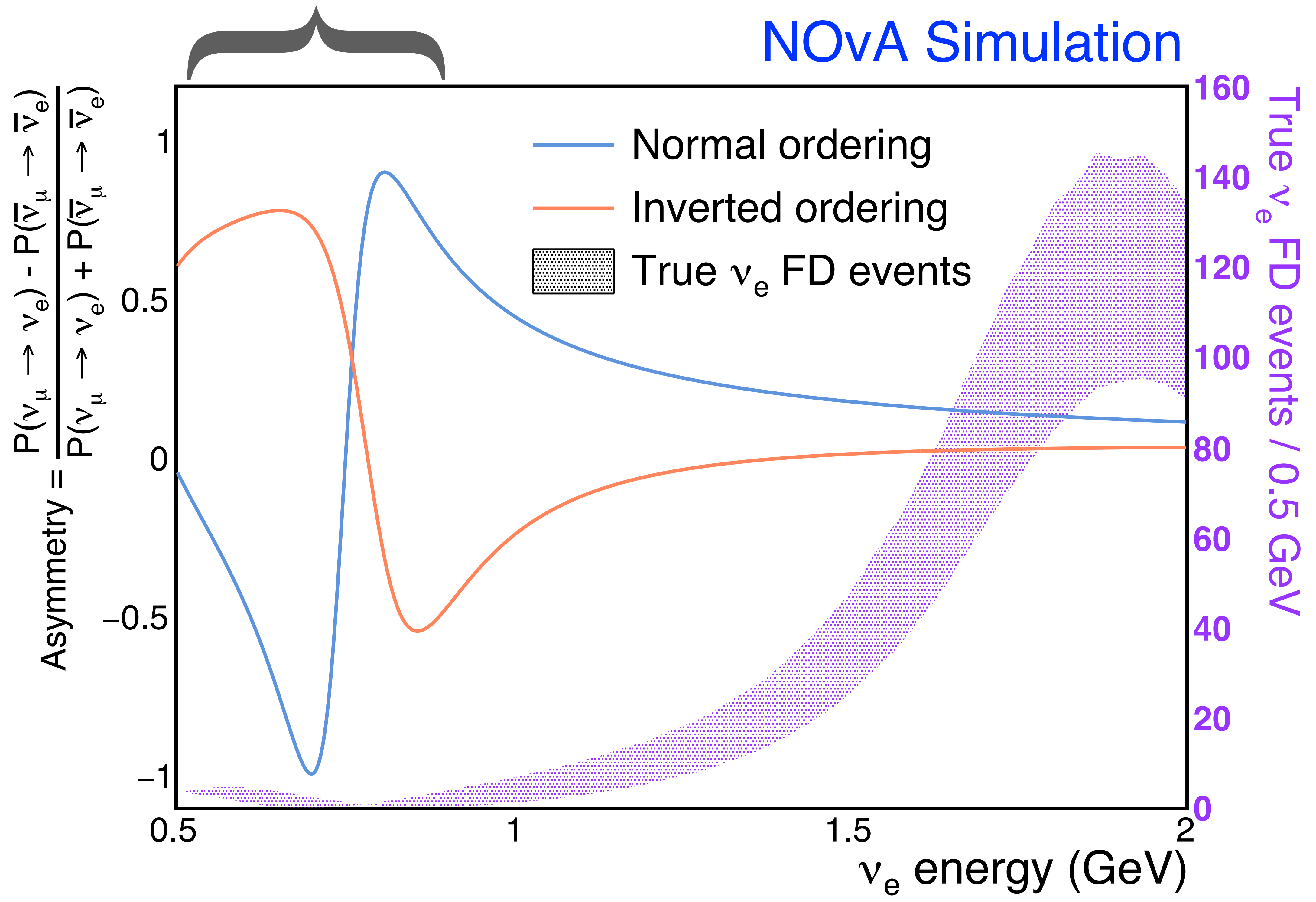
FD EVENT SELECTION



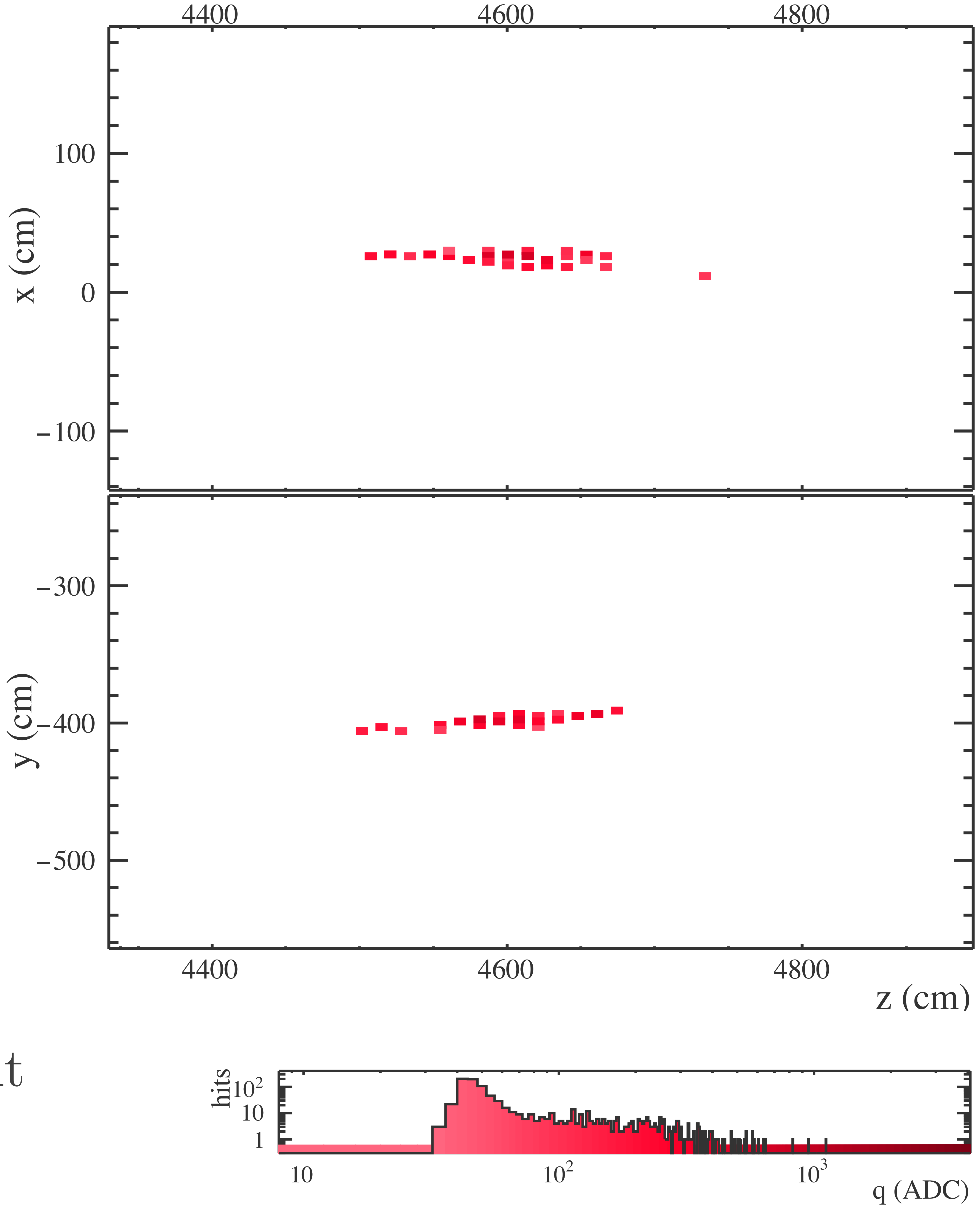


NEW LOW E SAMPLE

Previously excluded



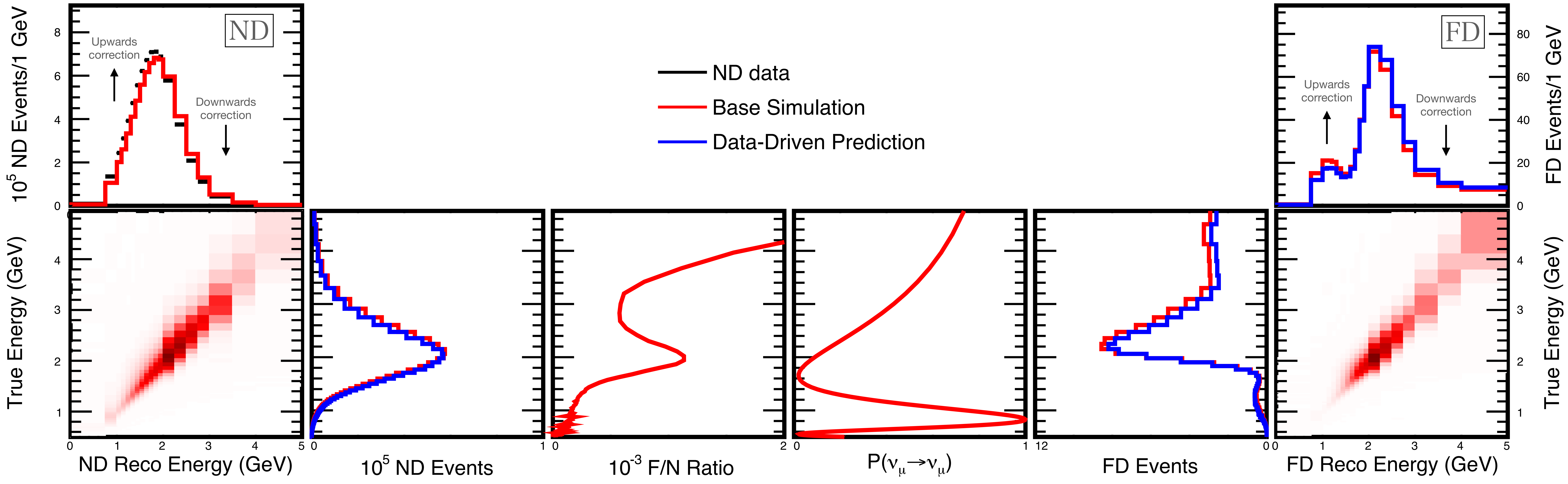
Designed new selection to retain lower-E ν_e candidates



* ✳ Maximum ordering sensitivity from $\nu_e - \bar{\nu}_e$ asymmetry at lower E_ν. Increases mass ordering sensitivity by ~few % (depends on oscillation parameters)
* ✳ For now, ν only (Analogous $\bar{\nu}_e$ sample currently too small, but future exposure gains will improve sensitivity to asymmetry).

EXTRAPOLATION

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



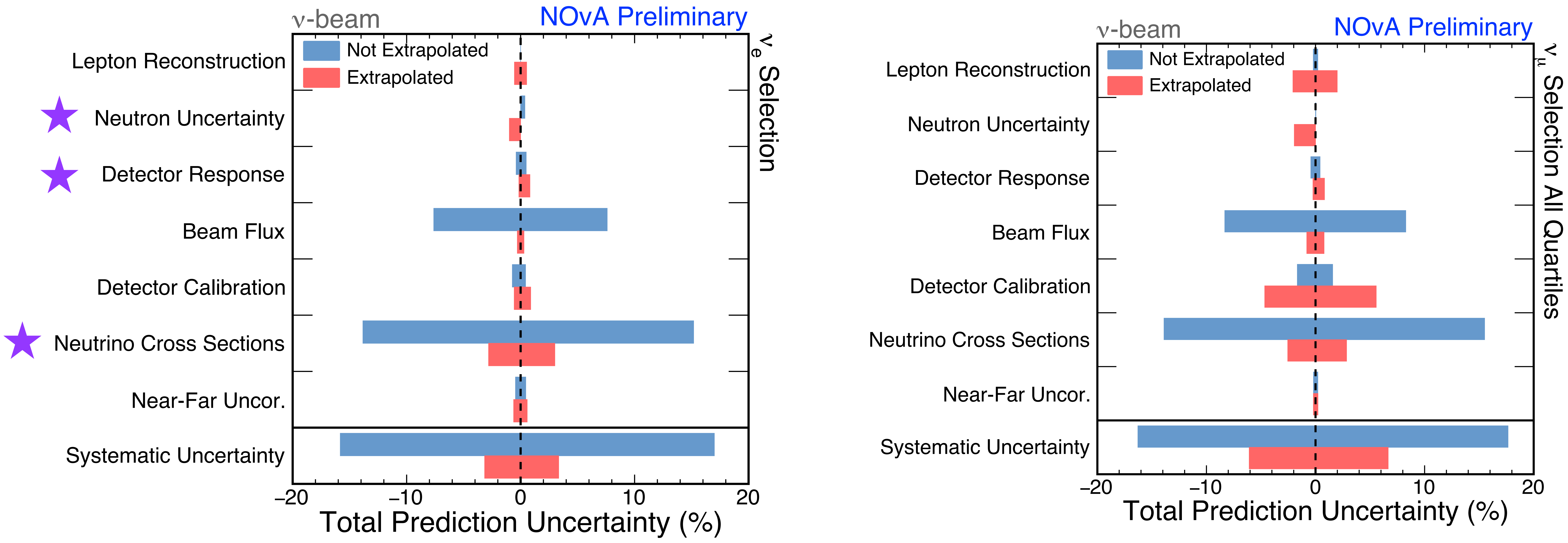
Correcting ND simulation to agree with data in reco E_ν...

... 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

Extrapolate in sub-ranges of lepton $|p_T|$ for matching the acceptance between detectors.

SYSTEMATIC UNCERTAINTIES



✳ 2024 improvements: new pion-production systematic uncertainties, improved light response model and neutron propagation uncertainty.

✳ ND constraints reduce the systematic uncertainties in the FD predictions from ~15% to 4-5%. Statistical uncertainties are dominant in the oscillation measurement.

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 Bay1D

θ_{13} constraint

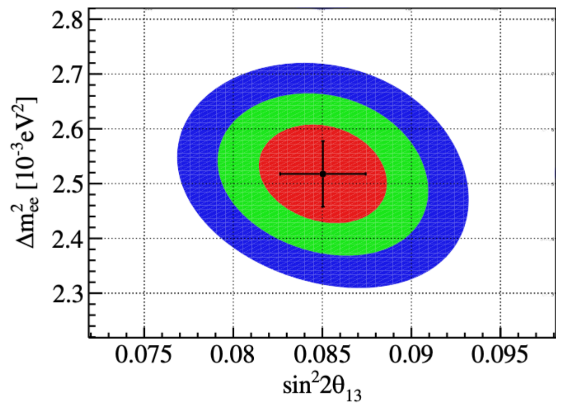
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

OR

Daya Bay 2D

$(\Delta m^2_{32}, \theta_{13})$ 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

Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}

Octant, Hierarchy, CP-violation

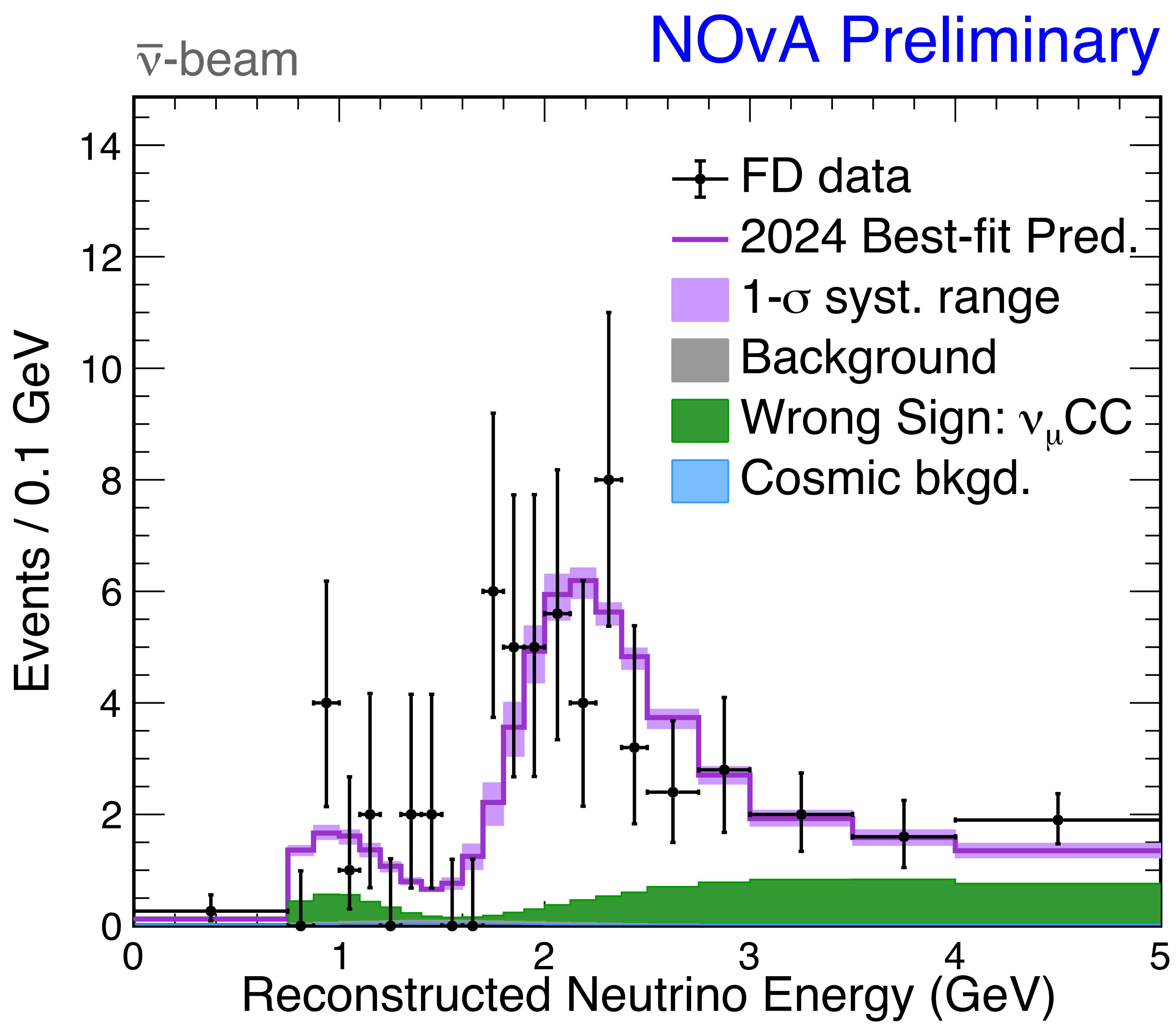
Other mixing parameters:

$\sin^2\theta_{12} = 0.307$ (PDG 2023)

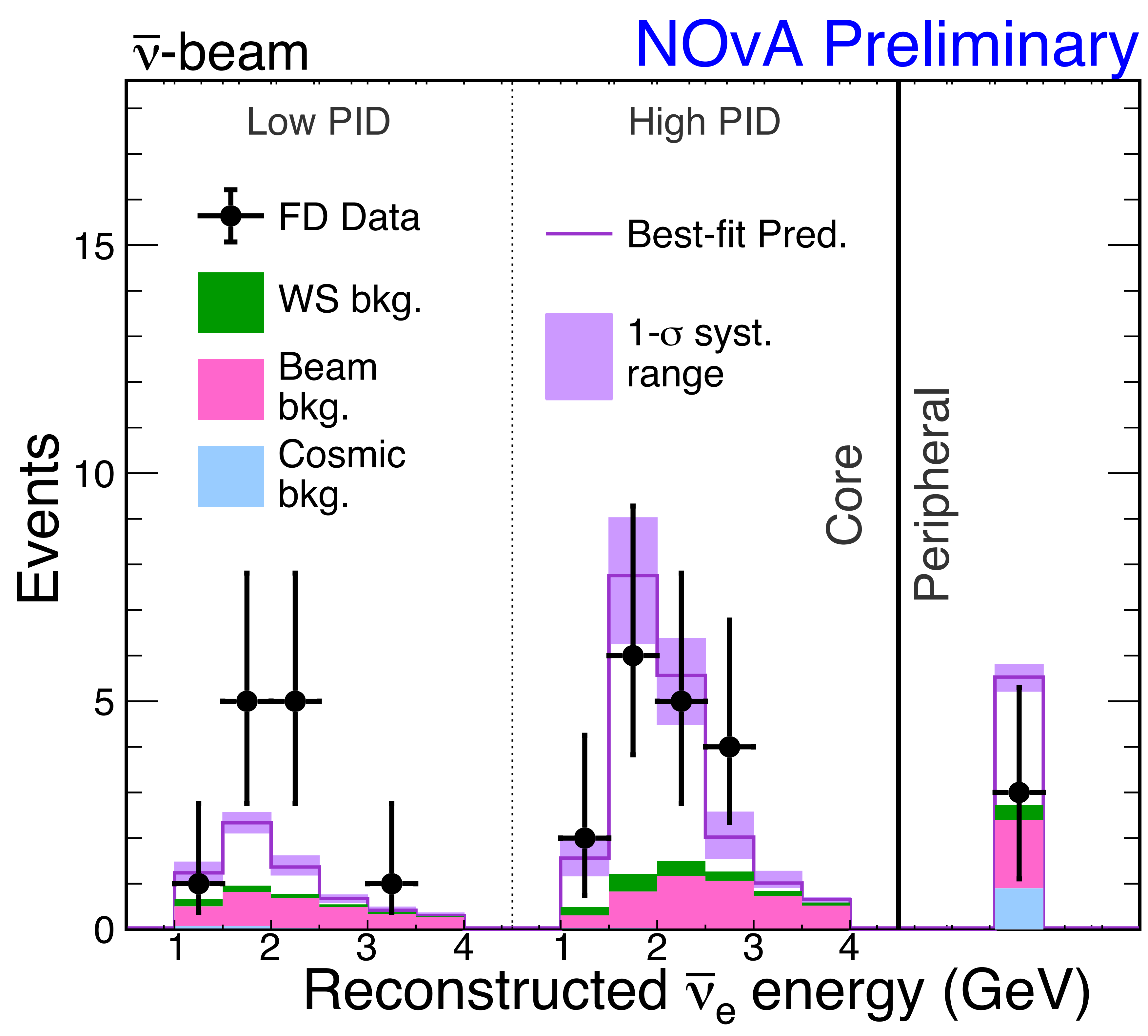
$\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2 (PDG 2023)

$\rho = 2.74$ g/ cm^3 (CRUST 1.0)

FD DATA: ANTINEUTRINO BEAM

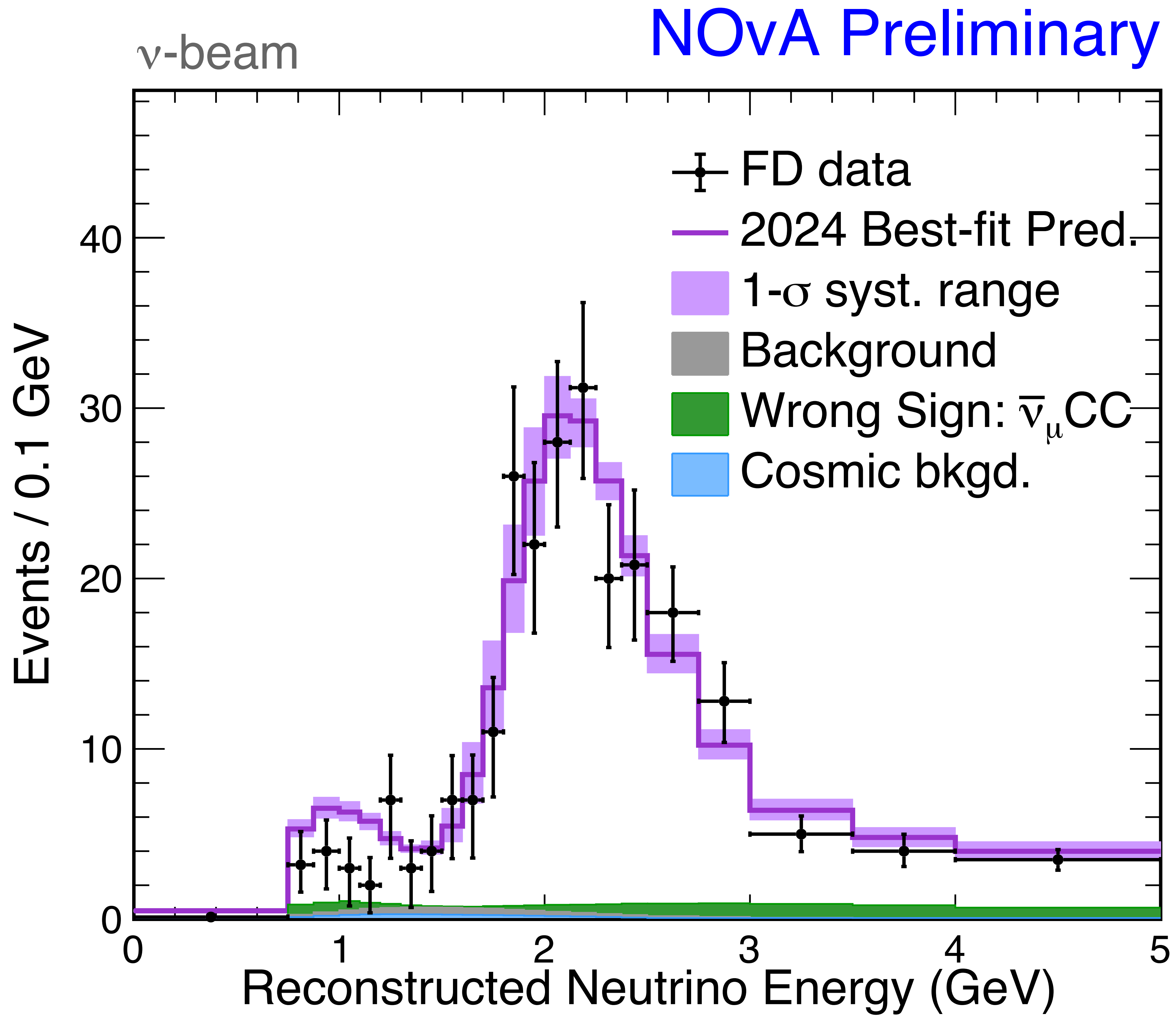


106 $\bar{\nu}_\mu$ candidates
(expected total bkg 1.7)

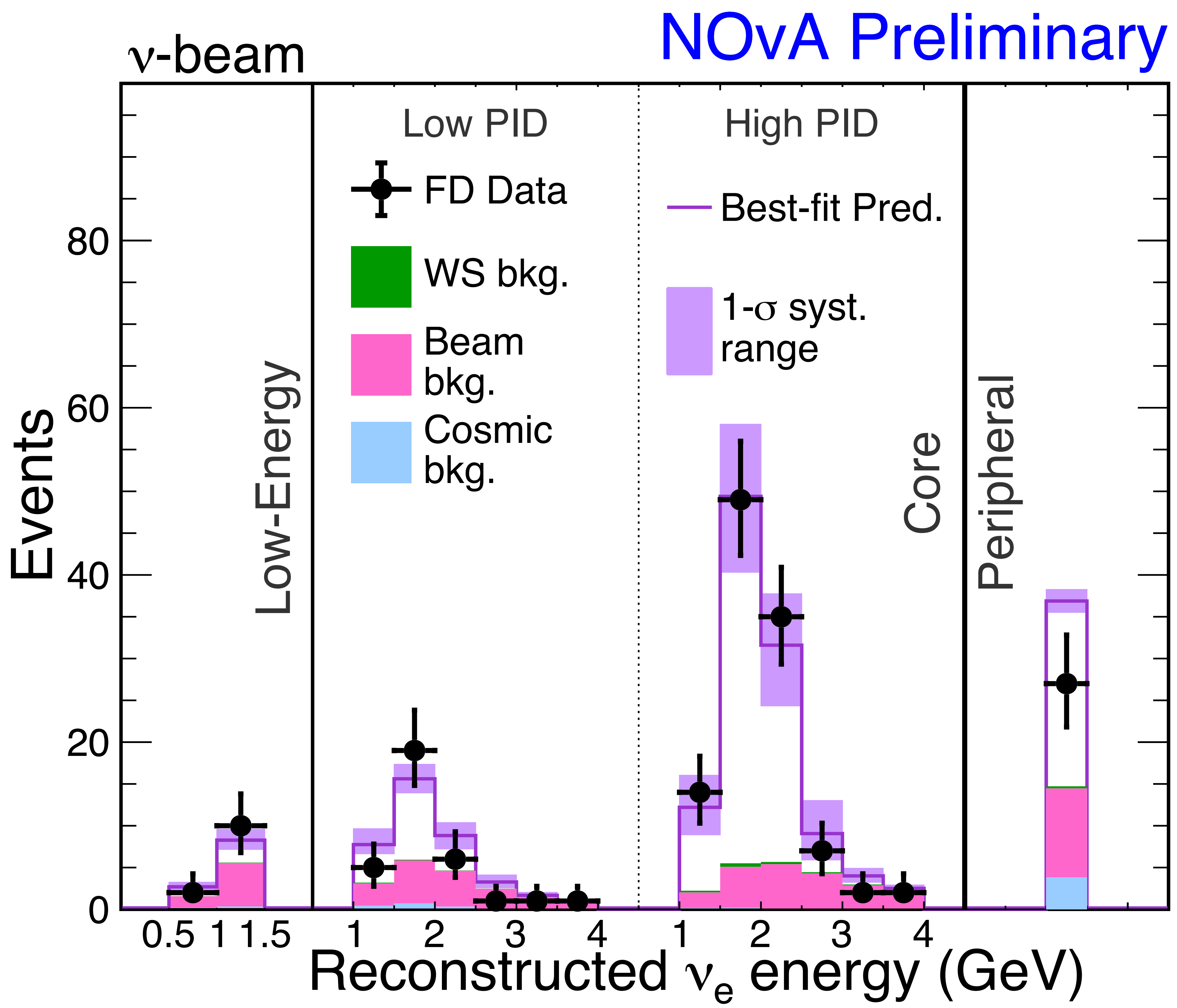


32 $\bar{\nu}_e$ candidates
(expected total bkg 12.2)

FD DATA: NEUTRINO BEAM



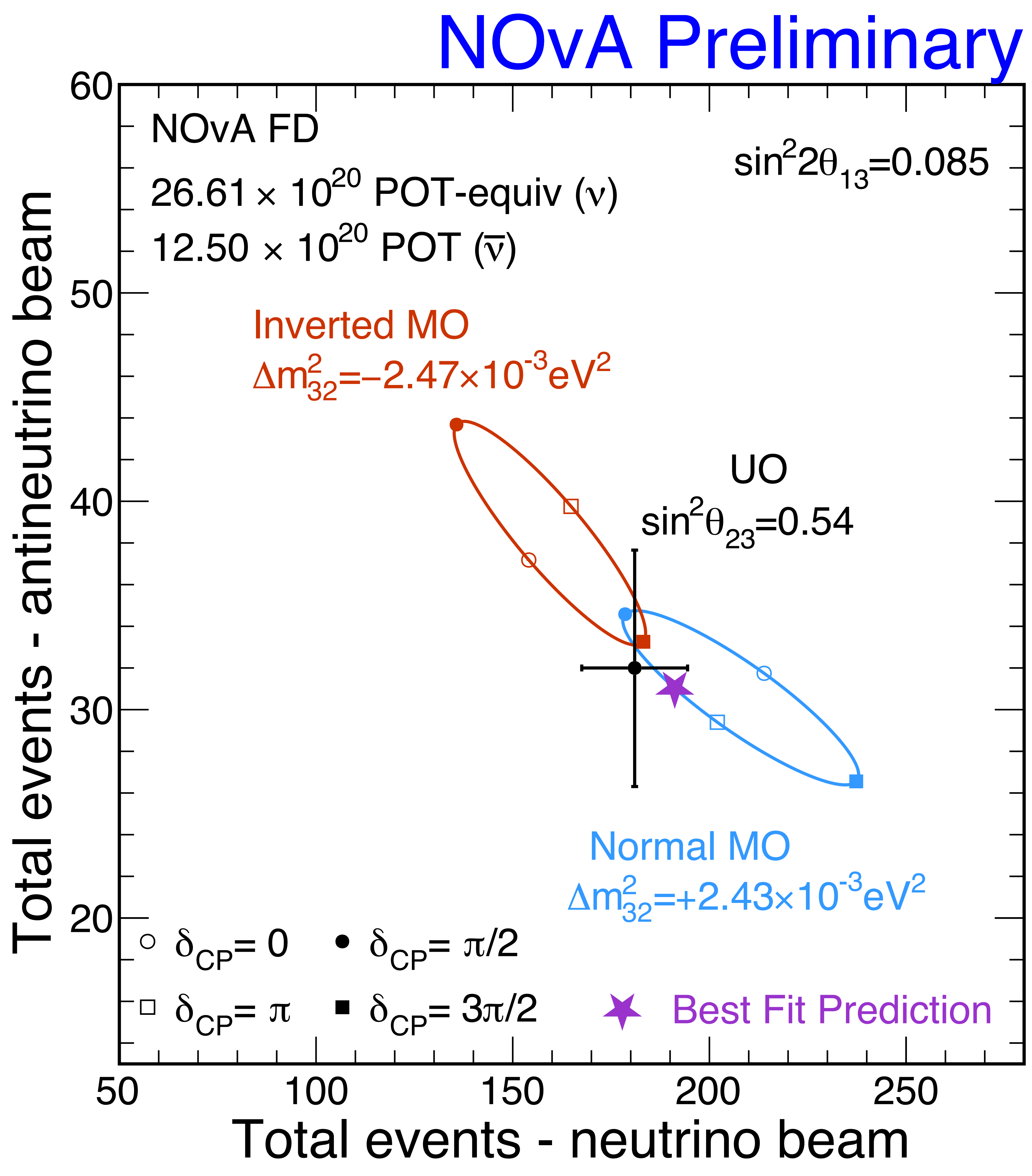
384 ν_μ candidates
(expected total bkg 11.3)



181 ν_e candidates
(expected total bkg 61.7)

3-flavor oscillations describe these data well: Bayesian posterior predictive p-value = 0.54

FD DATA AND BEST FIT

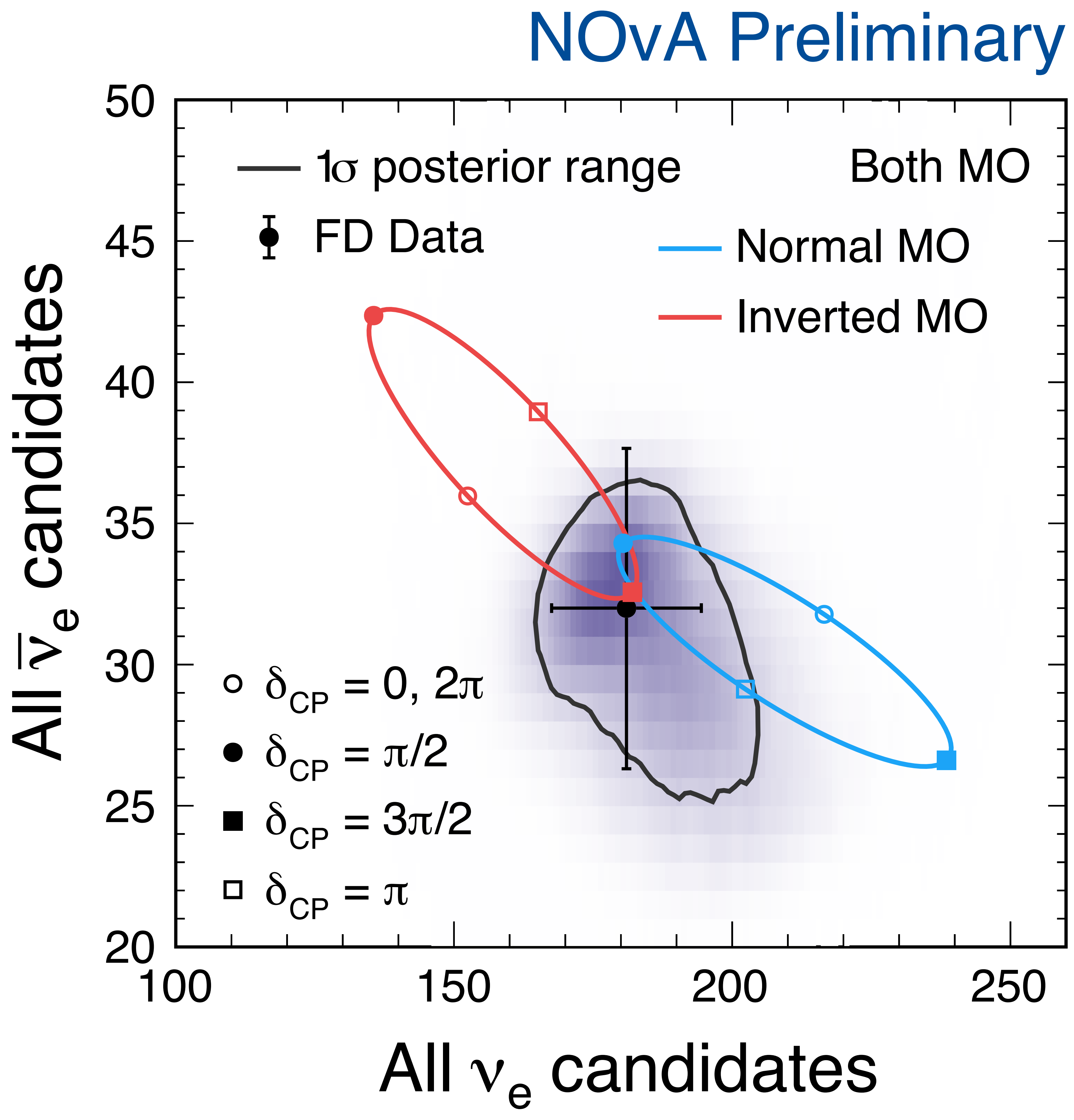


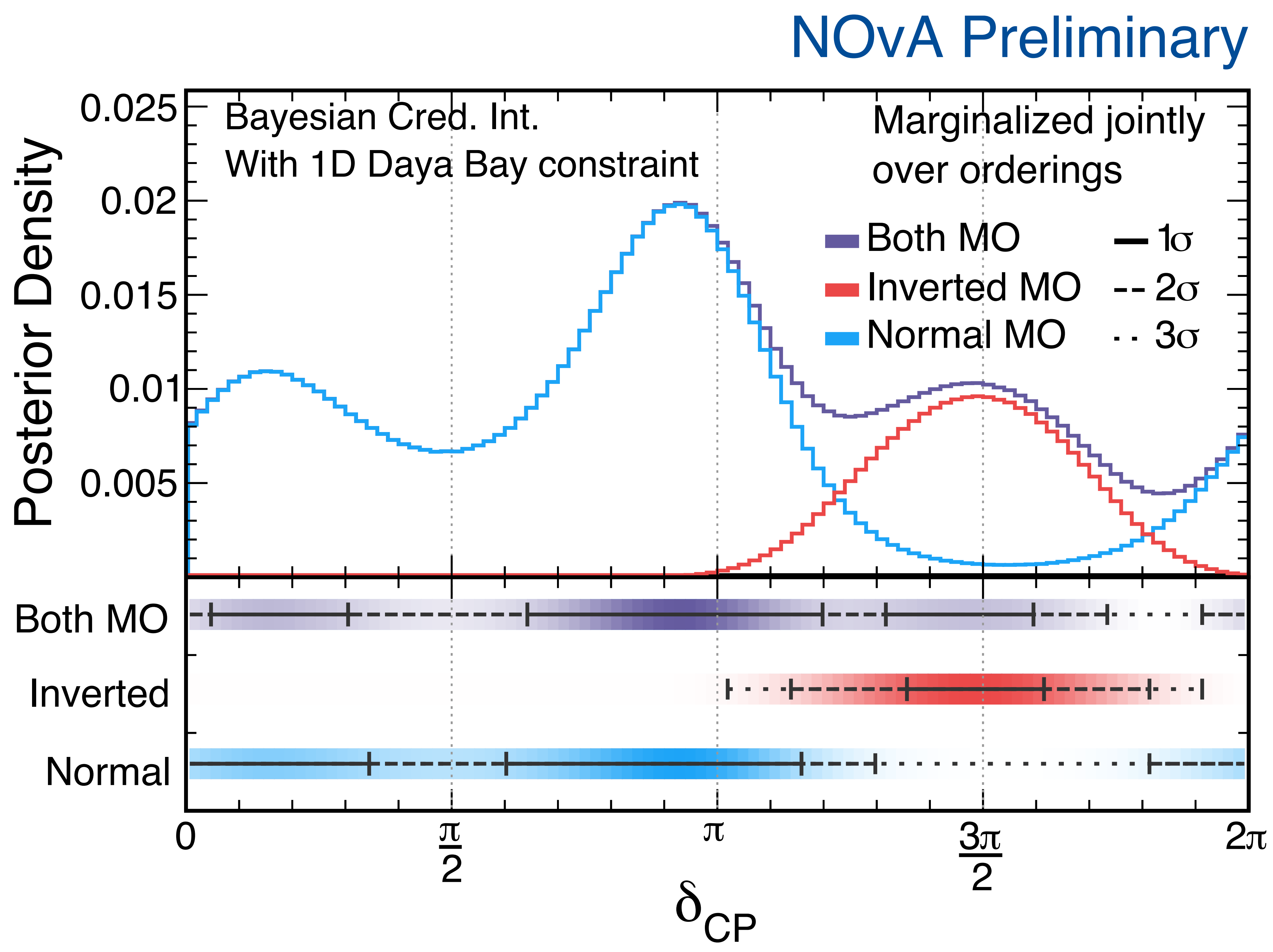
Frequentist results (w/ Daya Bay 1D ϑ_{13} constraint)

	Normal MO	Inverted MO
$\Delta m^2_{32}/10^{-3}$ eV^2	$+2.433^{+0.035}_{-0.036}$	$-2.473^{+0.035}_{-0.035}$
$\sin^2\theta_{23}$	$\mathbf{0.546}^{+0.032}_{-0.075}$	$0.539^{+0.028}_{-0.075}$
δ_{CP}	**0.88 π**	1.51 π
Rejection significance (σ)		1.36

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

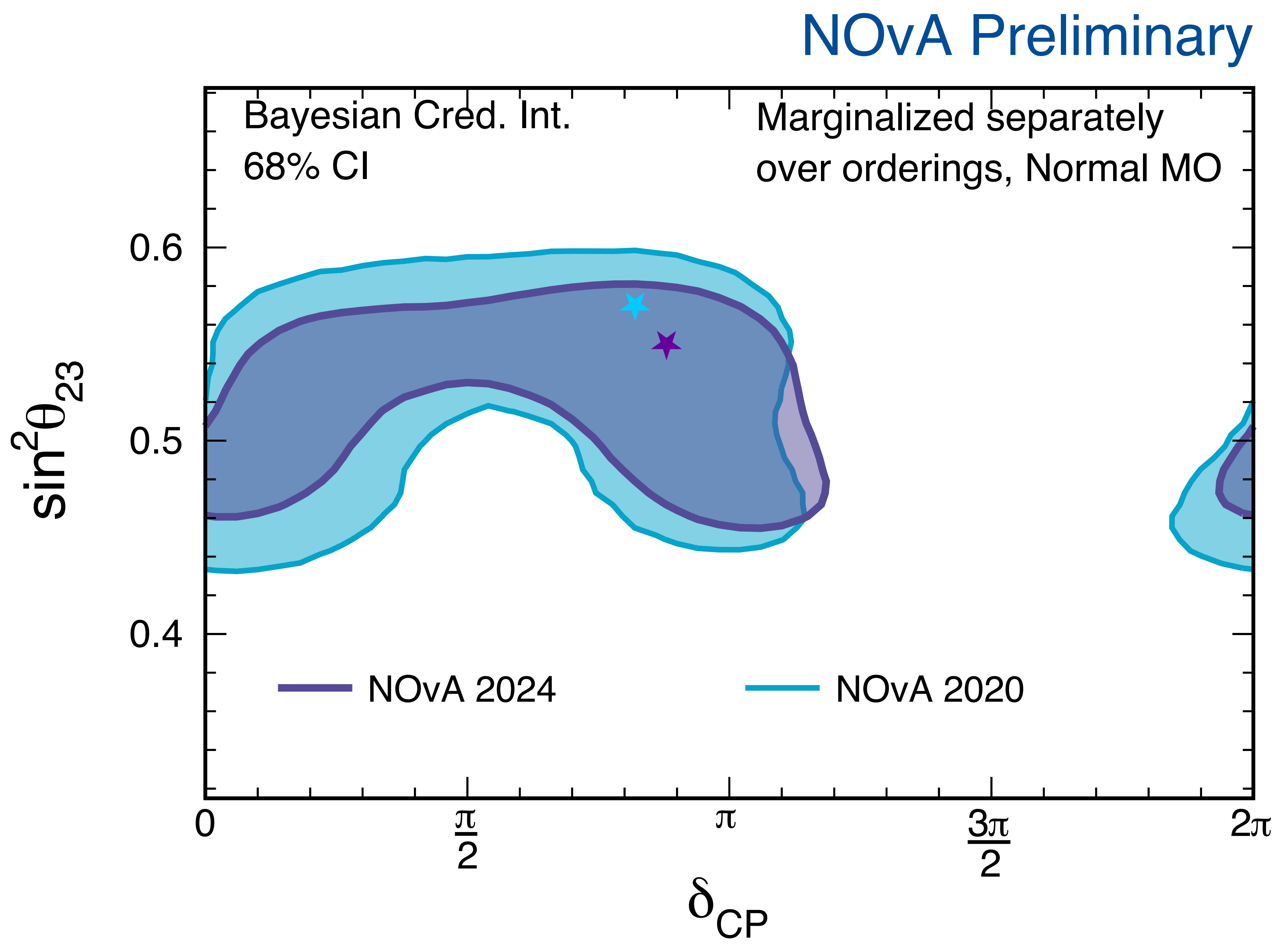
RESULTS

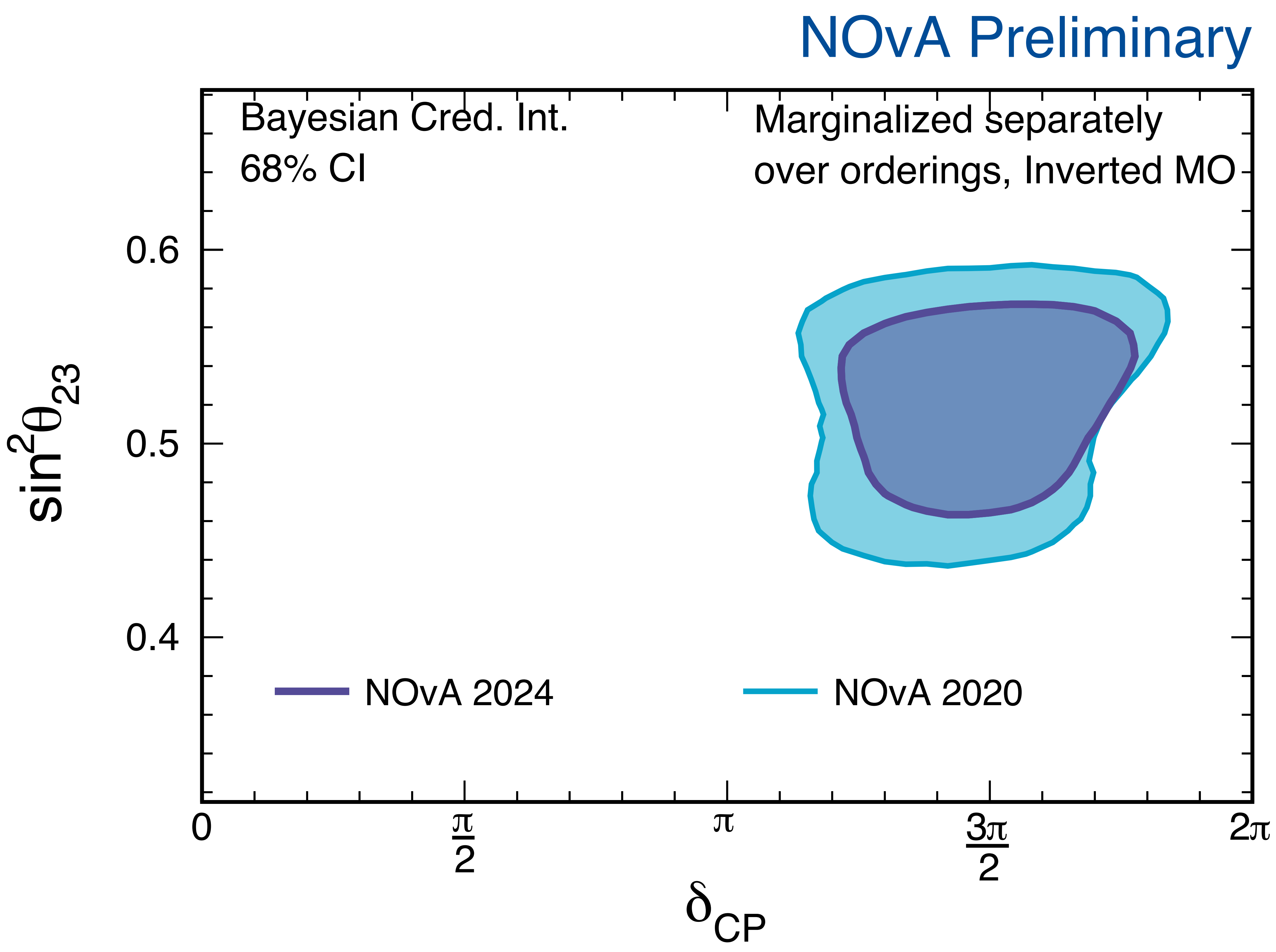




* The data disfavor "extreme" asymmetry combinations: (IO, $\delta = \pi/2$) and (NO, $\delta = 3\pi/2$).
* CP-conserving points outside 3σ interval in IO.

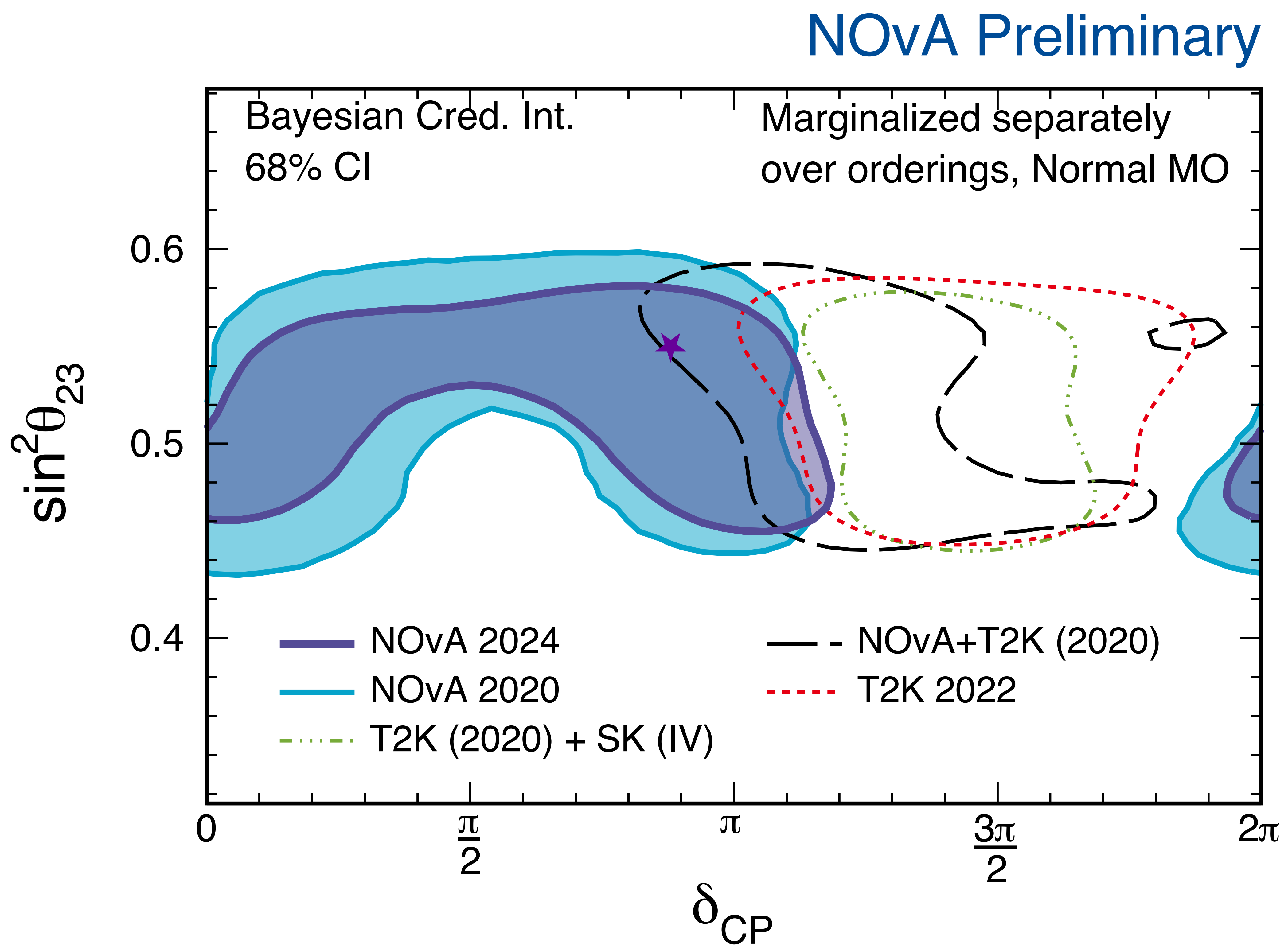
RESULTS

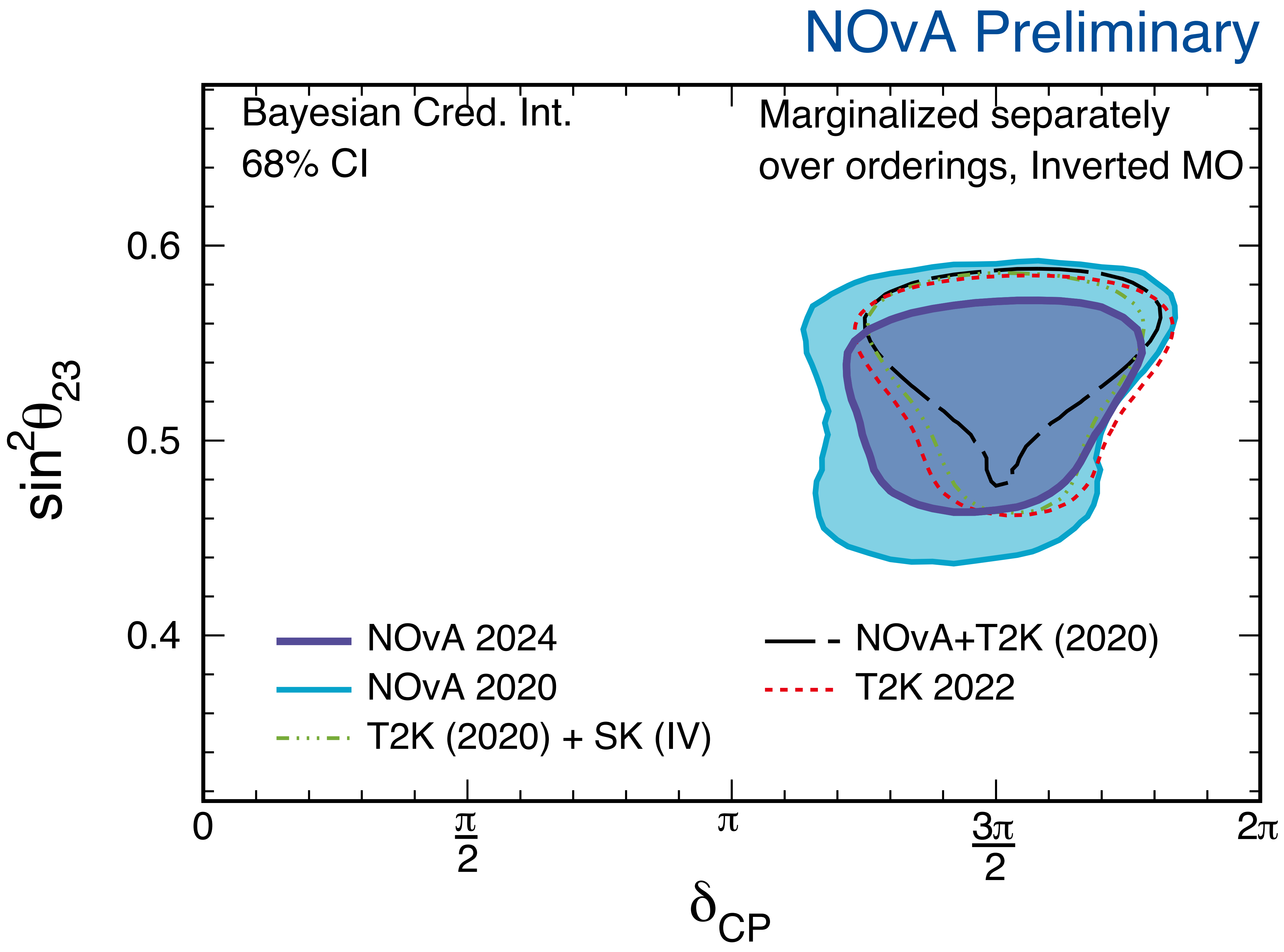




- ✴ The new NOvA result is consistent with our previous analysis: improved constraints lie in ∼ the same regions.
- ✴ NB: different choices of reactor constraint.

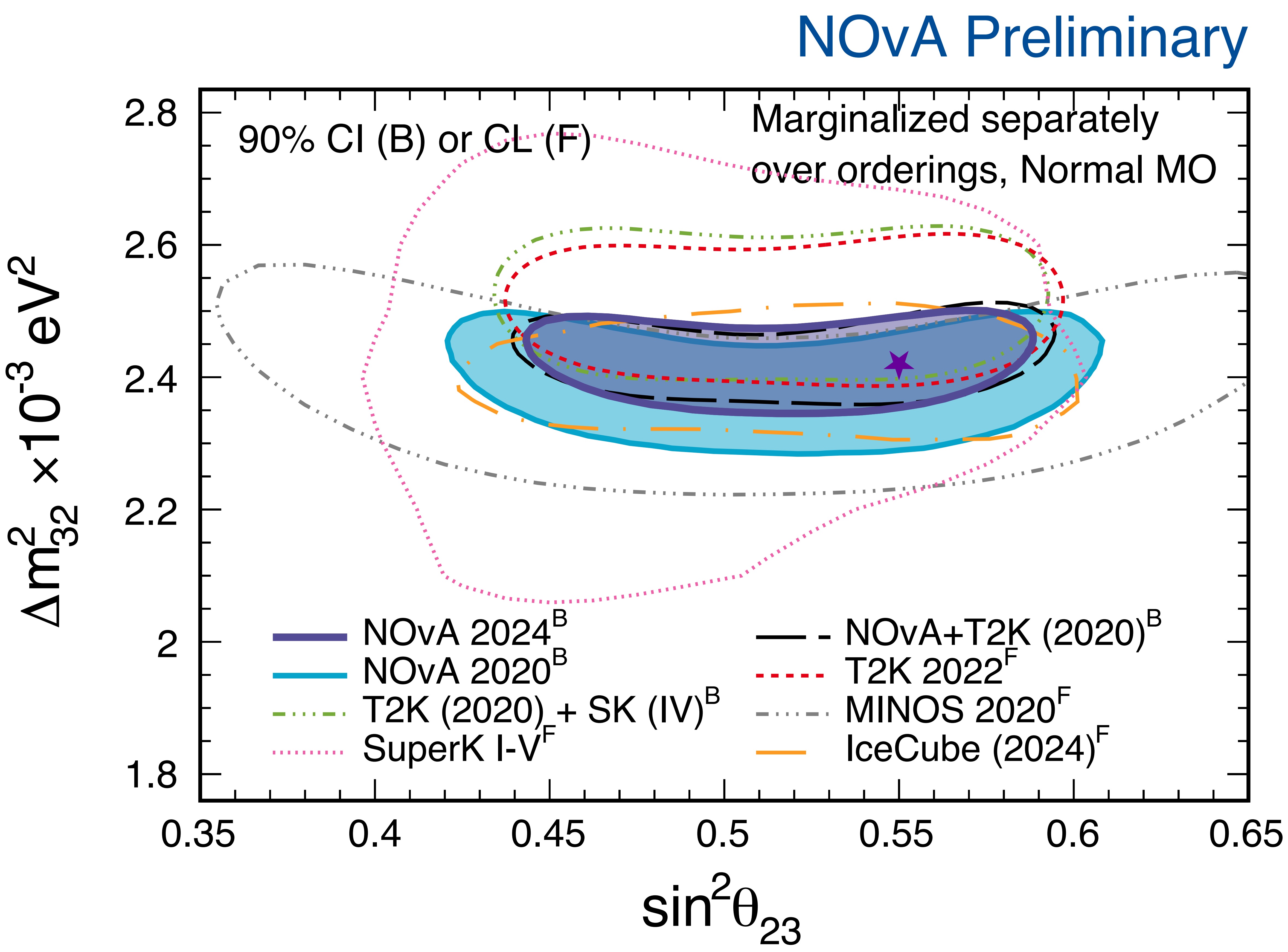
RESULTS





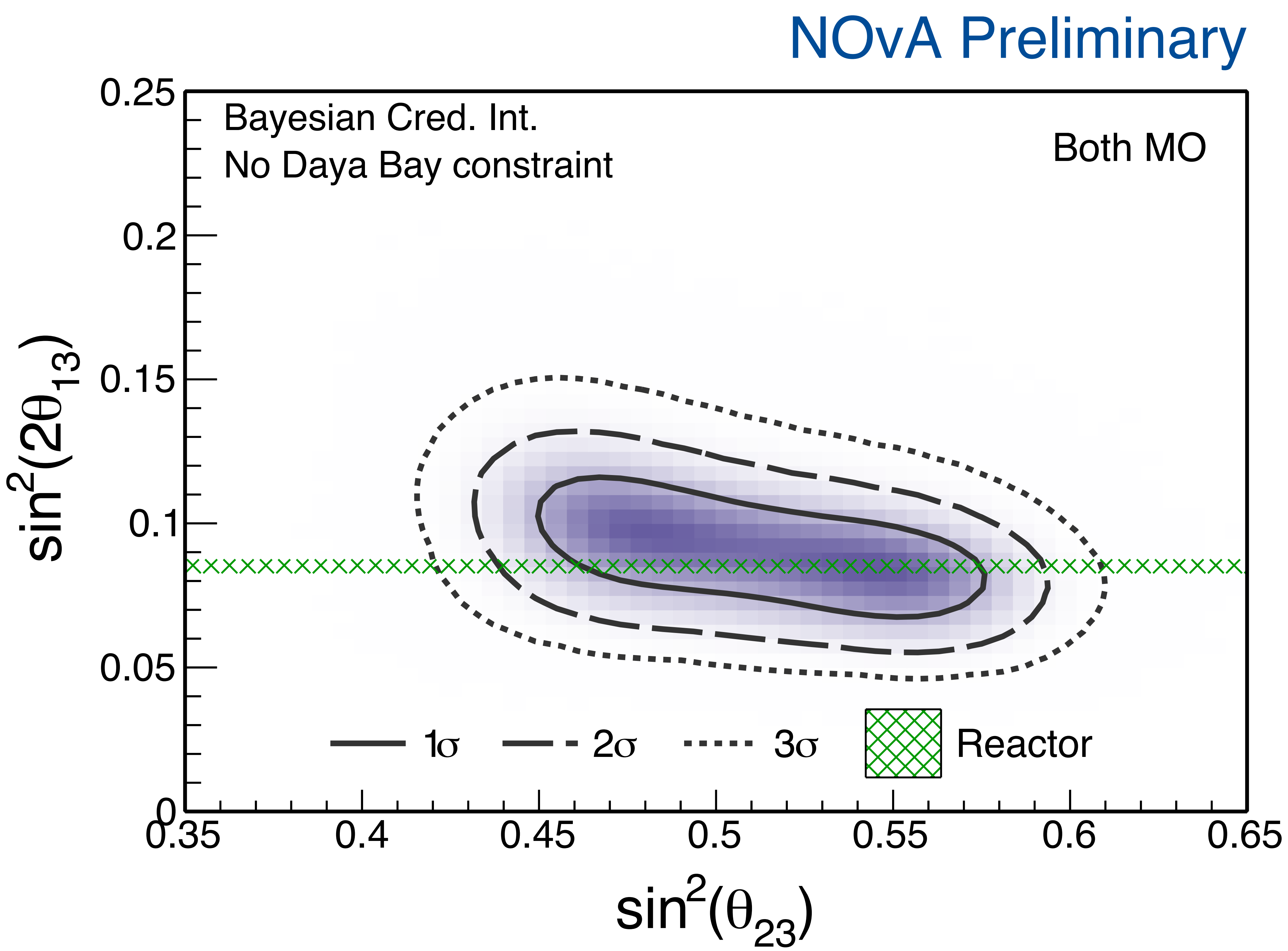
- ✳ The new NOvA result is consistent with its previous analysis.
- ✳ T2K, joint fits, favor different regions in NO, same region in IO.
- ✳ NB: different choices of reactor constraint.

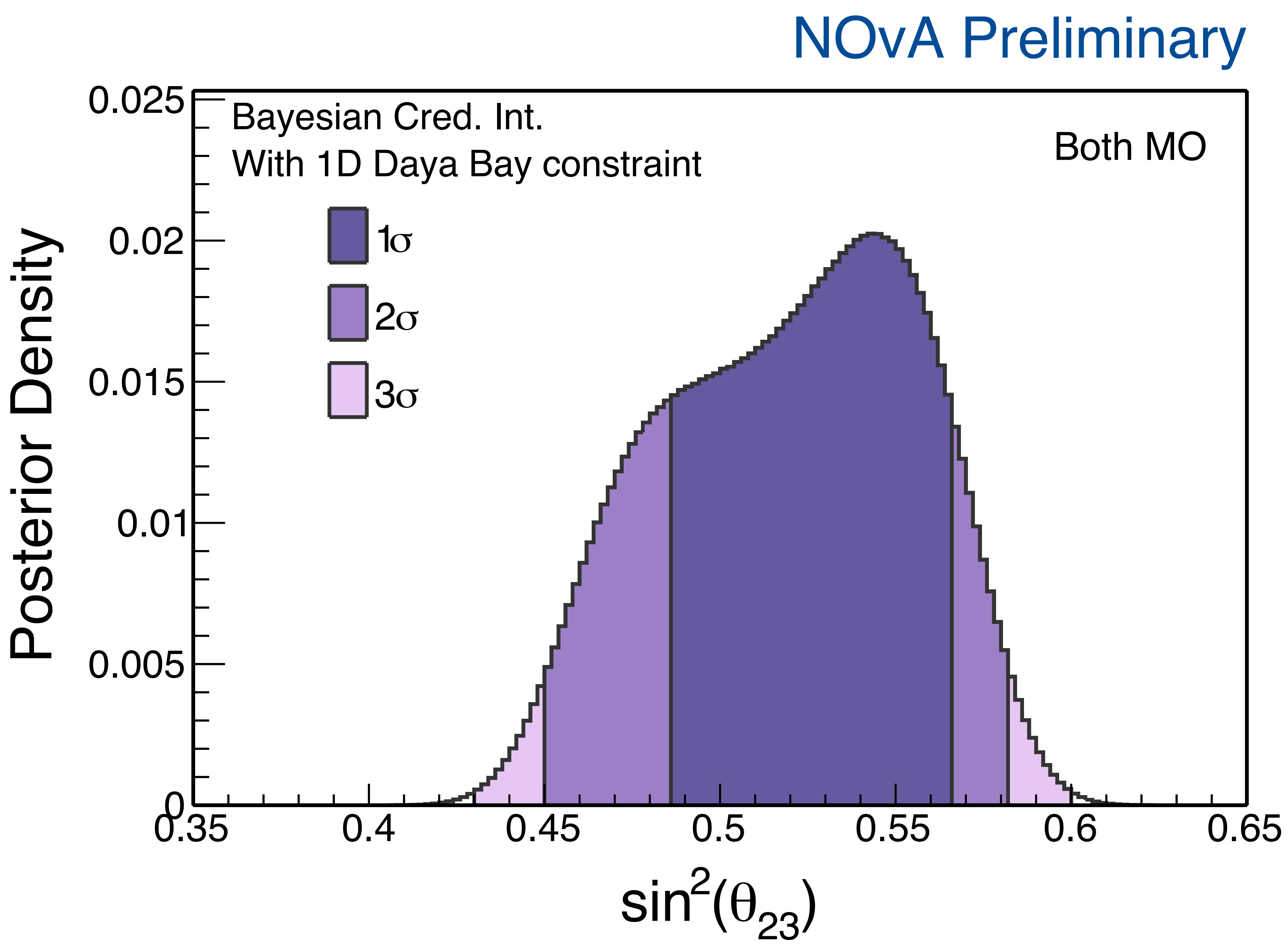
RESULTS



- ✳ The new NOvA result is consistent with its previous analysis.
- ✳ Overall consistency between all experiments in $\nu_2 - \nu_3$ sector.

RESULTS

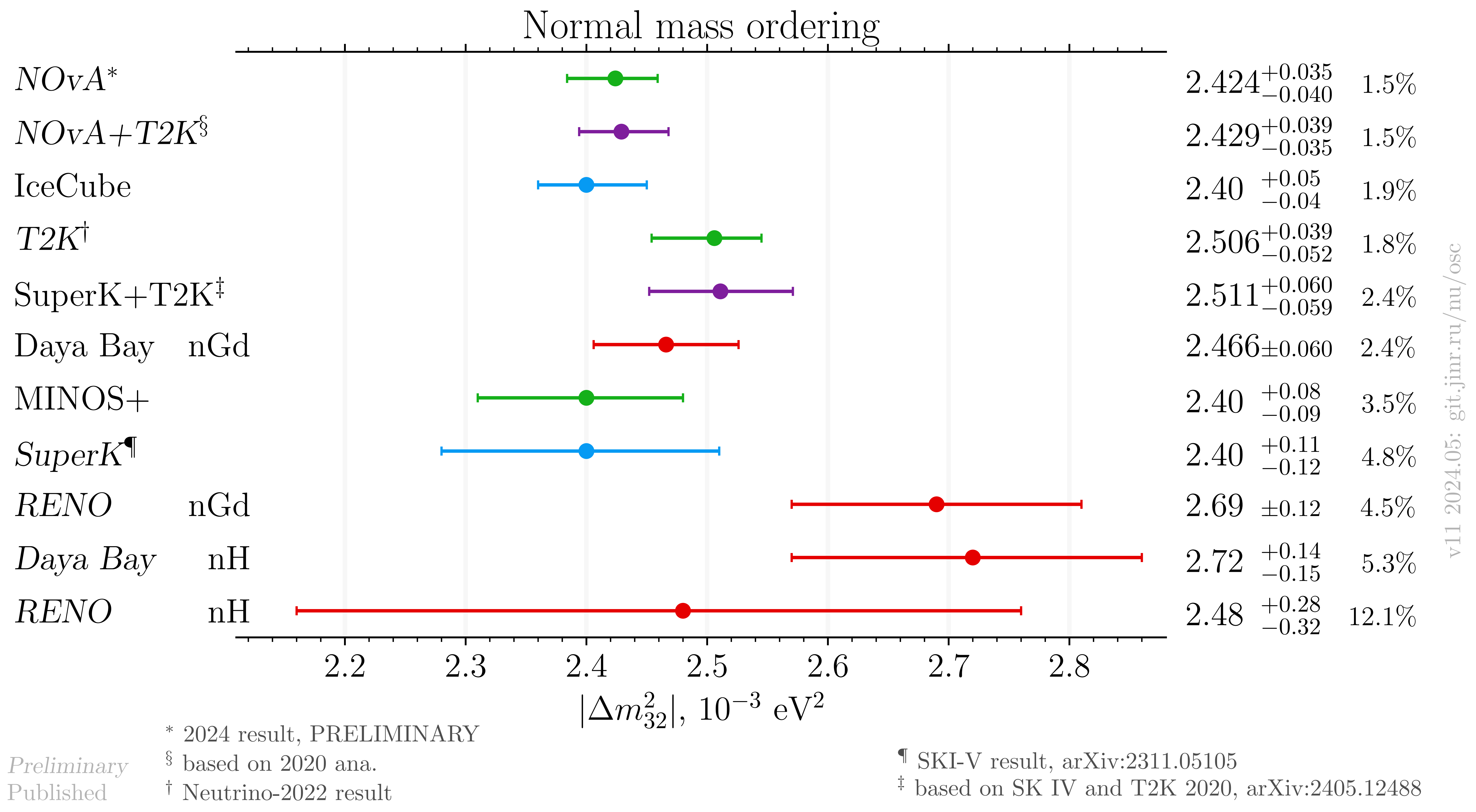




	No Constraint		1D Constraint	
	Prob	BF	Prob	BF
Upper Octant Preference	57%	1.3	69%	2.2

- ✳ UO preferred with 1D Daya Bay constraint
- ✳ Peak flips from LO to UO with and without constraint

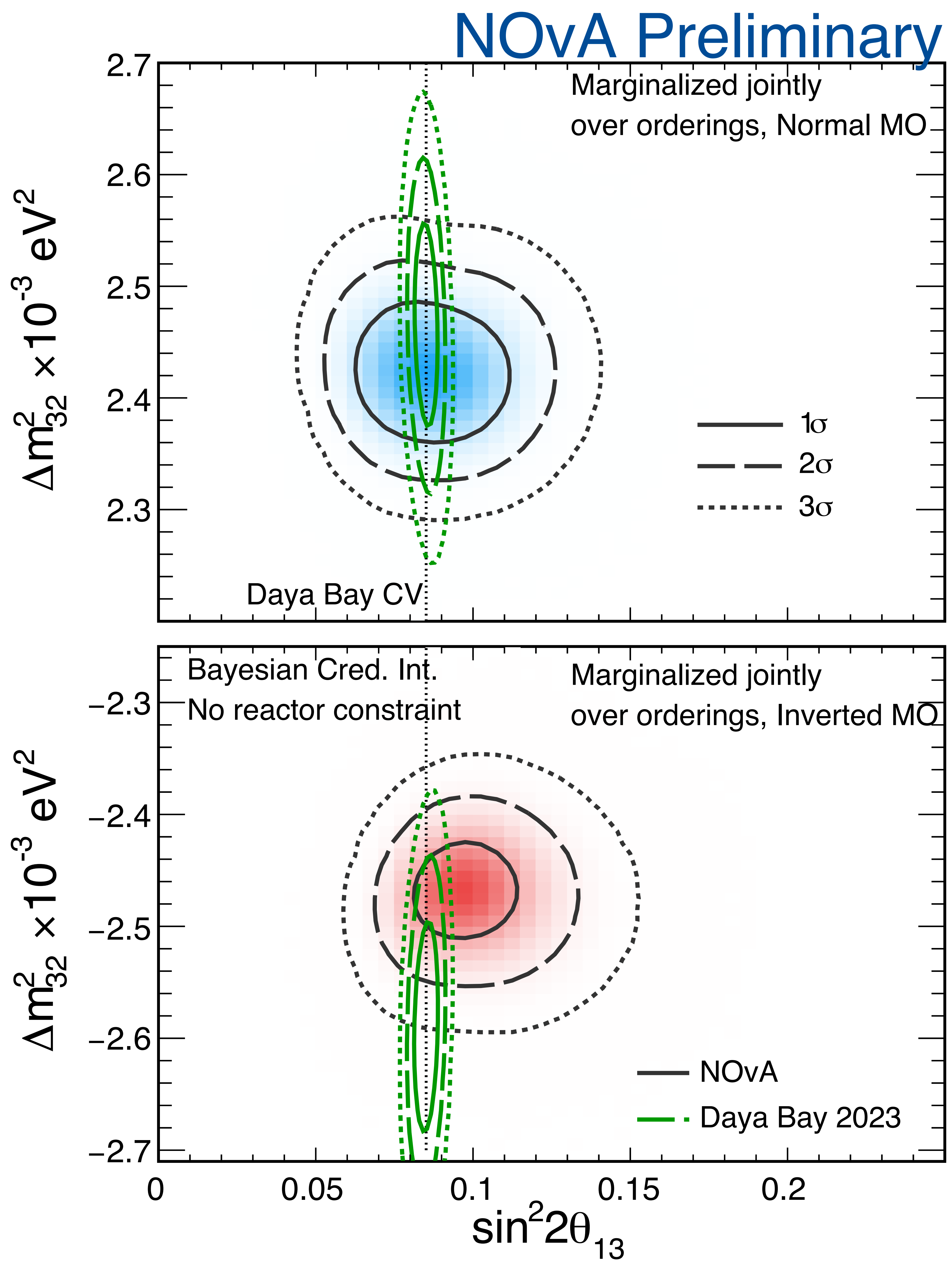
RESULTS



✴ The new NOvA result gives the most precise single experiment measurement of Δm^2_{32}.

✴ Δm^2_{32} is now the most precisely know PMNS parameter.

RESULTS



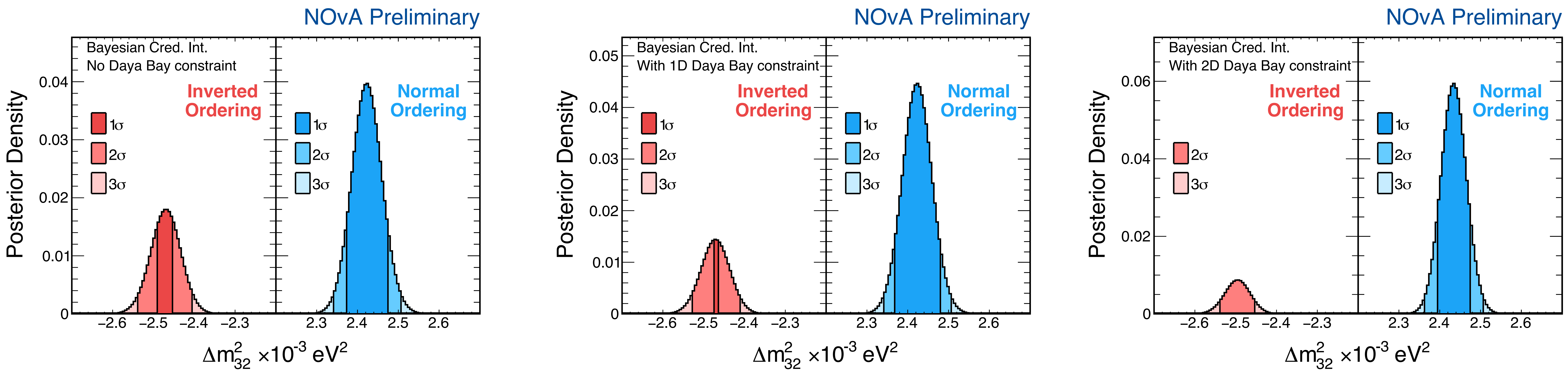
- ✴ Precision measurements of Δm^2_{32} in both accelerator and reactor experiments offer more ways to resolve degeneracies
- ✴ Use 2D reactor constraint to boost sensitivity to the Mass ordering.
  - ✴ In the true mass ordering reactor LBL measurements of Δm^2_{32} would be consistent but in incorrect 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^2_{32} (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^2_{32} 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!