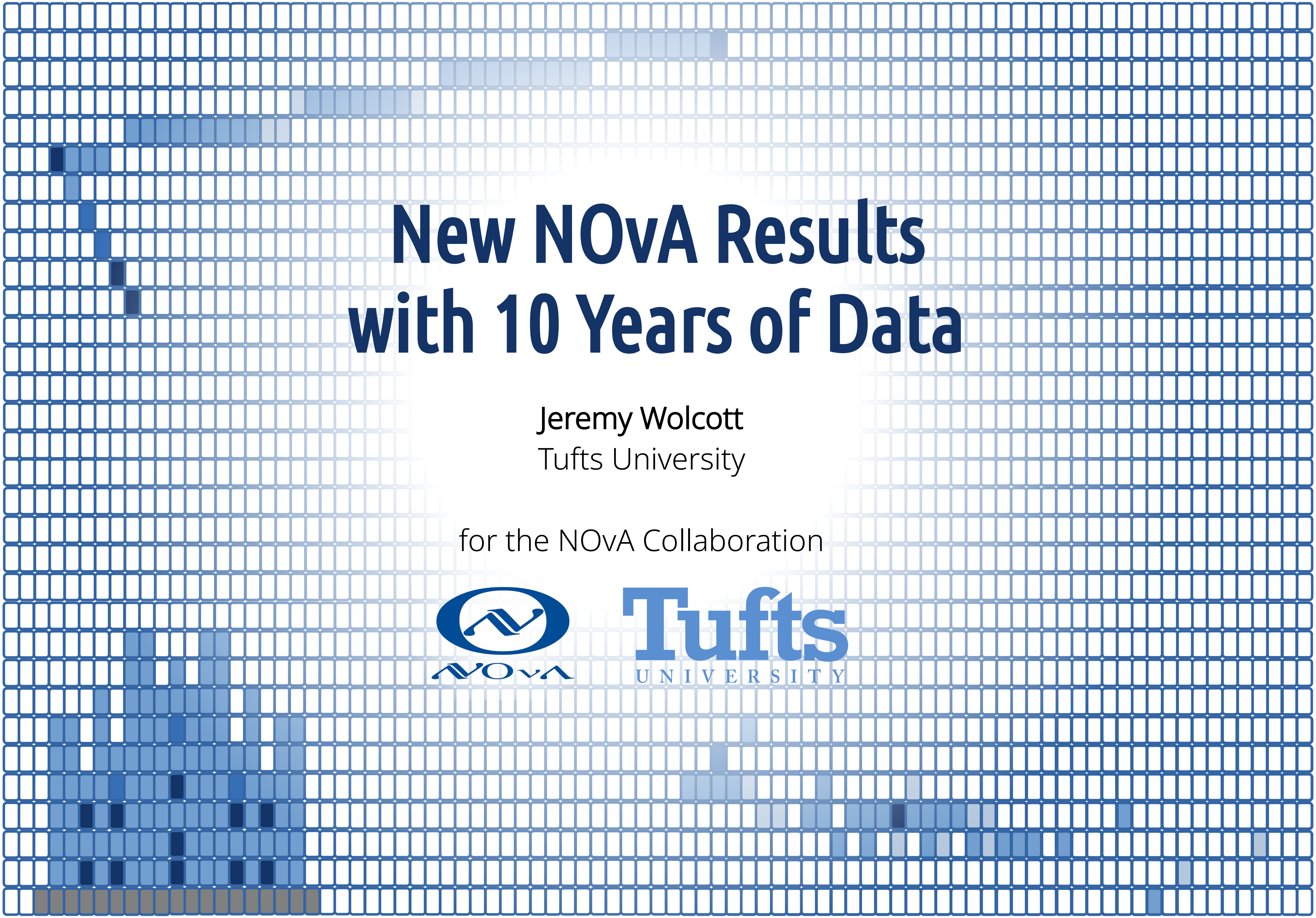
New NOvA Results with 10 Years of Data

Jeremy Wolcott
Tufts University

for the NOvA Collaboration



Duomo di Milano, as seen by NOvA
(not 1:1 scale)

But FIRST

Recent NOvA -T2K Joint Fit Results

Jeremy Wolcott
Tufts University

for the NOvA & T2K Collaborations

NOvA and T2K are complementary

Interested in same PMNS physics...

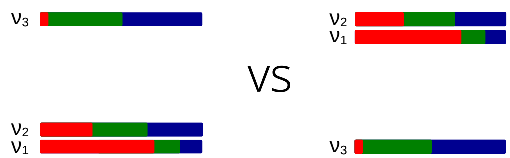
①

Is θ_{23} = 45º?

Do ν_μ/ν_τ **mix equally into** ν_3?

Normal ordering

Inverted ordering

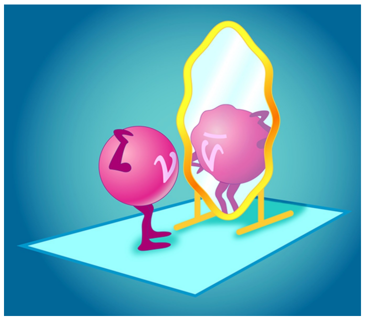


Which way are the **neutrino mass states ordered**?

②

③

APS/Carin Cain



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

Do neutrinos exhibit **CP violation**?

... but explore with different experimental considerations

[NOvA & T2K are complementary]

NOvA and T2K are complementary

Compared to T2K*, NOvA has **Higher E_ν**

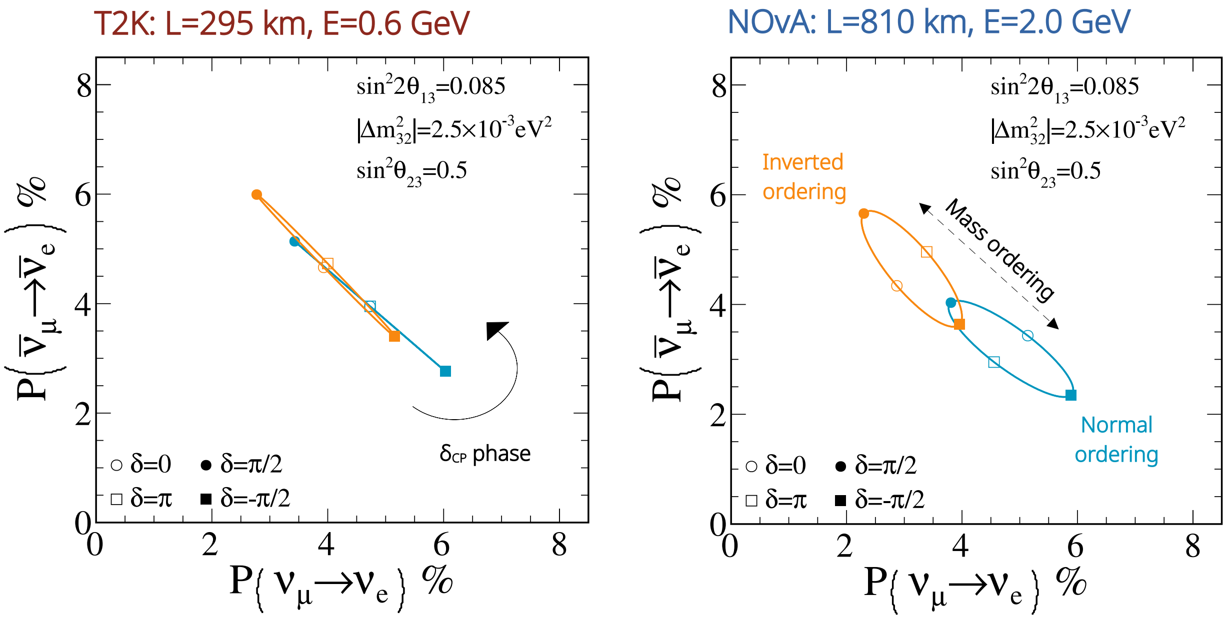
* See previous talk for more on T2K

NOvA and T2K are complementary

Compared to T2K*, NOvA has **Higher E_ν**

(and a corresponding longer baseline)

Larger matter effects



Stronger mass ordering sensitivity;
more δ_{CP} degeneracy

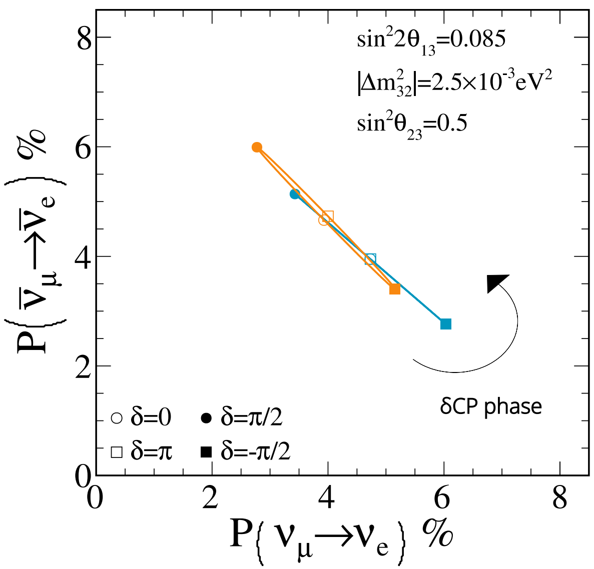
* See previous talk for more on T2K

NOvA and T2K are complementary

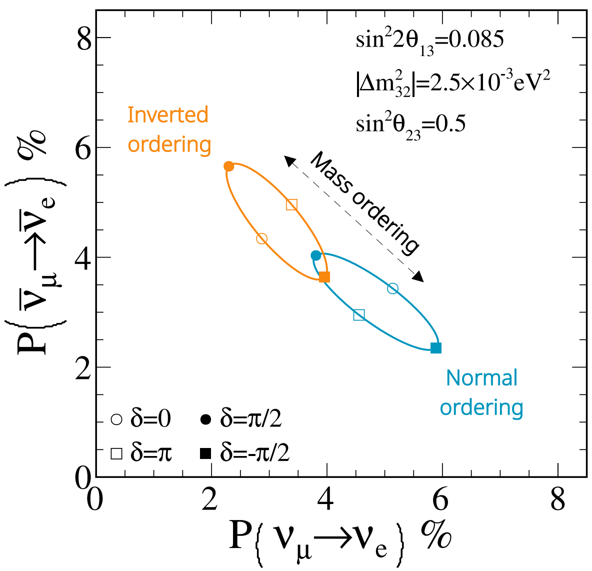
Compared to T2K*, NOvA has **Higher E_ν**

Larger matter effects

T2K: L=295 km, E=0.6 GeV



NOvA: L=810 km, E=2.0 GeV



Stronger mass ordering sensitivity;
more δ_{CP} degeneracy

Also...

- More antineutrinos
- More final-state pions

(see overflow slides)

* See previous talk for more on T2K

NOvA and T2K are complementary

Compared to T2K*, NOvA uses

a different experimental approach

* See previous talk for more on T2K

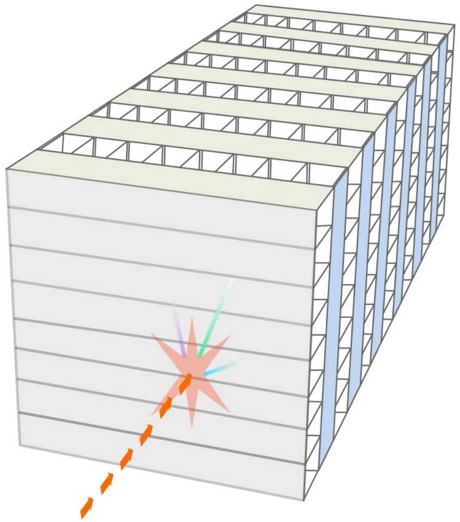
NOvA and T2K are complementary

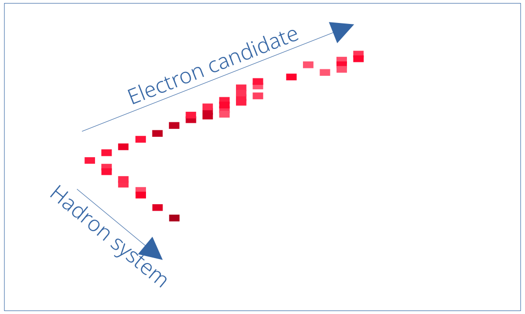
Compared to T2K*, NOvA uses

a different experimental approach

NOvA

active scintillator calorimeters





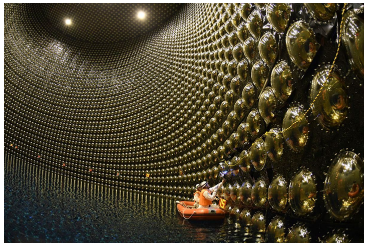
see significant energy from both lepton and hadron systems: "calorimetric" E_ν reconstruction

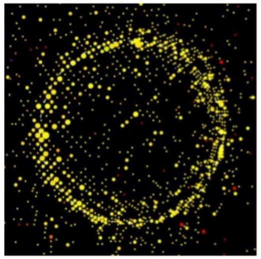
& functionally equivalent detectors

shared uncertainties mostly cancel

T2K

water Cherenkov FD





ν_e-like

see only lepton energy: "kinematic" E_ν reconstruction

Hybrid gas TPC & scintillator tracker ND

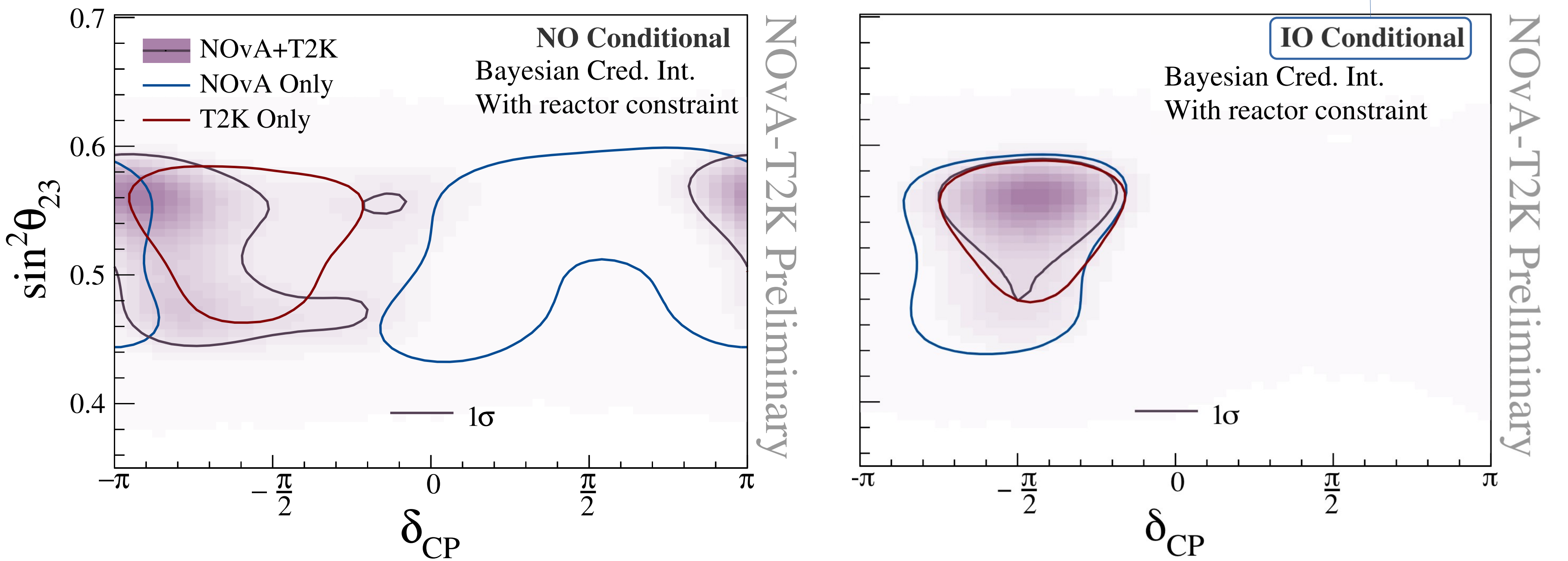
ND+FD shared uncertainties explicitly fitted & constrained via model

* See previous talk for more on T2K

NOvA-T2K joint fit: PMNS parameters

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

"assuming IO is true"
(does not include relative probability of IO vs. NO)

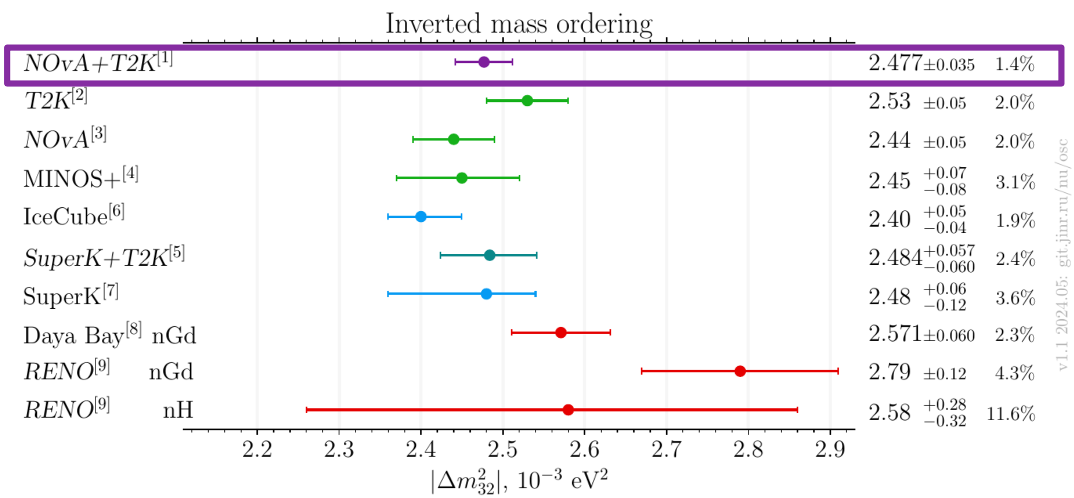


Joint fit splits the difference b/w NOvA-only & T2K-only in NO; improves constraint in IO

NOvA-T2K joint fit: takeaways

Advancing the precision frontier on $|\Delta m^2_{32}|$

<2% measurement!

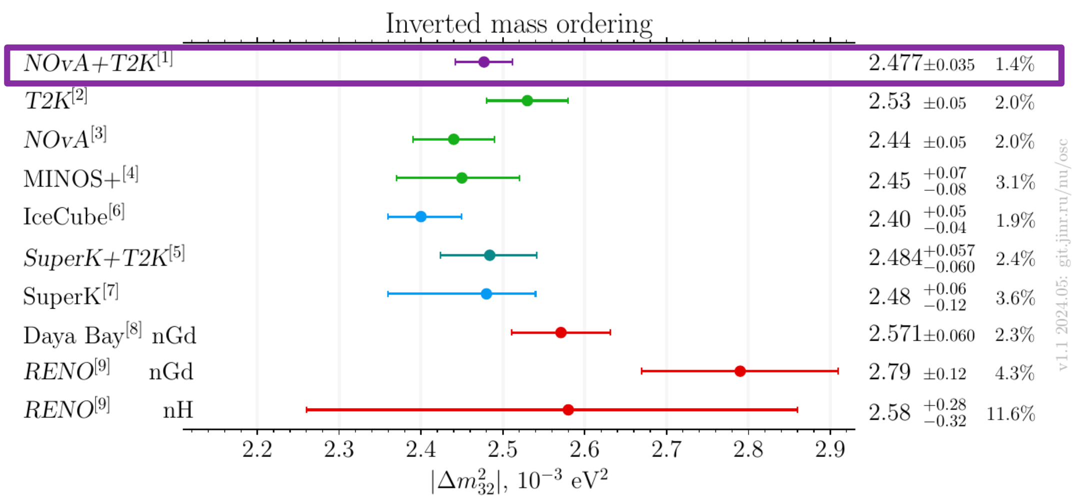


[1] KEK IPNS seminar, FNAL JETP seminar
[2] Eur. Phys. J. C83, 782 (2023)
[3] Phys. Rev. D106, 032004 (2022)
[4] Phys. Rev. Lett. 125, 131802 (2020)
[5] arXiv:2405.12488
[6] arXiv:2405.02163
[7] Phys. Rev. D109, 072014 (2024)
[8] Phys. Rev. Lett. 130, 161802 (2023)
[9] RENO @ Neutrino 2020 [10.5281/zenodo.3959697]

NOvA-T2K joint fit: takeaways

Advancing the precision frontier on $|\Delta m^2_{32}|$

<2% measurement!



Mild preference for Inverted Ordering

but **influenced by θ_{13} constraint**

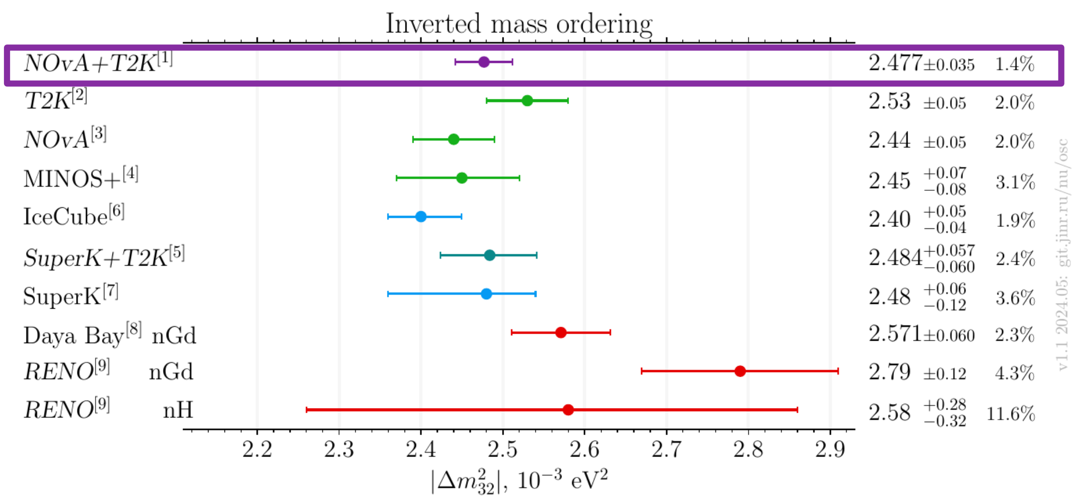
NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)

[1] KEK IPNS seminar, FNAL JETP seminar
[2] Eur. Phys. J. C83, 782 (2023)
[3] Phys. Rev. D106, 032004 (2022)
[4] Phys. Rev. Lett. 125, 131802 (2020)
[5] arXiv:2405.12488
[6] arXiv:2405.02163
[7] Phys. Rev. D109, 072014 (2024)
[8] Phys. Rev. Lett. 130, 161802 (2023)
[9] RENO @ Neutrino 2020 [10.5281/zenodo.3959697]

NOvA-T2K joint fit: takeaways

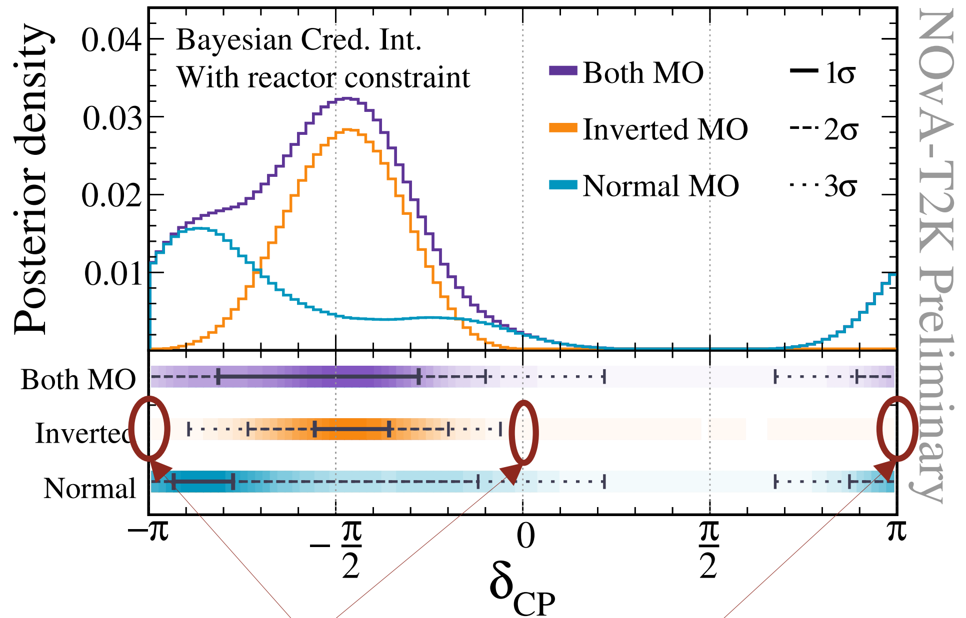
Advancing the precision frontier on $|\Delta m^2_{32}|$

<2% measurement!



Mild preference for Inverted Ordering but **influenced by θ_{13} constraint**

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)



CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

[1] KEK IPNS seminar, FNAL JETP seminar
[2] Eur. Phys. J. C83, 782 (2023)
[3] Phys. Rev. D106, 032004 (2022)
[4] Phys. Rev. Lett. 125, 131802 (2020)
[5] arXiv:2405.12488
[6] arXiv:2405.02163
[7] Phys. Rev. D109, 072014 (2024)
[8] Phys. Rev. Lett. 130, 161802 (2023)
[9] RENO @ Neutrino 2020 [10.5281/zenodo.3959697]

NOvA+T2K summary & outlook

- NOvA & T2K's **first joint results**:
  - Yield **strong constraint on Δm^2_{32}**
  - Weakly prefer IO or NO depending on which reactor constraint is applied
  - **Strongly favor CP violation in Inverted Ordering**
- Collaborations in active discussion about **joint fit next steps**

POSTER
463. Results from the Joint NOvA-T2K Analysis
Kathryn Sutton (Caltech)
6/18/24, 5:30 PM

[more detail also available in Feb. 16, 2024 results seminars]

Edward Atkin, KEK IPNS seminar

Zoya Vallari, FNAL JETP seminar

New NOvA Results

New NOvA Results

T2K experiment status and plans *Claudio Giganti*

Milano 11:10 - 11:35

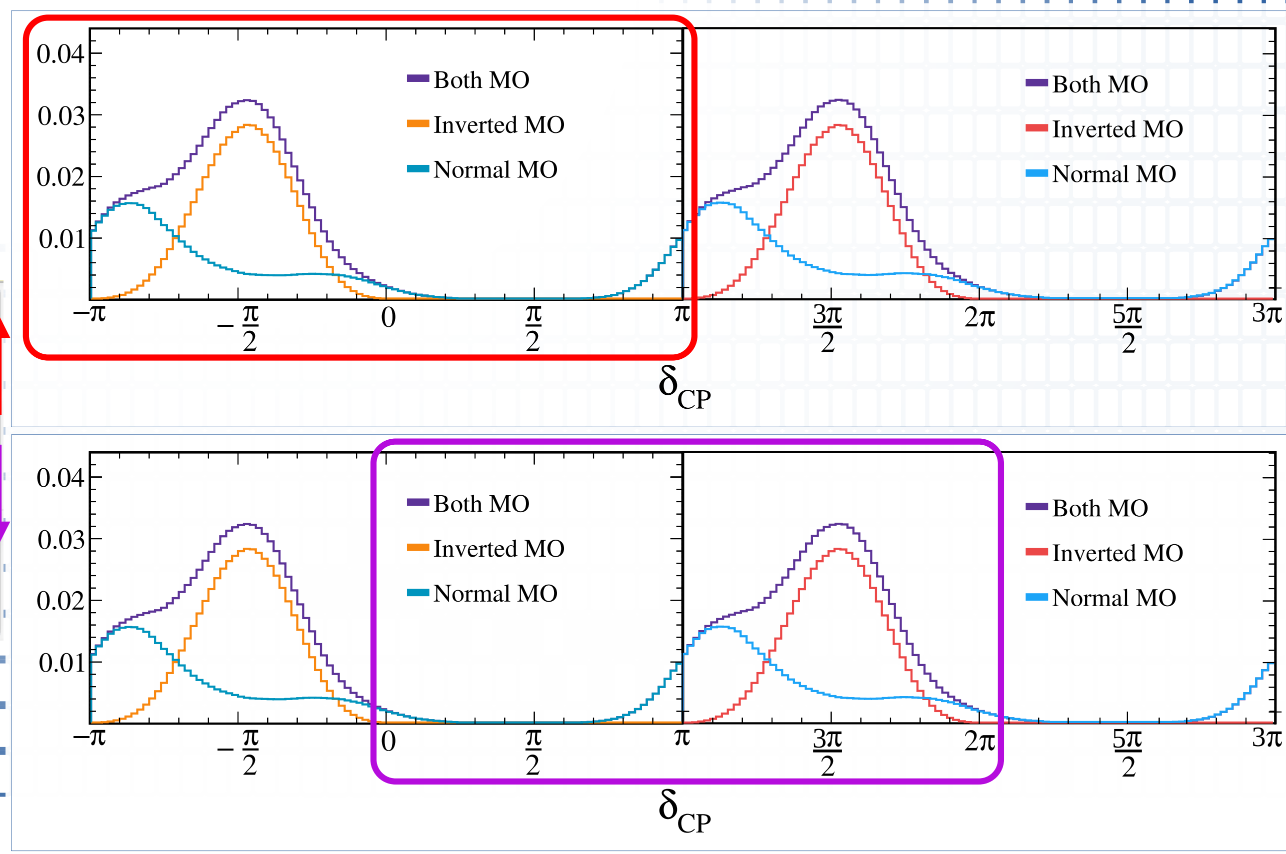
Recent NOvA-T2K Joint Fit Results

New neutrino oscillation results from NOvA with 10 years of data

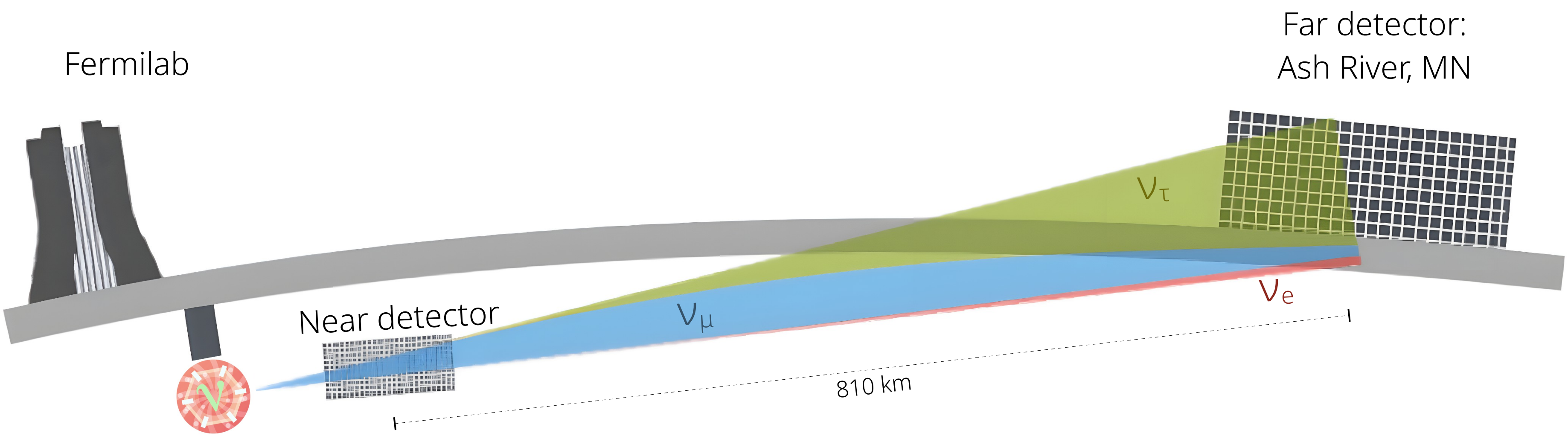
Jeremy Wolcott

3 nu current global analysis *Mariam Tórtola*

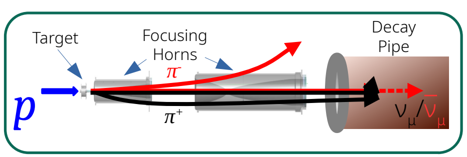
Milano 12:00 - 12:30



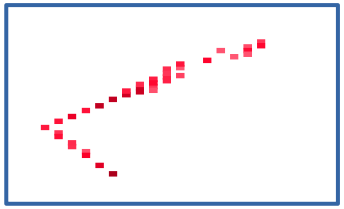
Anatomy of NOvA measurement



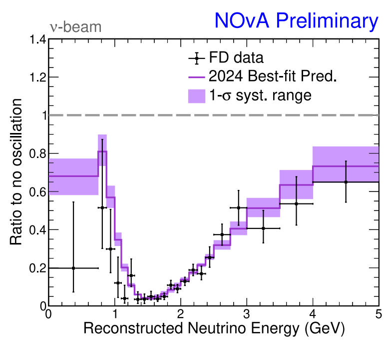
1. Make a beam of ν_μ

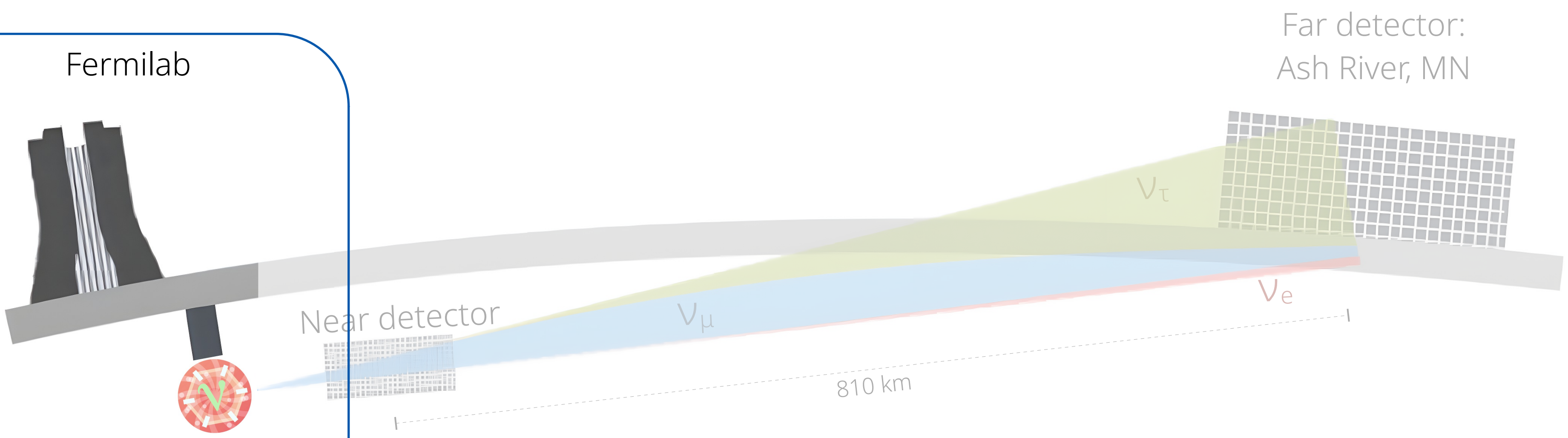


2. Select ν_μ and ν_e candidates at both detectors

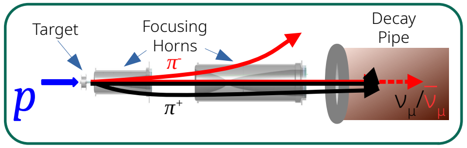


3. Interpret E_ν distributions

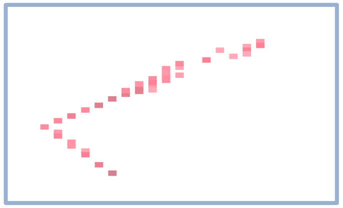




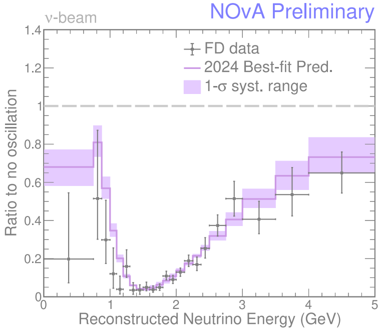
1. Make a beam of ν_μ



2. Select ν_μ and ν_e candidates at both detectors



3. Interpret E_ν distributions

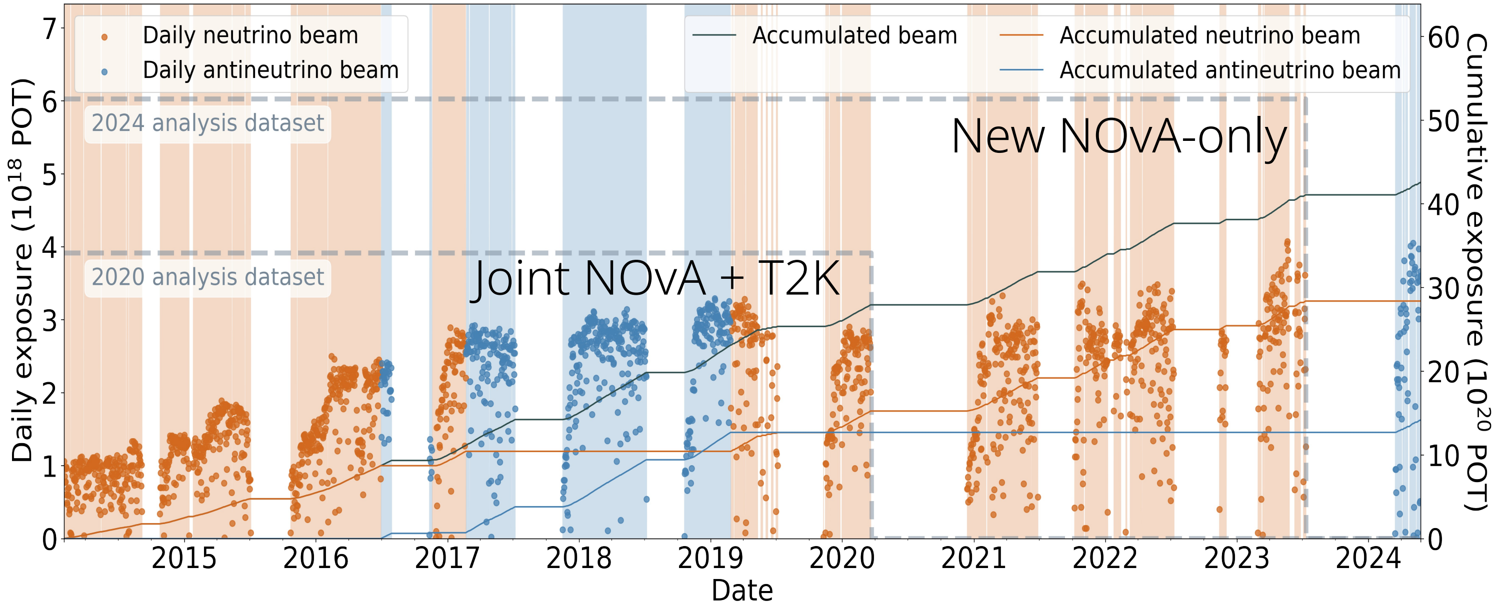


The NuMI neutrino beam

MW capable target, horn installed in 2019-2020

Approaching megawatt beam!

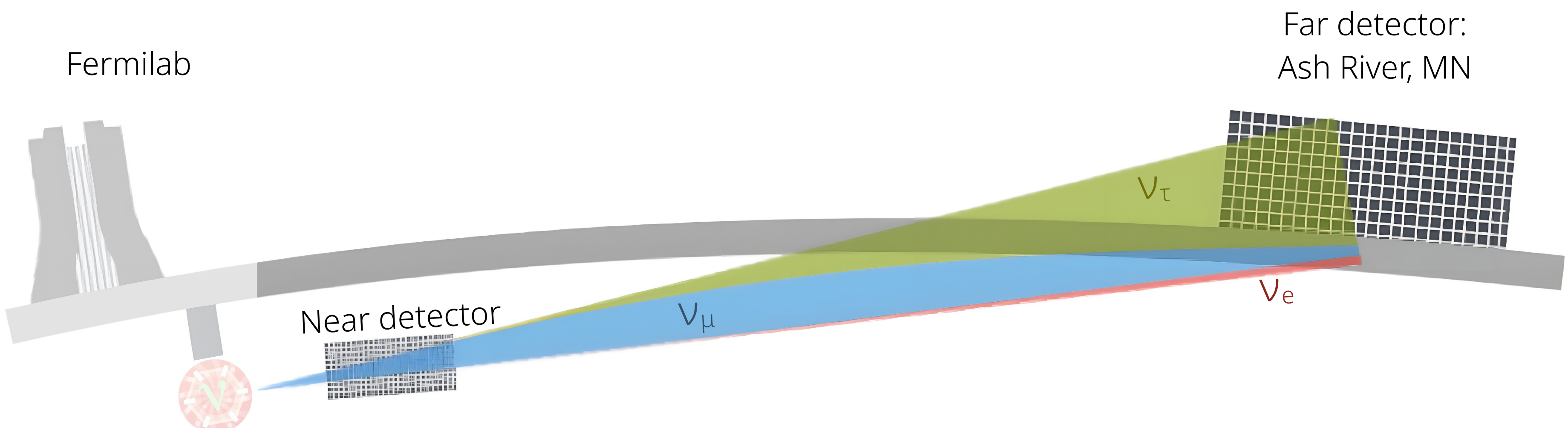
- Typically ~900 kW
- Record 959 kW



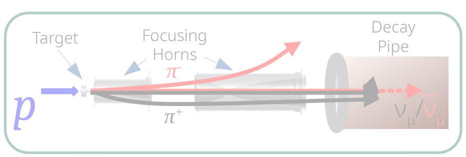
2014-2023:
10 years of beam to NOvA!

This analysis:
+96% neutrino beam

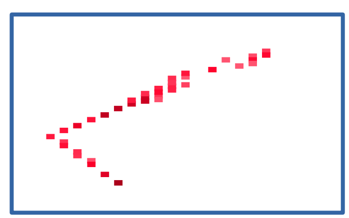
ν: 26.61×10^{20} POT
$\bar{\nu}$: 12.50×10^{20} POT



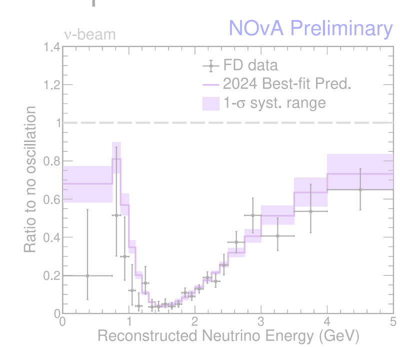
1. Make a beam of ν_μ



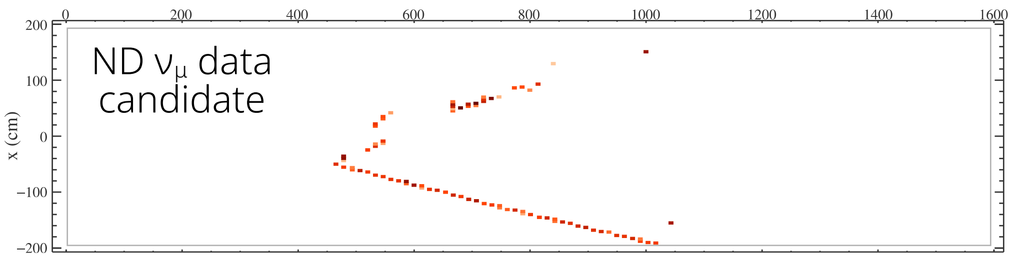
2. Select ν_μ and ν_e candidates at both detectors



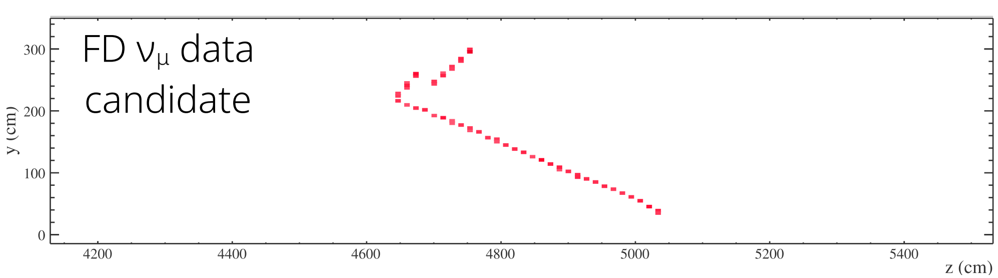
3. Interpret E_ν distributions

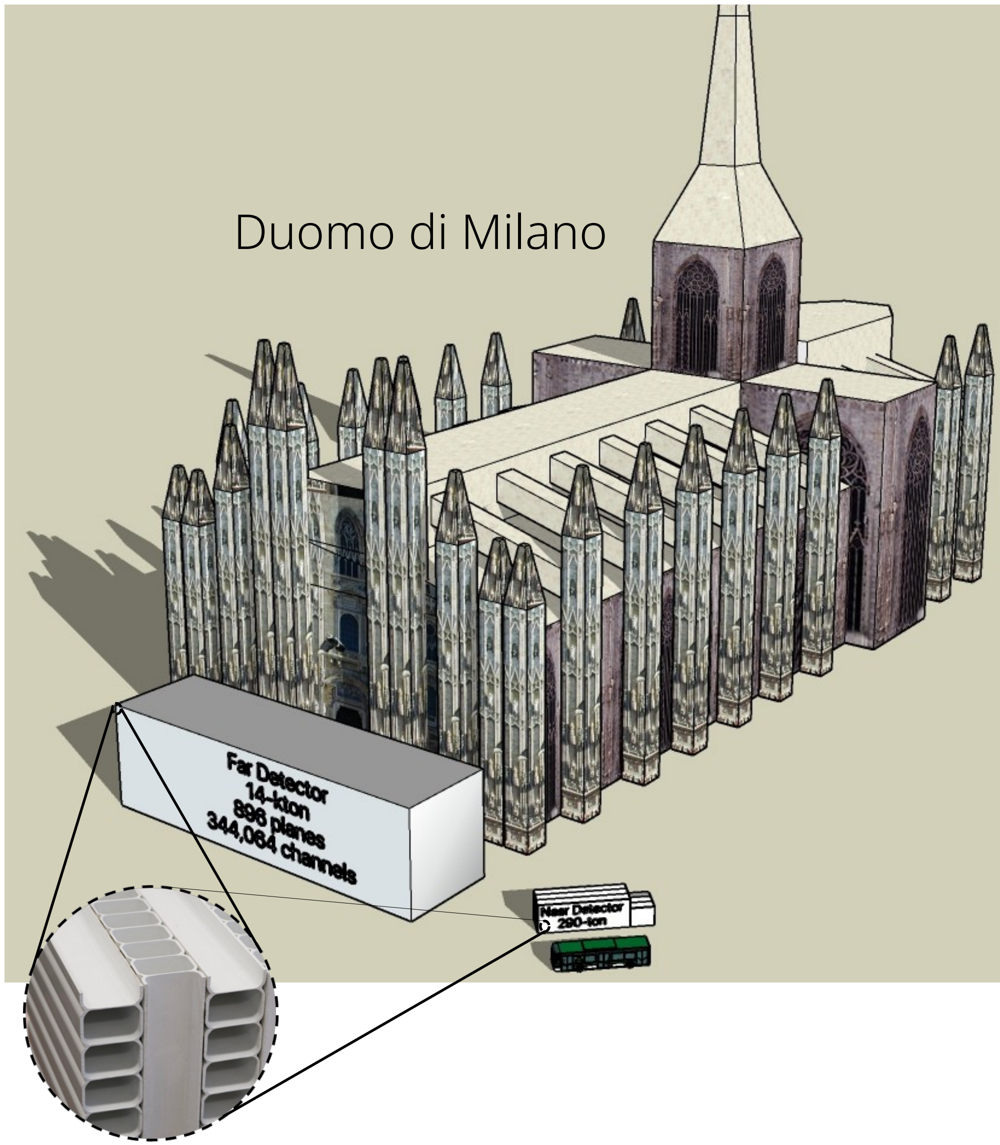


The NOvA detectors

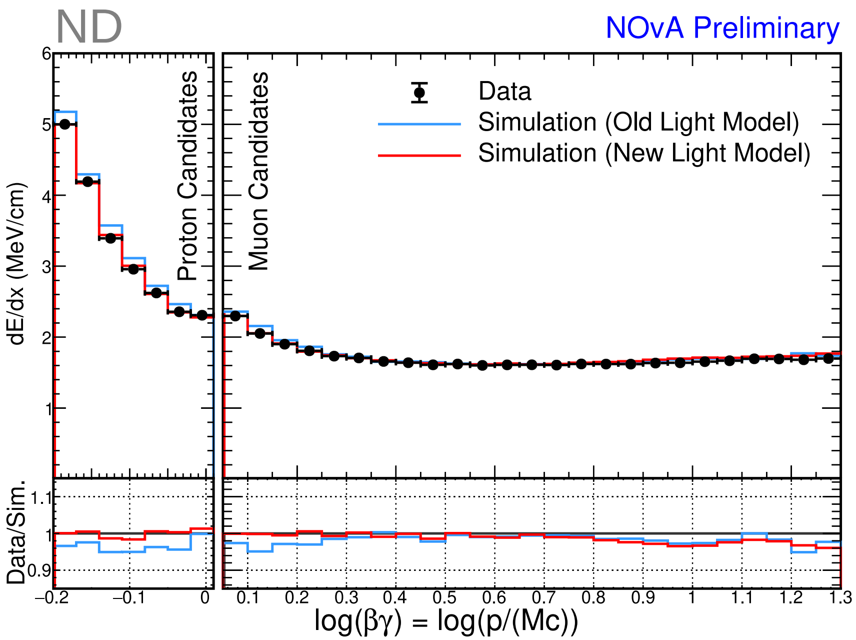


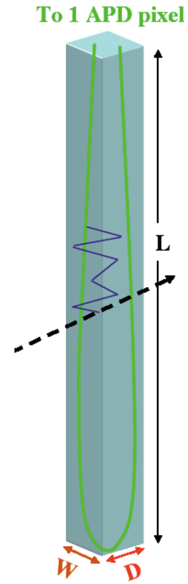
- ND & FD are **segmented liquid scintillator** detectors
  - $4{\times}6$ cm^2 PVC cells → few-cm spatial resolution
  - ~6 samples / rad. length → EM showers
  - ~60% active
  - Time resolution of ~few ns
- Detectors **differ mainly in size**:
  - ND: 290 tons, ~$4{\times}4$ m$^2 \times 16$ m
  - FD: 14,000 tons, ~$16{\times}16$ m$^2 \times 60$ m





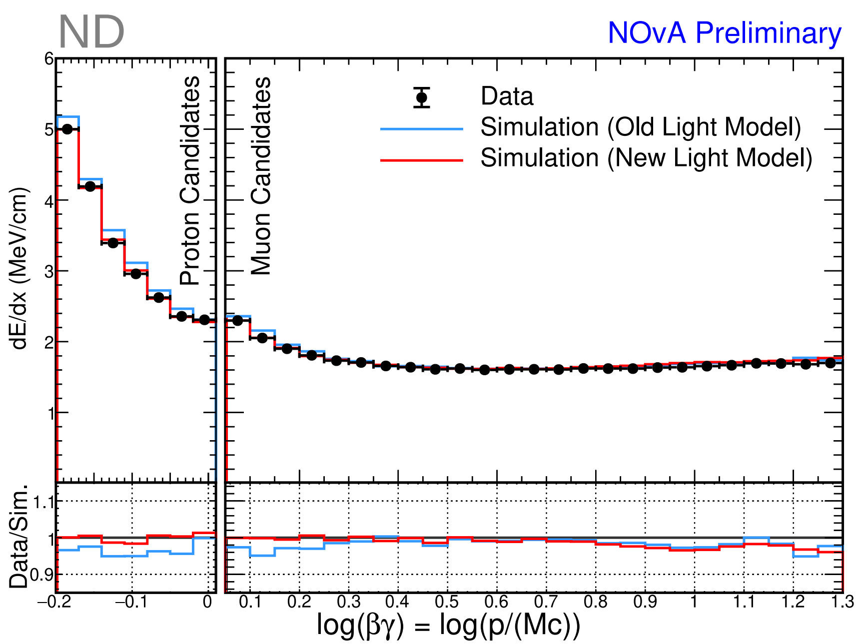
NOvA detector characterization

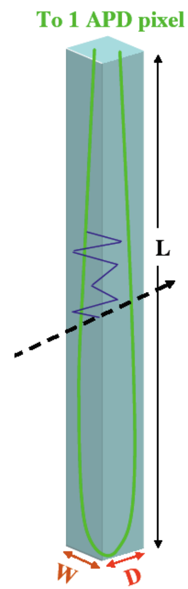




Improved light production model
(Cherenkov & scintillation)
in both detectors, from dedicated bench measurements & *in situ*
stopping muon and proton tracks

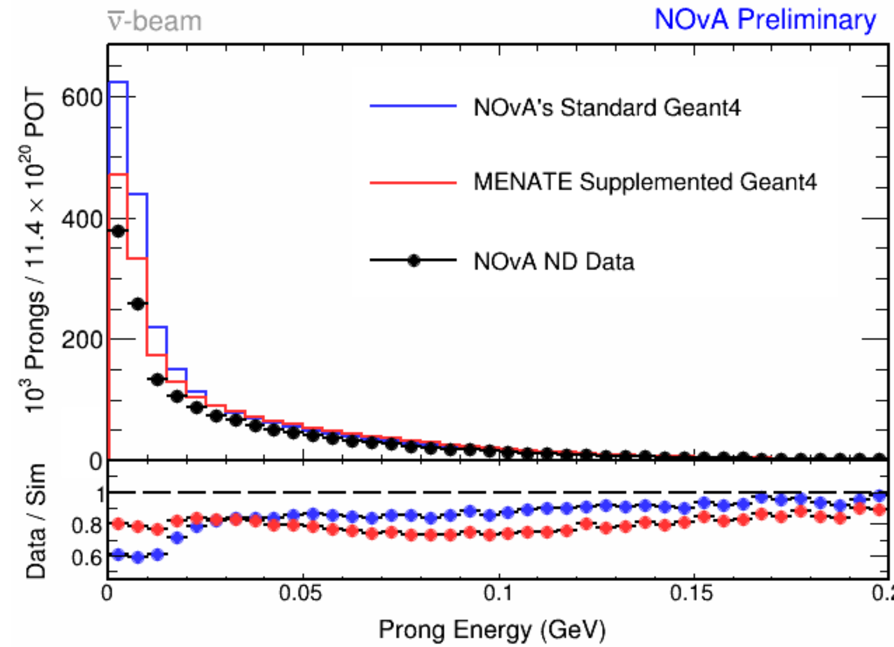
NOvA detector characterization





Improved light production model
(Cherenkov & scintillation)
in both detectors, from dedicated bench measurements & *in situ* stopping muon and proton tracks

Improved n-^{12}C inelastic scattering model



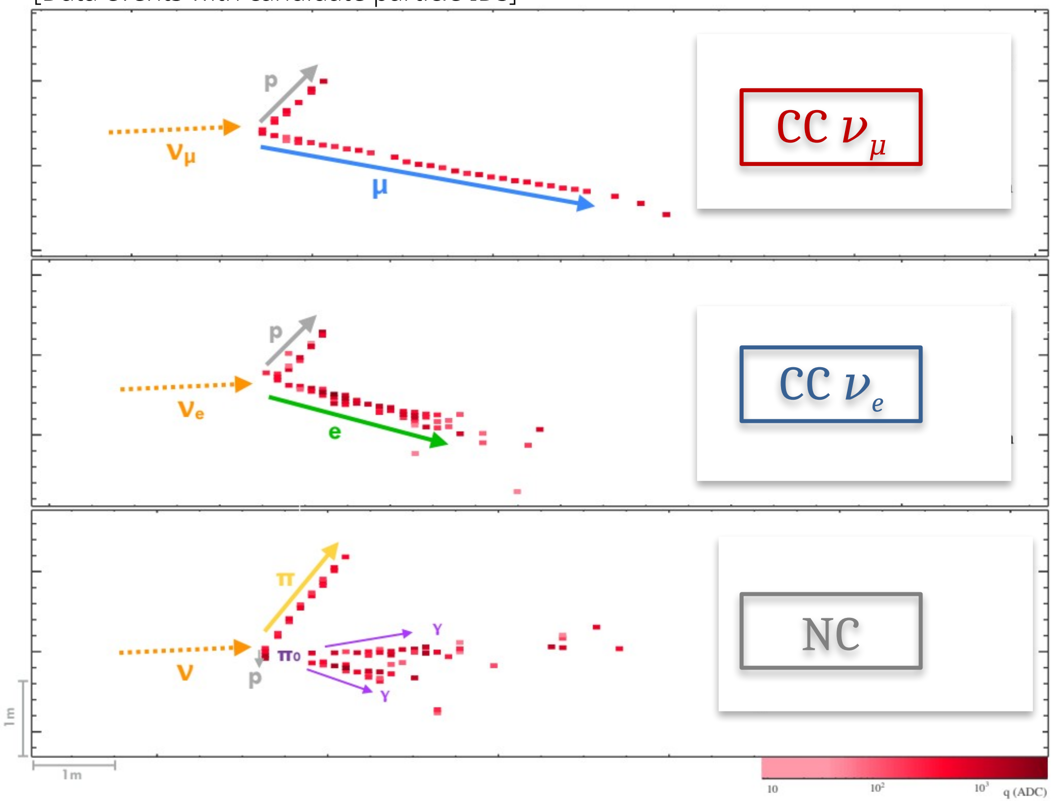
Difference between
MENATE_R* and default Geant4.10.4
informs systematic uncertainty

POSTER
403. Medium Energy Neutron Detector Response in NOvA
Andrew Sutton (Florida State Univer... , Miranda Rabelhofer
6/18/24, 5:30 PM

* P. Désesquelles, et al., NIM A307 366-373 (1991), Z. Kohley, et al., NIM A682 59-65 (2012)

Selecting ν_μ and ν_e candidates

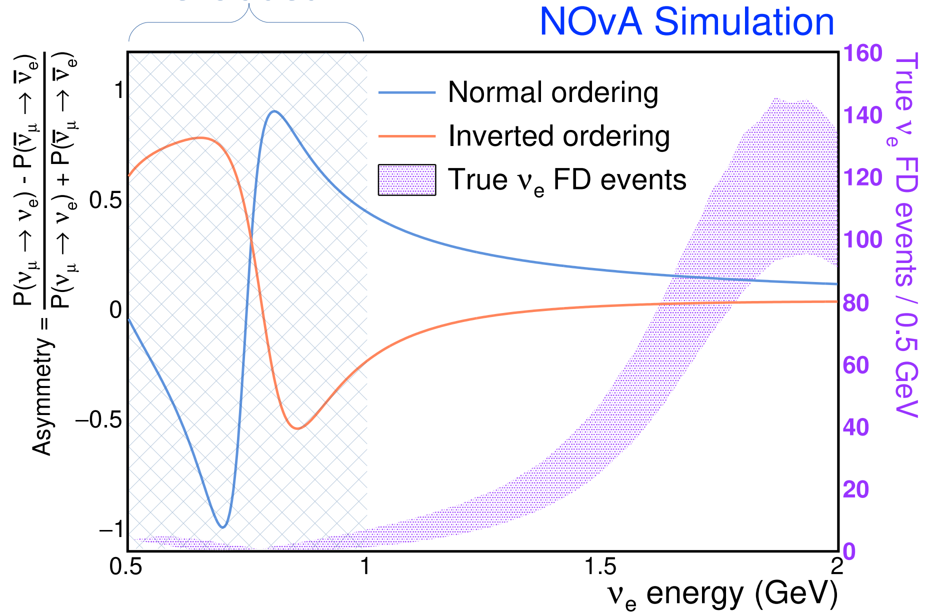
[Data events with candidate particle IDs]



- Make heavy use of **convolutional neural networks** (CNNs)
  - Cosmic rejection in FD
  - **Neutrino interaction flavor ID**
  - Particle PID
- **Performance is good**; only minor updates in 2024
- **Supplement with other classifiers** as needed
  - BDTs for cosmic rejection, selection of uncontained ν_es

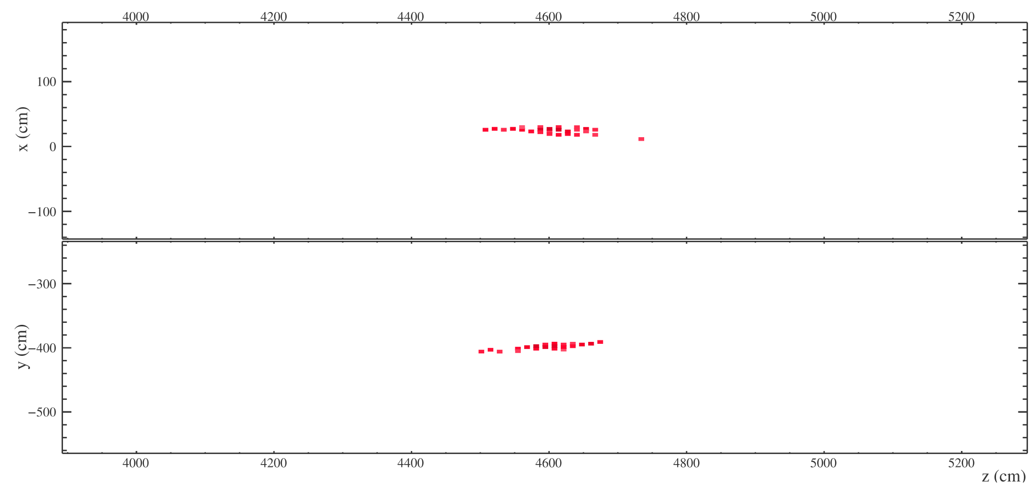
Expanding ν_e selection

Previously excluded



Maximum ordering sensitivity from ν_e–$\bar{\nu}_e$ asymmetry at lower E_ν (previous analysis had a cut reco. $E_\nu \geq 1$ GeV)

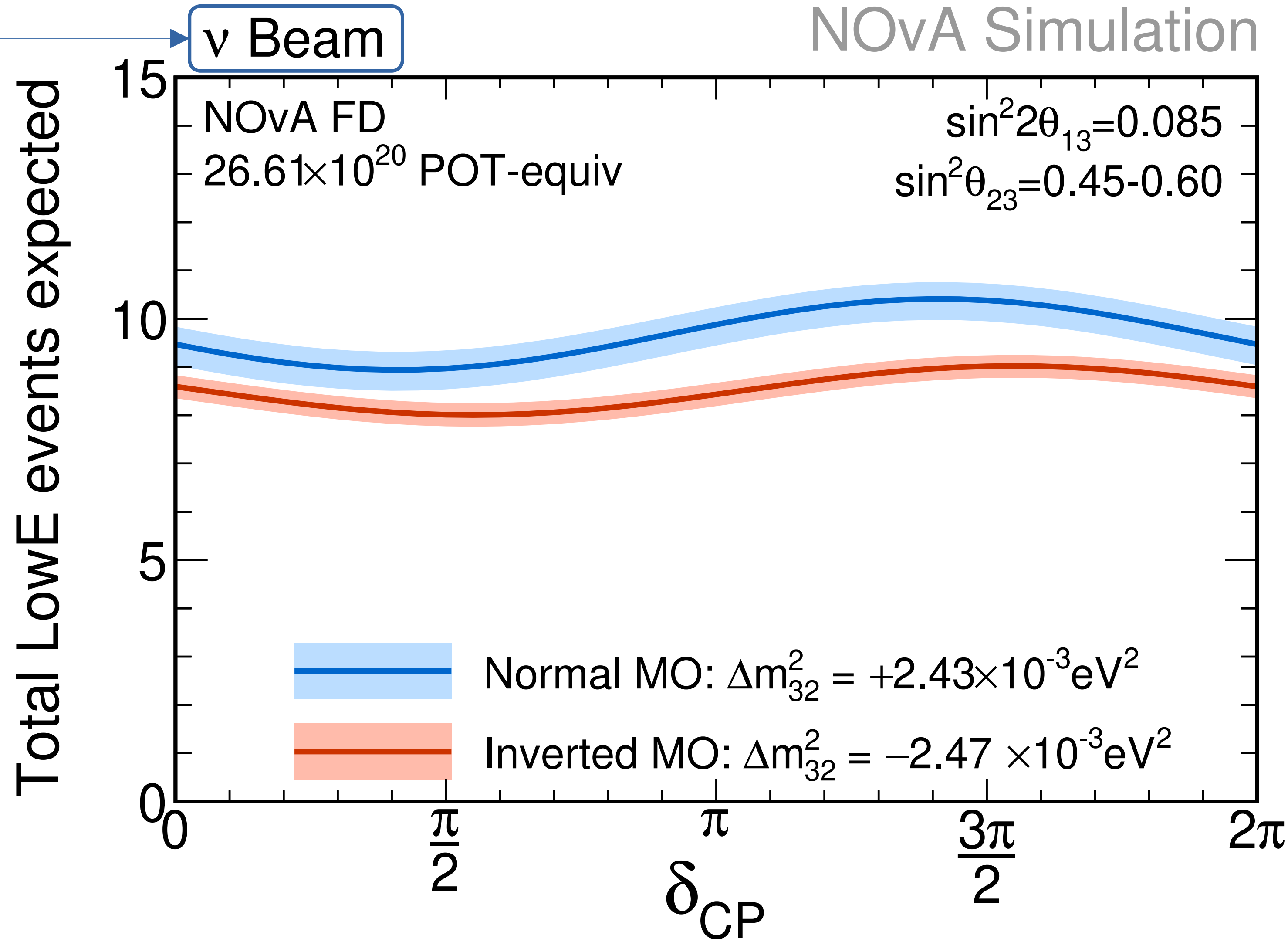
Designed new selection to retain lower-E ν_e candidates



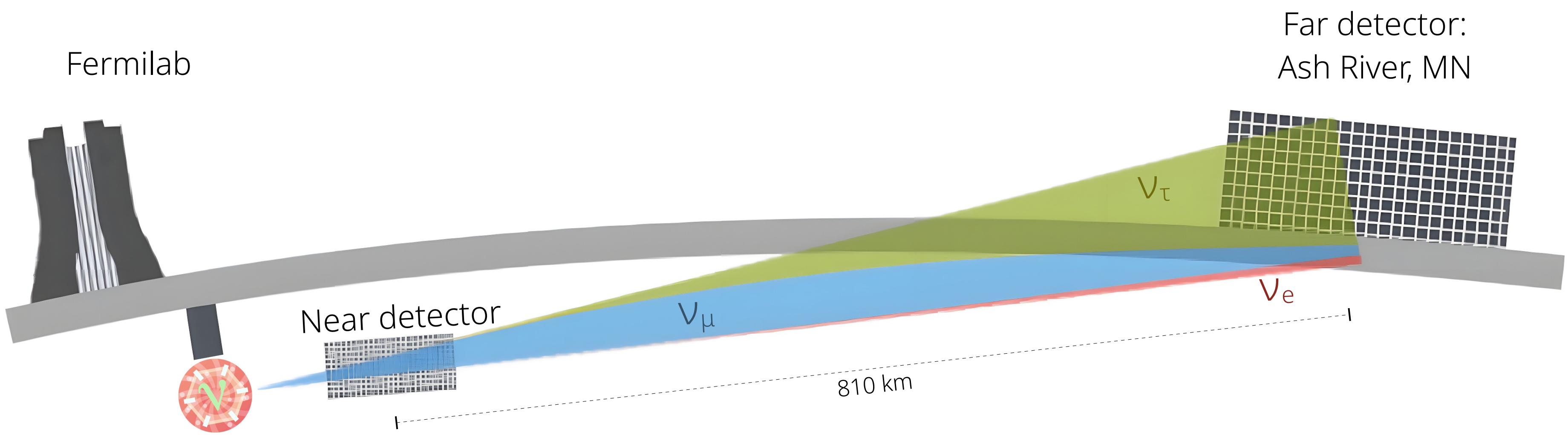
(uses BDT to reject backgrounds)

Expanding ν_e selection

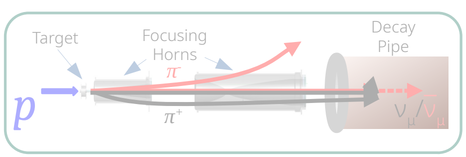
For now, ν only
(Analogous $\bar{\nu}$ sample currently too small, but future exposure gains will improve sensitivity to asymmetry)



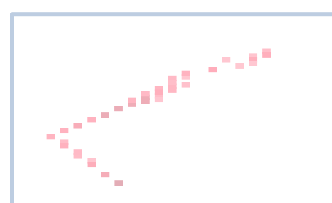
Increases mass ordering sensitivity by ~few %
(depends on oscillation parameters)



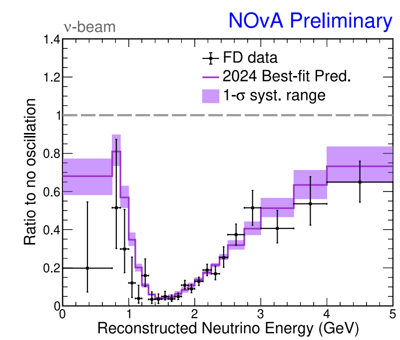
1. Make a beam of ν_μ



2. Select ν_μ and ν_e candidates at both detectors

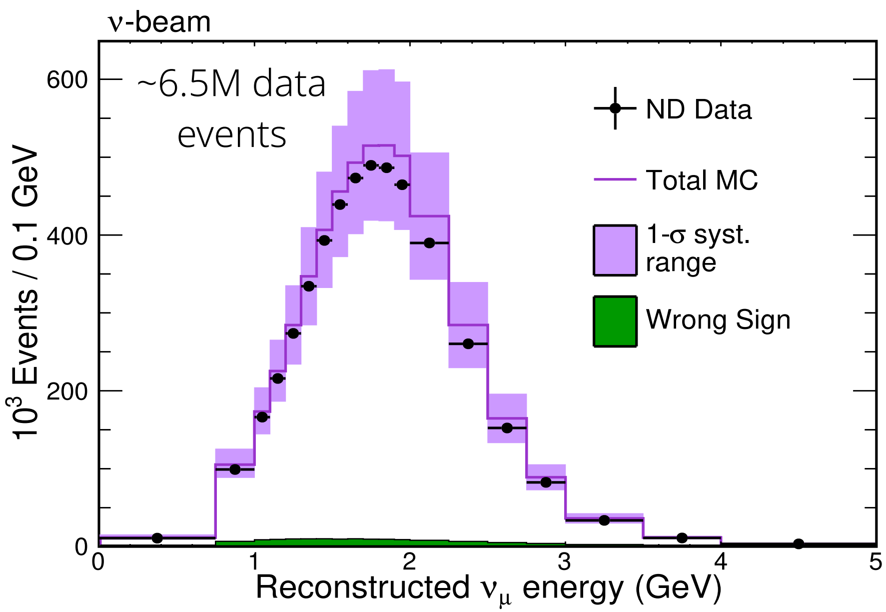


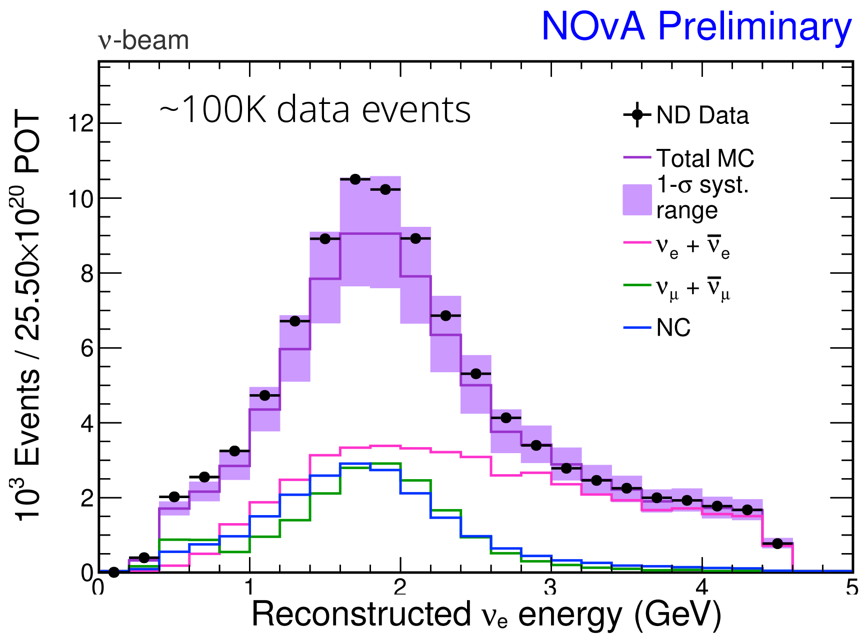
3. Interpret E_ν distributions



Near detector observations

ND spectra reflect *unoscillated* beam





ν_μ candidates

correspond to FD ν_μ *and* ν_e signal

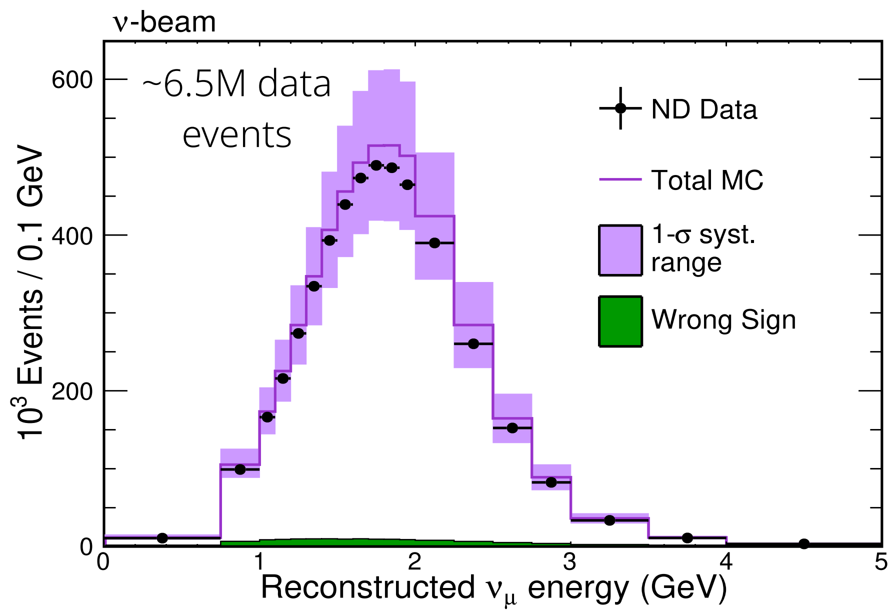
ν_e candidates

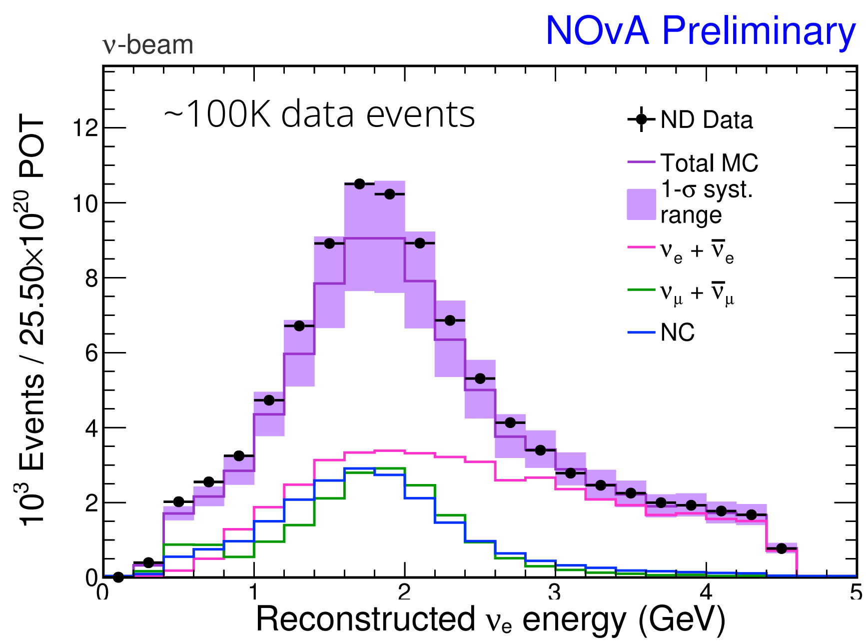
correspond to FD ν_e backgrounds

Dominated by beam ν_e (irreducible):
~50% for ν, ~70% for $\bar{\nu}$

Near detector observations

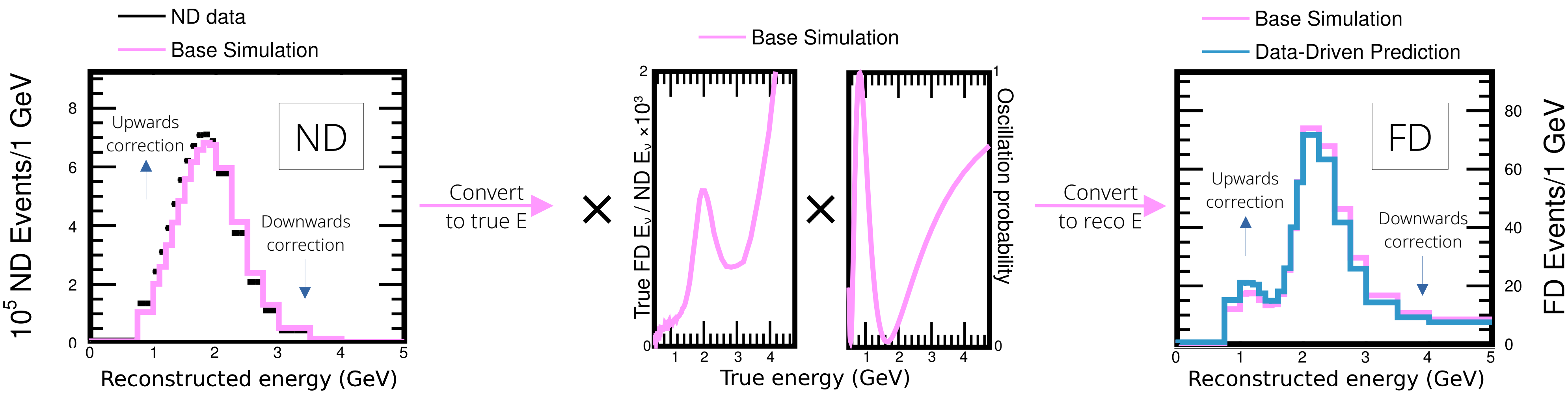
Uncertainties on single-detector measurements are large...





... but ND data forms basis for model correction & constraint

Constraining predictions

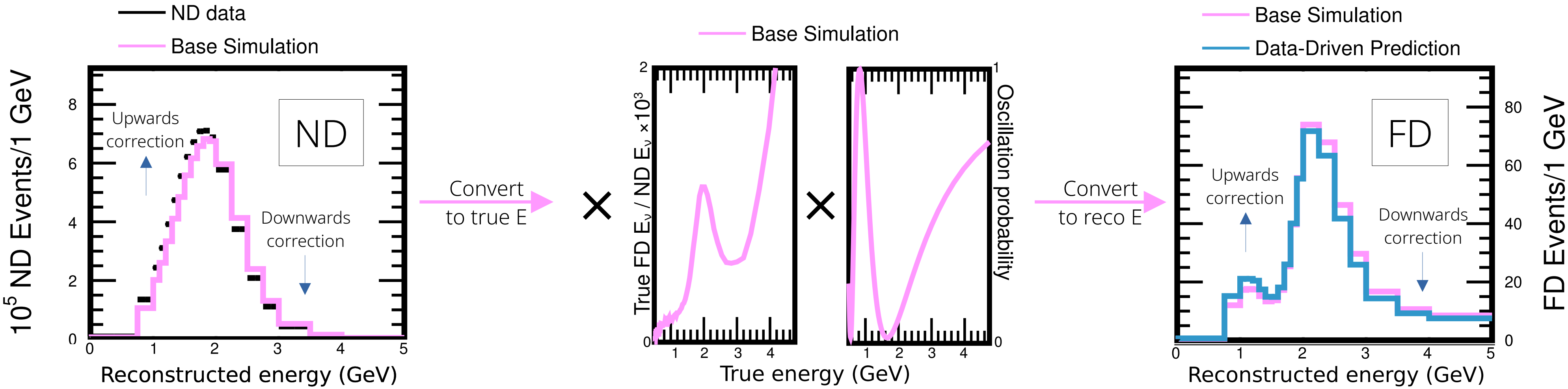


Correcting ND simulation
to agree with data in reco E_ν…

… **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

Constraining predictions



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

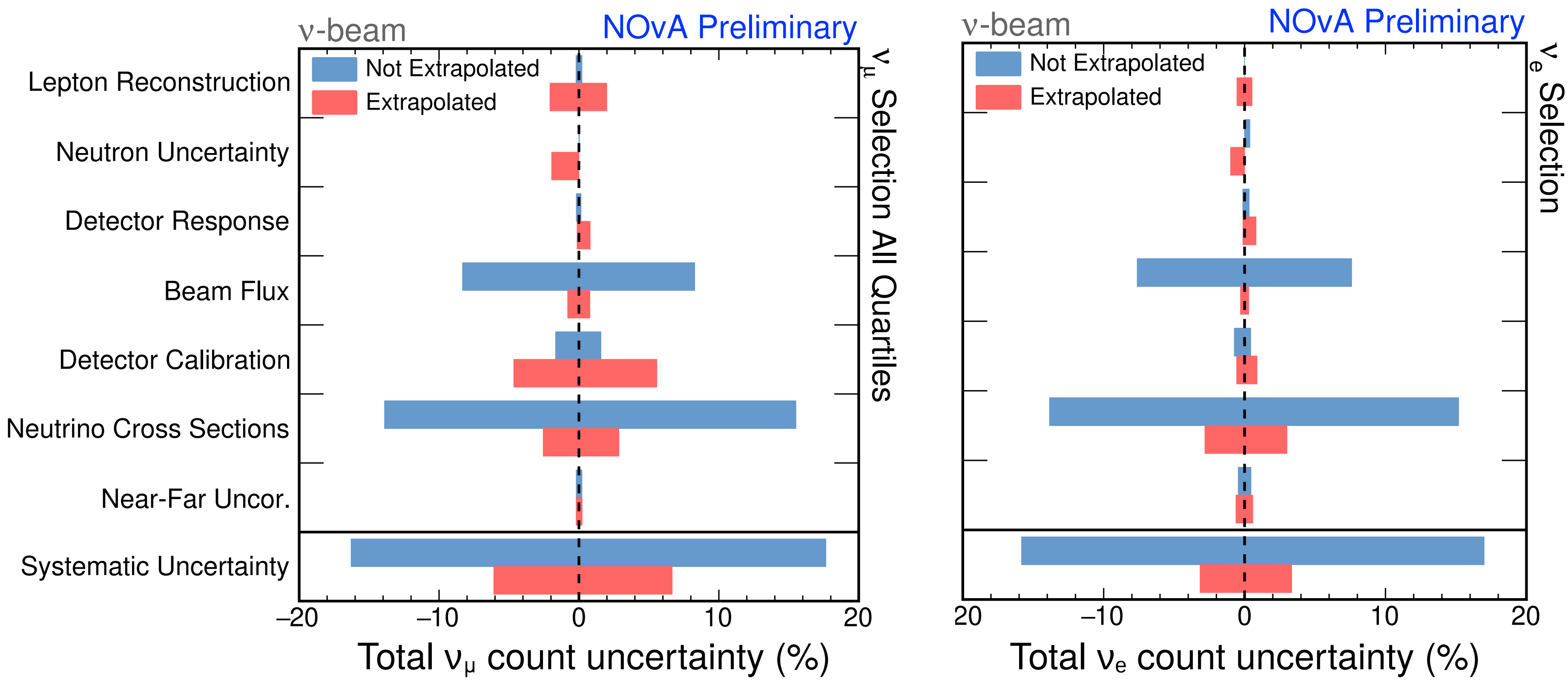
Constrain nominal prediction *and* effect of systematic uncertainties

- Shift *all* elements of sim., then redo constraint
- Since post-correction all variations forced to agree at ND, spread at FD is reduced
- Effects that are not shared between detectors unaffected, or increase in some cases (e.g.: calibration)

Subdivide or use different samples to better account for ND/FD differences:

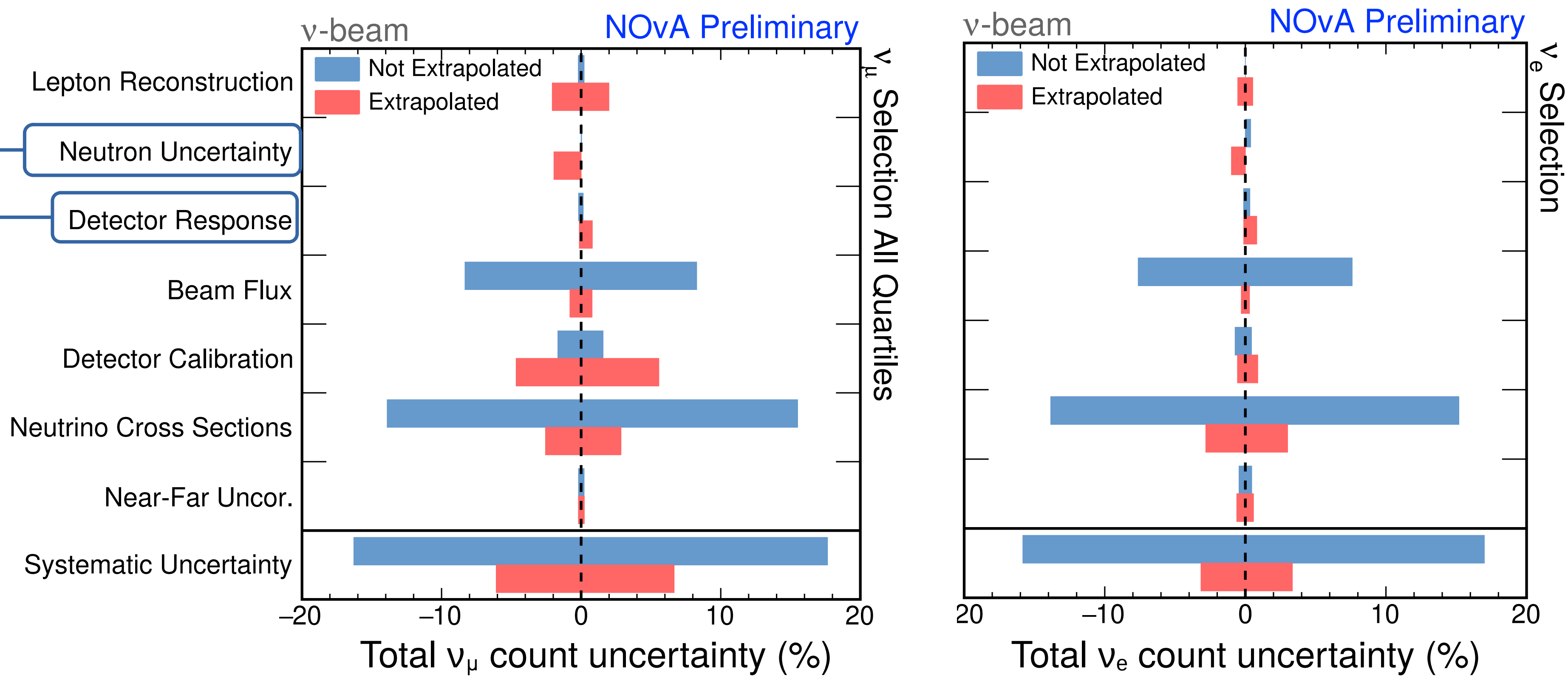
- **ν_μ: differences in resolution, acceptance**
  subdivide by E_{had}/E_ν × |p_t| [12 bins]
- **ν_e bknds: different oscillation behavior**
  constrain νs' parent π and K (beam ν_e);
  subdivide by Michel electron multiplicity (ν_μ, NC)

Systematic uncertainties



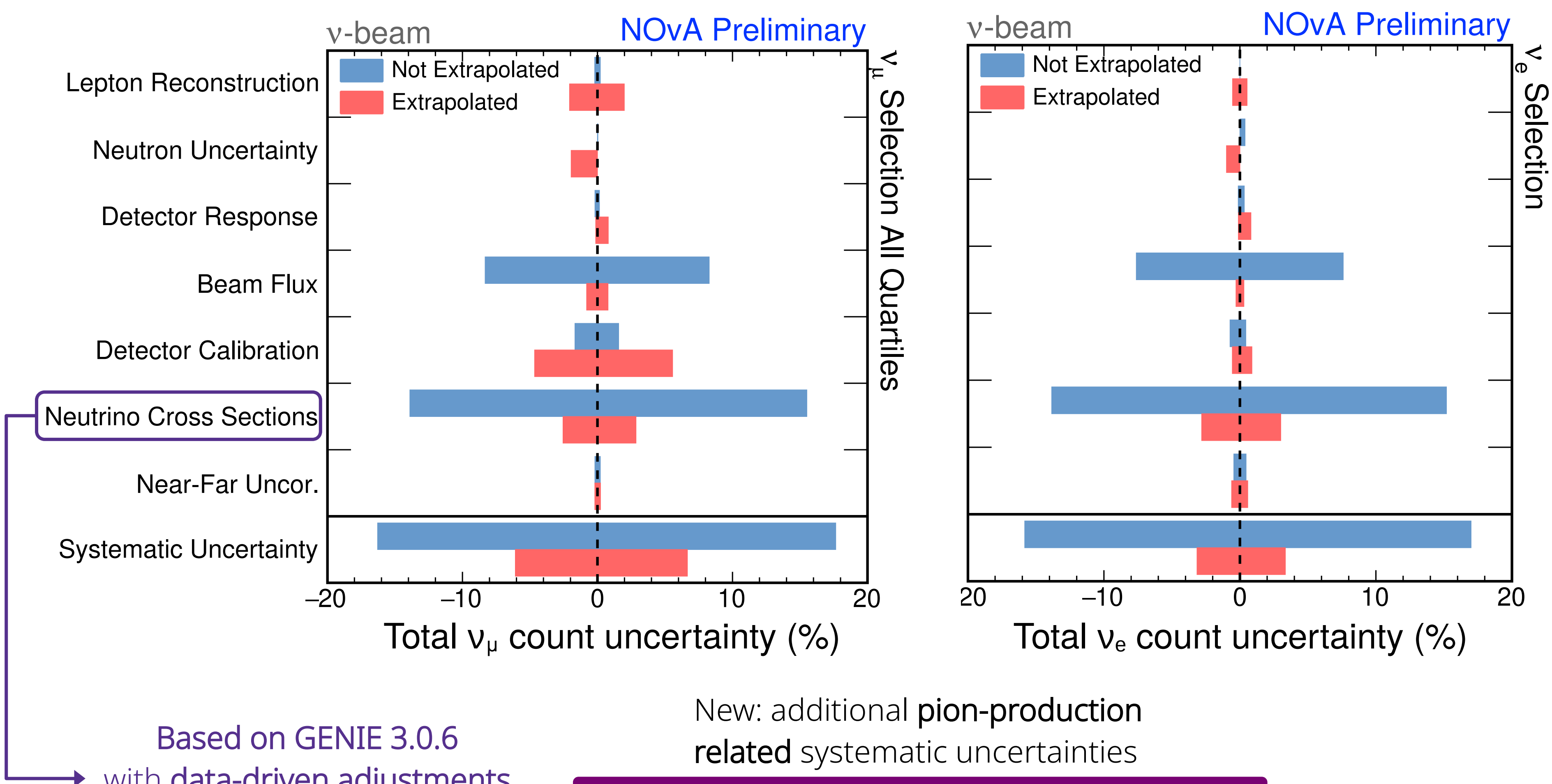
Systematic uncertainties

Include **improvements to light, neutron propagation models** mentioned previously



POSTER
403. Medium Energy Neutron Detector Response in NOvA
Andrew Sutton (Florida State Univer... , Miranda Rabelhofer
6/18/24, 5:30 PM

Systematic uncertainties

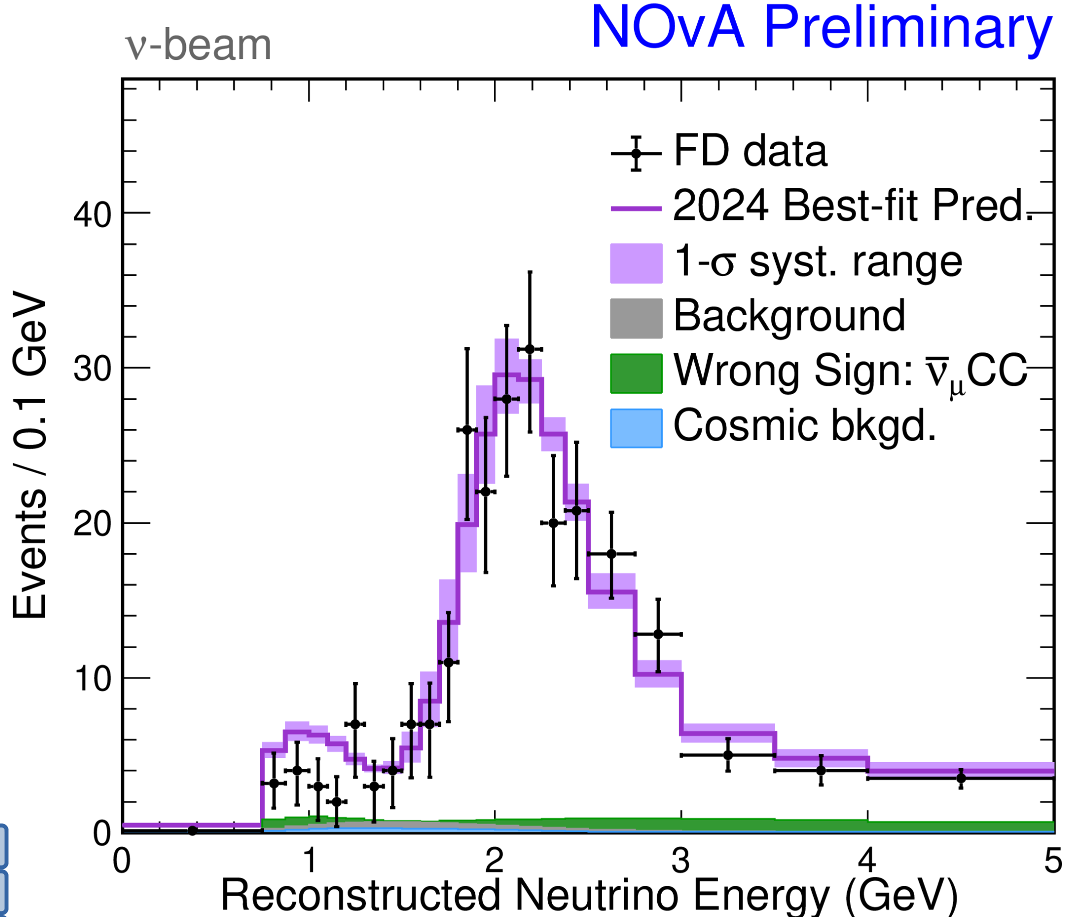


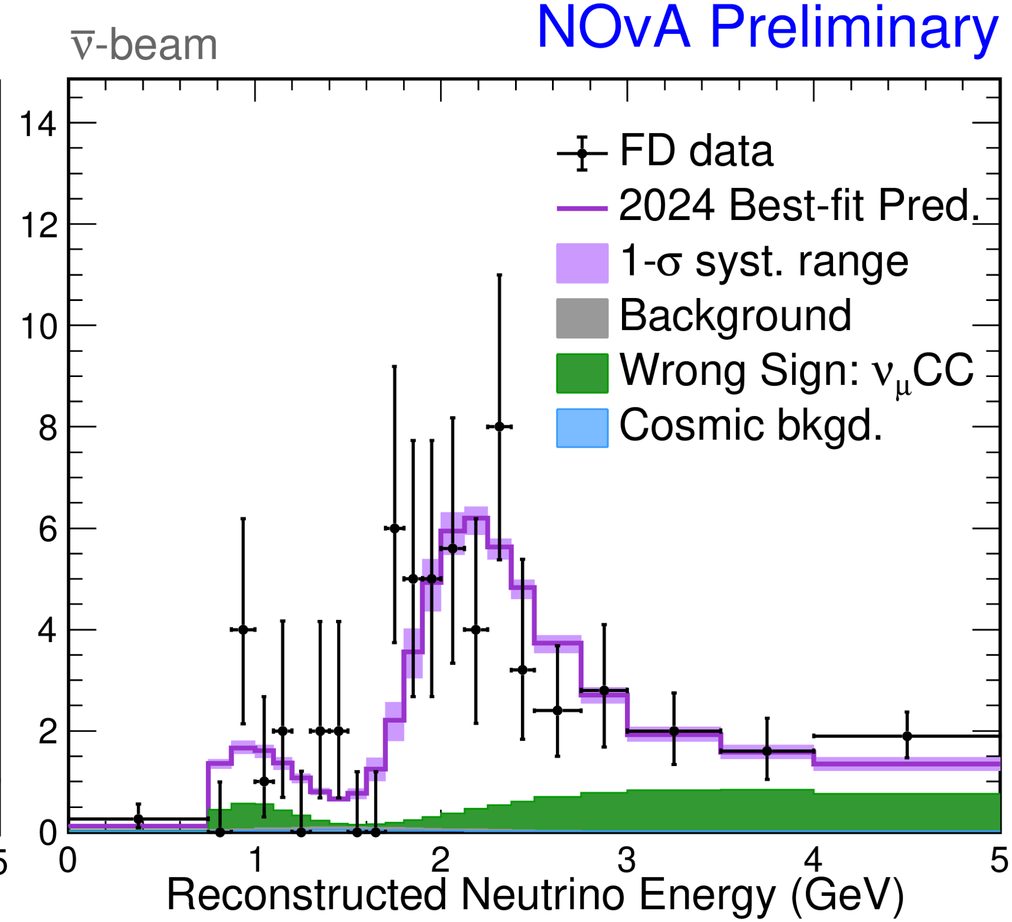
Based on GENIE 3.0.6
with **data-driven adjustments**
(see overflow slides)

New: additional **pion-production related** systematic uncertainties

POSTER
415. New RES and DIS uncertainties for NOvA cross-section model
Maria Martinez Casales (Fermilab), Michael Dolce
6/18/24, 5:30 PM

Far detector observations: ν_μ



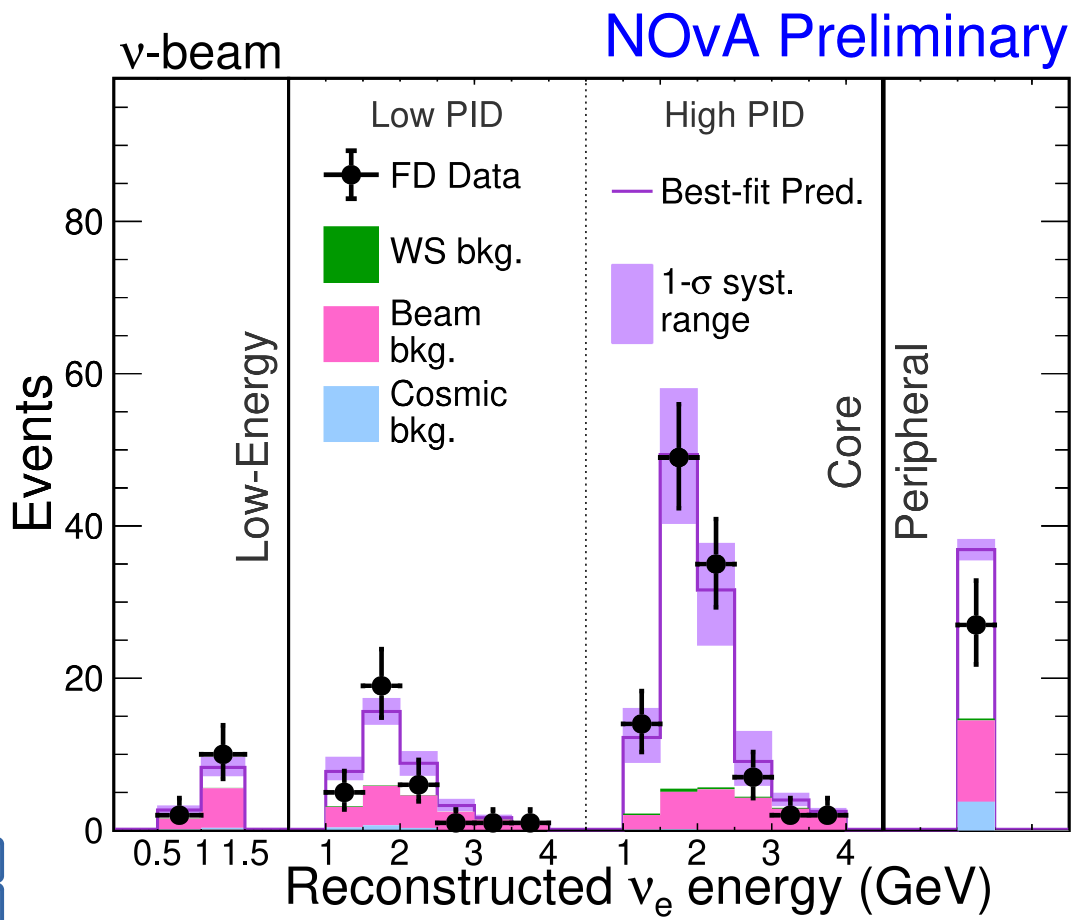


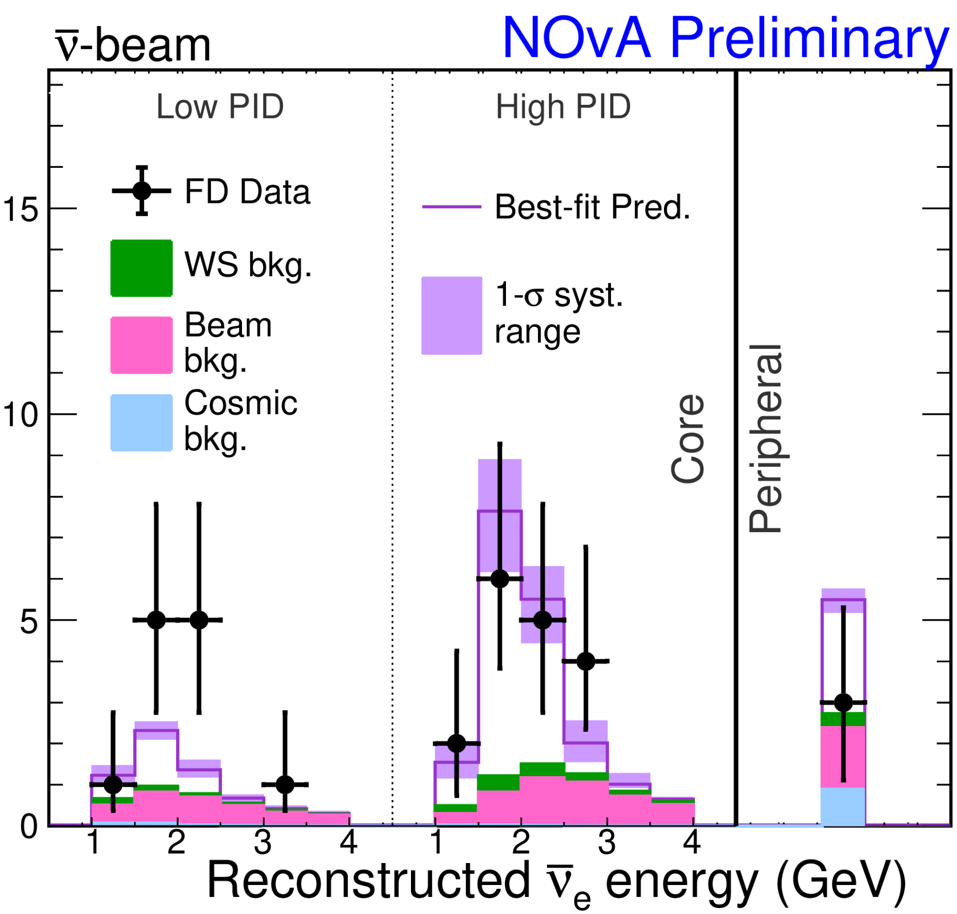
384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

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

Far detector observations: ν_e





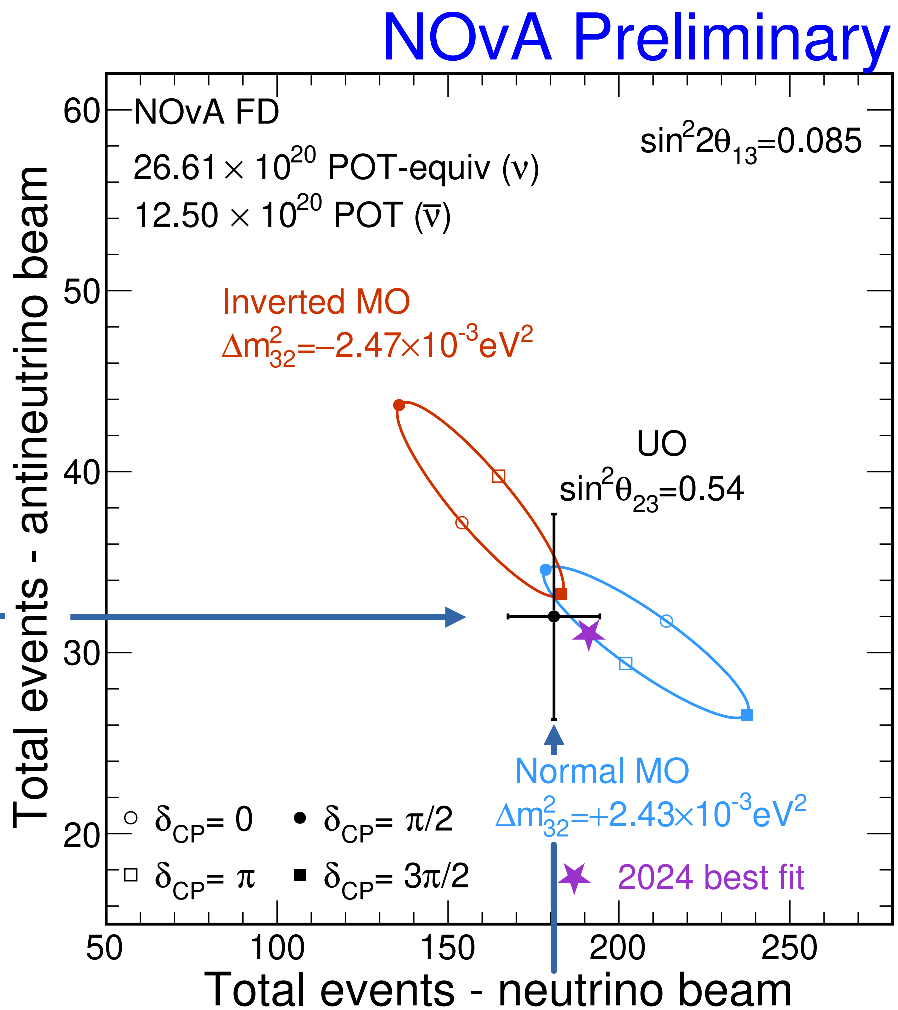
181 ν_e data candidates

	Best fit	Range
Total pred	186.2	119 – 250
Wrong-sign	1.8	1.6 – 2.8
Beam bknd.	53.7	
Cosmic bknd.	6.2	
Total bknd	61.7	61 – 63

32 $\bar{\nu}_e$ data candidates

	Best fit	Range
Total pred	30.4	28 – 38
Wrong-sign	2.1	1.0 – 3.2
Beam bknd.	9.0	
Cosmic bknd.	1.1	
Total bknd	12.2	11 – 13

Far detector observations: ν_e



32 $\bar{\nu}_e$ data candidates

181 ν_e data candidates

Data favors region where **matter & CP violation effects oppose one another**

Future $\bar{\nu}$ data will be critical for disentangling

Extracting oscillation parameters

Goal:

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

Extracting oscillation parameters

Bayesian
Markov Chain
Monte Carlo
(marginalization)
(technique described in arXiv:2311.07835)

Frequentist
χ^2 minimization
(profiled
Feldman-Cousins)
(technique described in
arXiv:2207.14353)

Bayesian credible regions → Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP} ← frequentist confidence regions

POSTER
450. Bayesian Fit for the NOvA Three Flavor Oscillation Analysis
Ben Jargowsky (University Of Califor..., Liudmila Kolupaeva
6/18/24, 5:30 PM

POSTER
456. Determination of the neutrino oscillation parameters through the unified approach of Feldman and Cousins by the NOvA Experiment
Mr Andrew Dye (The University of Mi..., Mr Luiz R. Prais (The University of Mi...
6/18/24, 5:30 PM

Extracting oscillation parameters

Bayesian
Markov Chain Monte Carlo
(marginalization)
(technique described in arXiv:2311.07835)

→ Bayesian credible regions

Frequentist
χ^2 minimization
(profiled Feldman-Cousins)
(technique described in arXiv:2207.14353)

→ frequentist confidence regions

Bayesian credible regions → Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP} ← frequentist confidence regions

Consider three θ_{13} possibilities:

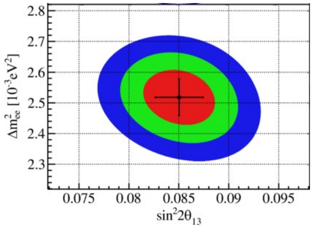
θ_{13} unconstrained (NOvA only)

or

Daya Bay 1D θ_{13} constraint
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

or

Daya Bay 2D (Δm^2_{32}, θ_{13}) constraint

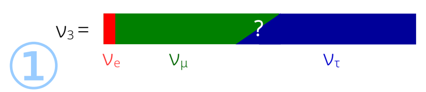


PRL 130, 161802

Other mixing parameters:

$\sin^2\theta_{12} = 0.307$ (PDG 2023)
$\Delta m^2_{21} = 7.53\times10^{-5}$ eV^2 (PDG 2023)
$\rho = 2.74$ g/cm^3 (CRUST1.0)

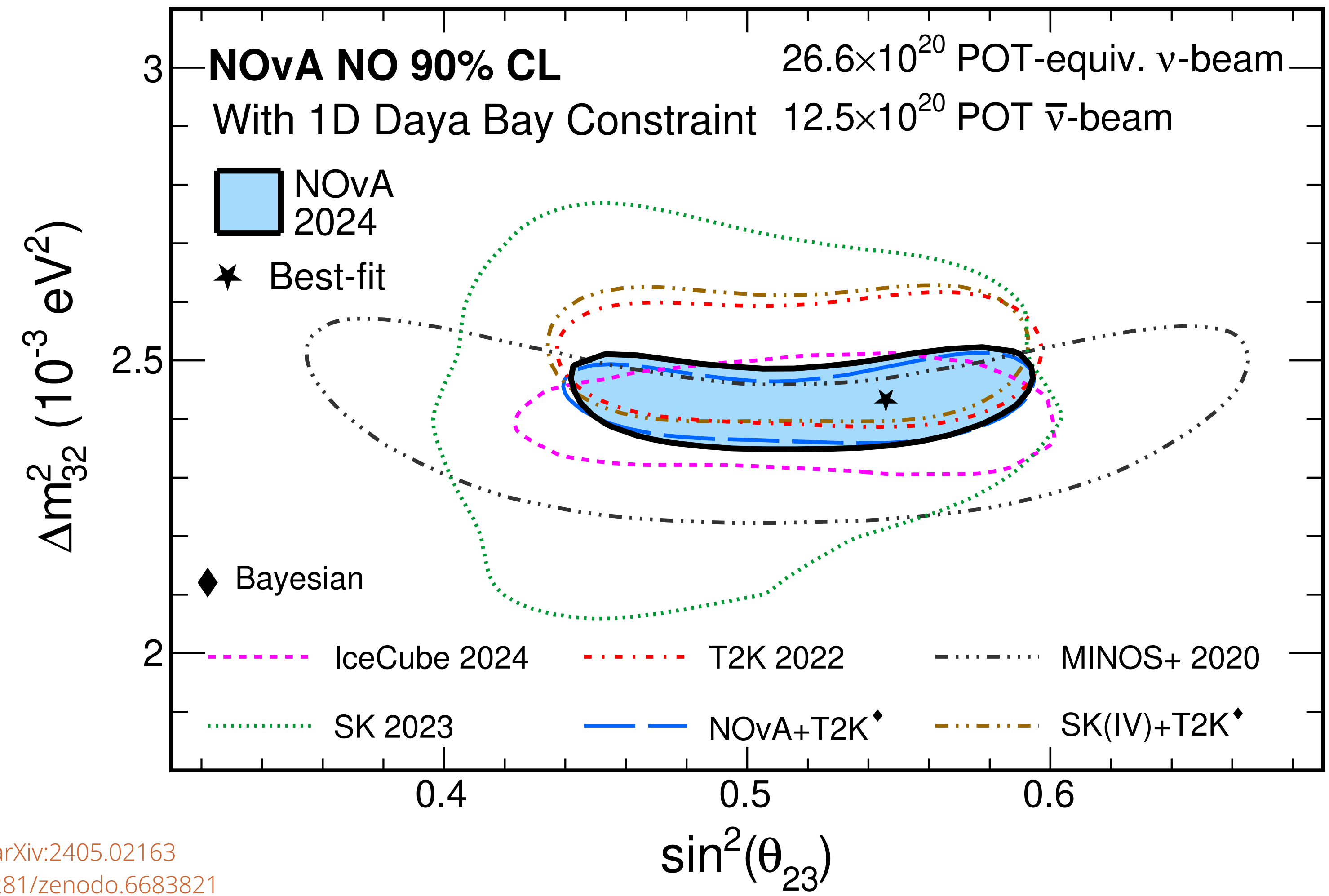
Oscillation parameter results



Is $\theta_{23} = 45°$?
Do ν_μ/ν_τ **mix equally** into ν_3?

$\nu_2 - \nu_3$ sector

NOvA Preliminary

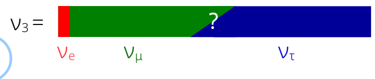


IceCube 2024: arXiv:2405.02163
T2K 2022: 10.5281/zenodo.6683821
MINOS+ 2020: Phys. Rev. Lett. 125, 131802
SK 2023: Phys. Rev. D109, 072014
NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar
T2K+SK 2024: arXiv:2405.12488

(Frequentist) best fit:

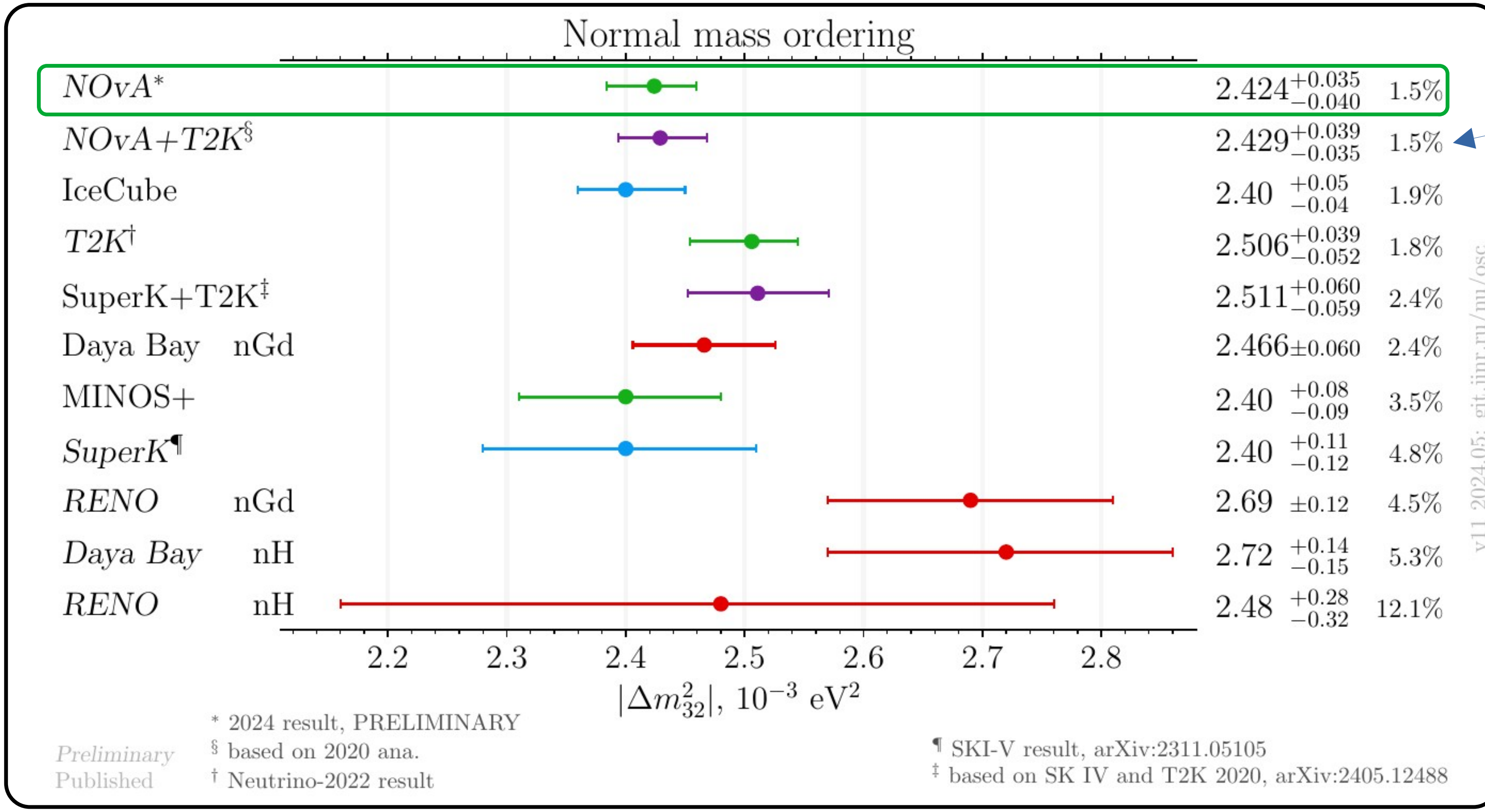
$$\Delta m^2_{32} = \left(+2.433^{+0.035}_{-0.036}\right) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.546^{+0.032}_{-0.075}$$

① 

Is θ_{23} = 45°?
Do ν_μ/ν_τ **mix equally** into ν_3?

$\nu_2 - \nu_3$ sector

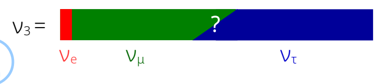


Note: 1.4% shown previously was for IO (NOvA-T2K preference); NO shown here according to NOvA-only preference

Squeezing precision on Δm^2_{32} (1.5%).
Most precisely known PMNS parameter!

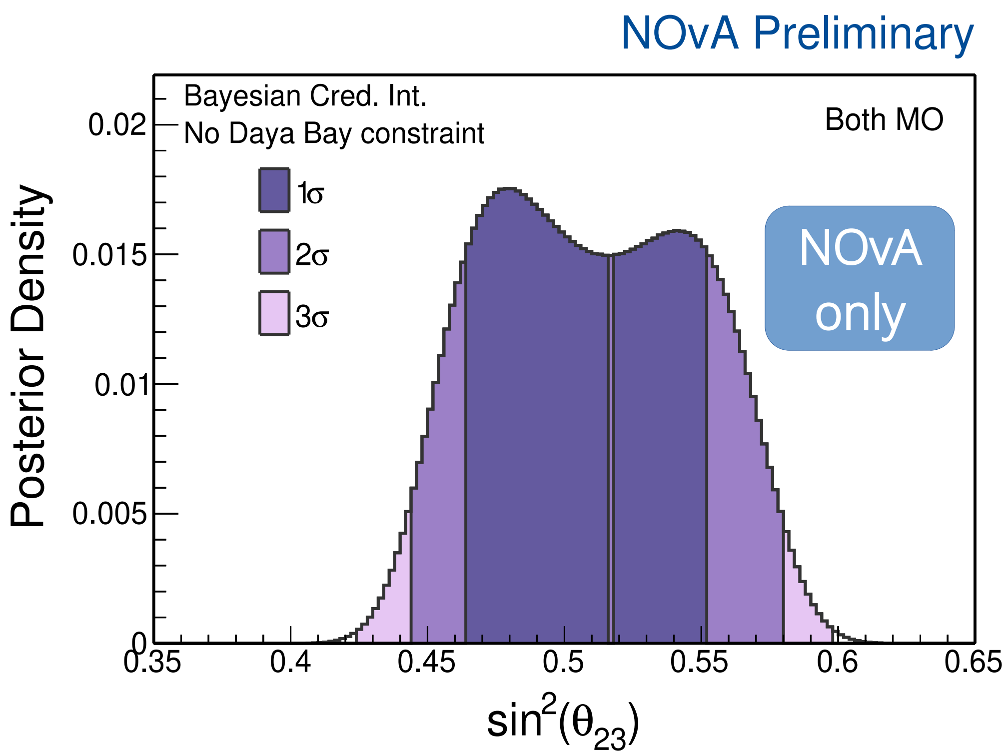
*Note: NOvA 2024 Bayesian range differs slightly from frequentist one on previous page

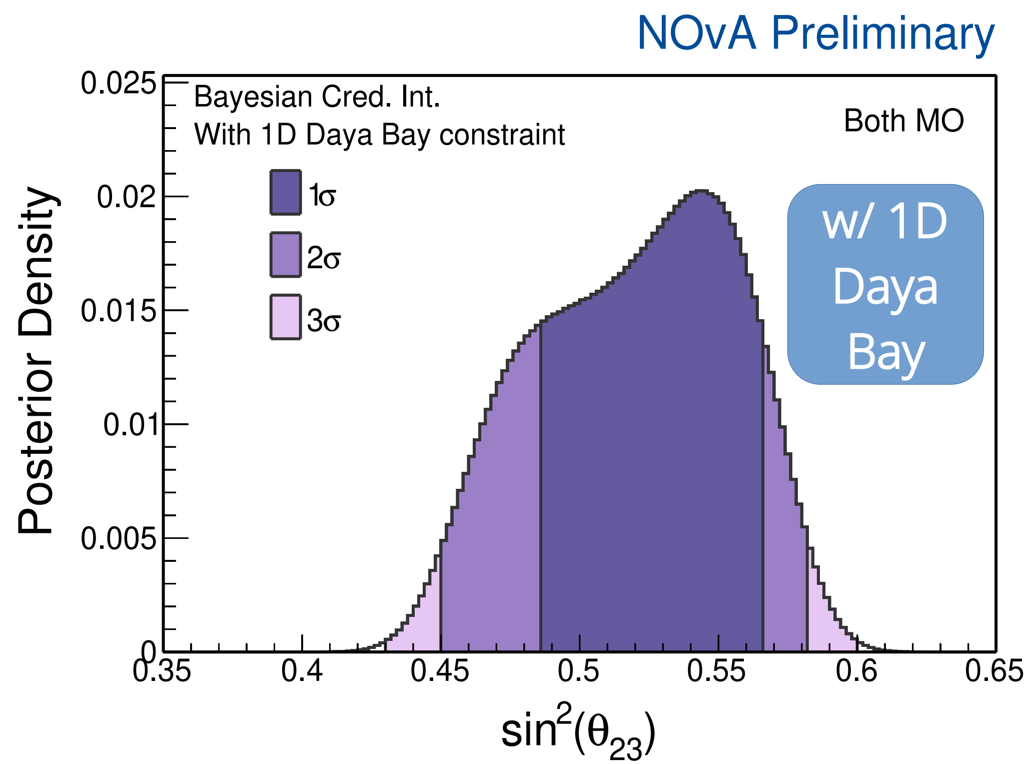
①



Is $\theta_{23} = 45°$?
Do ν_μ/ν_τ mix equally into ν_3?

$\nu_2 - \nu_3$ sector





Mild Upper Octant preference
(69% prob; Bayes factor = 2.2)
emerges from applying reactor constraint
(due to correlation between θ_{13} and θ_{23}, see overflow)

Maximal mixing is allowed at $<1\sigma$

NO vs IO

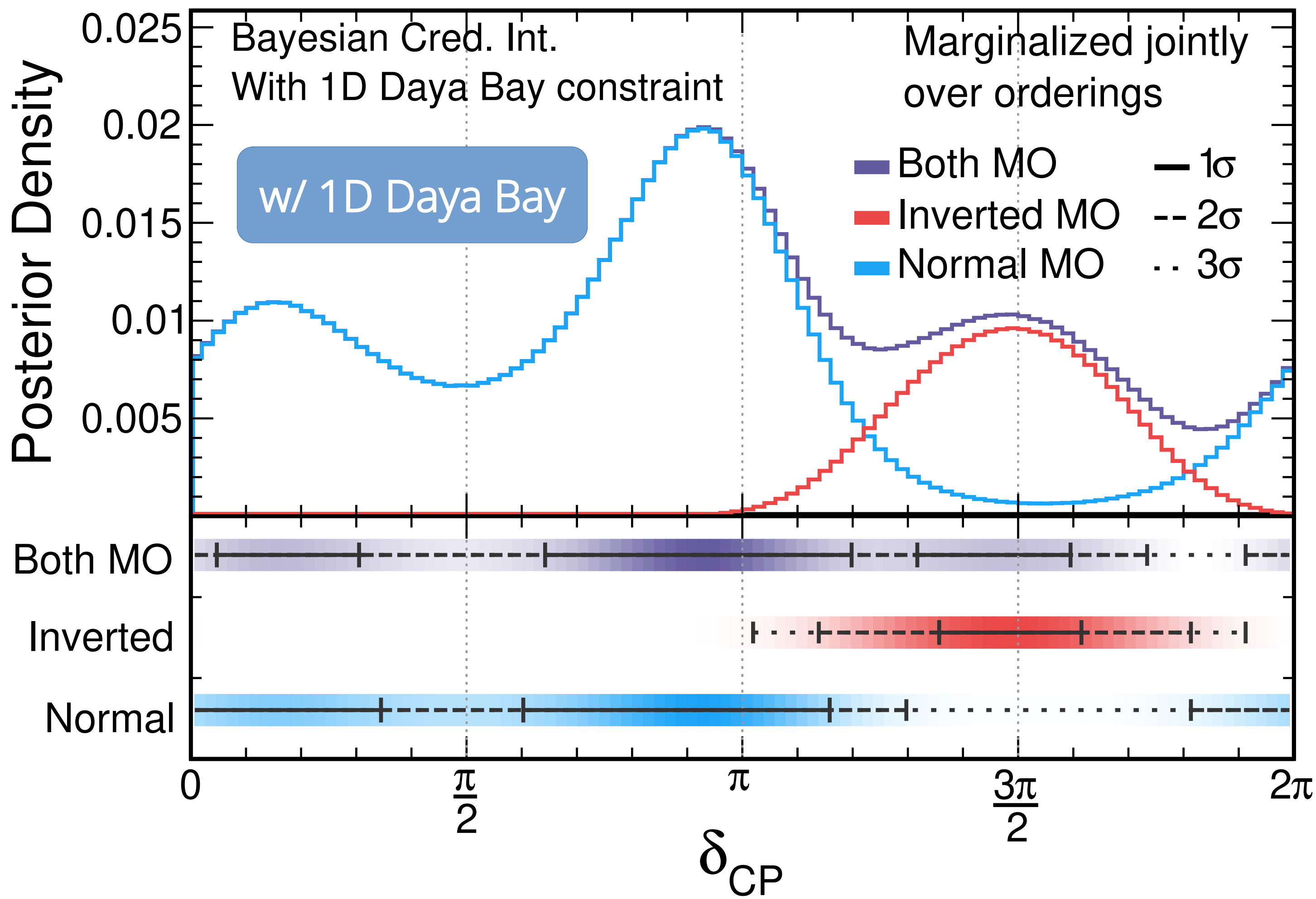
② Which way are the neutrino mass states ordered?

Mass ordering and CPV

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

③ Do neutrinos exhibit CP violation?

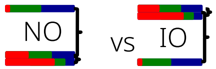
NOvA Preliminary



Mild normal ordering preference

(Posterior prob. = 76% → Bayes factor = 3.2;
Frequentist significance* = 1.4σ)

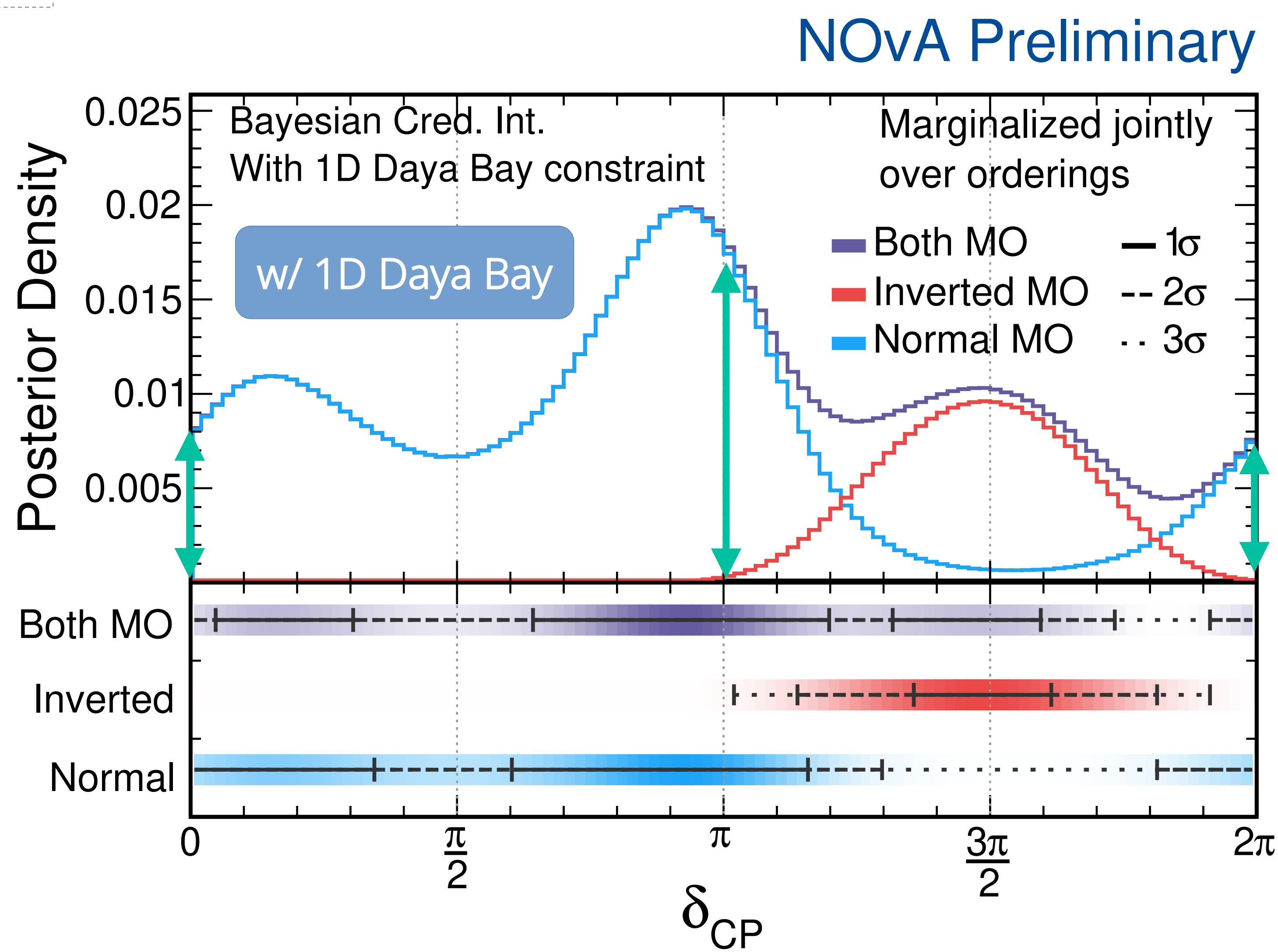
*Frequentist significance computed using Feldman-Cousins procedure thanks to NERSC



② Which way are the neutrino mass states ordered?

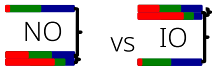
Mass ordering and CPV

③ $\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$
Do neutrinos exhibit CP violation?



CP-conserving points favored in NO but outside 3σ interval in IO

Mass ordering & CP violation heavily entangled:
data favors region with (ordering, δ_{CP}) degeneracy
(for CPV alone see Jarlskog invariant in overflow slides)

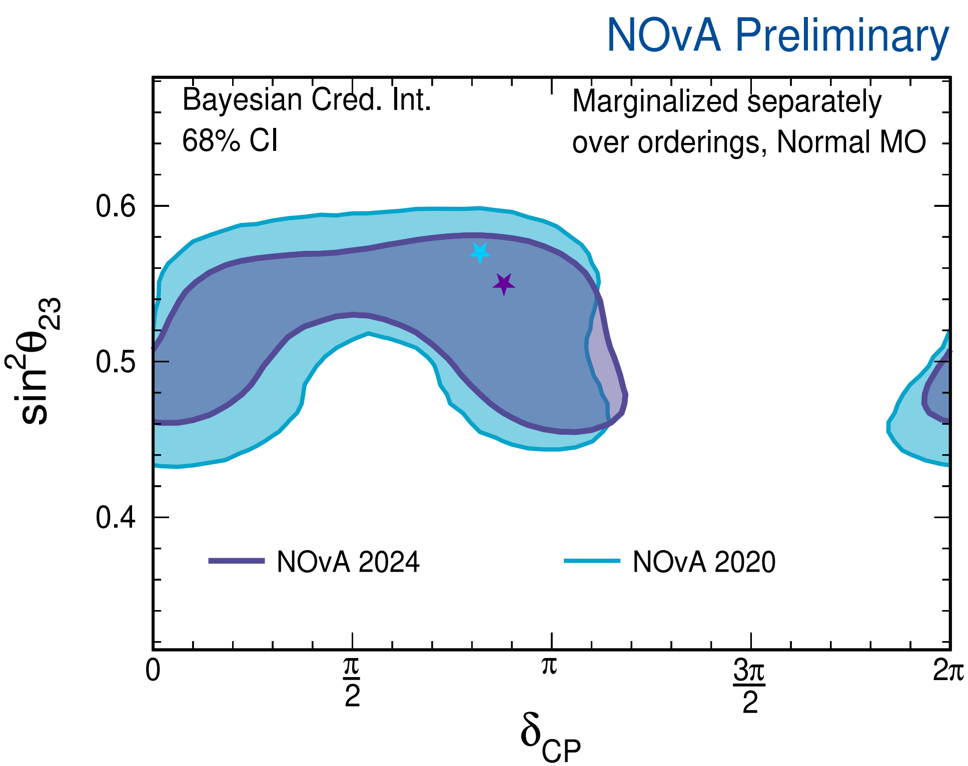


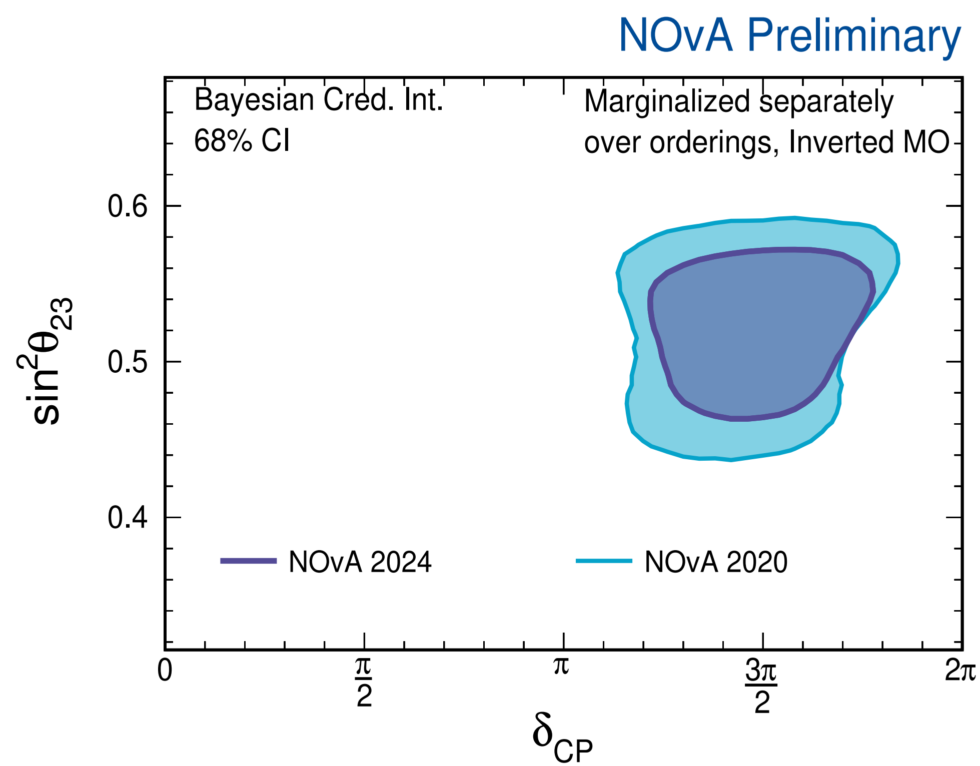
② Which way are the neutrino mass states ordered?

Mass ordering and CPV

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

③ Do neutrinos exhibit CP violation?



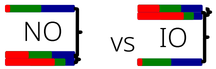


New NOvA data consistent with old data

improved constraints lie in ~same regions

Note: results use different choices of reactor constraint

NOvA 2020: 2019 PDG avg θ_{13}
NOvA 2024: Daya Bay 2023 1D θ_{13}

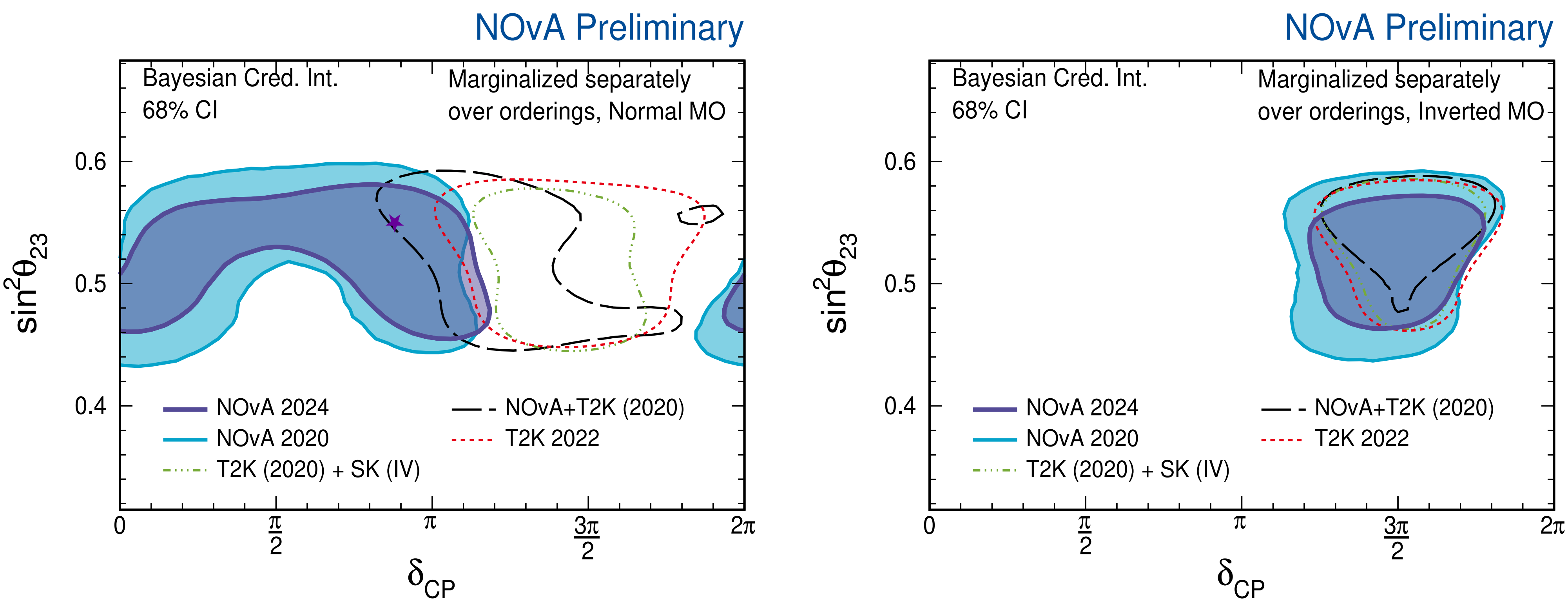


② Which way are the neutrino mass states ordered?

Mass ordering and CPV

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

③ Do neutrinos exhibit CP violation?

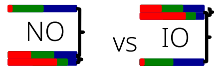


NOvA vs. other data favor different regions in NO, same region in IO

Note: results use different choices of reactor constraint

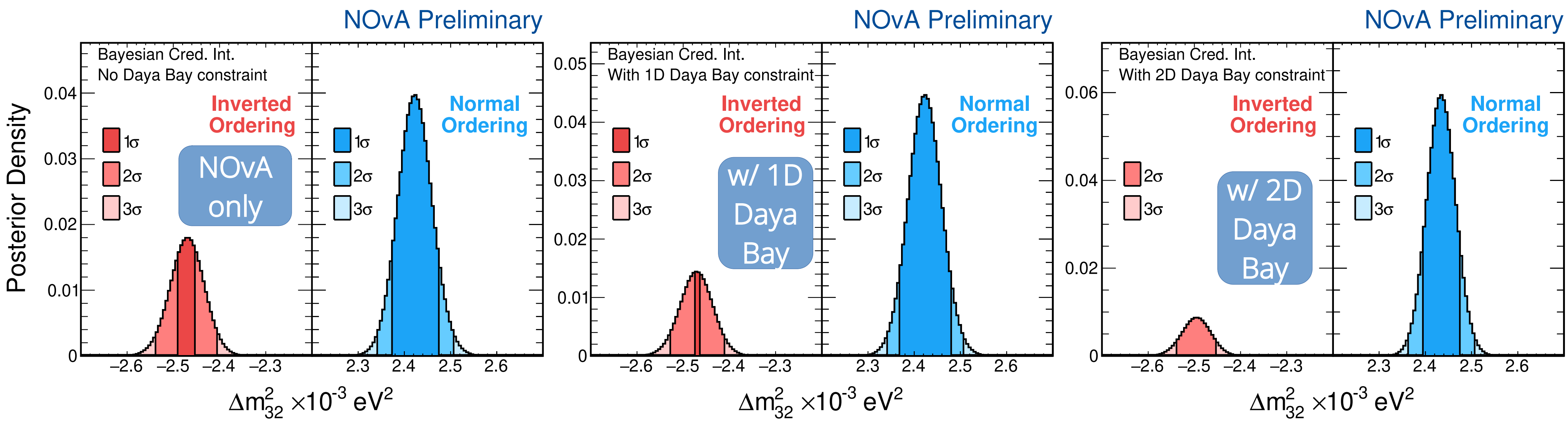
NOvA 2020: 2019 PDG avg θ_{13}
NOvA 2024: Daya Bay 2023 1D θ_{13}
T2K: 2019 PDG avg θ_{13}
NOvA+T2K: Daya Bay 2023 1D θ_{13}
T2K+SK: 2019 PDG avg θ_{13}

Mass ordering and CPV



② Which way are the neutrino mass states ordered?

③ $\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$
Do neutrinos exhibit CP violation?



No reactor constraint	Daya Bay $\sin^2 2\theta_{13}$ only	Daya Bay ($\sin^2 2\theta_{13}$, Δm_{32}^2)
N.O. preference:	N.O. preference:	N.O. preference:
69% prob. (Bayes factor: 2.2)	76% prob. (Bayes factor: 3.2)	87% (Bayes factor: 6.8)
	Frequentist significance*: 1.4σ	Frequentist significance*: 1.6σ

Mass ordering preference strengthened by applying reactor constraint

(not entirely unexpected: e.g., Phys. Rev. D 72: 013009, 2005)

*Frequentist significances computed using Feldman-Cousins procedure thanks to NERSC

NOvA 2024 summary & outlook

- First new NOvA neutrino oscillation measurement since 2020
  - Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data
  - Updated simulation, including improved light response model and neutron propagation uncertainty
  - New low-energy ν_e candidate sample
  - **Most precise single-experiment measurement of Δm^2_{32} (1.5%)**
  - **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)

NOvA 2024 summary & outlook

- First new NOvA neutrino oscillation measurement since 2020
  - Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data
  - Updated simulation, including improved light response model and neutron propagation uncertainty
  - New low-energy ν_e candidate sample
  - **Most precise single-experiment measurement of Δm^2_{32} (1.5%)**
  - **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)
- Compelling future prospects from NOvA
  - Goal: **doubling of antineutrino data** before 2027 – crucial to clarify MO/CPV
  - **Test beam** constraints on energy scales expected in near term
  - **Much more NOvA physics** than what's in this talk!
    (BSM oscillations, ν interactions, atmospheric- & astrophysics, non-beam BSM...)
    → check out our posters (list on next slide)

POSTER
455. Pions in the NOvA Test Beam
David Dueñas (University of Cincin...
6/21/24, 5:30 PM

403. Medium Energy Neutron Detector Response in NOvA
Miranda Rabelhofer, Andrew Sutton

406. Recent Advancements in Machine Learning Techniques Utilised in NOvA
Alejandro Yankelevich, Alexander Booth, Alexander Shmakov, Ashley Back, Erin Ewart, Wenjie Wu

138. PISCES two-detector covariance matrix fit for the NOvA Experiment
Miriama Rajaoalisoa

415. New RES and DIS uncertainties for NOvA cross-section model
Maria Martinez Casales, Michael Dolce

450. Bayesian Fit for the NOvA Three Flavor Oscillation Analysis
Ben Jargowsky, Liudmila Kolupaeva

456. Determination of the neutrino oscillation parameters through the unified approach of Feldman and Cousins by the NOvA Experiment
Andrew Dye, Luis R. Prais

271. Improving NOvA's Sterile Neutrino Search with the Booster Neutrino Beam
Adam Lister

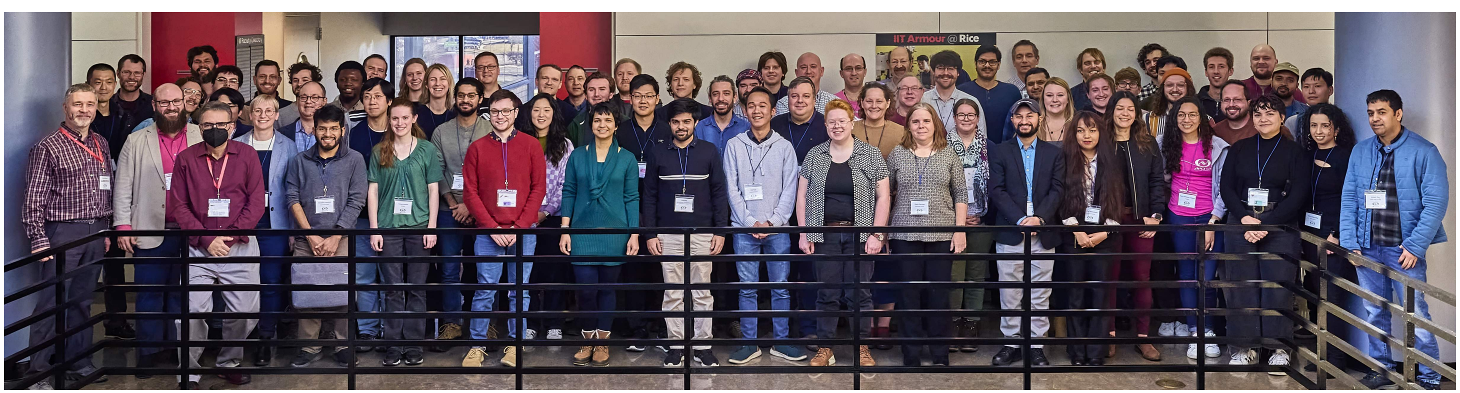
475. Constraining Neutral Current Uncertainties for Future Sterile Neutrino Search at NOvA Experiment
Shivam Chauhary, Stella Oh

455. Pions in the NOvA test beam
David Dueñas

411. Muon neutrino charged-current cross section measurement with zero mesons in NOvA
Sebastian Sanchez-Falero

565. Characterization of Charged Pions with the NOvA Detectors
Camilo Cortés Parra, Rafael Maldonado Agudelo, Juan Villamil Santiago, Enrique Arrieta Diaz

574. Charged-pion cross-section measurements in the NOvA near detector
Palash Roy, Mathew Muether



NOvA collaboration, Feb. 2024

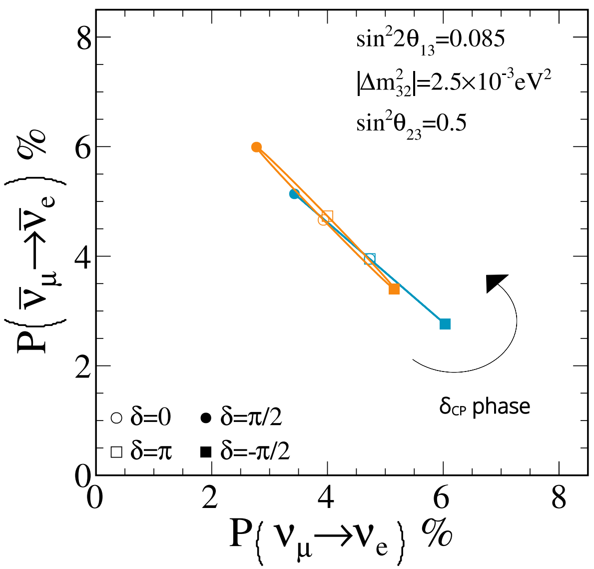
@novaexperiment

Overflow

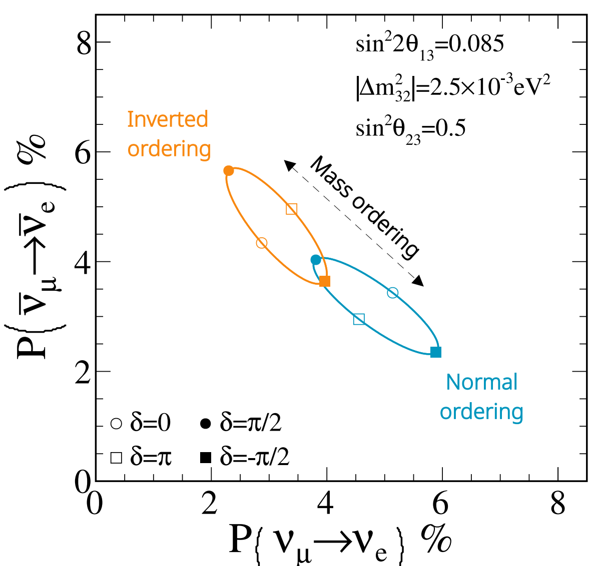
NOvA/T2K E_ν differences: implications

NOvA has larger matter effects

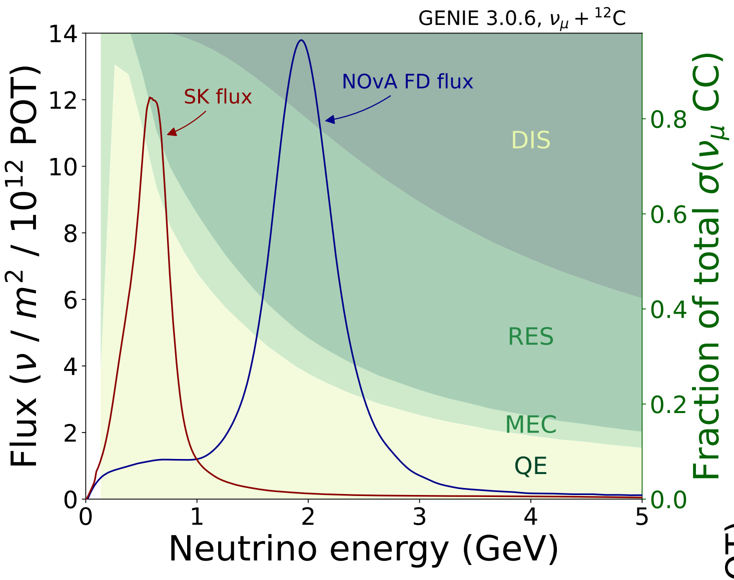
T2K: L=295 km, E=0.6 GeV



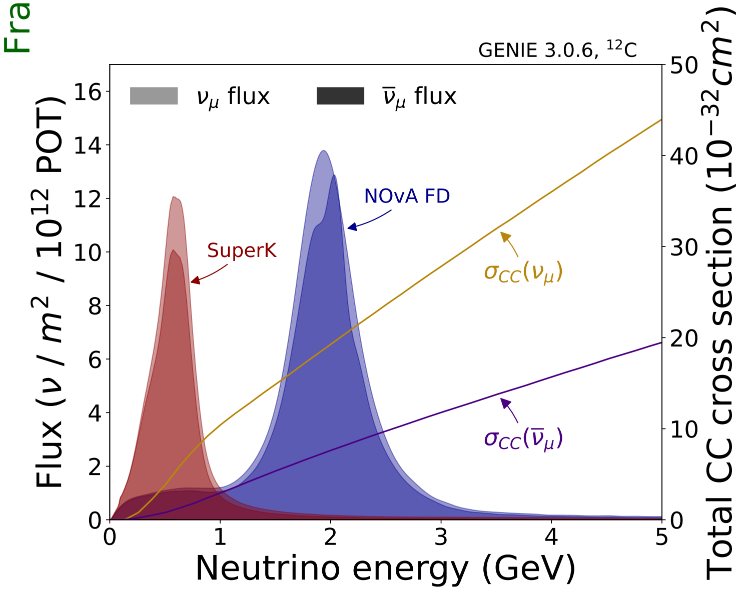
NOvA: L=810 km, E=2.0 GeV



NOvA has more final-state pions



NOvA sees more antineutrinos

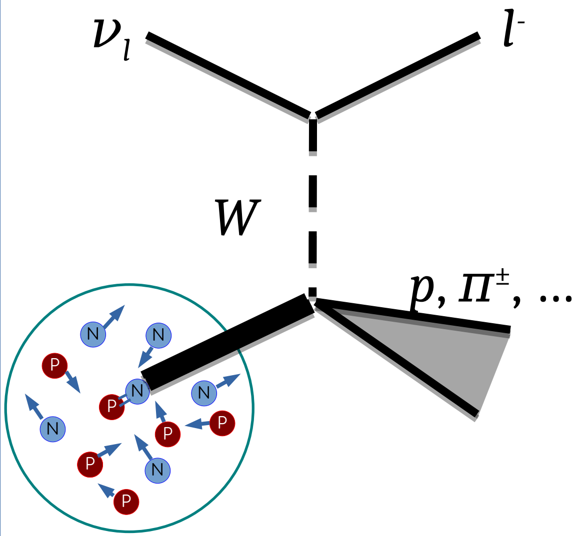


NOvA numerical results

Bayesian results	NOvA only		Daya Bay 1D		Daya Bay 2D	
	Prob.	BF	Prob.	BF	Prob.	BF
$\theta_{23} > 0.5$ preference	57%	1.3	69%	2.2	67%	2.0
N.O. preference	69%	2.2	76%	3.2	87%	6.8

Frequentist results (w/ Daya Bay 1D θ_{13} constraint)	N.O.	I.O.
Δm^2_{32} / 10^{-3} eV^2	$+2.433^{+0.035}_{-0.036}$	$-2.473^{+0.035}_{-0.035}$
$\sin^2\theta_{23}$	$0.546^{+0.032}_{-0.075}$	$0.539^{+0.028}_{-0.075}$
δ_{CP} / π	0.88	1.51
Rejection significance (σ)	—	1.36

Cross section model



Base simulation: GENIE 3.0.6

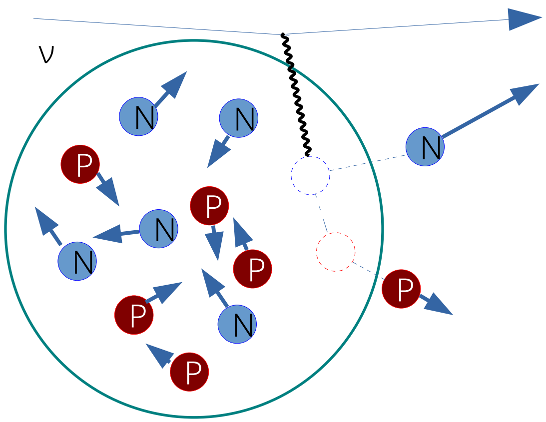
- No stock comprehensive model configuration (CMC) agrees well with data
- We choose a “theory-driven” set of models* and make *post hoc* adjustments to improve agreement

QE	Multinucleon	RES	DIS	FSI
València 1p1h w/ Z-expansion axial form factor	València MEC	Berger-Sehgal	Bodek-Yang + AGKY/Pythia	hN semi-classical cascade

Apply custom tuning in two places (see following slides)

* We call our model collection **`N18_10j_00_000`**. It is built by starting with GENIE's `G18_10b_00_000` and substituting the Z-expansion QE axial form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions.

Multinucleon knockout



"2p2h"

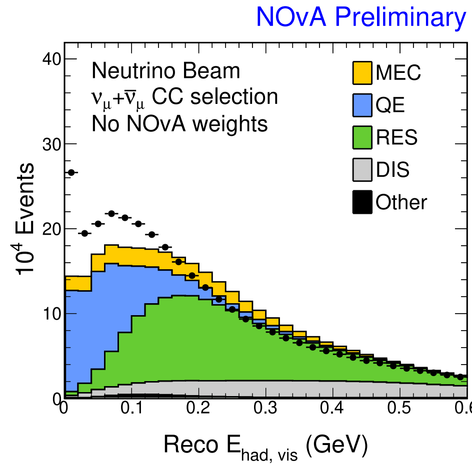
Knock out two nucleons with an elastic-like interaction.

Lots of recent progress on theory, but no model in GENIE (yet) describes extant data well

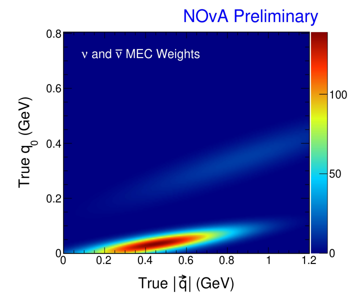
Employ **fits to NOvA ND data** in the meantime

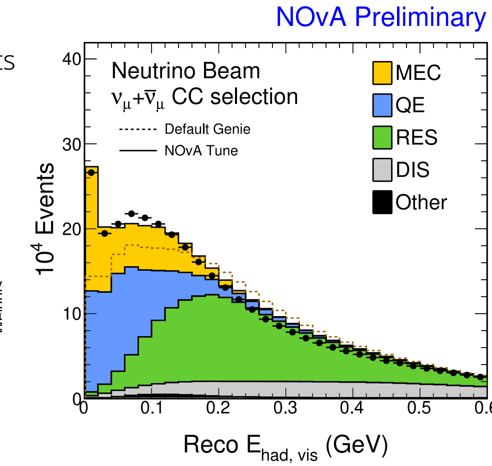
Only minor updates from 2020

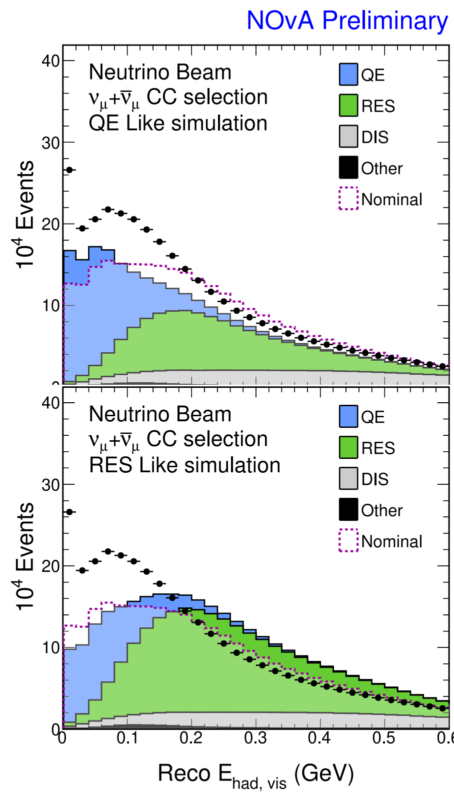
[detailed discussion of 2020 technique in NuSTEC CTGWG Seminar Dec. 14, 2022 (J. Wolcott)]



Fitted double-Gaussian weights applied to true CC MEC

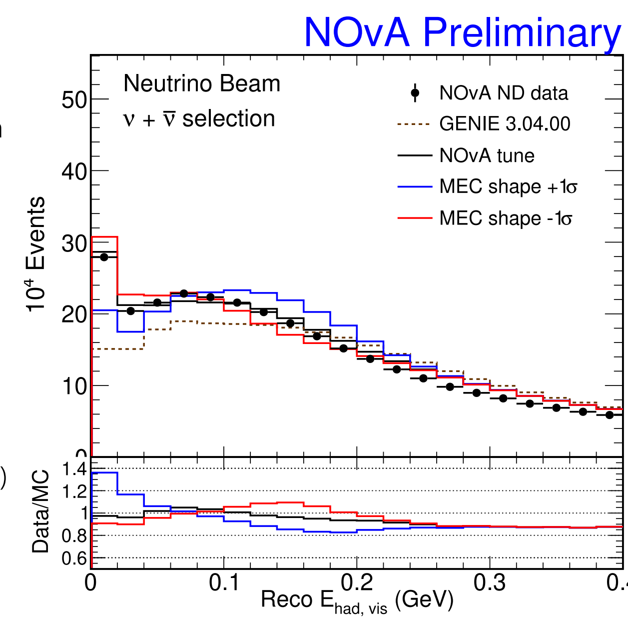






Address dependence on non-MEC models by re-fitting using "extreme" variations of QE, RES systematics to bracket impact on fitted MEC

(these alternate MEC predictions used as systematic uncertainties)

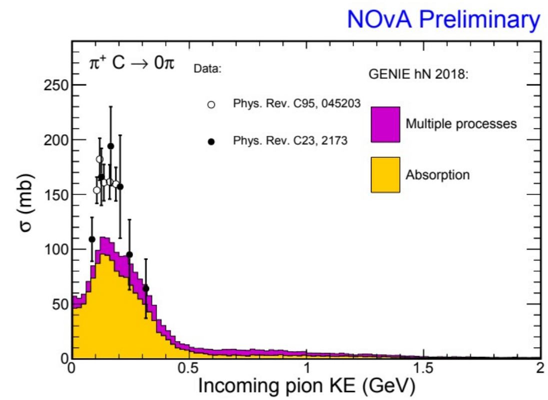


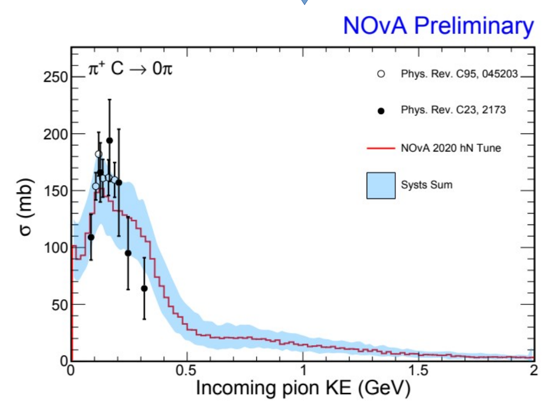
FSI tuning & uncertainties

- Only minor updates from 2020
  → detailed discussion of 2020 technique in NuSTEC CTGWG Seminar Dec. 14, 2022 (J. Wolcott)
- FSI model choice: "hN"
  – Propagates hadrons through nucleus in finite steps
  – Interaction probabilities simulated according to Oset quantum model
  – More rigorous foundation than older "hA" effective model (hA applies hadron scattering data directly to FSI and … hopes for the best)
- Challenge: hN not directly reweightable
  → Addressed with BDT reweighting technique adapted from DUNE (see also J. Phys. Conf. Series 762, 012036)

Tuning

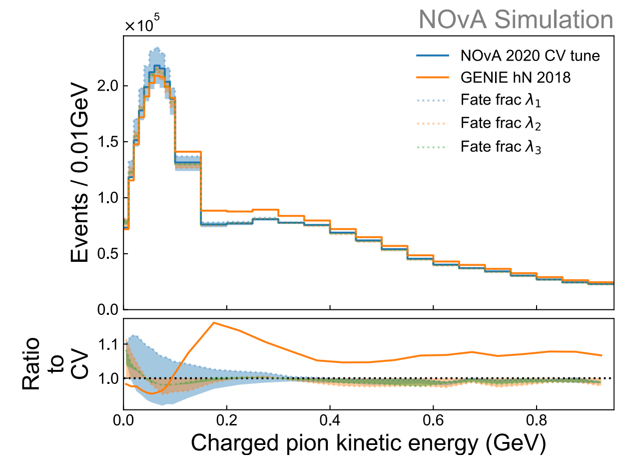
- Adjust nominal prediction to agree better with pion scattering data at low energies where most relevant for NOvA
- Construct uncertainty bands in same spirit as work from T2K [Phys. Rev. D99, 052007]

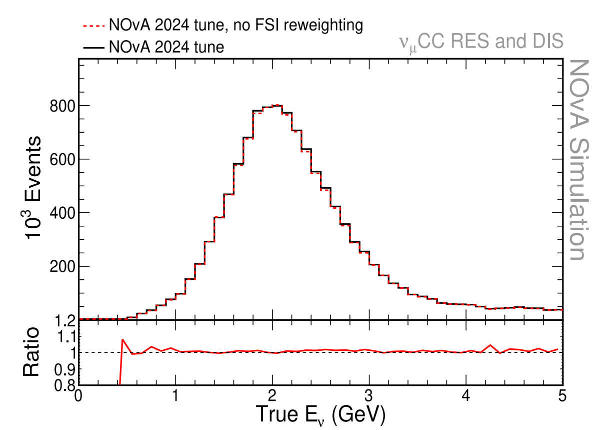




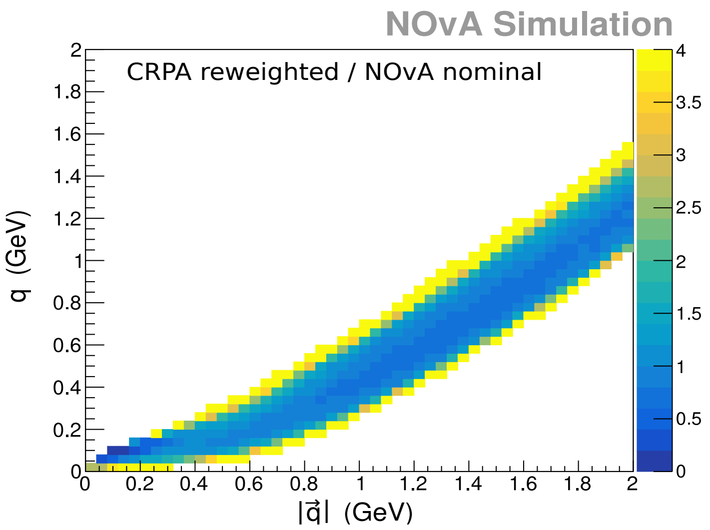
Impact

- 5-10% effect on pion kinematics
- Ultimately subdominant for calorimetric E_ν reco. used in NOvA



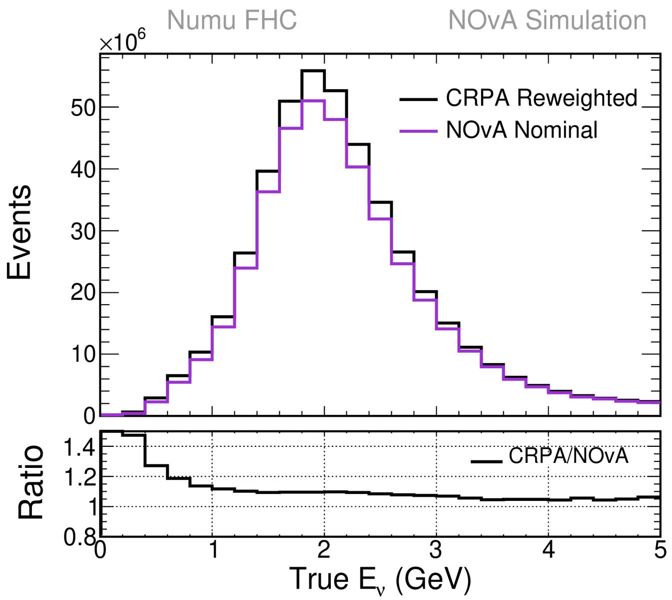


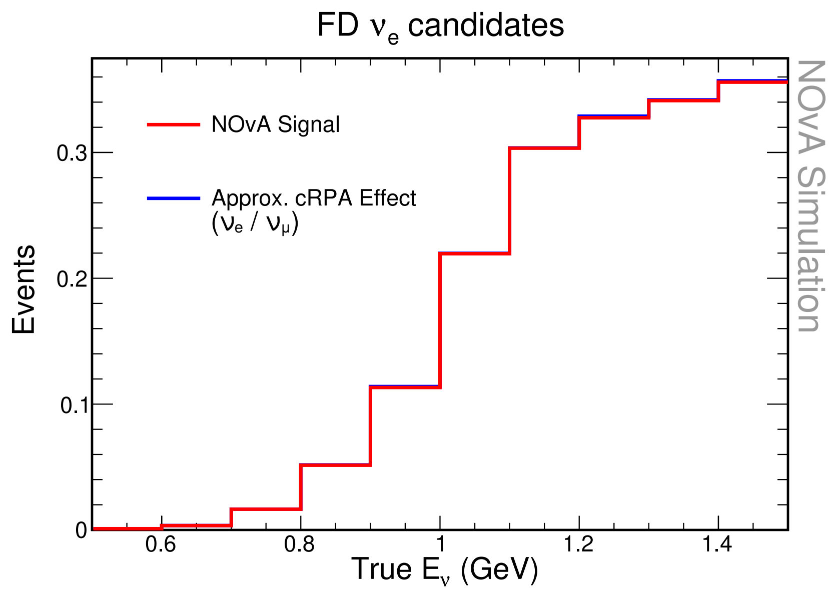
Alternate CCQE model: CRPA (1)



- Continuum Random Phase Approximation (CRPA) CCQE model*
  - Improved treatment of low-momentum-transfer nuclear dynamics
  - Opens additional phase space at edges of kinematically allowed region relative to base NOvA model (València)
  - Affects lowest neutrino energies most
- Studied impact on NOvA samples
  - Generated alternate sample using GENIE 3.4 implementation†
  - Reweighted NOvA events using ratio to base GENIE prediction
  - Found effect of ν_e/ν_μ difference to be negligible on NOvA samples, so used weights for $\nu_\mu(\bar{\nu}_\mu)$ everywhere

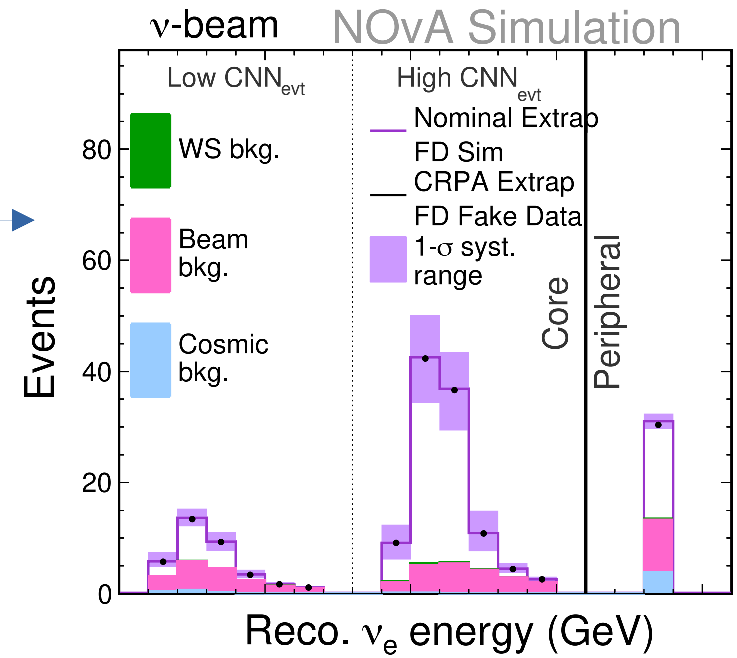
*Phys. Rev. C92, 024606 †Phys. Rev. D106, 073001

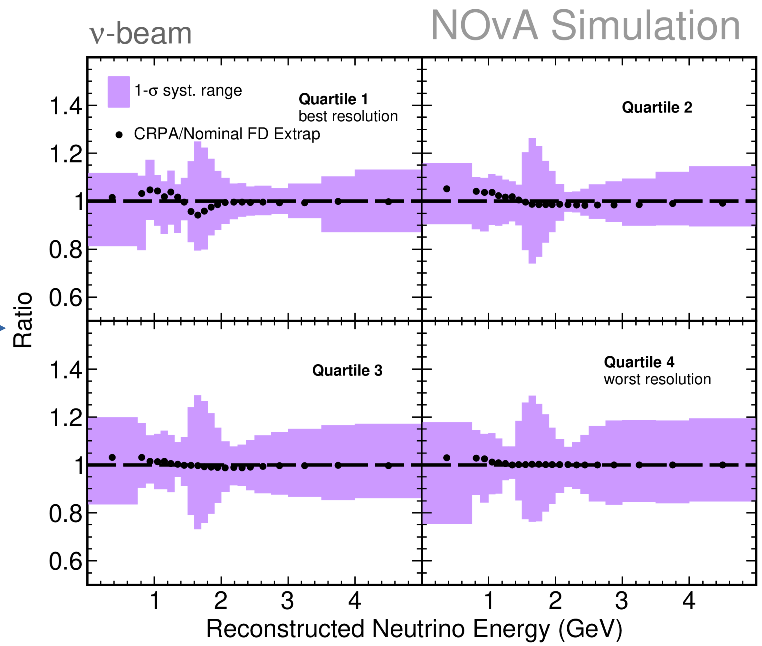


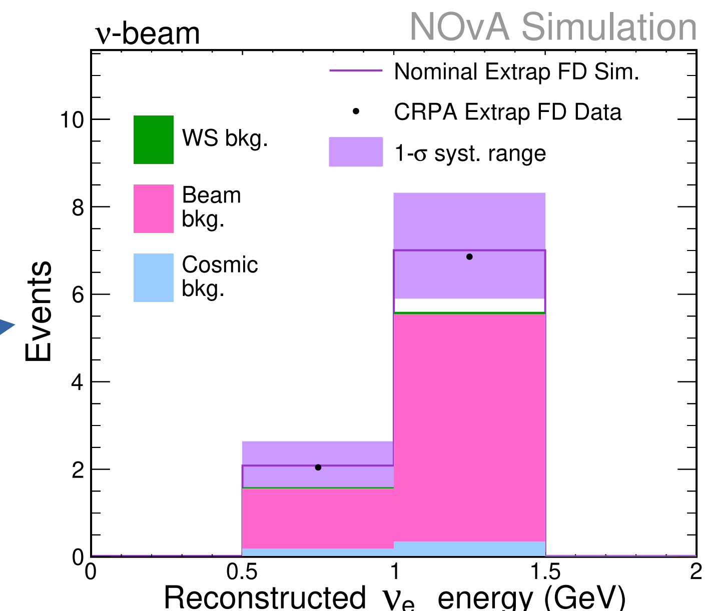


Alternate CCQE model: CRPA (2)

- Tested impact on NOvA analysis with fake data
  - Compared extrapolated CRPA prediction to extrapolated nominal
  - Spectral impact is well within extrapolated uncertainty budget
    - Impacts ν_μ quartile 1 the most, as expected (highest CCQE fraction)
    - ~Negligible impact on ν_e samples
  - Performed fits using extrapolated CRPA prediction as fake data
- Overall analysis impact is very small
  - **Δm^2_{32}: resulting bias ~ 0.1%** (~7% of 1σ interval)
  - **$\sin^2\theta_{23}$: resulting bias ~0.4%** (~3-8% of 1σ interval)



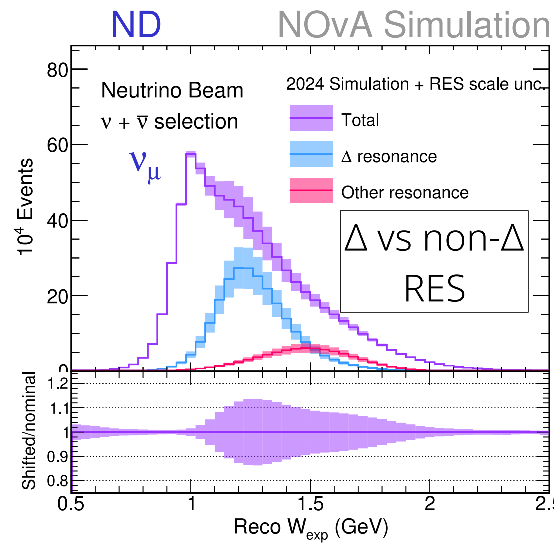


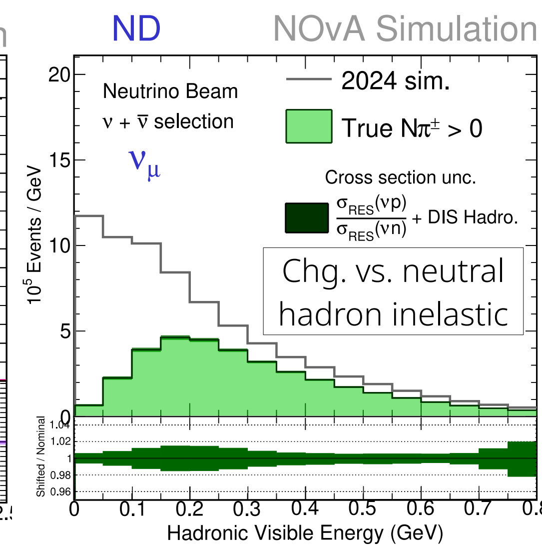


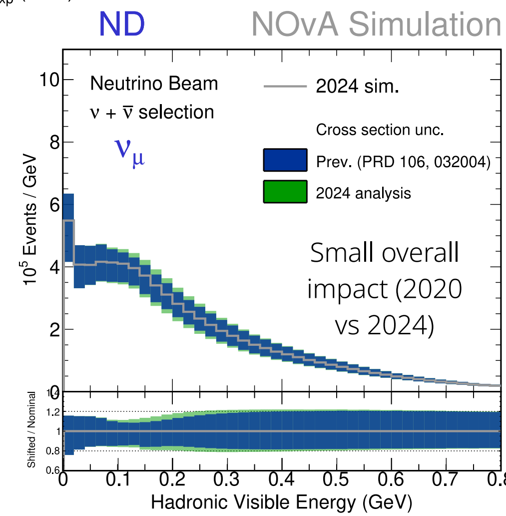
Pion production uncertainties

Introduce **3 pion-production related systematic uncertainties** for 2024

- Relative strength of Δ vs non-Δ resonant production (1 uncertainty)
  → Shift Δ and non-Δ resonances ±20% independently
  - Default GENIE: all resonances affected together
  - Overcounts Δ-specific uncertainty somewhat with other GENIE knobs, but "conservative"
- Charged vs. neutral hadron production in RES, DIS (2 uncertainties)
  - Shift ratio of RES Δ-channel proton/neutron final states by ±5%
  - Shift composition of proton/neutron final states in DIS
- Moderate impacts on pion-rich subsamples, but overall effect on uncertainty budget is minor





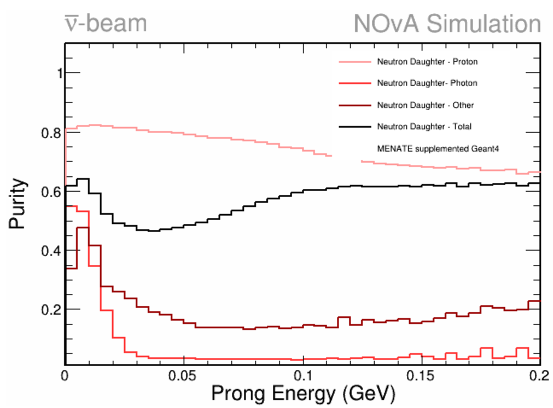


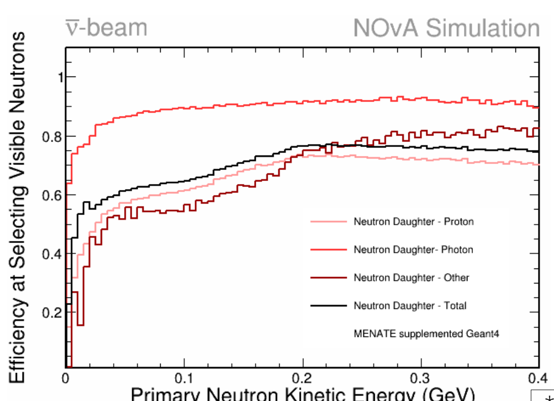
POSTER
415. New RES and DIS uncertainties for NOvA cross-section model
Maria Martinez Casales (Fermilab), Michael Dolce
6/18/24, 5:30 PM

Neutron propagation

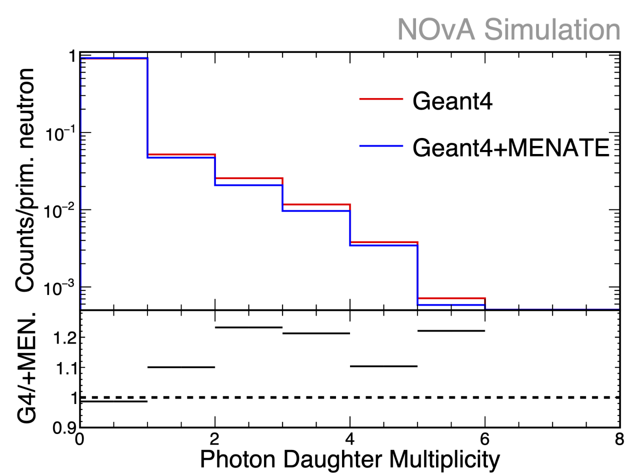
In situ ND neutron candidate sample

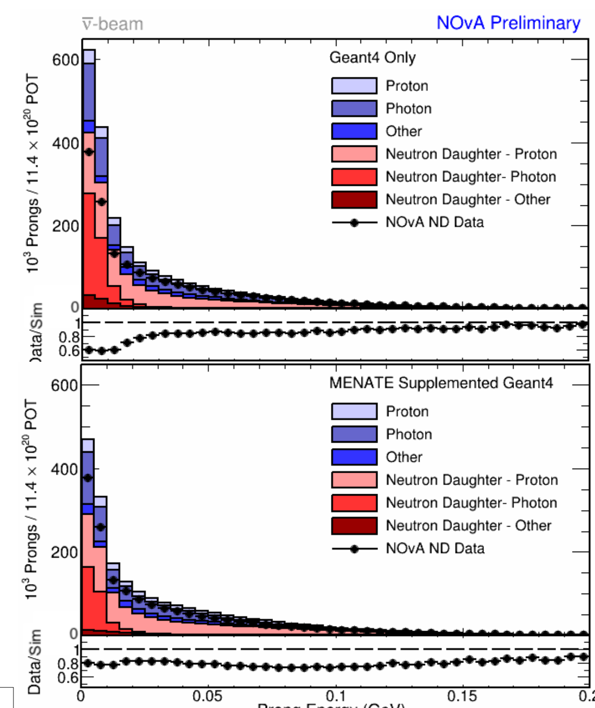
- 44% of primary neutrons deposit visible energy in NOvA (but deposited energy ~uncorrelated w/ primary KE)
- Simple cuts on number of cells illuminated ($1 \geq N_{cells} \geq 5$) and distance from vertex (≥ 20cm)
- Select ~pure sample (61%) at high efficiency (73%) (relative to visible neutrons)





- Compare simulations of deposited energy to *in situ* ND data sample
  - Two options:
    - stock Geant4.10.4 (QGSP-BERT)
    - Geant4.10.4 with MENATE_R* neutron inelastic scattering cross section model (~20-100 MeV)
  - MENATE_R agrees well with NOvA data in shape (significant improvement over G4)
  - Biggest difference b/w MENATE and G4 is in photon production
- Difference between MENATE_R and GEANT4.10.4 used as input to systematic uncertainity
  - Normalization inflated to also cover residual data/sim. difference
  - Residual normalization difference may also suggest issue with neutron *production* simulation (GENIE)



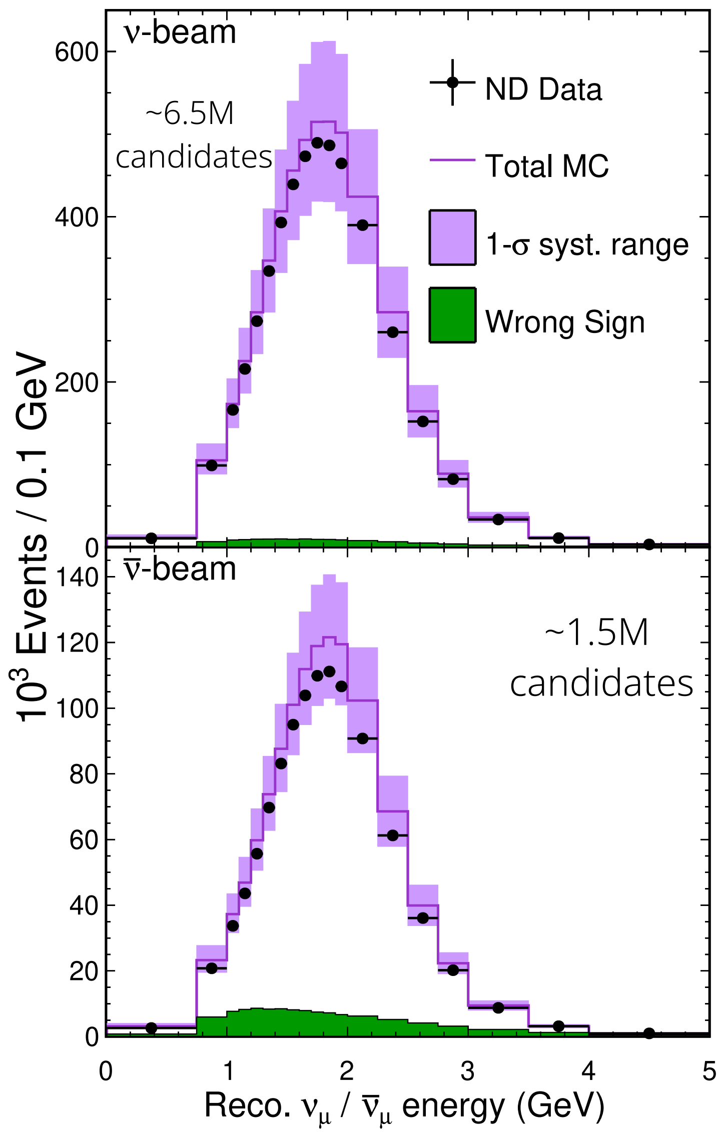


POSTER
403. Medium Energy Neutron Detector Response in NOvA
Andrew Sutton (Florida State Univer... , Miranda Rabelhofer
6/18/24, 5:30 PM

* P. Désesquelles, et al., NIM A307 366-373 (1991), Z. Kohley, et al., NIM A682 59-65 (2012)

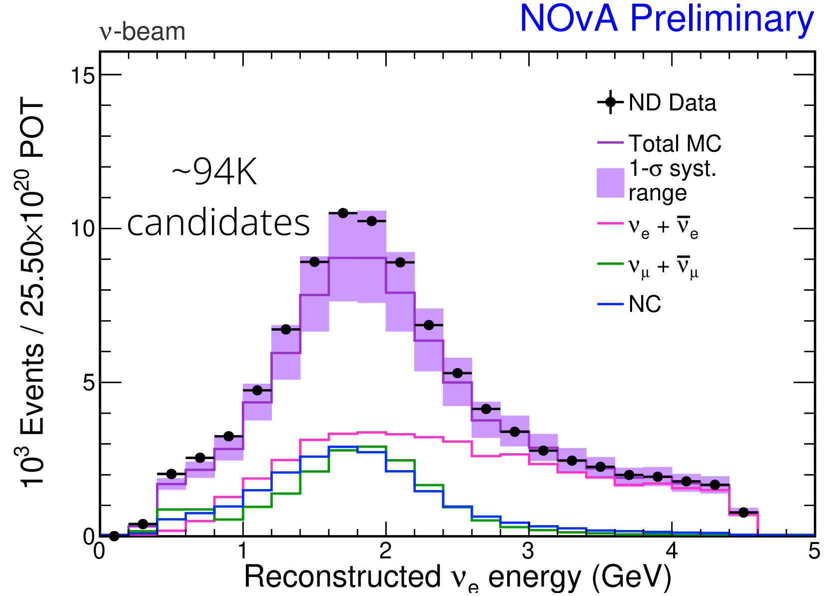
ND data distributions

ν_μ candidates

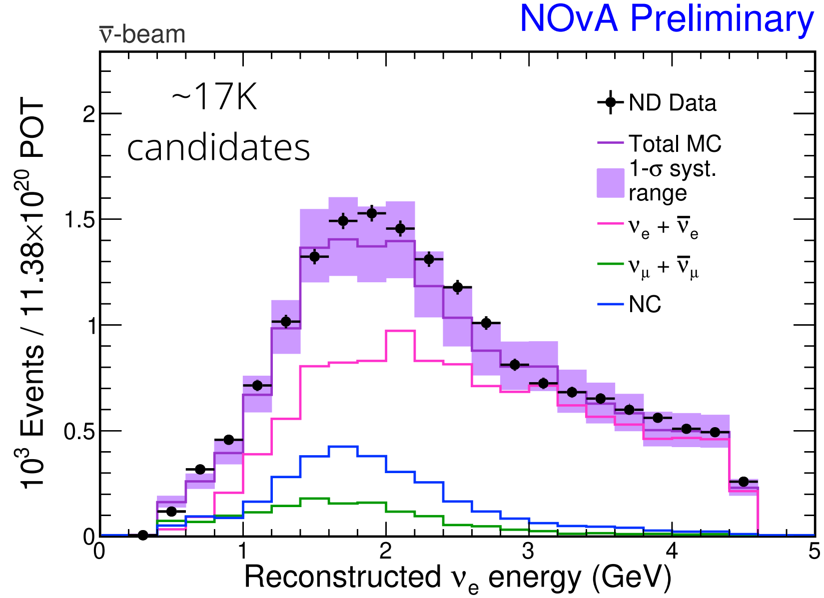


ν_e candidates

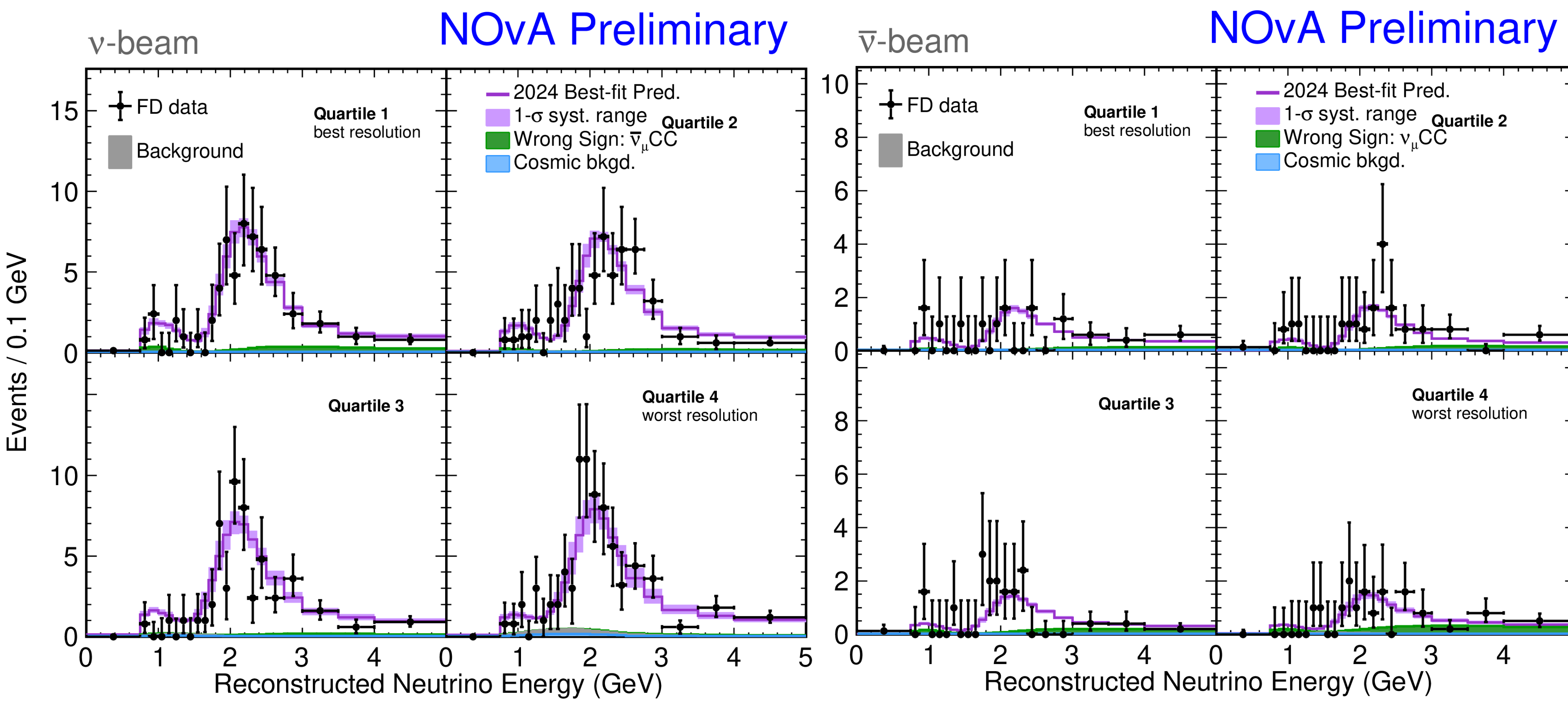
NOvA Preliminary



NOvA Preliminary



FD data: ν_μ in E_{had}/E_ν quantiles

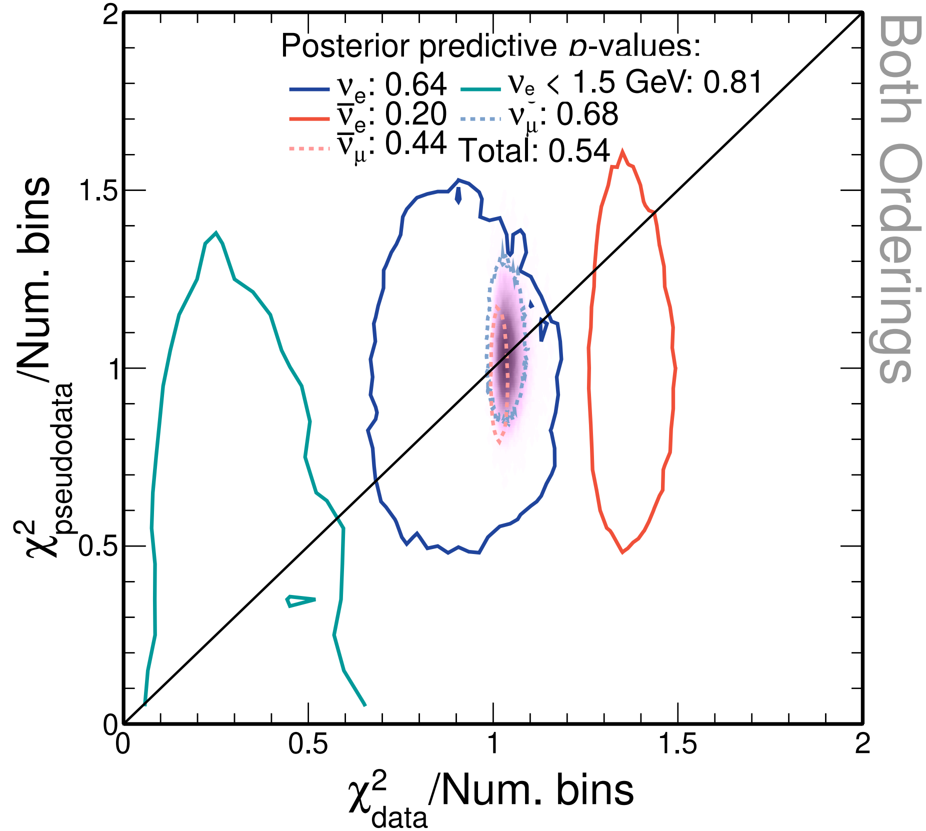


Extrapolation procedure is performed in

$|p_t|$ subpopulations of E_{had}/E_ν quartiles

Resolutions range from Q1 6.5% (5.4%) to Q4 12.6% (11.2%) in ν ($\bar{\nu}$) mode

Goodness of fit



Bayesian posterior predictive *p*-values

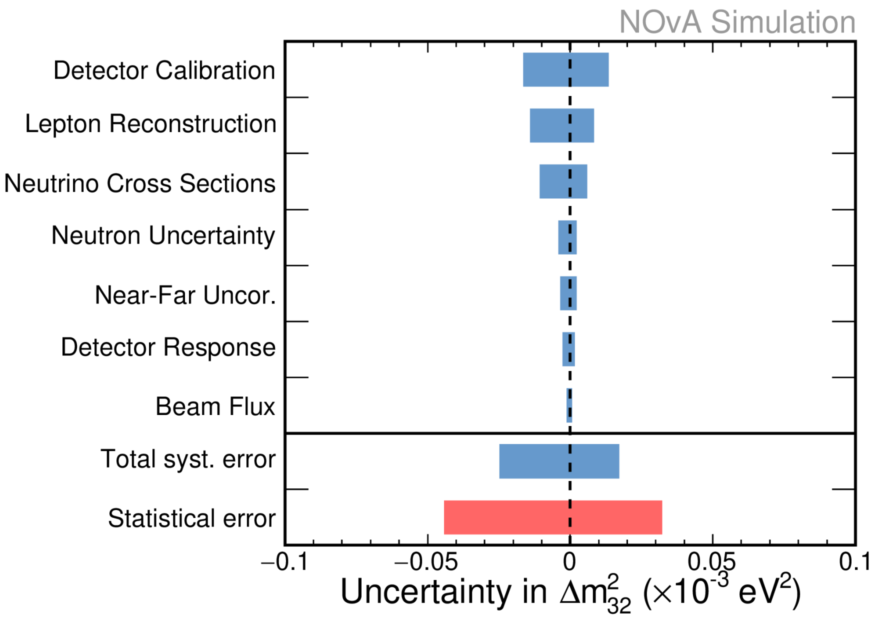
- Procedure:
  - Throw pseudoexperiments (PSE) w/ Poisson fluctuations from each MCMC sample's parameter set θ_i
  - Make predictions for energy spectra
  - Compute χ^2(PSE$_i$, Asimov$_i$) and χ^2(data, Asimov$_i$) for each MCMC sample *i*
  - *p* = fraction of points where $\chi^2_{pseudodata} > \chi^2_{data}$
- Asymptotic expectation is *p* = 0.5
  - Deviations from 0.5 can indicate insufficient or excessive model freedom can push higher or lower
  - Large fluctuations can also push away from 0.5 (as in lowE ν_e, $\bar{\nu}_e$ samples here)

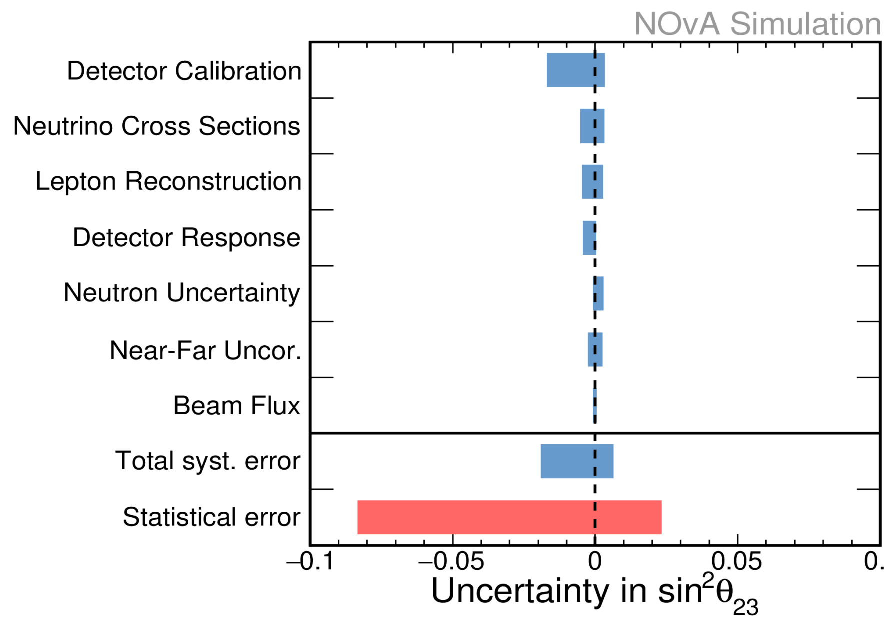
3-flavor oscillations + NOvA systematic uncertainty model represents NOvA data well

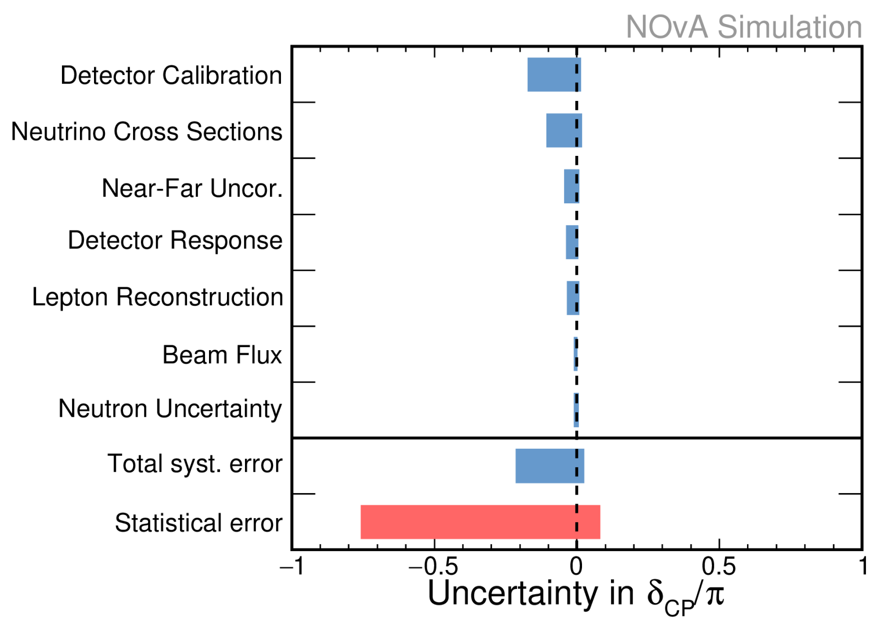
Bayesian priors

- Intent is to use "uninformed" prior where NOvA data constrains parameter
  - Typically: uniform
    → θ_{23}, Δm^2_{32}, δ_{CP} marginals: uniform in those variables
  - In Jarlskog more complex: $J \propto \sin \delta_{CP}$. Uniform in δ_{CP} or $\sin \delta_{CP}$?
    → test both
- 1D constraints from external measurements treated as Gaussian priors
  - Solar parameters (θ_{12}, Δm^2_{21})
  - Daya Bay 1D $\sin^2 2\theta_{13}$
- 2D constraint from Daya Bay uses reported χ^2 surface directly
  - $\Pr(\Delta m^2_{32}, \theta_{13}) = \exp(-\frac{1}{2}\chi^2)$

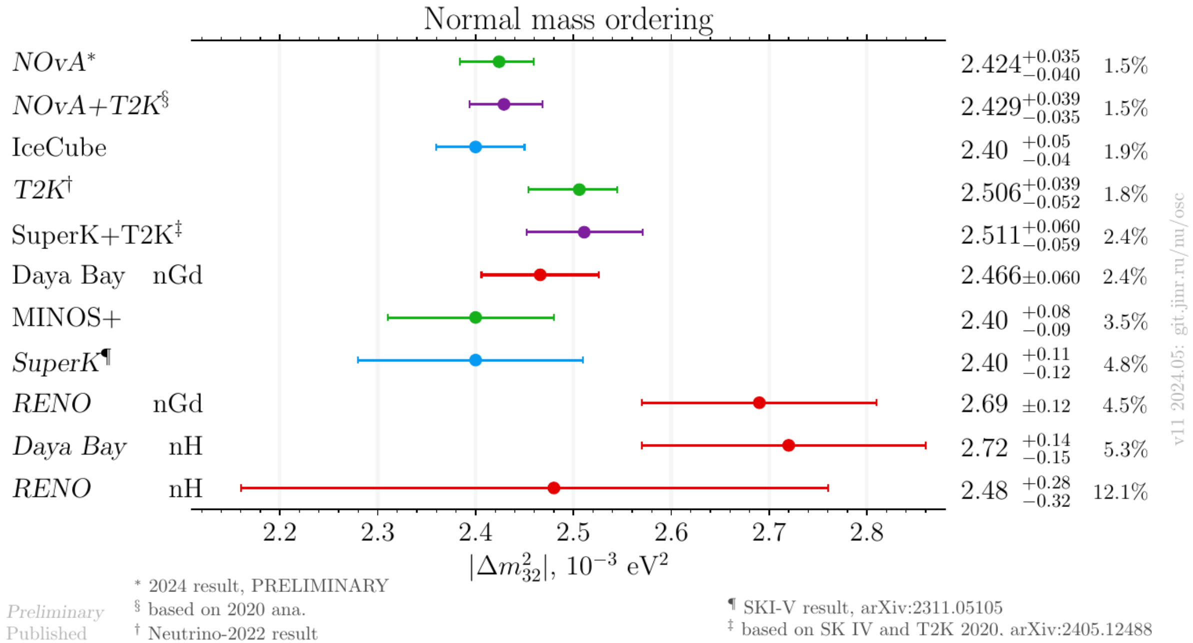
Uncertainties on PMNS parameters

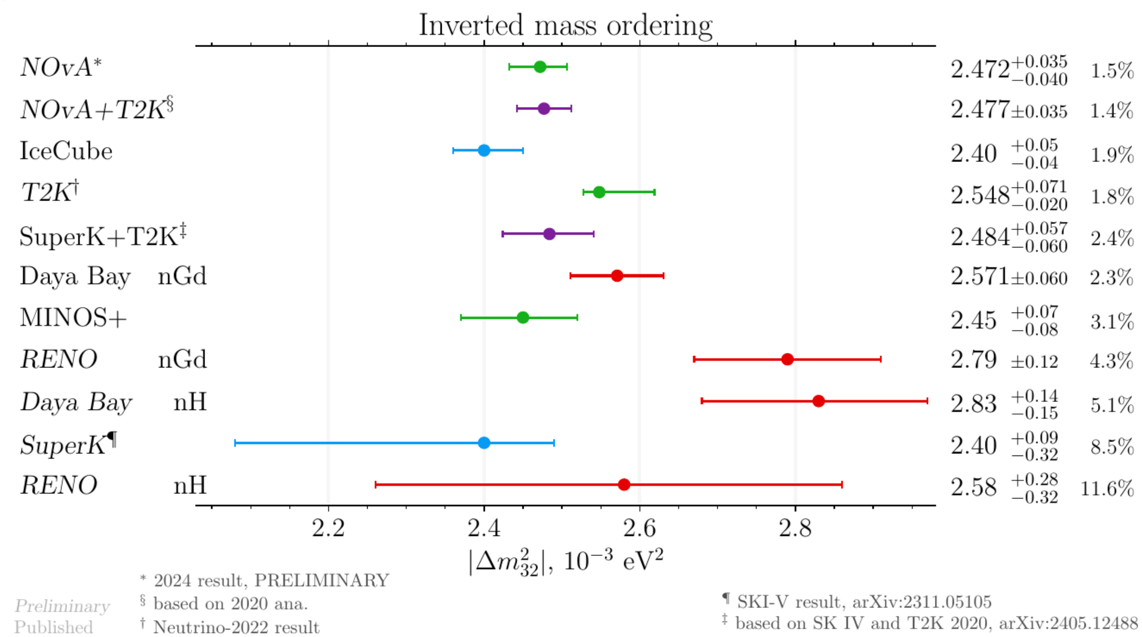




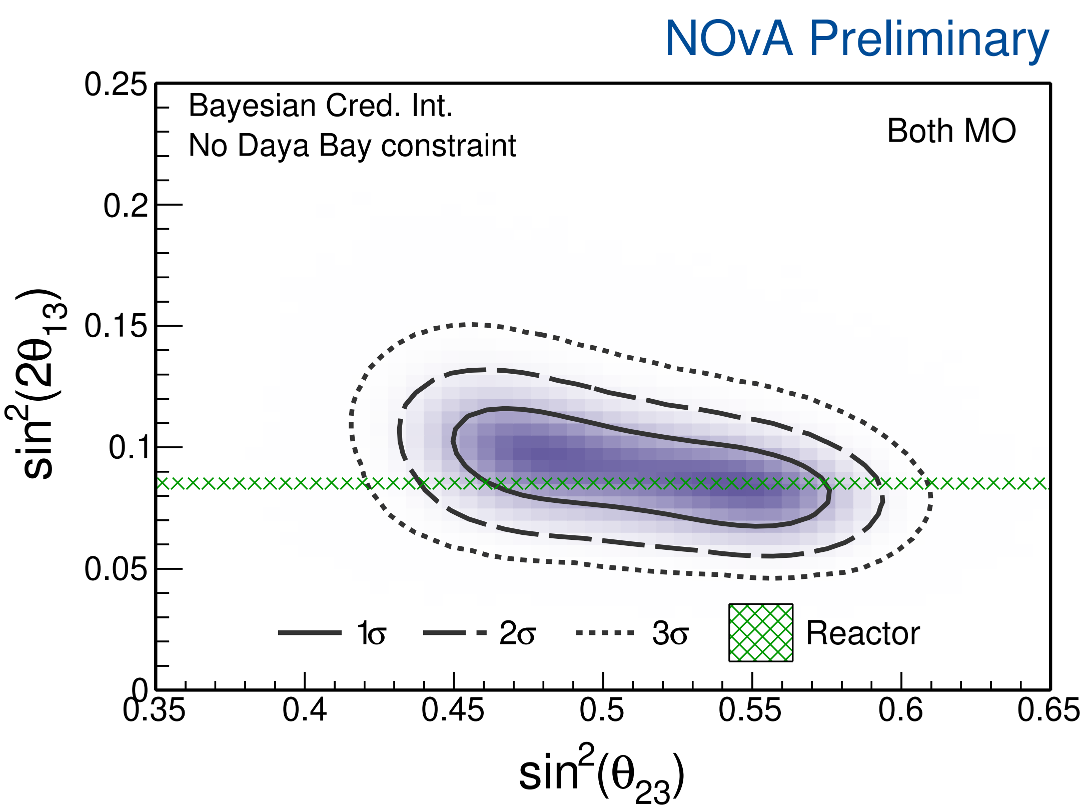


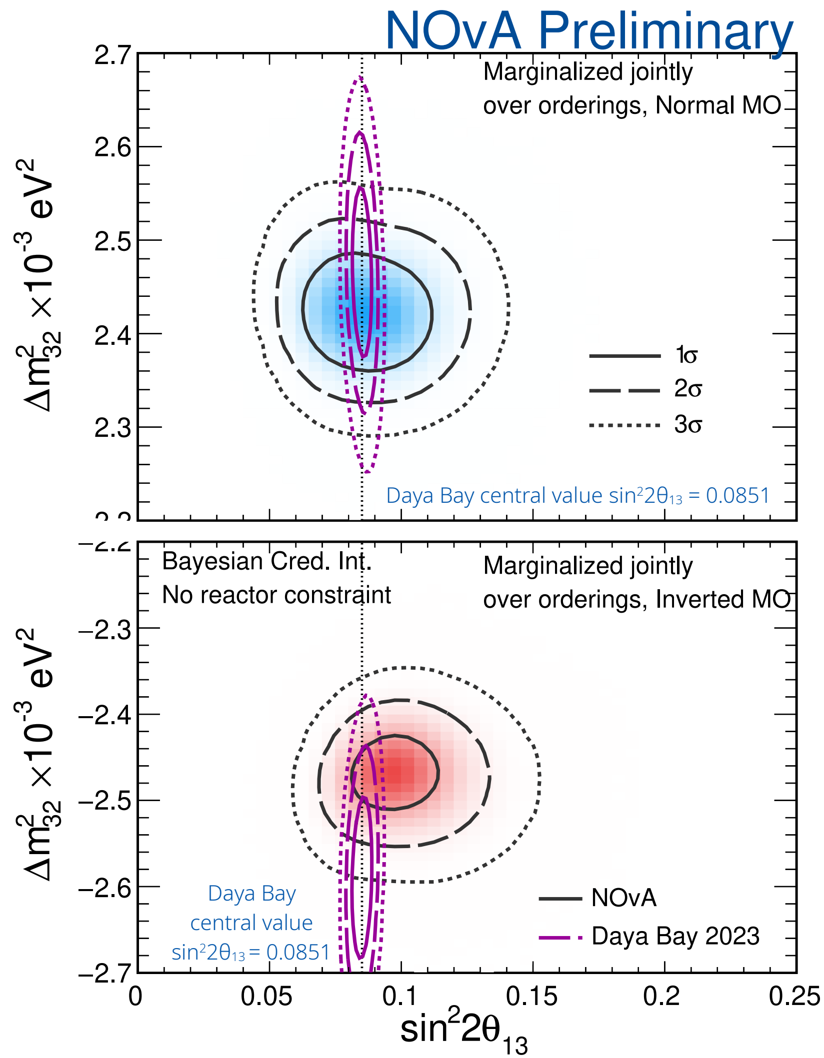
Δm^2_{32} across expts





Daya Bay – NOvA correlations

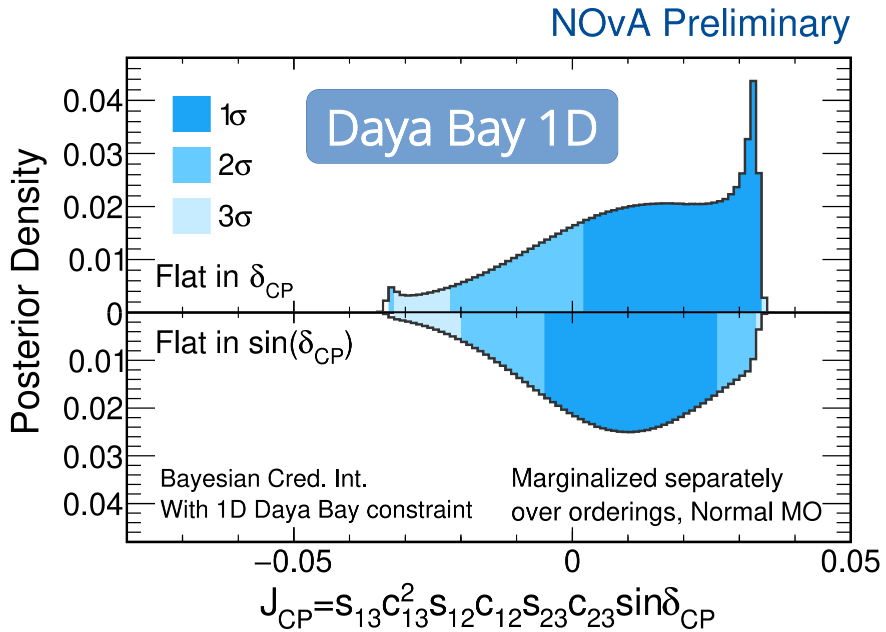


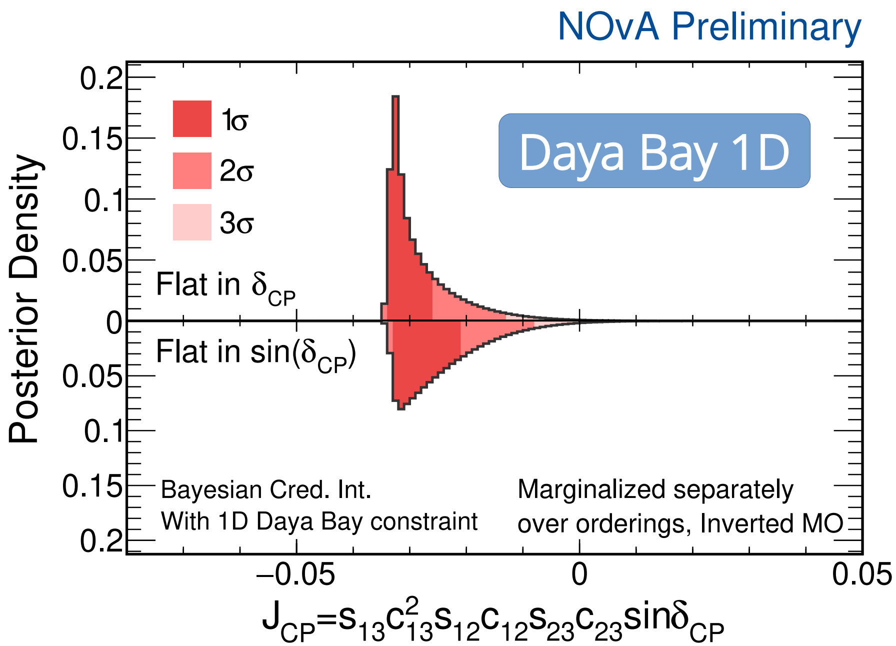


Daya Bay preferred regions resolve some degeneracies in NOvA-only data

Jarlskog invariant

- Jarlskog* is parameter-independent measure of CP violation
  - J=0 indicates CP conservation regardless of parameterization
  - J≠0 correspondingly indicates CP violation
- Jarlskog posterior shape depends on assumptions
  - Depends on all mixing angles and δ_{CP}
  - Uniform prior on δ_{CP} not uniform in *J* and vice versa → consider both
  - Use 1D θ_{13} constraint from Daya Bay
  - Other parameters constrained sufficiently well to that (reasonable) prior choice does not influence result
- CP conservation (J=0):
  - Strong compatibility w/ posterior in NO, regardless of δ_{CP} prior
  - Strong tension w/ posterior in IO, but only "uniform in δ_{CP}" prior has J=0 outside 3σ interval





*See, e.g., PRD 100, 053004