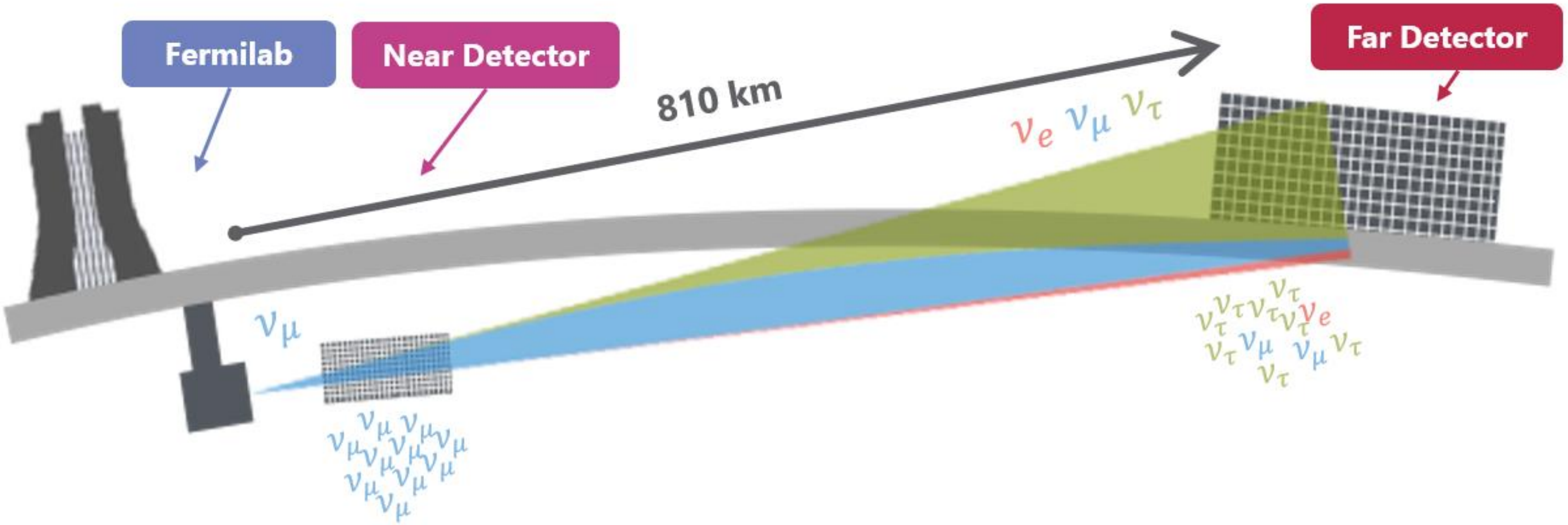
NOvA+T2K and NOvA oscillation results

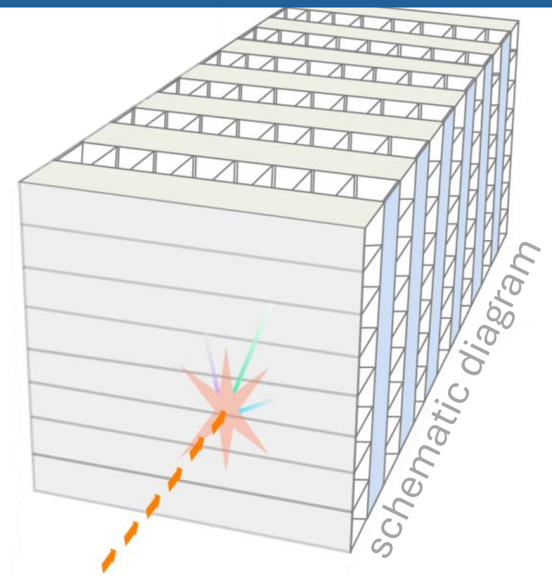
Ryan Patterson
Caltech

NuFact
September 19, 2024

NOvA at a glance



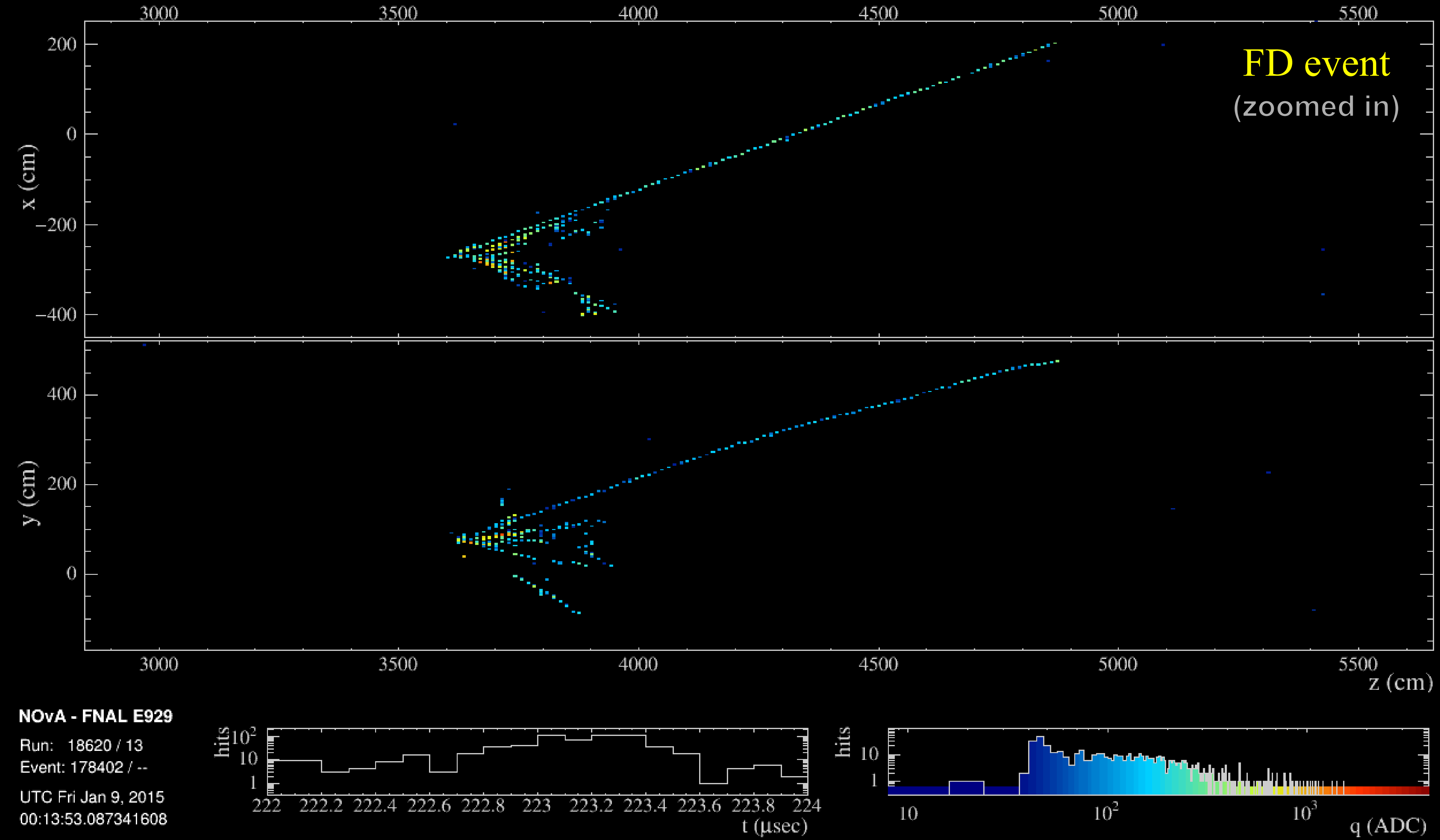
Detector elements:
PVC cells, liquid scintillator, WLS fibers, and APDs

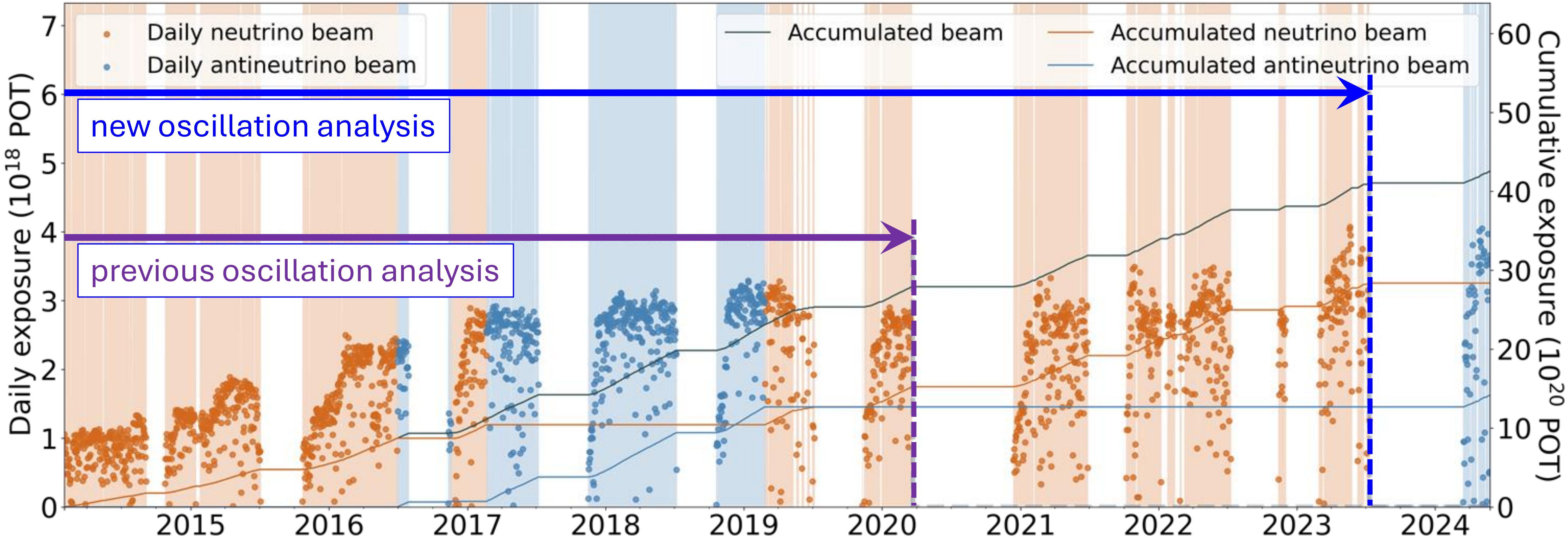


NOvA Collaboration: 200+ members from 50 institutions in 8 countries

Far Detector
14 kton
344k channels

Near Detector
0.3 kton
20k channels


FD event
(zoomed in)
x (cm)
y (cm)
z (cm)
3000
3500
4000
4500
5000
5500
200
0
−200
−400
400
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
222
222.2
222.4
222.6
222.8
223
223.2
223.4
223.6
223.8
224
q (ADC)
10
10^2
10^3
1



Oscillation results in this talk

NOvA+T2K: data through 2020

NOvA only: data through 2023

❖ **Recent NuMI power record: 1.018 MW**

Cumulative Exposure
(in units of 10^{20} POT)

	2020		2023
ν beam:	14	→	**27**
$\bar{\nu}$ beam:	13	→	13

(now configured for $\bar{\nu}$ running)

Some recent papers – a wide scope!

- Active/sterile ν mixing — arXiv:2409.04553 (submitted)
- CP-violating ν NSI — arXiv:2403.07266 (submitted)
- Bayesian oscillation results — PRD **110**, 012005 (2024)
- ν_μ CC π^0 differential XS — PRD **107**, 112008 (2023)
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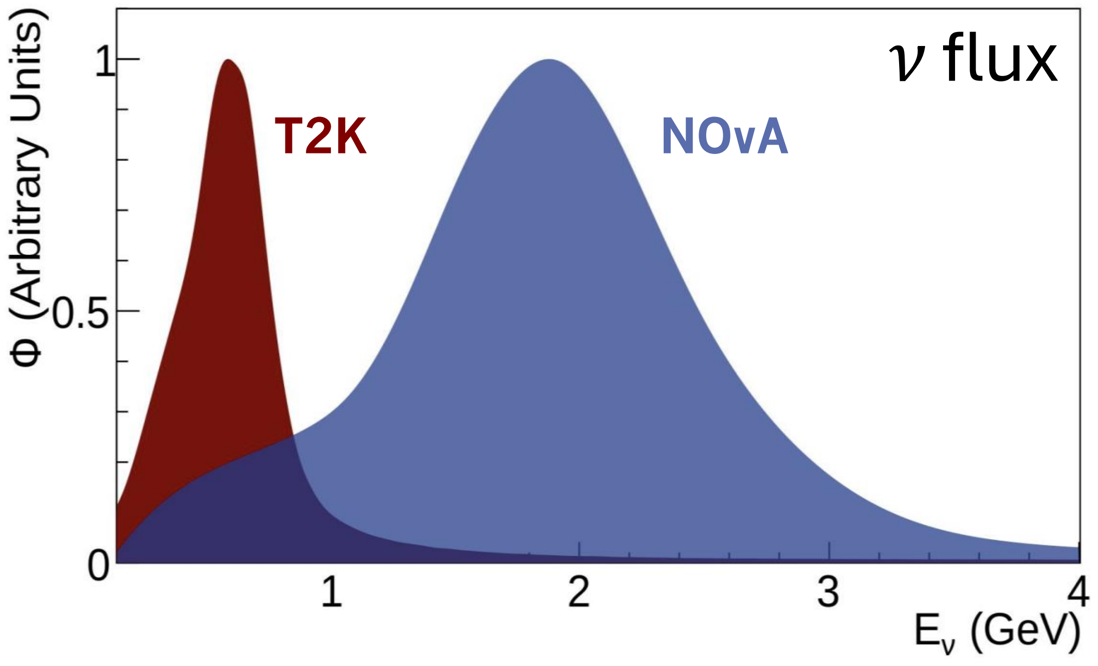
NOvA XS measurements	Joshua Barrow (UMN)
3-flavor oscillations	Jozef Trokan-Tenorio (W&M)
HF-CRPA studies	Amit Pal (NISER)
EM detector response	Dalton Myers (UT Austin)
Profiled Feldman-Cousins	Andrew Dye (U Miss.)
Cosmic μ variation	Amit Pal (NISER)

NOvA-T2K Joint Fit

- **Complementarity**
  - Different energies →
    Different balance of CPv and νMO effects
  - Power to break degeneracies

- **Full implementations**
  - Energy reconstruction, detector response
  - Detailed likelihoods and systematics suites
  - Consistent statistical inferences
  - Full dimensionality

- **In-depth reviews**
  - Different analysis approaches driven by contrasting detector designs, energy scales
  - Models, systematics, possible correlations



(both use off-axis detectors for a narrow-band spectrum)

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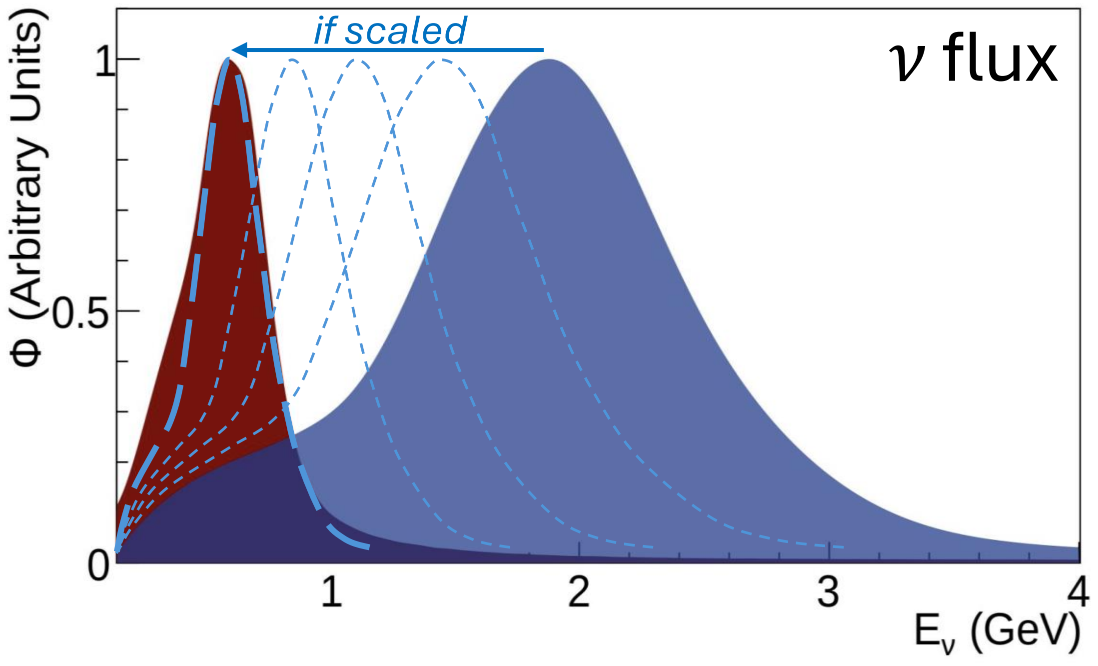

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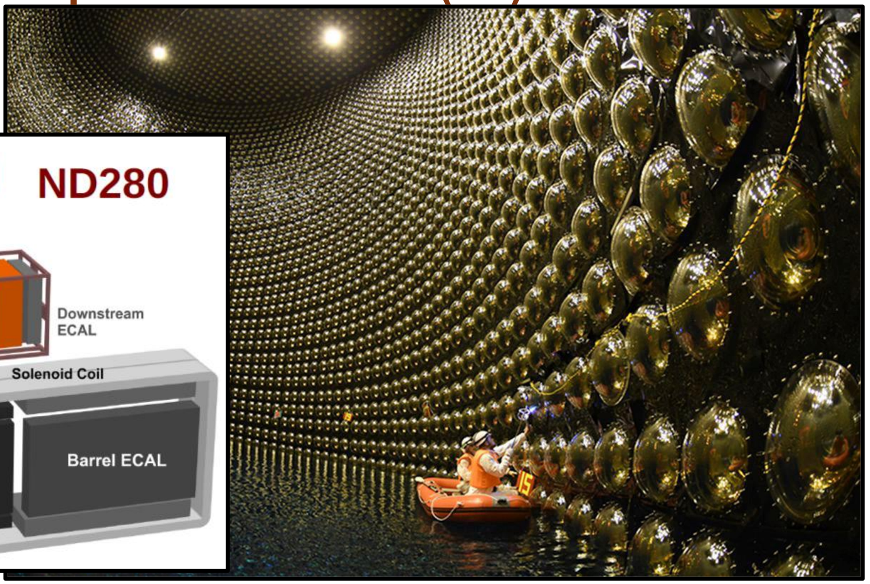
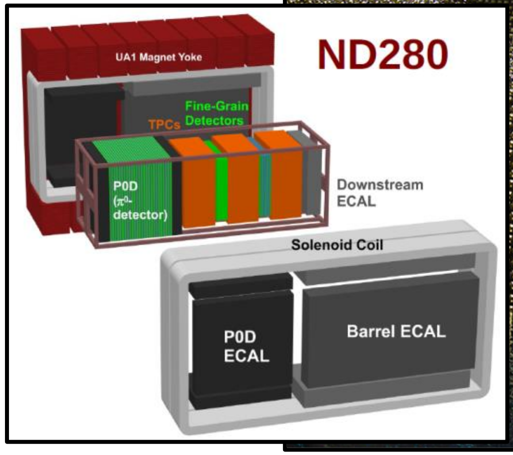
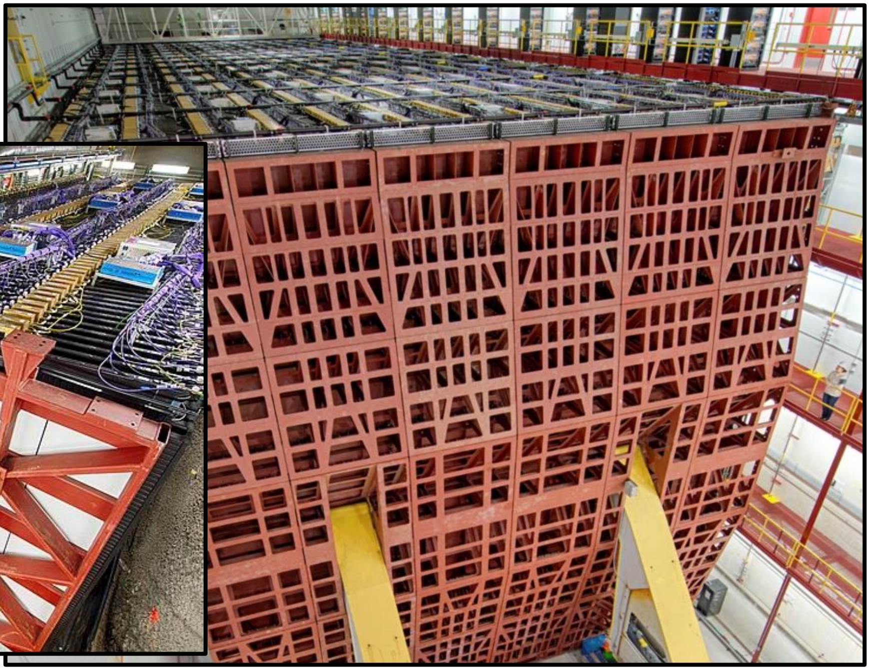
Super-Kamiokande (SK) – T2K FD

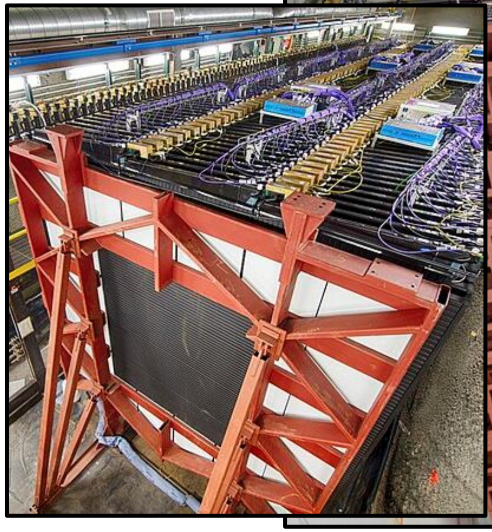




NOvA FD



NOvA ND

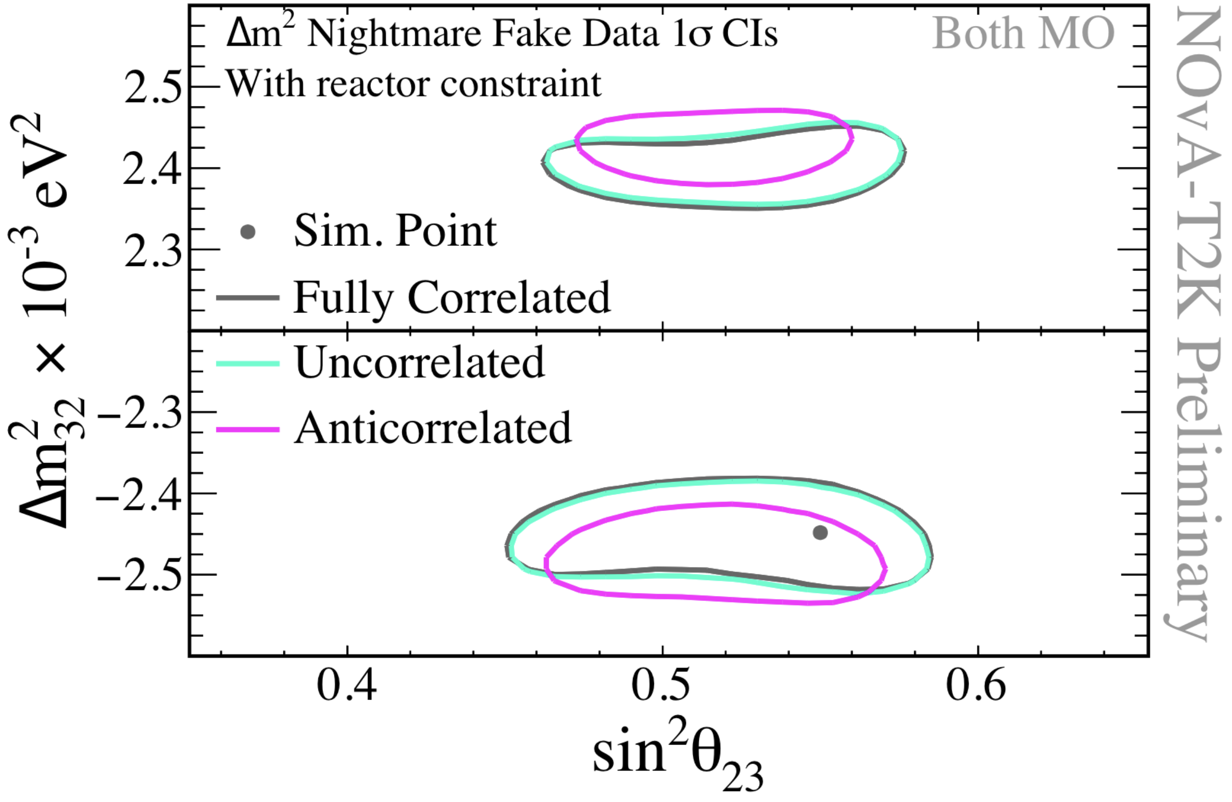


Systematics and correlations, in brief

- **Flux** and **detector** uncertainties: ***no significant cross-experiment correlations present***
- **Cross sections:**
  - $\boldsymbol{\nu_e/\nu_\mu}$ **and** $\boldsymbol{\bar{\nu}_e/\bar{\nu}_\mu}$ **uncertainties** are **correlated** between experiments in the joint fit (both already based on Day and MacFarland, PRD **86**, 053003 (2012)
  - Other cross section parameters have **no practical, direct mapping**

→ Explore a variety of scenarios to **bracket impact**

- *Example*: fabricate amplified systematics comparable in impact to statistical uncertainty
- **Uncorrelated** and **correctly correlated** cases have **negligible differences**, while incorrectly correlating systematics shows a bias.



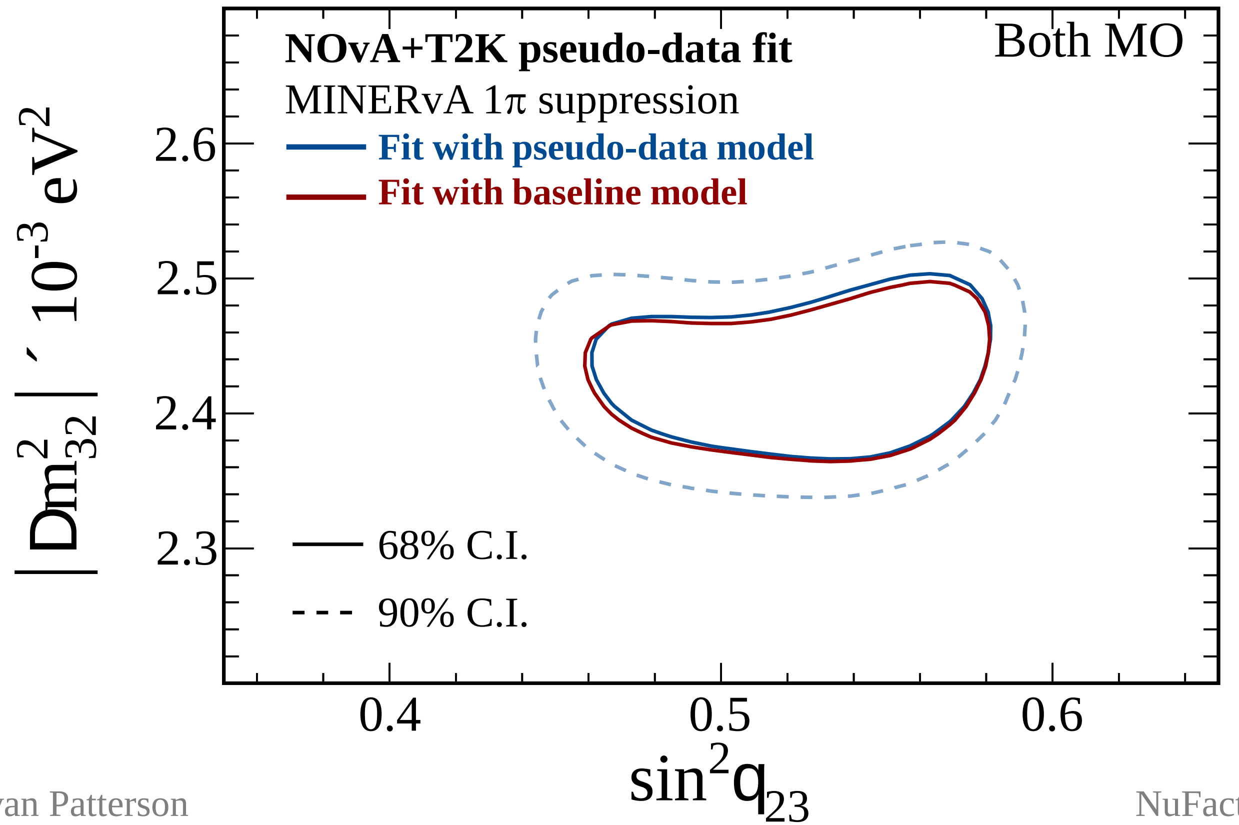
Based on a range of studies in this vein:

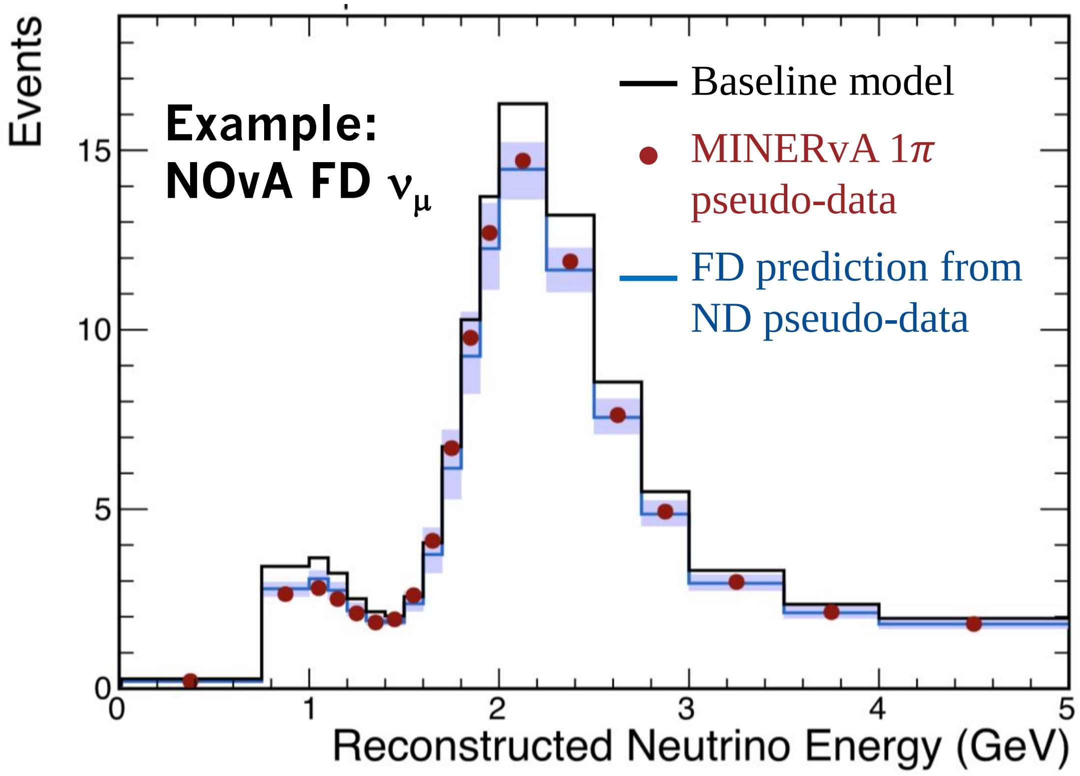
→ **No additional correlations need be applied** given current experimental exposures

Alternative model tests

- **Test robustness** by fitting pseudo-data generated under **various alternative models**
  - *Example*: Suppress single pion production based on tune to MINERvA data, Phys. Rev. D **100**, 072005 (2019)

- **No significant impact seen under all alternative models tested**





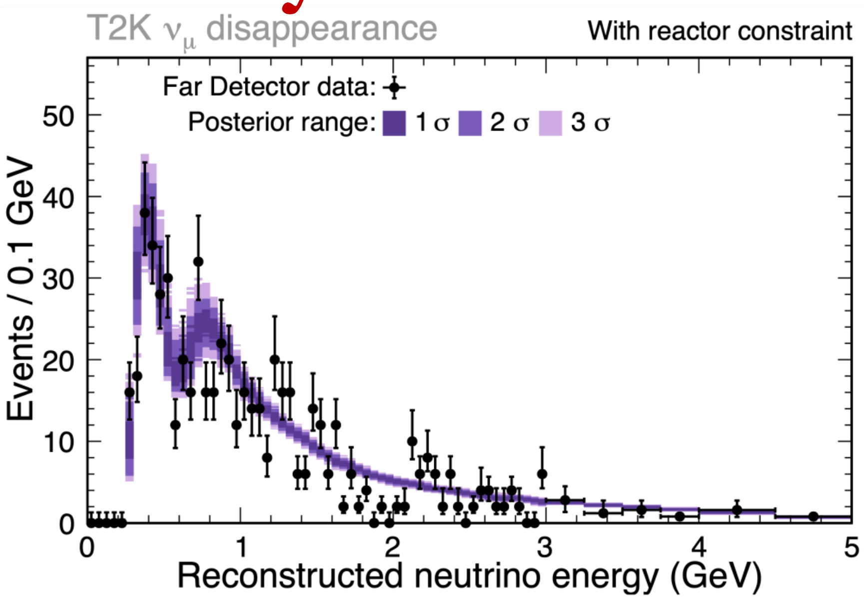
Fit results: compatibility

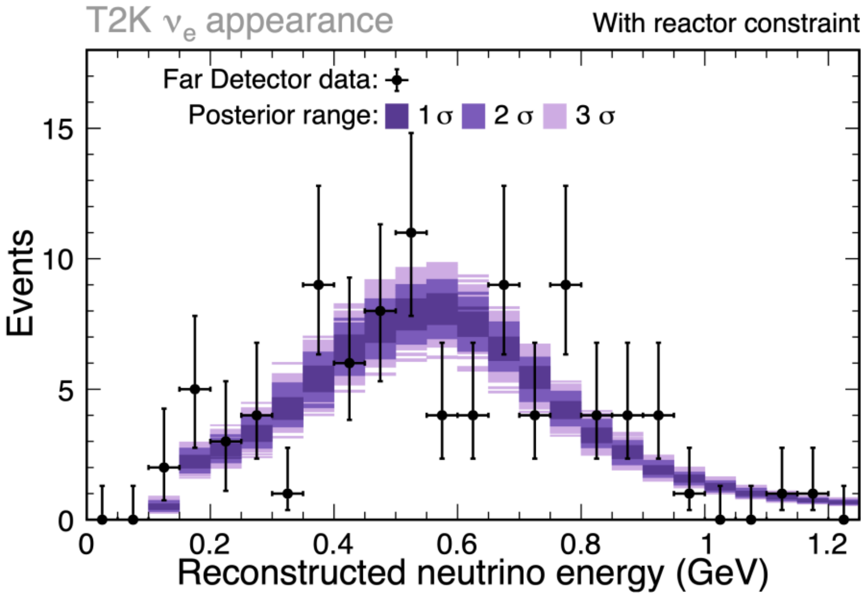
Posterior predictive *p*-values*
by sample

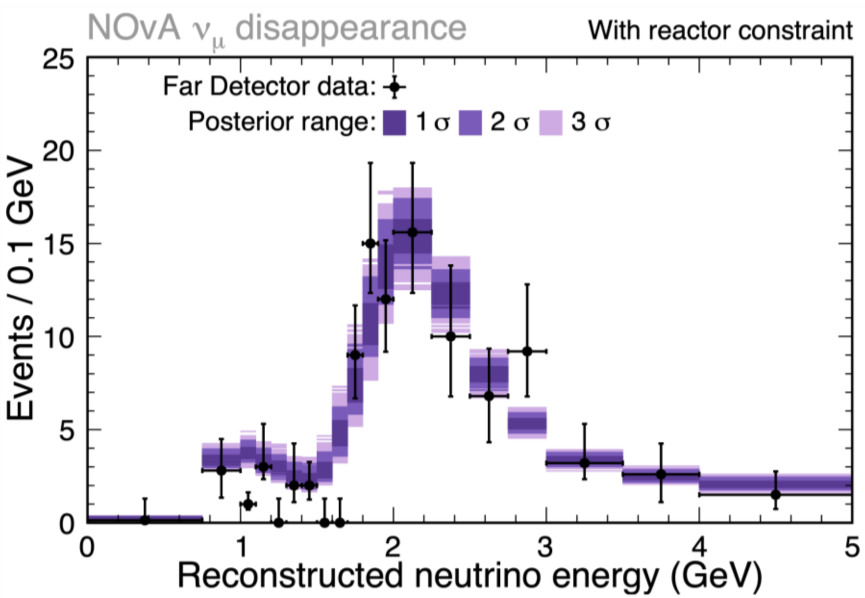
	NOvA	T2K	Combined
ν_e	0.90	0.19 (0p) 0.79 (1p)	0.62
$\bar{\nu}_e$	0.21	0.67	0.40
ν_μ	0.68	0.48	0.62
$\bar{\nu}_\mu$	0.38	0.87	0.72
Total	0.64	0.72	**0.75**

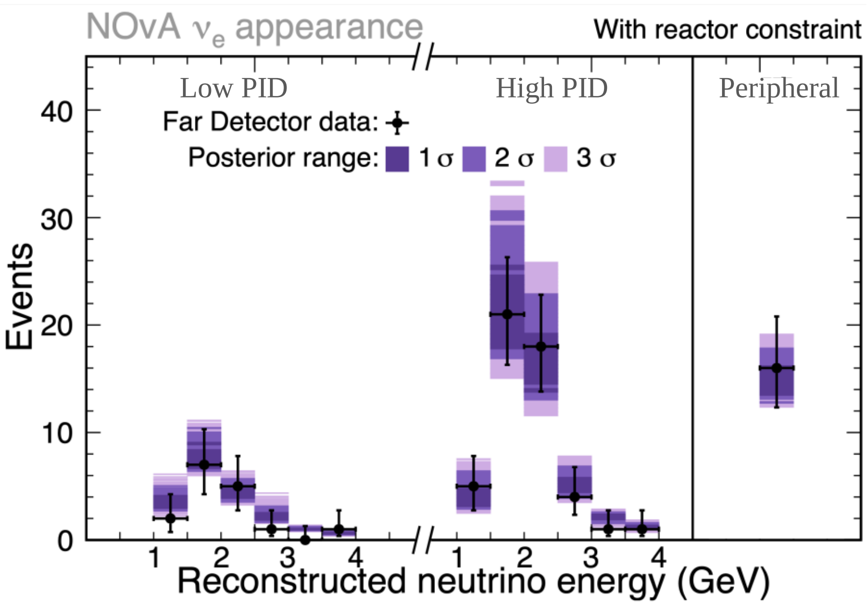
*Gelman, Meng and Stern, Stat. Sinica **6**, 733 (1996)

$\bar{\nu}$ and T2K ν_e 1π plots in backup



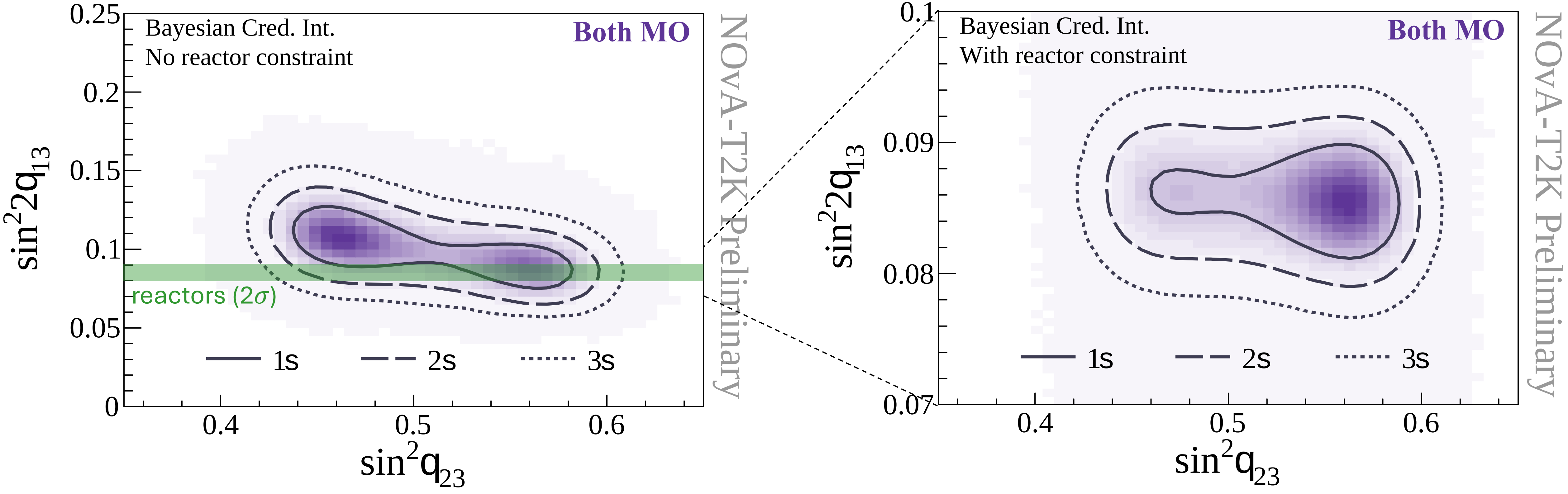






θ_{13} and θ_{23}

Without and **with** reactor θ_{13} constraint
(lifts an LBL experiment degeneracy)



Octant and mass ordering

θ_{23} octant preference

Upper : Lower = 78% : 22%

(Bayes factor = 3.6)

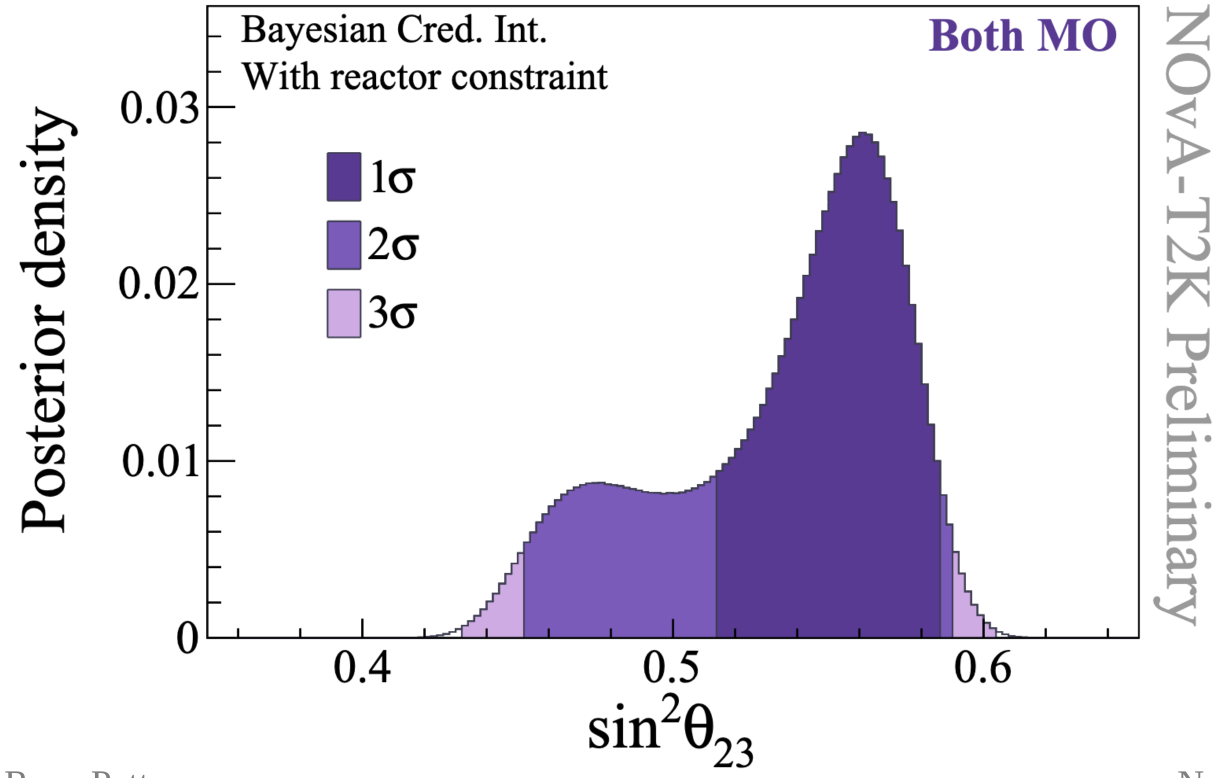
And also compatible with maximal mixing

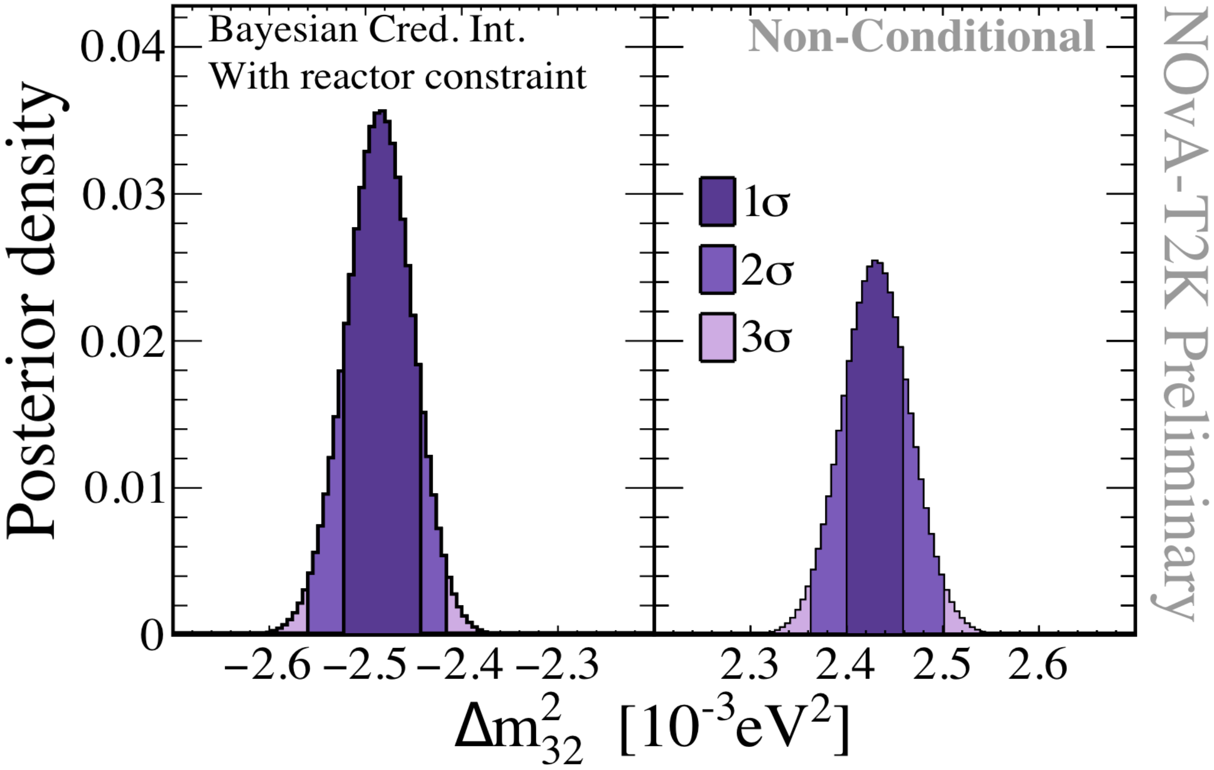
Mass ordering preference

Inverted : Normal = 58% : 42%

(Bayes factor = 1.4)

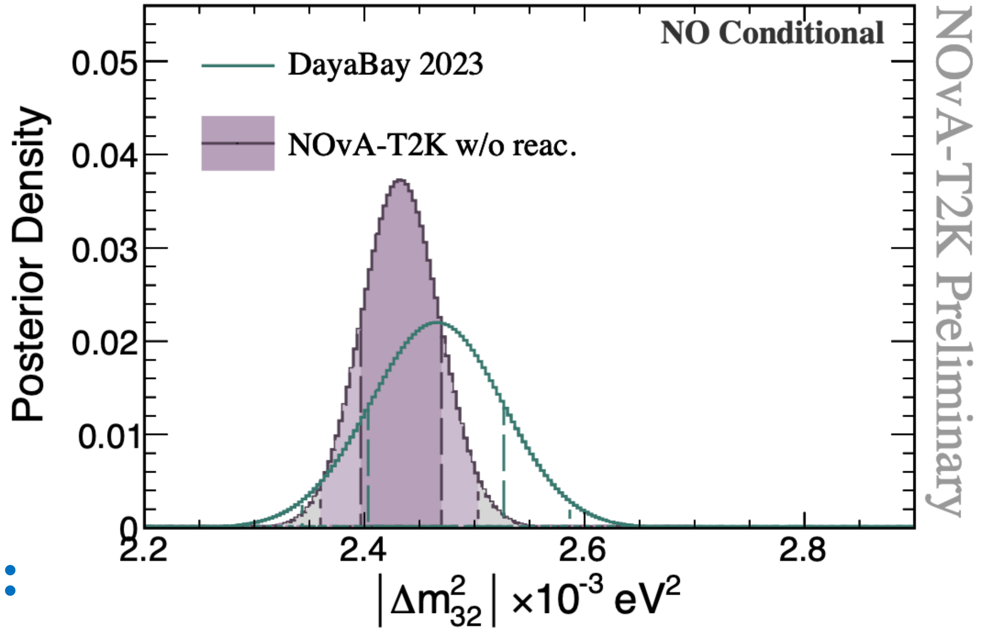
(no significant preference)





NOvA+T2K+Daya Bay (with reactor Δm^2_{32})

- **Under wrong νMO**, reactor and long-baseline Δm^2_{32} measurements will **disagree***
- Look for such tension ⇒ **inform νMO determination**



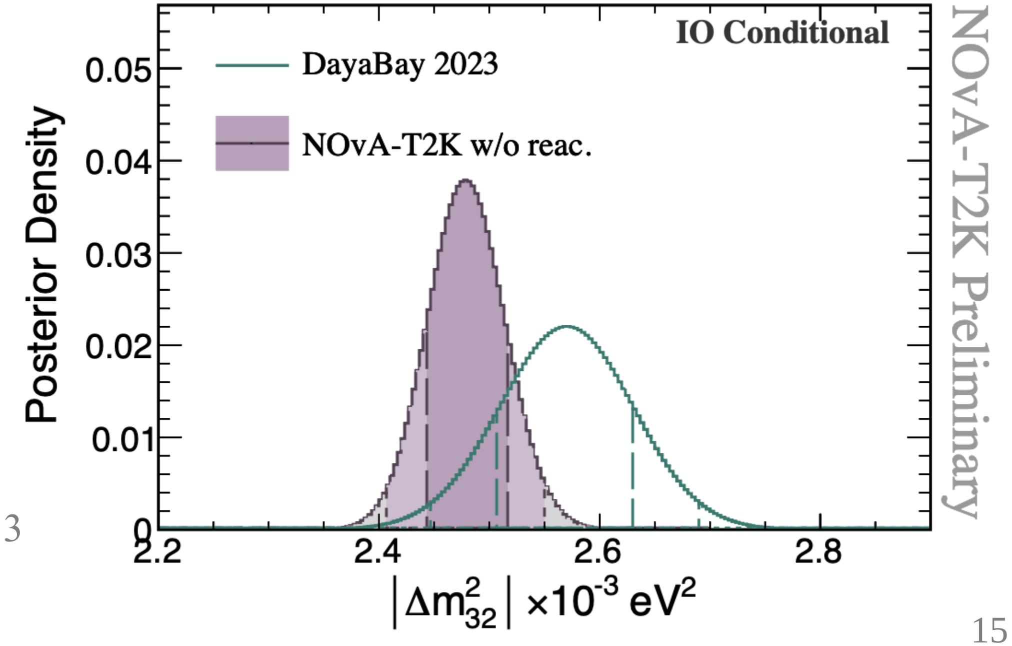
NOvA+T2K fit with Daya Bay 2D (θ_{13}, Δm^2_{32}) constraint:

νMO preference

Normal : Inverted = 59% : 41%

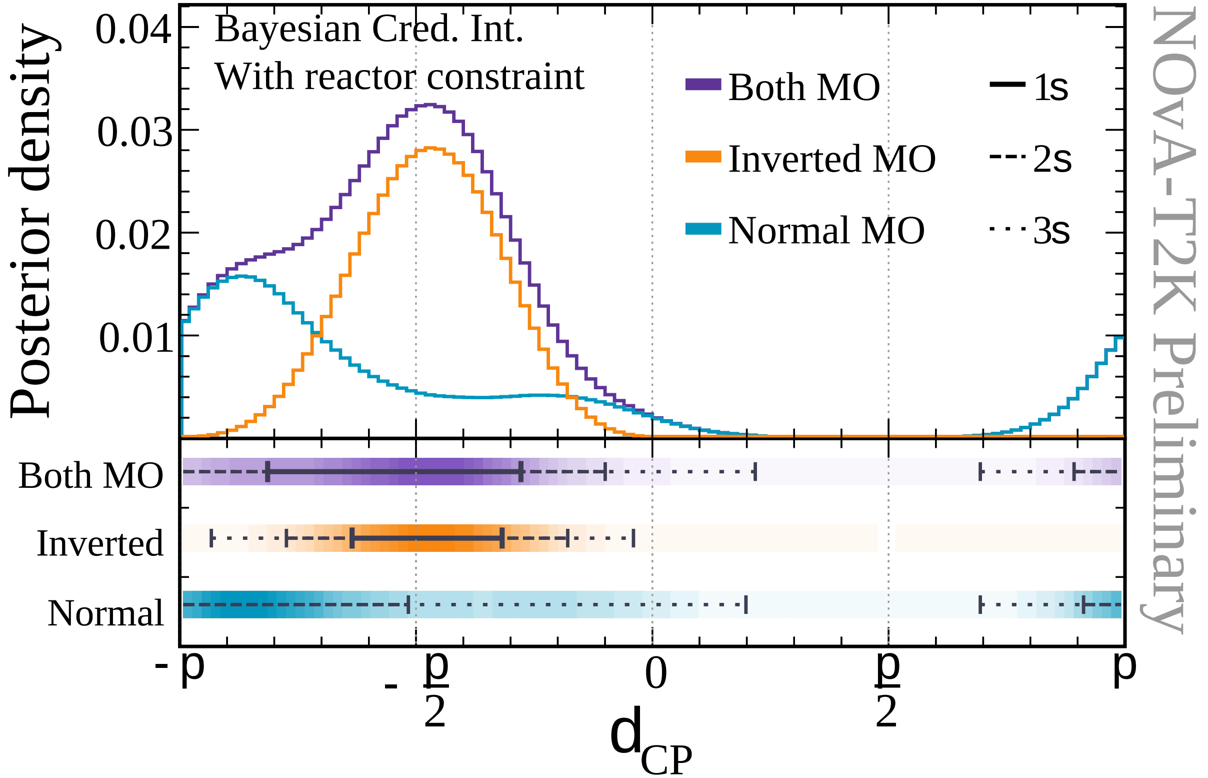
(Bayes factor = 1.4)

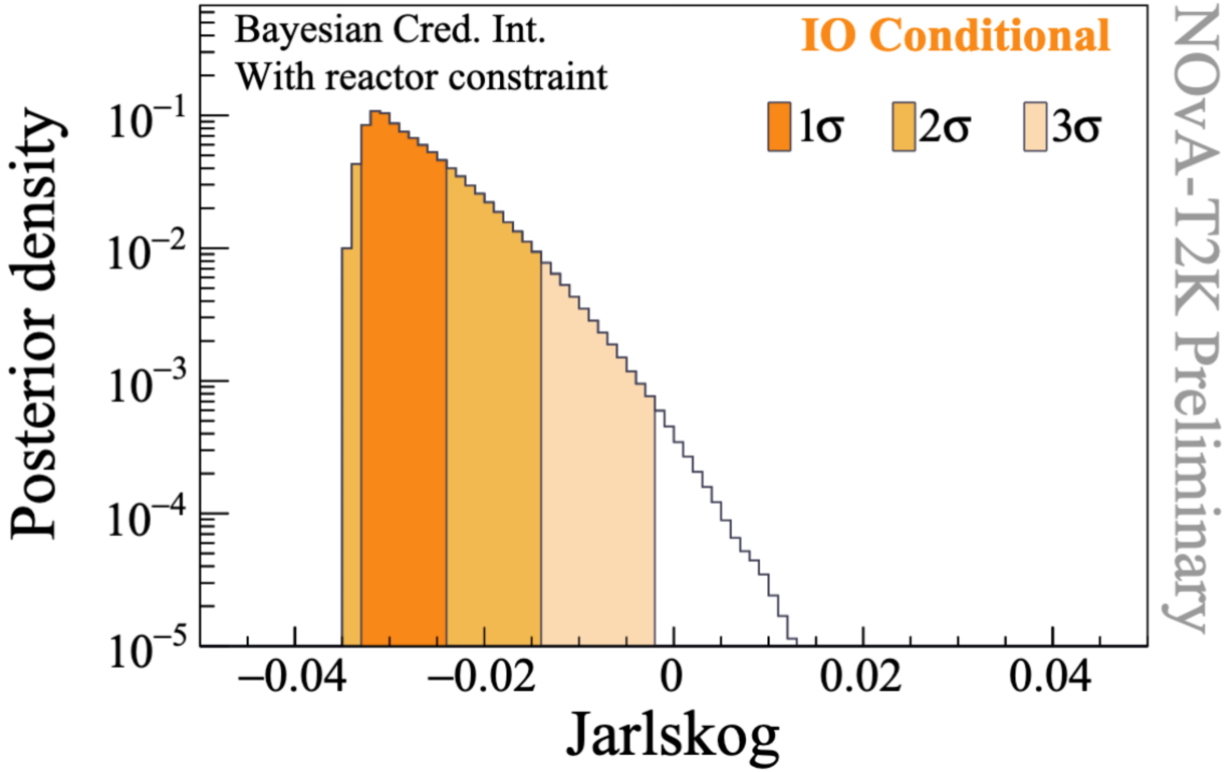
(flipped preference relative to previous slide, but still not significant)



* Nunokawa, Parke and Funchal, PRD **72**, 013009 (2005); Parke and Funchal, arXiv:2404.08733

δ_{CP} and J_{CP}





At and around **$\delta_{CP} = \pi/2$ lies outside 3σ** credible interval (regardless of mass ordering)

If the ordering is inverted, CP conserving values lie outside 3σ credible interval
(**δ_{CP} = 0, π;** Jarlskog invariant** **J_{CP} = 0**)

* only the right plot assumes IO; left plot shows posterior over both νMO simultaneously
** tested with prior uniform in sin δ_{CP} or δ_{CP}

Latest NOvA oscillation results

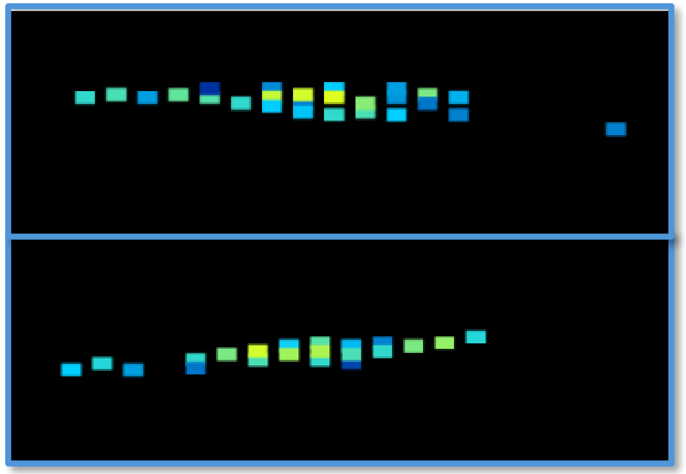
(highlights)

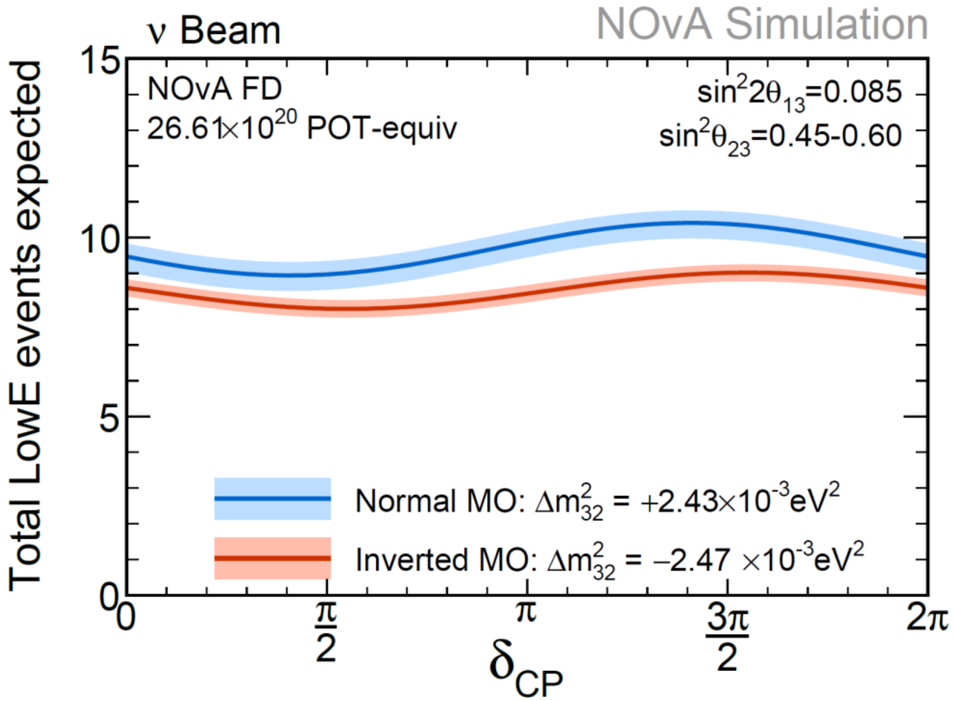
Jozef Trokan-Tenorio gave a
detailed view earlier this week

What's new in 2024 version

- **Double the neutrino-mode data** relative to 2020-era analysis!

- New **low-energy ν_e** sample:





- Improved ***n*-[12]C inelastic scattering model**; informs systematic uncertainty
  MENATE_R model; P. Désesquelles et al., NIM A **307**, 366 (1991); Z. Kohley et al., NIM A **682**, 59 (2012)

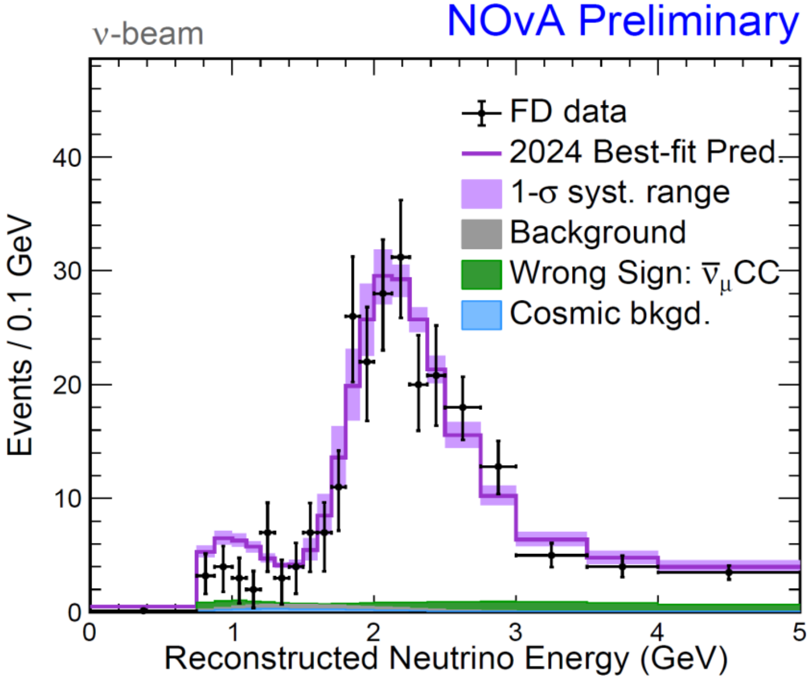
- Additional freedom + uncertainties in **RES and DIS models**

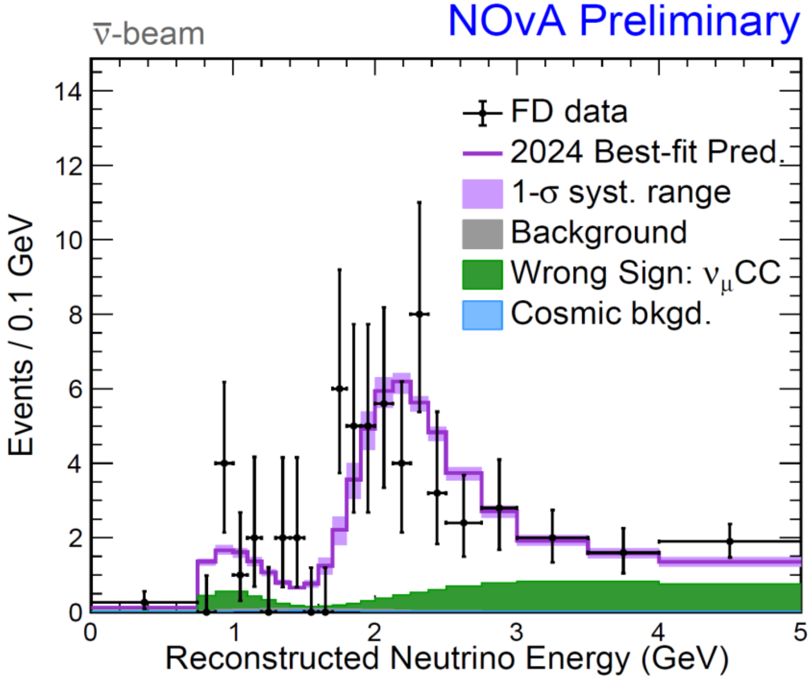
- Improved **light production model** in detector simulation
  → Better data/simulation agreement at high *dE*/*dx*

FD samples

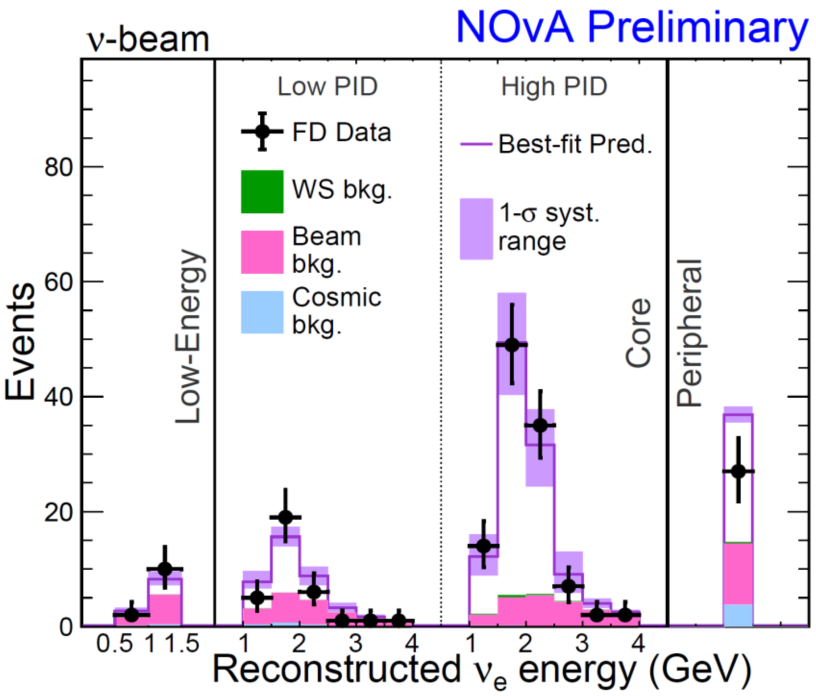
Disappearance	**Total**	**BG est.**
$\nu_\mu \rightarrow \nu_\mu$	**384**	11
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	**106**	2

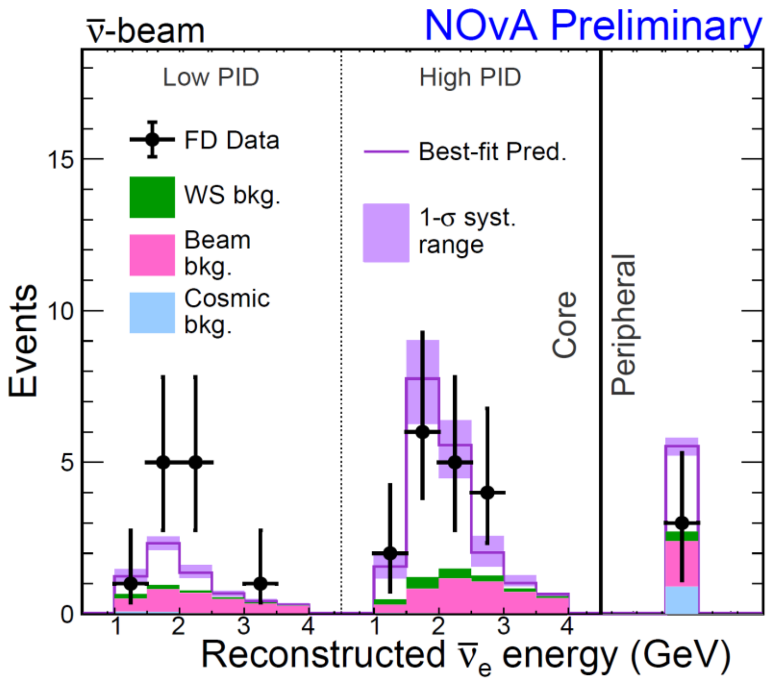
(further binned into E_{had} quartiles in fit)





Appearance	**Total**	**BG est.**
$\nu_\mu \rightarrow \nu_e$	**181**	62
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	**32**	12

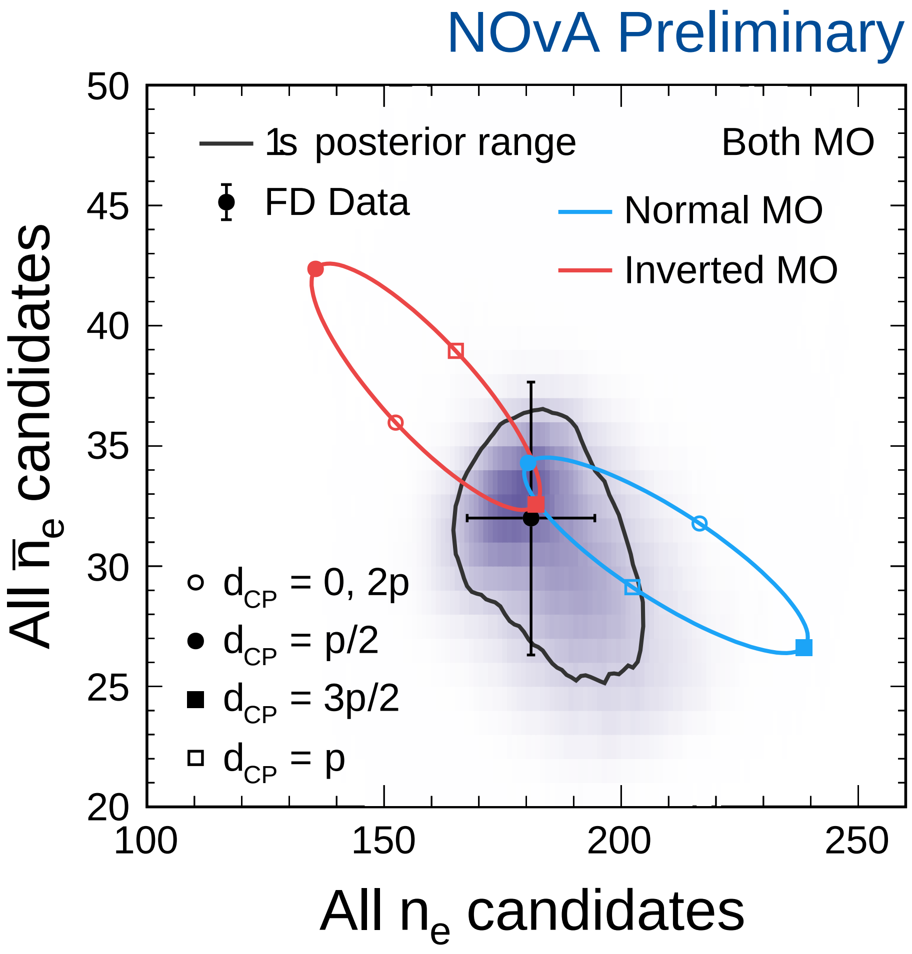


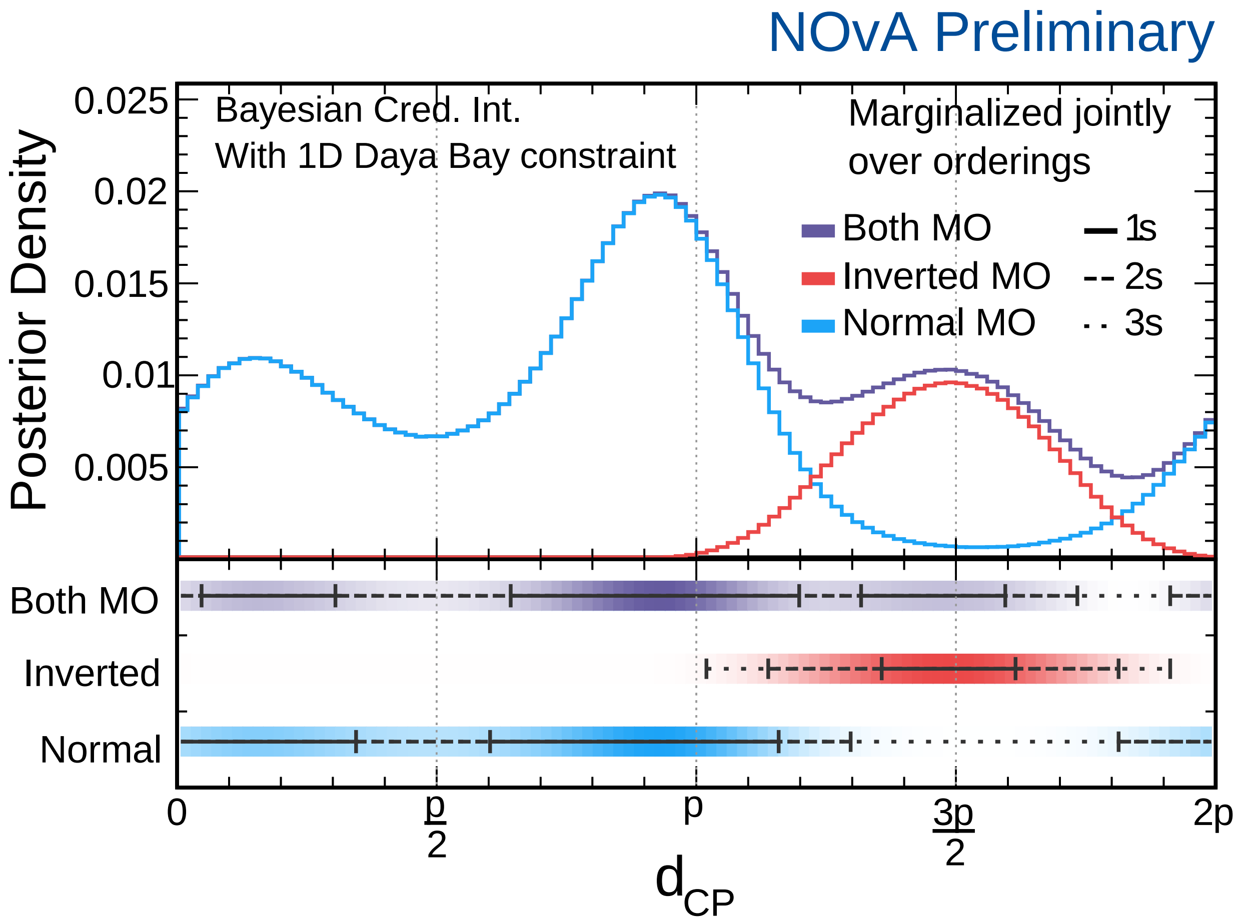


Mass ordering and δ_{CP}

Caution: δ_{CP} axis convention change

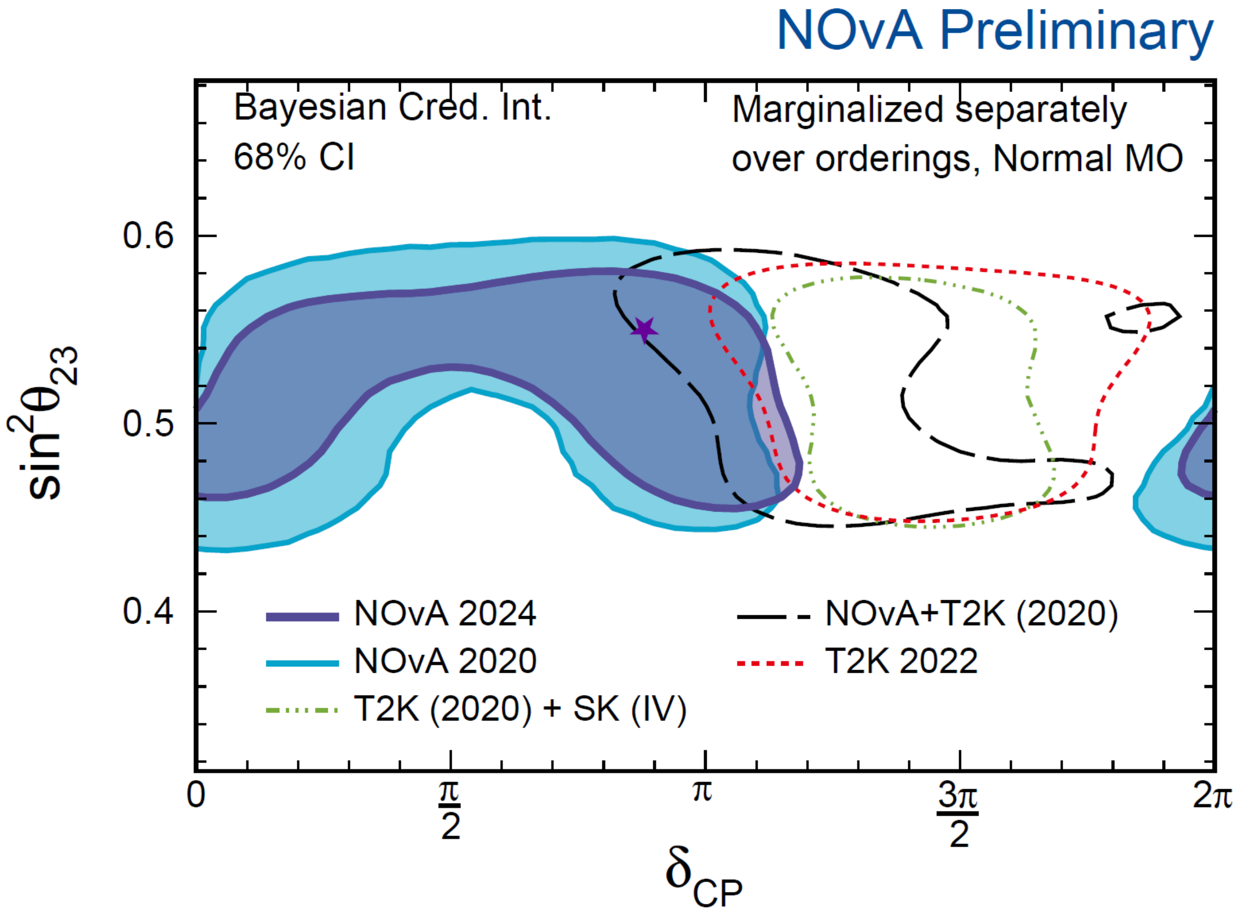
NOvA data favor combinations where **mass ordering and CP effects cancel**

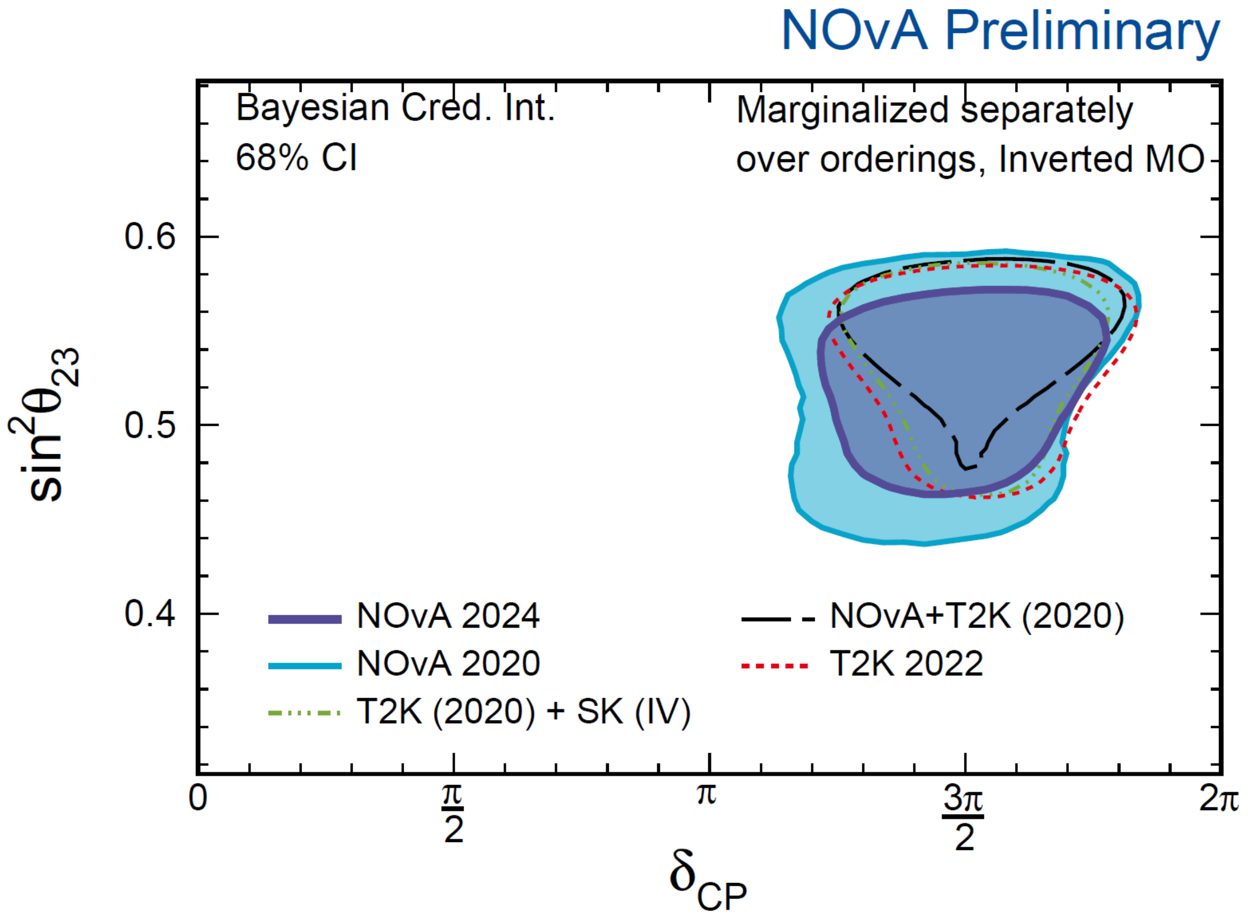




θ_{23} and δ_{CP}

Caution: δ_{CP} axis convention change

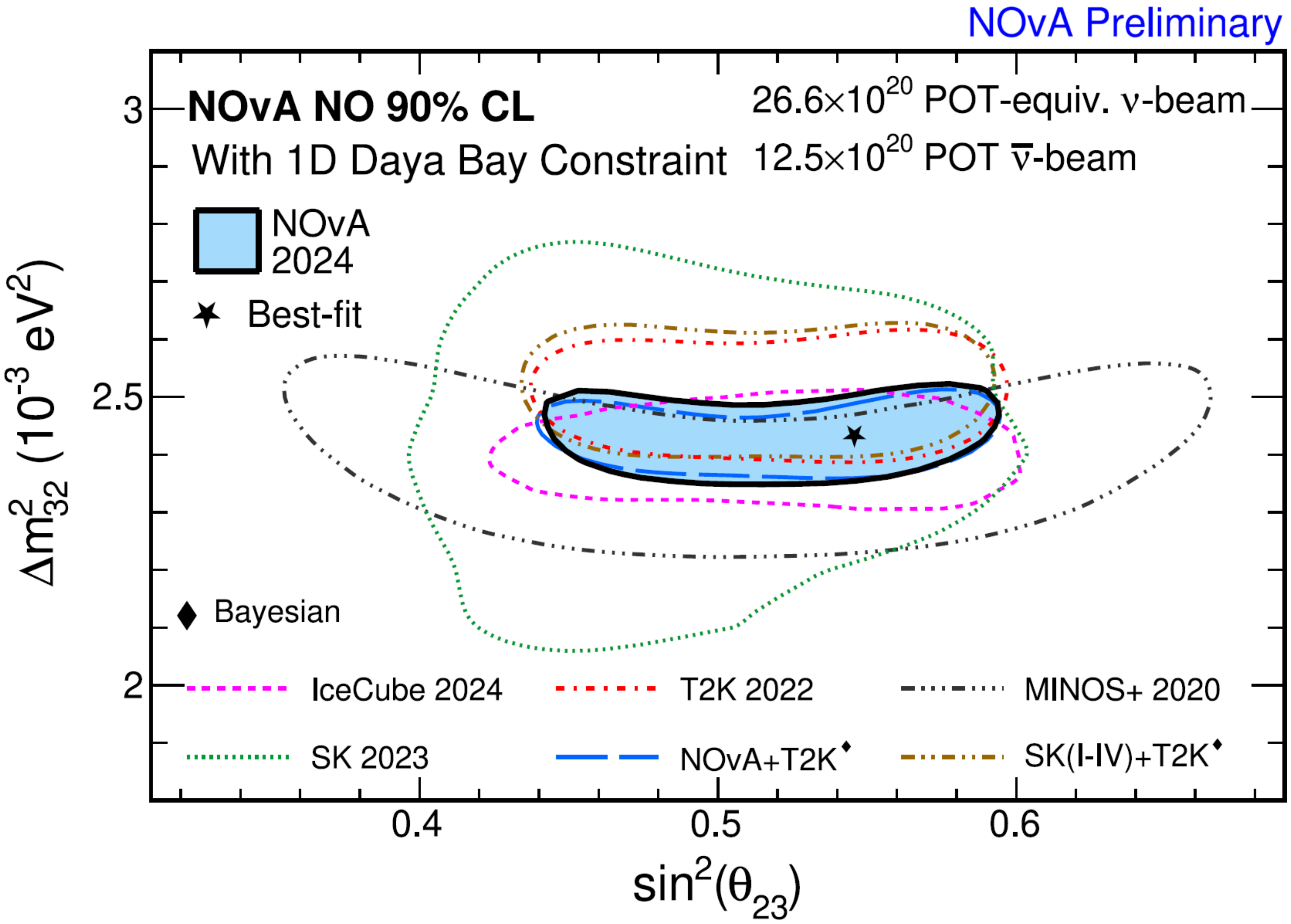




- Consistent with previous NOvA result, with improved constraints

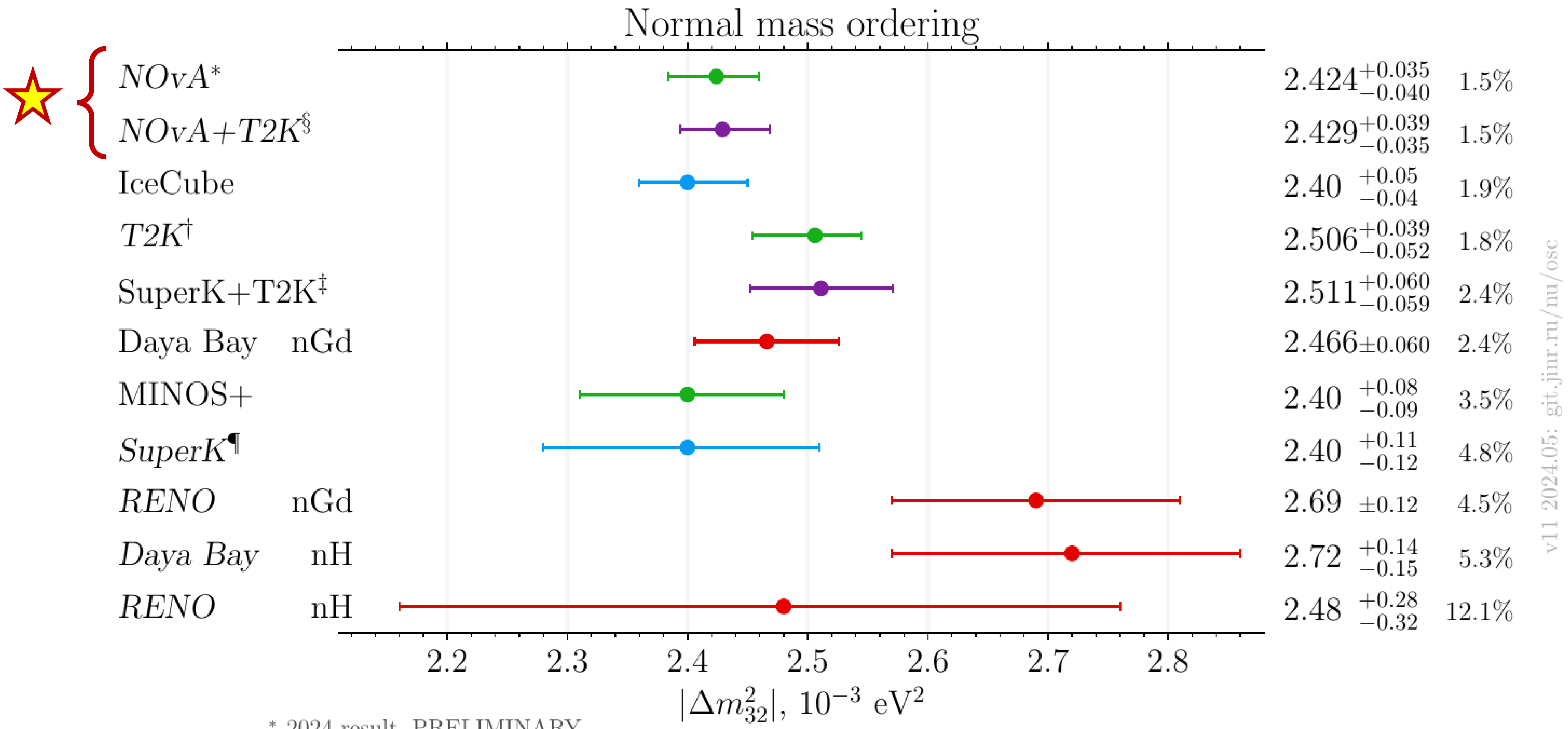
- T2K, T2K+NOvA, and T2K+SK also shown

Δm^2_{32} and θ_{23}



Global consistency

Maximal mixing consistency

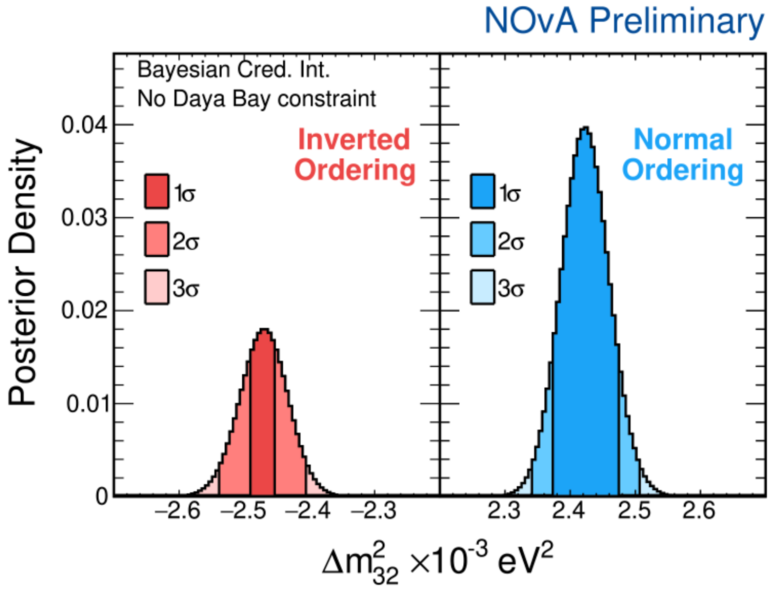


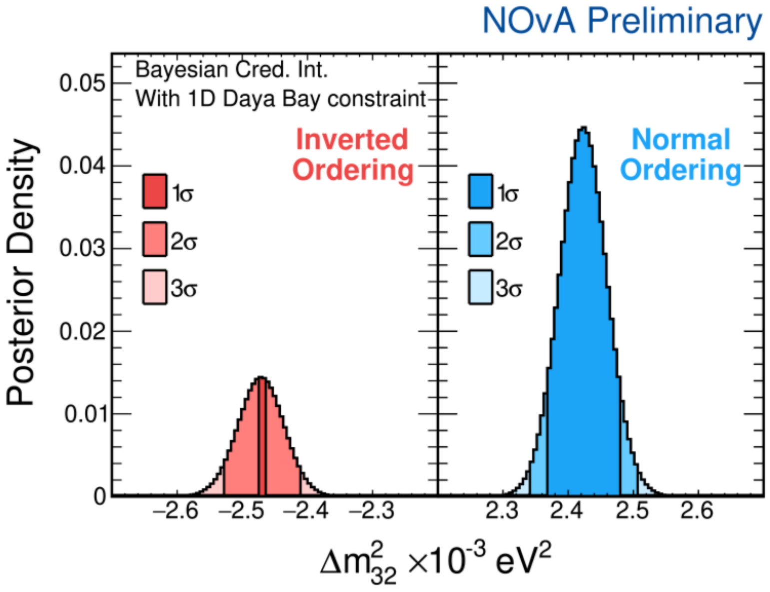
Preliminary
Published

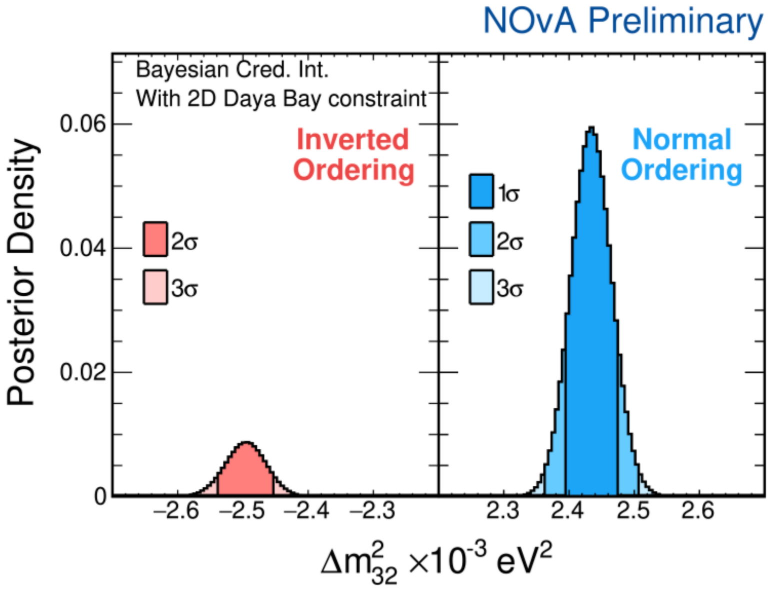
* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result

¶ SKI-V result, arXiv:2311.05105
‡ based on SK IV and T2K 2020, arXiv:2405.12488

Mass ordering preference







No reactor constraint	1D θ_{13} constraint	2D (θ_{13}, Δm^2_{32}) constraint
69% (2.2)	**76%** (3.2)	**87%** (6.8)

Normal ordering preference
(and Bayes factor)

Closing

2024 NOvA oscillation results

- **Doubled** neutrino data set plus **analysis upgrades.**
  Improved constraints with consistent overall picture:
  → Data favor "degenerate" mass ordering/δ_{CP} points
  → With 2D reactor constraint, normal ordering pref. at 87%
  → Excellent **precision on Δm^2_{32}**
  For next step in sensitivity, aim to **double antineutrino data set**
  → Further systematics reduction also in the works

NOvA+T2K joint result (Using earlier data sets)

- Fit demonstrates **compatibility** of the datasets. From joint fit:
  → $\delta_{CP} = \pi/2$ (and vicinity) lies **outside 3σ C.I.** for both orderings
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- Both experiments **continue to collect data.** More to come here!

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Reminder of Slide 6!

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Backups

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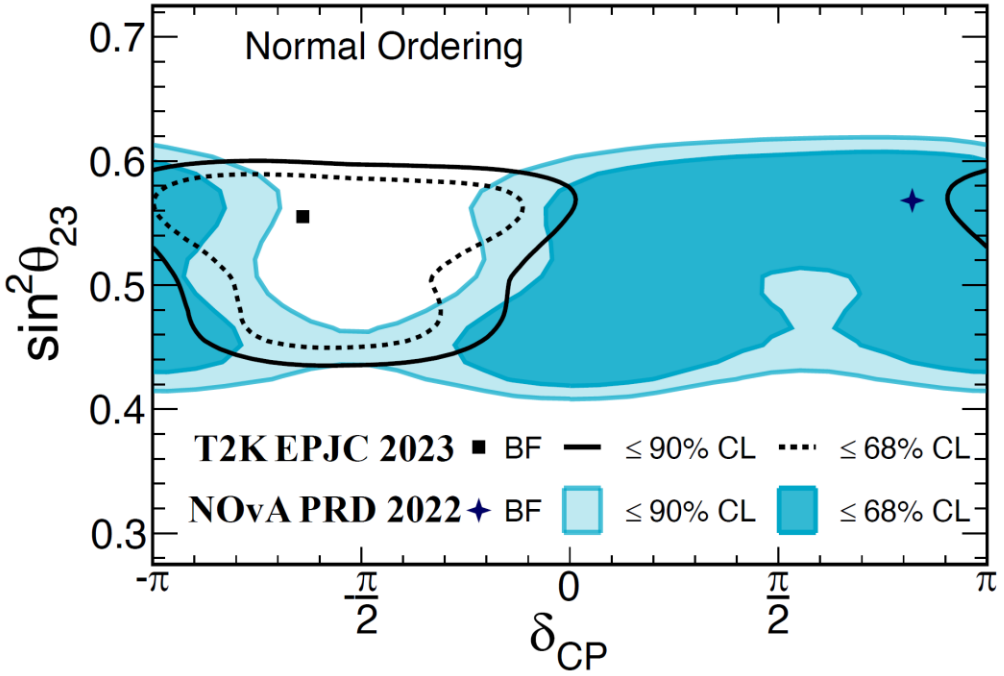
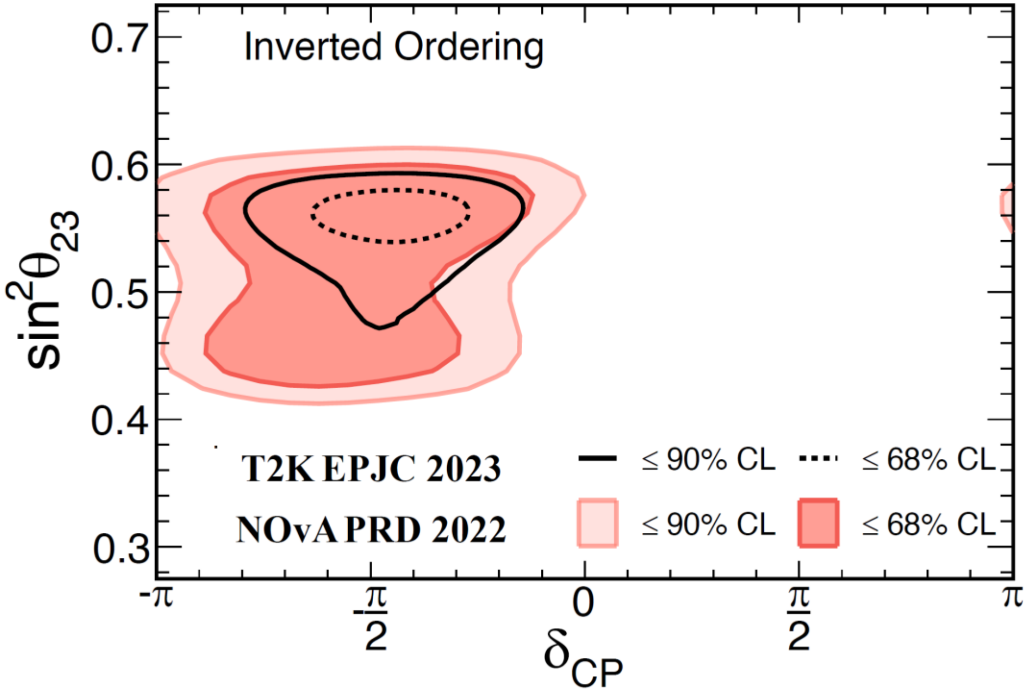


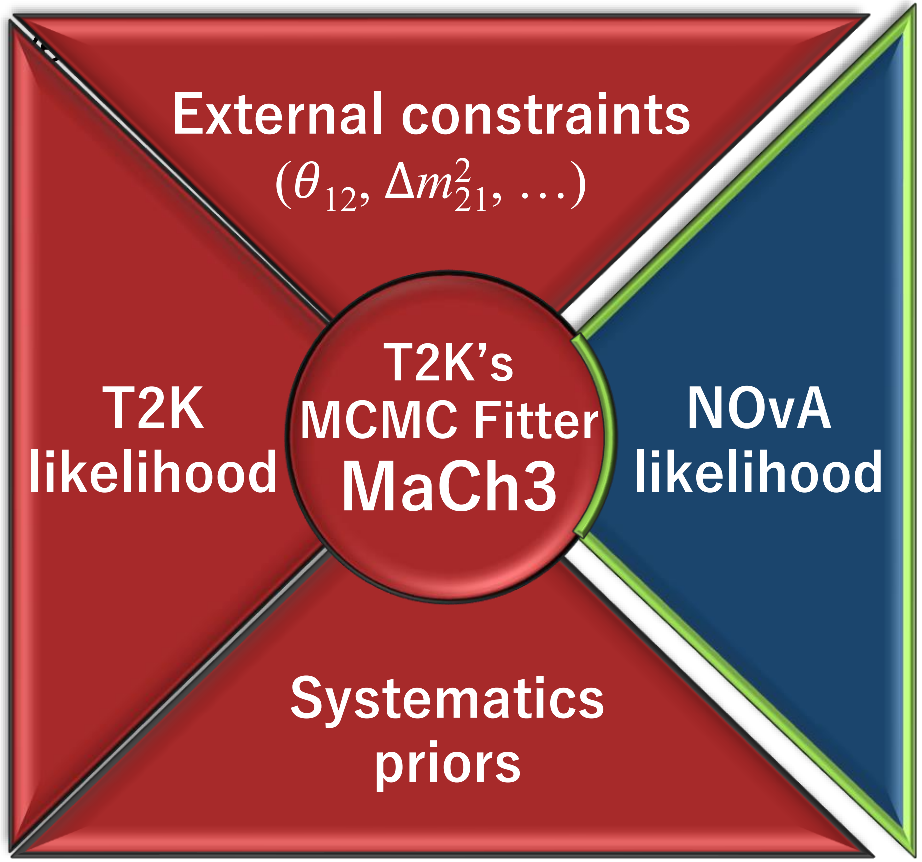


Constructing the fit

Using both experiments' full likelihoods

<u>All</u> analysis details, <u>all</u> parameters (oscillation and nuisance)
Access each other's likelihood via containerized environment

T2K version

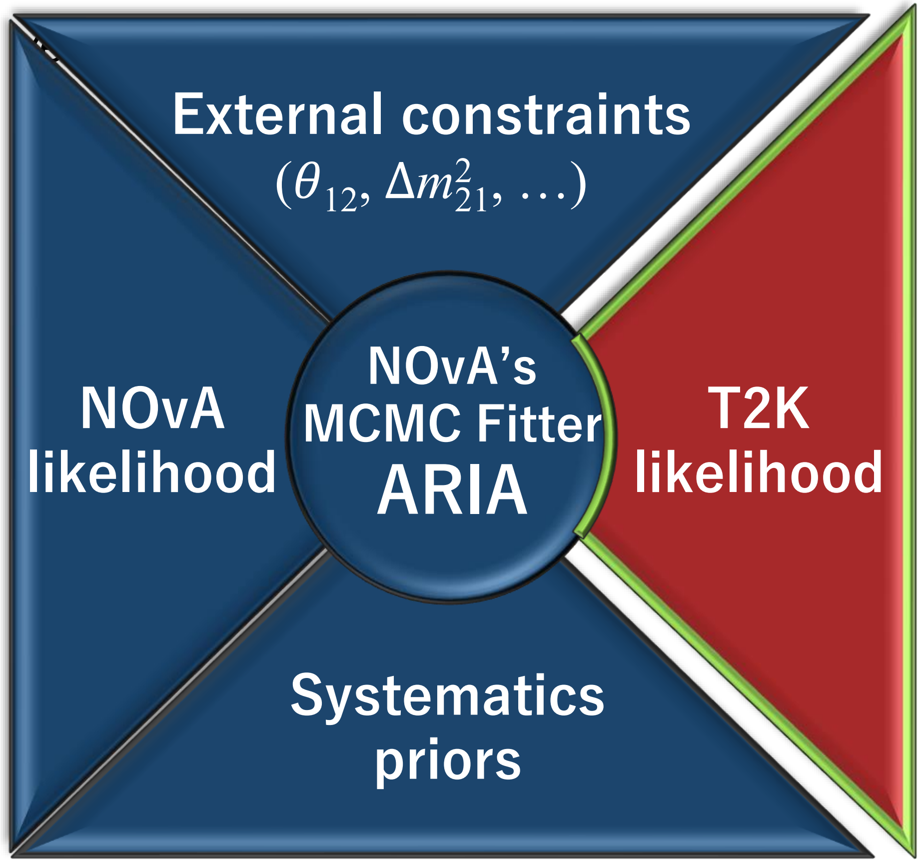


Two independent implementations.

BLUE:
NOvA codebase

RED:
T2K codebase

NOvA version

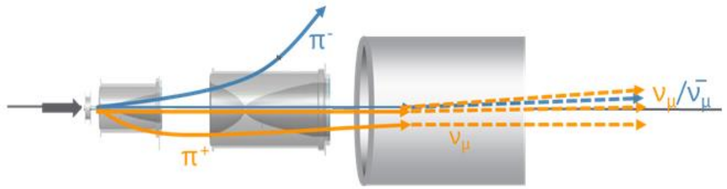


Systematics / model connections?

Flux

- Many aspects unrelated
- *For hadron production*: thin vs. thick target data, different energies, tunings
- Different analysis connections

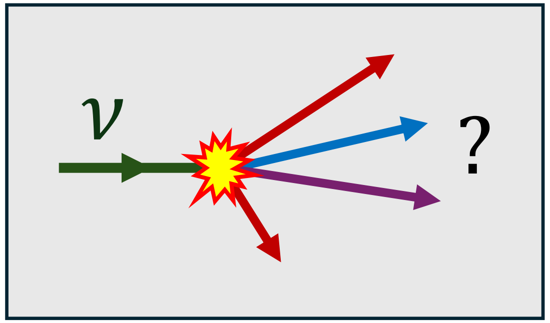
→ **No significant correlations**



ν interactions

- Different energies, nuclei, models, analysis contexts
- However, same underlying physics

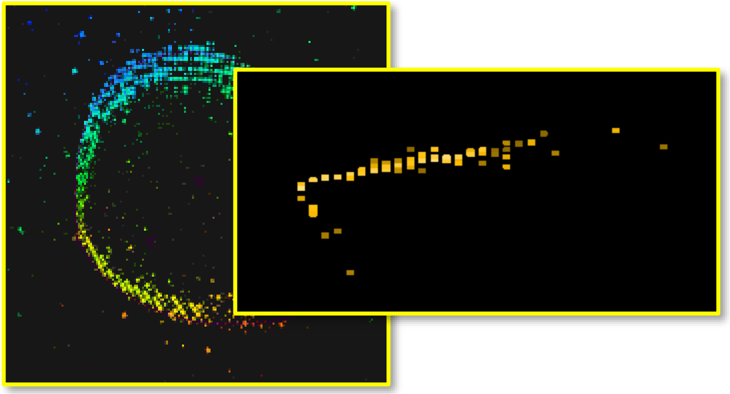
→ **Investigate** potential impact of model correlations

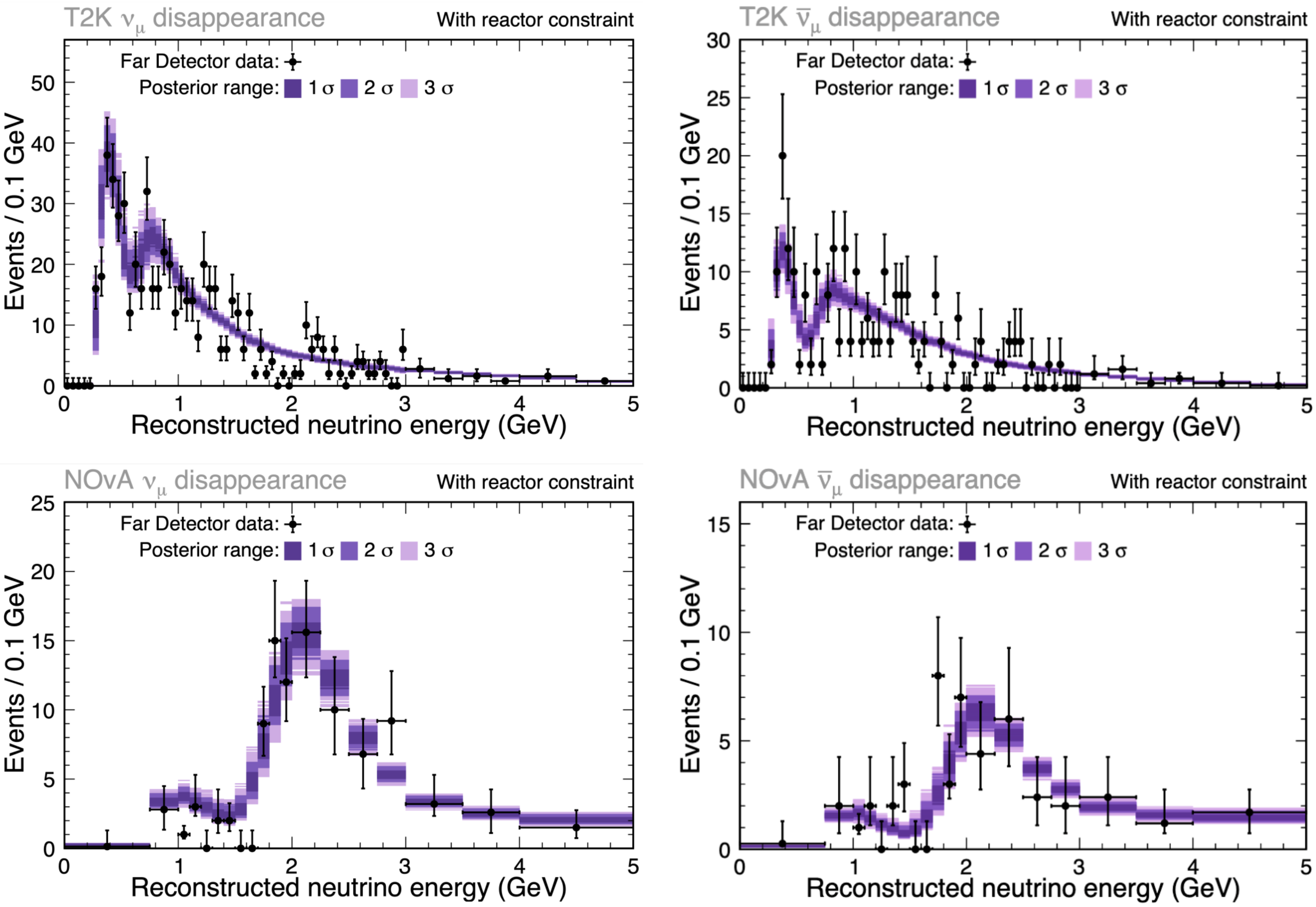


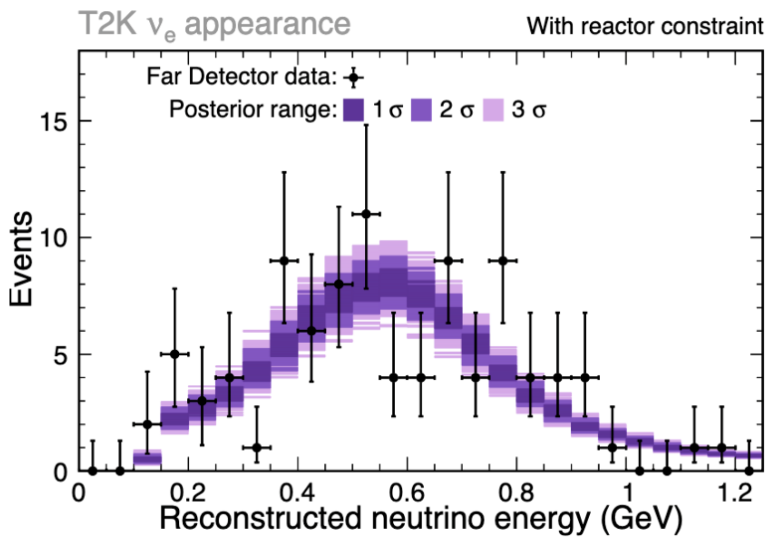
Detector response

- Nearly all aspects unrelated.
- *For shared secondary interactions:* different selections and energy reconstruction techniques (*e.g.*, inclusive vs. exclusive samples)

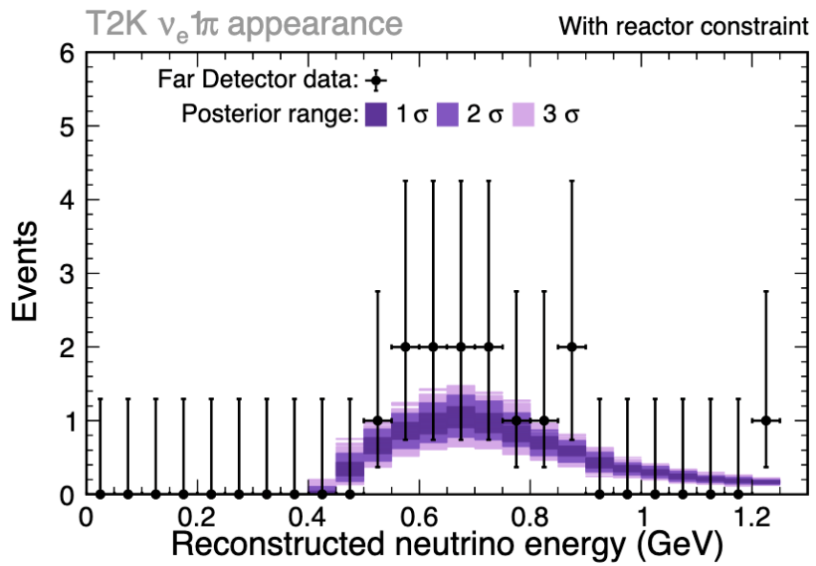
→ **No significant correlations**



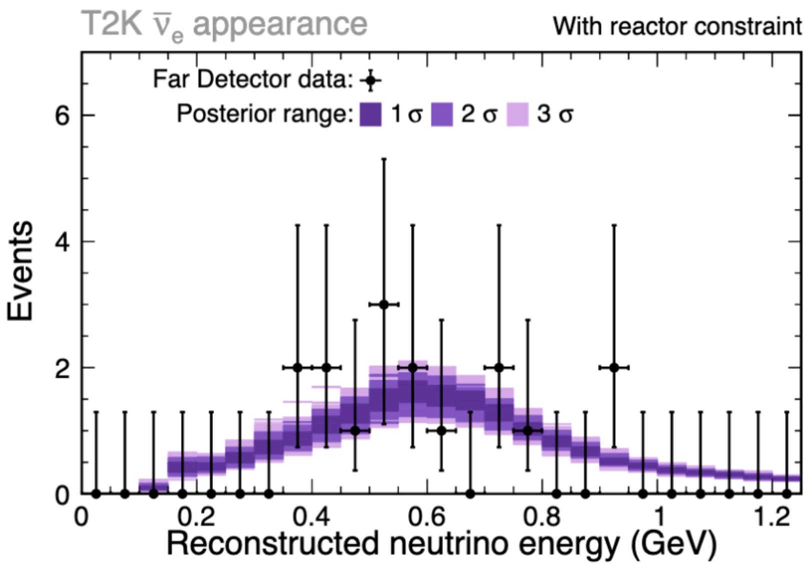

T2K ν_μ disappearance
With reactor constraint
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events / 0.1 GeV
Reconstructed neutrino energy (GeV)
T2K $\bar{\nu}_\mu$ disappearance
With reactor constraint
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events / 0.1 GeV
Reconstructed neutrino energy (GeV)
NOvA ν_μ disappearance
With reactor constraint
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events / 0.1 GeV
Reconstructed neutrino energy (GeV)
NOvA $\bar{\nu}_\mu$ disappearance
With reactor constraint
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events / 0.1 GeV
Reconstructed neutrino energy (GeV)



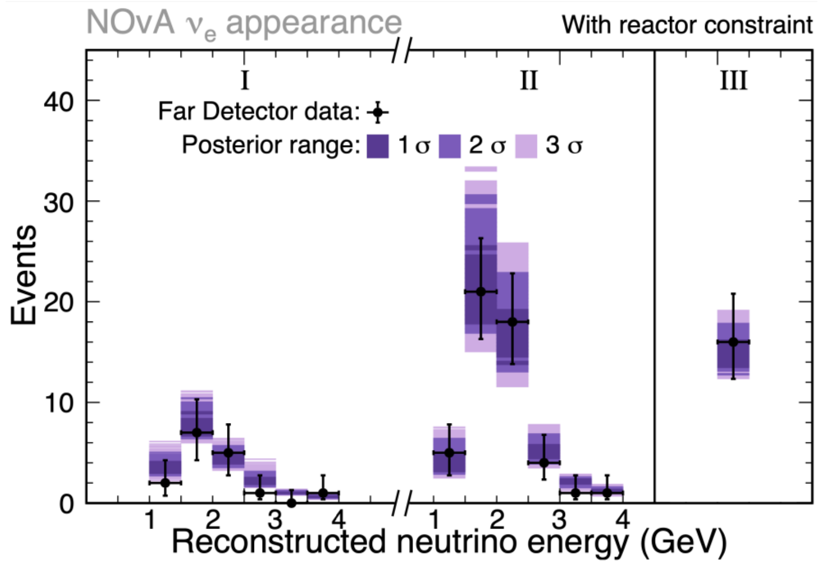
T2K ν_e appearance
With reactor constraint
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events
Reconstructed neutrino energy (GeV)



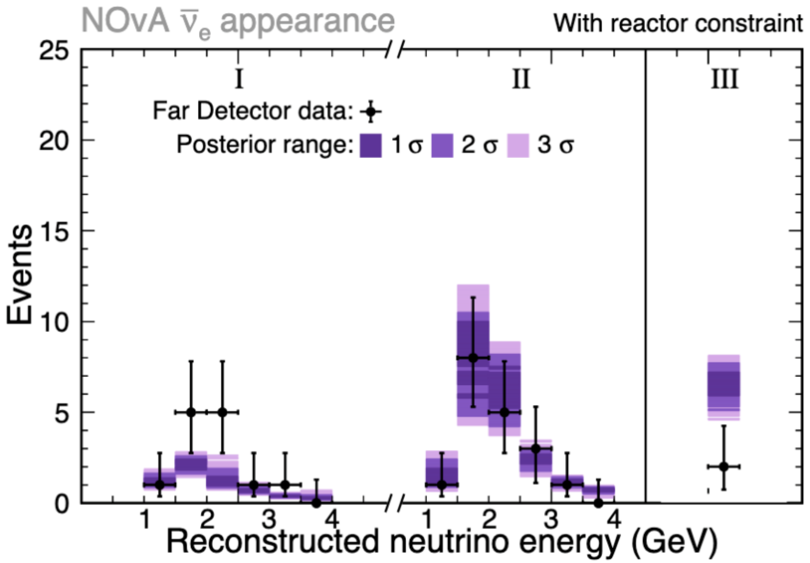
T2K $\nu_e 1\pi$ appearance
With reactor constraint
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events
Reconstructed neutrino energy (GeV)



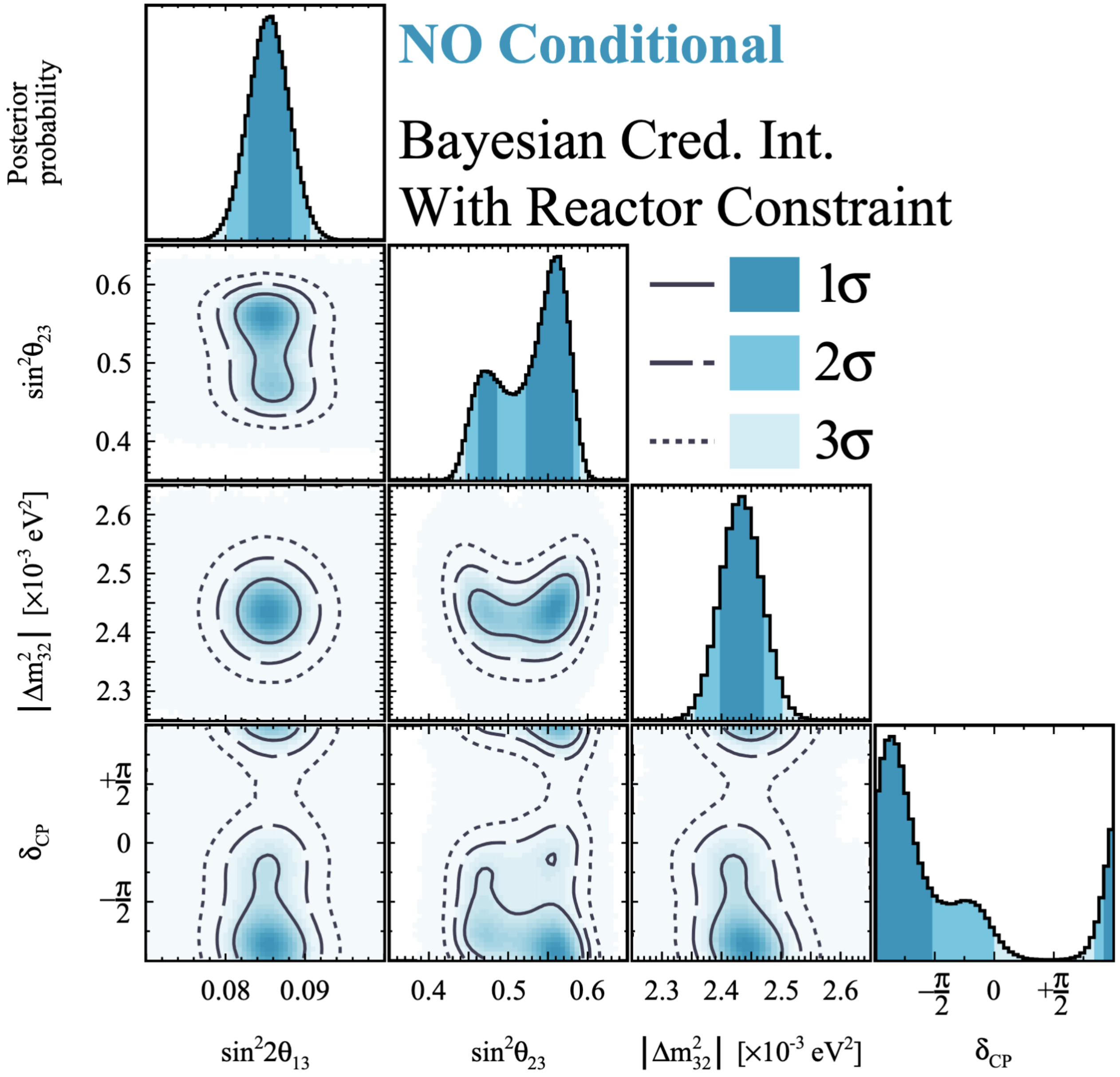
T2K $\bar{\nu}_e$ appearance
With reactor constraint
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events
Reconstructed neutrino energy (GeV)

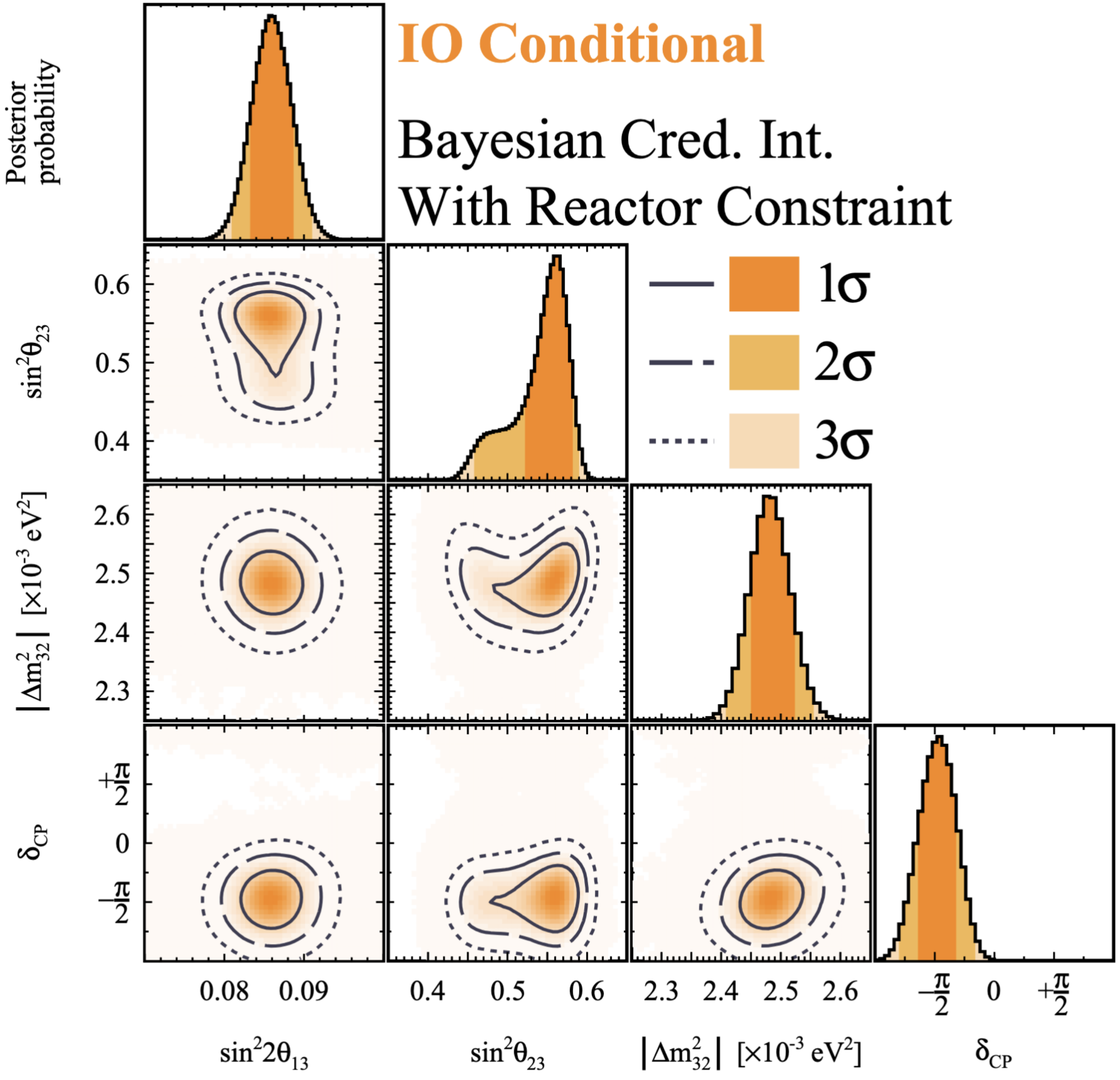


NOvA ν_e appearance
With reactor constraint
I
II
III
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events
Reconstructed neutrino energy (GeV)



NOvA $\bar{\nu}_e$ appearance
With reactor constraint
I
II
III
Far Detector data:
Posterior range: 1 σ 2 σ 3 σ
Events
Reconstructed neutrino energy (GeV)


NO Conditional
Bayesian Cred. Int.
With Reactor Constraint
1σ
2σ
3σ
Posterior probability
sin²θ₂₃
|Δm²₃₂| [×10⁻³ eV²]
δCP
sin²2θ₁₃
0.08 0.09
0.4 0.5 0.6
2.3 2.4 2.5 2.6
-π/2 0 +π/2


IO Conditional
Bayesian Cred. Int.
With Reactor Constraint
1σ
2σ
3σ
Posterior probability
sin²θ₂₃
|Δm²₃₂| [×10⁻³ eV²]
δCP
sin²2θ₁₃
0.08 0.09
0.4 0.5 0.6
2.3 2.4 2.5 2.6
-π/2 0 +π/2

Joint fit: Alternate model tests

- Models that had the largest impact on T2K's 2020-era fit plus two cross-experiment model checks:

  - Non-QE: ND280 CC0π data are under-predicted by the T2K pre-fit prediction. This difference can be taken accounted for by the large freedom in the CCQE model. To check this large freedom does not cause bias, an alternate model where this under-prediction is attribution to only non-QE processes is produced.
  - Minerva 1π: suppression of CC and NC resonant pion production at low-Q^2 for GENIE v2 implementation of Rein-Seghal model to describe the data.
  - Pion SI: GEANT4 model* was replaced with NEUT's Salcedo–Oset model**

* S. Agostinelli et al., (The GEANT4 collaboration), Nucl. Instrum. Meth. A 506 (2003) 250–303 SLAC-PUB-9350

** L. L. Salcedo, E. Oset, M. J. Vicente-Vacas, and C. Garcia-Recio, Nucl. Phys. A 484 (1988) 557–592 Print-87-1084 (Valencia)

Joint fit: Alternate model tests

- Small "error on the error" → width of the 1D intervals changes by <10%
- Movement of central value (center of interval) well covered by systematic uncertainty (center moves by < 50% of systematic uncertainty)

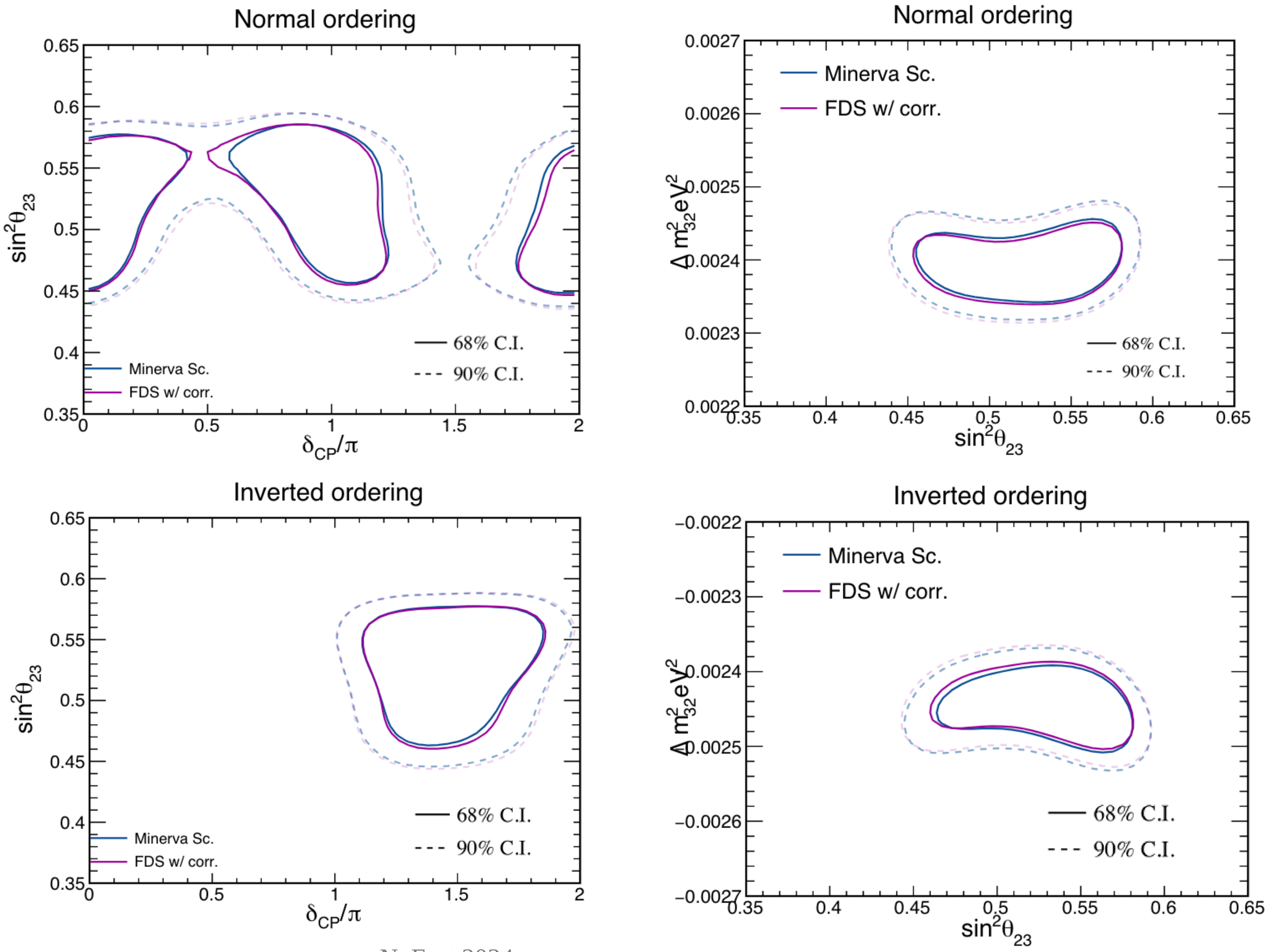
Alternate Model	$\mathbf{\Delta m^2_{32}}$ **Change in 1D contour < 10%**	$\mathbf{\Delta m^2_{32}}$ **Bias in central value < 50%**	$\mathbf{\sin^2\theta_{23}}$ **Change in 1D contour < 10%**	$\mathbf{\sin^2\theta_{23}}$ **Bias in central value < 50%**
Non-QE	✔	✔	✔	✔
Minerva1p	✔	✔	✔	✔
Pion-SI	✔	✔	✔	✔
NOvA-like	✔	✔	✔	✔
T2K-like	✔	✔	✔	✔

Joint fit: Alternate model tests

- Discrete model tests:
  - Fractional change in Bayes factor for mass ordering and octant seen in pseudo-data tests should not change any conclusions if applied to data
- Test whether alternate models could change our conclusions on the CPv significance

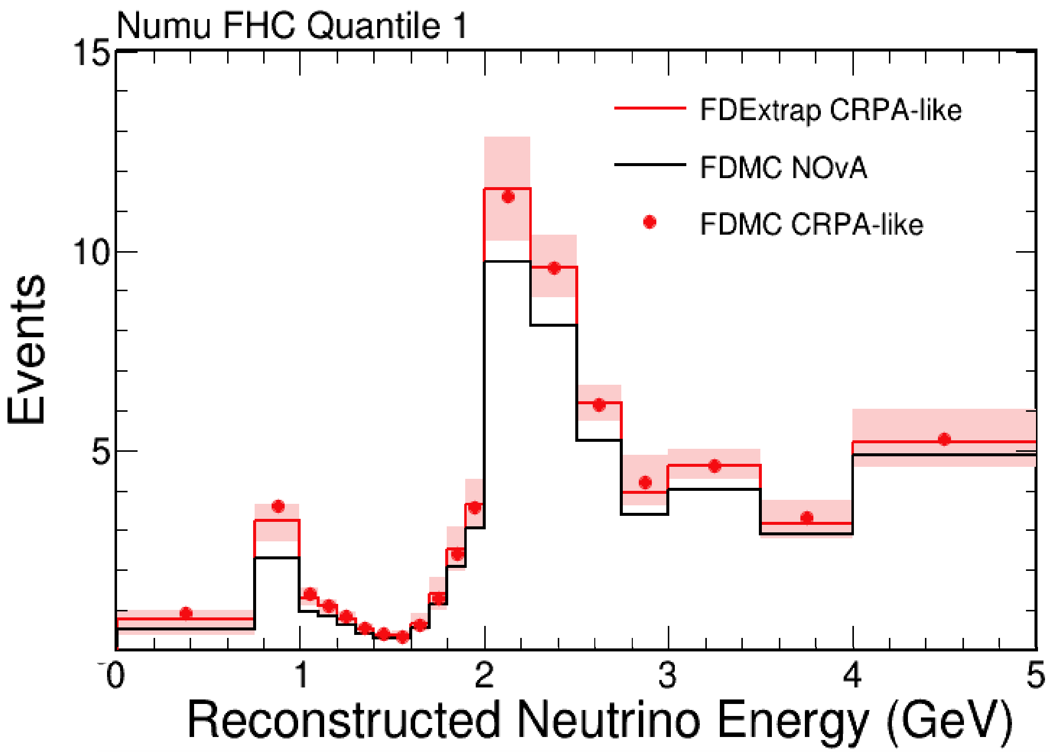
Alternate Model	Conclusion on δ_{CP}	Conclusions on J	Mass Ordering Fractional change in BF	Octant Fractional change in BF
Non-QE	✔	✔	1.02	0.88
Minerva1p	✔	✔	1.03	0.92
Pion-SI	✔	✔	0.94	1.11
NOvA-like	✔	✔	1.10	1.00
T2K-like	✔	✔	1.08	1.16

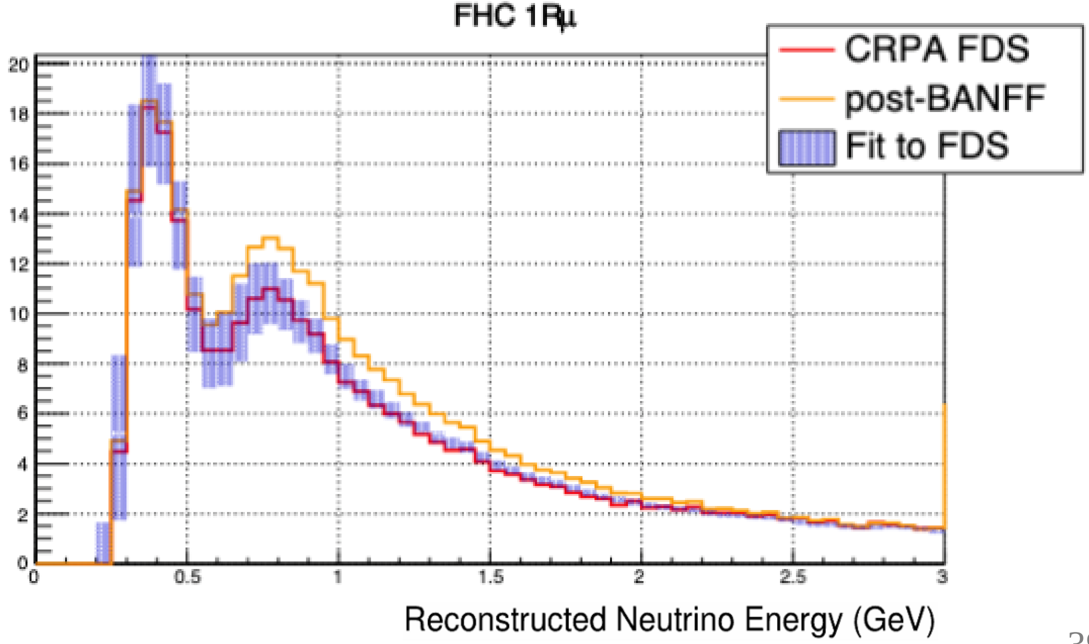
Minerva1π pseudo-data fits



- **Hartree Fock (HF) – Continuum Random Phase Approximation (CRPA)***
- Applies modifications to the nuclear models (Spectral Function for T2K, Local Fermi Gas for NOvA)
- Recent T2K analyses have included an additional smearing on Δm^2_{32} based on variations seen when considering the HF-CRPA nuclear model.
  - Both NOvA and T2K independently studied the impact of this alternate nuclear model on their 2020-era analyses.
  - When taken together in the context of the joint fit, the bias is no larger than the thresholds set for any of the fake data metrics.

* Phys. Rev. D 106, 073001 (2022)





Model & Systematics comparison

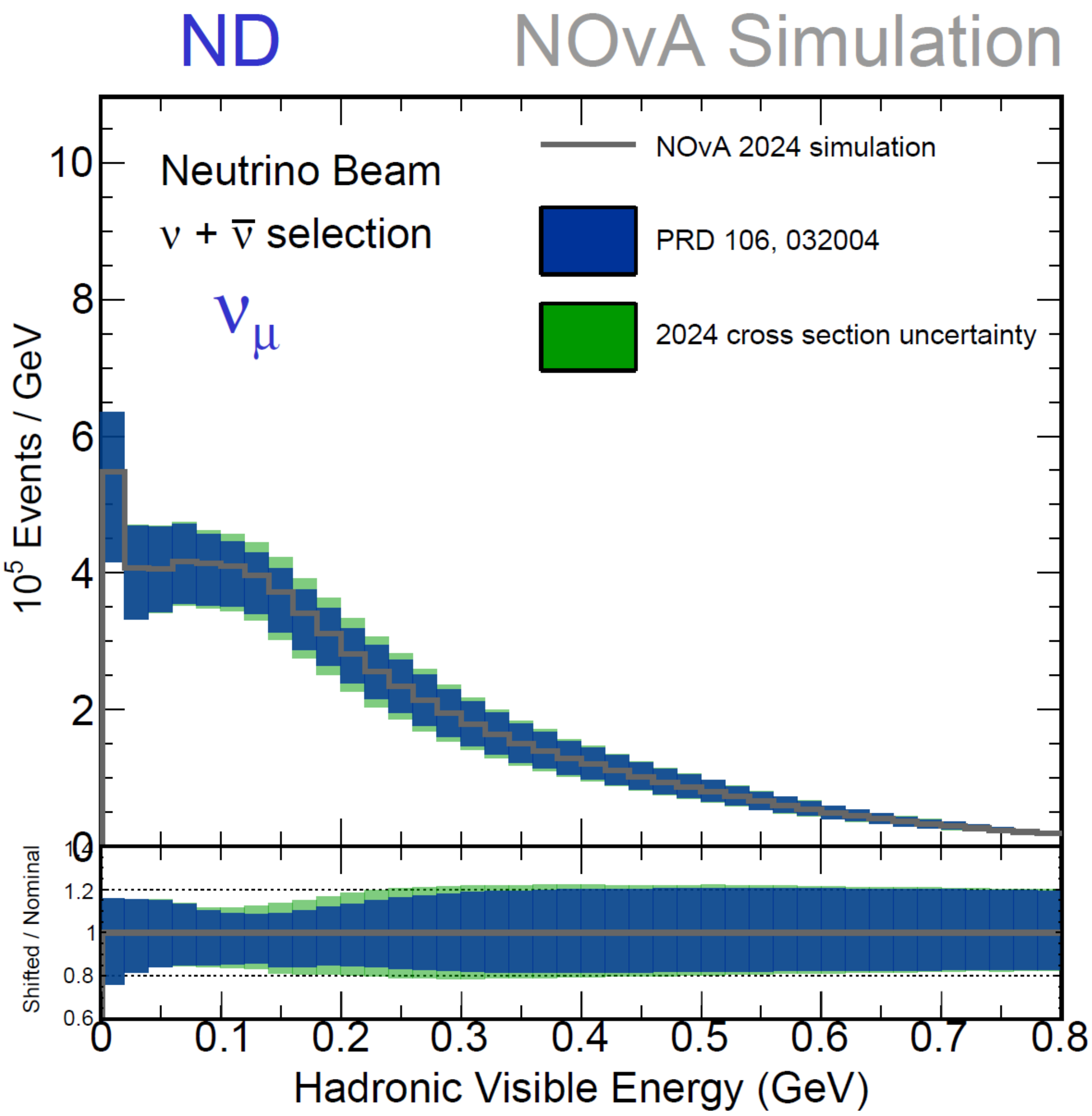
Category	NOvA Parameters	T2K Parameters
CCQE	ZNormCCQE ZExpAxialFFSyst2020_EV1 ZExpAxialFFSyst2020_EV2 ZExpAxialFFSyst2020_EV3 ZExpAxialFFSyst2020_EV4 RPAShapeenh2020 RPAShapesupp2020	M_A QE Q2_norm_0 Q2_norm_1 Q2_norm_2 Q2_norm_3 Q2_norm_4 Q2_norm_5 Q2_norm_6 Q2_norm_7 EB Dial C nu EB Dial C nubar EB Dial O nu EB Dial O nubar
MEC	MECEnuShape2020Nu MECEnuShape2020AntiNu MECShape2020Nu MECShape2020AntiNu MECInitStateNPFrac2020Nu MECInitStateNPFrac2020AntiNu	2p2h Norm nu 2p2h Norm nubar 2p2h C to O 2p2h Shape C 2p2h Shape O 2p2h Edep low Enu 2p2h Edep high Enu 2p2h Edep low Enubar 2p2h Edep high Enubar
RES	MaCCRES MvCCRES MaNCRES MvNCRES LowQ2RESSupp2020	CA5 MA RES ISO Bkg Low PPi ISO Bkg
FSI	hNFSI_MFP_2020 hNFSI_FateFracEV1_2020	FEFQE FEFQEH FEFINEL FEFABS FEFCX

- Models and systematics used for 2020 analysis [NOvA: PhysRevD.106.032004, T2K:arXiv:2303.03222v1] are used in the joint fit.
- The base-models are tuned to internal (NOvA-ND data by NOvA) and external datasets.
- The tuning modifies the underlying models drastically (eg: NOvA's 2p2h tune.)

Experiment	Generator	QE	MEC/2p2h	RES	DIS	FSI
NOvA	GENIE v3.0.6	Local Fermi Gas Z-expansion axial form factor	Valencia* (*with NOvA 2020 tune)	Berger-Sehgal	Bodek-Yang	hN Semi Classical Cascade (*fit to pion scattering data)
T2K	NEUT 5.4	Spectral Function M_A^{QE} form factor	Valencia	Rein-Sehgal	Bodek-Yang	Semi-Classical Cascade

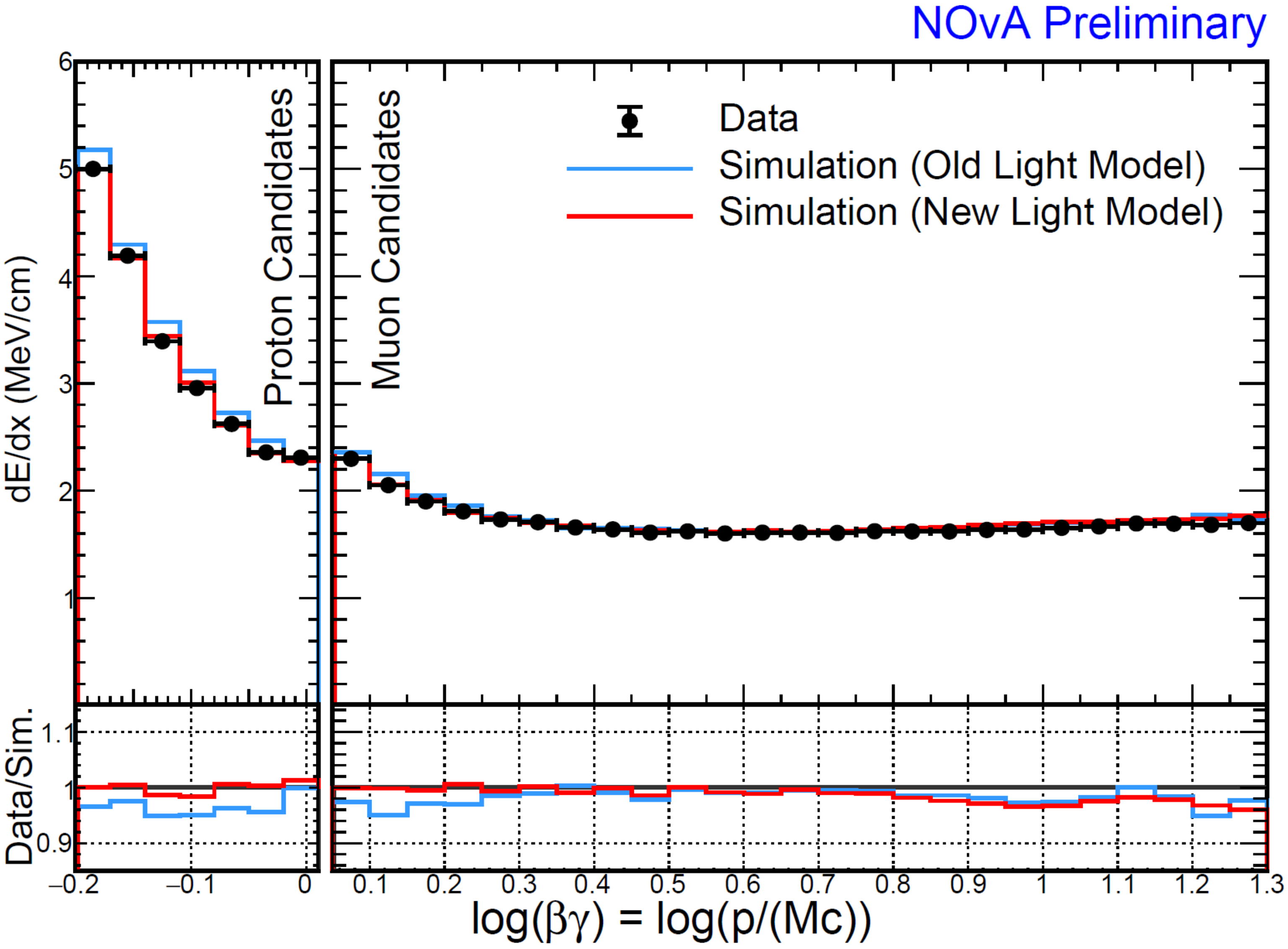
Updated RES and DIS uncertainties

Showing level of effect on hadronic visible energy in Near Detector

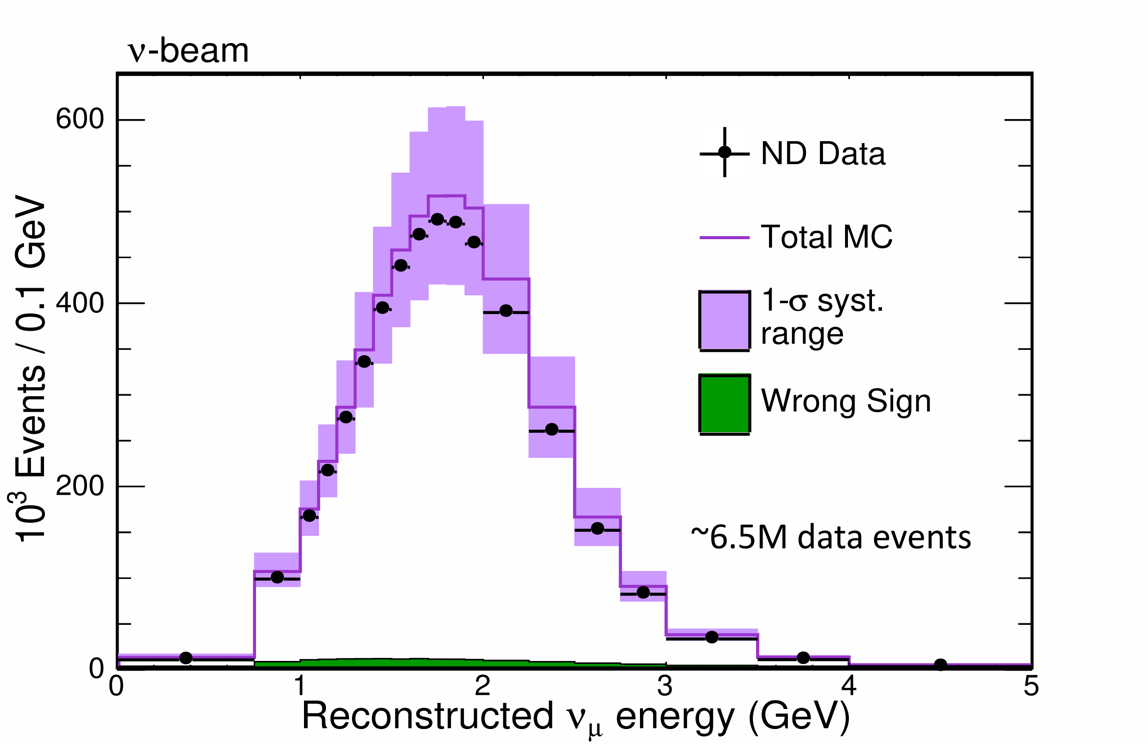


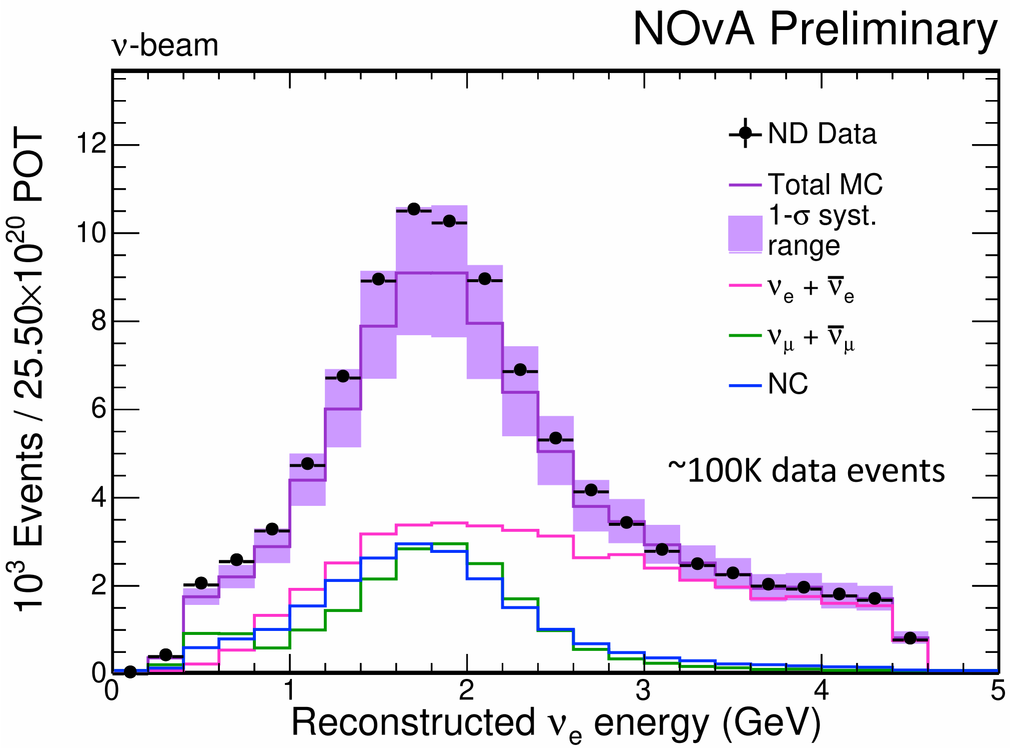
Updated light model

a look at protons and muons as standard candles



NOvA Near Detector Samples (neutrino mode)





ν_μ candidates

informs FD ν_μ *and* ν_e predictions

ν_e candidates

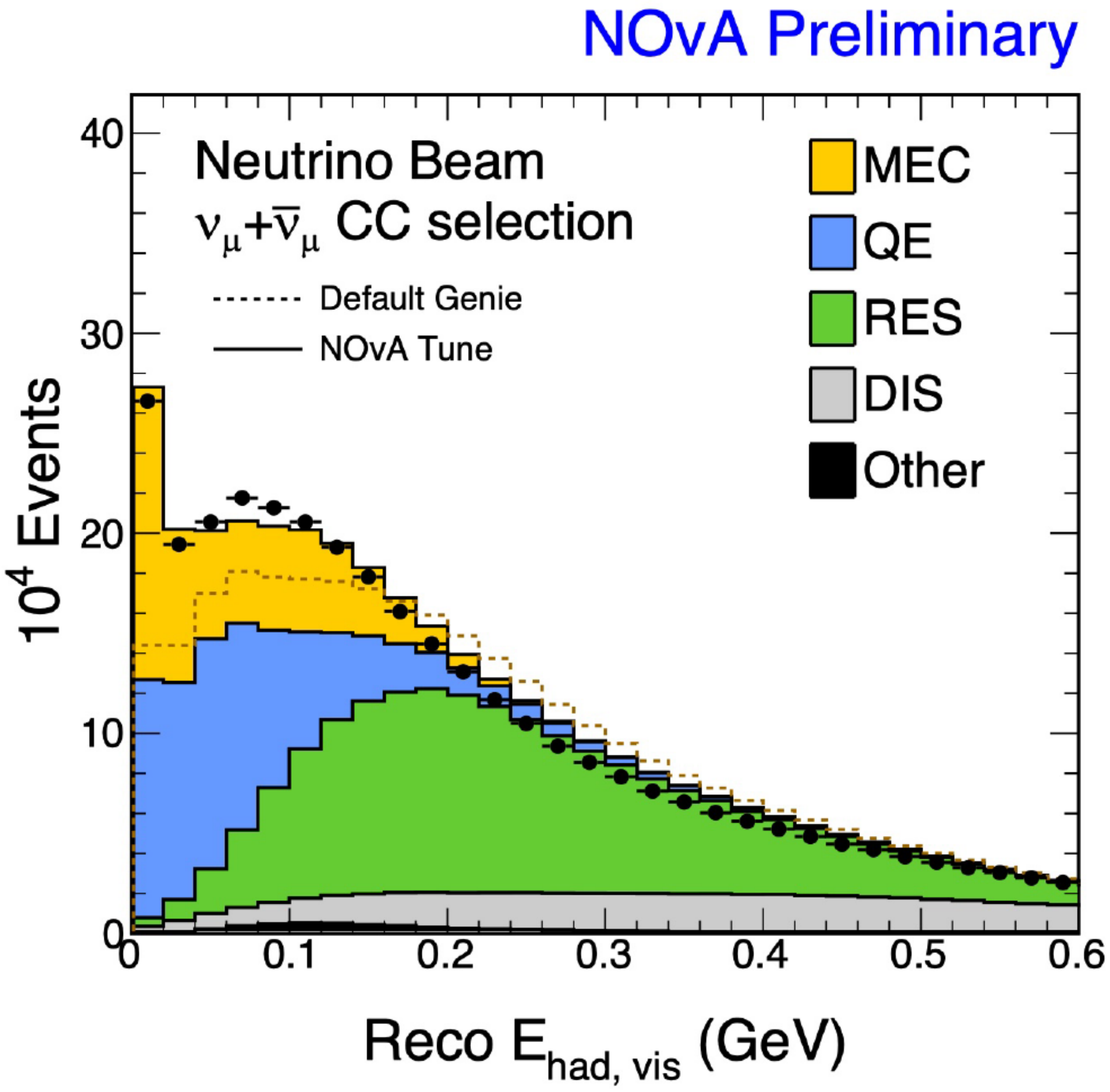
informs FD ν_e backgrounds

Dominated by beam ν_e (irreducible)

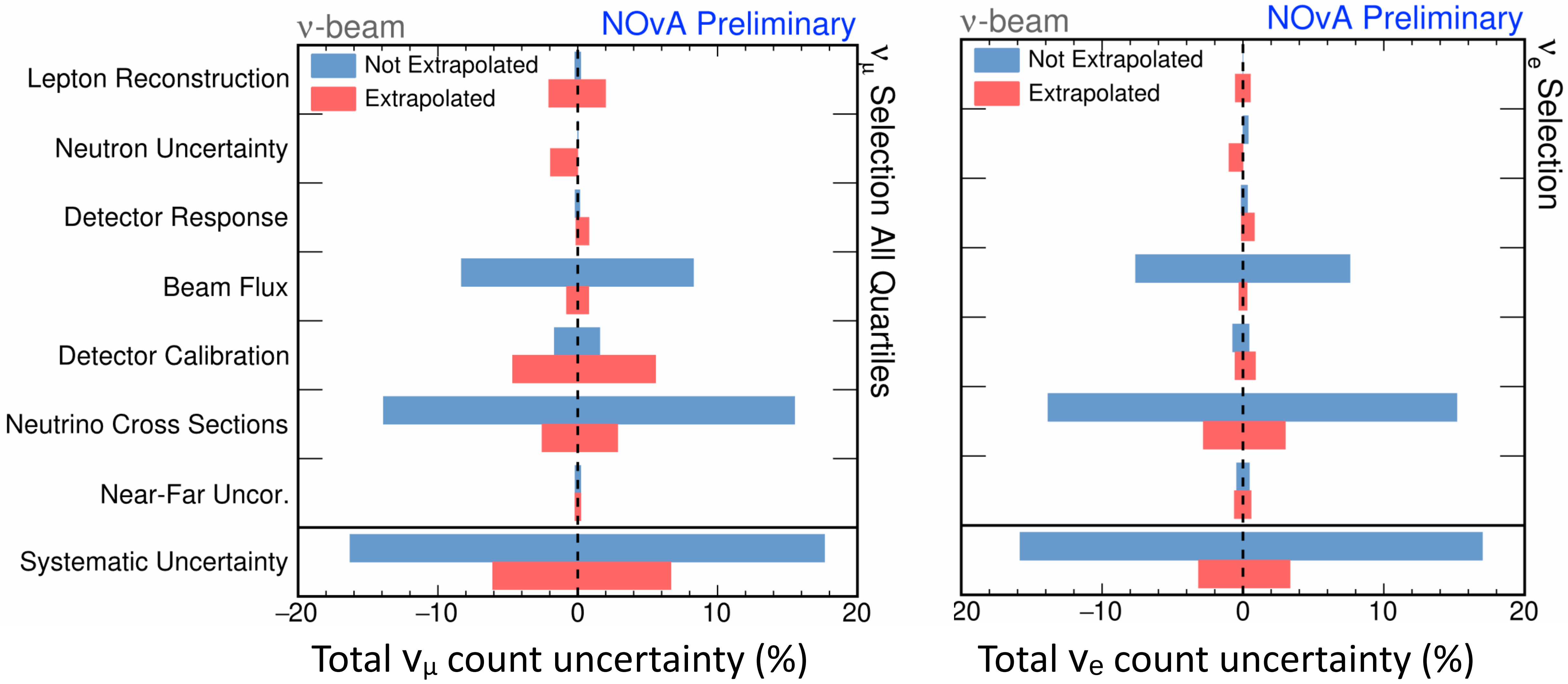
NOvA cross section model:

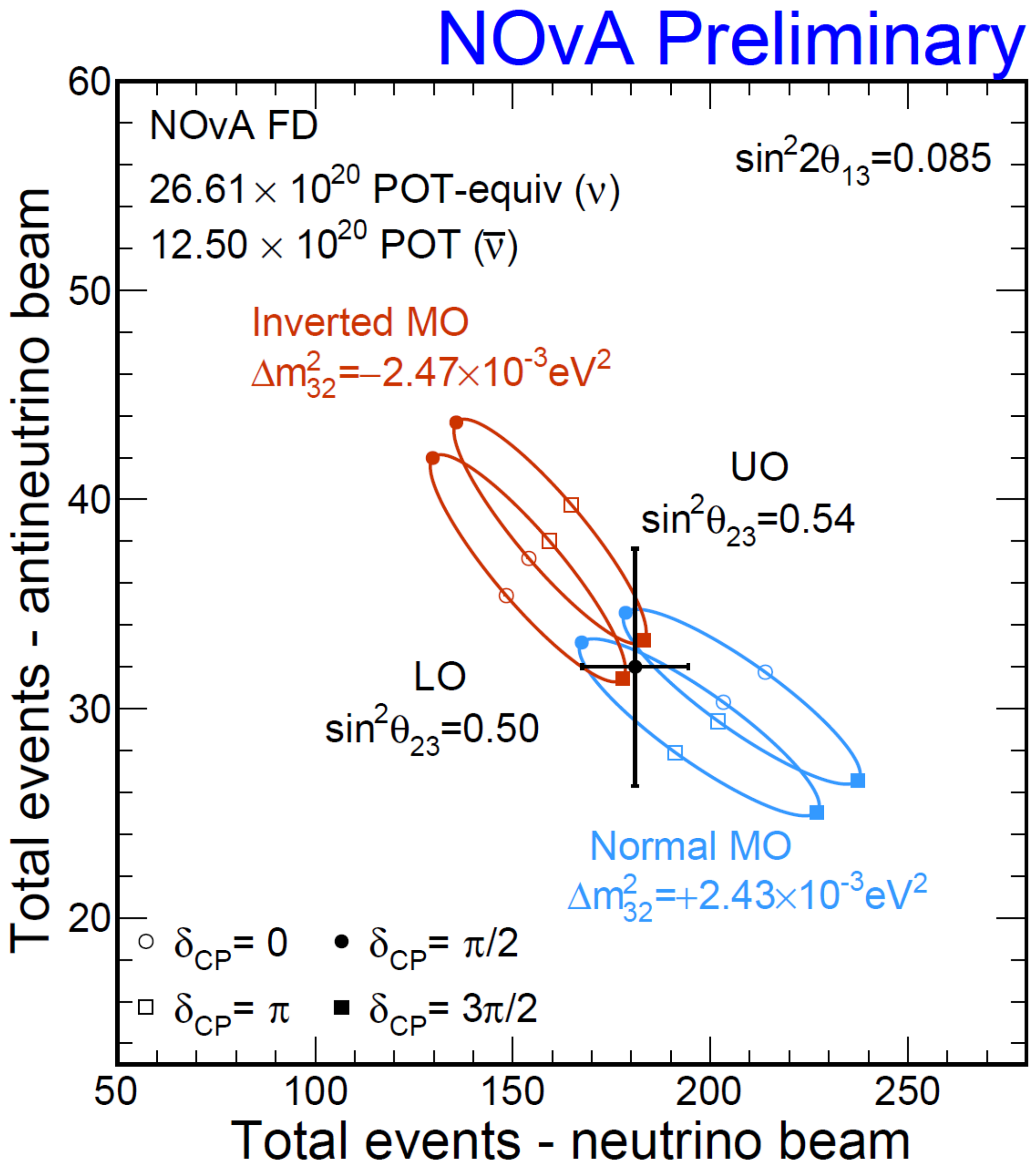
GENIE 3.0.6 custom configuration tuned to external data and NOvA ND Data, with expanded uncertainty suite

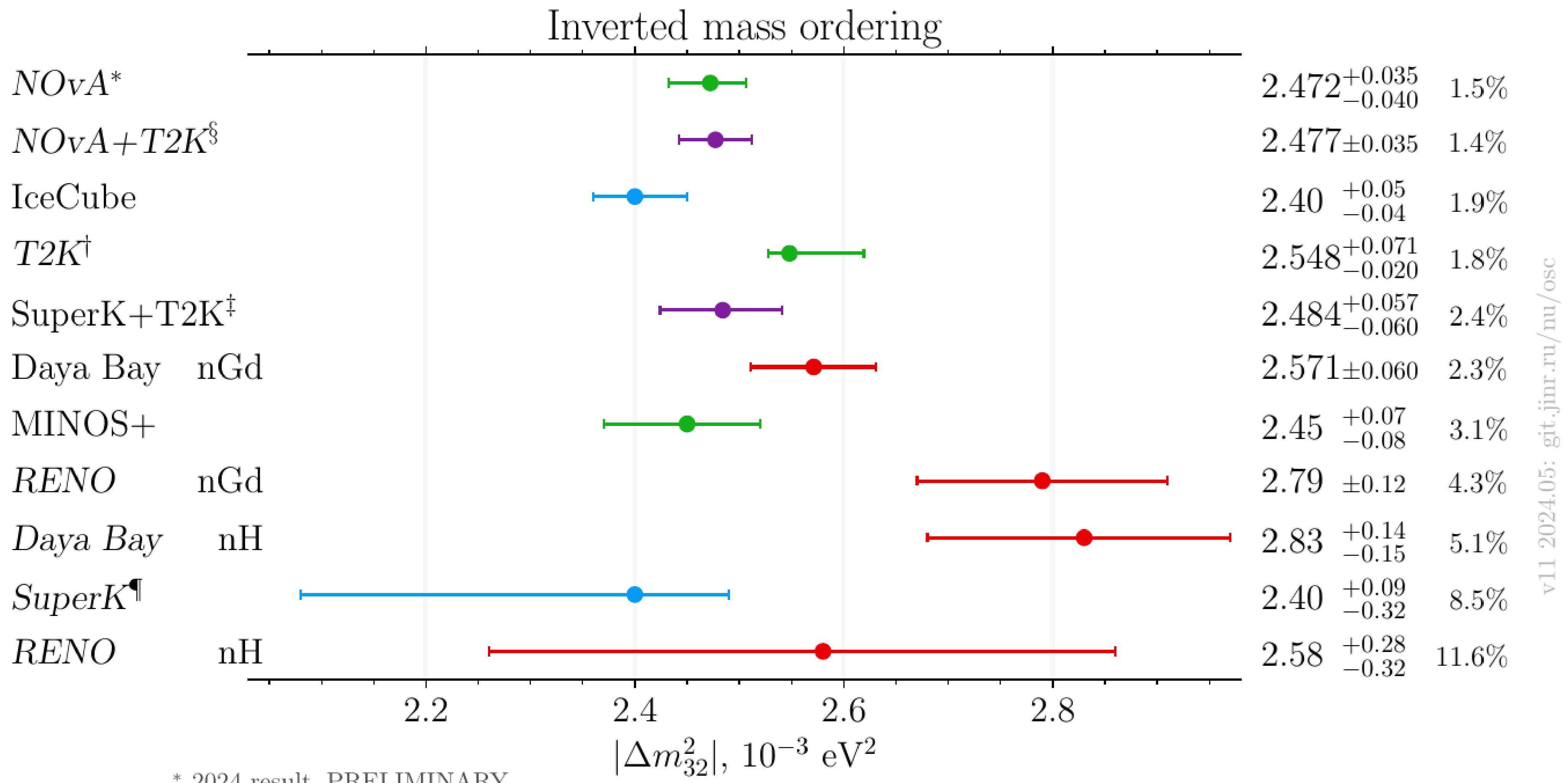
Neutrino - free nucleon interactions	
Quasi-Elastic (QE)	Valencia 1p1h Z-expansion axial form factor
Resonance (RES)	Berger-Sehgal
Deep inelastic Scattering (DIS)	Bodek-Yang
Multinucleon interactions	
Meson exchange current (MEC)	Valencia MEC custom adjustment to NOvA data for 2p2h
Interactions with the nuclear environment	
Final State Interactions (FSI)	hN Semi Classical Cascade Custom fit to external pion scattering data.



Example of systematic uncertainty mitigation




NOvA Preliminary
NOvA FD
26.61 × 10^20 POT-equiv (ν)
12.50 × 10^20 POT (ν̄)
sin²2θ13=0.085
Inverted MO
Δm²32=−2.47×10⁻³eV²
UO
sin²θ23=0.54
LO
sin²θ23=0.50
Normal MO
Δm²32=+2.43×10⁻³eV²
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
Total events - antineutrino beam
Total events - neutrino beam
20
30
40
50
60
50
100
150
200
250



Preliminary
Published

* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result

¶ SKI-V result, arXiv:2311.05105
‡ based on SK IV and T2K 2020, arXiv:2405.12488