

# Probing the 3-Flavor paradigm with NOvA

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**Zoya**

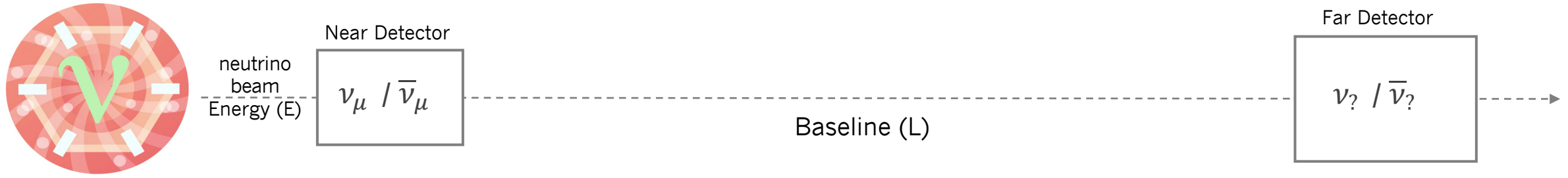
on behalf of NOvA collaboration

June 23, 2026

Neutrino Conference, UC Irvine



# NOvA is a long-baseline neutrino oscillation experiment.



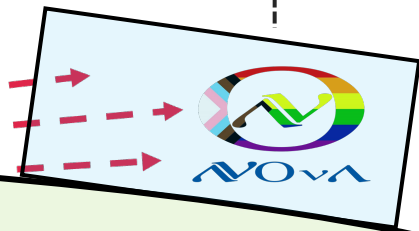
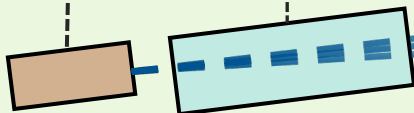
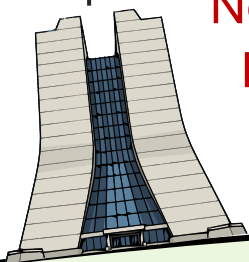
Fermilab  
Batavia, IL

810 km

Far Detector  
Ash River, MN

Neutrino  
Beam

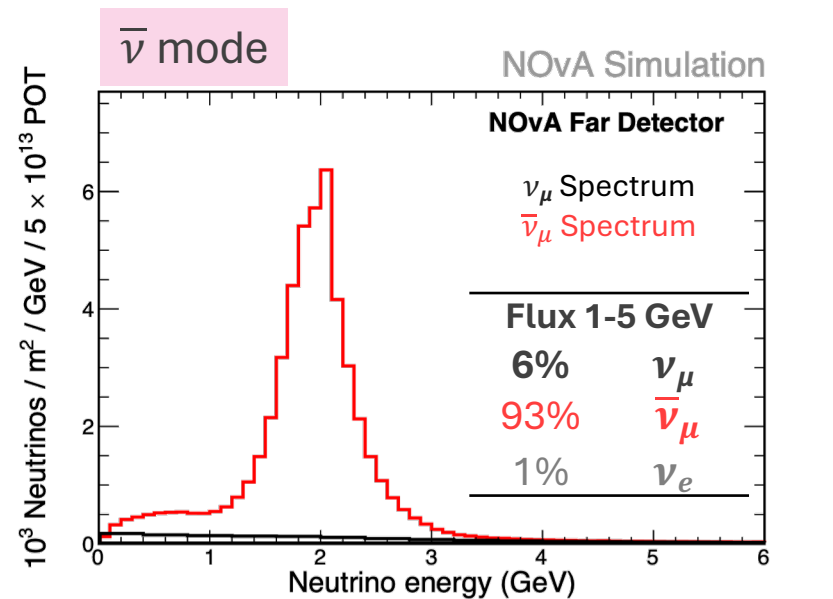
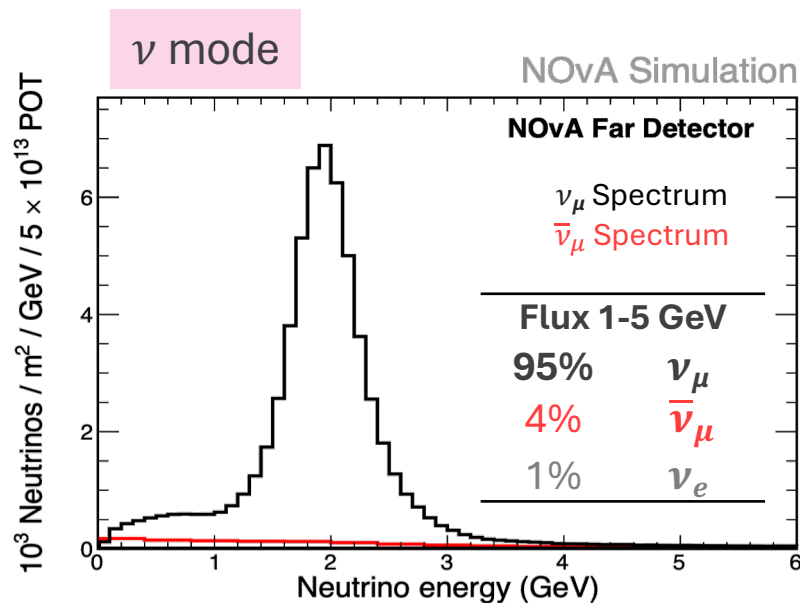
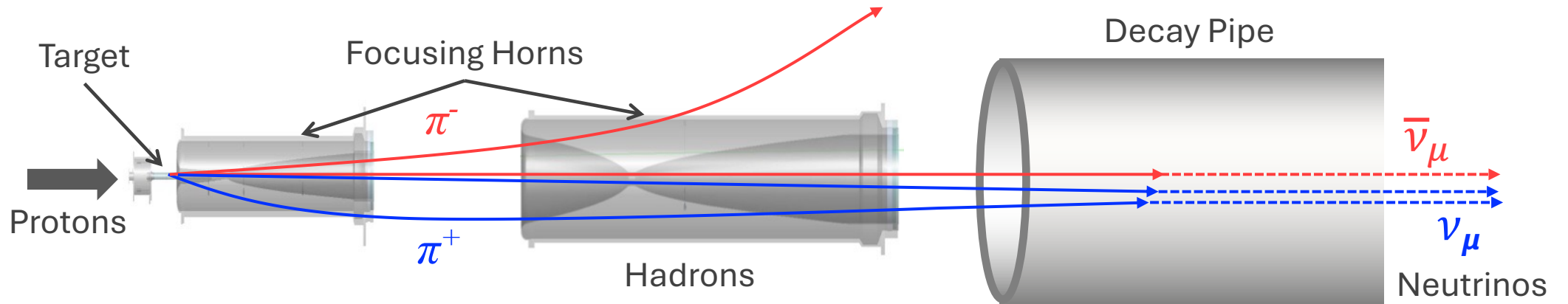
Near  
Detector



Not to scale

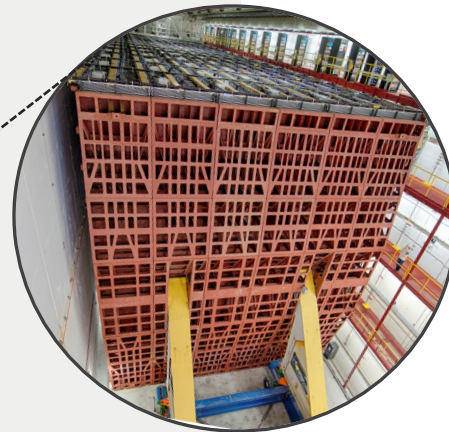
# The NuMI beam

- Narrow band of pure muon (anti)neutrino beam peaked at **2 GeV** to NOvA detectors sitting 14 mrad off-axis.

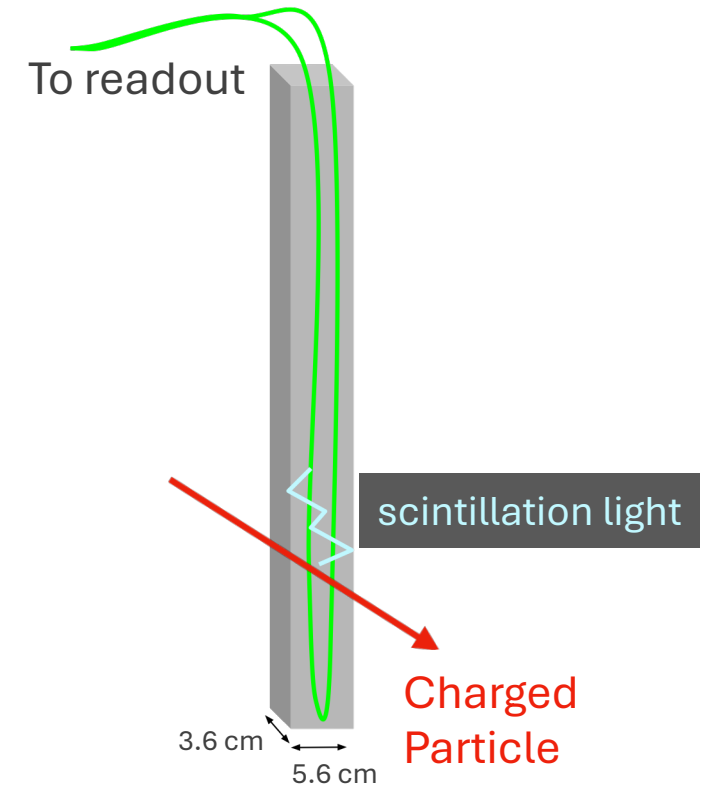
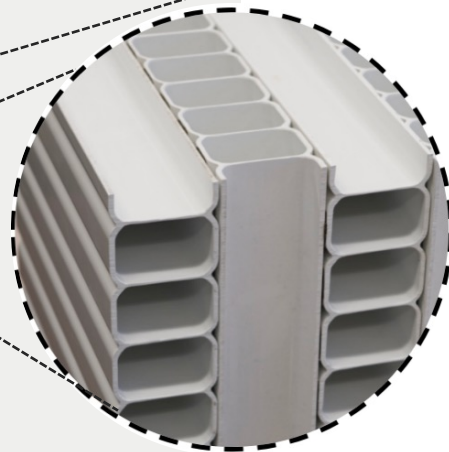
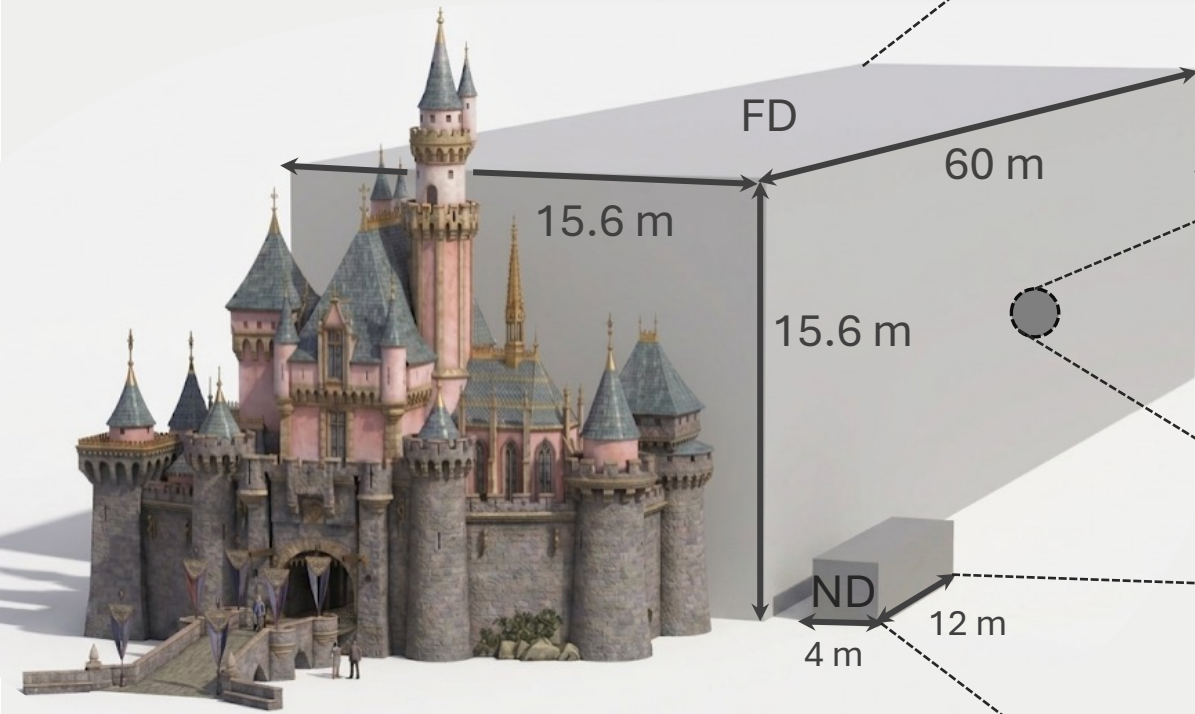


# The Detectors

Far Detector (FD)  
14 kT, on the surface

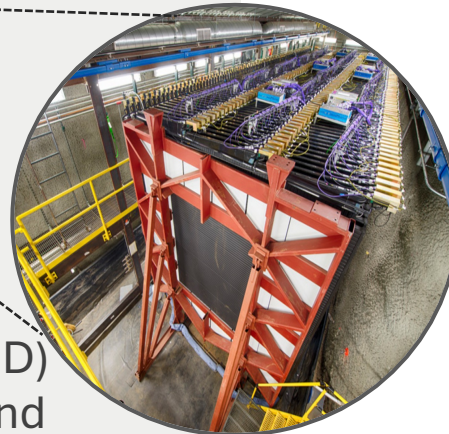


ND and FD are functionally identical **segmented liquid scintillator detectors.**



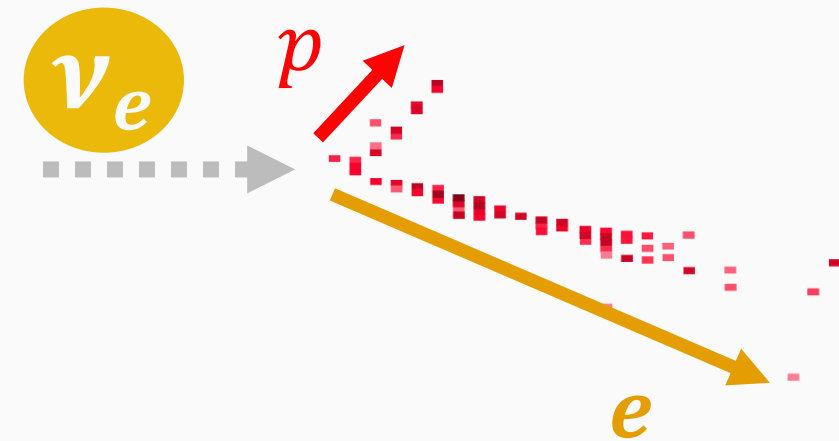
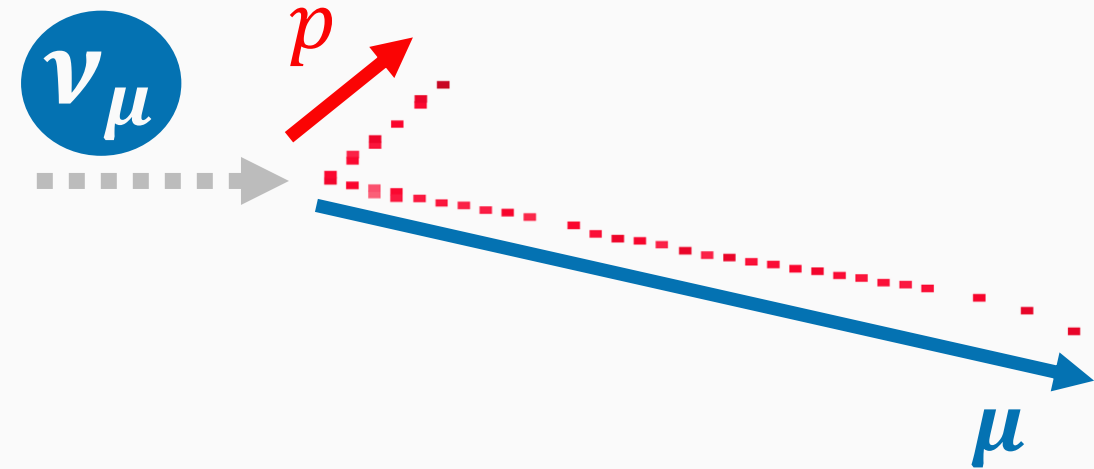
Sleeping Beauty Castle,  
Disneyland, California

Near Detector (ND)  
300 T, underground

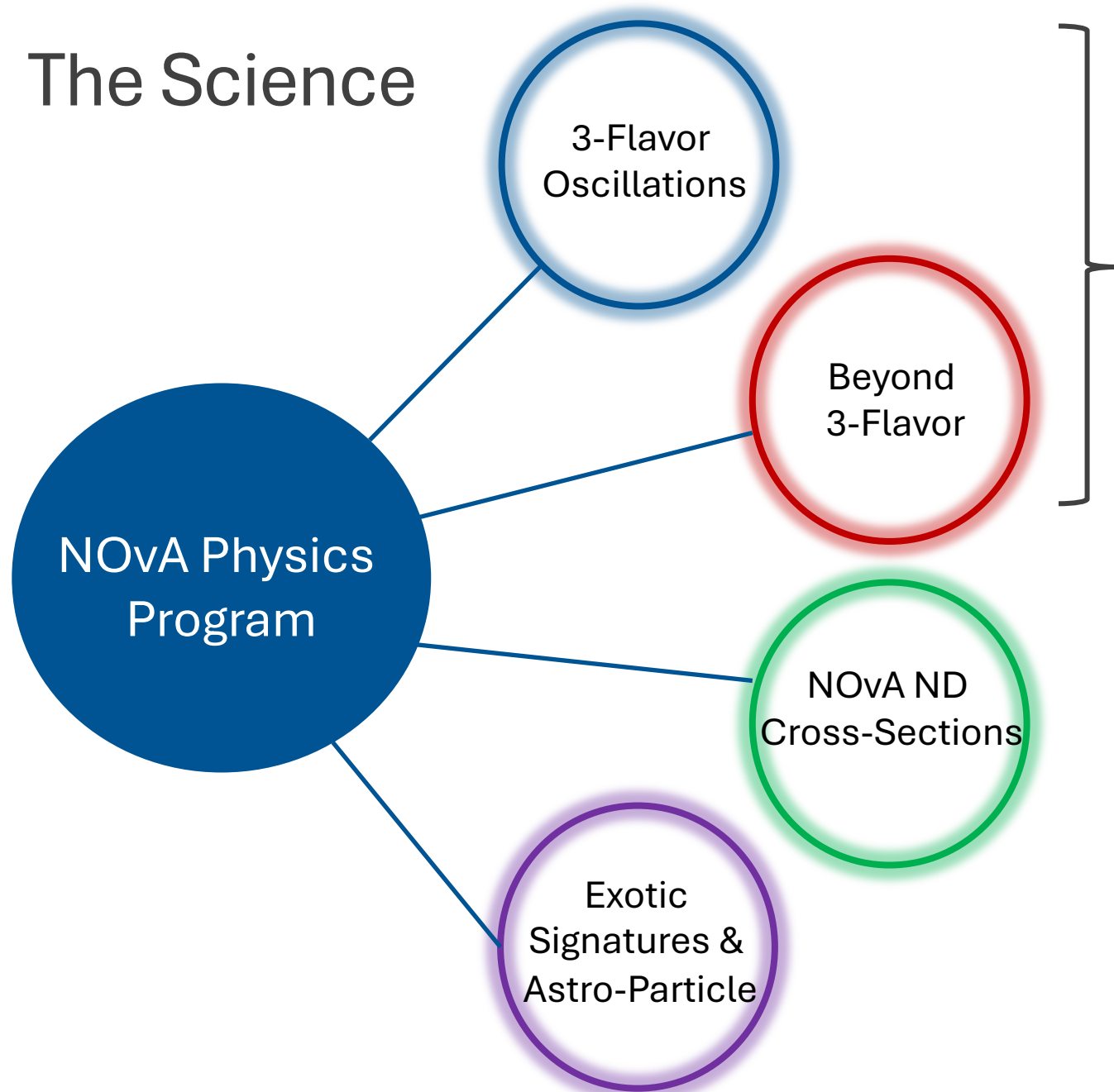


# Neutrinos in NOvA

- Optimized for EM showers.
  - ~6 samples per radiation length (~40 cm) making **muon-electron** identification easy.
- Neutrino candidates are identified using a **convolutional neural network (CNN)**.
- Energy is reconstructed via **tracking (muon)** and **calorimetry (electromagnetic, hadronic)**.



# The Science



# Presented Today

*Legend for this talk*

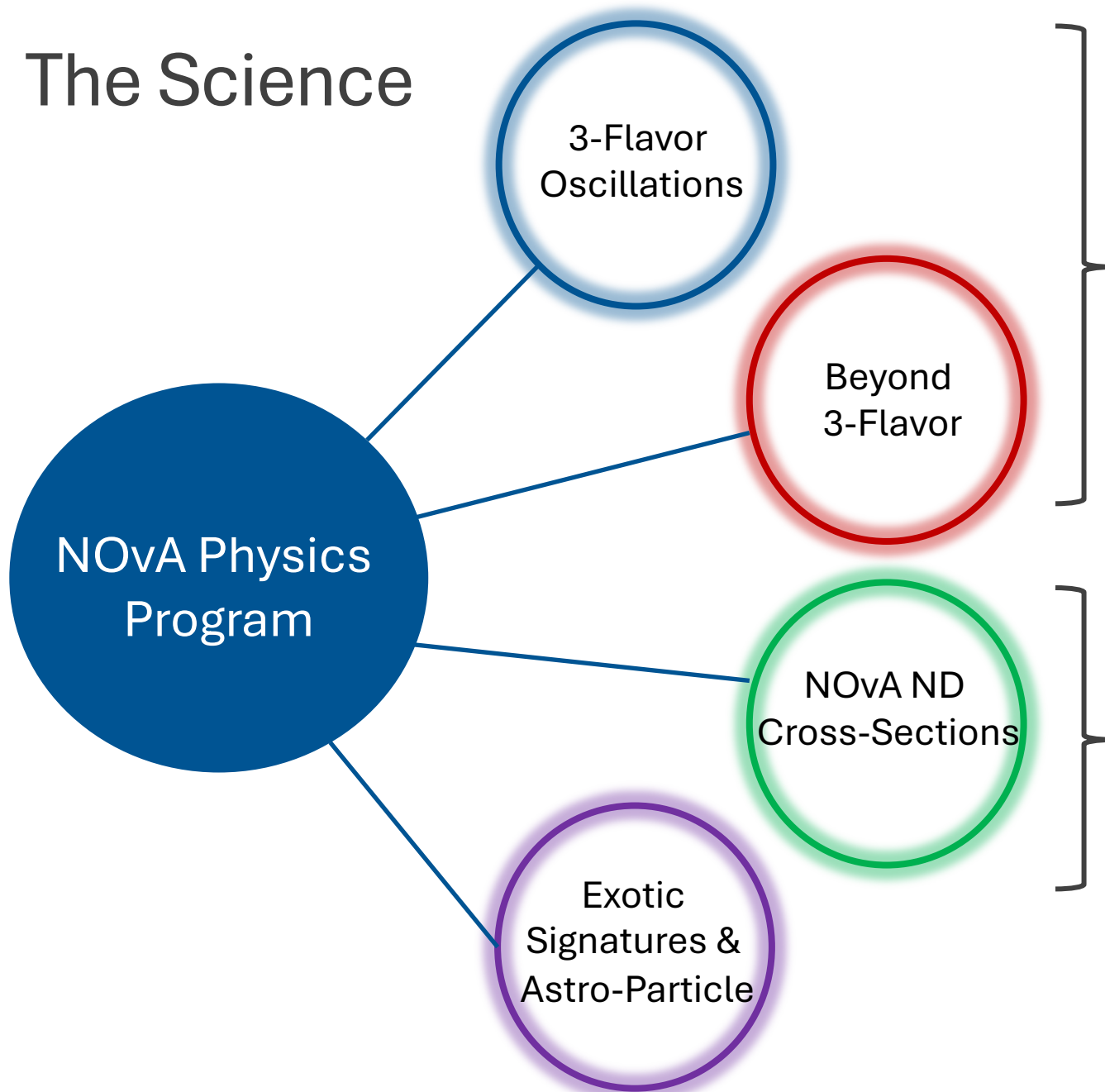


New Content



Posters @ Neutrino

# The Science



# Presented Today

*Legend for this talk*



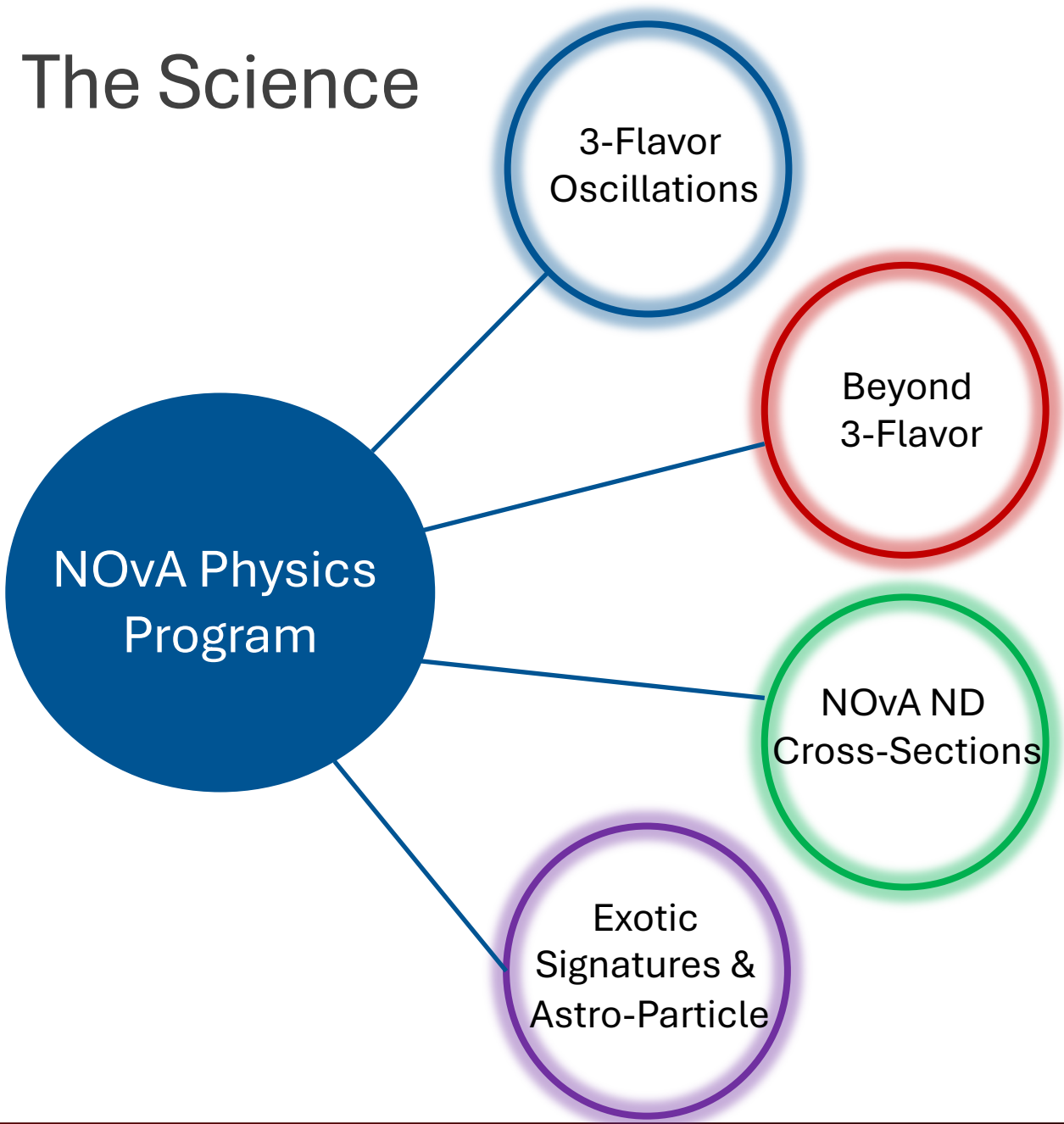
New Content



Posters @ Neutrino

See [Bryan Ramson's talk tomorrow](#)

# The Science



**#70 Charged Pions:** Joshua Barrow, Palash Roy, Ben Utt, Mat Muether, Greg Pawloski

**#138 Single Differential Charged Pion Kinetic Energy:** Erin Ewart

**#95 Neutron Multiplicity:** Georgette Kufatty, Alex Himmel, Mayly Sanchez

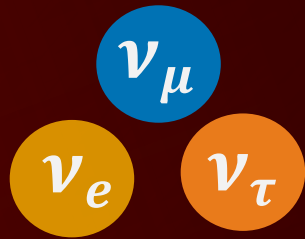
**#185 Charged Current Elastic  $\bar{\nu}_\mu$ -H:** Nibir Talukdar, Roberto Petti

**#190 Charge Current  $\bar{\nu}_\mu$  0 Mesons:** Kevin Vockerodt, Taylor Contreas

**#233 Charged Current 1 Proton:** Colin Weber, Ritesh Kumar Pradhan, Maria Martinez Casales, Josh Barrow, Greg Pawloski

**#442 Neutrino Magnetic Moments:** Sarah Choate, Jane Nachtman

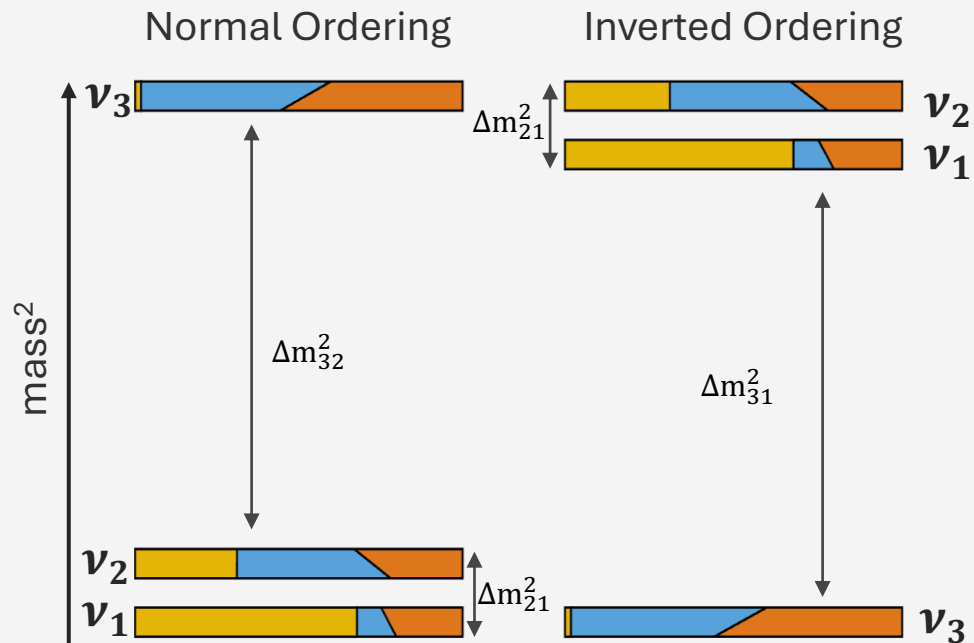
**#461 Atmospheric Neutrino Detection:** Aleksandra Ivanova, Andrey Sheshukov, Oleg Samoylov



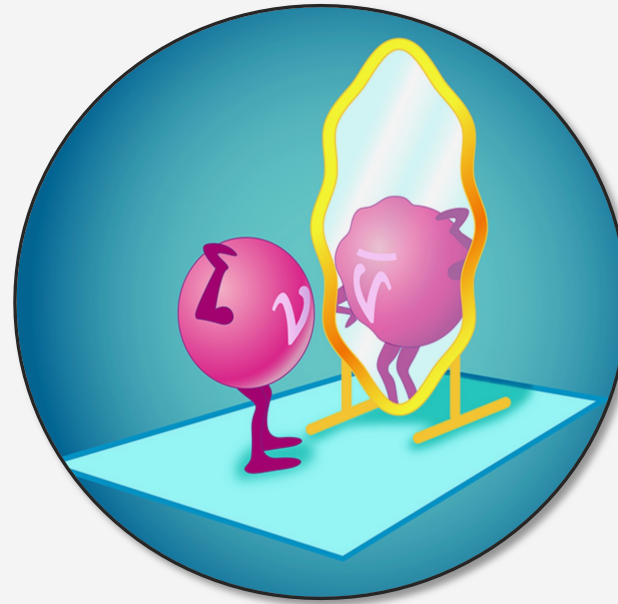
# 3-Flavor Oscillations

# Physics Goals

$\nu$  Mass Ordering (MO):  
Normal (NO) or Inverted (IO)?

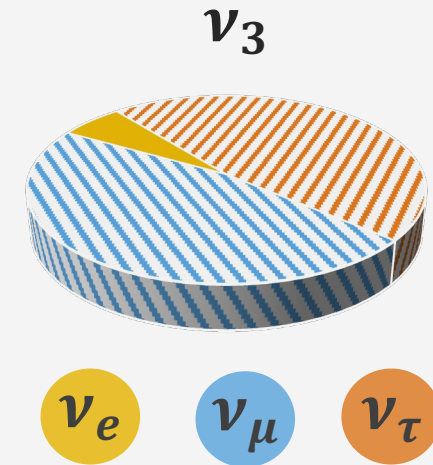


Parameters from NuFit6.1



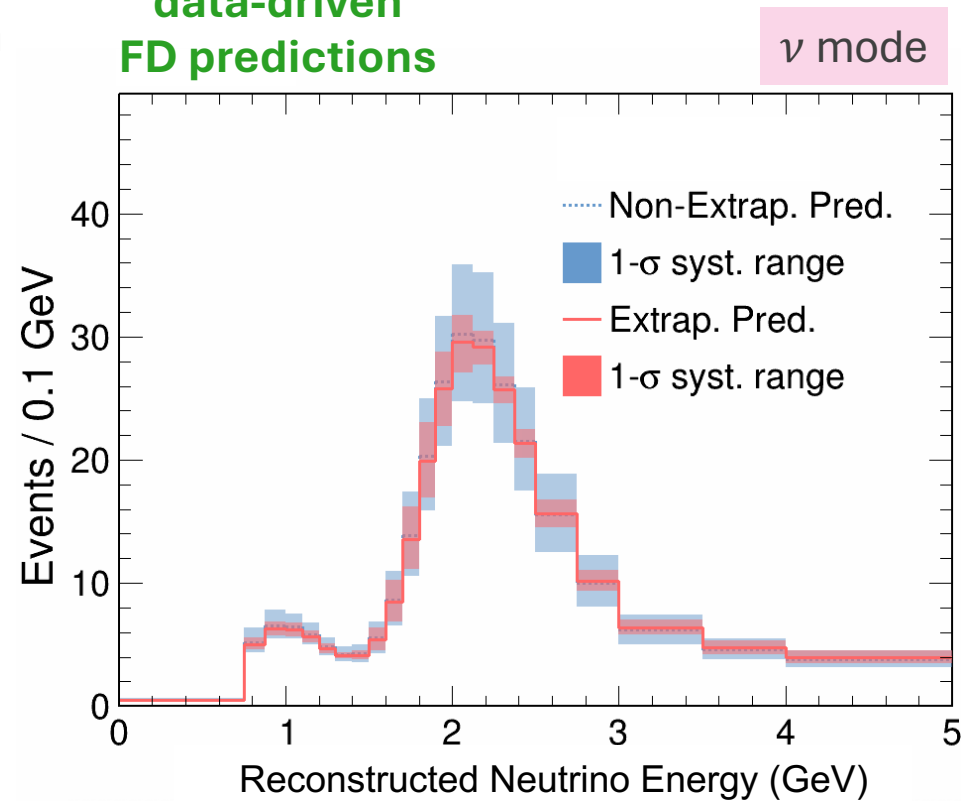
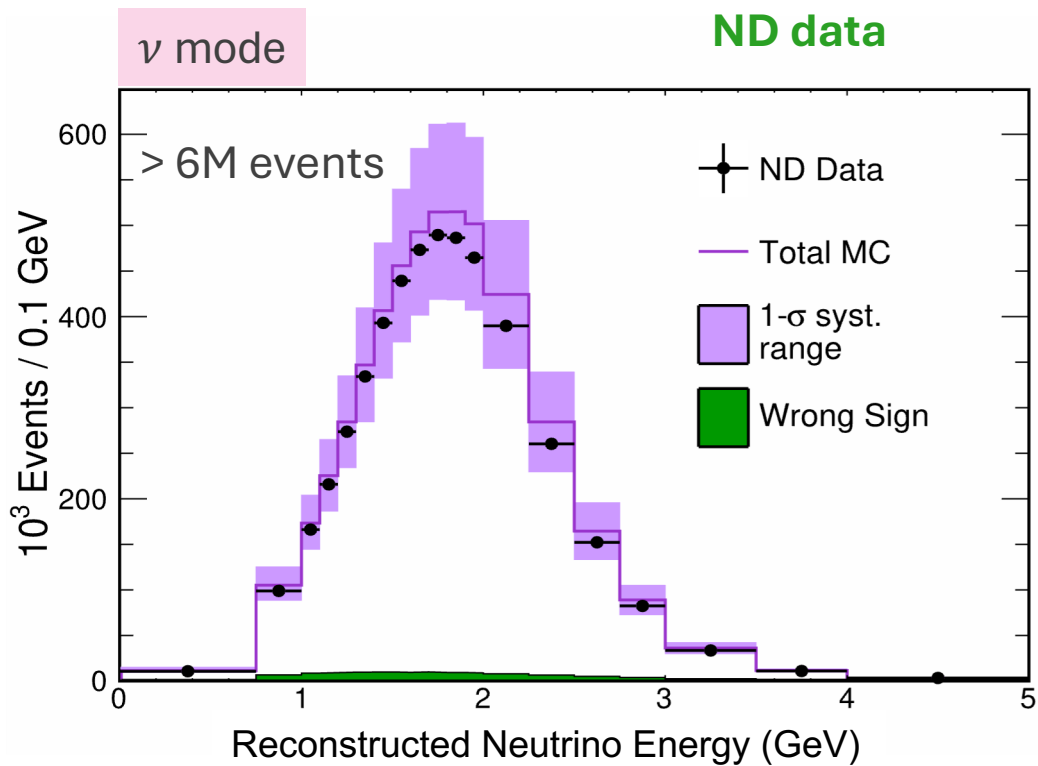
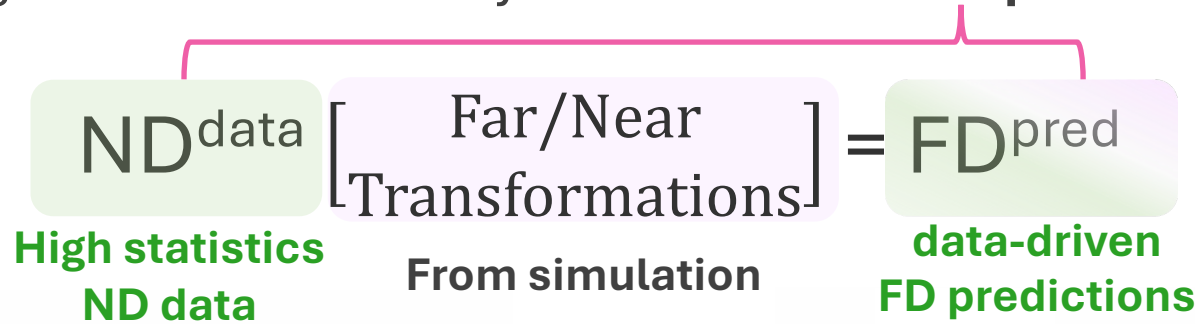
Do neutrinos violate the  
Charge Parity symmetry?  
Is  $\sin \delta_{CP} = 0$ ?

Is the  $\theta_{23}$  mixing maximal?  
If  $\theta_{23} = 45^\circ \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$



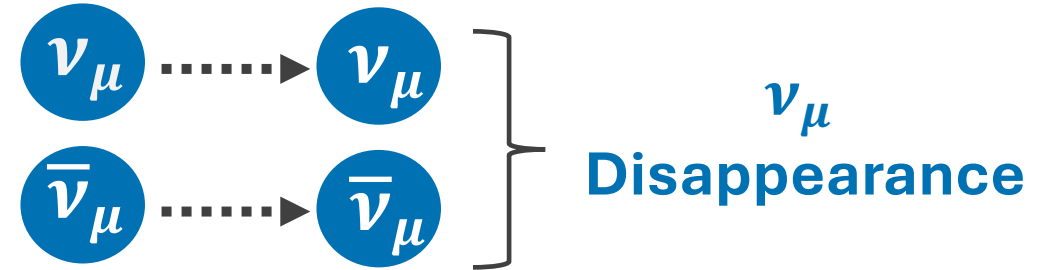
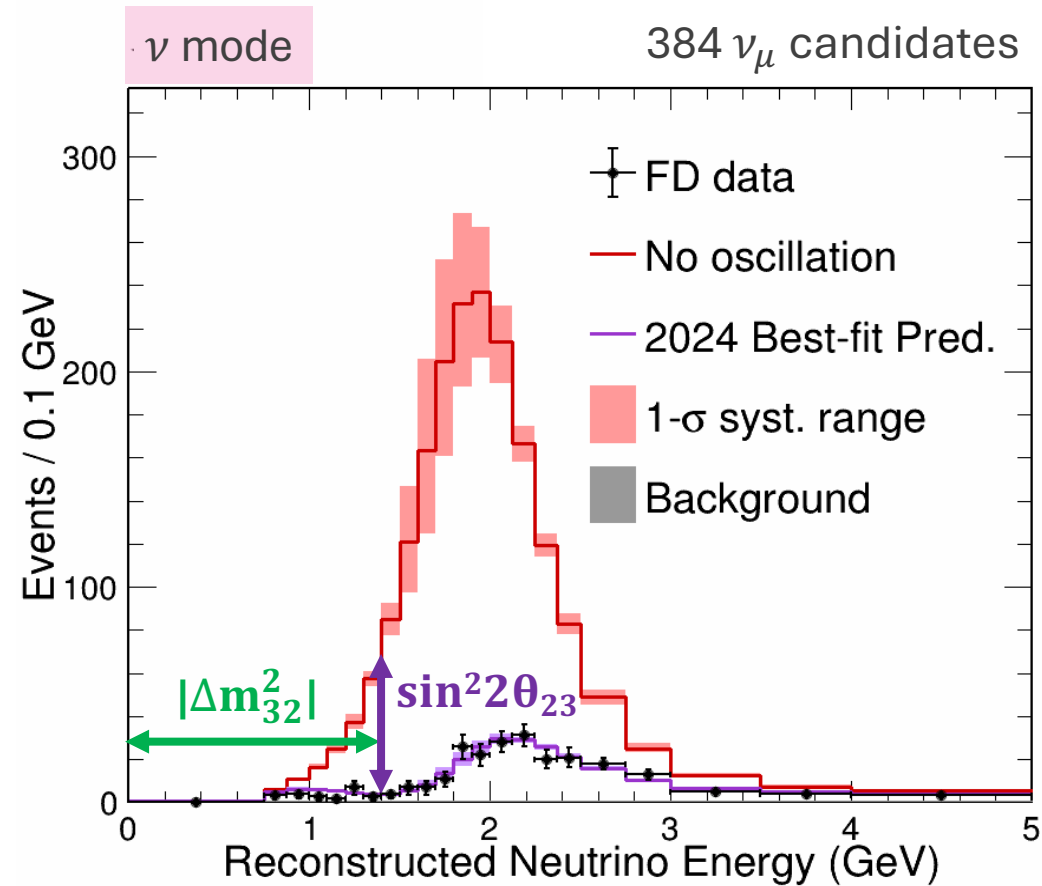
# 3-Flavor Oscillations in NOvA

- **No oscillations at ND.** Leverage identical ND design to build data-driven FD predictions and significant control of systematics via **Extrapolation.**



# 3-Flavor Oscillations in NOvA

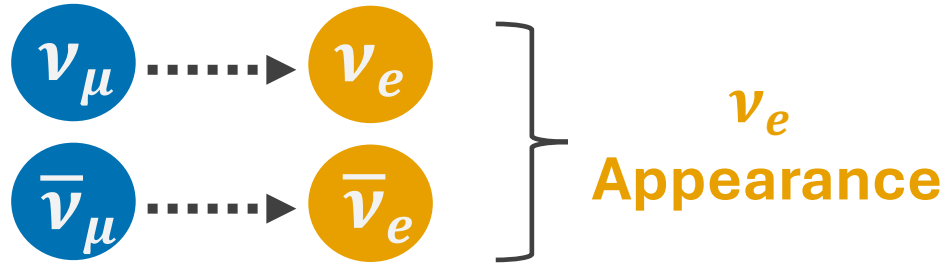
- Two complementary oscillation channels at the FD.



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

# 3-Flavor Oscillations in NOvA

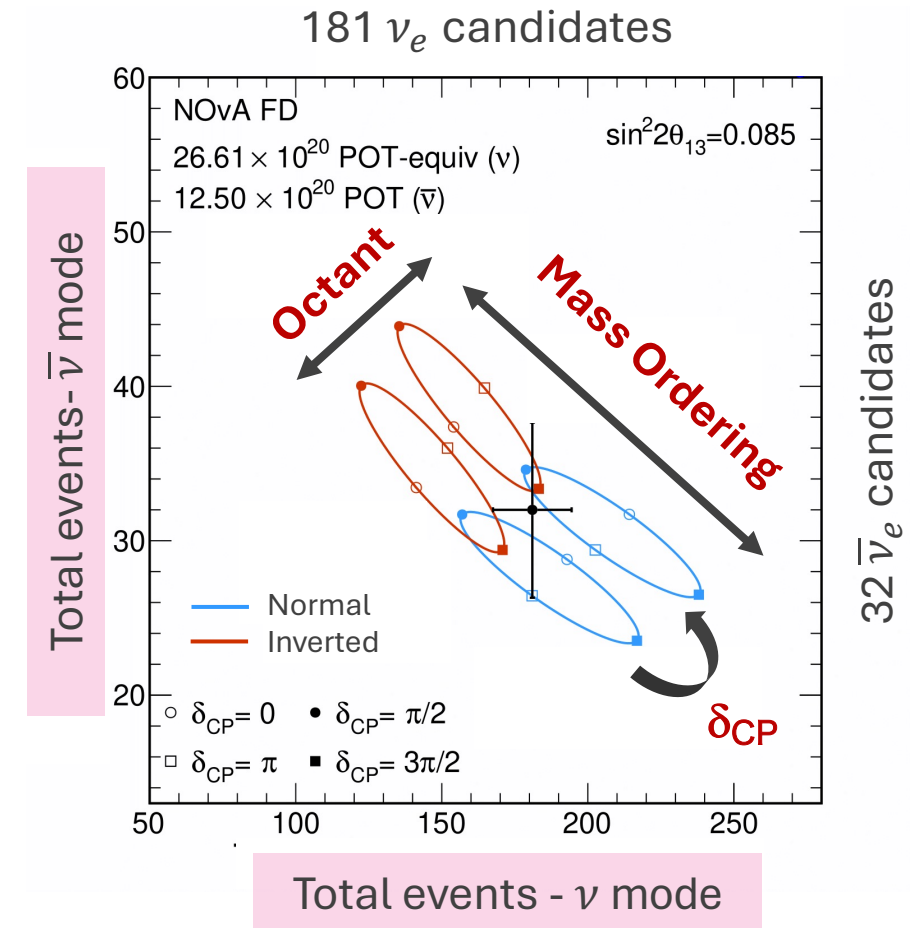
- Two complementary oscillation channels at the FD.



$$P\left(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\right) \simeq \underbrace{\sin^2 \theta_{23} \sin^2 2\theta_{13}}_{\text{Leading amplitude}} \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2$$

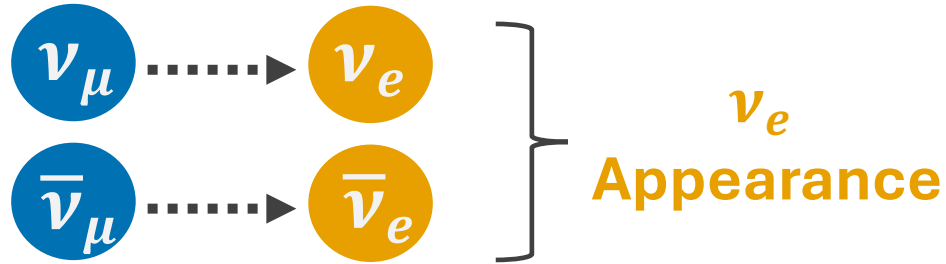
$\mp$  [CP-odd] + [CP-even] + [solar]

- Leading amplitude  $\propto \sin^2 \theta_{23} \times \sin^2 2\theta_{13}$
- External constraint on  $\theta_{13} \rightarrow$  resolves the **octant**.



# 3-Flavor Oscillations in NOvA

- Two complementary oscillation channels at the FD.

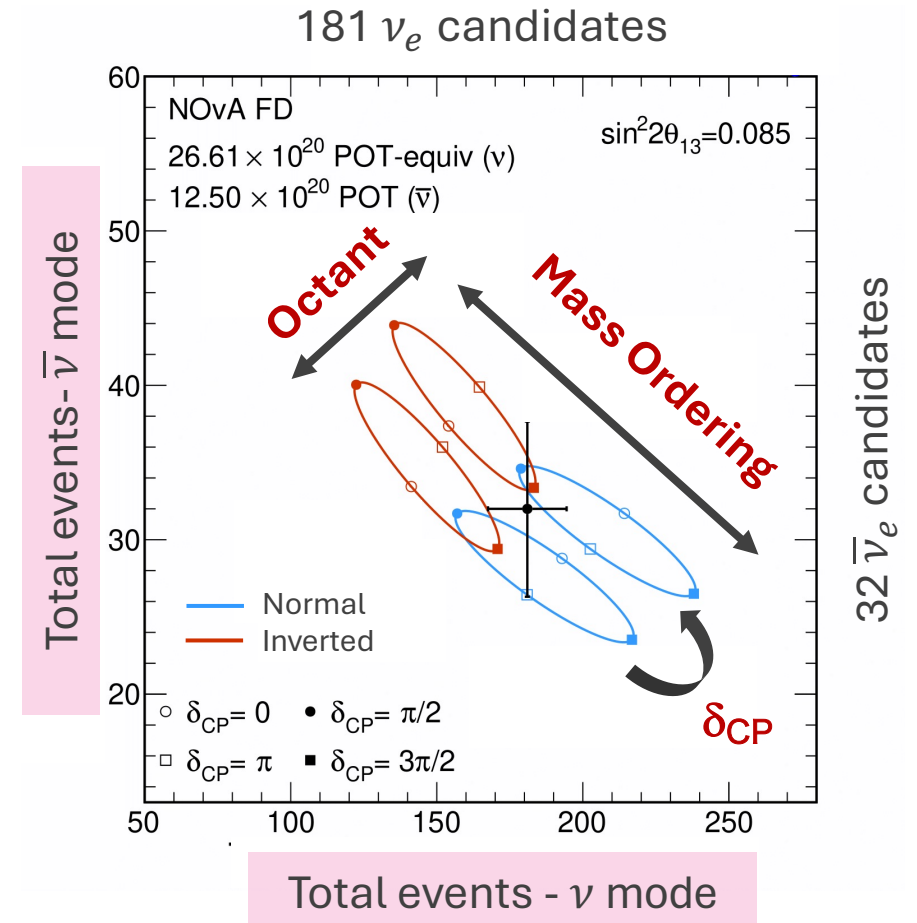


$$P\left(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}\right) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2$$

$\mp$  [CP-odd] + [CP-even] + [solar]

$\sin \delta_{CP}$

- Both Mass Ordering and  $\delta_{CP}$  term switch signs and create asymmetry in  $\nu_e$  vs  $\bar{\nu}_e$  appearance probability.



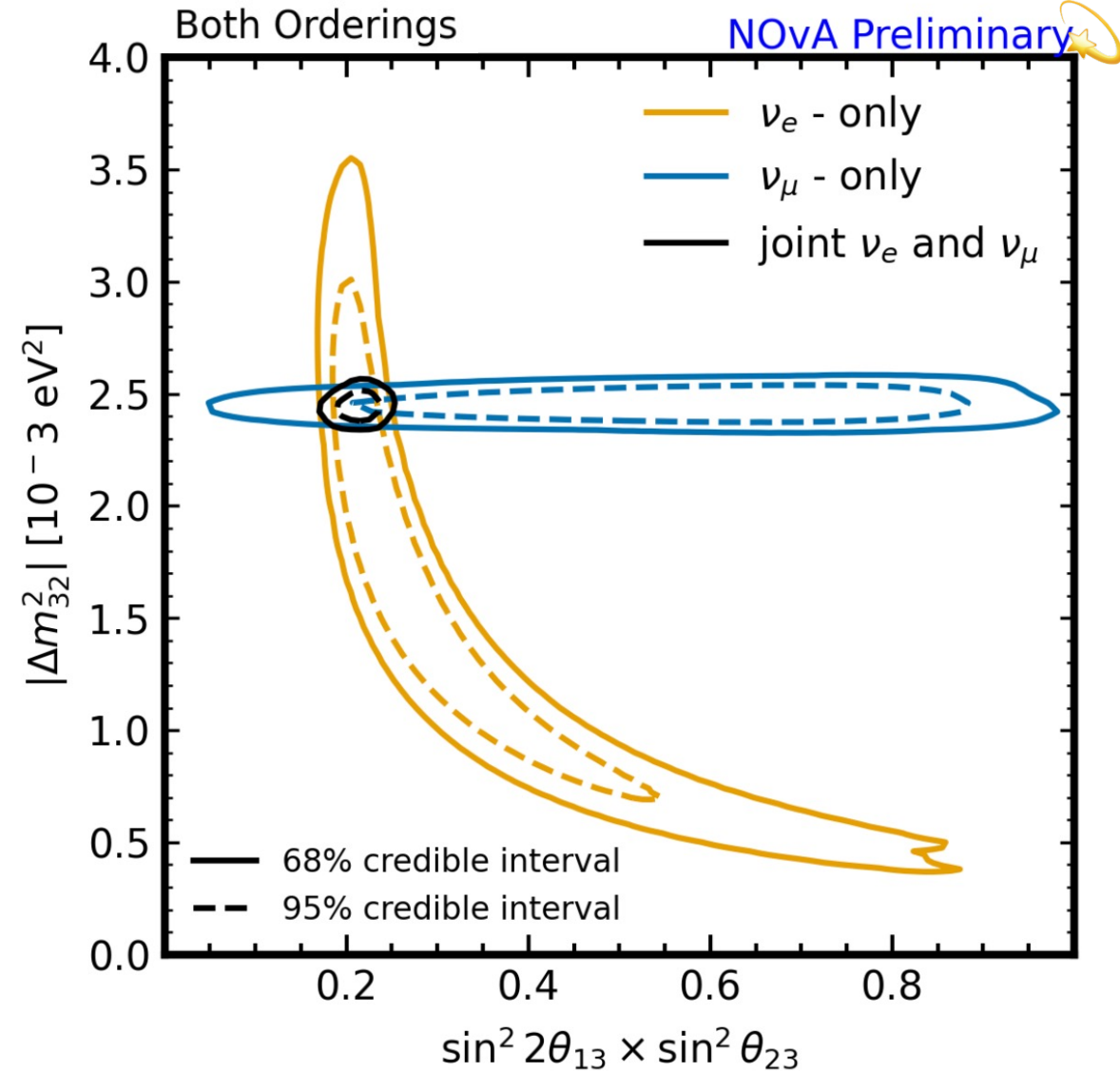
# $\nu_\mu$ vs $\nu_e$ vs $(\nu_\mu + \nu_e)$ data fits

Full 10-year dataset results:  
NOvA PRL 136, 01180 (2026)

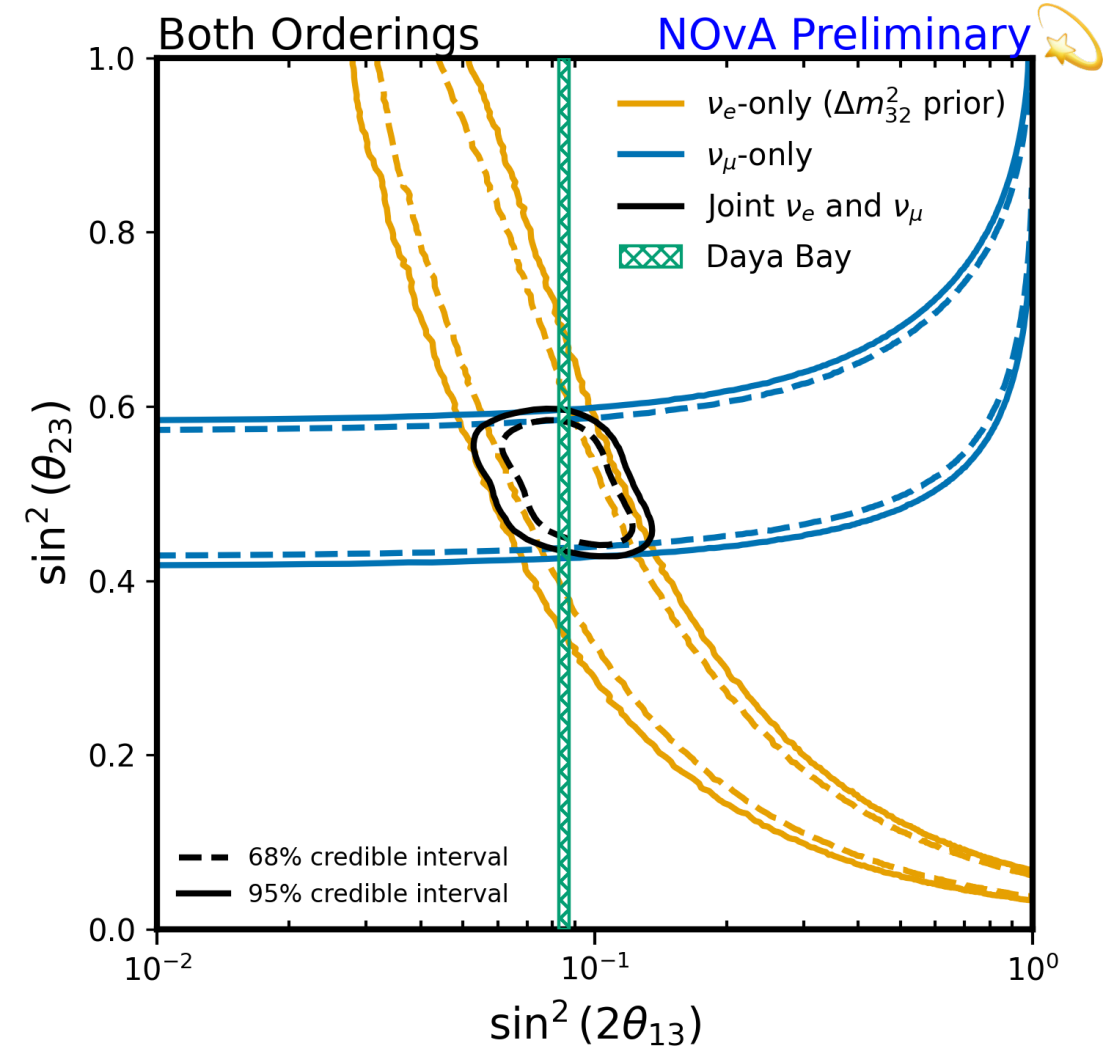
🌟 New today: 🌟

Stress test the 3-Flavor paradigm  
Fit the  $\nu_\mu$  only and  $\nu_e$  only subsamples separately on the same 10-year dataset!

- Measurements are correlated in 5D ( $\Delta m_{32}^2$ ,  $\sin^2 2\theta_{13}$ ,  $\sin^2 \theta_{23}$ , MO,  $\delta_{CP}$ ) space.
- $\Delta m_{32}^2$  is constrained by  $\nu_\mu$  disappearance.
- $\nu_e$  appearance amplitude is degenerate in  $\sin^2 2\theta_{13} \times \sin^2 \theta_{23}$ .



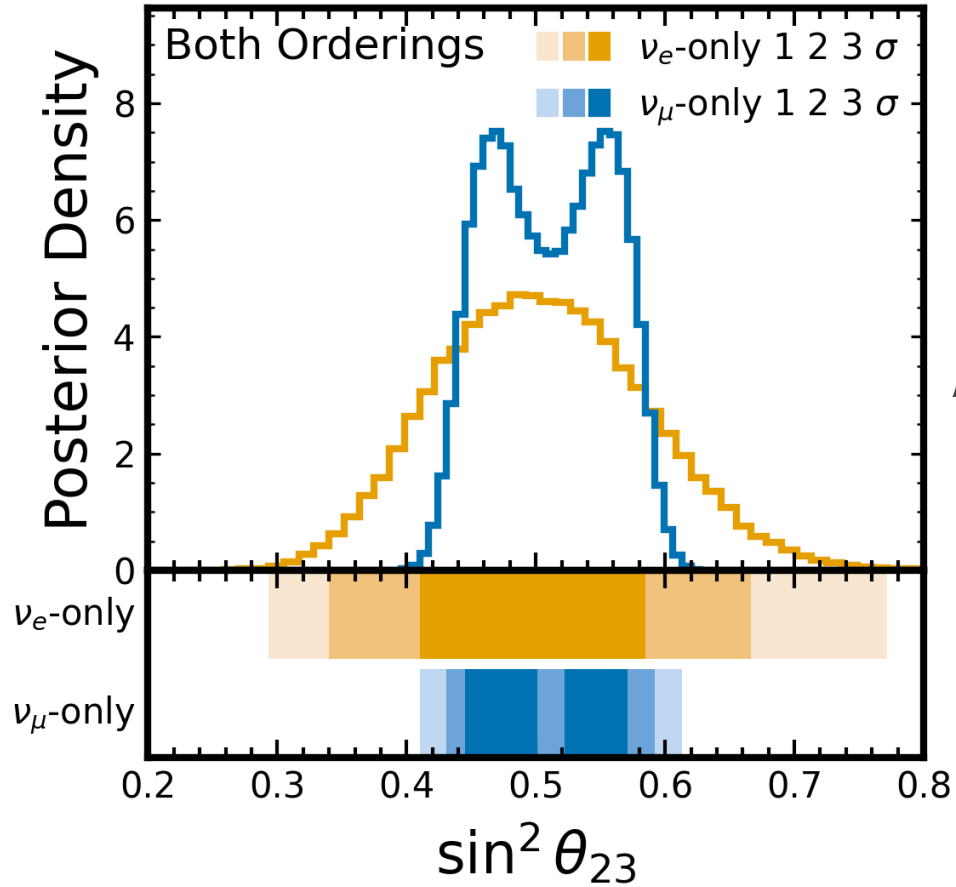
# $\nu_\mu$ vs $\nu_e$ vs $(\nu_\mu + \nu_e)$ data fits



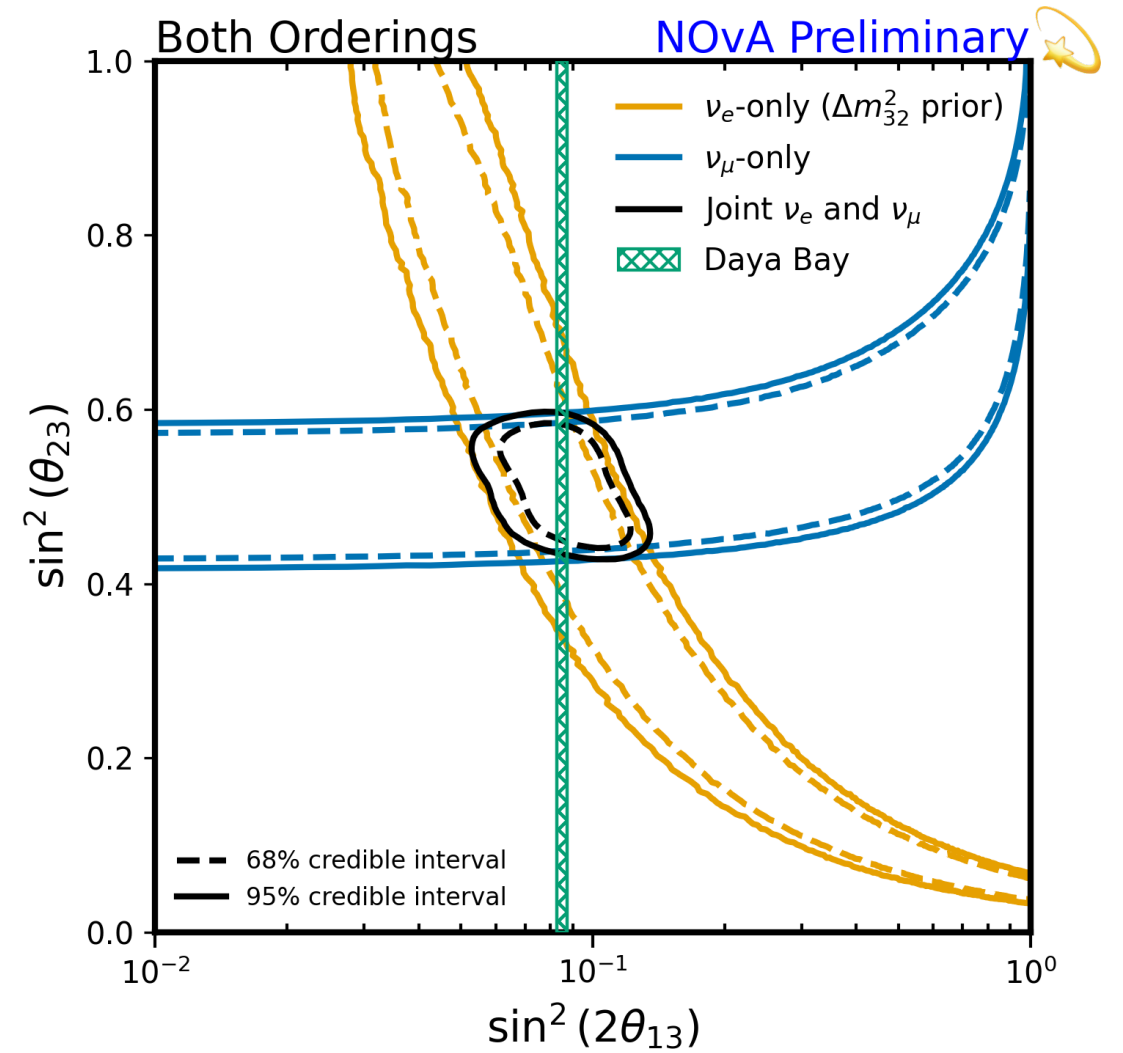
Excellent consistency across  $\nu_\mu$  only,  $\nu_e$  only, and  $\sin^2 2\theta_{13}$  from reactor demonstrates robustness of 3-flavor paradigm.

# $\nu_\mu$ VS $\nu_e$ VS $(\nu_\mu + \nu_e)$ data fits

NOvA Preliminary



Adding  $\sin^2 2\theta_{13}$  constraint from Daya Bay

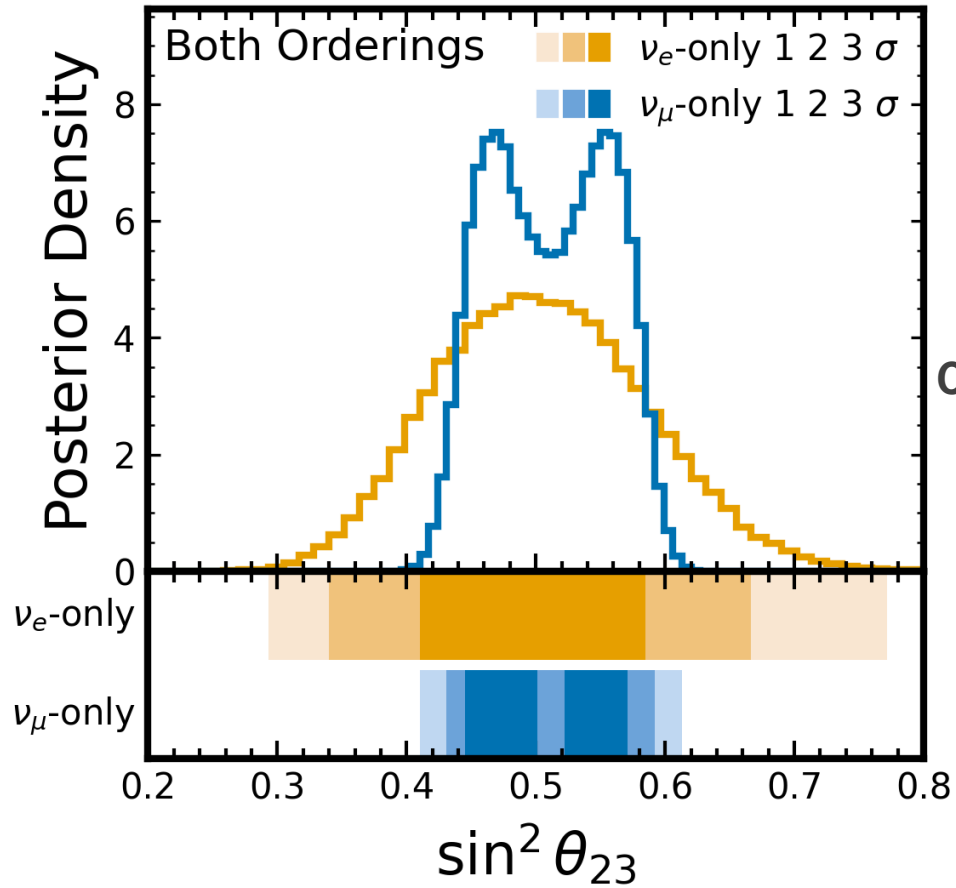


Both  $\nu_\mu$  only,  $\nu_e$  only are consistent with maximal mixing.

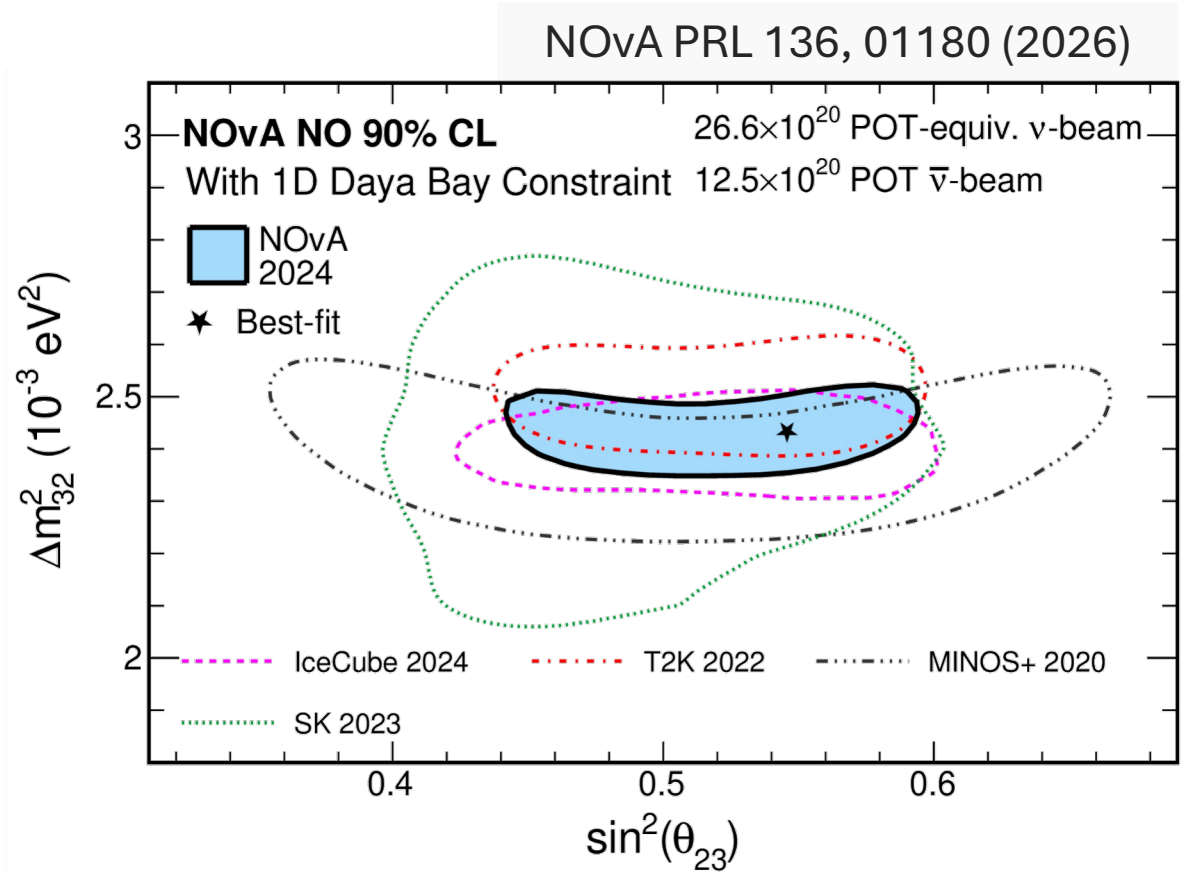
Excellent consistency across  $\nu_\mu$  only,  $\nu_e$  only, and  $\sin^2 2\theta_{13}$  from reactor demonstrates robustness of 3-flavor paradigm.

# $\nu_\mu$ VS $\nu_e$ VS $(\nu_\mu + \nu_e)$ data fits

NOvA Preliminary 

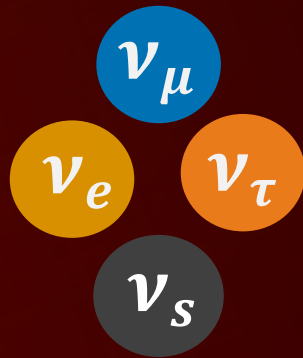


Combined fit of all samples retrieves PRL results.



Both  $\nu_\mu$  only,  $\nu_e$  only are consistent with maximal mixing.

Global agreement among atmospheric and accelerator experiments.



# Beyond 3-Flavor: Sterile Neutrinos

# A fourth neutrino?



3 x 3 Standard Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

4 x 4 Steriles Mixing Matrix

requires new mixing angles and CP violating phases  $\theta_{14}, \theta_{24}, \theta_{34}, \delta_{14}, \delta_{24}$

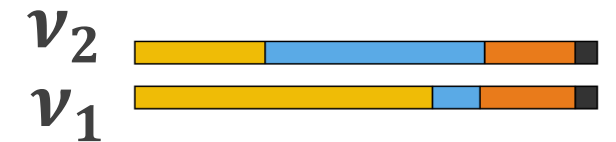
- Motivated by long standing anomalies in the short-baseline oscillation experiments.



$$\Delta m_{41}^2 \approx 1 \text{ eV}^2$$

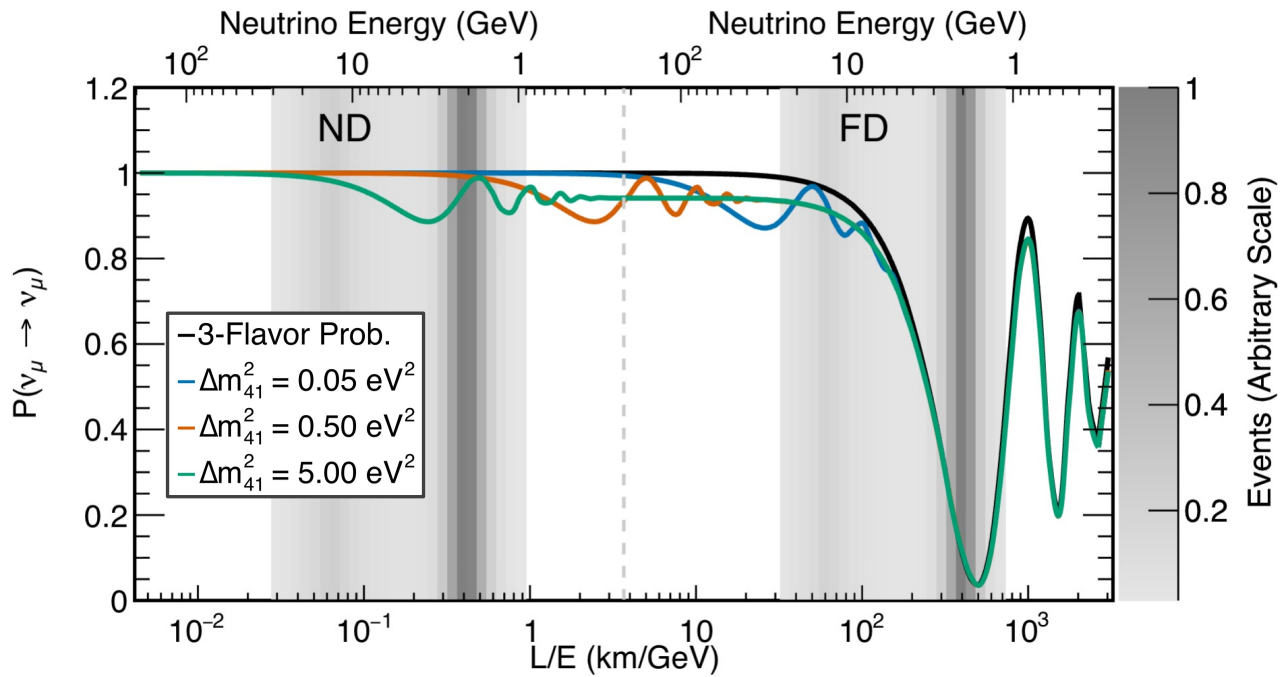
$$|\Delta m_{31}^2| \sim 2 \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{21}^2 \sim 7 \times 10^{-5} \text{ eV}^2$$



# Steriles in NOvA

CC Disappearance



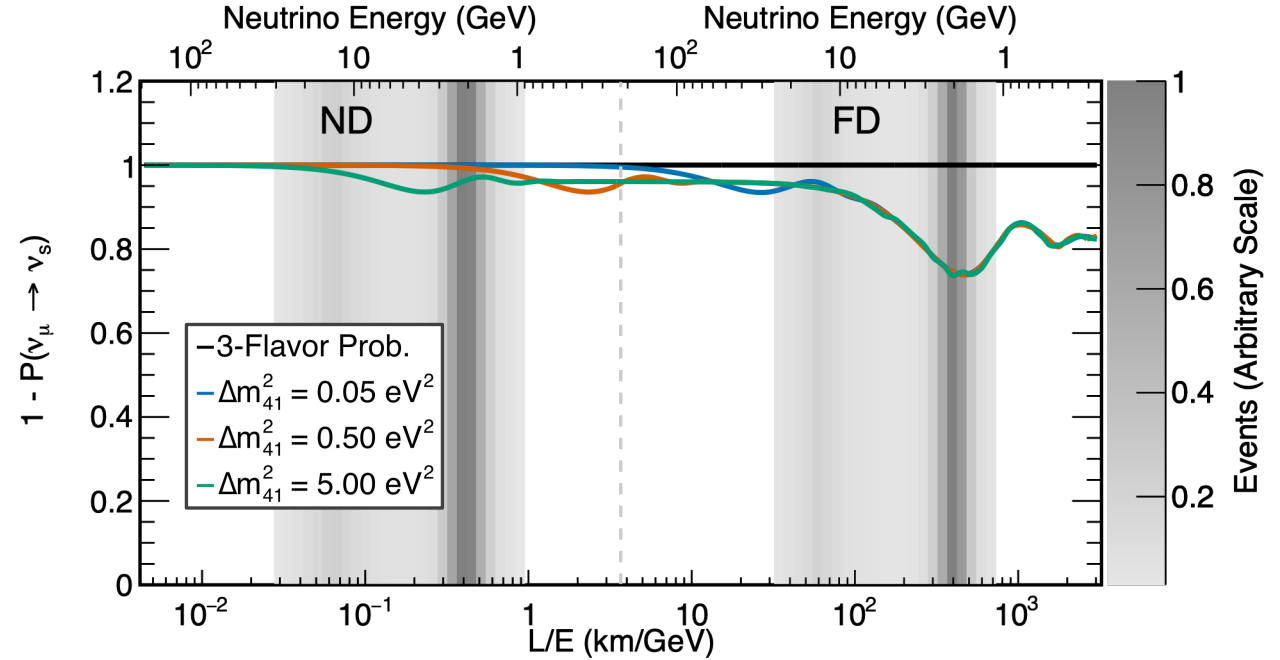
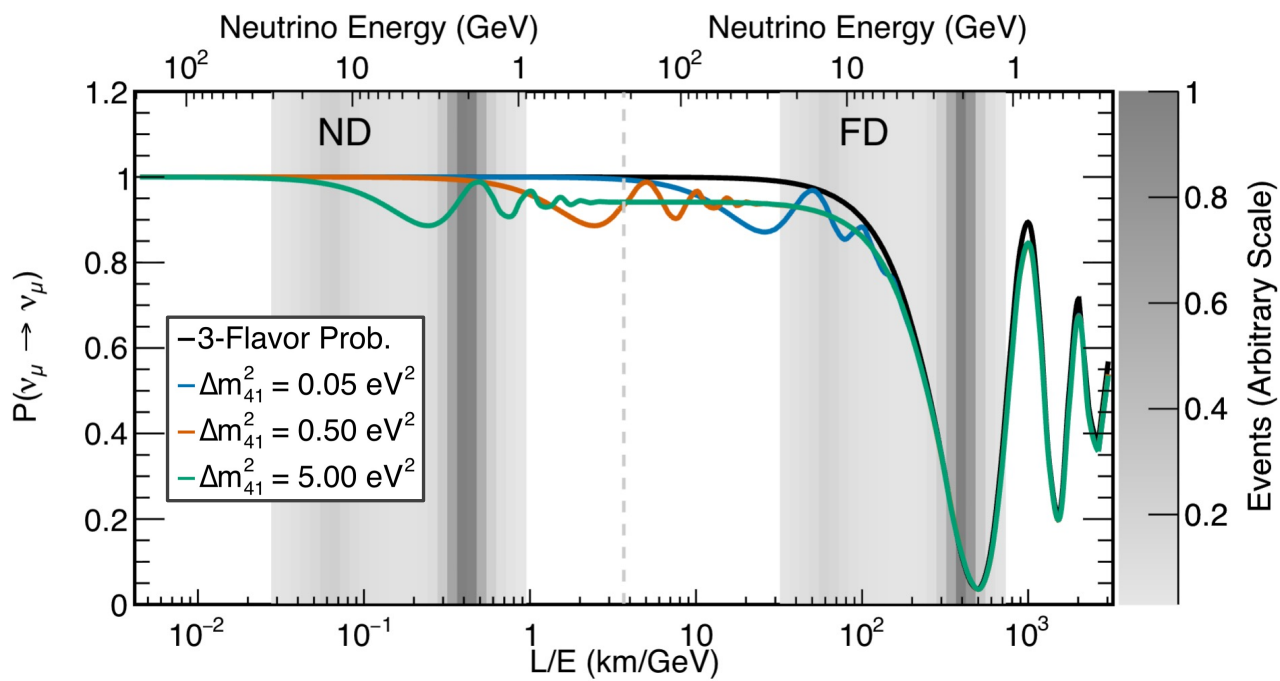
**Enhanced CC Disappearance in addition to 3-Flavor oscillations**

# Steriles in NOvA

CC Disappearance



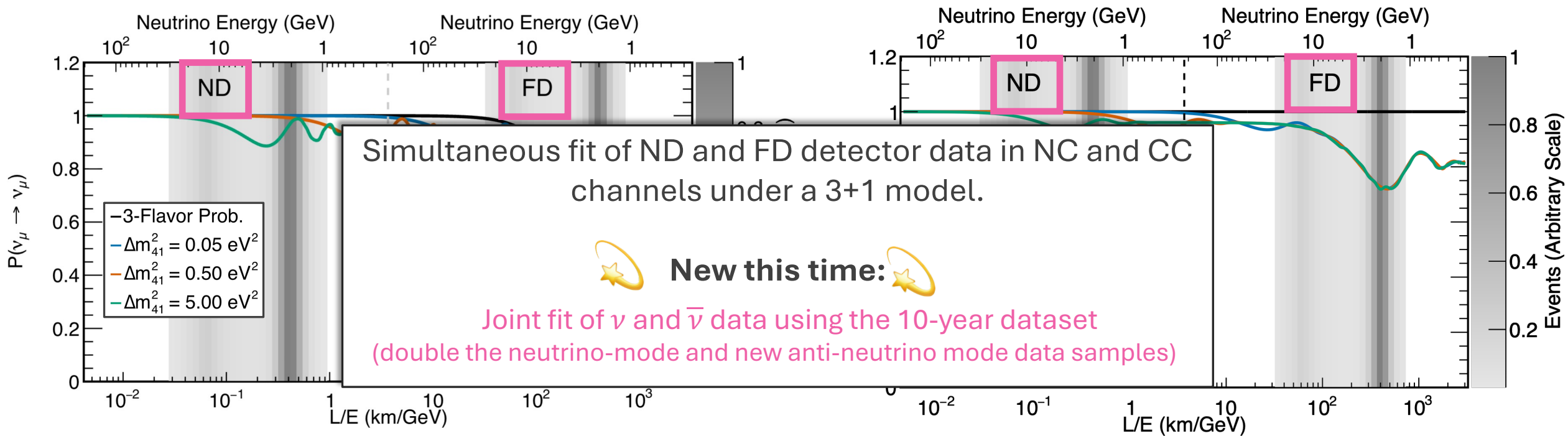
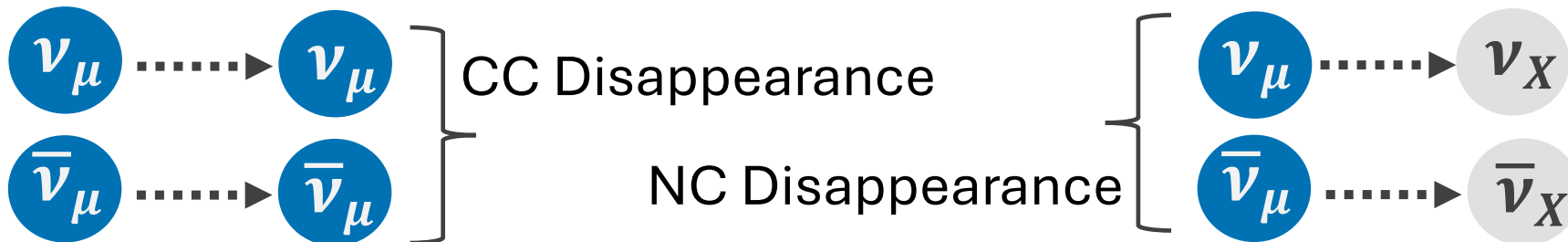
NC Disappearance



**Enhanced CC Disappearance in addition to 3-Flavor oscillations**

**No NC Disappearance for 3-Flavor oscillations**

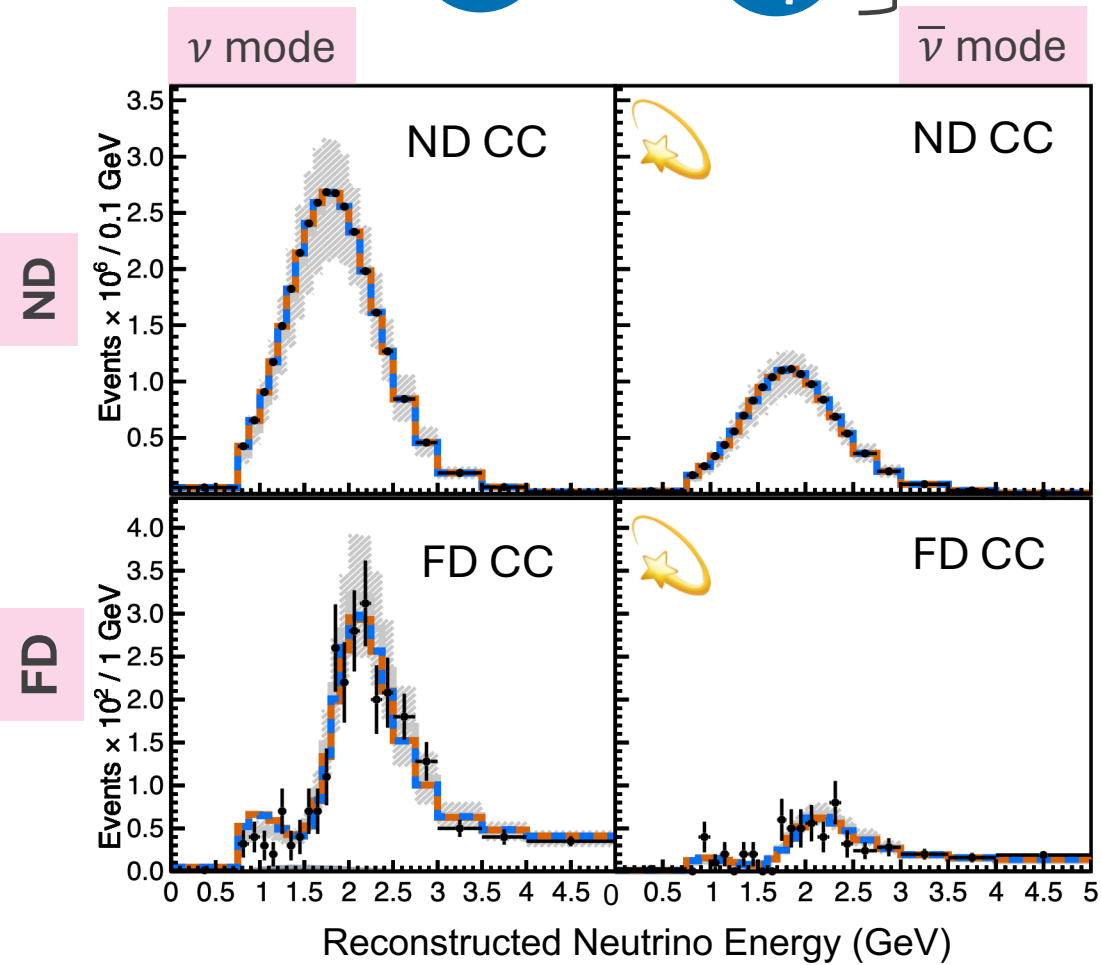
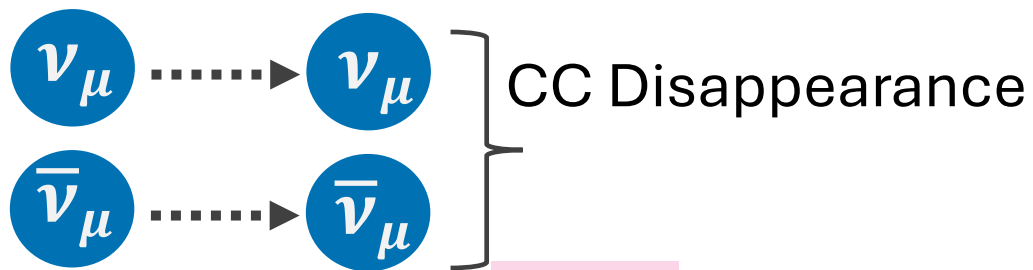
# Steriles in NOvA



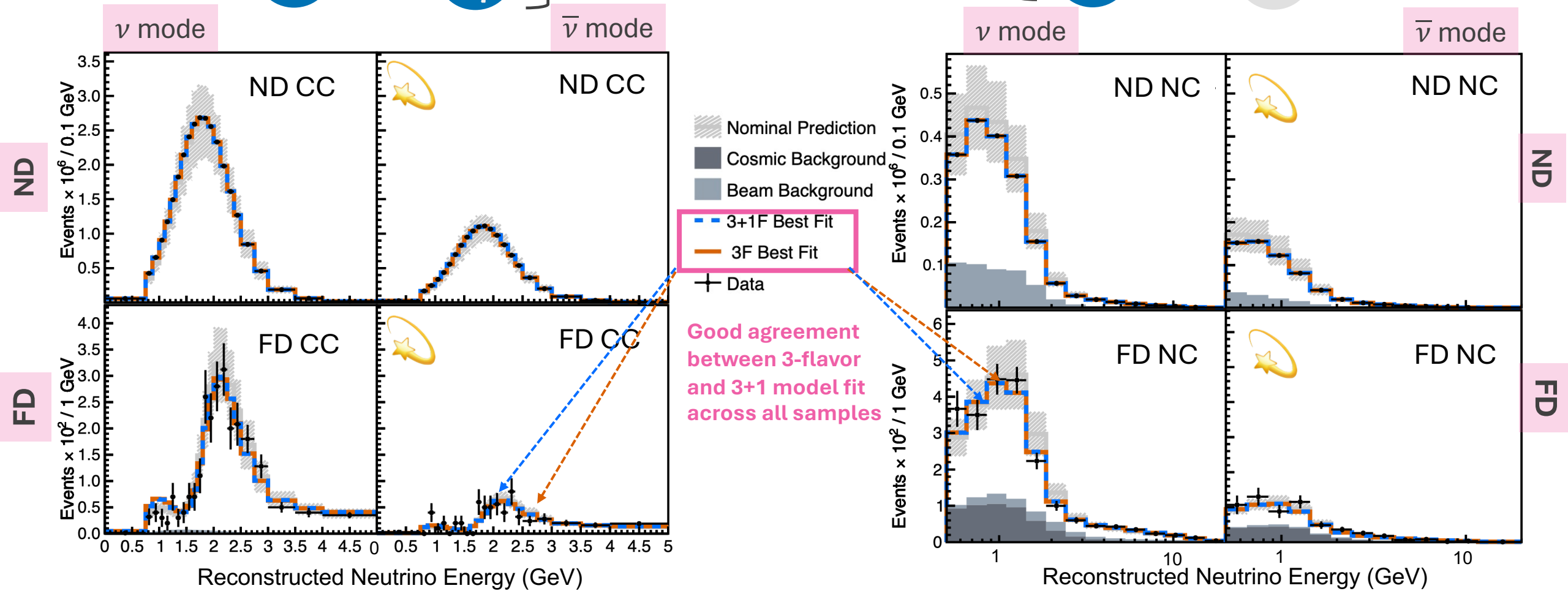
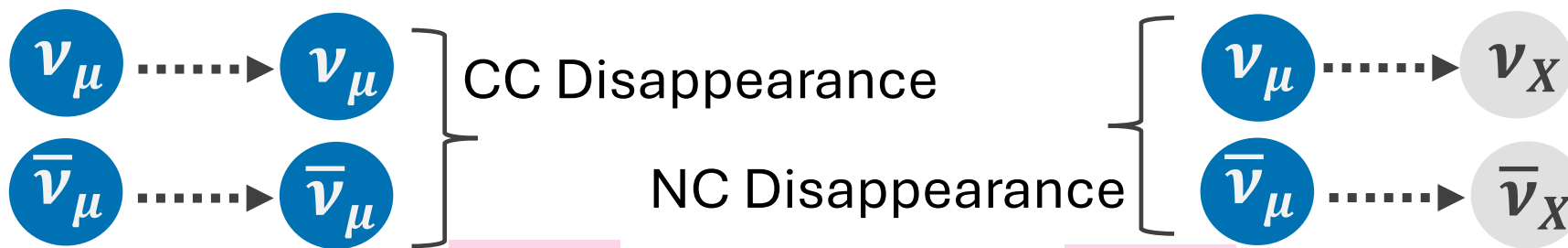
**Enhanced CC Disappearance in addition to 3-Flavor oscillations**

**No NC Disappearance for 3-Flavor oscillations**

# Steriles in NOvA



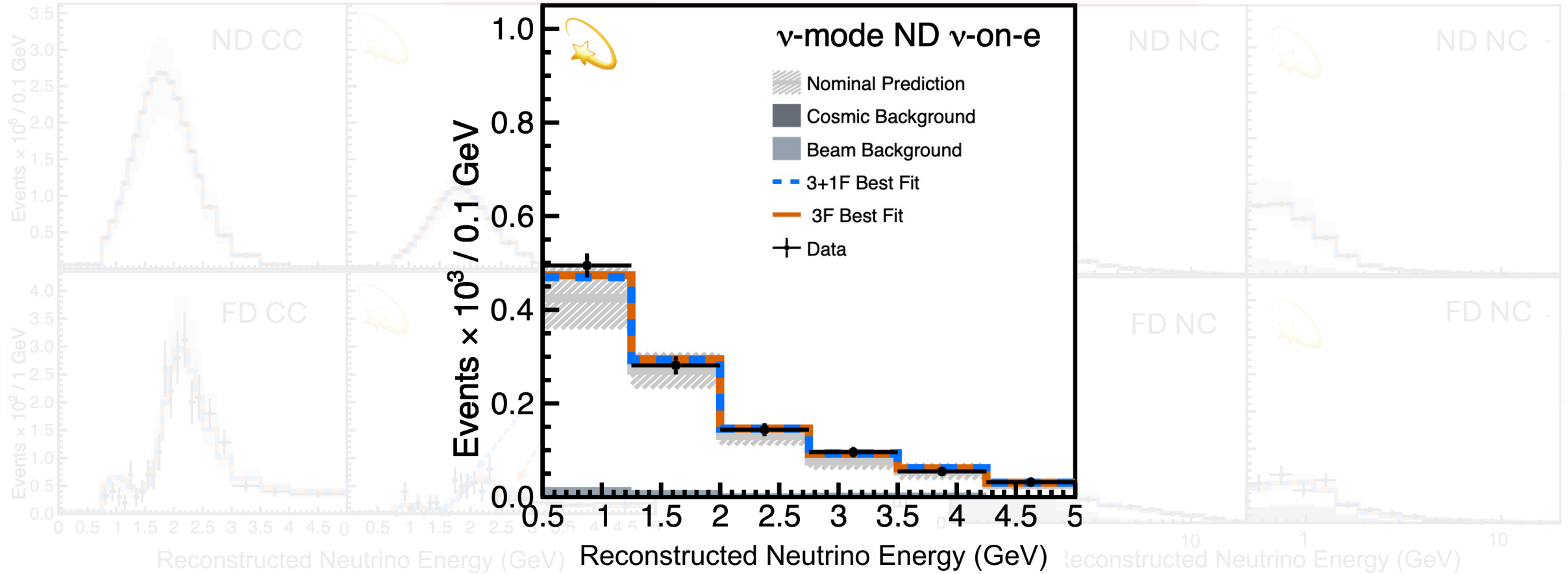
# Steriles in NOvA



# Steriles in NOvA

#157 ND  $\nu$ -on-e scattering : Yiwen Xiao

New ND  $\nu$ -on-e scattering sample  
constrains beam systematics through its  
precisely known cross-section



# Steriles in NOvA

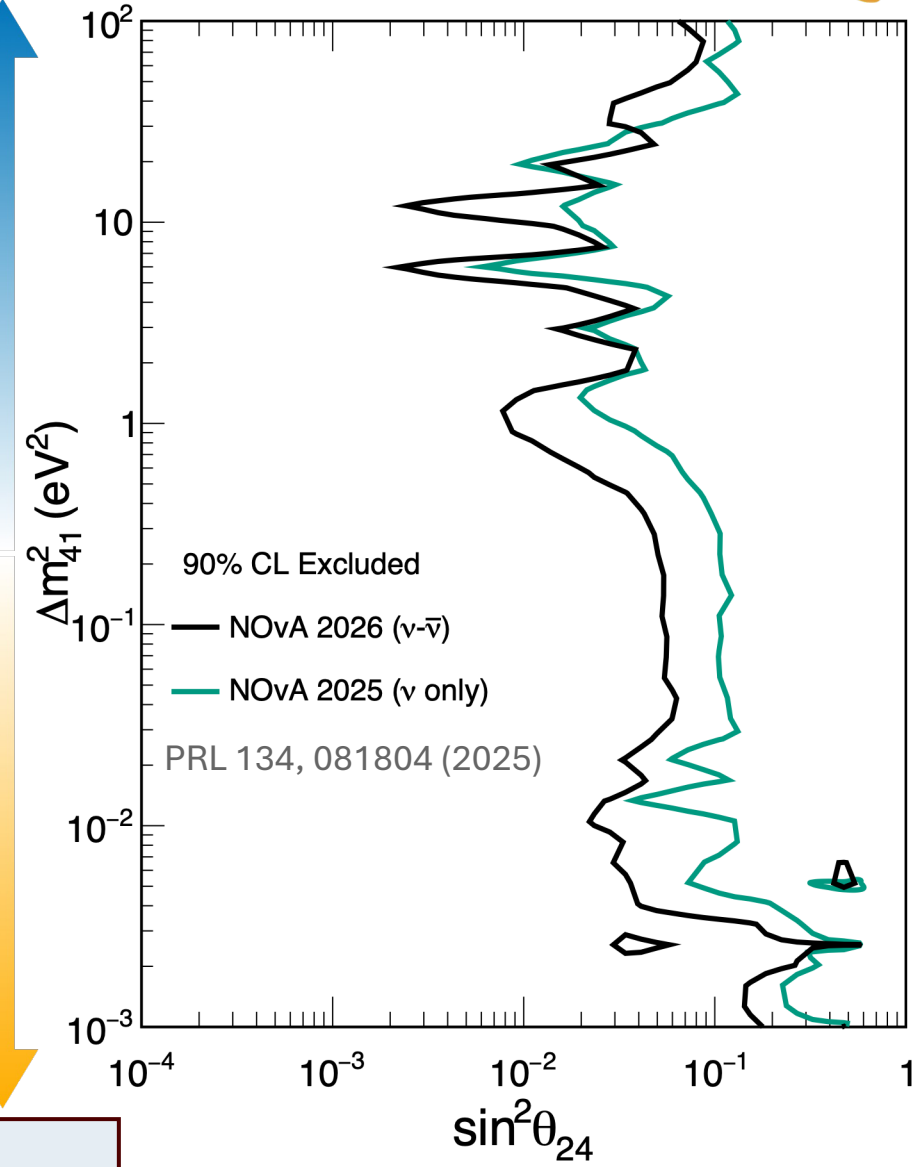
$\nu\bar{\nu}$  Beam



**High  $\Delta m_{41}^2$ : fast oscillations**  
Driven by high-statistics ND Data  
Systematics limited

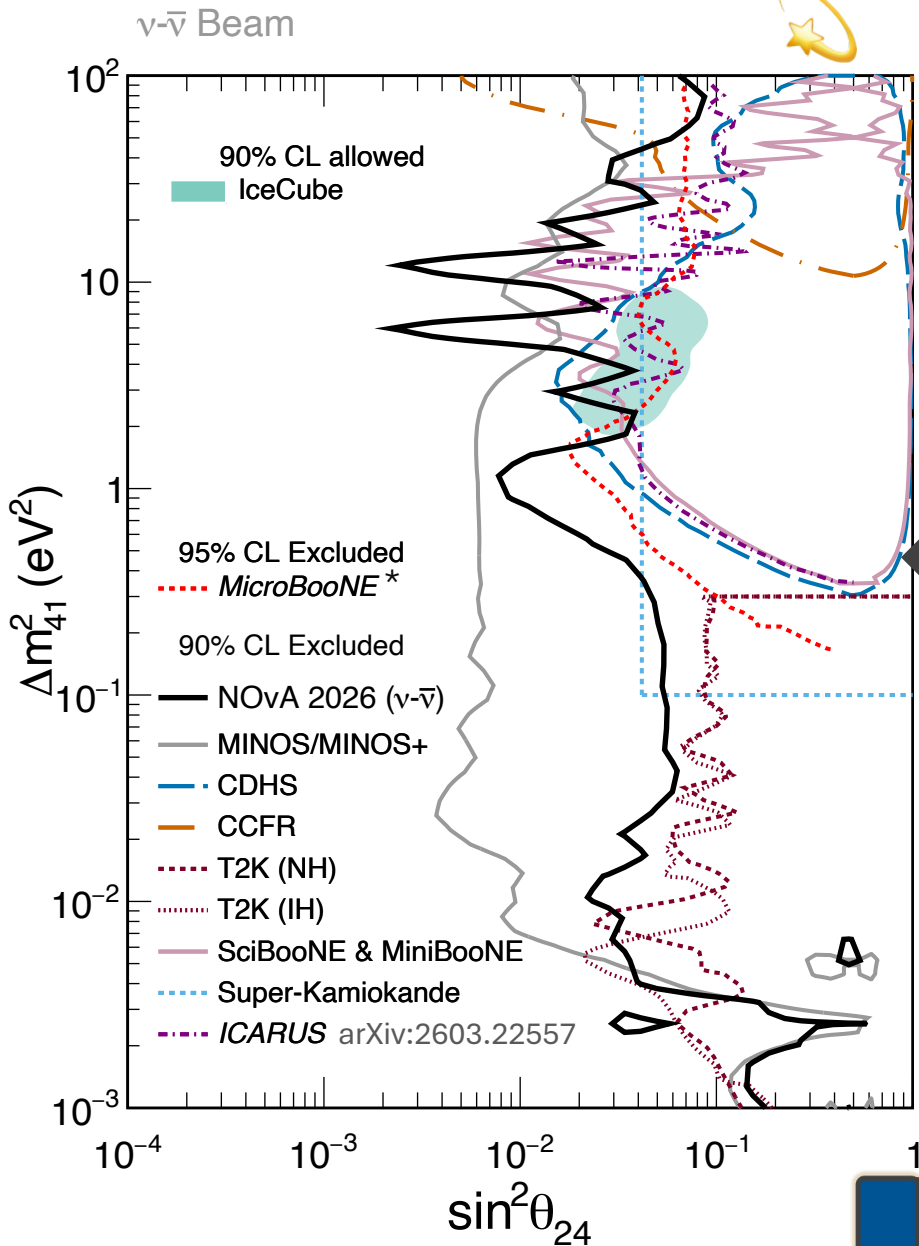
**Significantly improved limits  
beyond previous NOvA  
results.**

**Low  $\Delta m_{41}^2$ : slow oscillations**  
Driven by low-statistics FD Data  
Statistics limited



**#195 NOvA Steriles 2026:** Shivam Chaudhary, Adam Lister, Adam Aurisano

# Steriles in NOvA



**High  $\Delta m_{41}^2$ : fast oscillations**  
 Driven by high-statistics ND Data  
 Systematics limited

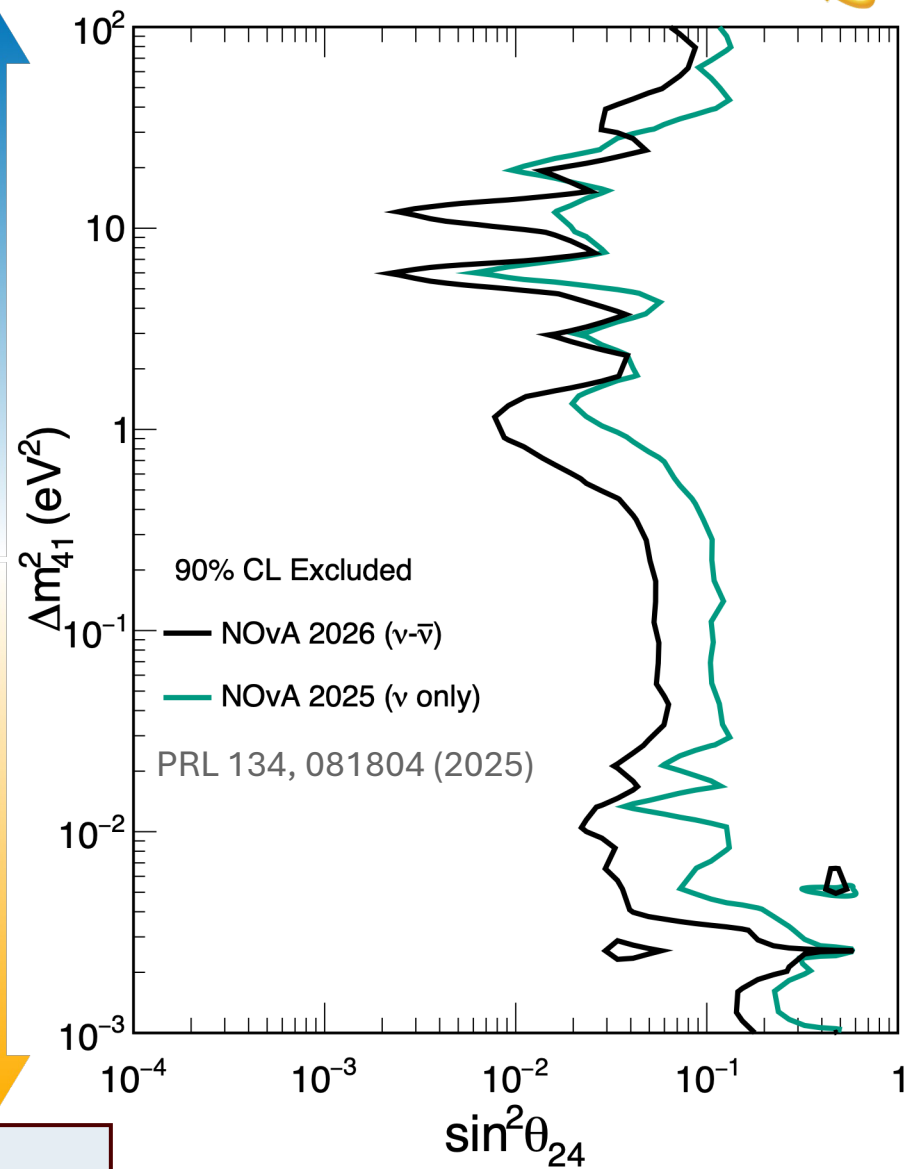
**Significantly improved limits beyond previous NOvA results.**

**World-leading at high  $\Delta m_{41}^2$**

**Excludes most of the region allowed by IceCube at 90% CL.**

**Low  $\Delta m_{41}^2$ : slow oscillations**  
 Driven by low-statistics FD Data  
 Statistics limited

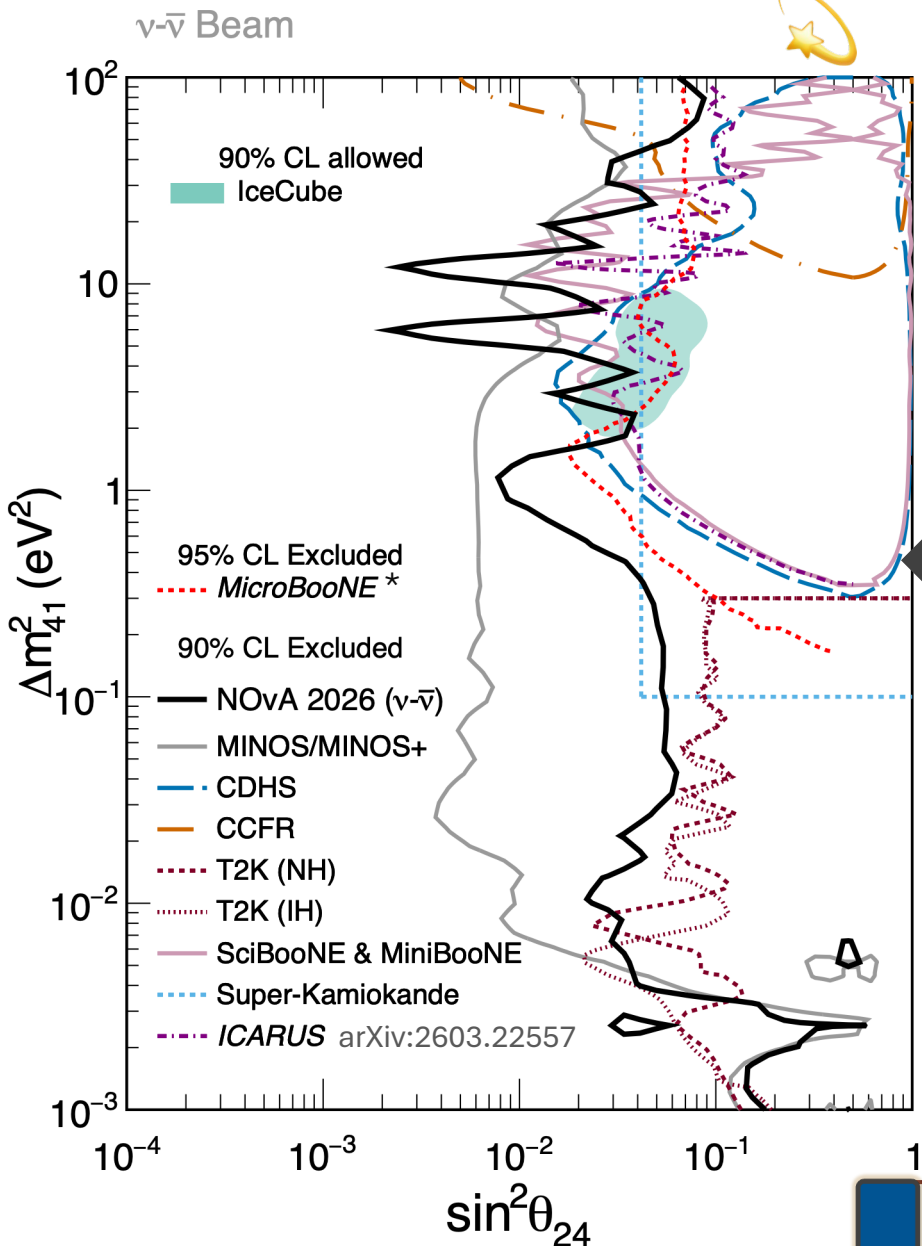
$\nu$ - $\bar{\nu}$  Beam



**#195 NOvA Steriles 2026:** Shivam Chaudhary, Adam Lister, Adam Aurisano

\*From [MicroBooNE's Neutrino 2026 Results](#)

# Steriles in NOvA

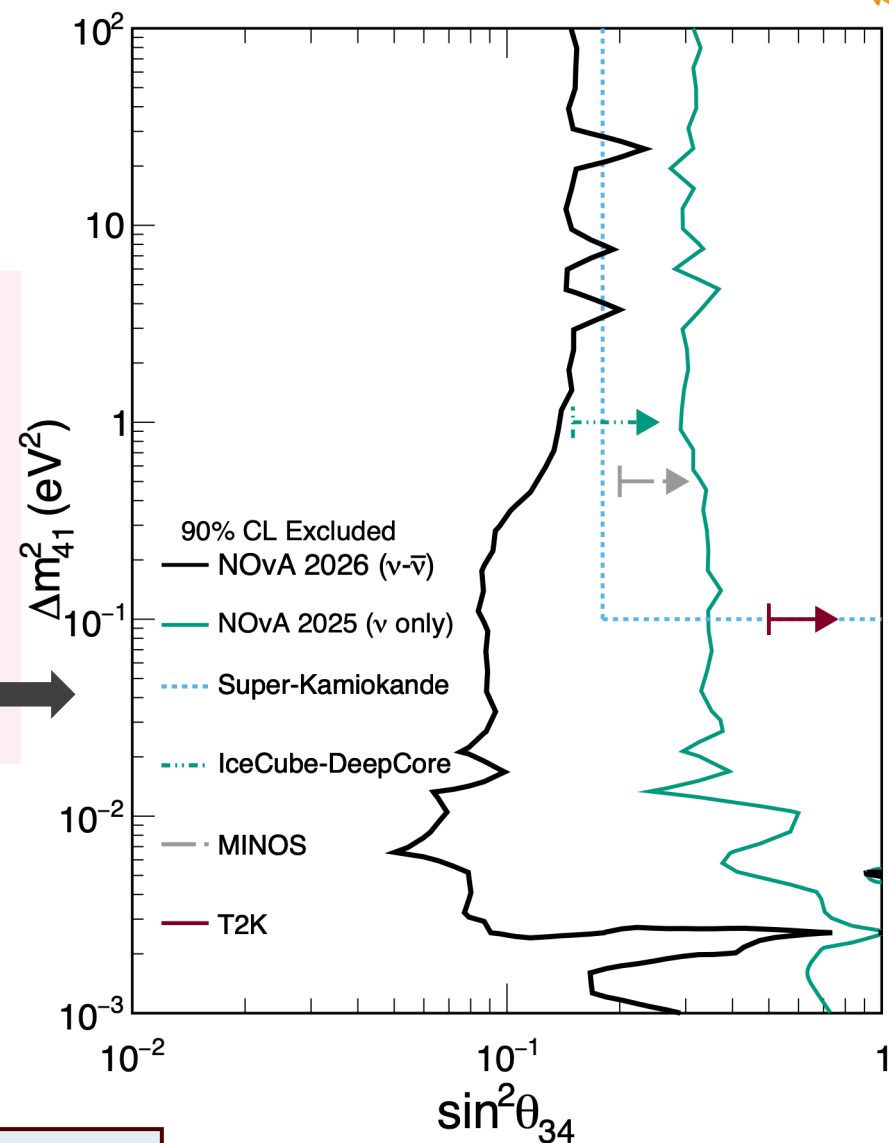


Significantly improved limits beyond previous NOvA results.

World-leading at high  $\Delta m_{41}^2$

At low  $\Delta m_{41}^2$ , NOvA is the first to set limits.

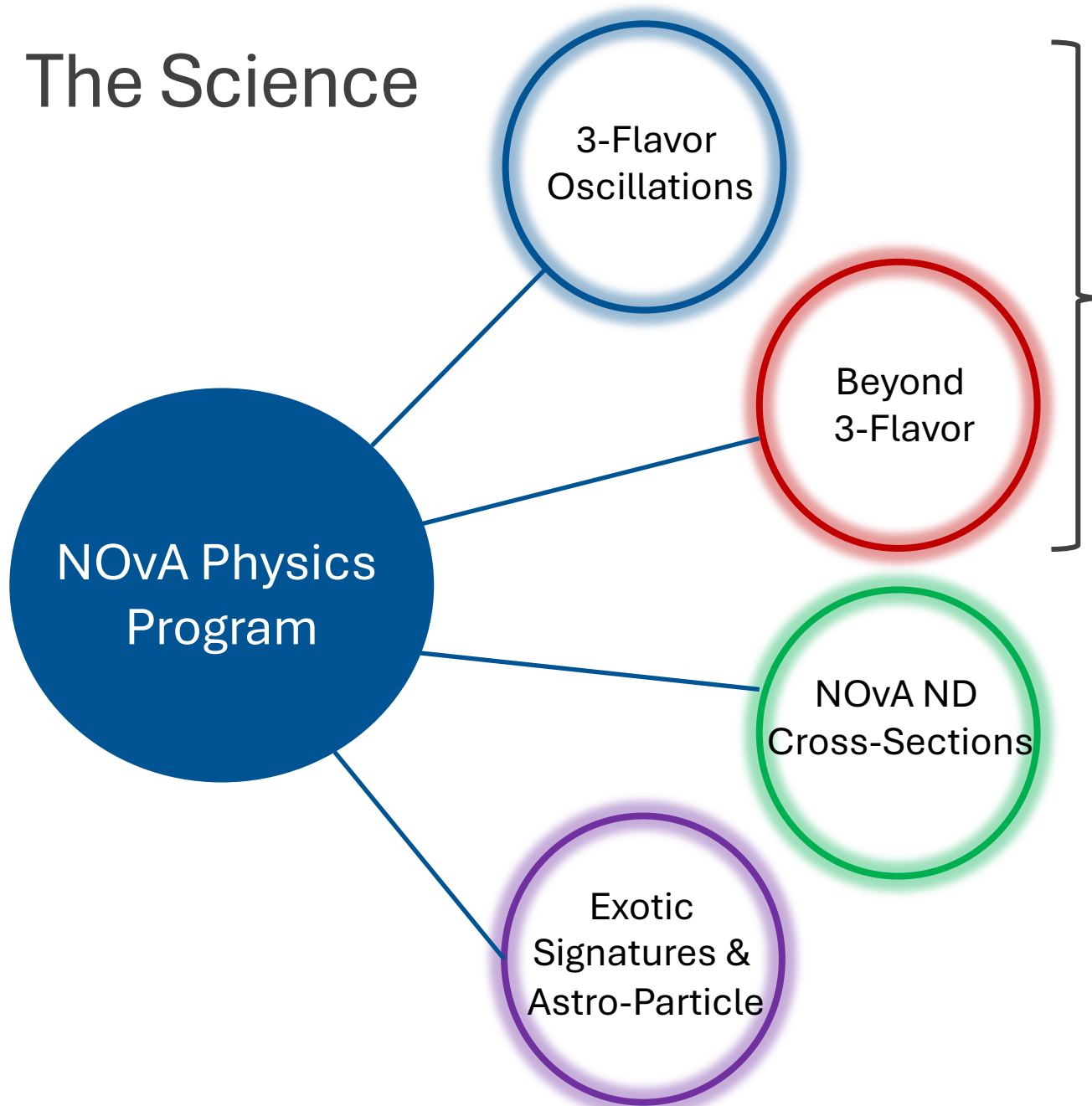
$\nu\text{-}\bar{\nu}$  Beam



\*From [MicroBooNE's Neutrino 2026 Results](#)

#195 NOvA Steriles 2026: Shivam Chaudhary, Adam Lister, Adam Aurisano

# The Science



## NOvA Posters @ Neutrino 2026

#215 PISCES 2-detector Fit: Miriama Rajaoalisoa

#397 Bayesian 2-detector Fit: Cullen Sullivan, Hugh Gallagher, Jeremy Wolcott

#434 Unitarity of lepton mixing matrix: Aditya Marathe

#206 New Beam Constraints for Steriles: Jessica Burns, Adam Aurisano

#21 Steriles with  $\nu_e$  in ND: Bishnu Acharya, Gavin Davies

#309 Bayesian NSI in NOvA: Xiaoyan Huang, Gavin Davies

#27 Expanding NSI Searches: Mario A. Acero

#160 Neutrino Decay in NOvA: Andrea Barros, Mario A. Acero

... and many more analysis improvements in the pipeline for **3-Flavor, 3+1, and Non-Standard Interactions** physics with NOvA.

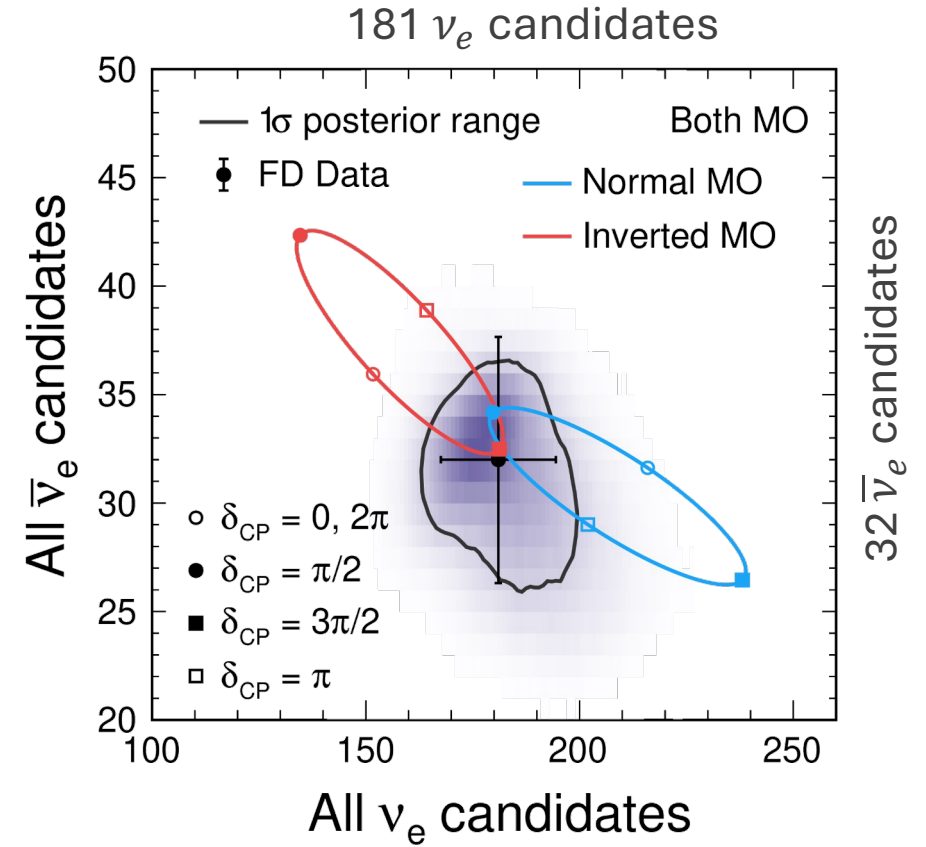
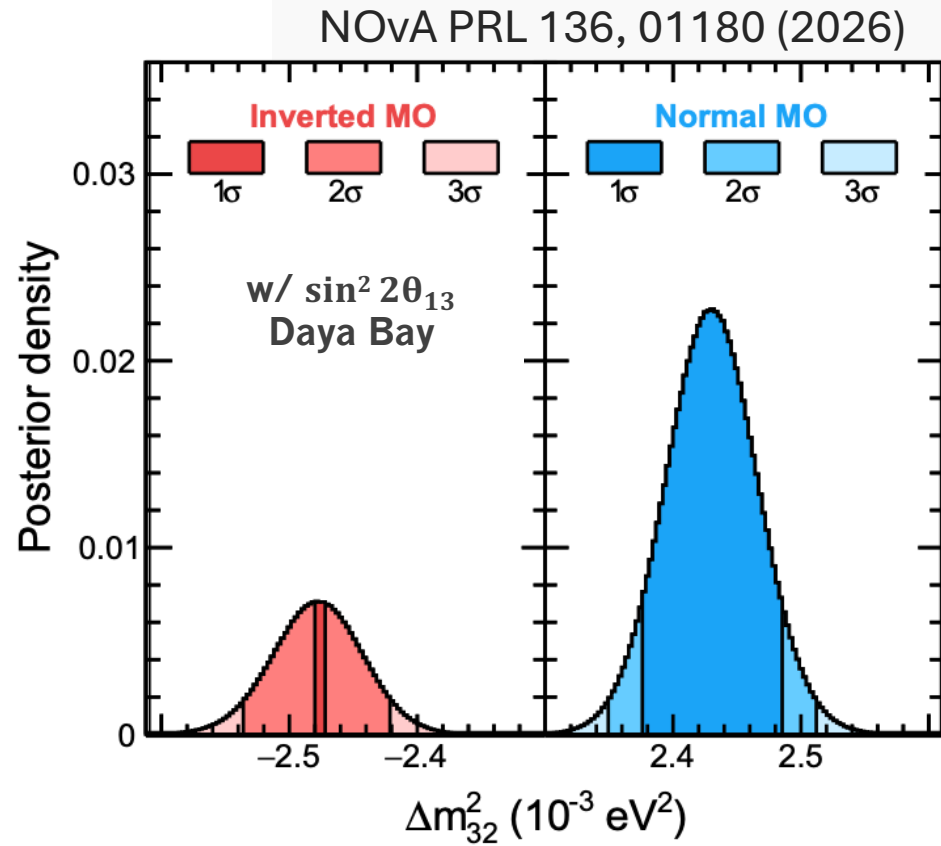


# NOvA + Other Experiments

(with a focus on  $\nu$  Mass Ordering)

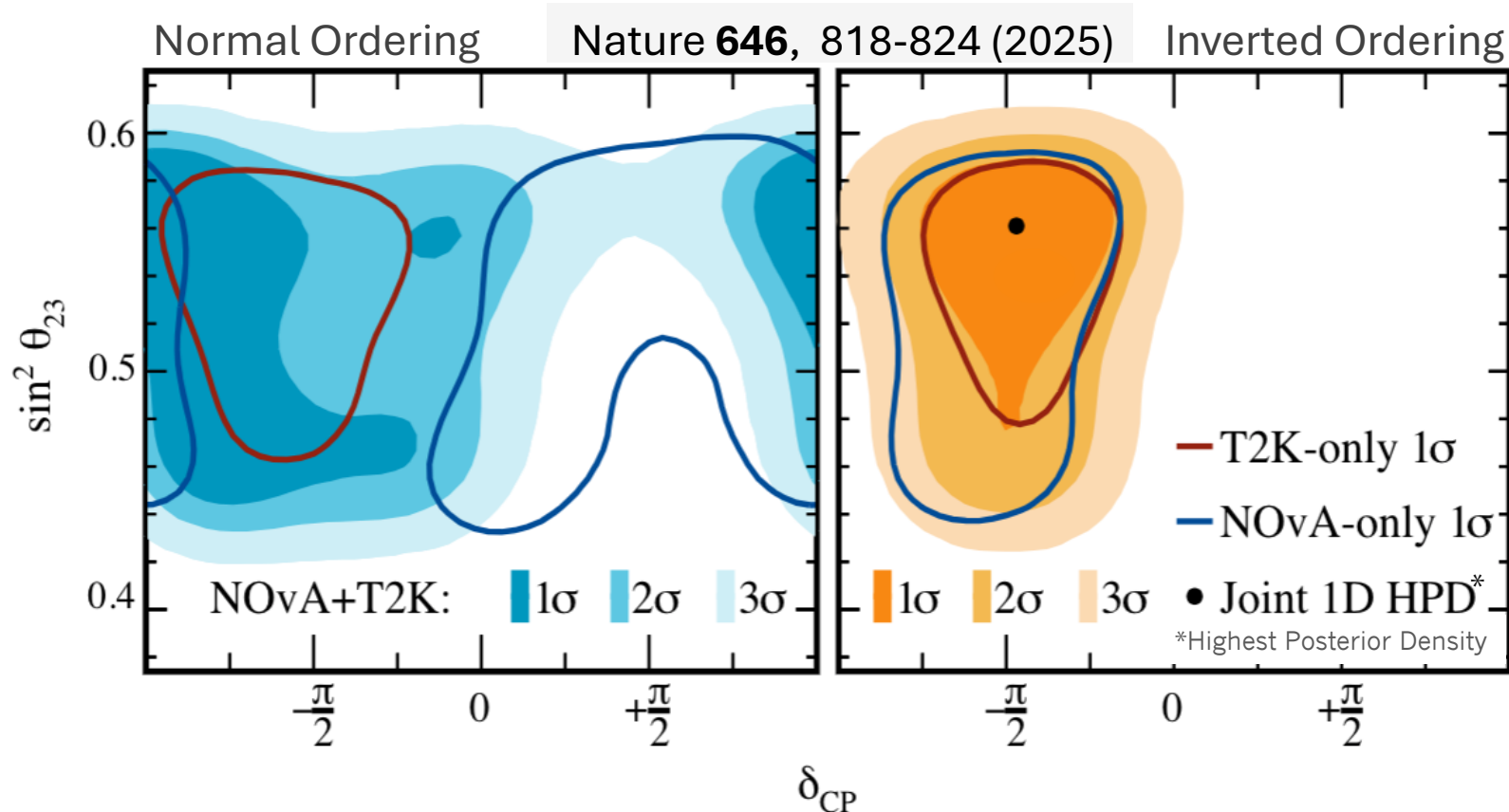
# Mass Ordering: NOvA Only

Degeneracy between MO &  $\delta_{CP}$  measurements in long-baseline experiments



- Disfavors asymmetric combinations of (MO,  $\delta_{CP}$ ): ● (IO,  $\pi/2$ ) at  $> 4\sigma$  ■ (NO,  $3\pi/2$ ) at  $\sim 2.5\sigma$
- NOvA data show a preference for NO (77% posterior) with a Bayes factor of 3.3

# Synergies for measuring Mass Ordering: NOvA + T2K



- **NOvA+T2K joint fit weakly prefers IO** (Bayes factor 1.3), driven by overlap in  $\delta_{CP}$  space.
- Even across different baselines **MO** and  $\delta_{CP}$  remain degenerate.

To see what's next for the joint analysis, check out these posters:

#499 NOvA-T2K Developments & Machinery: Hank Hua

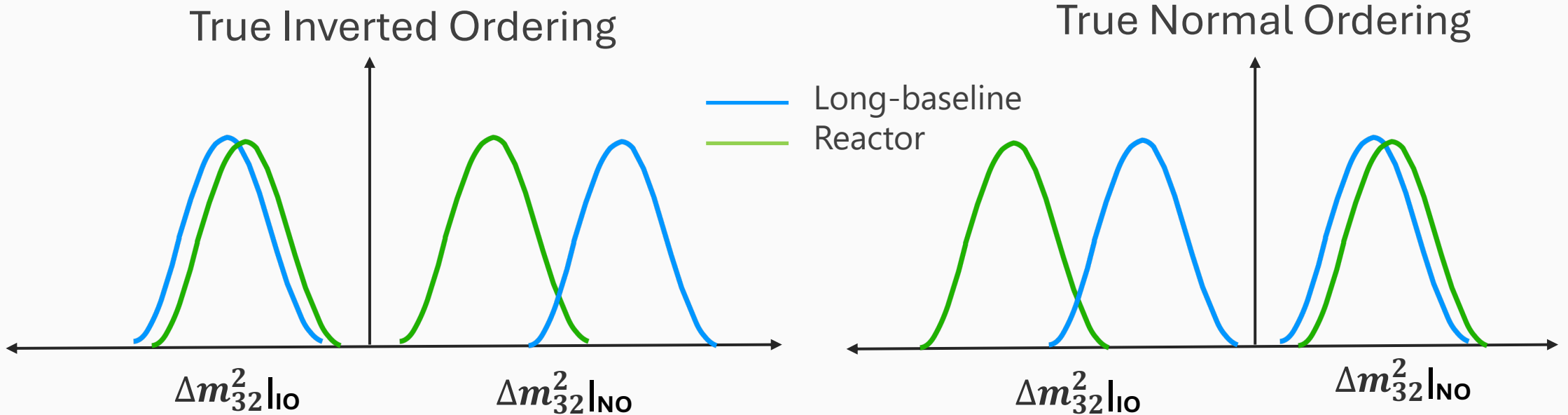
#420 New Directions for NOvA-T2K: Gavin Davies, Veera Mikola, Luiz Prais

# Synergies for measuring Mass Ordering: NOvA + Reactor

Precision in  $\Delta m_{32}^2$  measurements presents an orthogonal lever to measure MO\*:

- Under wrong mass ordering assumption, reactor and long-baseline measurements of  $\Delta m_{32}^2$  will disagree.

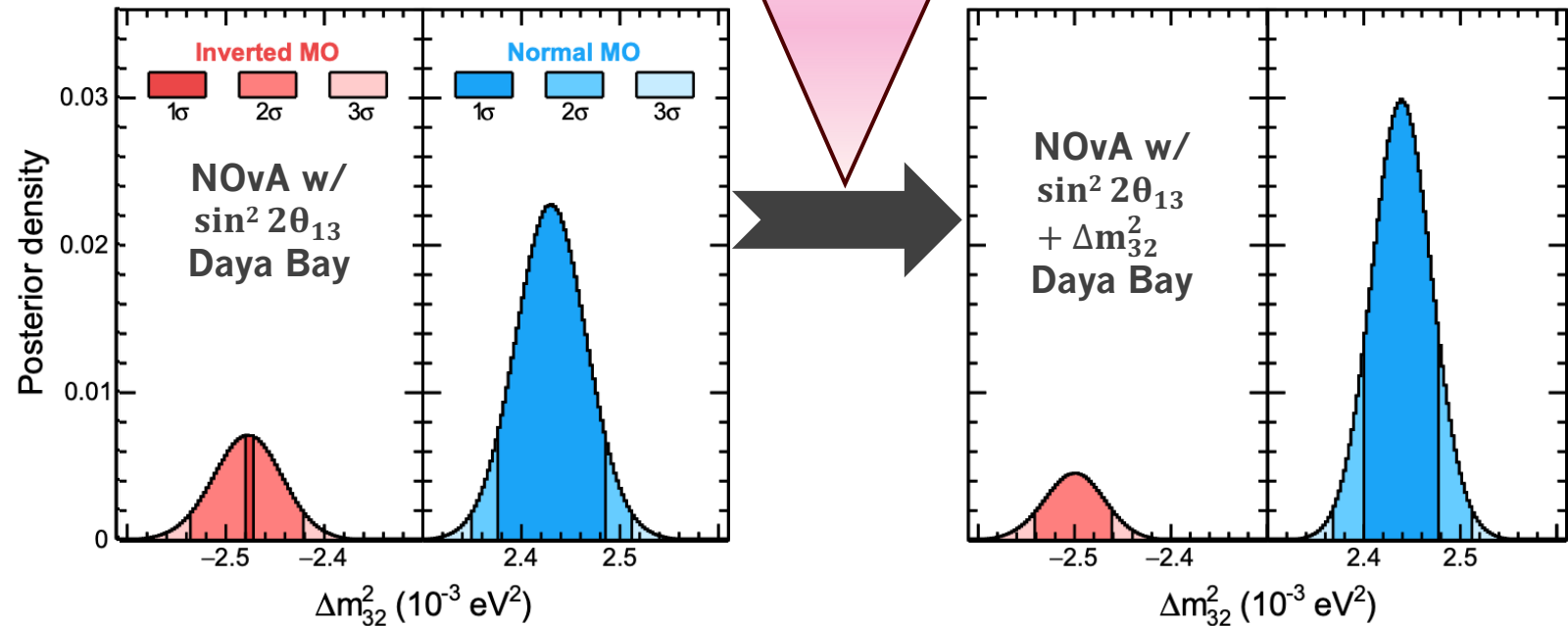
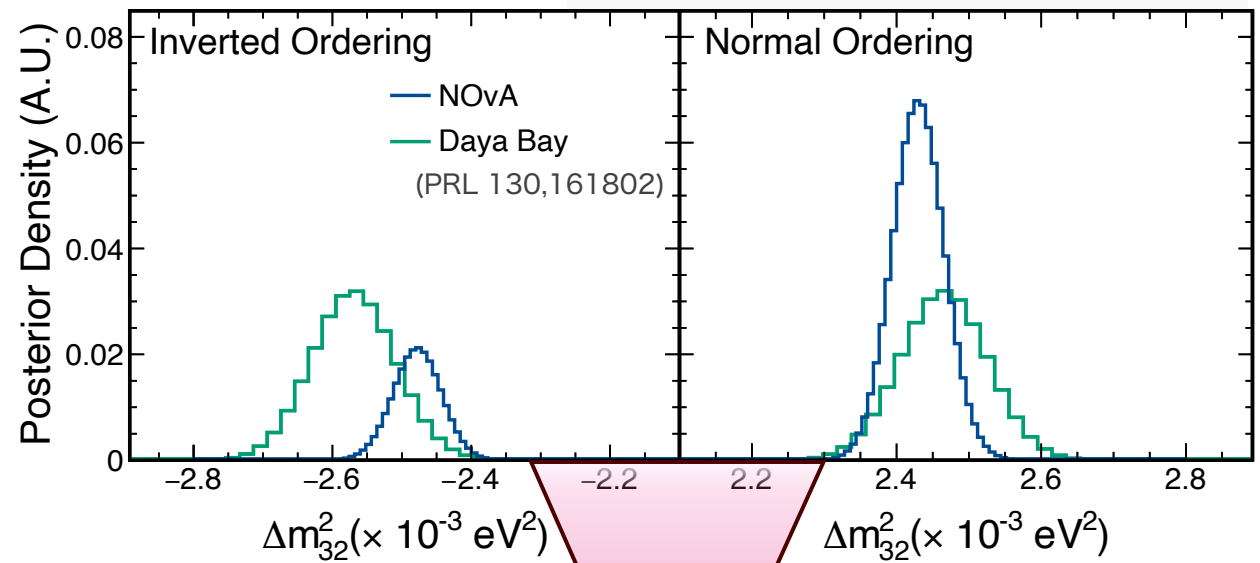
Conceptual Sketch (not to scale)



\*Nunokawa, Parke and Funchal, PRD 72, 013009 (2005);  
Parke and Funchal, PRD 111, 013008 (2025)

# NOvA + Daya Bay

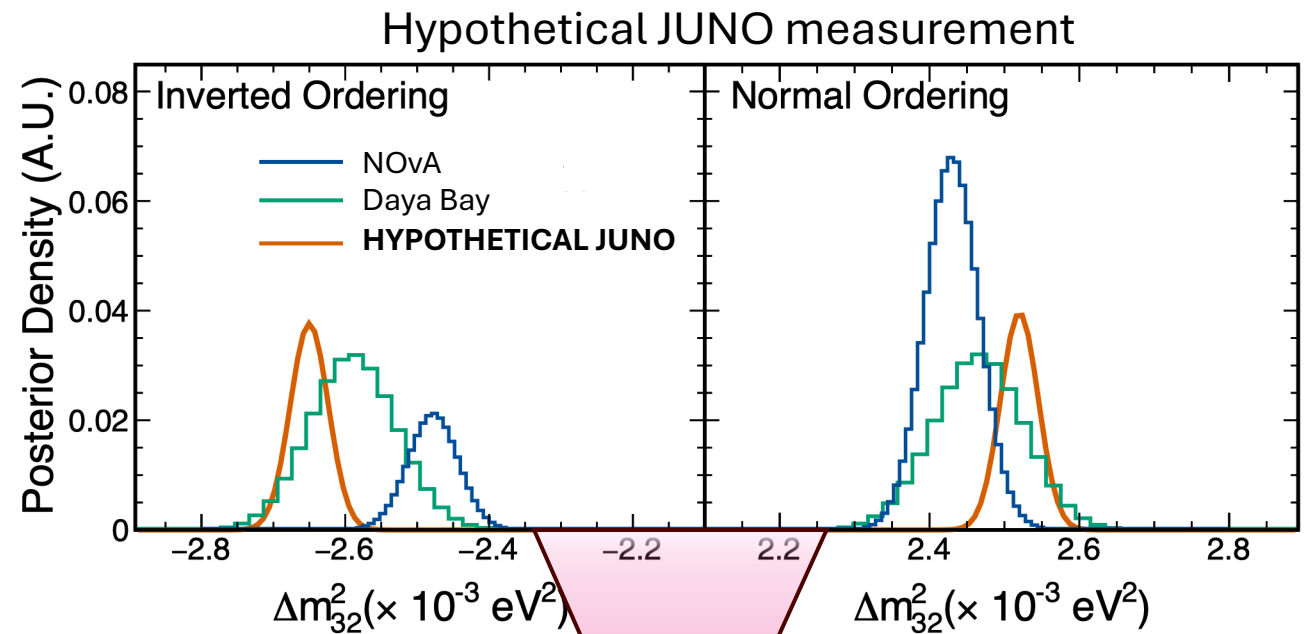
- Including  $\Delta m_{32}^2$  from reactor experiments enhances mass ordering significance.
- Driven by precision in  $\Delta m_{32}^2$  measurement.



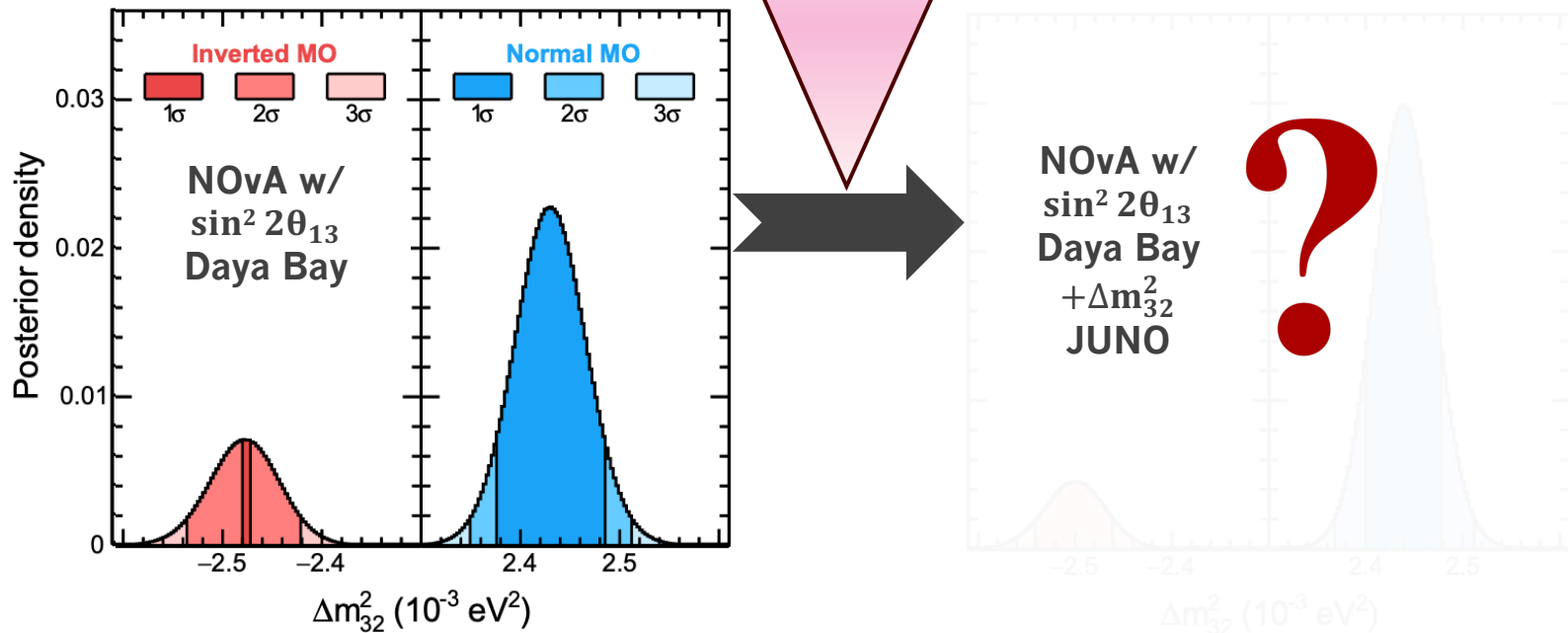
External Constraints	Bayes Factor (Normal/Inverted)
NOvA w/ $\sin^2 2\theta_{13}$ Daya Bay	<b>3.3</b> 77% / 23% Posterior density
NOvA w/ $\sin^2 2\theta_{13} + \Delta m_{32}^2$ Daya Bay	<b>6.6</b> 87% / 13% Posterior density

# NOvA + JUNO?

- Once JUNO's  $\Delta m_{32}^2$  value and measurement precision are known, the combined mass ordering preference can be determined.

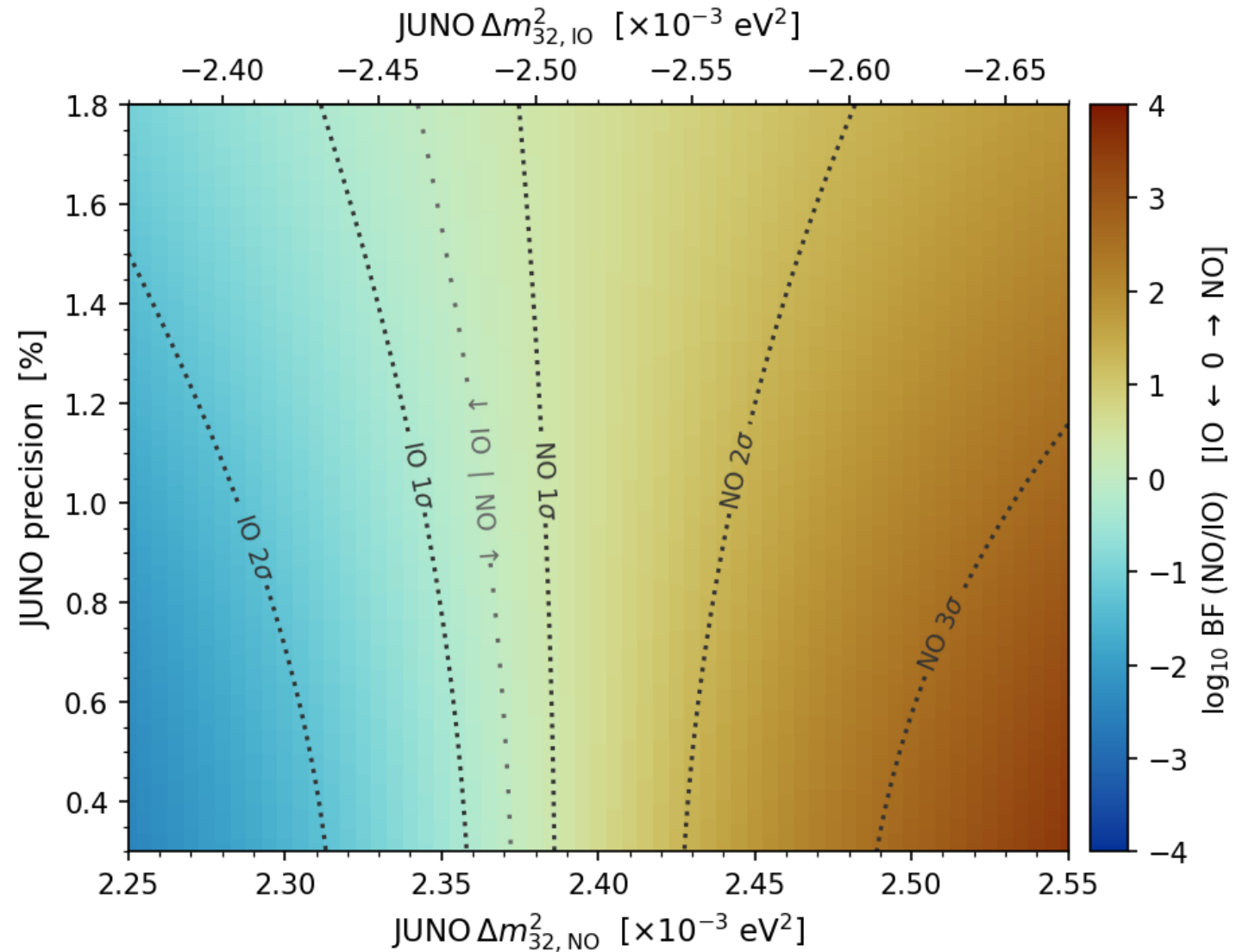


External Constraints	Bayes Factor (Normal/Inverted)
NOvA w/ $\sin^2 2\theta_{13}$ Daya Bay	3.3 77% / 23% Posterior density
NOvA w/ $\sin^2 2\theta_{13}$ Daya Bay + $\Delta m_{32}^2$ JUNO	?



# NOvA + JUNO

- Once JUNO's  $\Delta m_{32}^2$  value and measurement precision are known, the combined mass ordering preference can be determined.
- ... or we can scan over the full possible range!

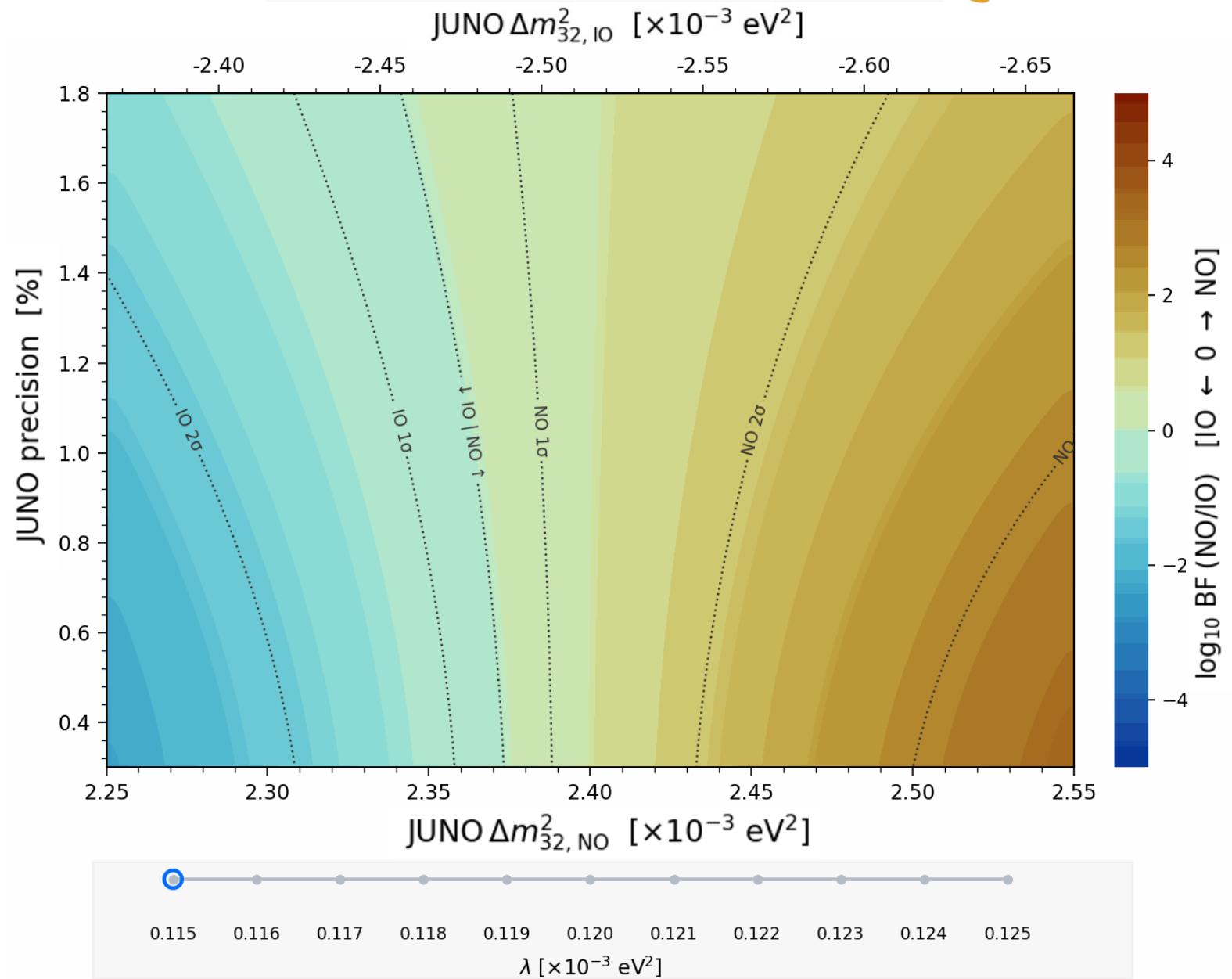


#451 NOvA MO Sensitivity: Artur Sztuc, Alex Booth, Liudmila Kolupaeva, Cullen Sullivan, Zoya Vallari, Larry Zhao

# NOvA + JUNO

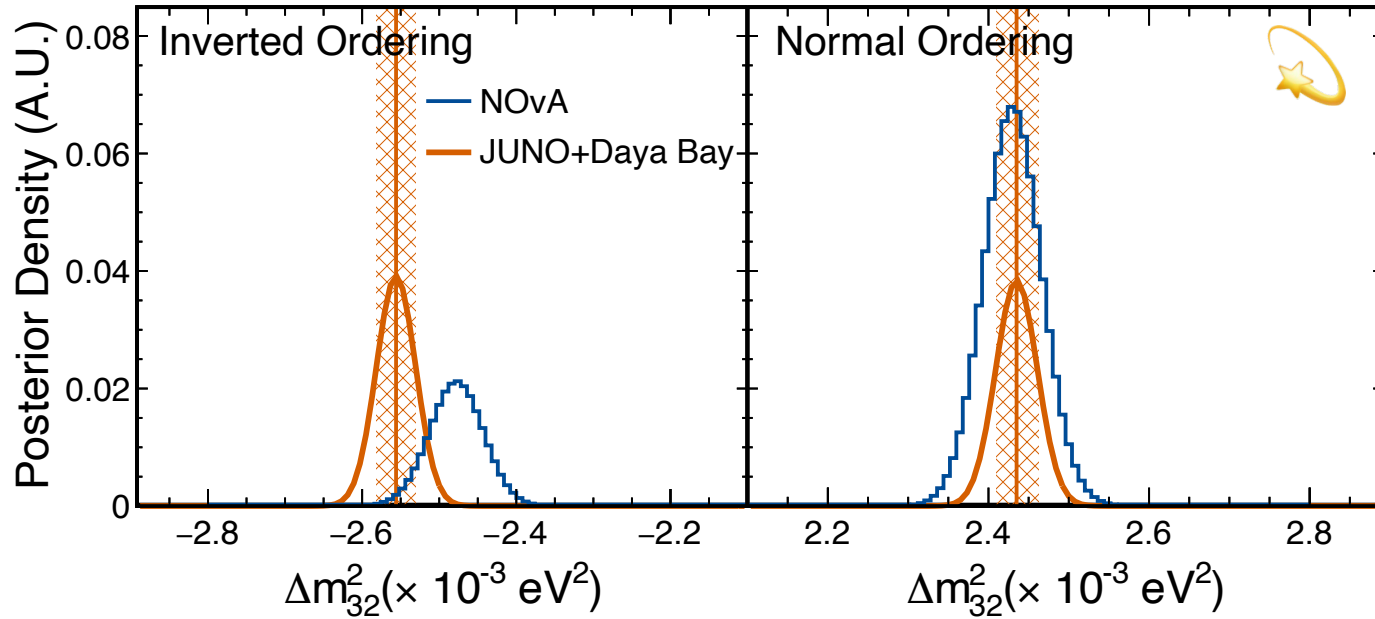
- Once JUNO's  $\Delta m_{32,IO}^2$  value and measurement precision are known, the combined mass ordering preference can be determined.
- ... or we can scan over the full possible range!
- Changes with offset  
 $\lambda \cong |\Delta m_{32,IO}^2| - |\Delta m_{32,NO}^2|$  values
- Includes  $\sin^2 2\theta_{13}$  from Daya Bay.

Also available as an [interactive website](#).

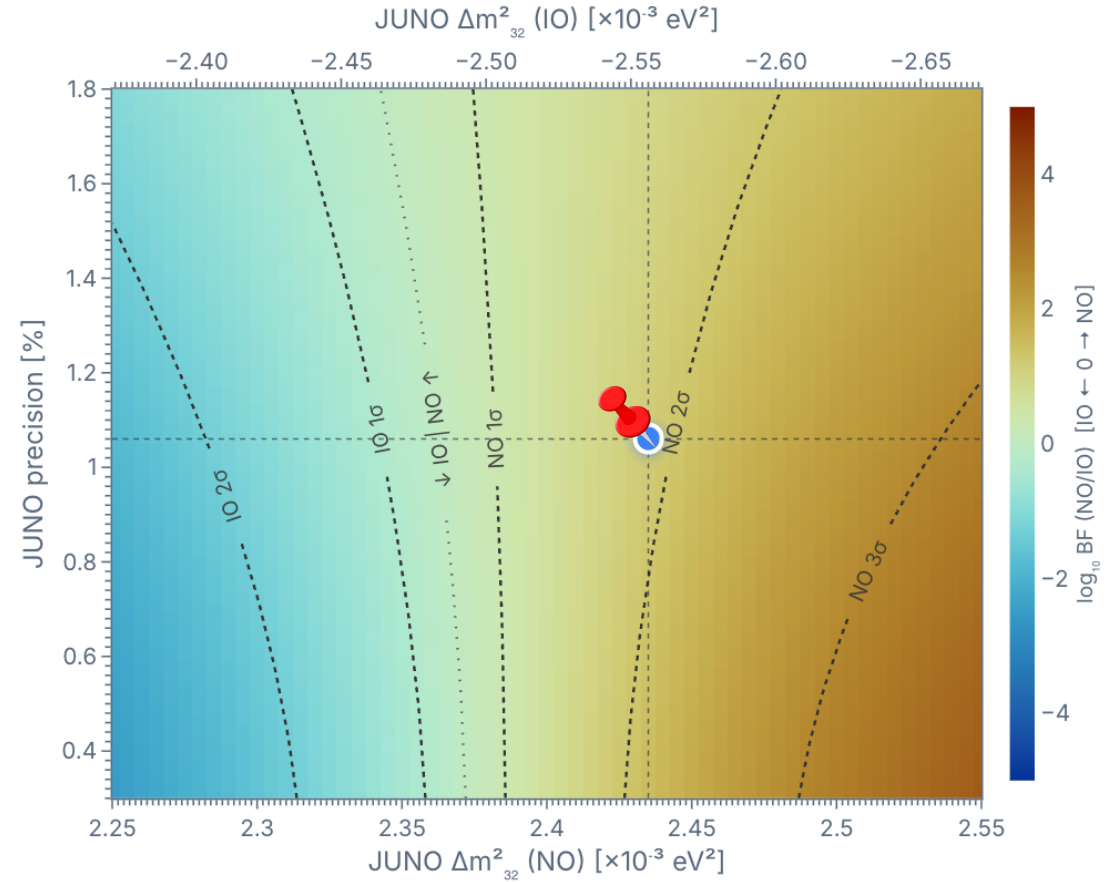


# NOvA + JUNO

- Magnificent consistency between JUNO and NOvA's  $\Delta m_{32}^2$  measurement in the Normal Ordering.



Exp.	JUNO*	NOvA
$\Delta m_{32}^2$ NO	2.435	2.431
$\Delta m_{32}^2$ IO	-2.556	-2.479
Precision	1.05%	1.4%

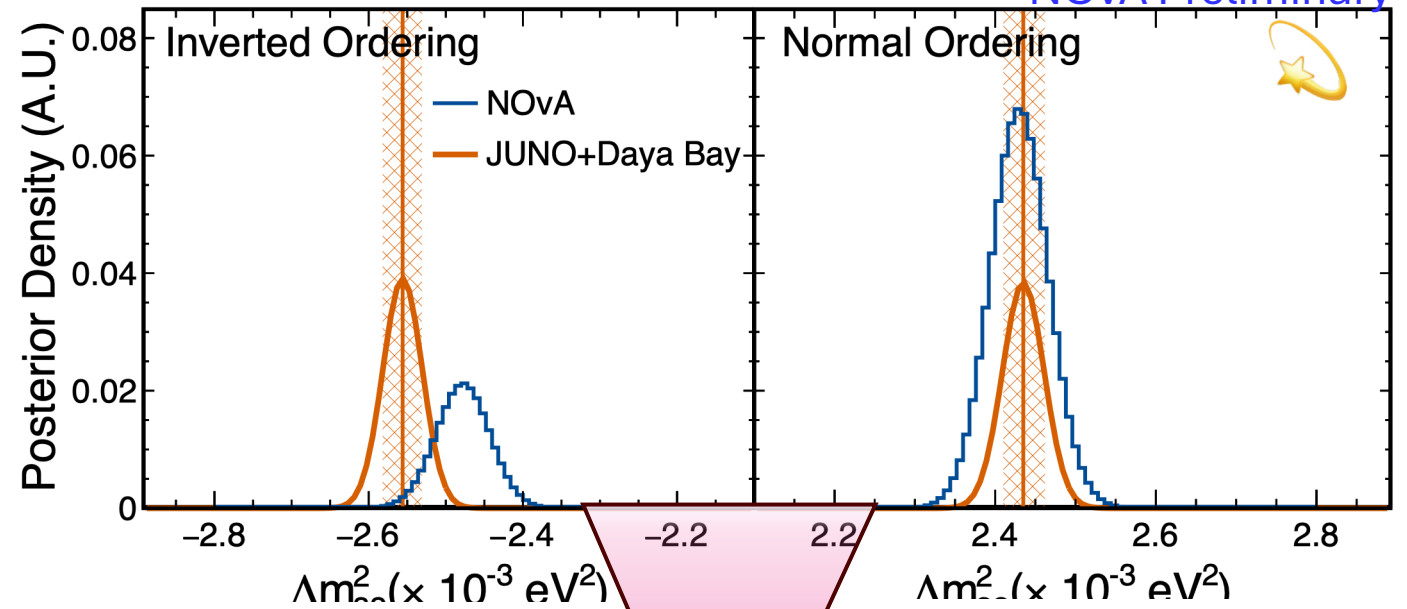


\*See JUNO's Talk (Note: Switch from  $\Delta m_{31}^2$  to  $\Delta m_{32}^2$  convention)

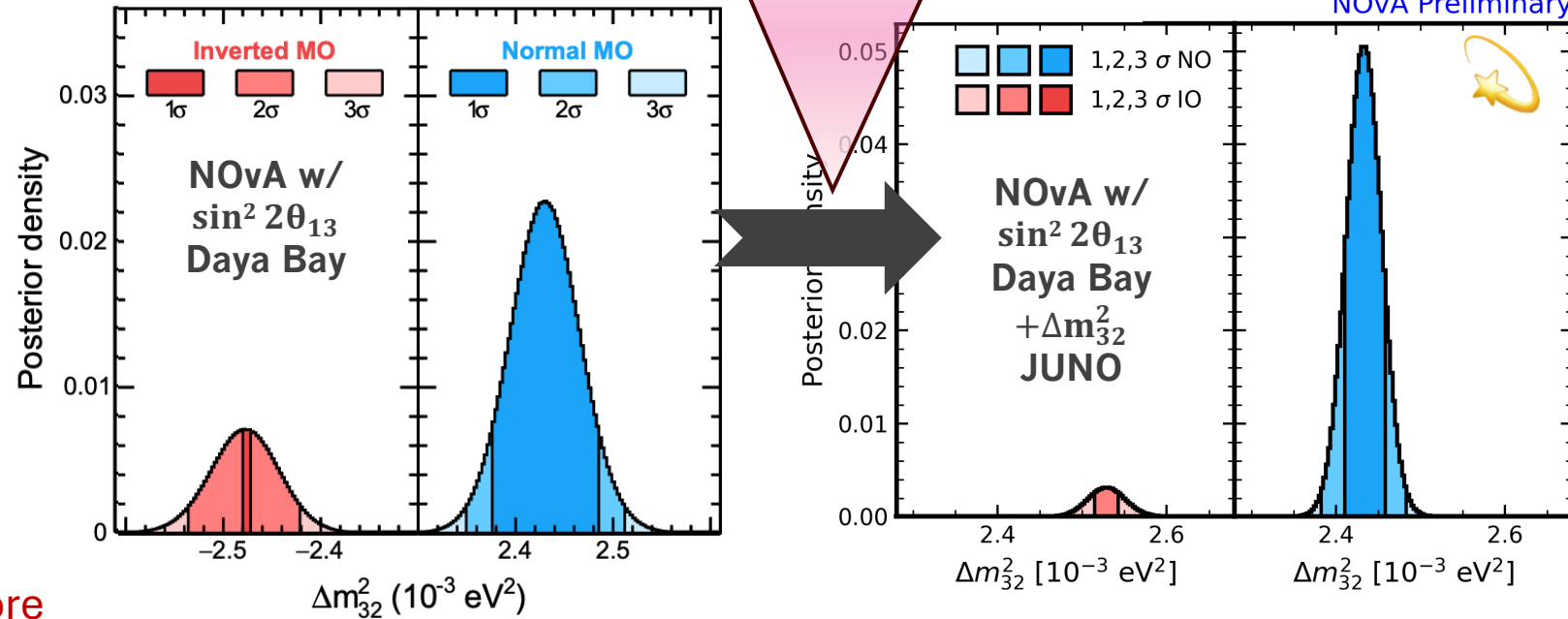
# NOvA + JUNO

NOvA Preliminary

- With JUNO's  $\Delta m_{32}^2$  value and measurement precision, the combined mass ordering preference can be determined.



NOvA Preliminary



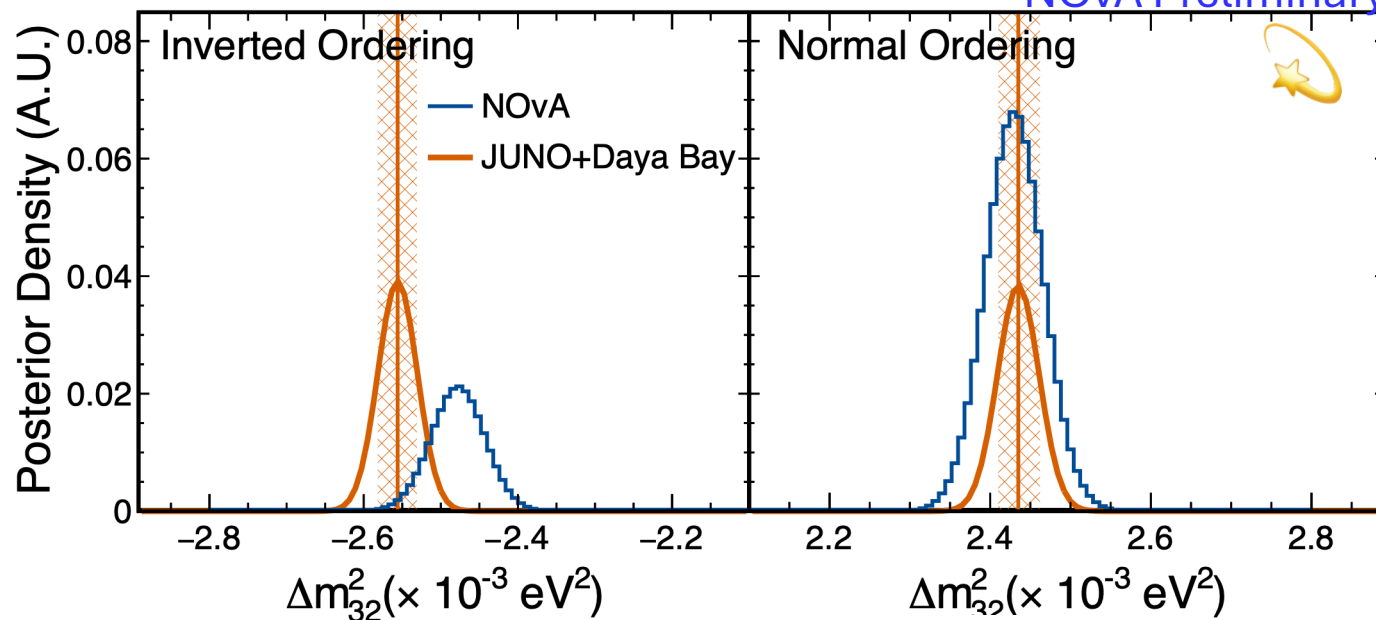
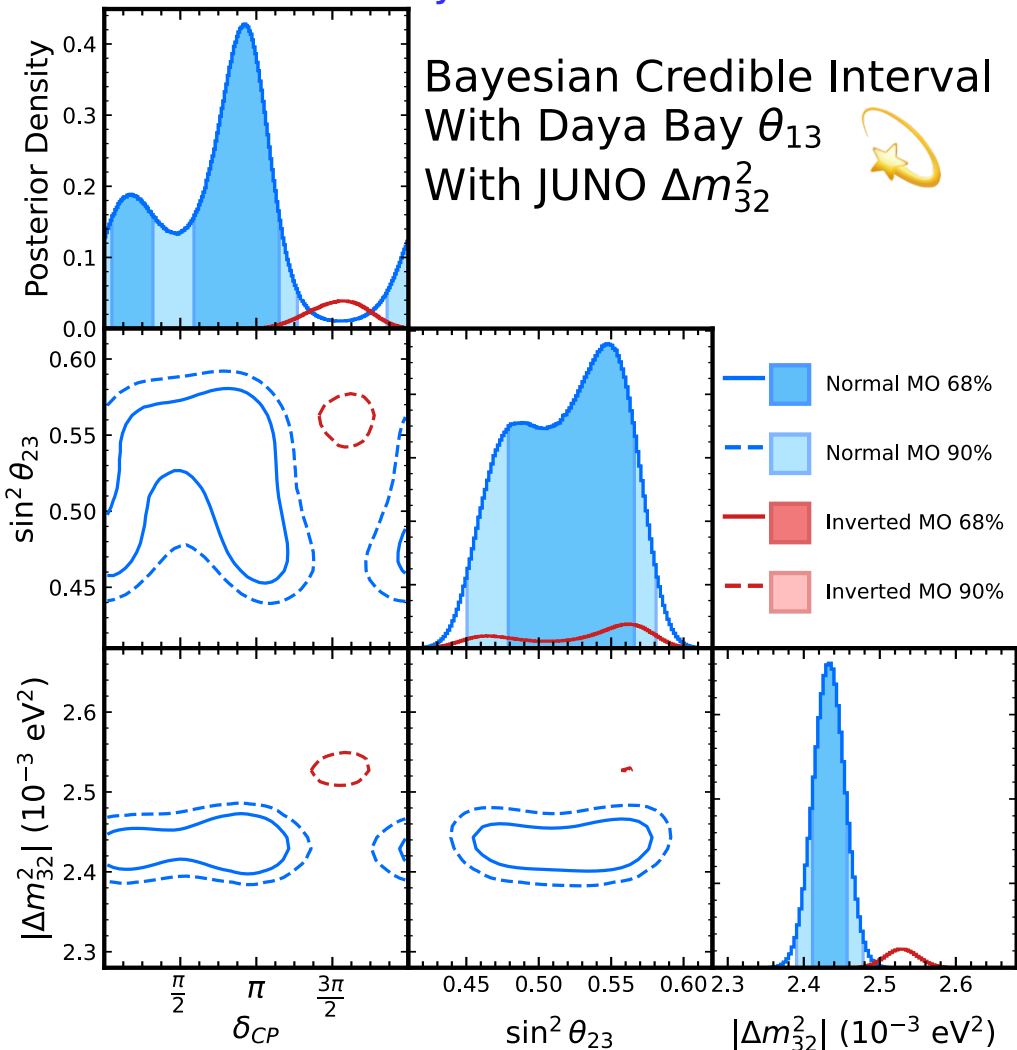
\*1.88 $\sigma$  preference for NO, using 2-sided Gaussian z-score

External Constraints	Bayes Factor (Normal/Inverted)
NOvA w/ $\sin^2 2\theta_{13}$ Daya Bay	3.3 77% / 23% Posterior density
NOvA w/ $\sin^2 2\theta_{13}$ Daya Bay + $\Delta m_{32}^2$ JUNO	15.74* 94% / 6% Posterior density

# NOvA + JUNO

NOvA Preliminary

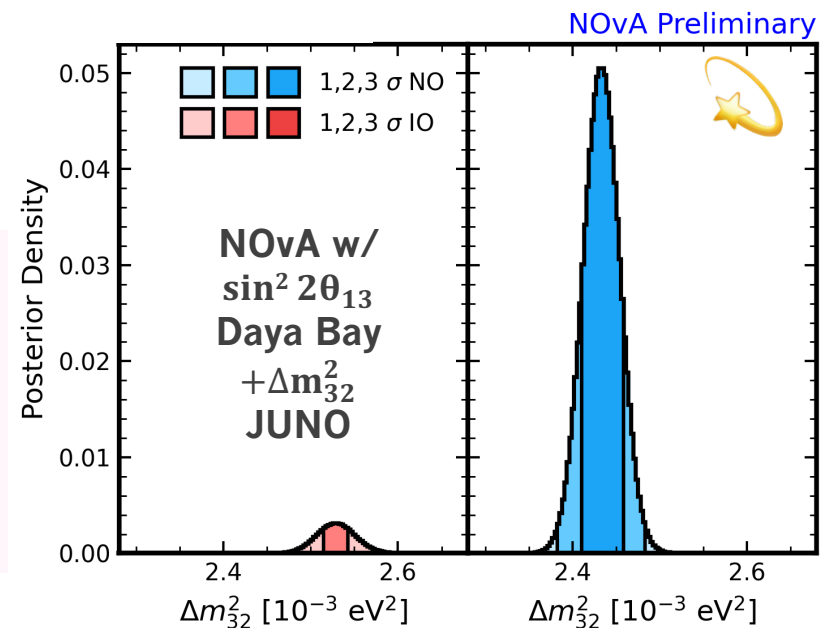
Bayesian Credible Interval  
With Daya Bay  $\theta_{13}$   
With JUNO  $\Delta m_{32}^2$



NOvA Preliminary



**MO preference moves,  
but  $\delta_{CP}$  preference holds!  
That's the  
complementarity of the  
method at work!**



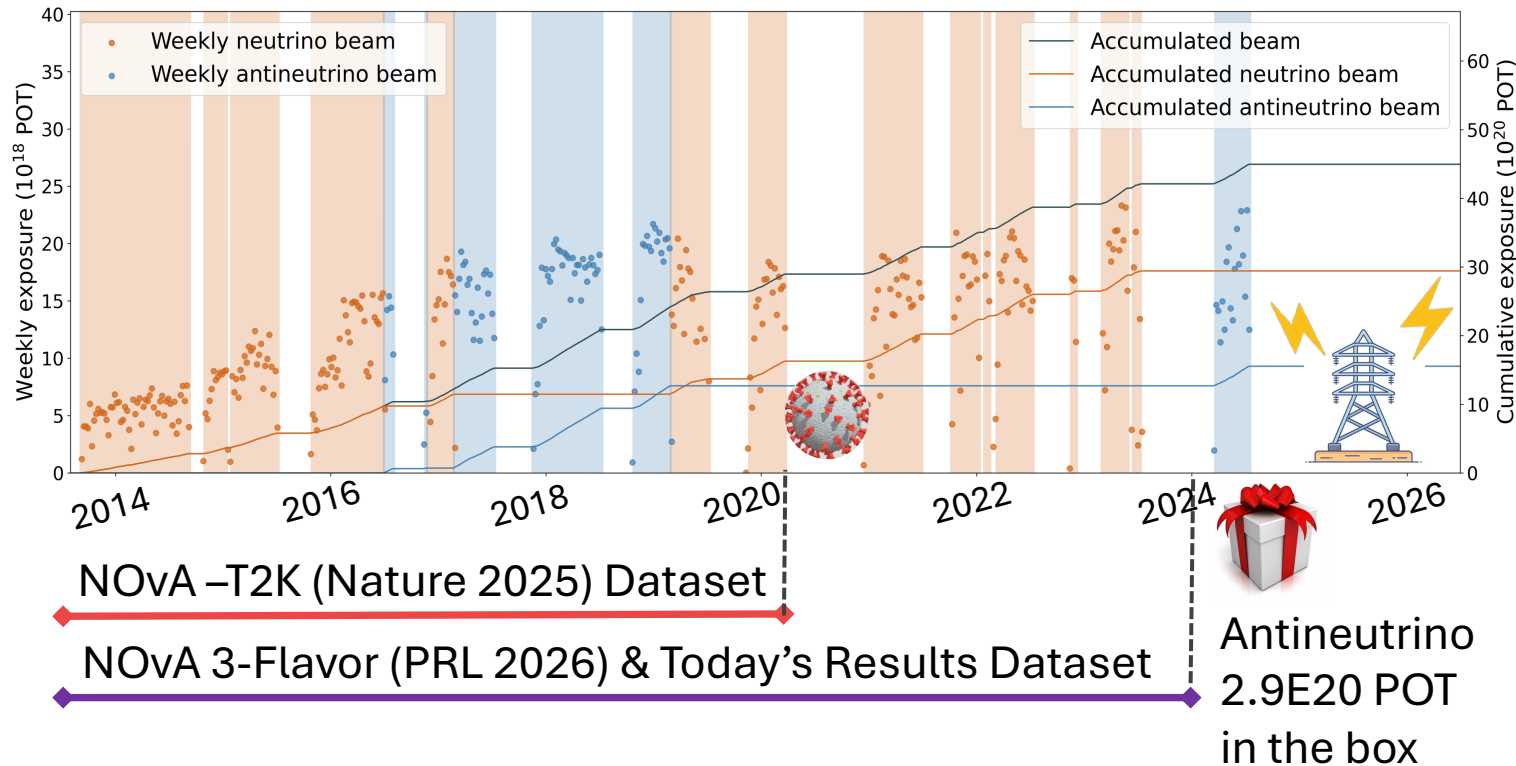
NOvA Preliminary



**What's next  
for NOvA?**

# More Data

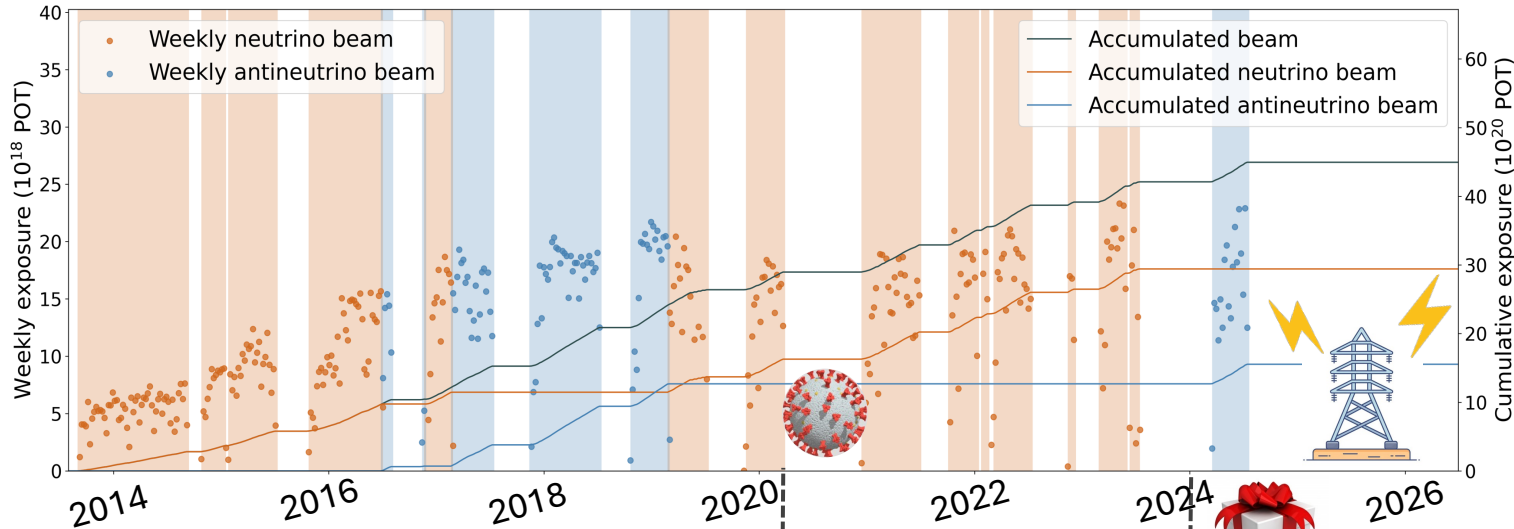
- NuMI reached record power of  $> 1\text{MW}$  in 06/2024.
  - No beam since 07/2024.
- Expected return  $\sim 09/2026$  for a final run.



# More Data



- NuMI reached record power of  $> 1\text{ MW}$  in 06/2024.
  - No beam since 07/2024.
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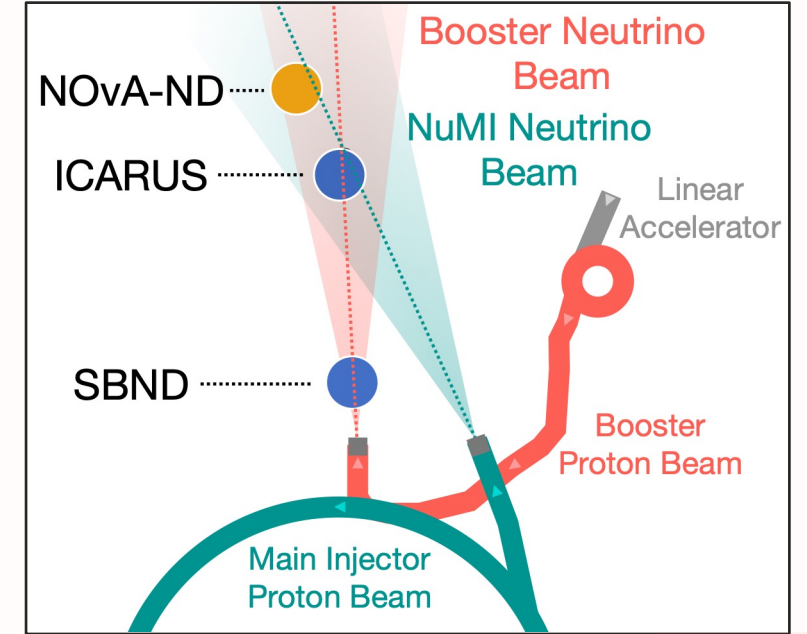
NOvA –T2K (Nature 2025) Dataset

NOvA 3-Flavor (PRL 2026) & Today's Results Dataset



Antineutrino  
2.9E20 POT  
in the box

Collecting BNB triggers since 2015.  
Comparable exposure to **MiniBooNE!**



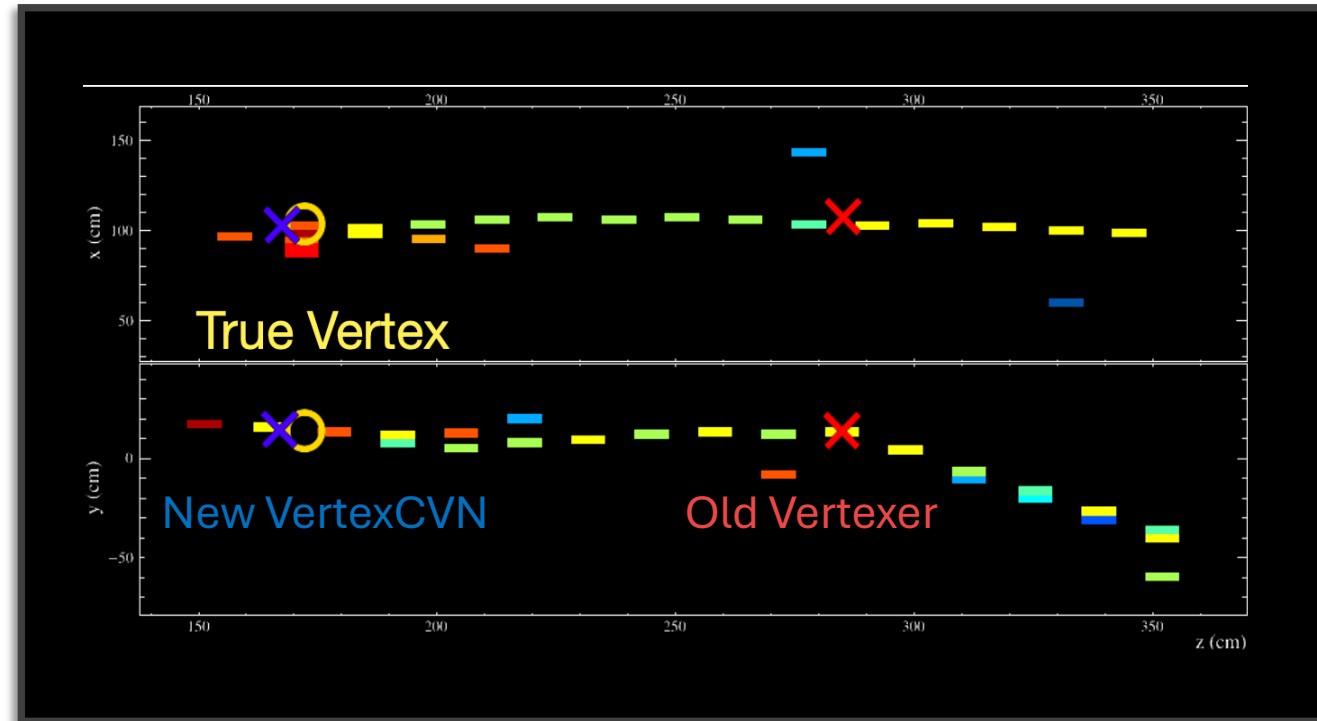
	NuMI	BNB
Protons Per Pulse	5e13	5e12
Rep Rate (Hz)	<1	5
Proton Energy (GeV)	120	8
Off-axis angle (°)	0.8	9.24
Baseline (km)	~1	~0.768

#194 BNB Neutrinos in NOvA: Adam Lister

# Improved Reconstruction

“no neutrino left behind”

- New ML-based vertexing algorithm “VertexCVN” to address known failure modes.
- Improved Prong-ID, Energy Estimators.



## #71 Prong Segmentation using Point Set Transformer:

Jiaxi Liu, Alejandro Yankelevich, Dikshant Sagar, Edgar Robles, Jianming Bian, Pierre Baldi, Wenjie Wu

## #62 Transformer Energy Estimator: Leon Tong

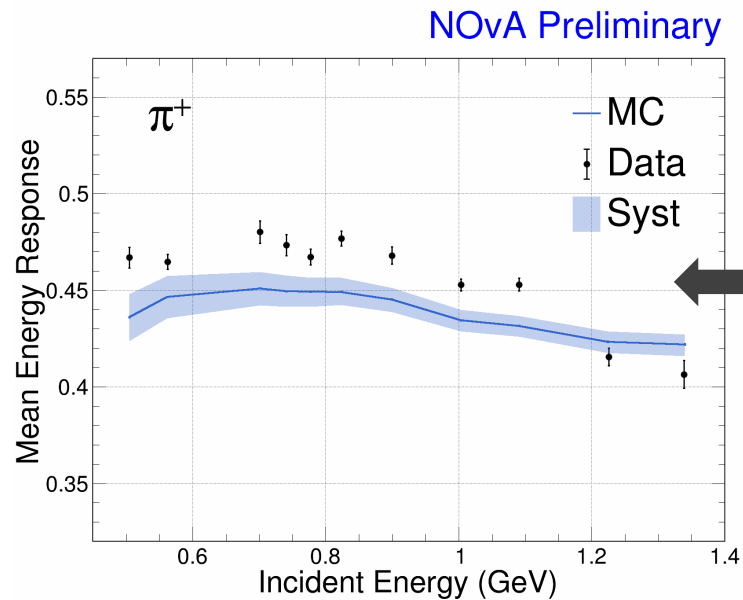
# New Interaction Model

- New production with updated cross-section model used **across Fermilab experiments (“AR-23”)** with custom NOvA adjustments.

#241 Cross-Section Model: Bryan Ramson, Georgia Nissen, Jeremy Wolcott

## Updated Systematics

Data-Driven Systematics

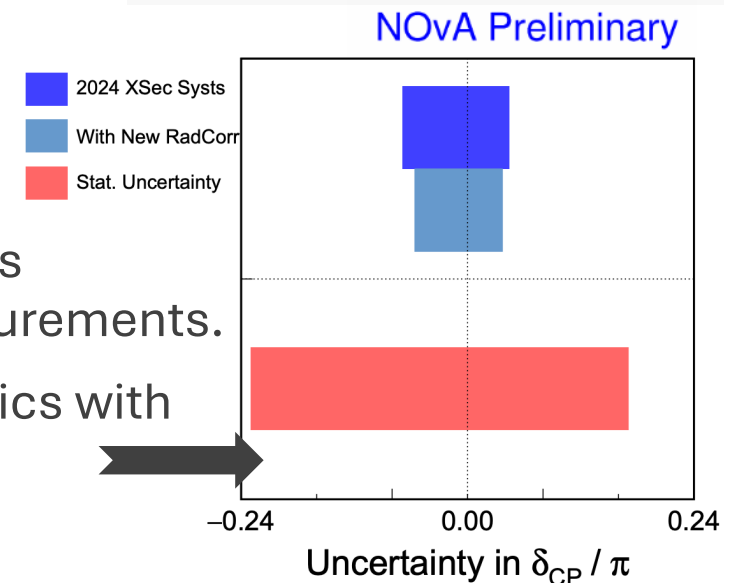


Target high impact systematics on  $\Delta m_{32}^2$  and  $\delta_{CP}$ .

- Particle-specific calibration systematics constrained by **NOvA Test Beam** measurements.
- Improved *radiative correction* systematics with theory-driven\* updates.

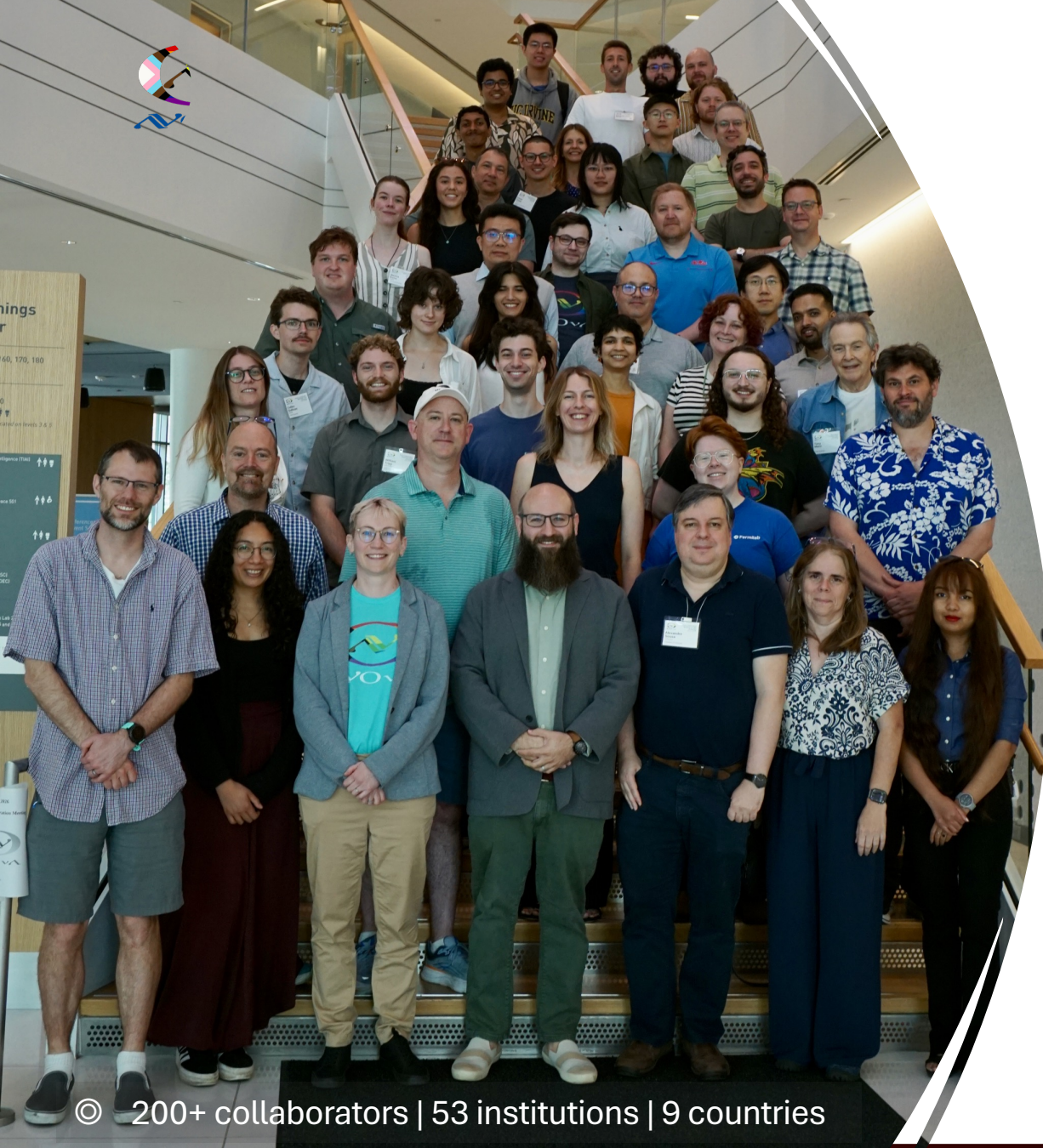
\*Tomalak, Chen, Hill, McFarland, Wret: PRD **106**, 09300

Theory-Driven Systematics



#451 Protons in NOvA Test Beam: Emerson Bannister

#92 QED Radiative Corrections: Will Tripp, Jeremy Wolcott

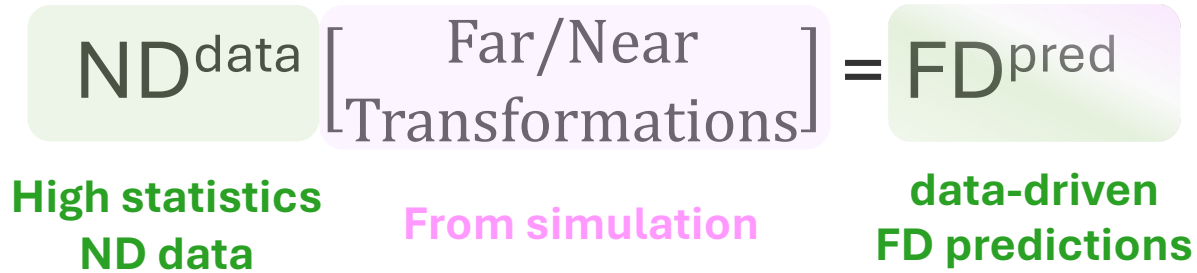


© 200+ collaborators | 53 institutions | 9 countries

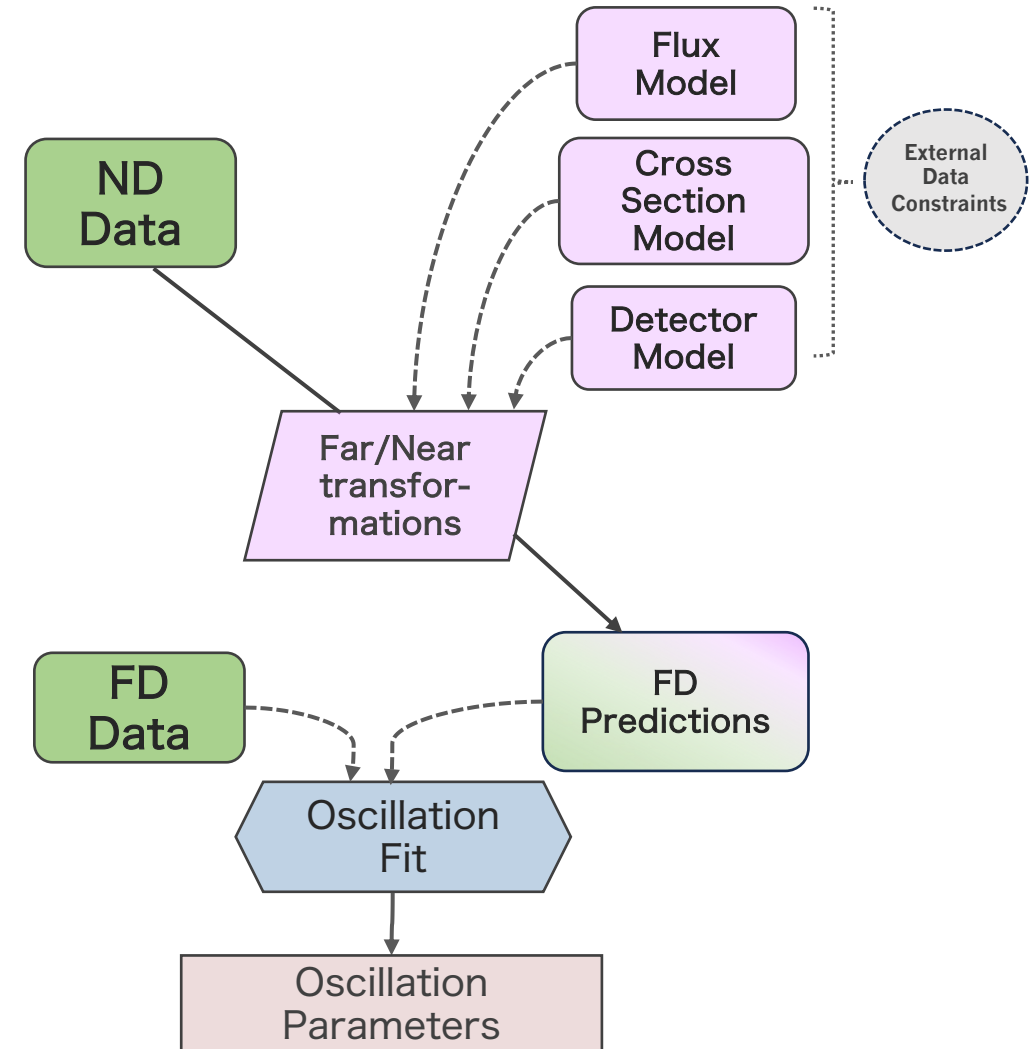
- **Summary:**
  - Consistent measurements across  $\nu_\mu$  only,  $\nu_e$  only, joint 3-flavor, and 3+1 steriles fits.
  - **World leading limits on sterile neutrino mixing  $\theta_{24}$  and  $\theta_{34}$ .**
  - Strong agreement across atmospheric, accelerator, and reactor neutrino measurements: **3-flavor paradigm holds!**
- **Open Questions:**
  - Mass Ordering and CP violation remain unresolved.
  - NOvA + JUNO combined: **Normal Ordering 16x more likely than the the Inverted Ordering**, a  $1.88\sigma$  indication.
- **Next up:**
  - More data, improved reconstruction, new models, updated systematics for upcoming NOvA analyses!
  - NOvA-T2K joint fits with expanded dataset and including Non-Standard Interactions.

Supplementary

# 3-Flavor Analysis: Extrapolation



- Leverages the identical detector design to build data-driven FD predictions.

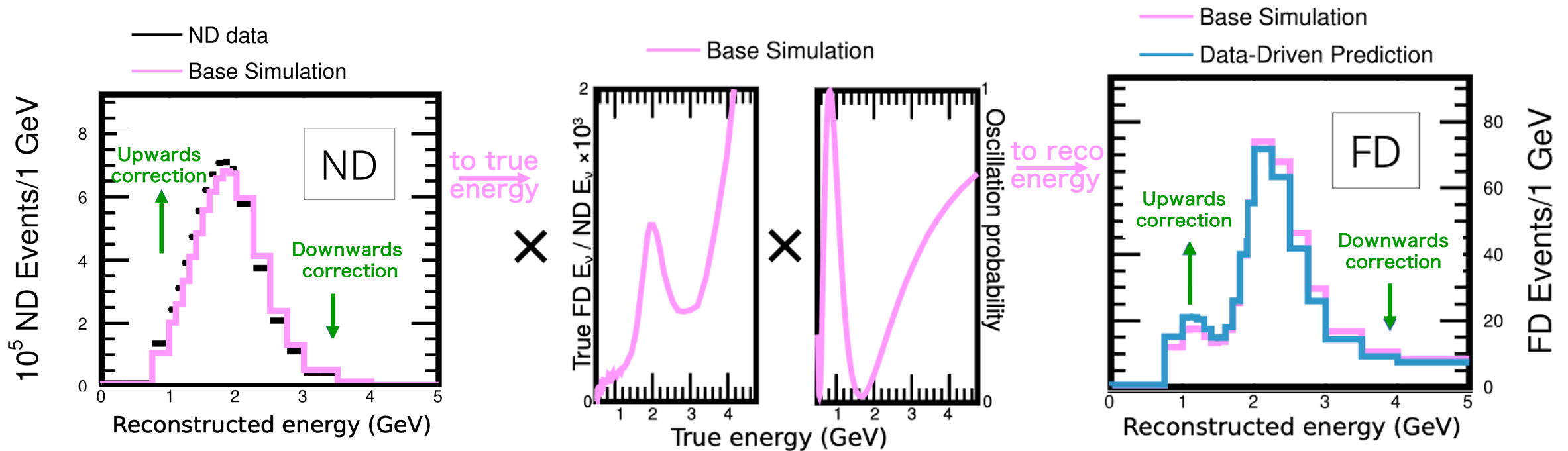


# Role of ND

- Leverages the identical detector design to build data-driven FD predictions.

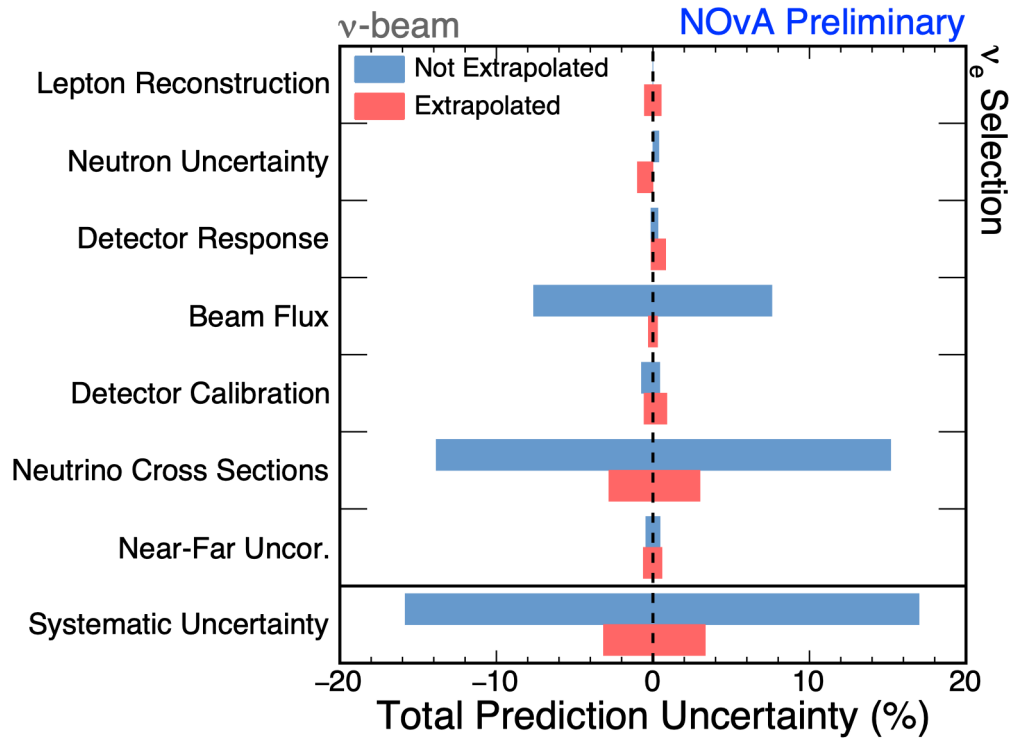
$$\text{ND}_{\text{data}} \left[ \begin{array}{c} \text{Far/Near} \\ \text{Transformations} \end{array} \right] = \text{FD}_{\text{pred}}$$

High statistics ND data
From simulation
data-driven FD predictions

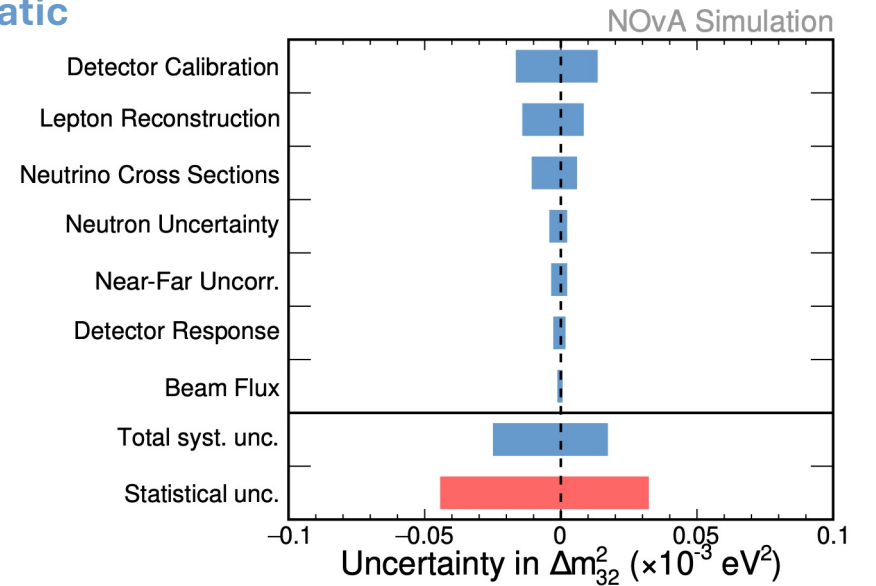
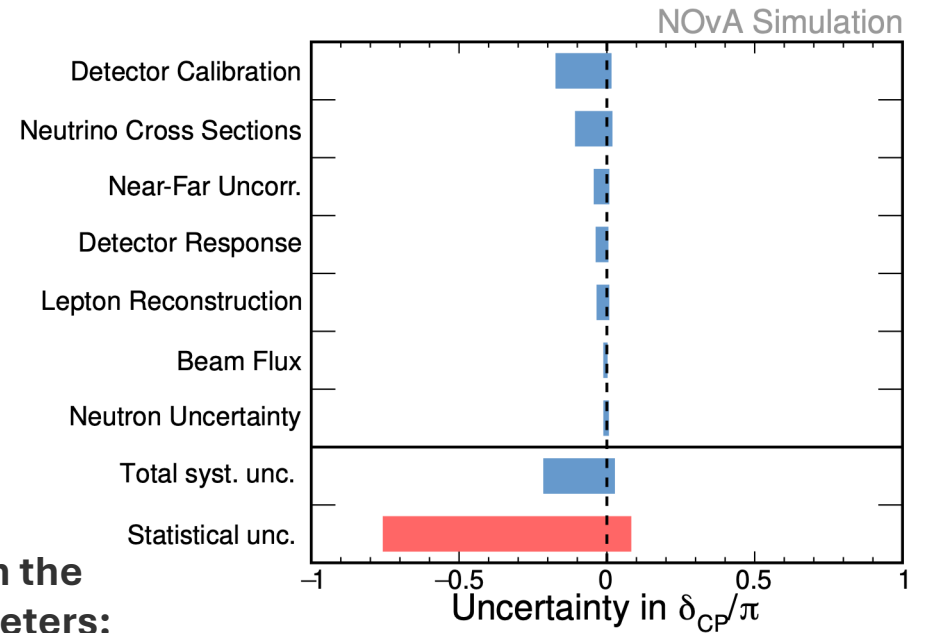


# Systematics

Example: Systematic uncertainties on the  $\nu_e$  candidate count: **a-priori** vs **improved** predictions



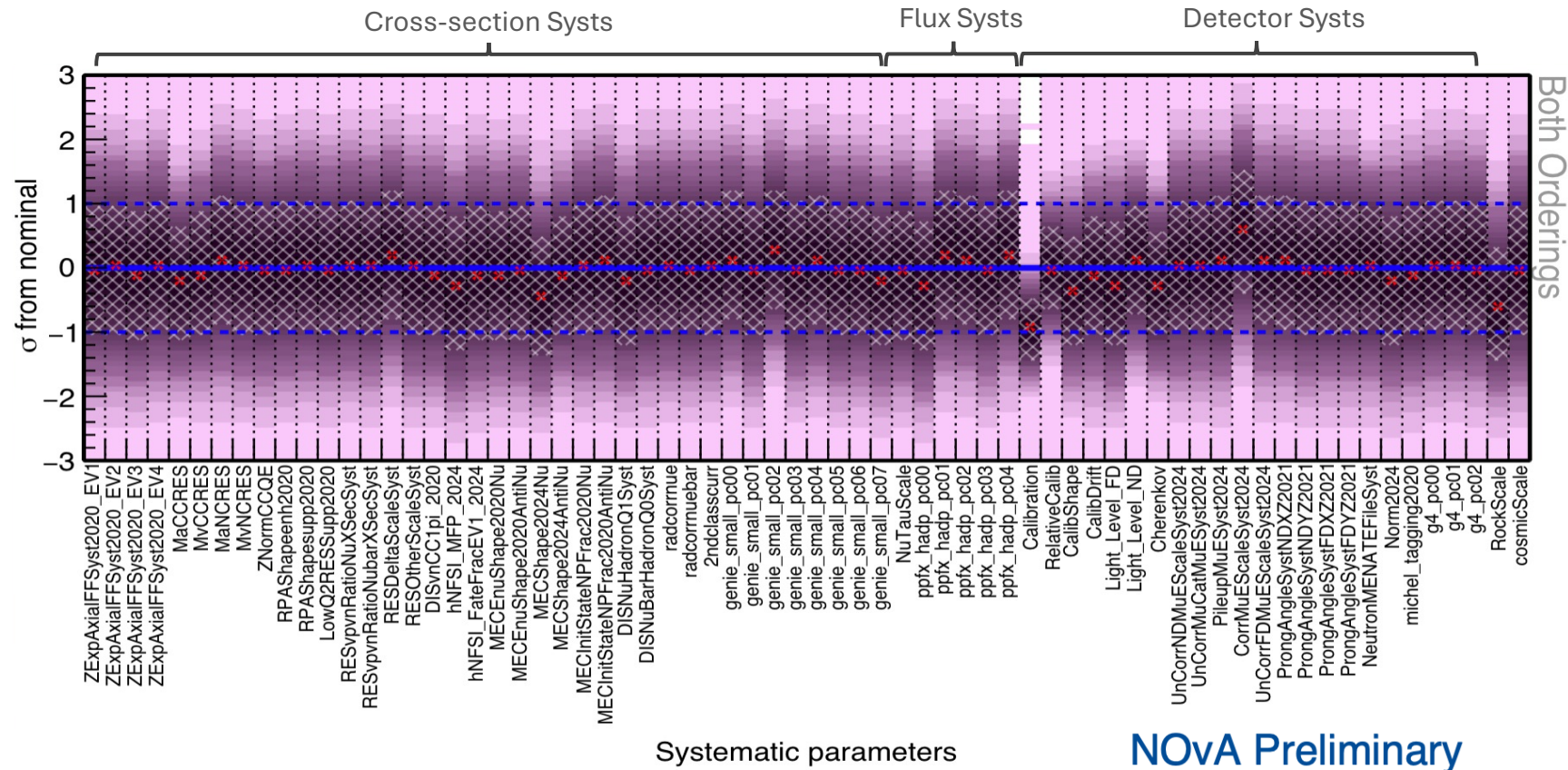
Uncertainties on the oscillation parameters: **statistical** vs **systematic**



**NOvA measurements remain statistically limited!**

# Systematics

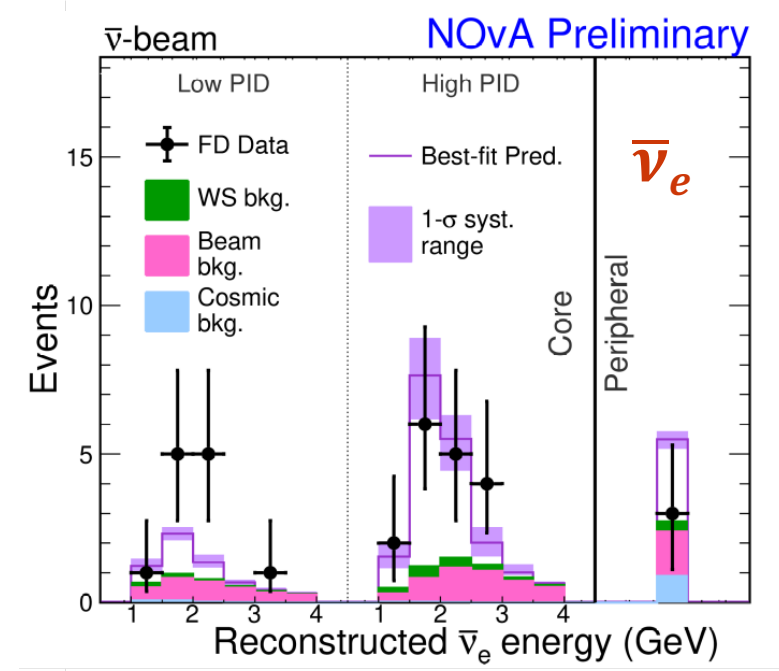
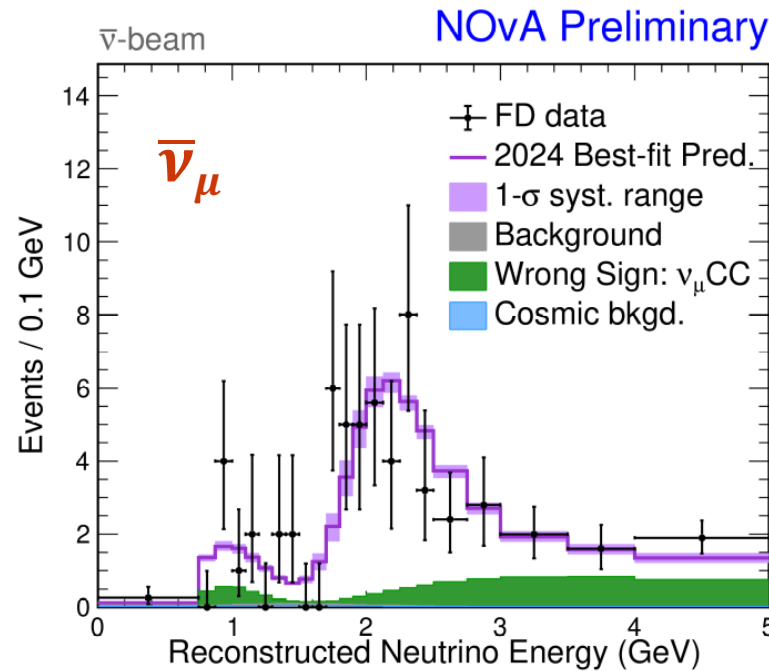
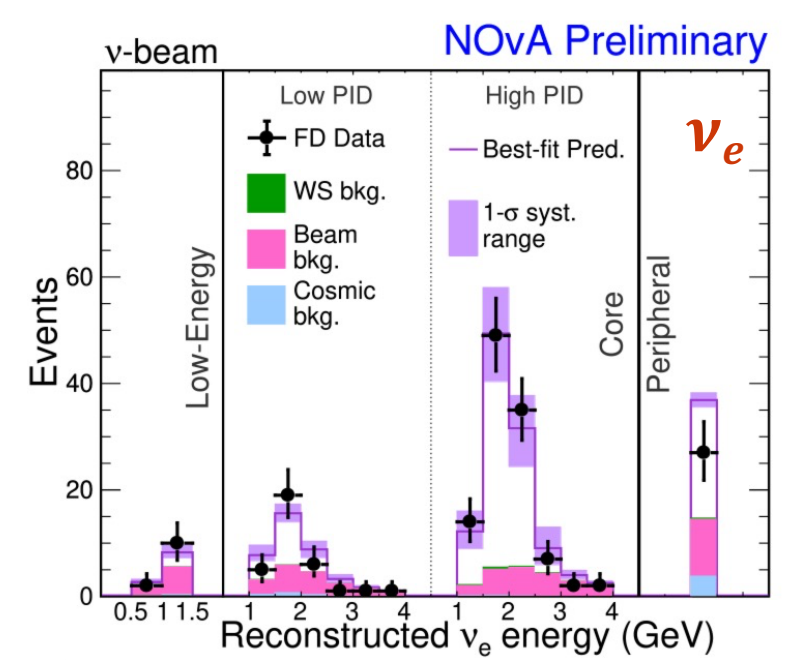
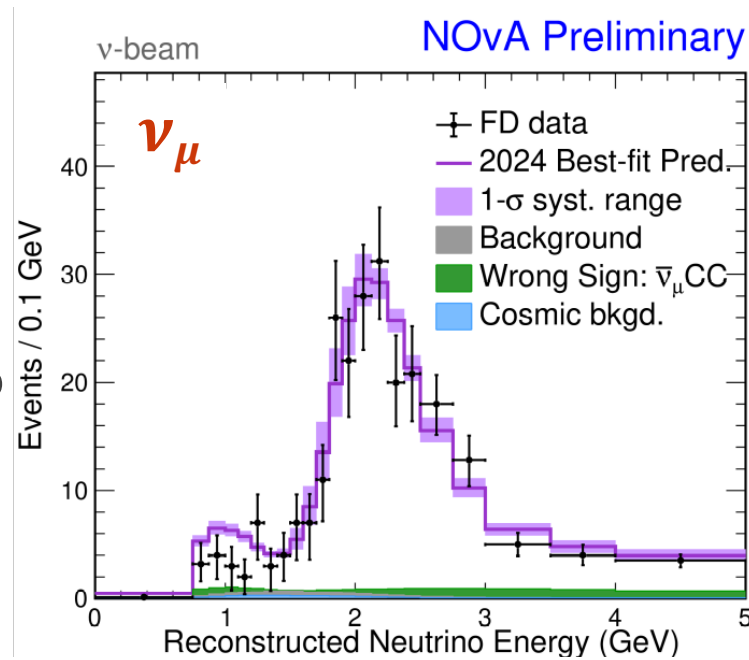
- Extrapolation reduces the impact of the systematics on the measurements but typically does not constraint the systematics itself.
- A comparison of posterior to prior shows no change for most parameters as expected.



# NOvA 2024 Dataset

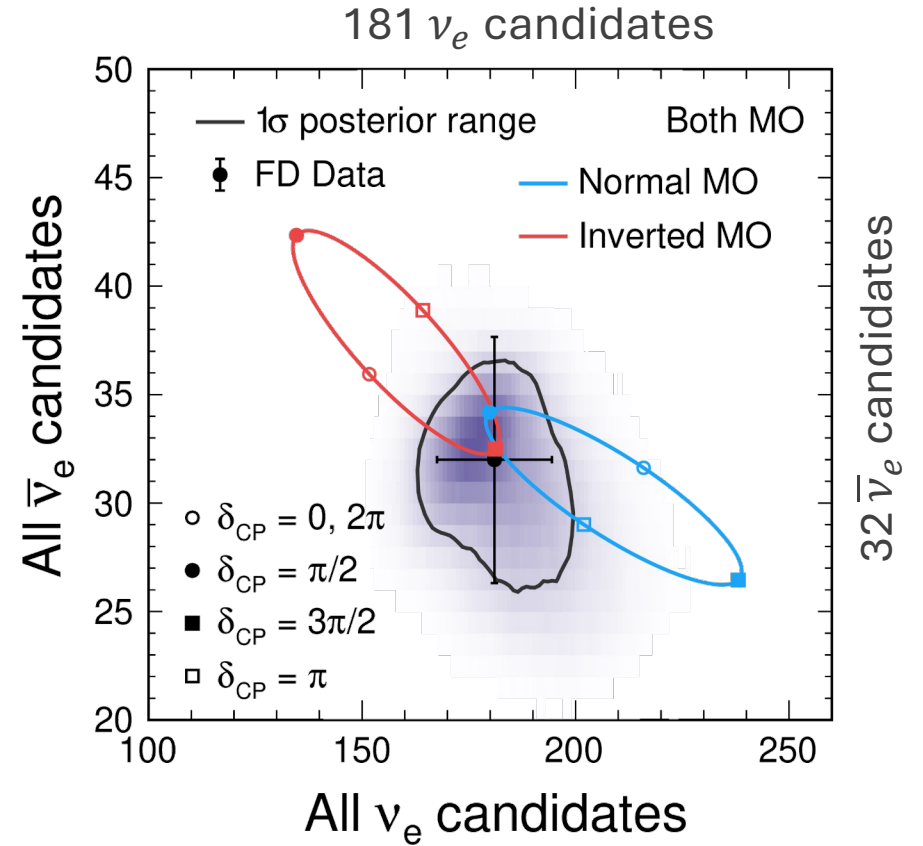
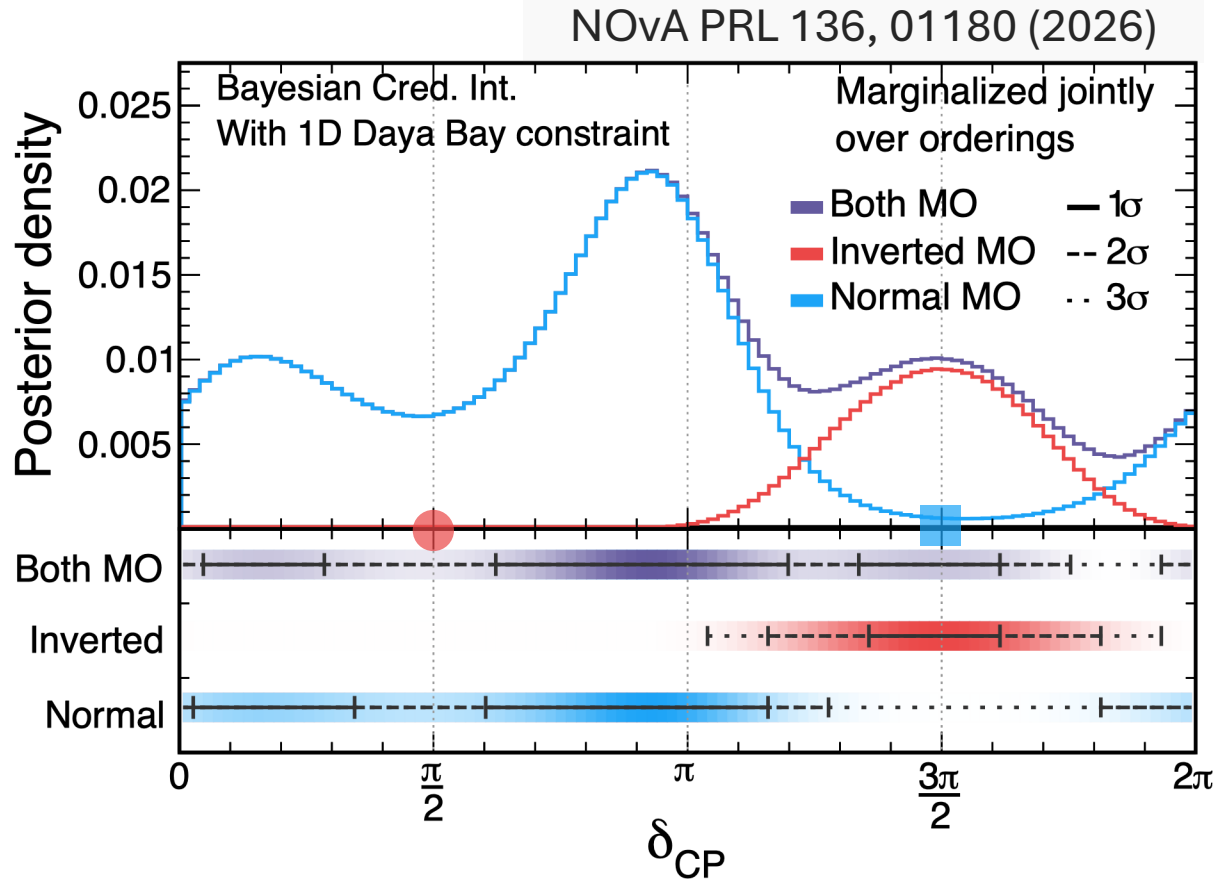
- The 3-Flavor fit describes the data well.
- NOvA performs one frequentist and two Bayesian (ARIA: MR<sup>2</sup>T<sup>2</sup>H and STAN: Hamiltonian MCMC) fits. All fits agree well with each other.

Channel	2024 Dataset	PPP value =
$\nu_e$	169 ( $\nu_e$ ) 12 (Low E)	0.58 ( $\nu_e$ ) 0.72 (Low E)
$\bar{\nu}_e$	32	0.19
$\nu_\mu$	384	0.59
$\bar{\nu}_\mu$	106	0.39



# MO & $\delta_{CP}$

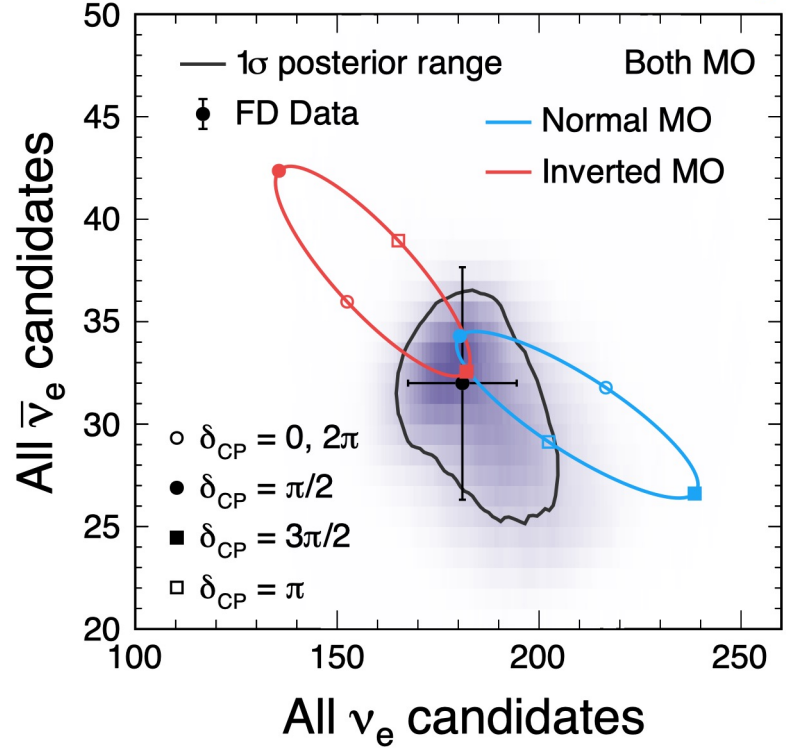
Degeneracy between MO &  $\delta_{CP}$  measurements in long-baseline experiments



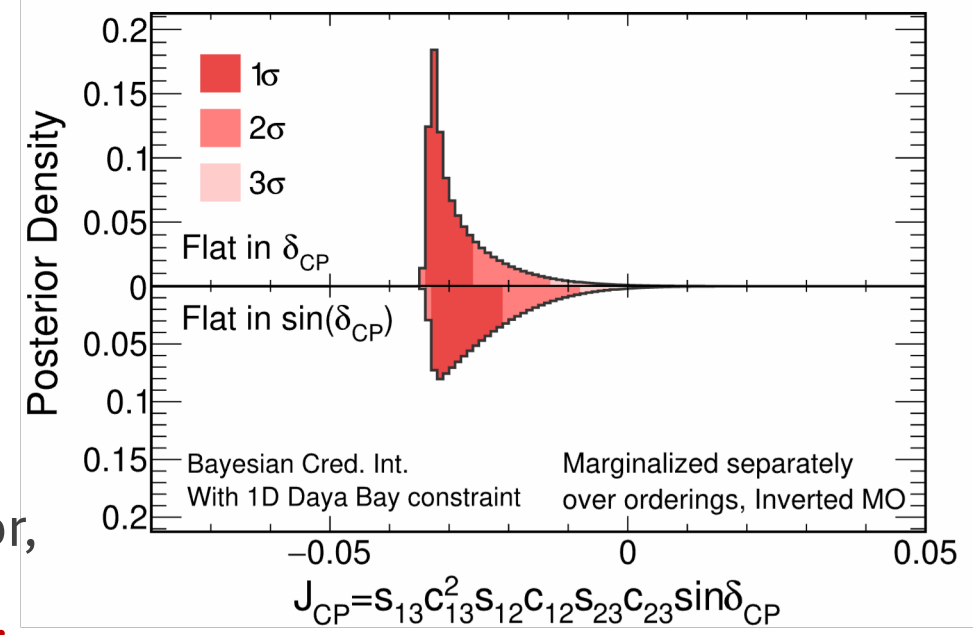
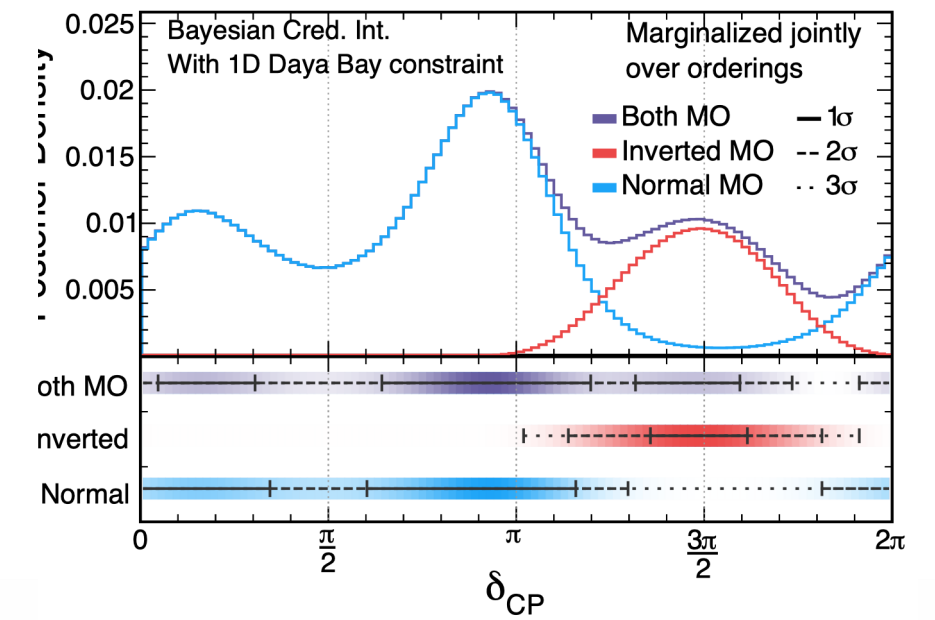
- Disfavors asymmetric combinations of (MO,  $\delta_{CP}$ ): ■ (NO,  $3\pi/2$ ) at  $\sim 2.5\sigma$ , ● (IO,  $\pi/2$ ) at  $> 4\sigma$
- NOvA data show a preference for NO (77% posterior) with a Bayes factor of 3.3

# CPV: $\delta_{CP}$ and $J_{CP}$

NOvA Preliminary



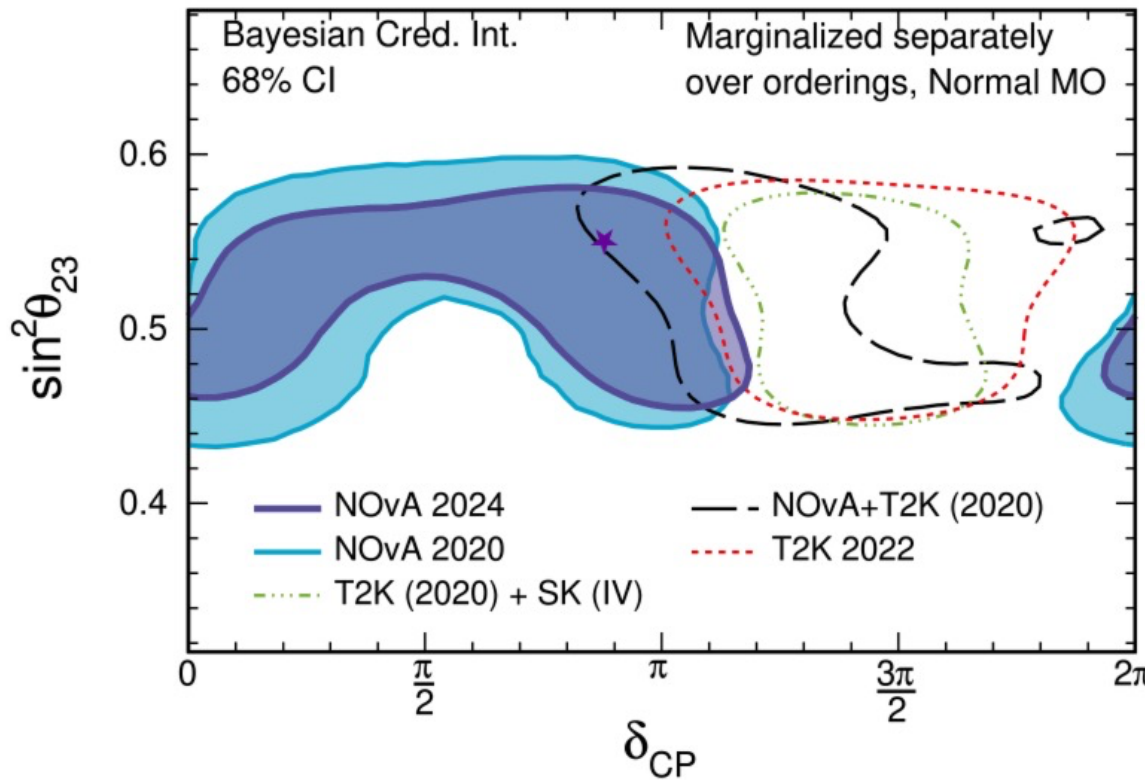
- The data disfavors large asymmetry combinations: (IO,  $\delta_{CP} = \pi/2$ ) and (NO,  $\delta_{CP} = 3\pi/2$ ).
- In the Inverted Ordering,  $J=0$  (CPC) is in tension w/ posterior, but only "uniform in  $\delta_{CP}$ " prior has  $J=0$  outside  $3\sigma$  interval.



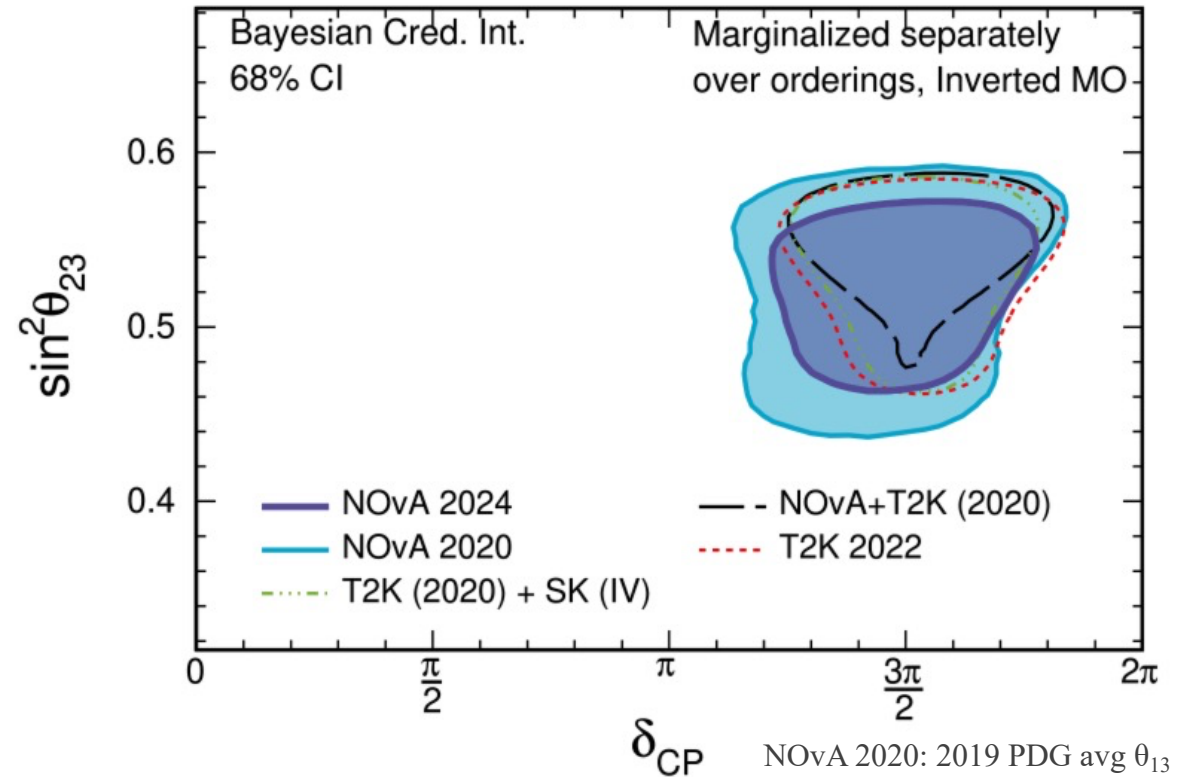
# CPv:

- NOvA result is **consistent with its previous analysis**.  
T2K, joint fits, favor different regions in Normal Ordering, same region in Inverted Ordering.

NOvA Preliminary



NOvA Preliminary

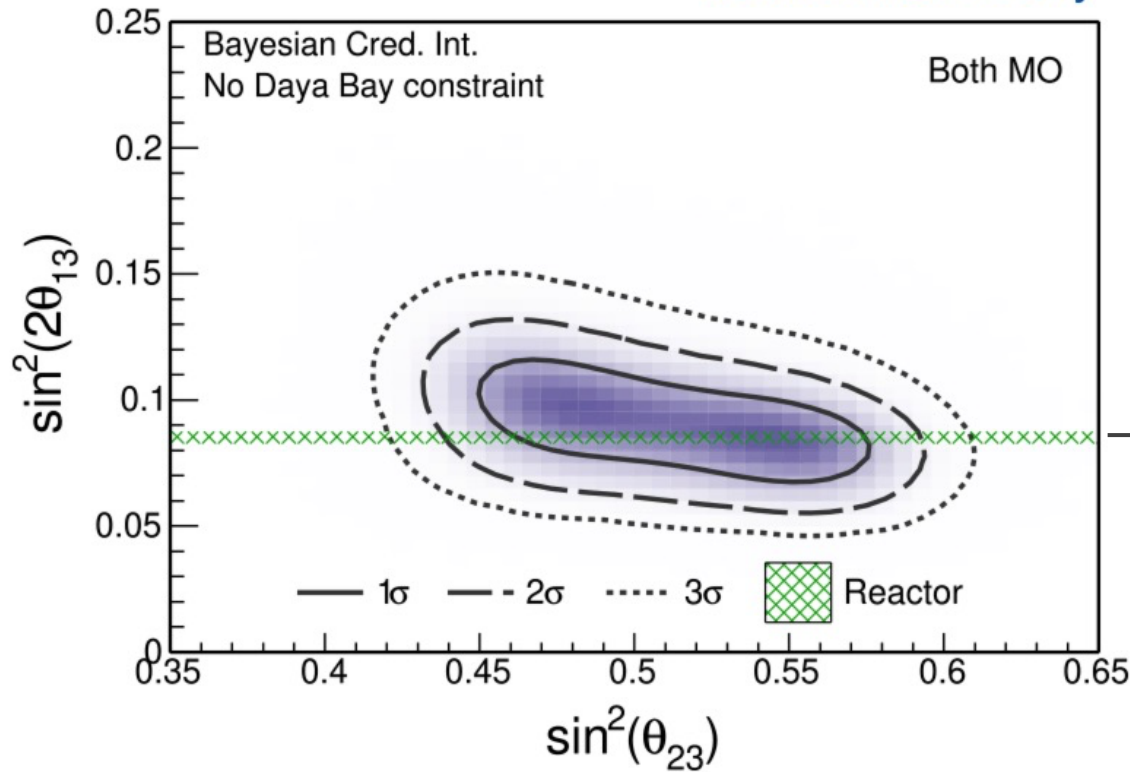


Note: results use slightly different choices of reactor constraint

NOvA 2020: 2019 PDG avg  $\theta_{13}$   
 NOvA 2024: Daya Bay 2023 1D  $\theta_{13}$   
 T2K: 2019 PDG avg  $\theta_{13}$   
 NOvA+T2K: Daya Bay 2023 1D  $\theta_{13}$   
 T2K+SK: 2019 PDG avg  $\theta_{13}$

# Mixing Angles: $\theta_{23}$ and $\theta_{13}$

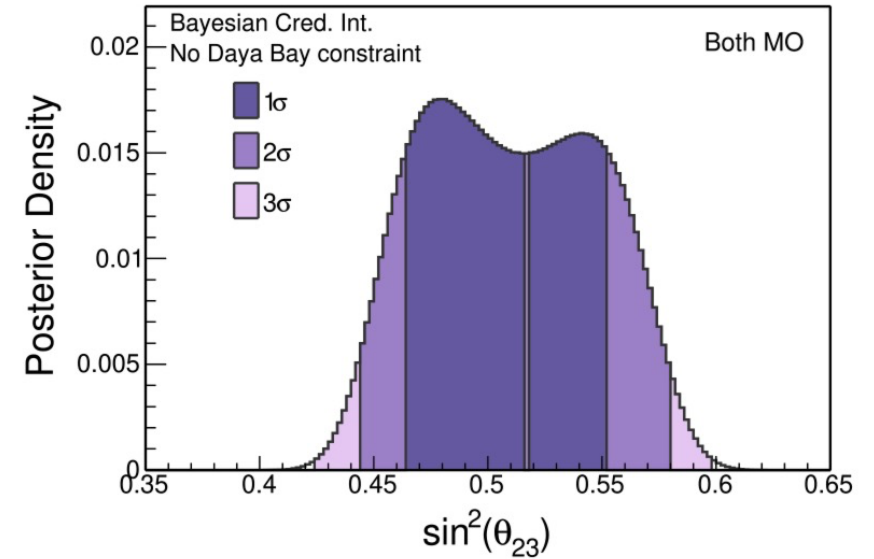
NOvA Preliminary



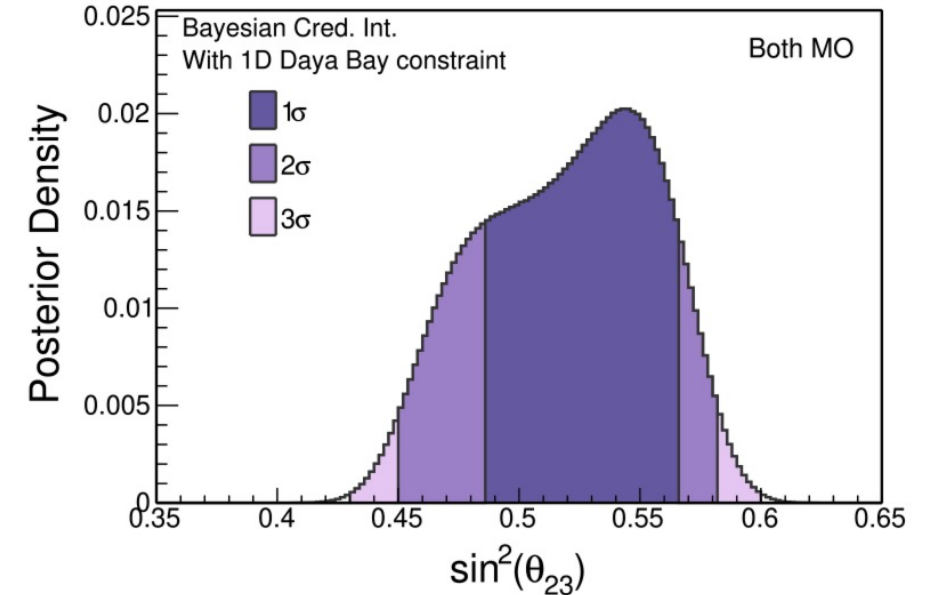
$$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$$

Daya Bay (PRL 130, 161802)

NOvA Preliminary



NOvA Preliminary

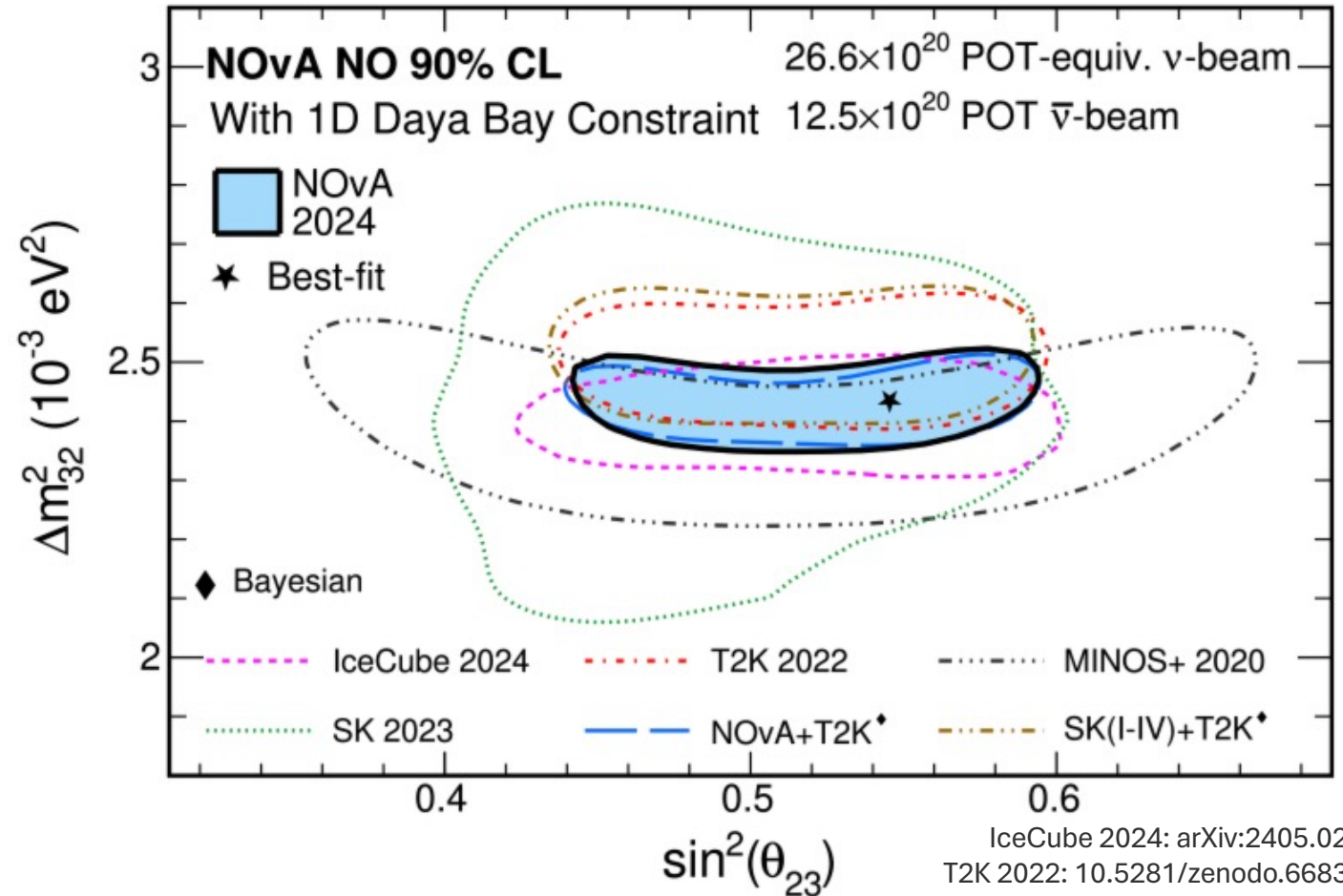


	No constraint		Daya Bay 2023 1D $\theta_{13}$	
	Probability	Bayes Factor	Probability	Bayes Factor
Upper Octant preference	<b>57%</b>	1.3	<b>69%</b>	2.2

# $\Delta m_{32}^2$ and $\theta_{23}$

- Global consistency across accelerator, atmospheric and joint-fit results.
- All data is **consistent with maximal mixing** hypothesis for  $\theta_{23}$

NOvA Preliminary



IceCube 2024: arXiv:2405.02163  
 T2K 2022: 10.5281/zenodo.6683821  
 MINOS+ 2020: Phys. Rev. Lett. 125, 131802  
 SK 2023: Phys. Rev. D109, 072014  
 NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar  
 T2K+SK 2024: arXiv:2405.12488

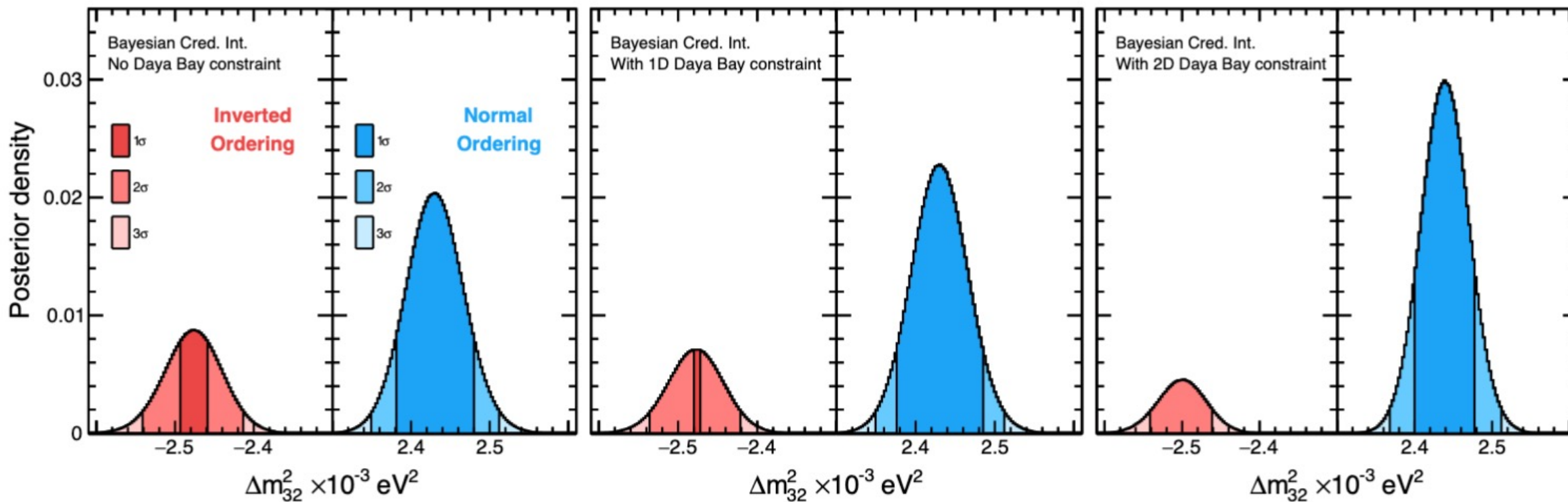
**Frequentist results  
 (w/ Daya Bay 1D  $\theta_{13}$  constraint)**

		Normal MO		Inverted MO	
$\Delta m_{32}^2 / 10^{-3} \text{ eV}^2$	<b>+2.433</b>	+0.035	-0.036	-2.473	+0.035
$\sin^2 \theta_{23}$	<b>0.546</b>	+0.032	-0.075	0.539	-0.075
$\delta_{CP}$	0.88 $\pi$			1.51 $\pi$	



# NOvA 2024 + Daya Bay

NOvA Preliminary



NOvA - only w/o reactor

NOvA - only - 1D Daya Bay

NOvA - only - 2D Daya Bay

Bayes factor

**2.2**  
Normal/Inverted  
~69% : ~31% posterior

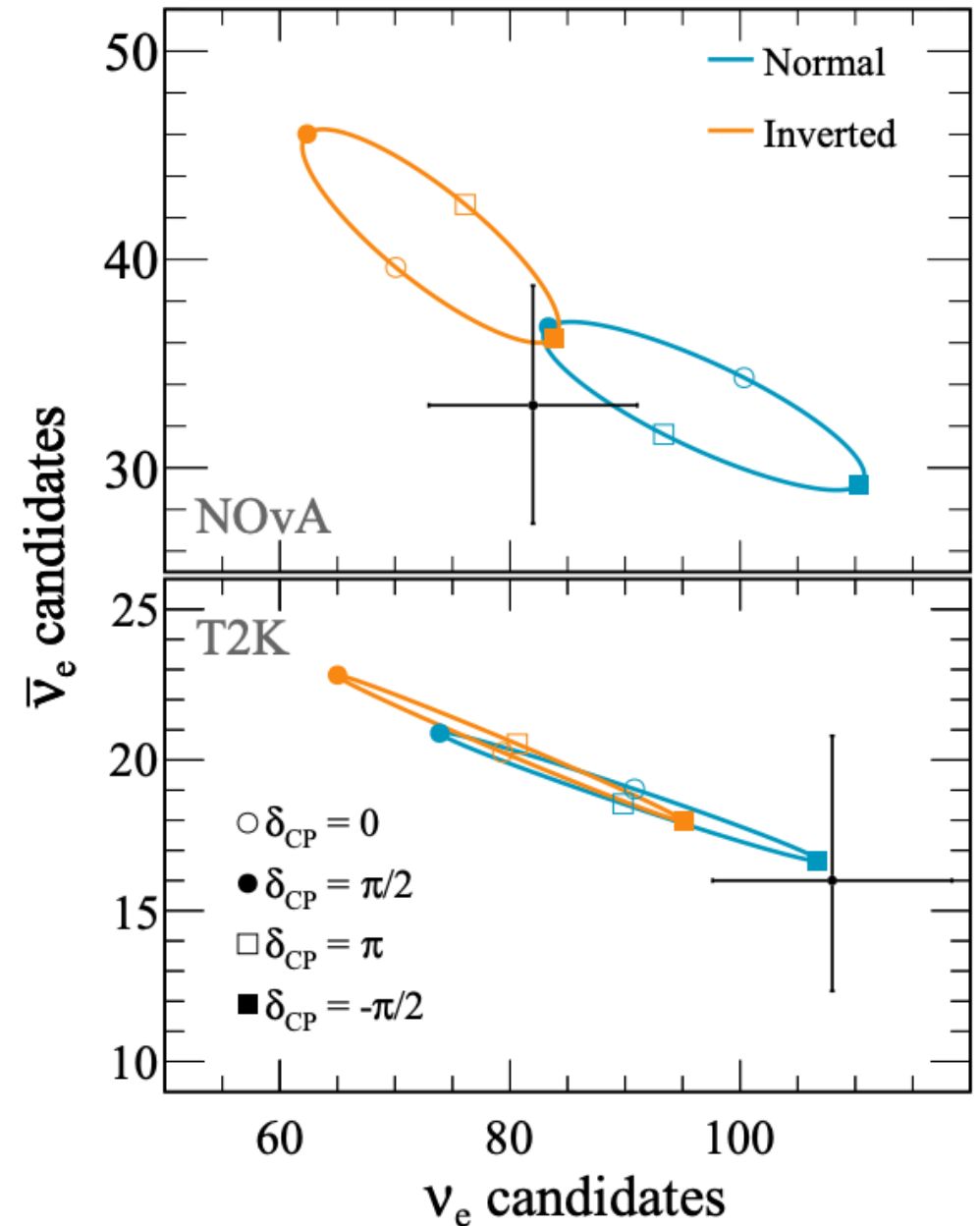
**3.3**  
Normal/Inverted  
~77% : ~23% posterior

**6.6**  
Normal/Inverted  
~87% : ~13% posterior

# NOvA & T2K Dataset

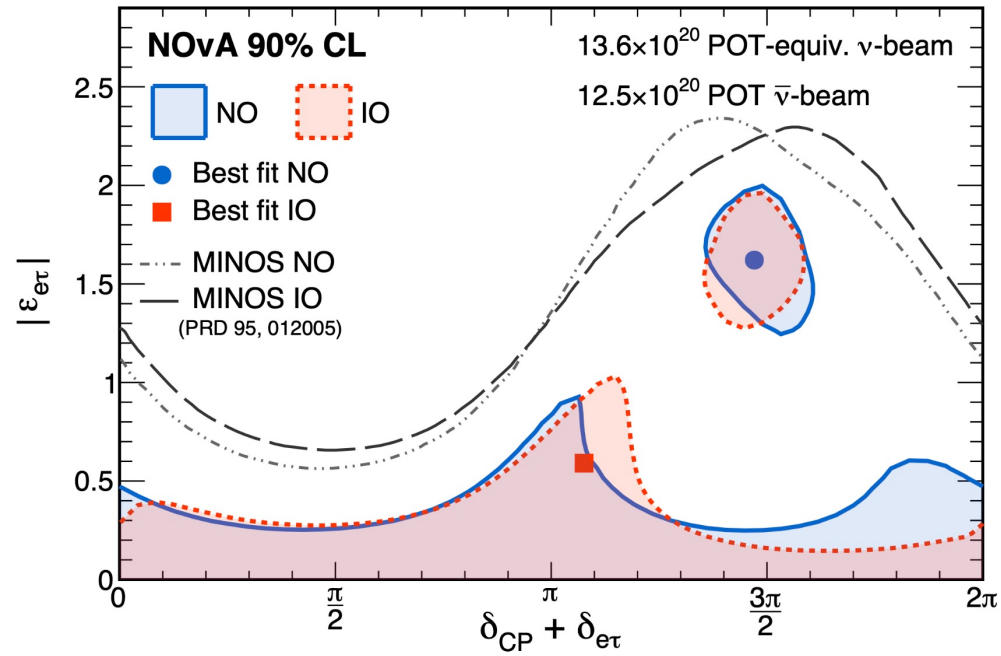
Channel	NOvA	T2K
$\nu_e$	82	94 ( $\nu_e$ ) 14 ( $\nu_e 1\pi$ )
$\bar{\nu}_e$	33	16
$\nu_\mu$	211	318
$\bar{\nu}_\mu$	105	137

- 2020-era dataset from both experiments used for the joint-fit.

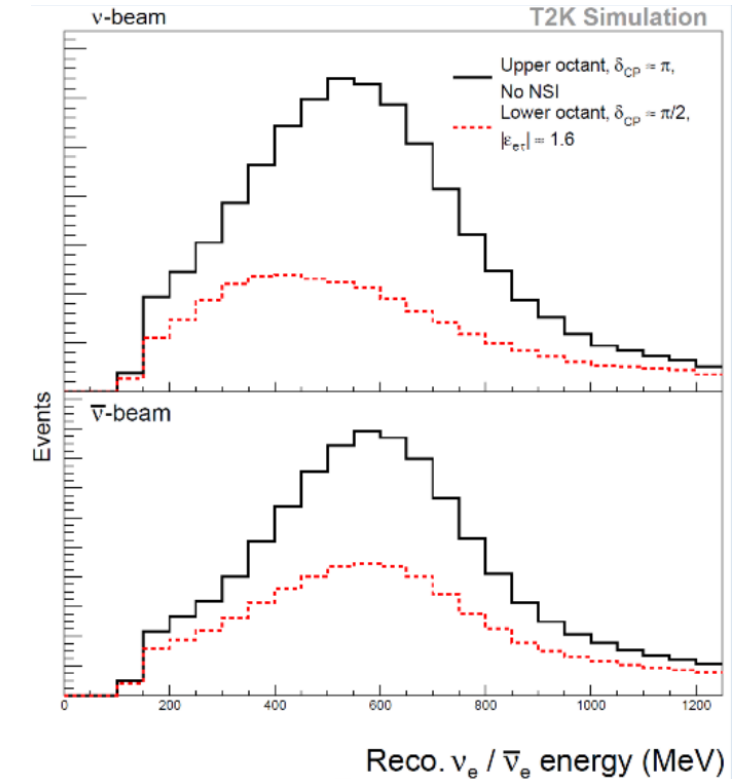
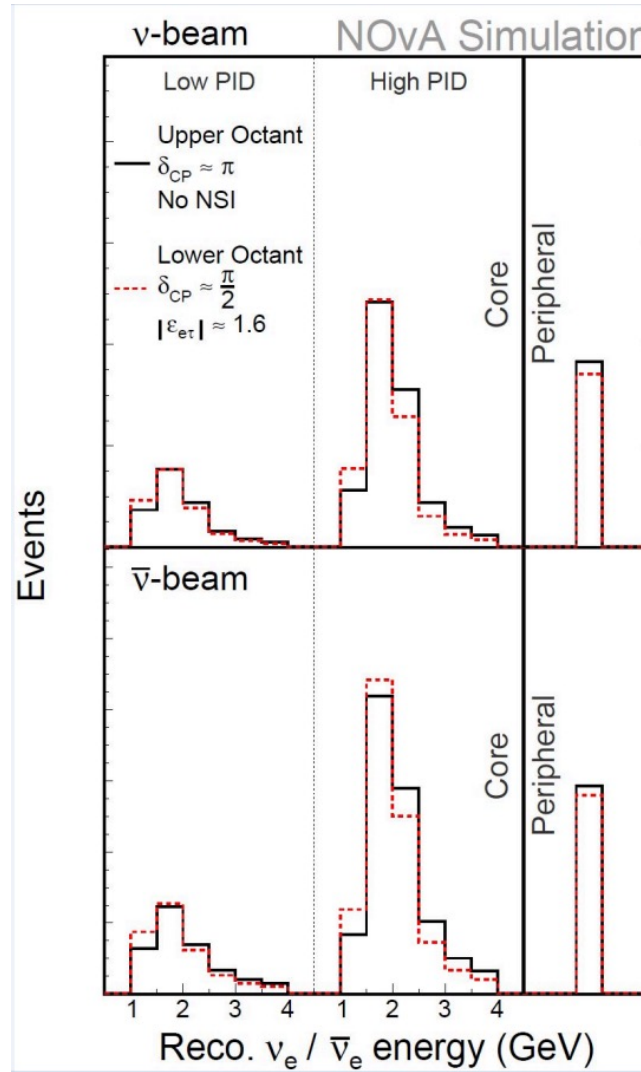


# NOvA & T2K: NSI

Example spectra from NOvA & T2K at NOvA's NSI best-fit values



NOvA puts excellent constraints on NSI but certain parameter combinations mimic the 3F oscillation. T2K's different baseline is important for breaking these degeneracies.

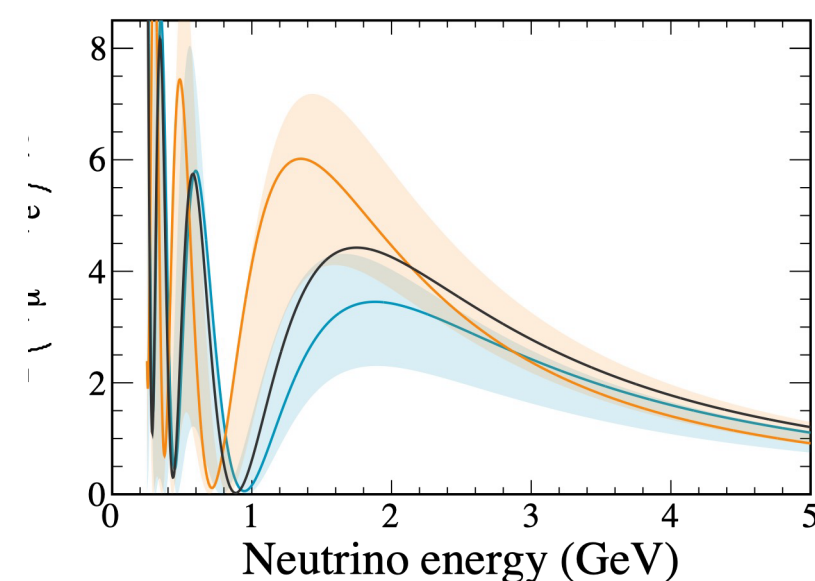
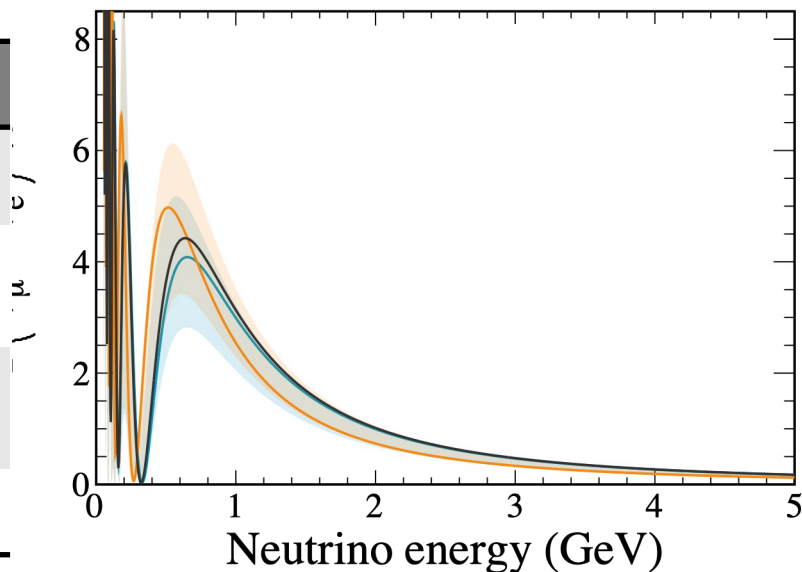
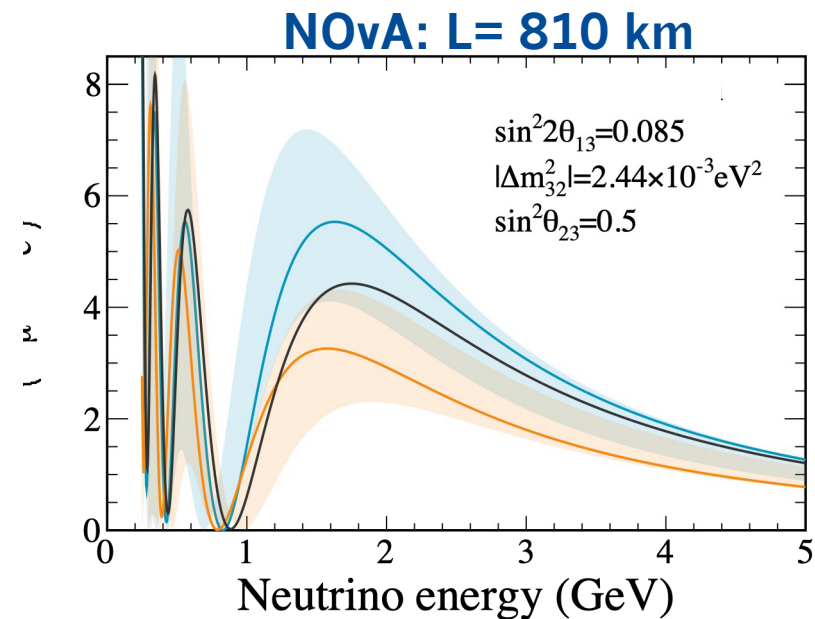
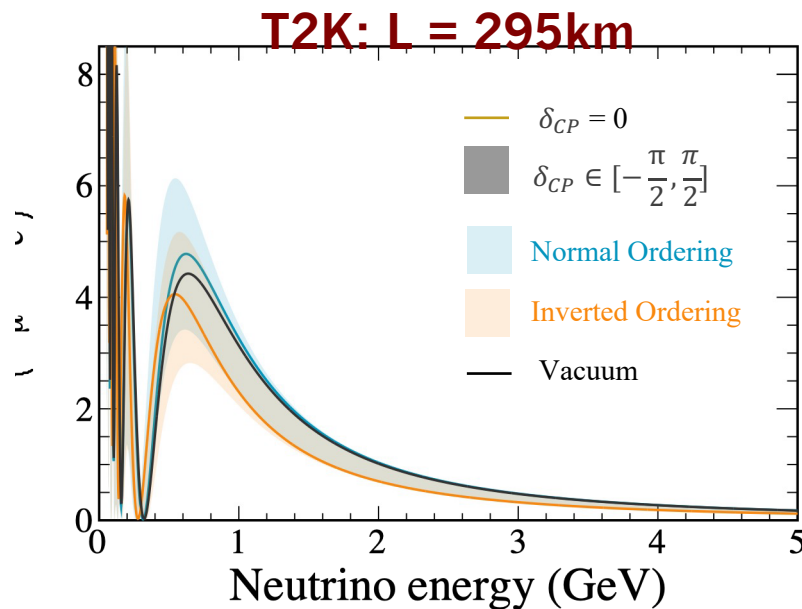


# Baselines

- Larger matter effect for higher neutrino energy  $\rightarrow$  higher sensitivity to mass ordering.
- Therefore, associated asymmetry is higher for the longer baseline.

	T2K	NOvA
L (baseline)	295 km	810 km
Energy (beam peak)	0.6 GeV	2 GeV
Matter effect*	$\sim \pm 9\%$	$\sim \pm 19\%$
CP effect*	$\sim \pm 30\%$	$\sim \pm 25\%$

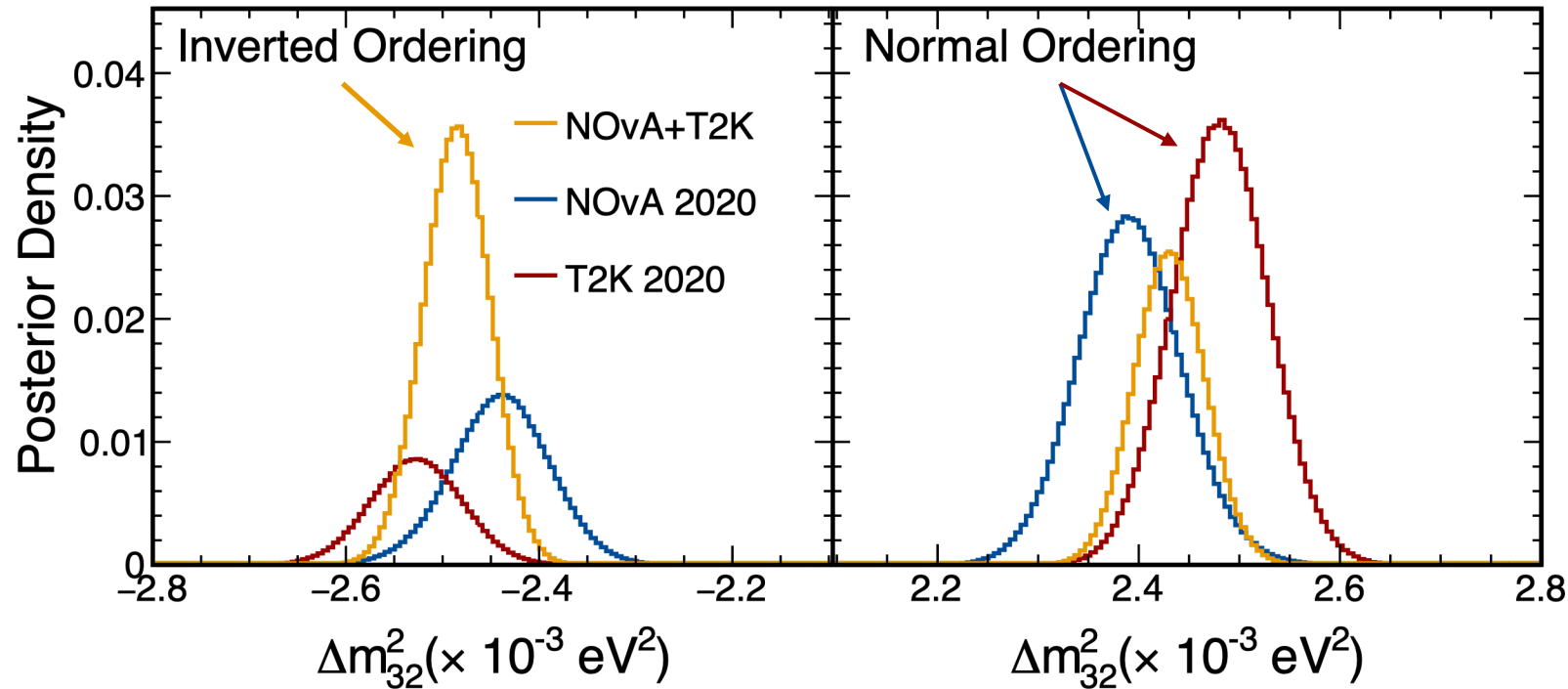
\*calculated at beam peak energy



# Synergies for measuring Mass Ordering



Nature **646**, 818-824 (2025)



- Despite difference in experimental baseline, **MO** and  $\delta_{CP}$  remain degenerate in the long-baseline experiments.
- NOvA+T2K joint fit **weakly prefers Inverted Ordering**, driven by overlap in  $\delta_{CP}$  space.

To see what's next for the joint analysis, check out these posters:

#499 NOvA-T2K Developments & Machinery: Hank Hua

#420 New Directions for NOvA-T2K: Gavin Davies, Veera Mikola, Luiz Prais

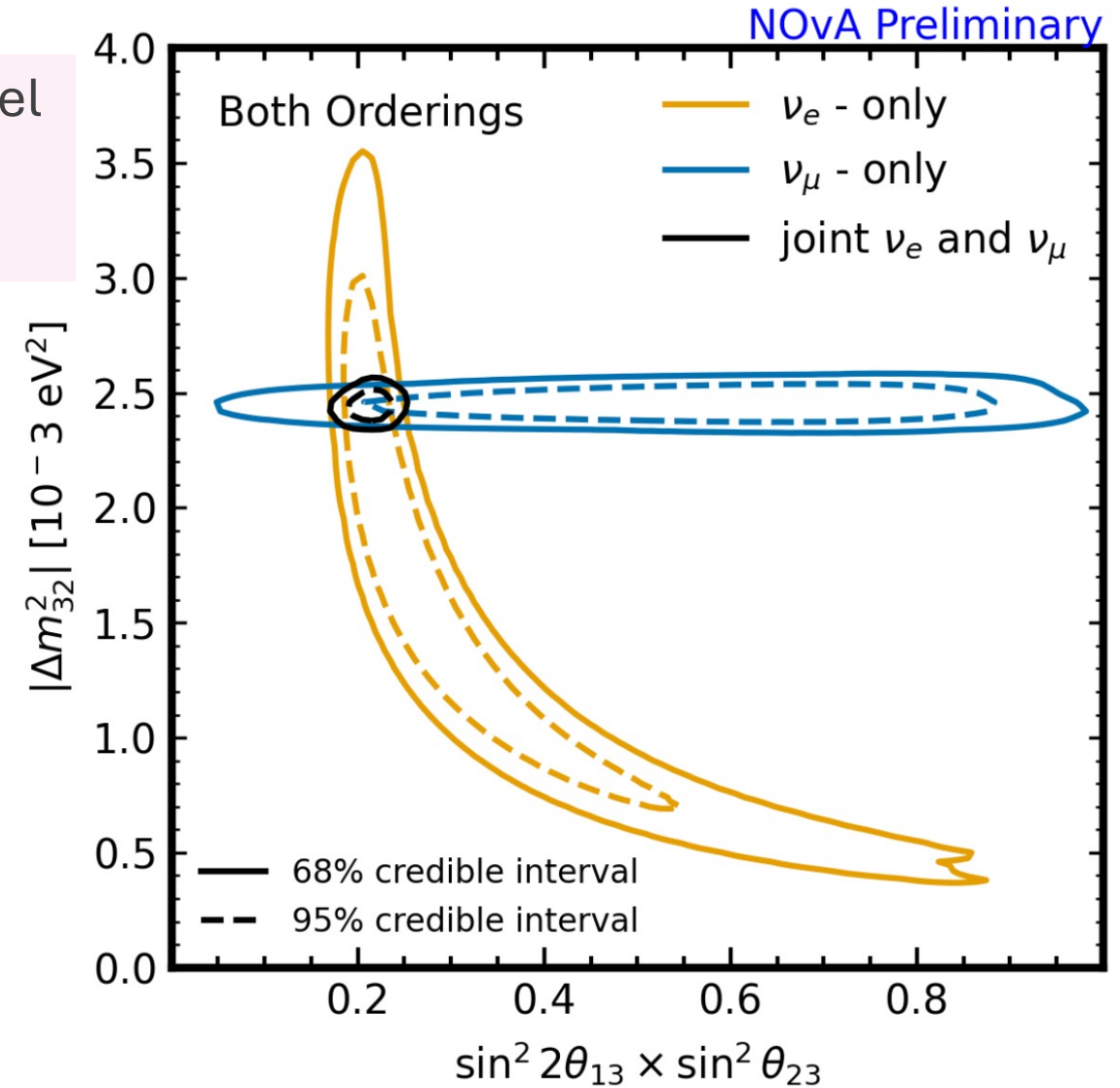
# $\nu_\mu$ vs $\nu_e$ vs $(\nu_\mu + \nu_e)$ data fits

To probe 3-Flavor paradigm, refit the oscillation model to  $\nu_\mu$  only and  $\nu_e$  only subsamples with the same 10-year dataset!

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

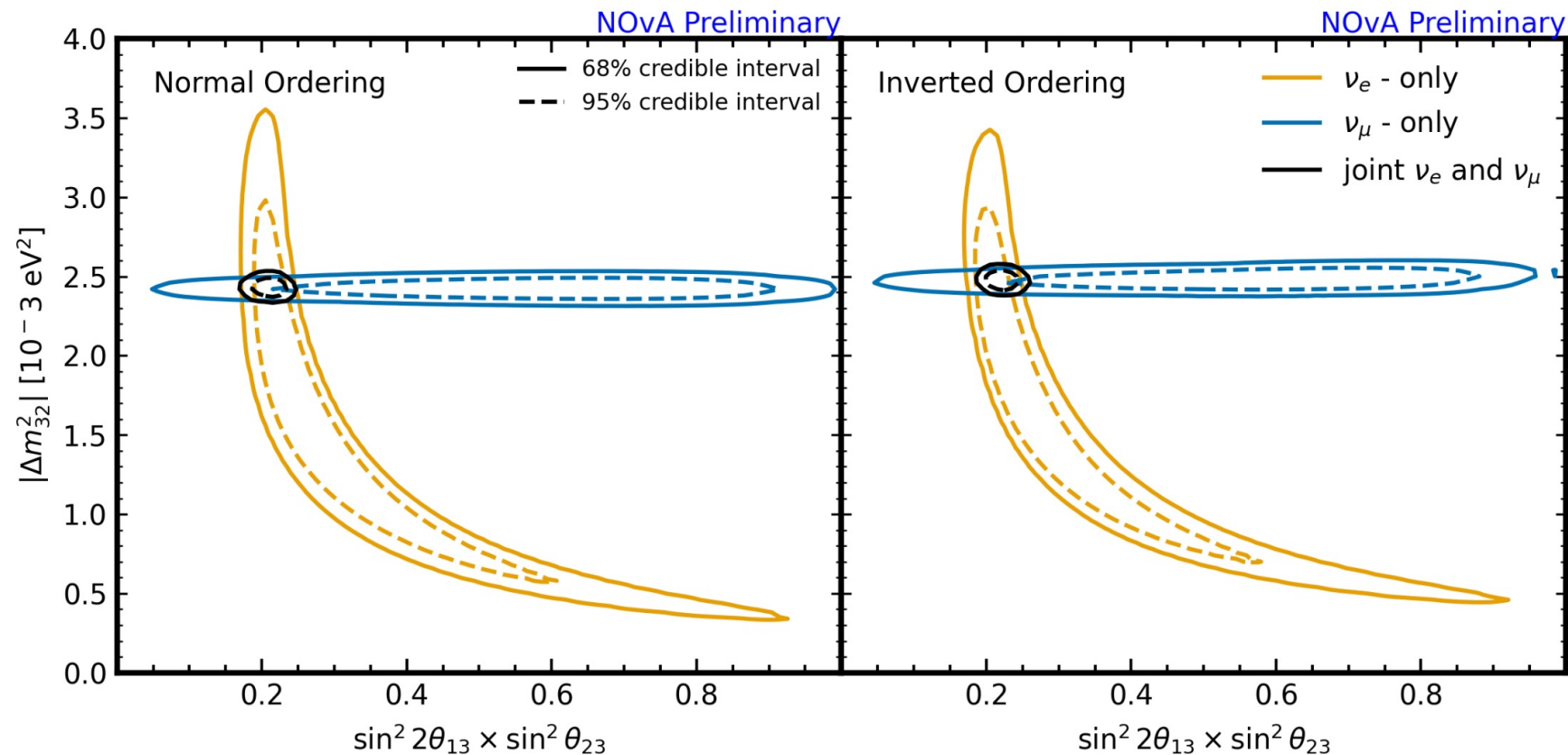
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2$$

$\mp$  [CP-odd] + [CP-even] + [solar]



# $\nu_\mu$ VS $\nu_e$ VS $(\nu_\mu + \nu_e)$ data fits

- Measurements are correlated in 5D ( $\Delta m_{32}^2$ ,  $\sin^2 2\theta_{13}$ ,  $\sin^2 \theta_{23}$ , MO,  $\delta_{CP}$ ) space.
- $\Delta m_{32}^2$  is constrained by  $\nu_\mu$  disappearance.
- $\nu_e$  appearance amplitude is degenerate in  $\sin^2 2\theta_{13} \times \sin^2 \theta_{23}$ .

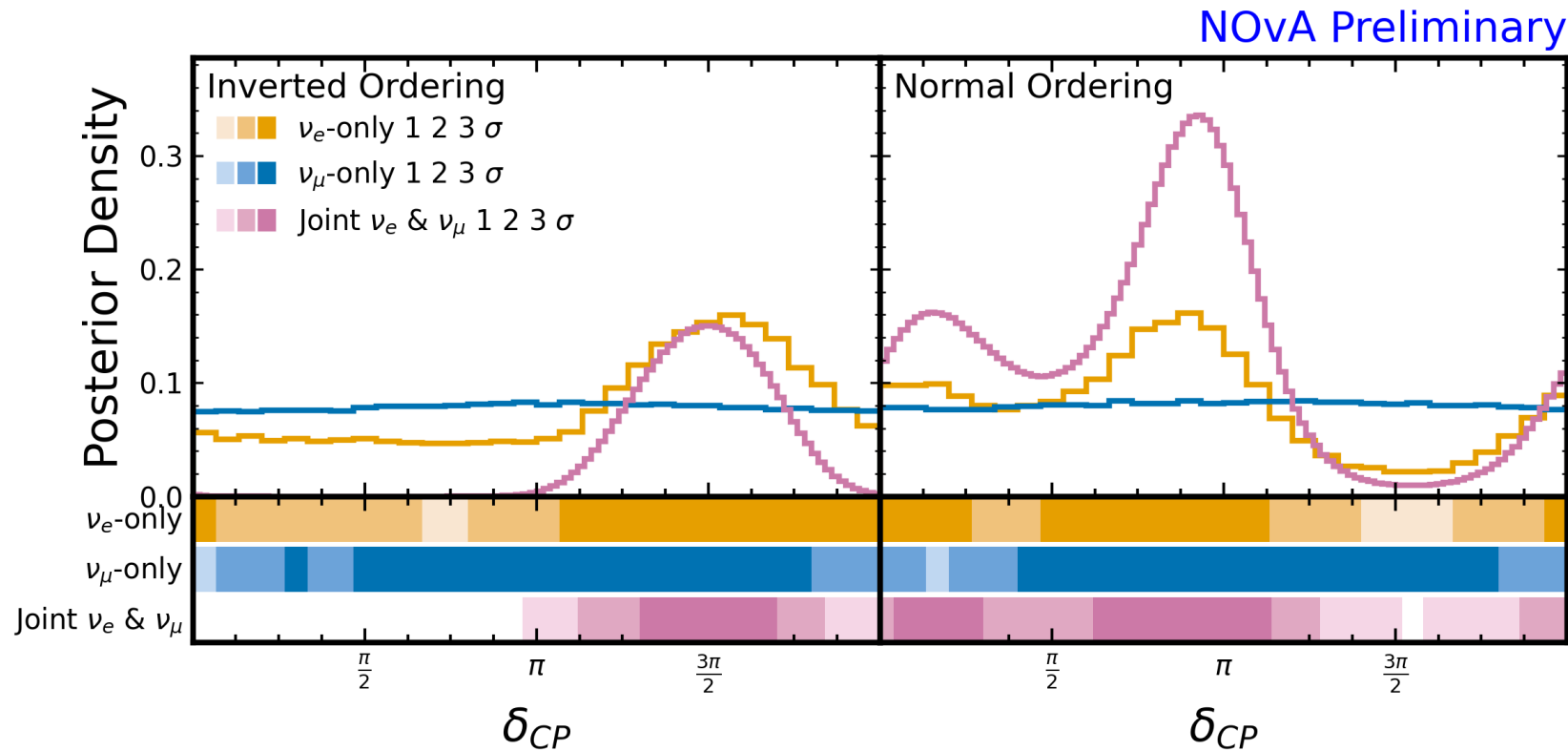


# $\nu_\mu$ vs $\nu_e$ vs $(\nu_\mu + \nu_e)$ data fits

🌟 New today: 🌟

Stress test the 3-Flavor paradigm  
Fit the  $\nu_\mu$  only and  $\nu_e$  only subsamples separately on the same 10-year dataset!

- Measurements are correlated in 5D ( $\Delta m_{32}^2$ ,  $\sin^2 2\theta_{13}$ ,  $\sin^2 \theta_{23}$ , MO,  $\delta_{CP}$ ) space.



# Steriles in NOvA

$\nu\bar{\nu}$  Beam

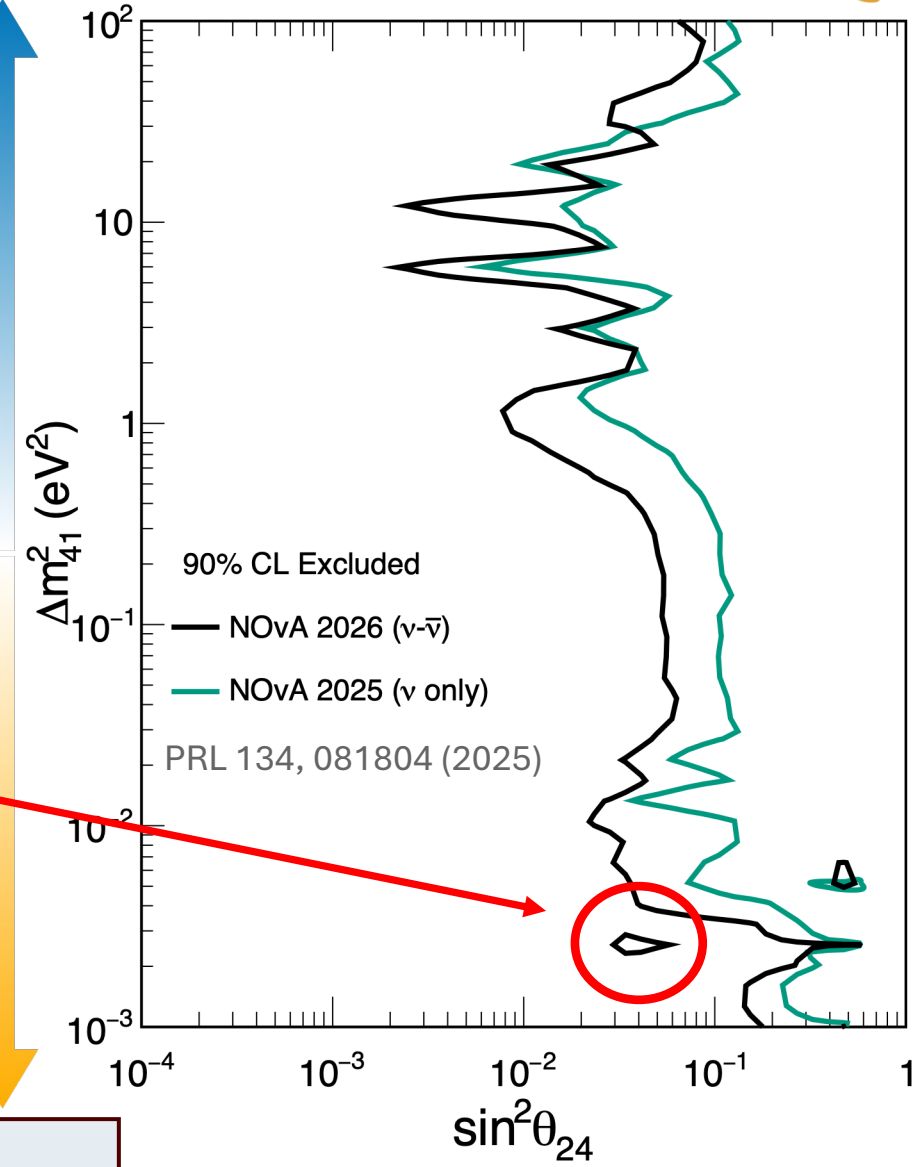


**High  $\Delta m_{41}^2$ : fast oscillations**  
Driven by high-statistics ND Data  
Systematics limited

**Significantly improved limits  
beyond previous NOvA  
results.**

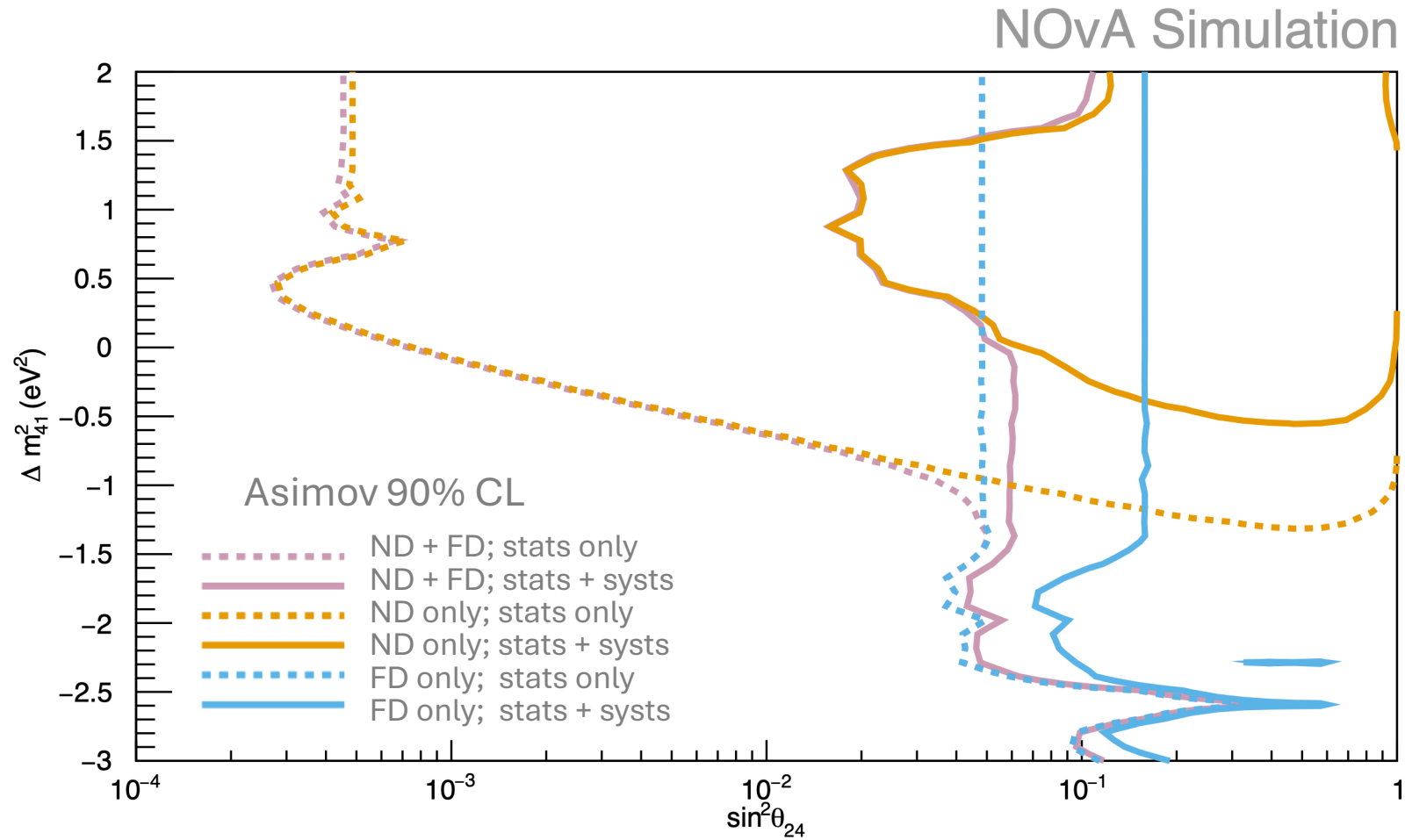
The island of rejection comes from FHC+RHC fits which strongly constrain  $\delta_{24}$  to be 0, and there is not enough flexibility in  $\theta_{23}, \theta_{34}$  to get a good fit across all subsamples simultaneously for these values of  $\theta_{24}$ .

**Low  $\Delta m_{41}^2$ : slow oscillations**  
Driven by low-statistics FD Data  
Statistics limited



**#195 NOvA Steriles 2026:** Shivam Chaudhary, Adam Lister, Adam Aurisano

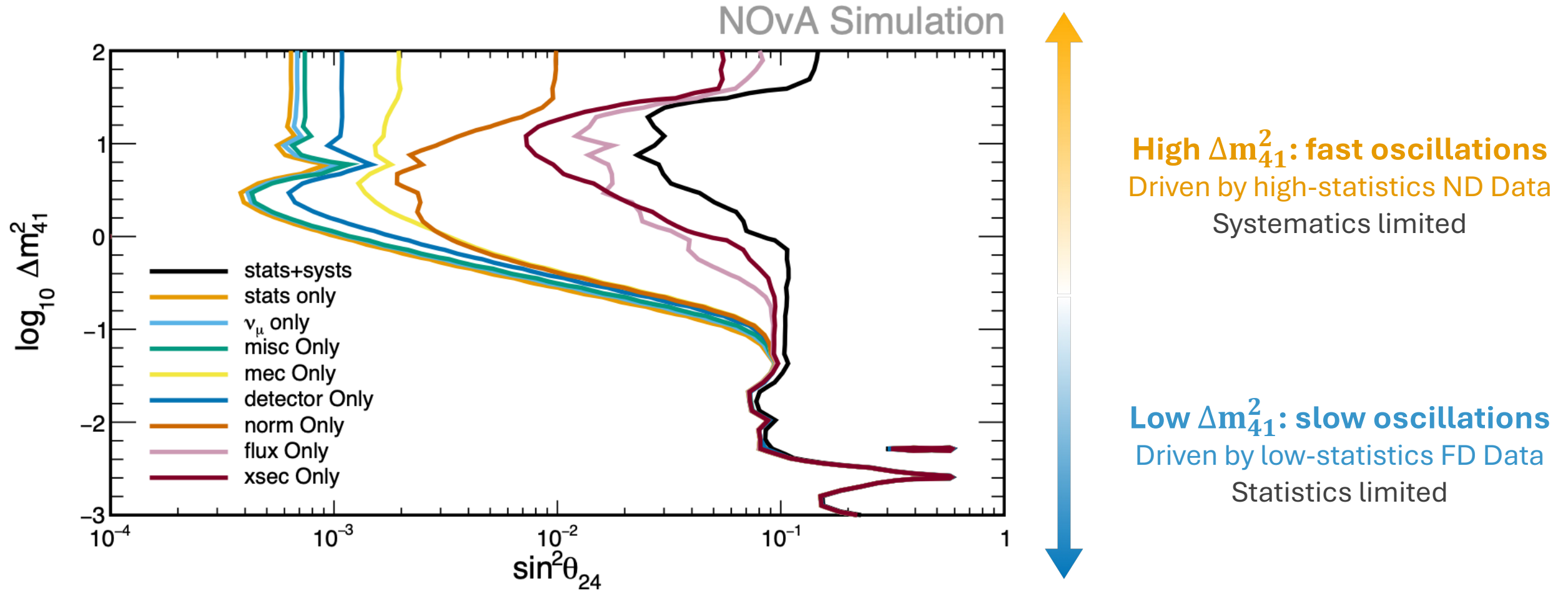
# Asimov Sensitivities



**High  $\Delta m_{41}^2$ : fast oscillations**  
Driven by high-statistics ND Data  
Systematics limited

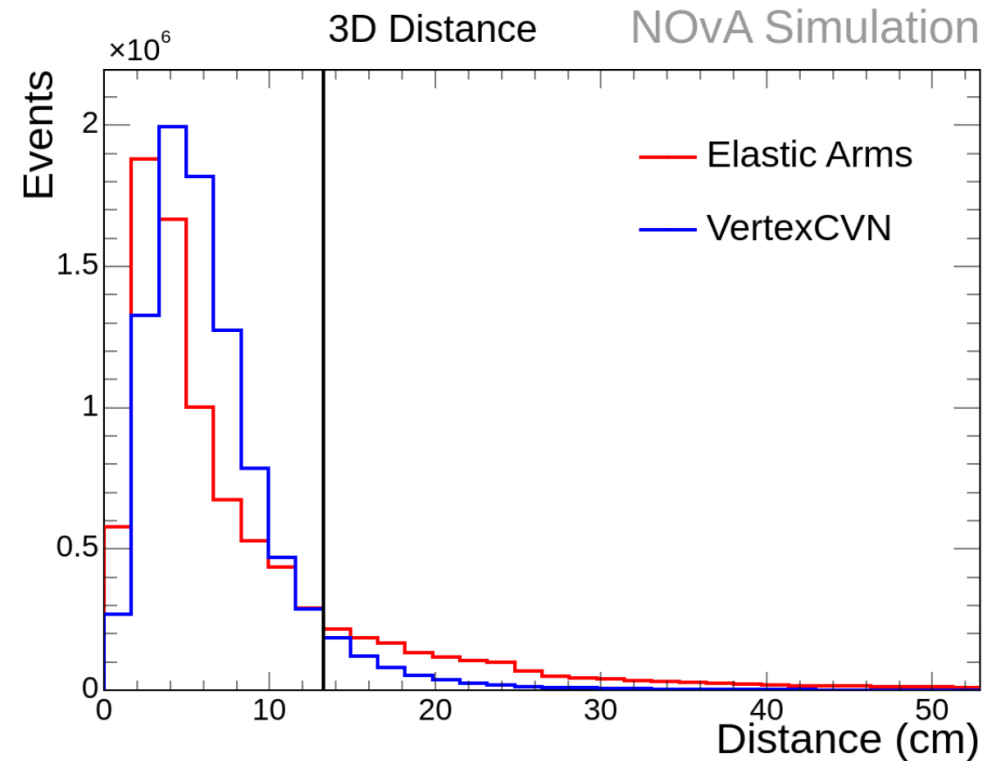
**Low  $\Delta m_{41}^2$ : slow oscillations**  
Driven by low-statistics FD Data  
Statistics limited

# Impact of Systematics



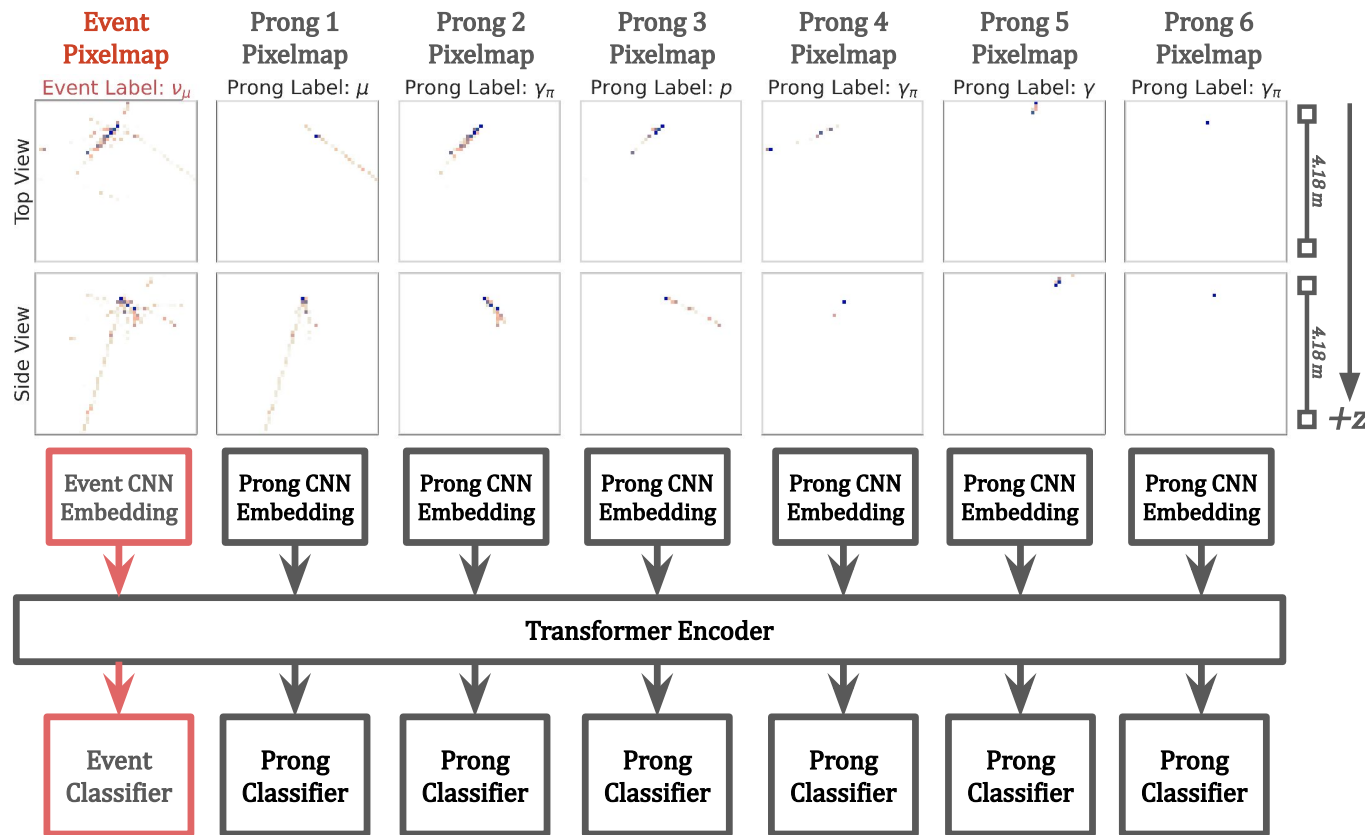
# Improved Reconstruction: VertexCVN

- Apply machine learning to address several known failure modes of NOvA existing algorithm “Elastic Arms”.
  - **Forward failure** - tendency for main prong to be split in two.
  - **Backward failure** - tendency for multiple, small prongs to be combined into one.
- VertexCVN uses same CNN architecture as NOvA’s event-level classifier (modified MobileNetv2, arXiv:1801.04381) to predict a single 3D position.
- Training samples with **beam modes combined** but **separated** for **Near** (~18 million) and **Far** (~26 million events) detector.
- VertexCVN is **more precise** than Elastic Arms but slightly **less accurate**.



# Improved Reconstruction: TransformerCVN

- Transformer network for joint event/particle classification.
- Better particle classification and interpretability due to context from other reconstructed particles in event.



Event class	$\nu_e$ CC	$\nu_\mu$ CC	NC	Cosmic
TransformerCVN	0.981	0.987	0.965	0.998
EventCVN	0.983	0.987	0.965	0.999

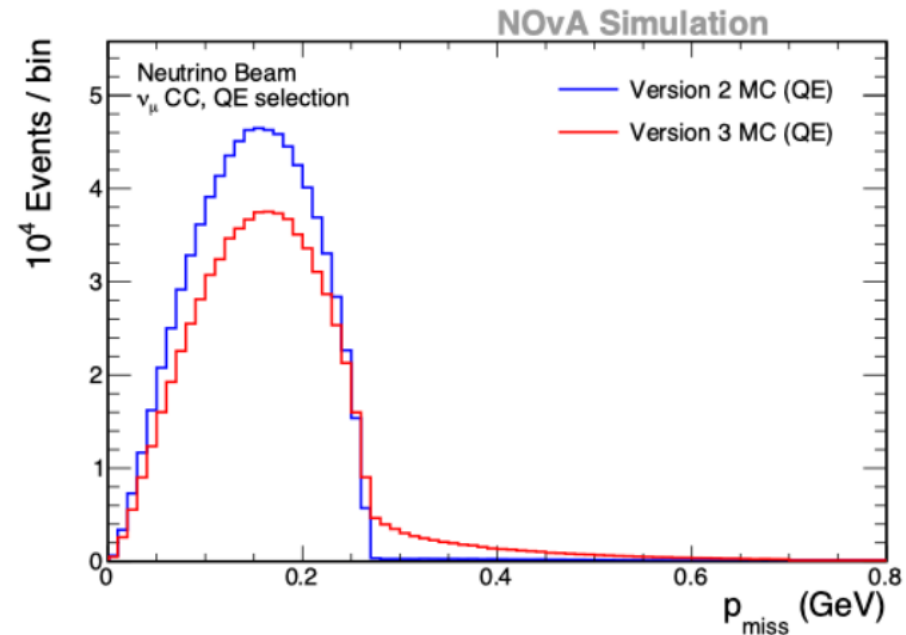
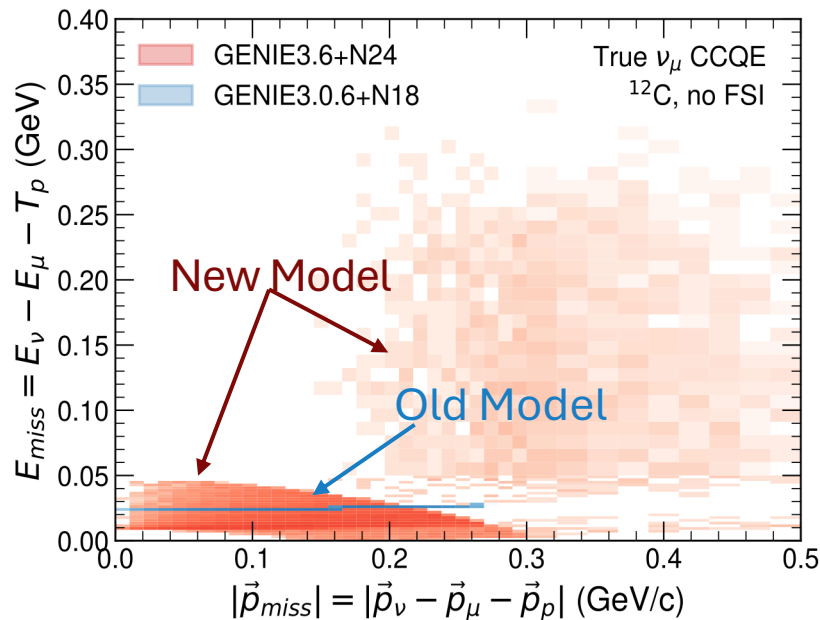
Prong class	$e$	$\mu$	$p$	$\pi^\pm$	$\gamma$
TransformerCVN	0.972	0.987	0.934	0.896	0.925
ProngCVN	0.956	0.981	0.926	0.884	0.911

# New Interaction Model

#241 Cross-Section Model: Bryan Ramson, Georgia Nissen, Jeremy Wolcott

- New production with updated cross-section model used **across Fermilab experiments (“AR-23”)** with custom NOvA adjustments. GENIE 3.6.0 with N24\_20i\_02\_11b model.

NOvA Version	CMC	Initial State	QE	Res	MNI/MEC	DIS	FSI	FSI Tune
<b>Version 2</b>	<b>N18_10j_00_000*</b>	LFG	Valencia	Berger-Seghal	Valencia	Bodek-Yang*	IntraNuke hN2018	None
<b>Version 3</b>	<b>N24_20i_02_11b</b>	LFG*	Valencia*	Berger-Seghal	SuSAv2 2p2h*	Bodek-Yang*	IntraNuke hA2018	Free-Nuke

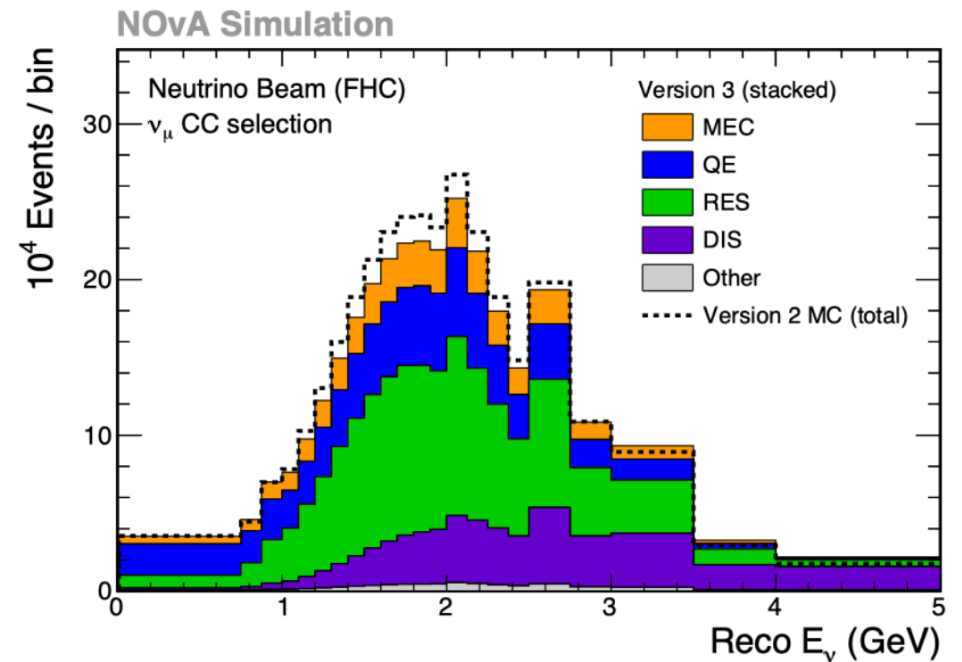
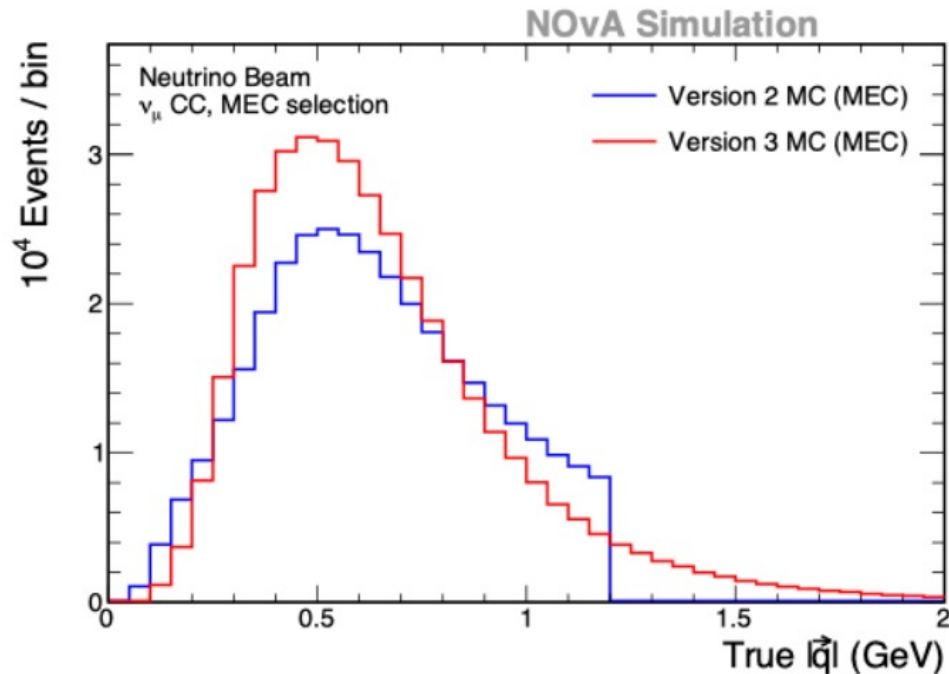


# New Interaction Model

#241 Cross-Section Model: Bryan Ramson, Georgia Nissen, Jeremy Wolcott

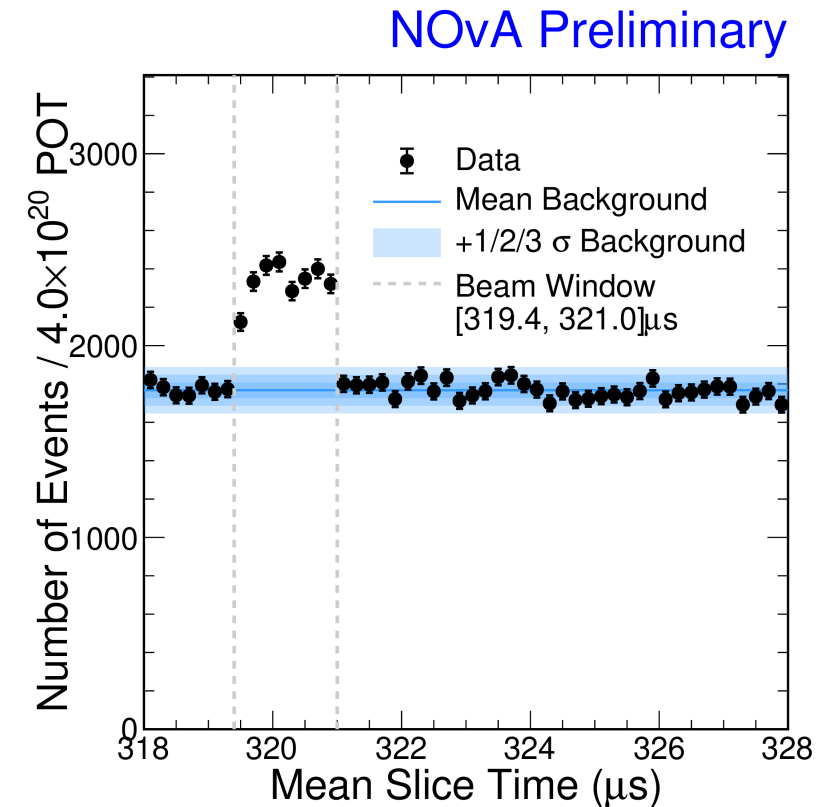
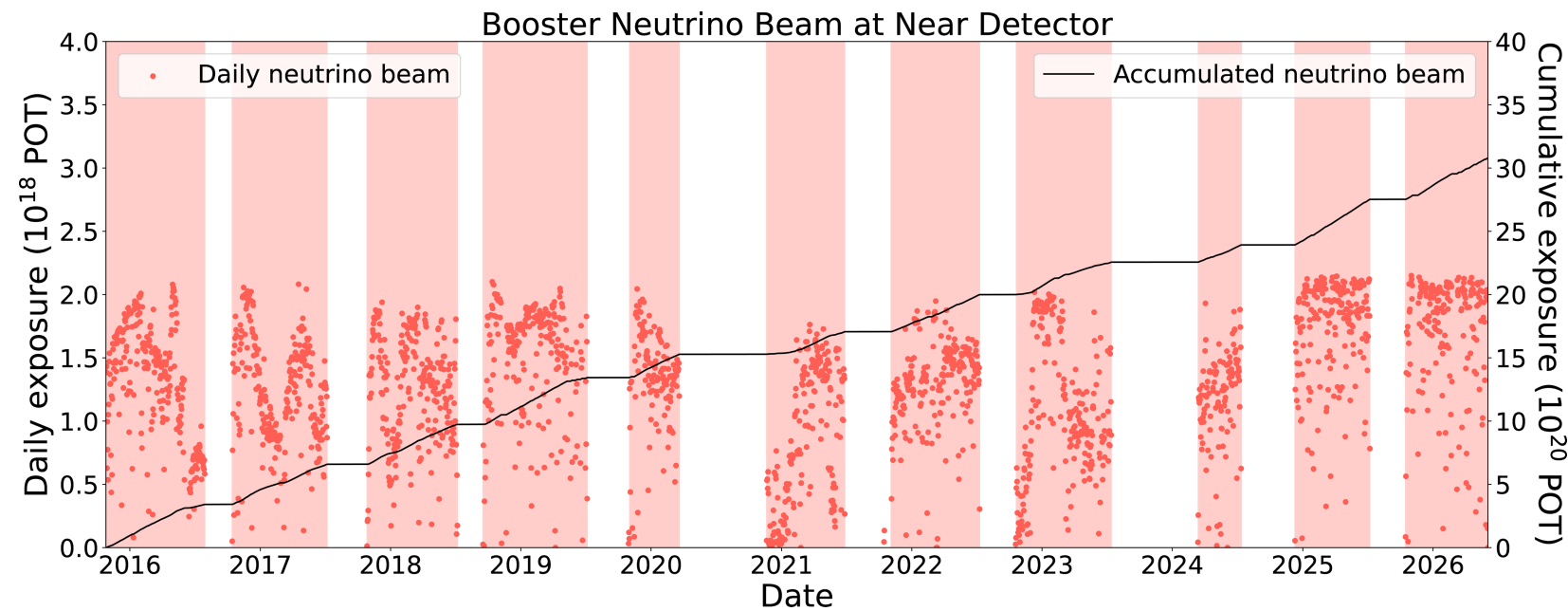
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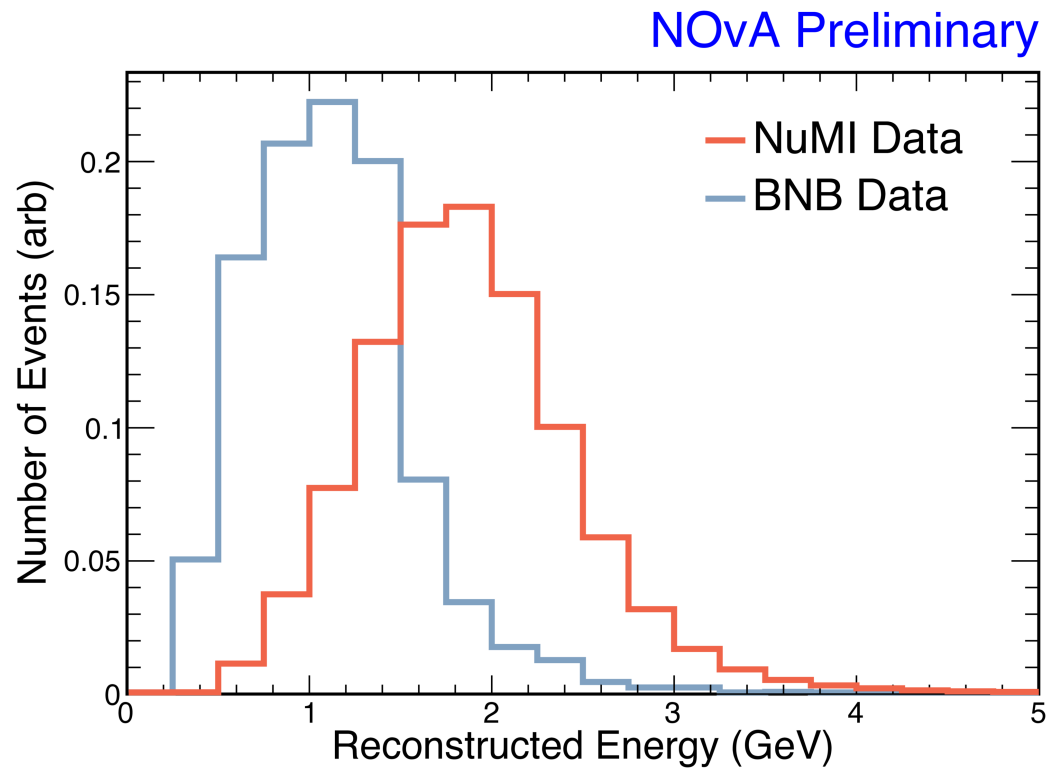
# Complimentary Data: BNB

- BNB and NuMI datasets have correlated interaction and detector uncertainties, uncorrelated beam uncertainties. Similar L/E & different E: break degeneracy in oscillations and uncertainties!

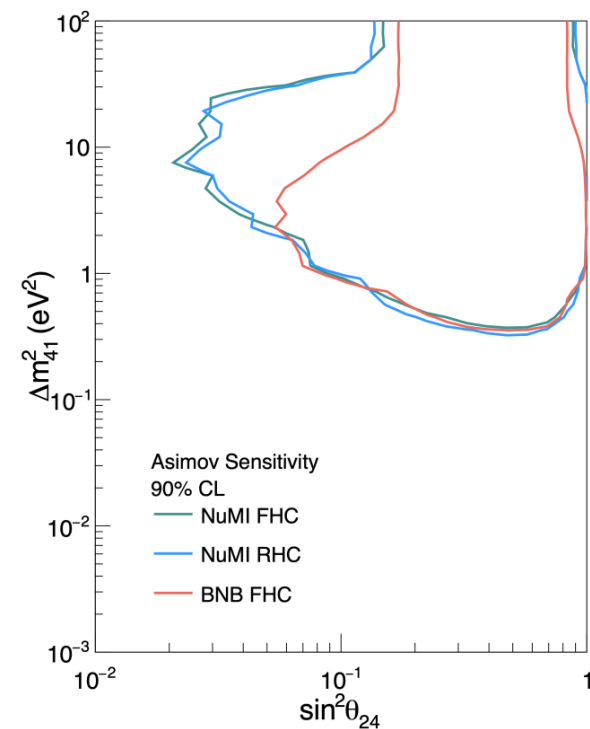


# Complimentary Data: BNB

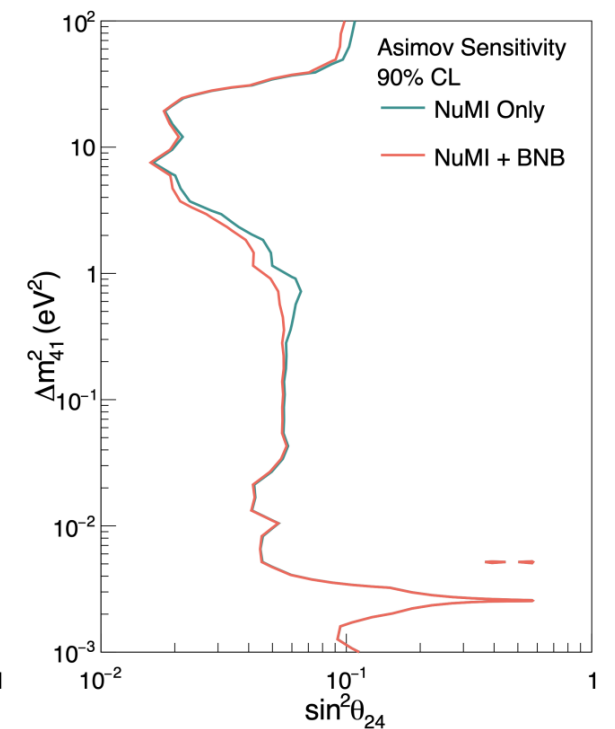
- BNB and NuMI datasets have correlated interaction and detector uncertainties, uncorrelated beam uncertainties. Similar L/E & different E: break degeneracy in oscillations and uncertainties!



Compare sensitivity of **ND Samples**  
NOvA Simulation

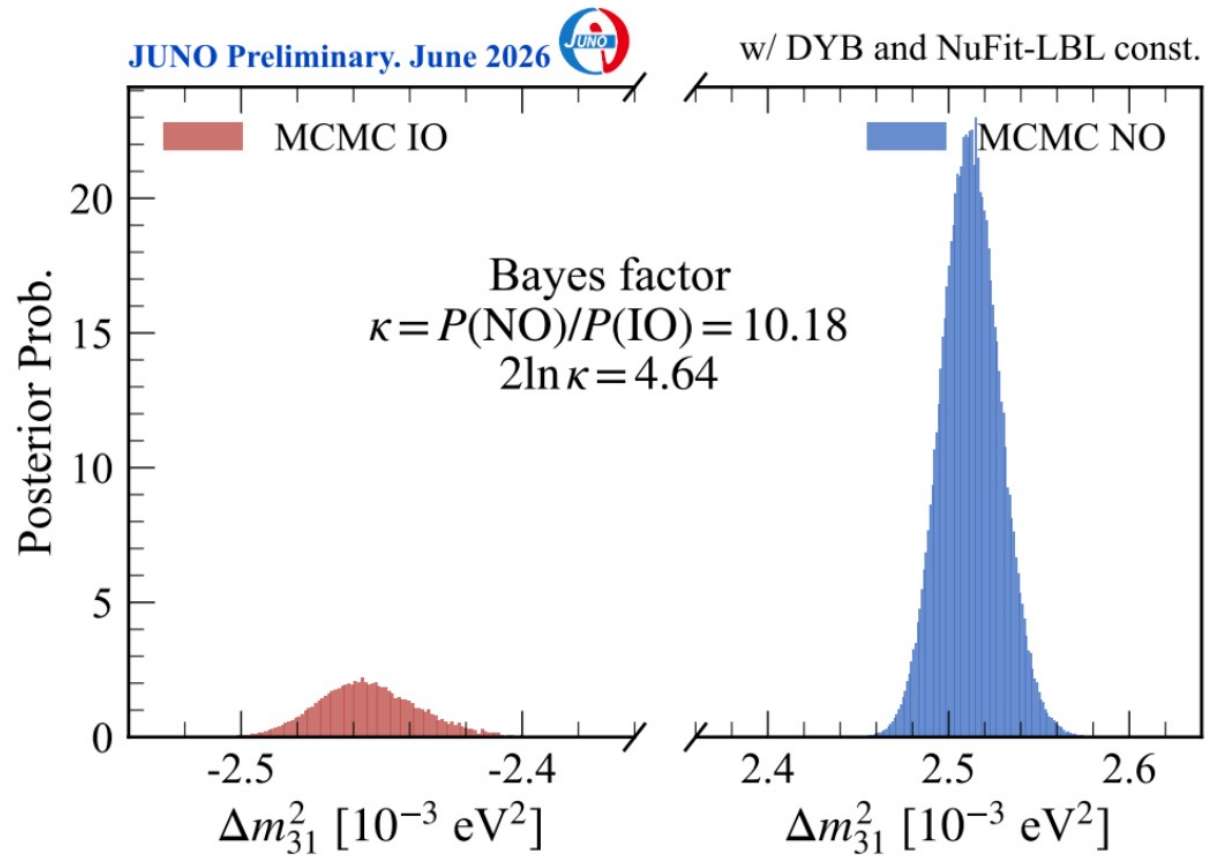


**Full sensitivity improvement**  
NOvA Simulation

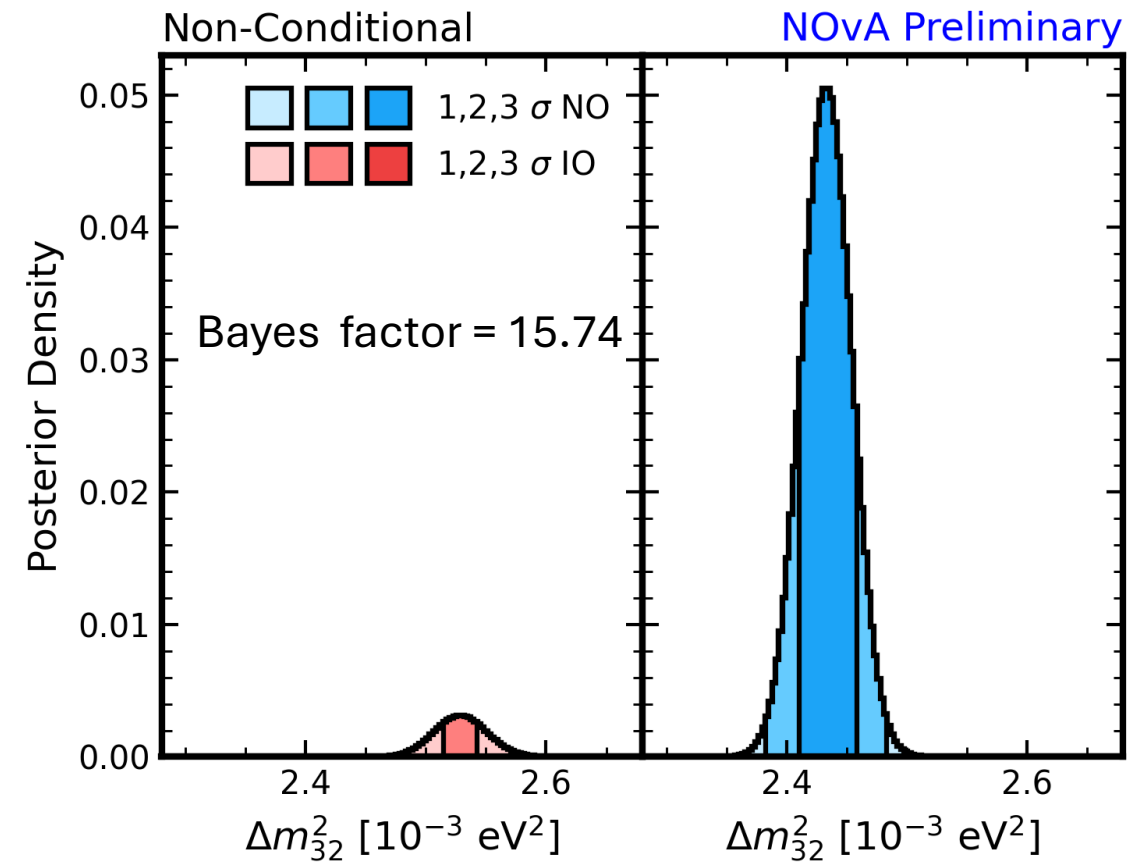


# NOvA + JUNO!

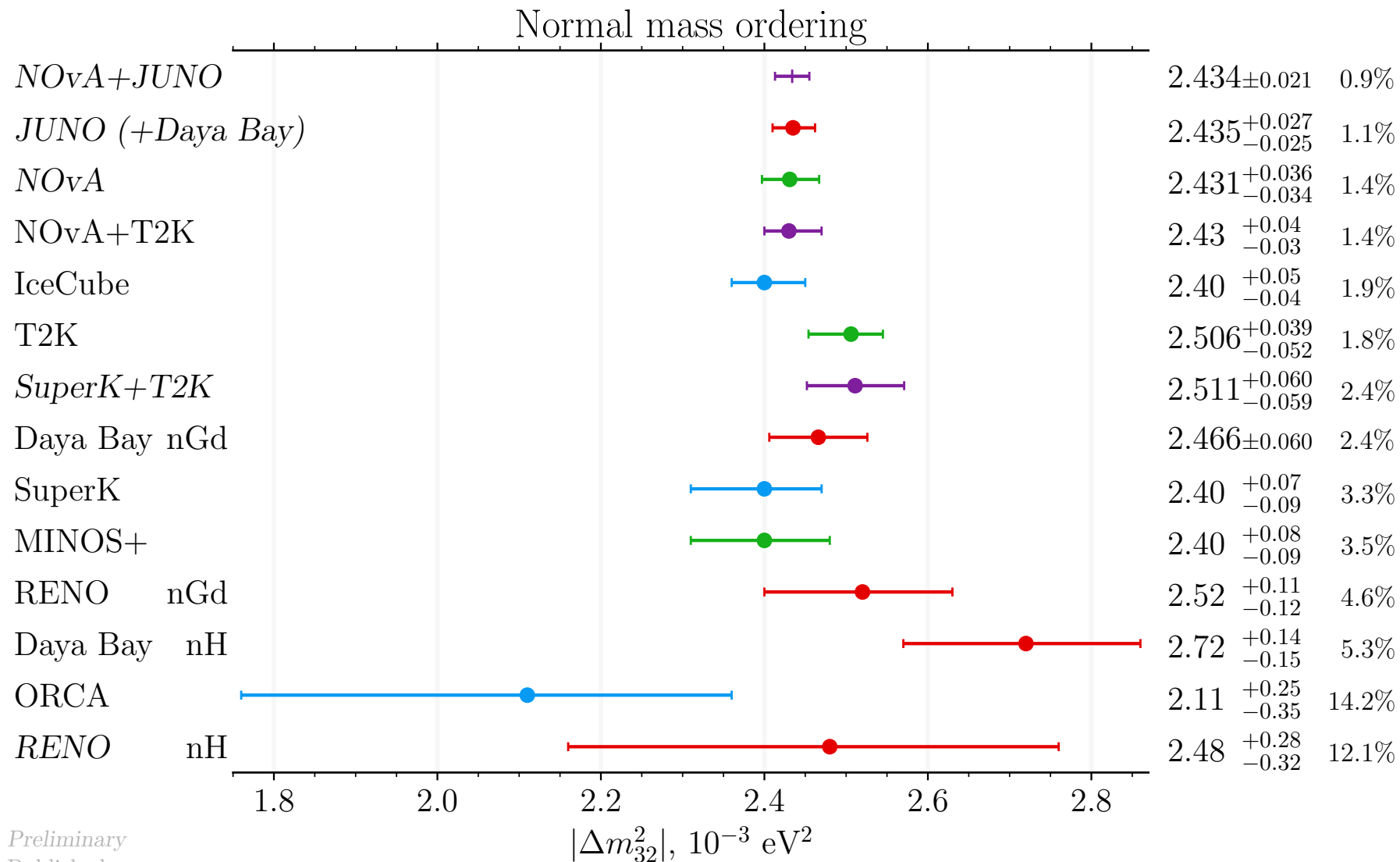
## JUNO + NuFit LBL



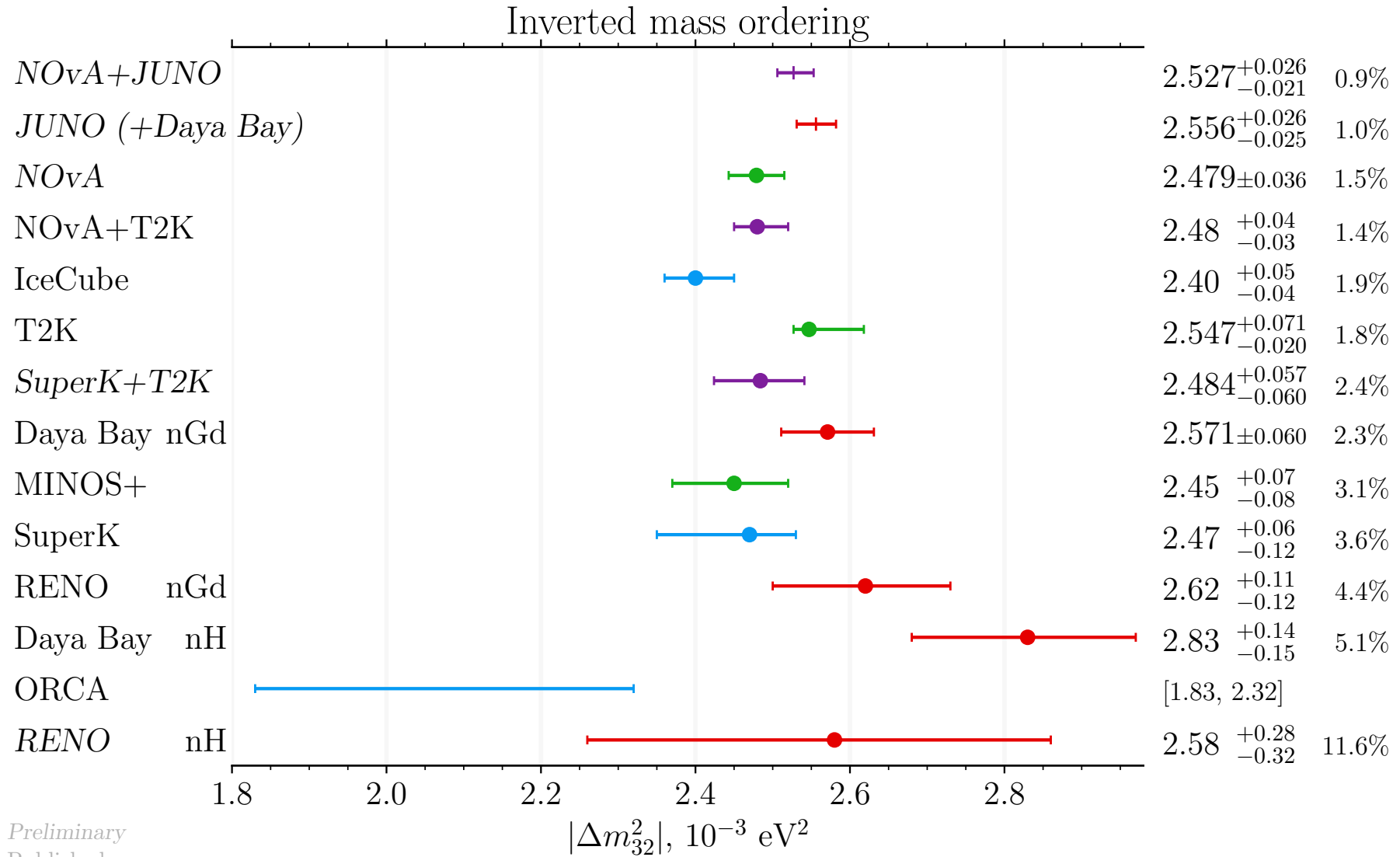
## JUNO + NOvA



# Precision on $\Delta m_{32}^2$



# Precision on $\Delta m_{32}^2$



Preliminary  
Published



# Precision on $\Delta m_{32}^2$

