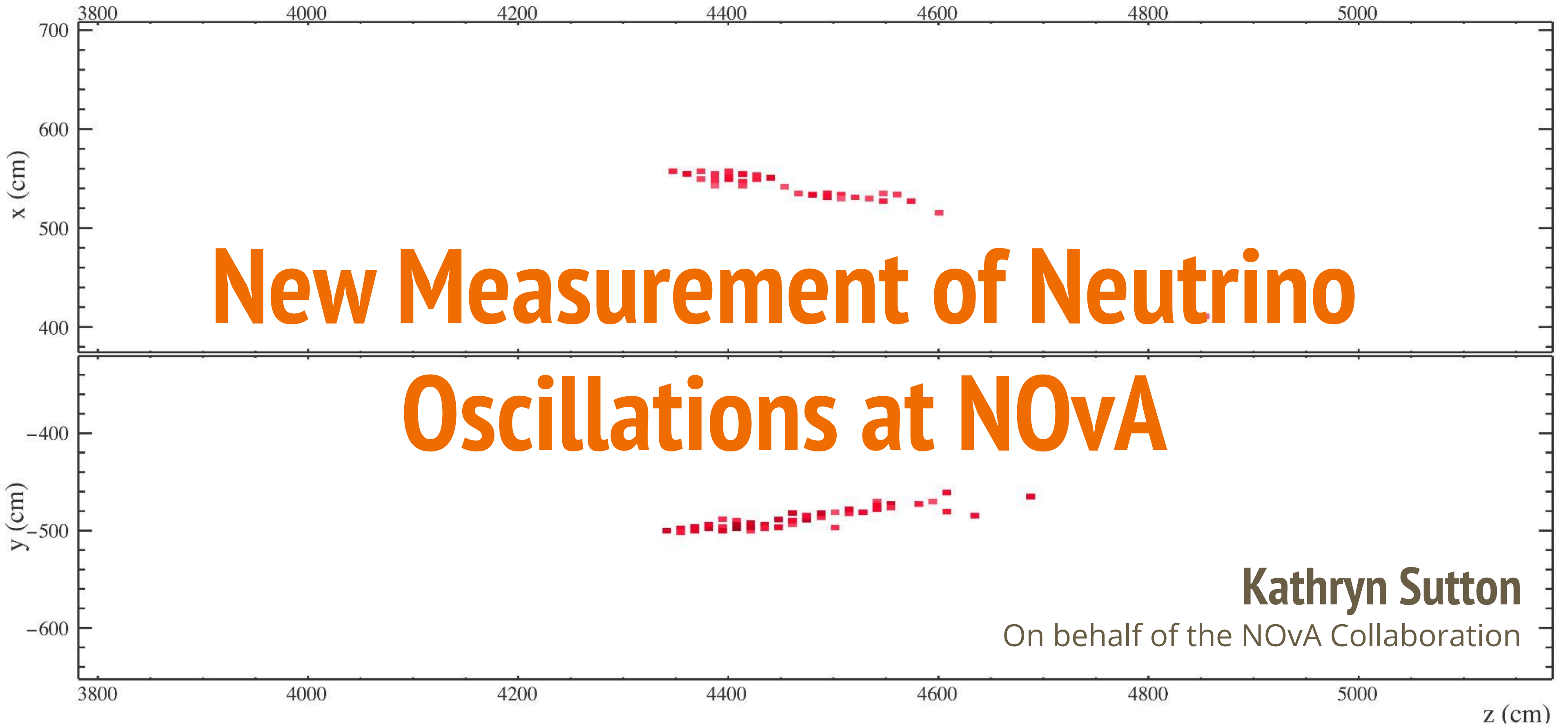


New Measurement of Neutrino Oscillations at NOvA

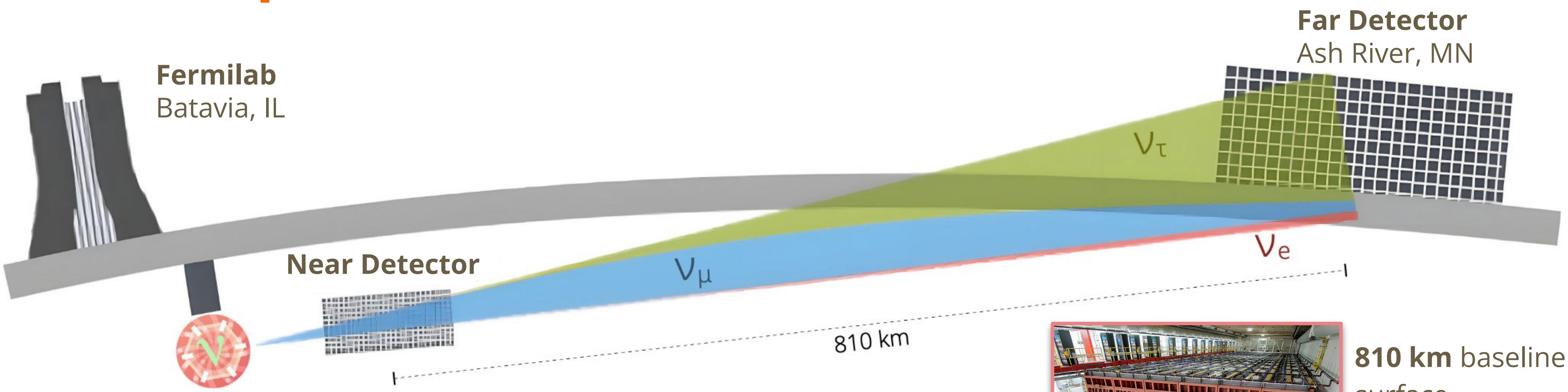
Kathryn Sutton
On behalf of the NOvA Collaboration

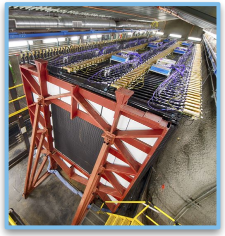
NOvA - FNAL E929
Run: 46043 / 46
Event: 6183 / NuMI
UTC Sun Mar 26, 2023
15:54:10.359626464

42nd International Conference on High Energy Physics
July 18th, 2024 - Prague, Czech Republic

Caltech

NOvA Experiment

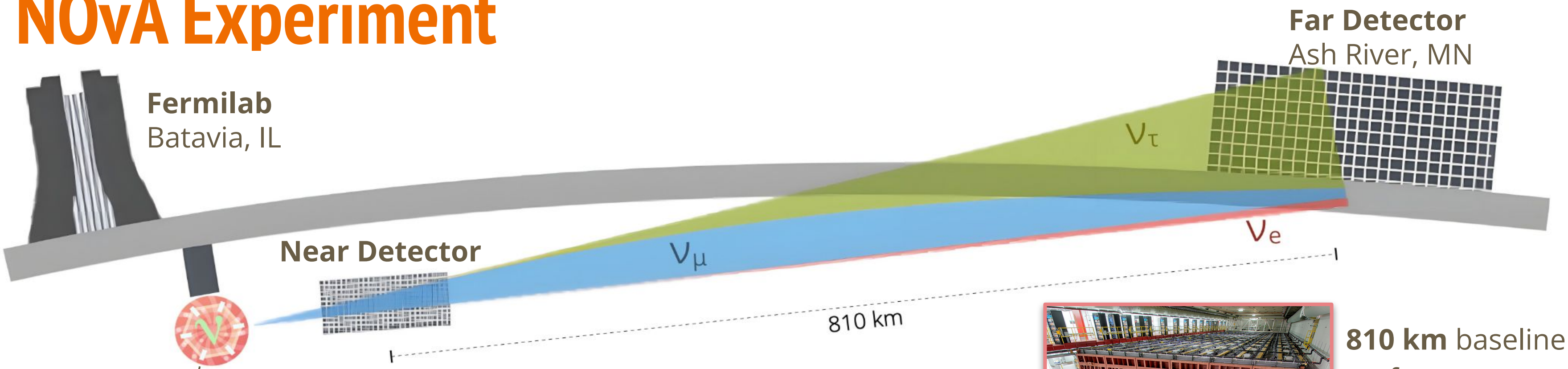


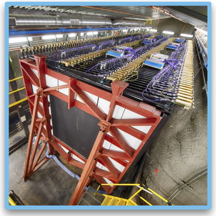


1 km baseline
100 m underground
0.3 kton mass

810 km baseline
surface
14 kton mass

NOvA Experiment





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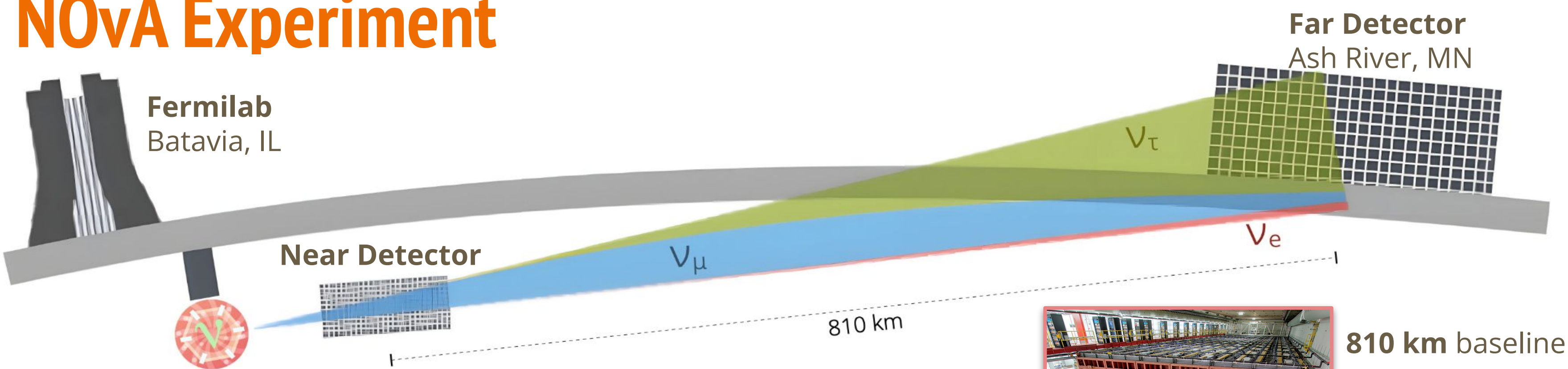
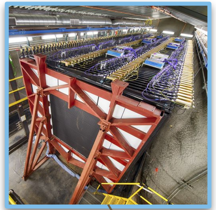
High intensity,
ν_μ-pure beam.
Run in neutrino and antineutrino mode

NOvA Experiment





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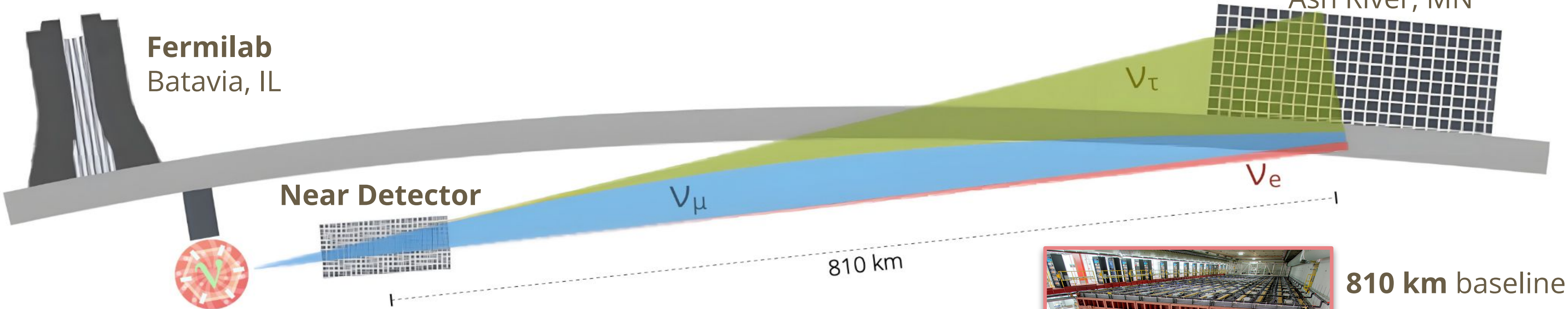
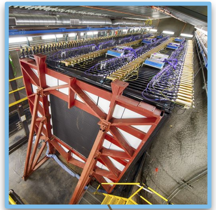
Use high-statistics in near detector to **constrain systematic uncertainties**

NOvA Experiment





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$\bar{\nu}_\mu/\nu_\mu$ disappearance
and **$\bar{\nu}_e/\nu_e$ appearance**

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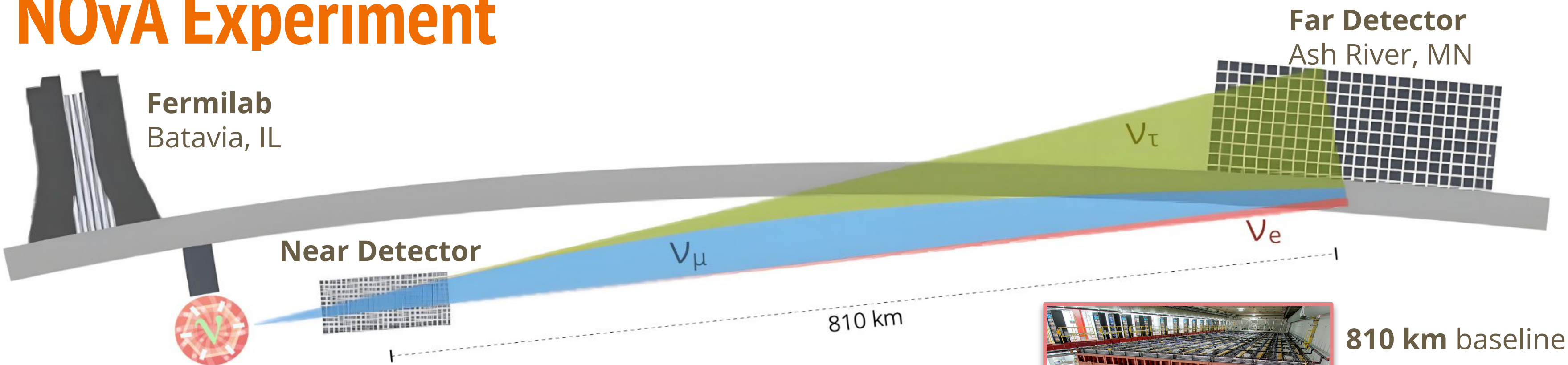

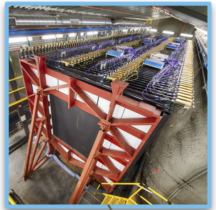

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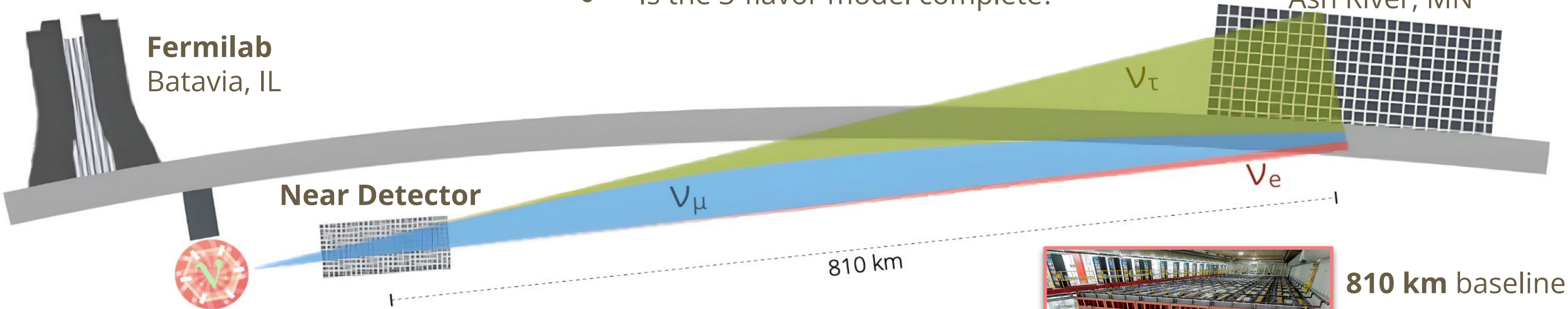
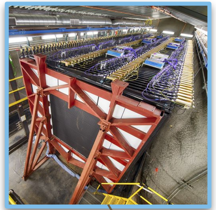
Fit oscillation parameters (Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP})
to observed FD data and simulated predictions

NOvA Experiment

NOvA addresses many compelling questions:

- What is the neutrino mass hierarchy?
- Is there CP symmetry violation in neutrinos?
- Is the 3-flavor model complete?





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High intensity, ν_μ-pure beam. Run in neutrino and antineutrino mode

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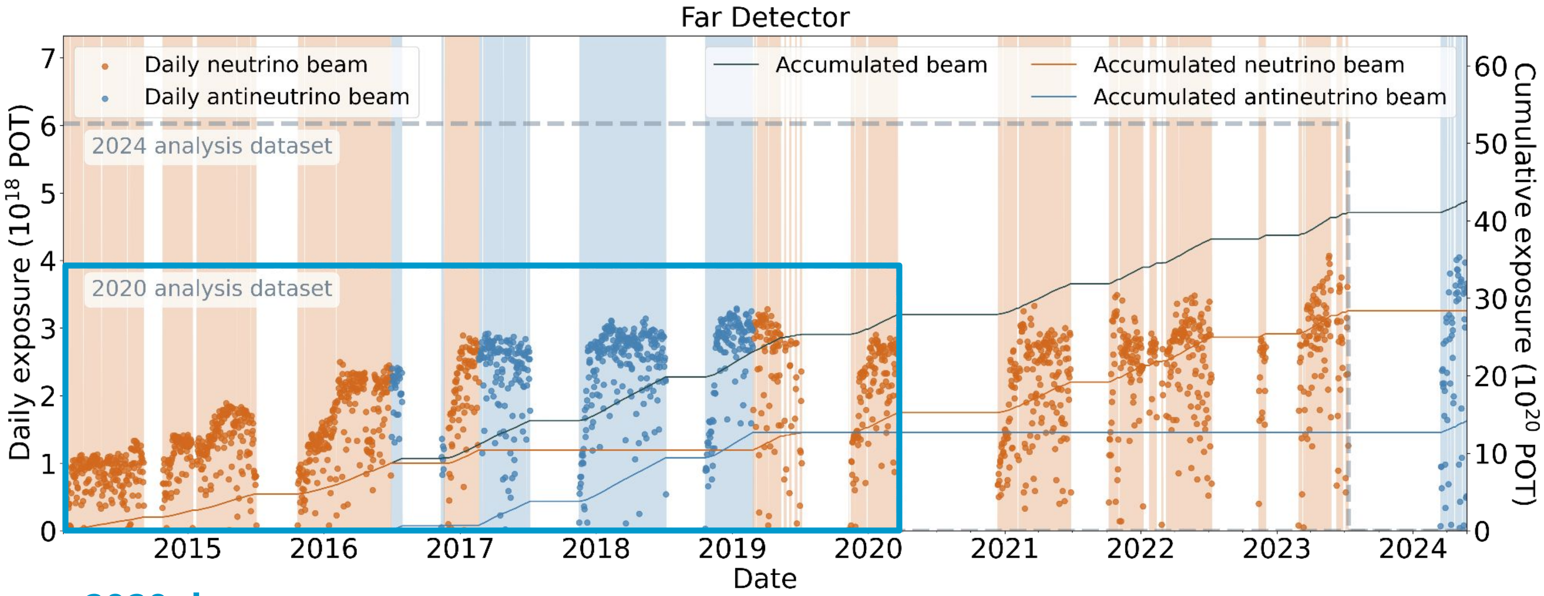
New 2024 Oscillation Result



2020 data set:

Frequentist: Phys. Rev D 106, 032004 (2022)

Sterile (ν-mode only): FNAL JETP (2022)

Bayesian: Phys. Rev. D 110, 012005 (2024)

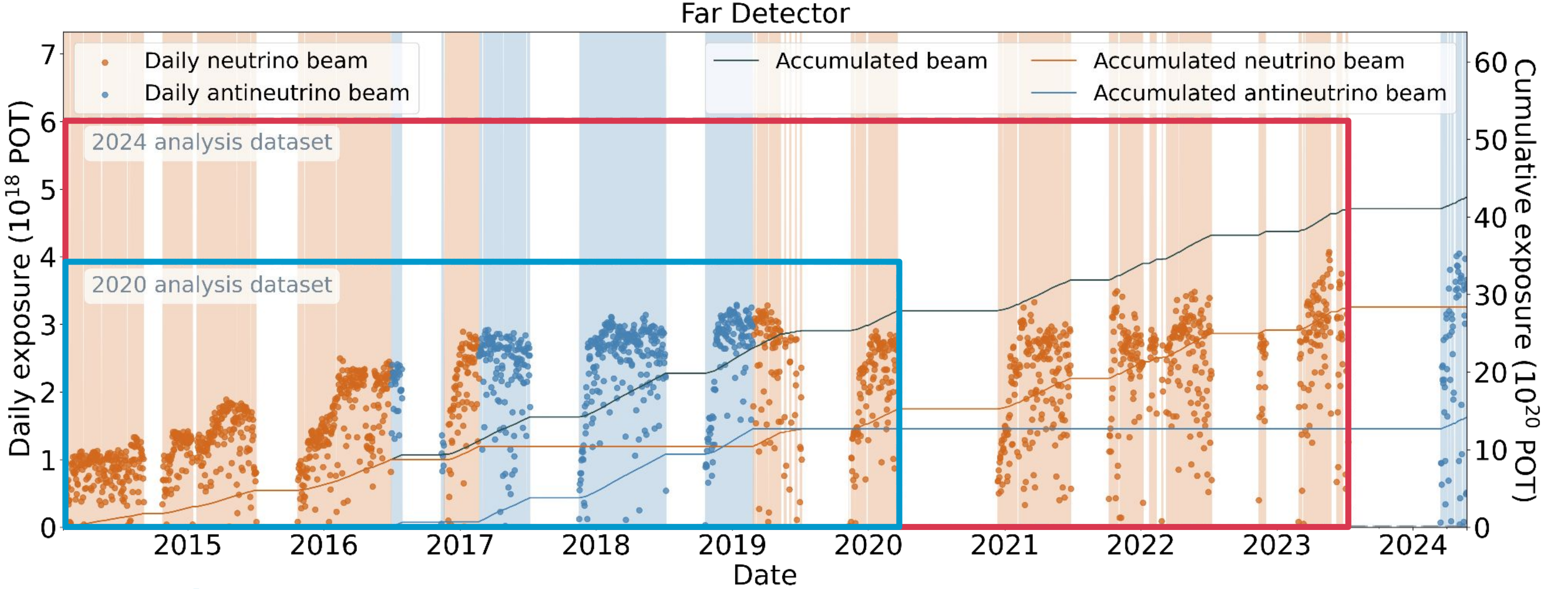
NSI: arXiv:2403.07266 (2024)

NOvA-T2K joint fit: following talk (T. Nosek)

New 2024 Oscillation Result

Celebrating **10 years of NOvA** data taking

Celebrating new 1.018MW NuMI beam power record.
See poster from K. Yonehara: Achievement in Beam Power Records for the NOvA Target System



New 2024 data set: Double the neutrino mode data since 2020!

2020 data set:
Frequentist: Phys. Rev D 106, 032004 (2022)
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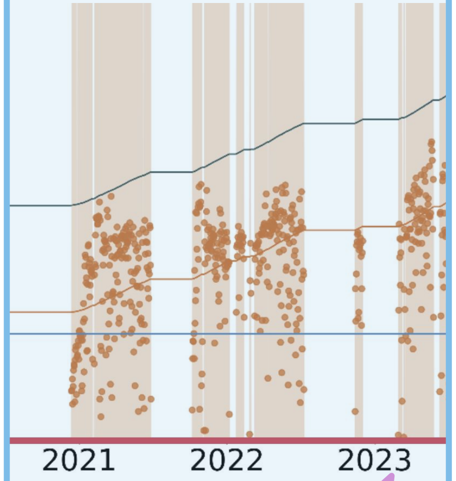
Improvements to Oscillation Analysis

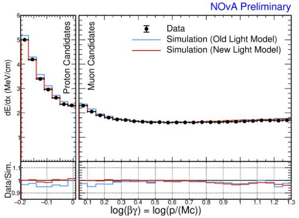
~2x Neutrino Mode Data



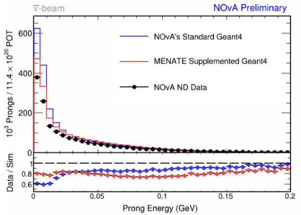
More statistics

Detector Characterization

Improved Light Production Model

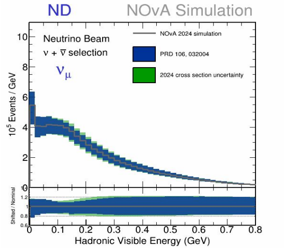


Improved n-C Scattering Model



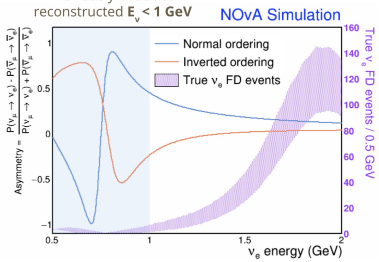
Cross Section Modeling

Additional Systematic Uncertainties for Pion Production



Low Energy ν_e Sample

New Selection to Enhance Sensitivity



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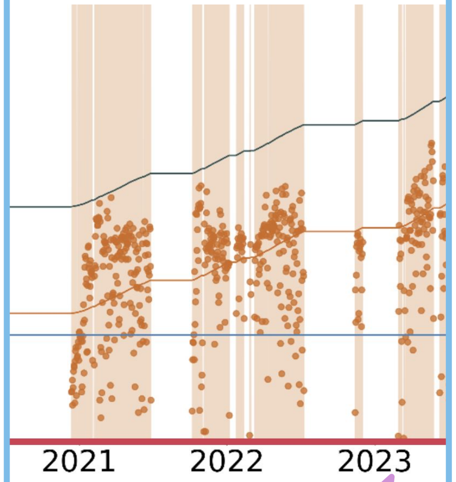

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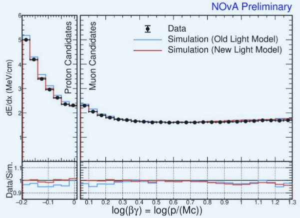

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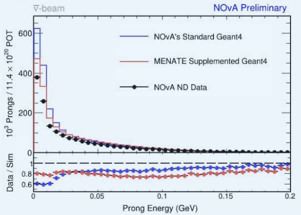

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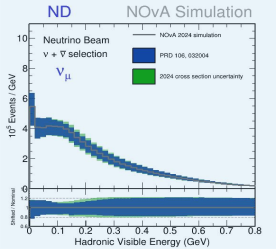

Simulation improvements

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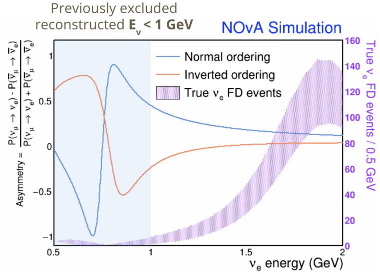

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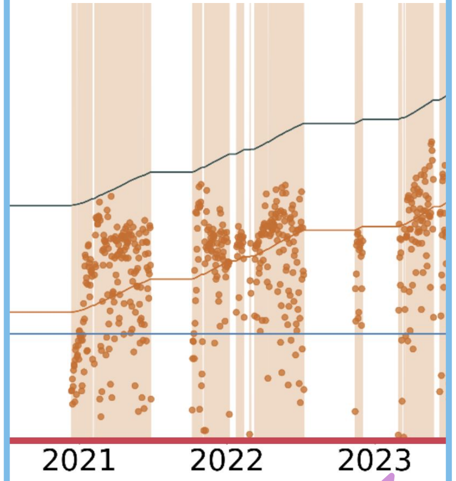

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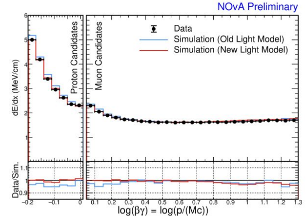

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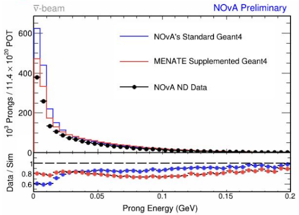

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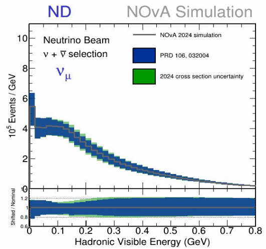

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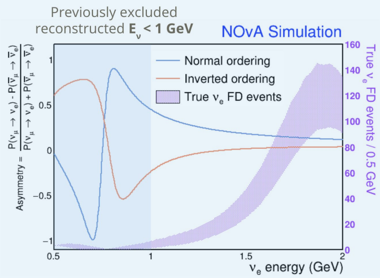
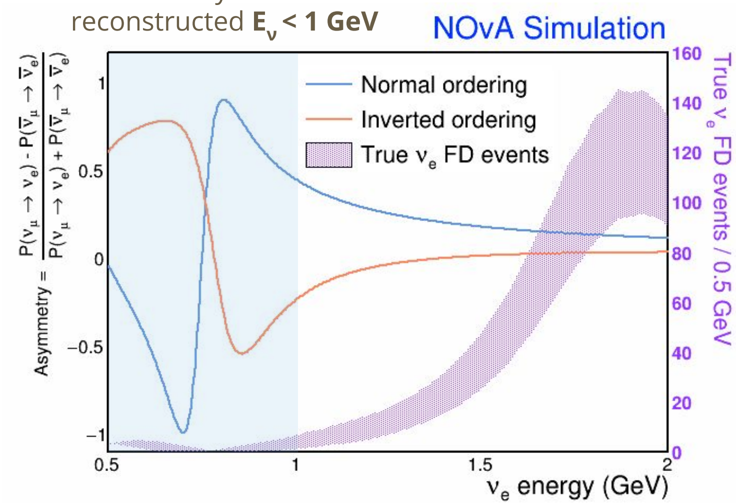


New selection

Low Energy ν_e Sample

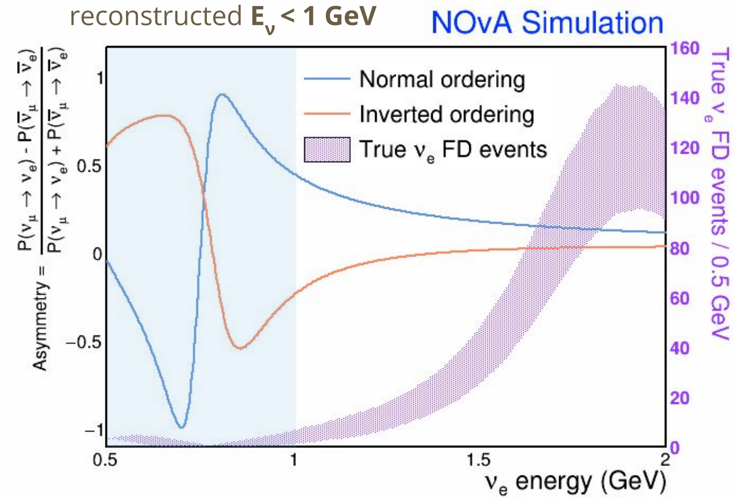
Previously excluded reconstructed $\mathbf{E_\nu < 1}$ **GeV**



Low expected event rate but maximum ordering sensitivity from $\nu_e - \bar{\nu}_e$ asymmetry at lower E_ν

Low Energy ν_e Sample

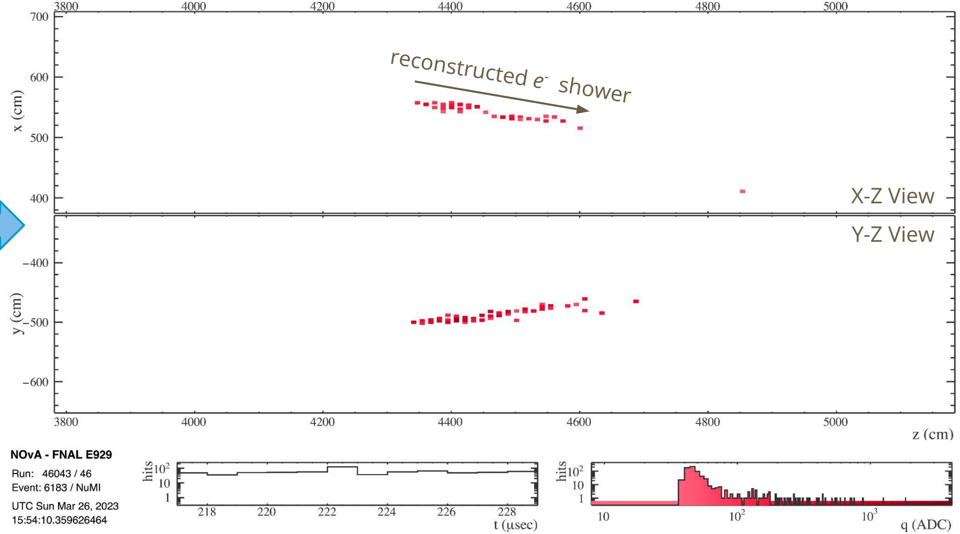
Previously excluded reconstructed E_ν **< 1 GeV**



Low expected event rate but maximum ordering sensitivity from ν_e– $\bar{\nu}_e$ asymmetry at lower E_ν

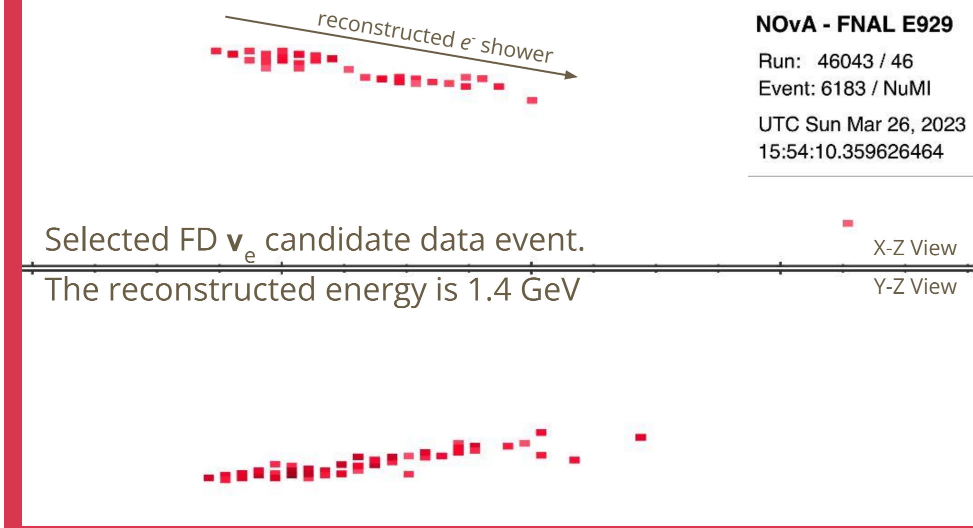
Neutrino-mode data event selected in the far detector by the low energy ν_e 2024 analysis.

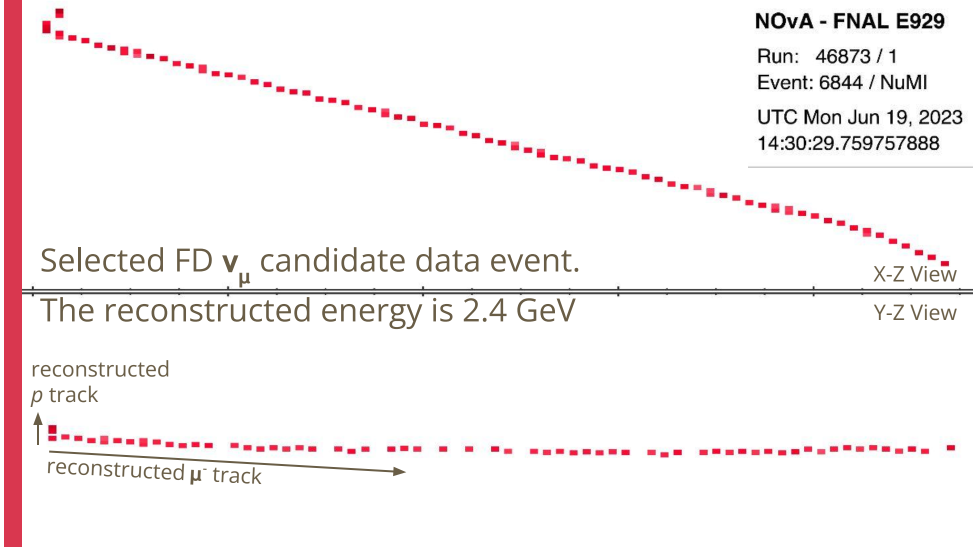
The reconstructed energy is 1.4 GeV.



Designed new selection to retain more ν_e candidates in the 0.5 GeV≤ reconstructed E_ν≤ 1.5 GeV range using BDT to reject backgrounds

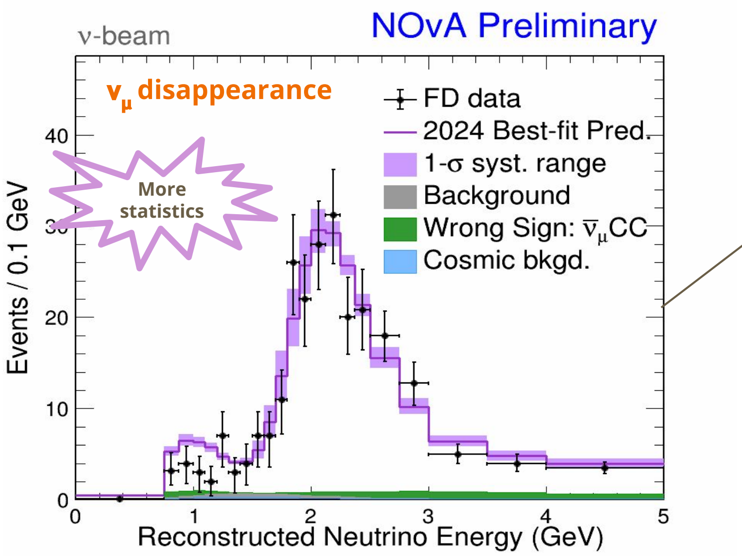
Results with 2024 Data Set

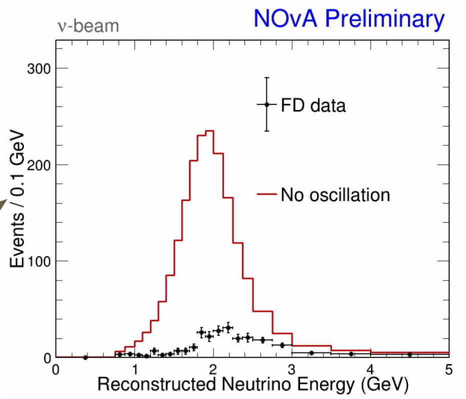




Simulation improvements

Far Detector Muon (Anti)Neutrinos



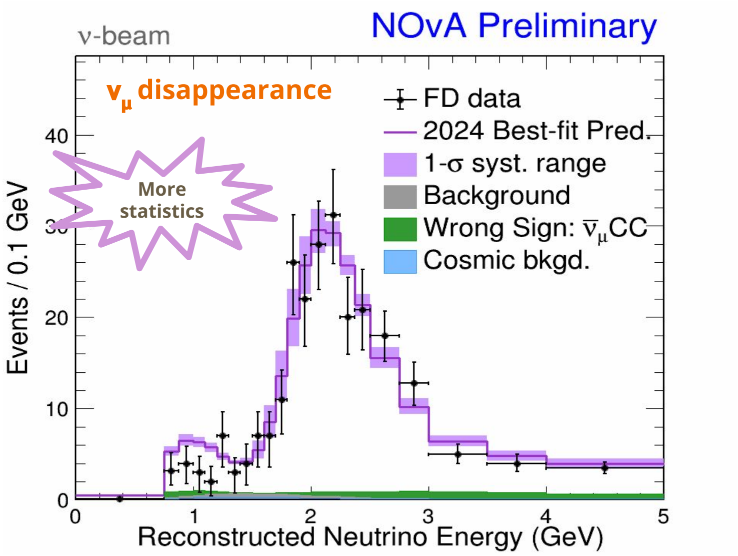


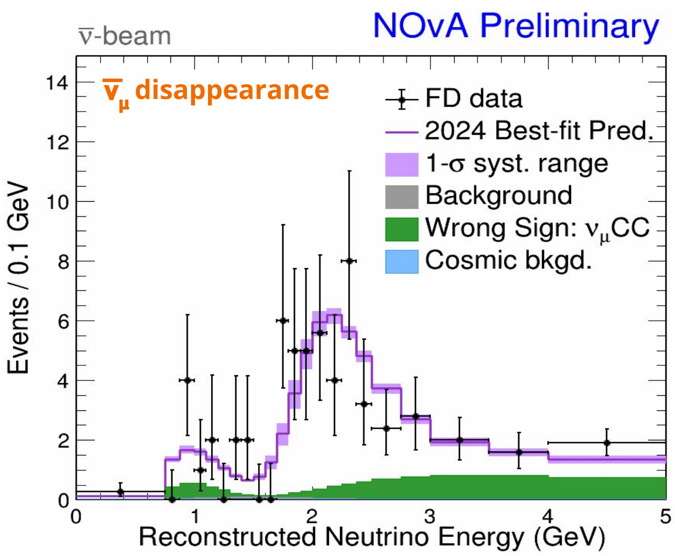
Clear oscillation signature as compared to no-oscillation prediction

We observe 384 ν_μ and 106 $\bar{\nu}_\mu$ candidates in the FD. The central value and uncertainties are constrained by selections in the high-statistics, functionally identical ND via extrapolation.

Far Detector Muon (Anti)Neutrinos

Simulation improvements





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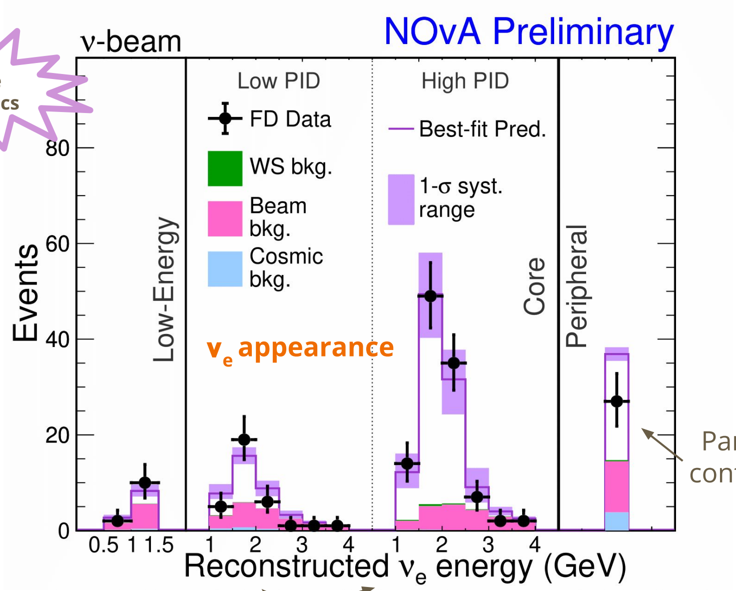
Far Detector Electron (Anti)Neutrinos

Simulation improvements

More statistics



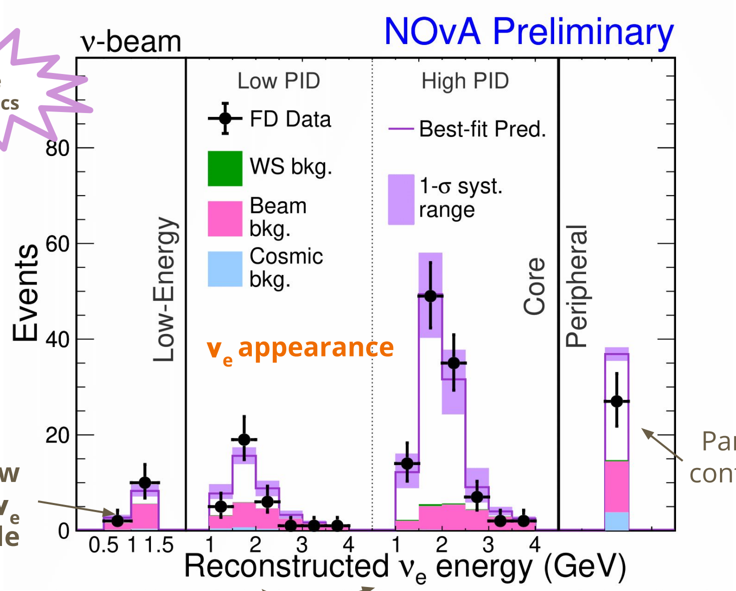
Partially contained

fully contained, split by PID

We observe 181 ν_e and 32 $\bar{\nu}_e$ candidates in the FD. The central value and uncertainties are similarly constrained by near-far detector extrapolation.

Far Detector Electron (Anti)Neutrinos

Simulation improvements



More statistics

ν_e appearance

New low energy ν_e sample

New selection

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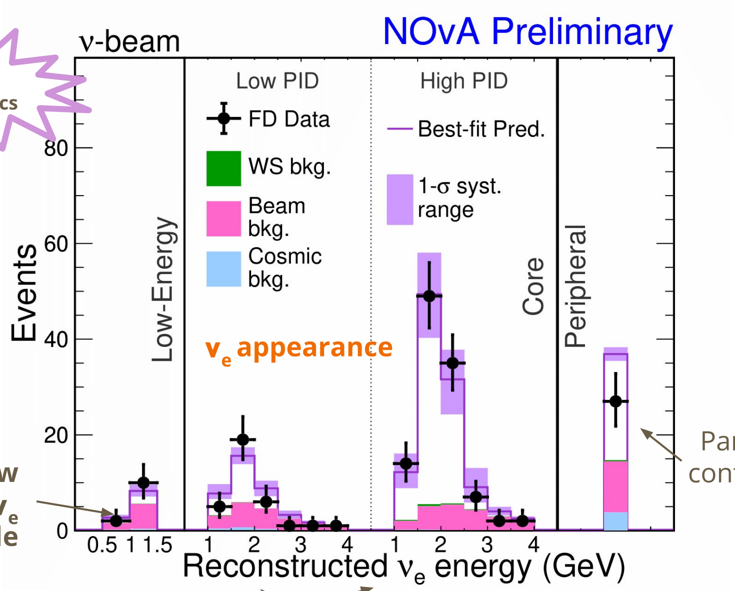

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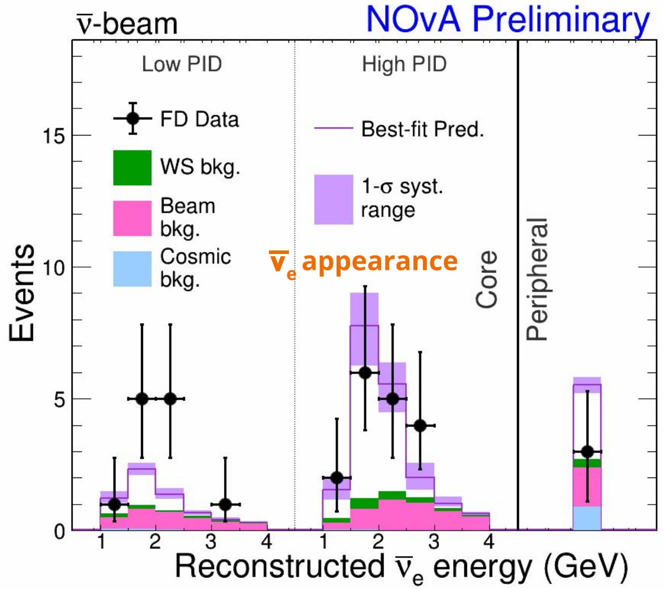

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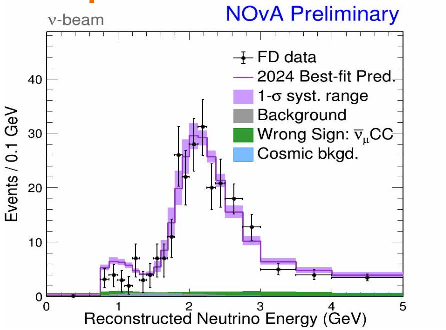
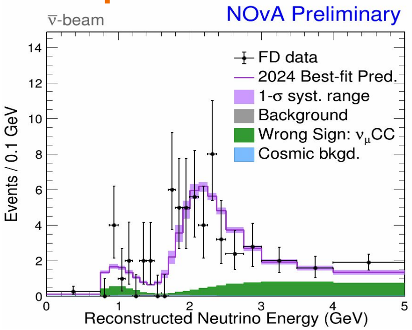
Fit to Oscillation Parameters

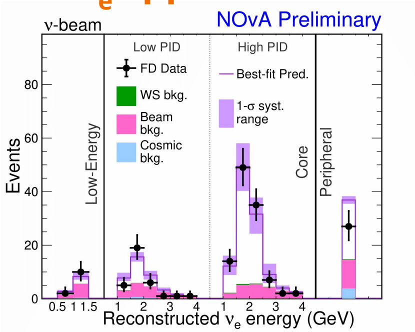
ν_μ disappearance



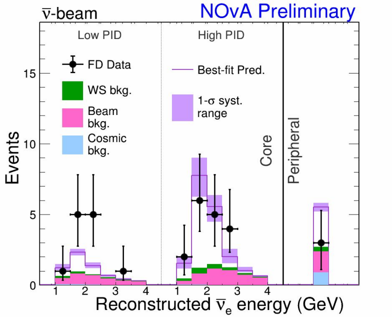
$\bar{\nu}_\mu$ disappearance



ν_e appearance



$\bar{\nu}_e$ appearance

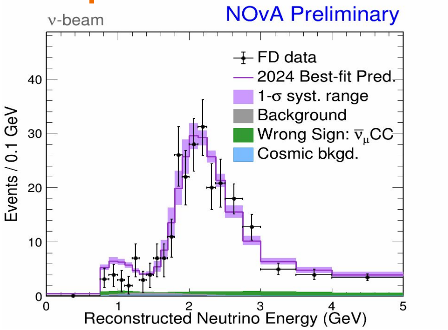


Fit to Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}

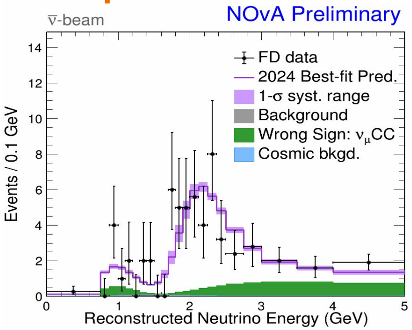
Phys. Rev. Lett. 130, 161802 (2023)

Fit to Oscillation Parameters

ν_μ disappearance



$\bar{\nu}_\mu$ disappearance



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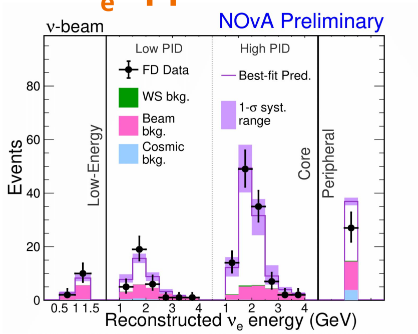
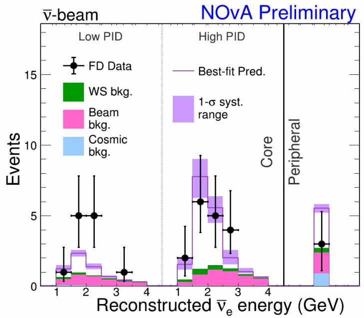


$\bar{\nu}_e$ appearance



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

Consider three θ_{13} possibilities:

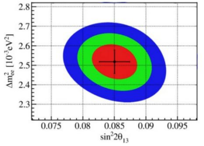
θ_{13} unconstrained (NOvA only)

or

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

or

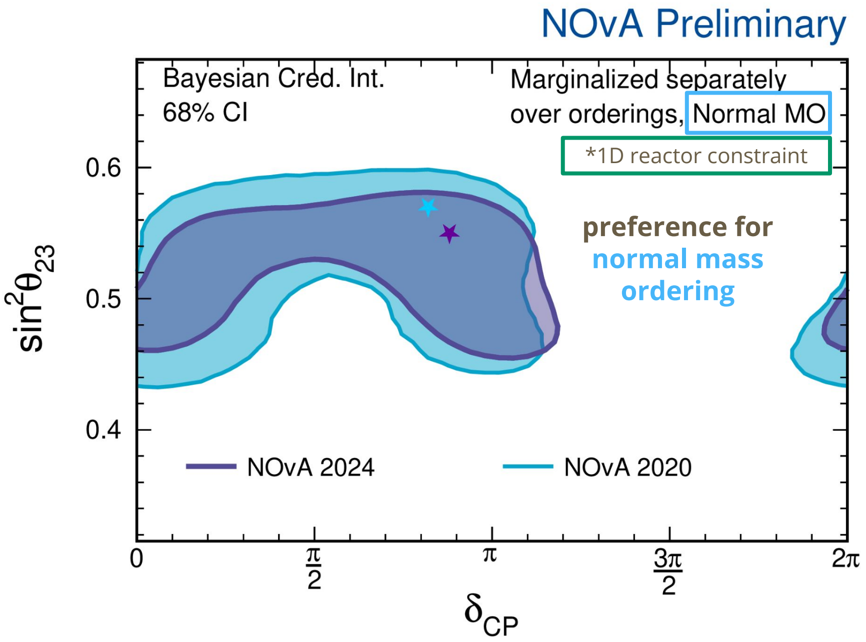
Daya Bay 2D (Δm^2_{32}, θ_{13}) constraint

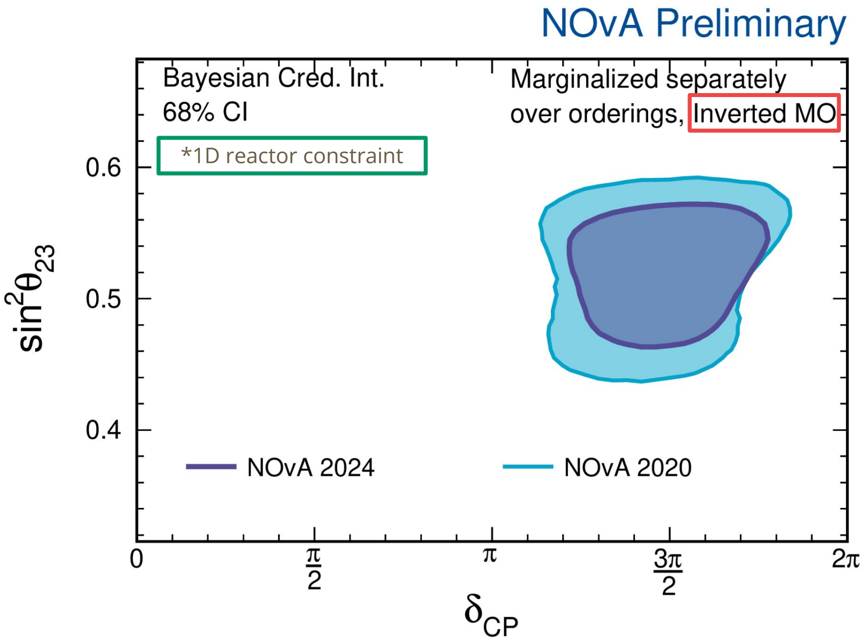


*Note: results use different choices of 1D reactor constraint
NOvA 2020: 2019 PDG avg θ13
NOvA 2024: Daya Bay 2023 1D θ13

Comparison 2020 and 2024 Results

See strong consistency between 2020 and 2024 results, with the improved constraint in ~same regions



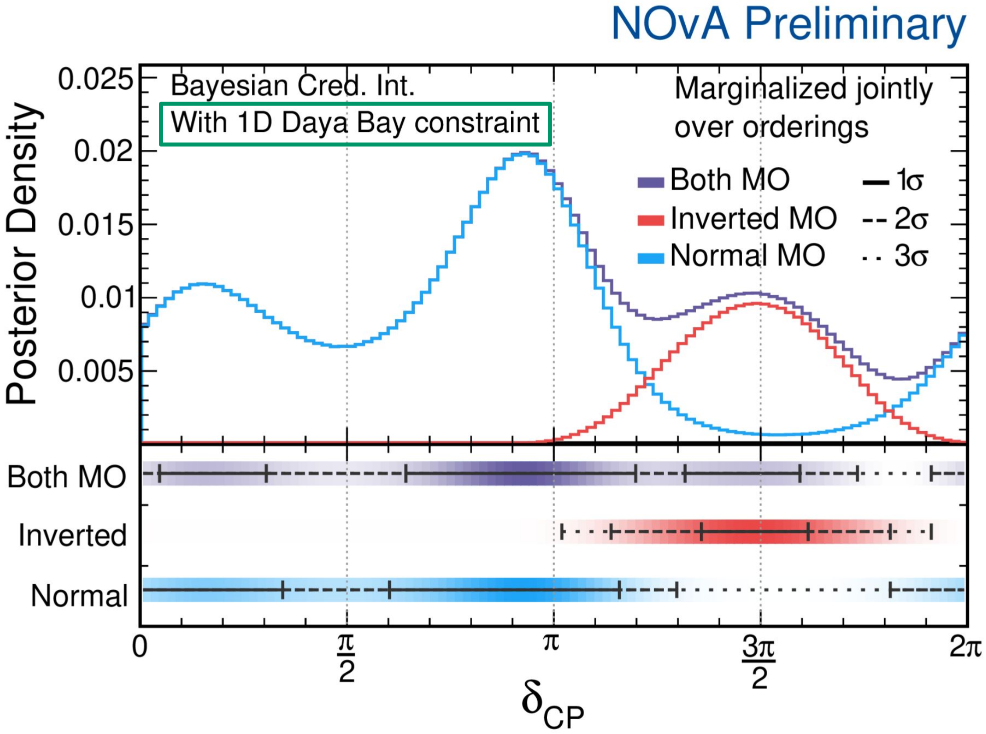


2024 Results: δ_{CP}

Statements on δ_{CP} dependent on mass ordering determination

CP-conserving points favored in **normal ordering**

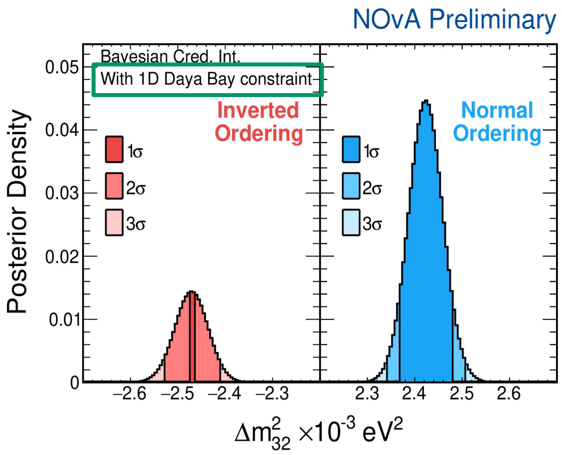
CP-conservation outside 3σ interval in **inverted ordering**, preference around maximal violation at $3\pi/2$



Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

2024 Results: Δm^2_{32}

Small preference for **normal mass ordering**

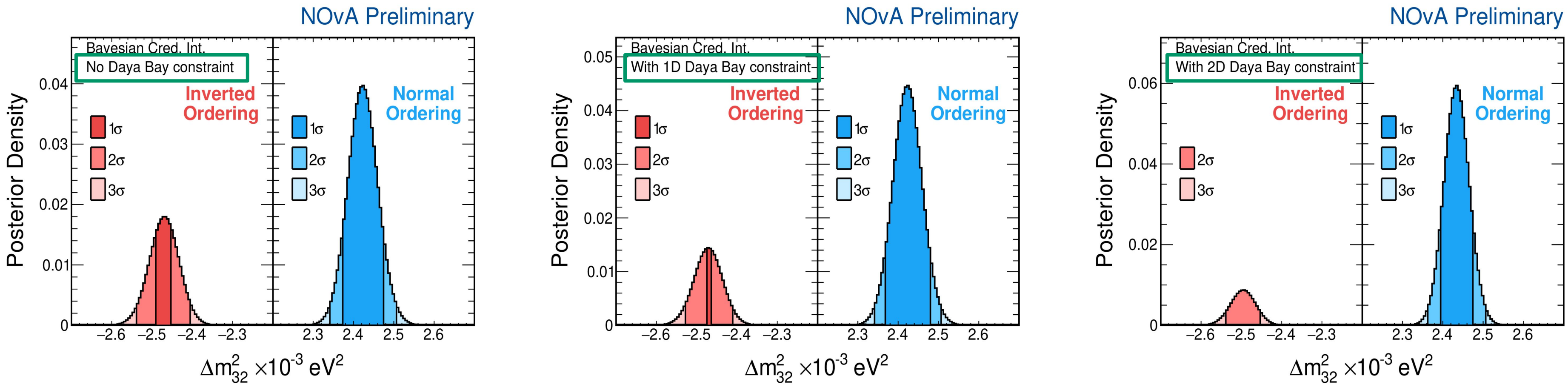


	Daya Bay 2023 1D $\sin^2 2\theta_{13}$	
	Probability	Bayes Factor
Normal MO preference	**76%**	3.2

Phys. Rev. Lett. 130, 161802 (2023)
Phys.Rev.D 72 013009 (2005)

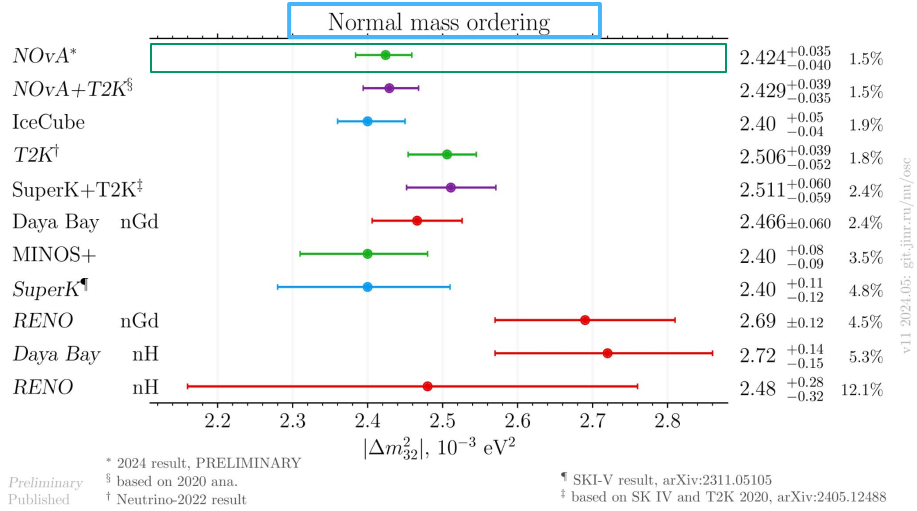
2024 Results: Δm^2_{32}

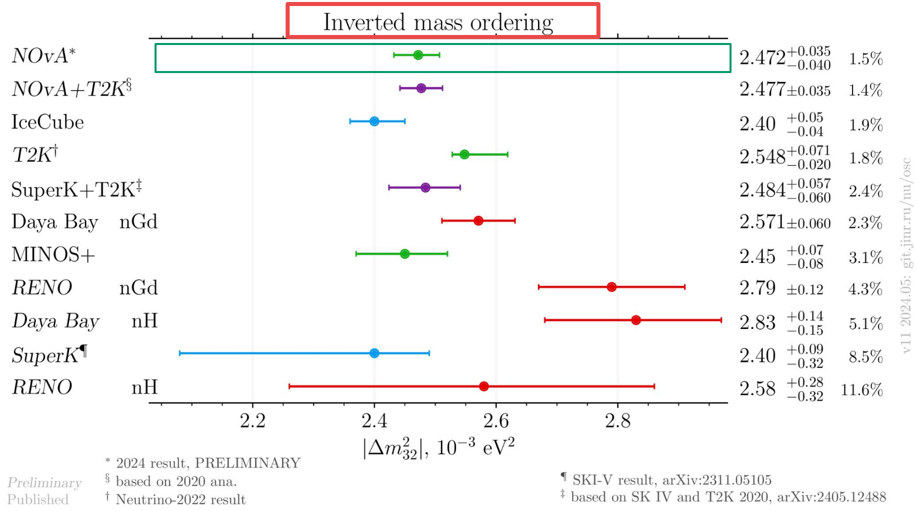
Preference for **normal mass ordering** is enhanced by choice of reactor constraint



	No constraint		Daya Bay 2023 1D $\sin^2 2\theta_{13}$		Daya Bay 2023 2D ($\sin^2 2\theta_{13}$, Δm^2_{32})	
	Probability	Bayes Factor	Probability	Bayes Factor	Probability	Bayes Factor
Normal MO preference	**69%**	2.2	**76%**	3.2	**87%**	6.8

2024 Results: Δm^2_{32}

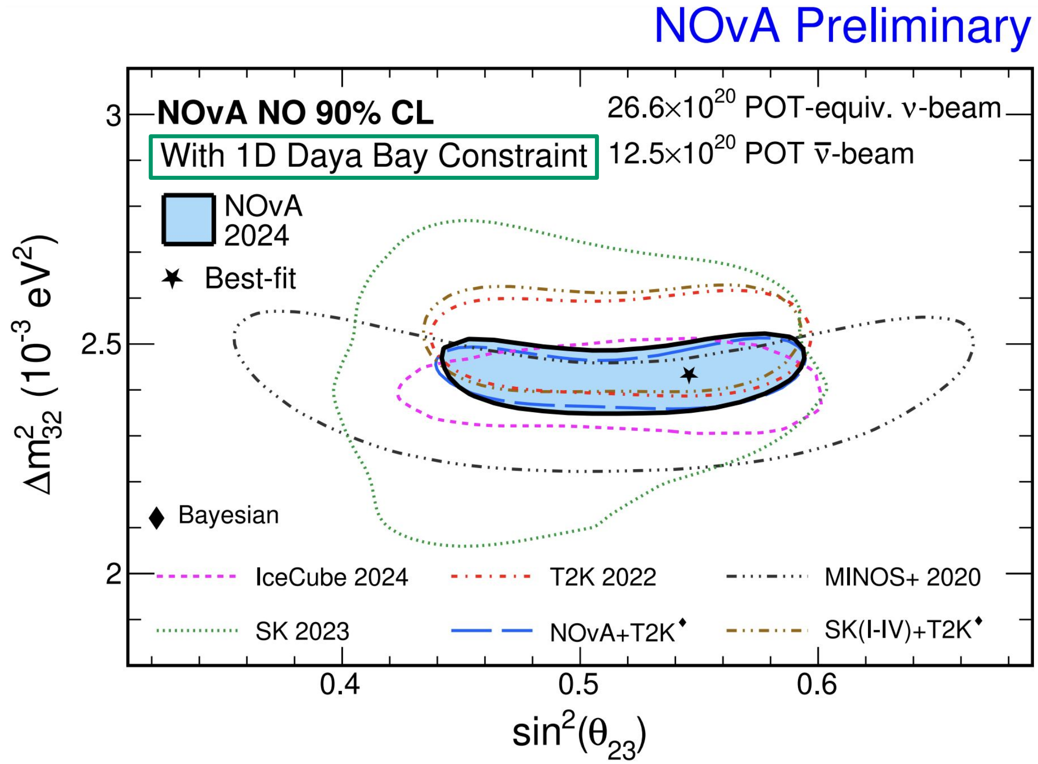




NOvA-only $|\Delta m^2_{32}|$ result has world-leading precision of ~1.5%, best single-experiment measurement.

2024 Results: $\sin^2\theta_{23}$

In the $\nu_2 - \nu_3$ sector, NOvA measurements are consistent with accelerator, atmospheric, and joint results



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

More NOvA Talks at ICHEP:

- Triple Differential Muon Antineutrino Charge Current Inclusive Cross Section Measurement in NOvA (P. Singh)
- Deep Learning Event Reconstruction at NOvA (W. Wu)

Summary

- **The new 2024 analysis is a major update to NOvA's oscillation result**
  - Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data
  - Improvements to the detector characterization, cross section uncertainties, and a new low-energy $\boldsymbol{\nu}_e$ sample
- **Most precise single-experiment measurement of Δm^2_{32} (1.5%)**
- Statements on **CP violation strongly coupled to mass-hierarchy determination**
- Strong synergy with reactor measurements
- The best is yet to come!
  - **Goal to double the anti-neutrino mode data in the final data set**
  - Test beam results could address some of the largest systematic uncertainties in NOvA
  - Broader program including sterile searches, NSI, cross section measurements, cosmic ray physics, exotics… and more!

@novaexperiment

Thanks!

ND data distributions

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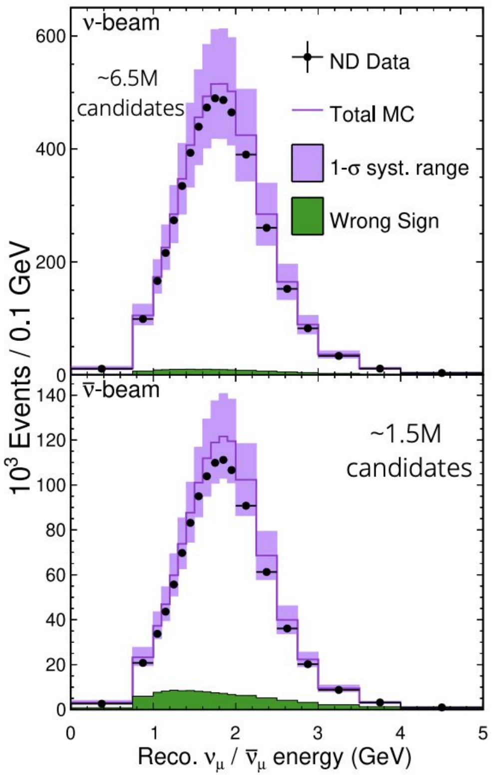
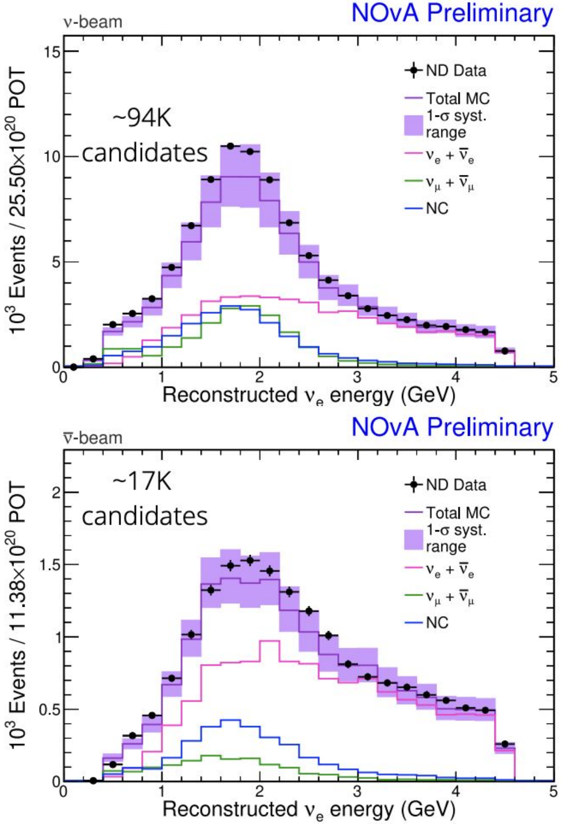
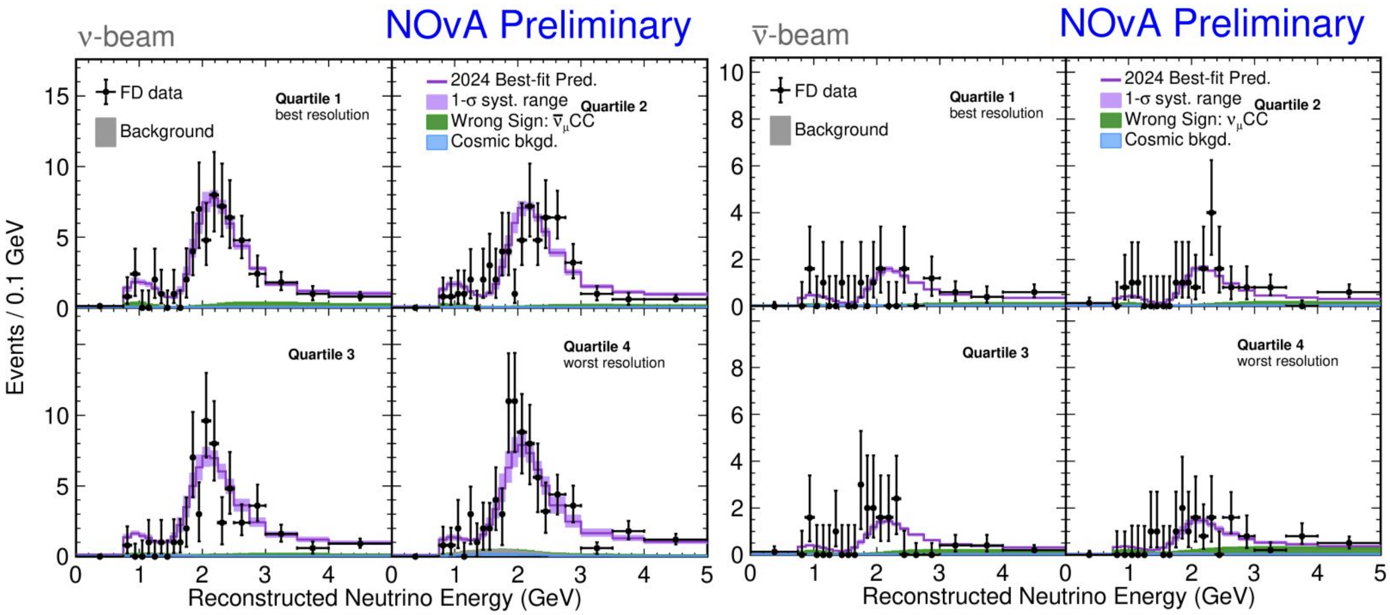
ν_μ candidates



ν_e candidates



FD data: ν_μ in E_{had}/E_ν quantiles



Extrapolation procedure is performed in

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

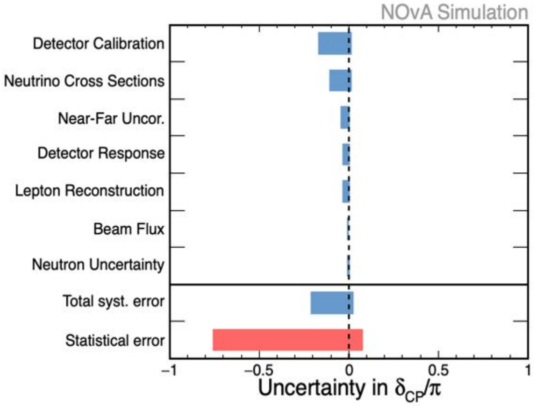
Resolutions range from Q1 6.5% (5.4%) to Q4 12.6% (11.2%) in ν ($\bar{\nu}$) mode

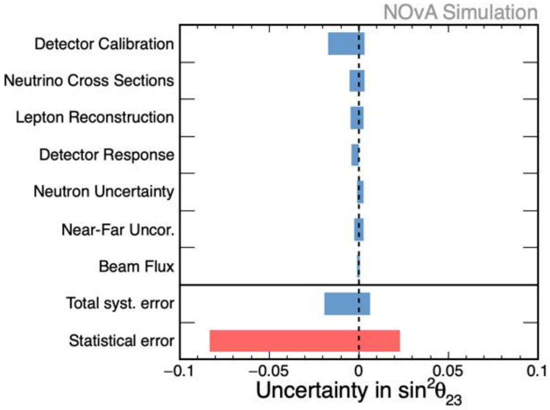
FD Selections

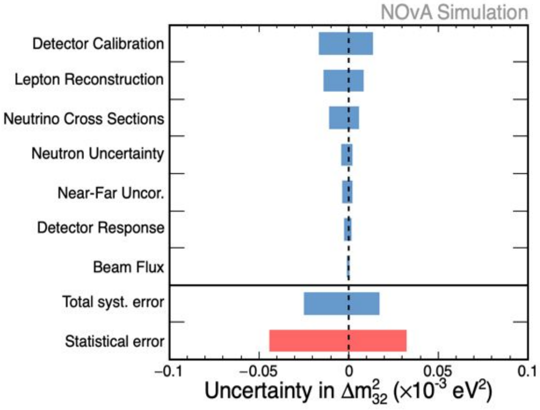
	Neutrino Beam			Anti-neutrino Beam	
	ν_μ	ν_e	LowE ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
$\nu_\mu \rightarrow \nu_\mu$	372.7	4.0	0.3	24.7	0.2
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	24.7	0.1	0.0	71.8	0.2
$\nu_\mu \rightarrow \nu_e$	0.4	121.6	2.9	0.0	2.1
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.0	1.7	0.1	0.0	18.2
Beam $\nu_e + \bar{\nu}_e$	0.1	26.3	0.8	0.0	6.5
NC	5.5	16.3	5.0	0.8	2.0
Cosmic	4.6	5.7	0.5	0.7	1.1
Others	1.5	0.8	0.1	0.2	0.1
Signal	398.2	121.6	2.9	96.7	18.2
Background	11.3	54.9	6.8	1.7	12.2
Best fit	409.5	176.5	9.7	98.4	30.4
Observed	384.0	169.0	12.0	106.0	32.0

Table: The Ana2024 observed and predicted $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance events at the Far Detector including the lowE ν_e events. The predicted number of events are scaled to the Ana2024 NOUO best-fit values.

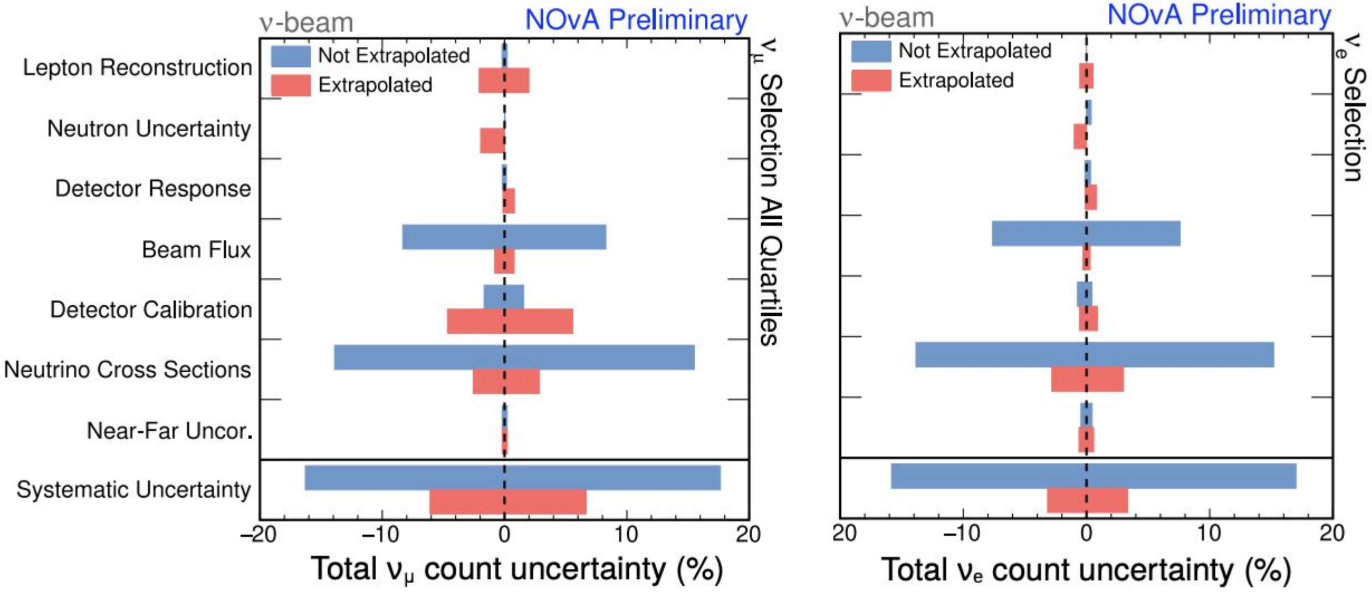
Uncertainties on Oscillation Parameters







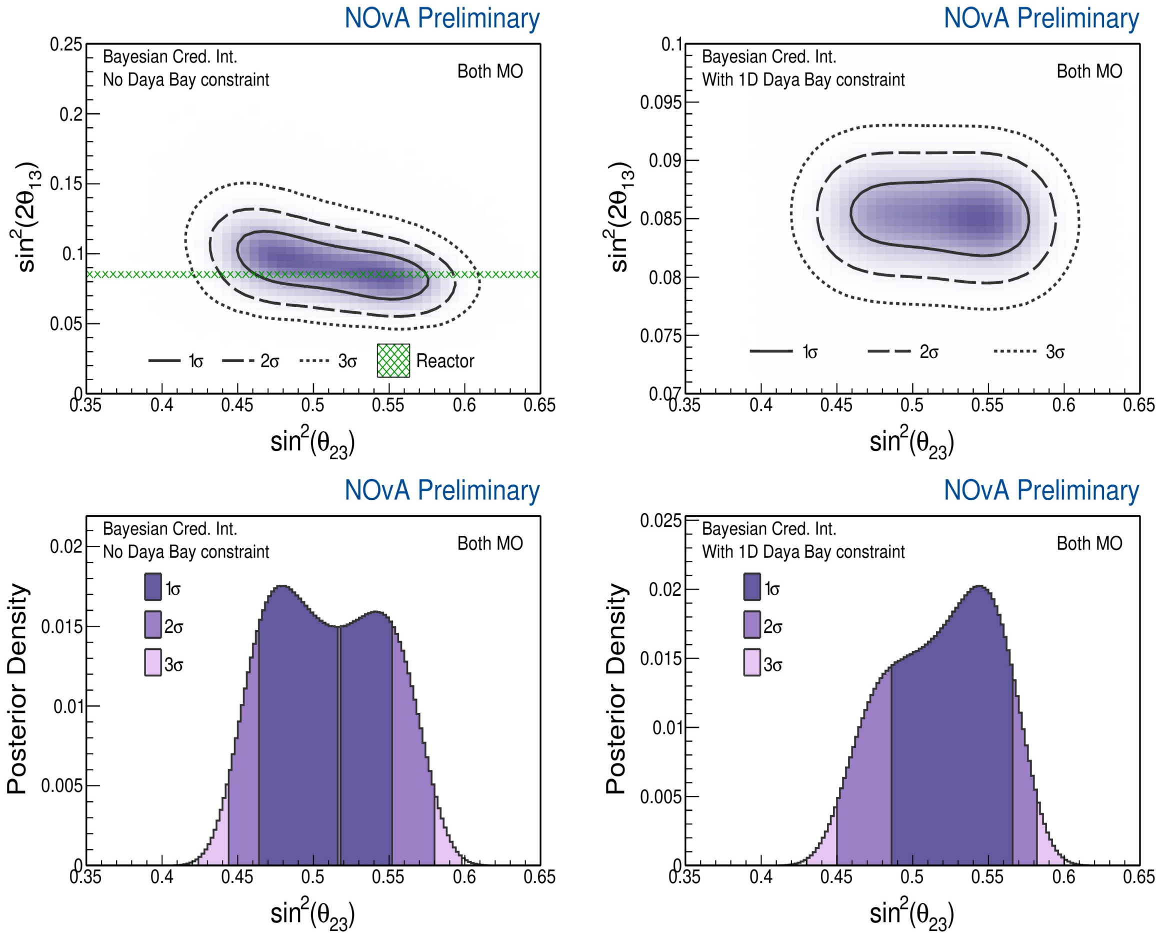
Systematic Uncertainties



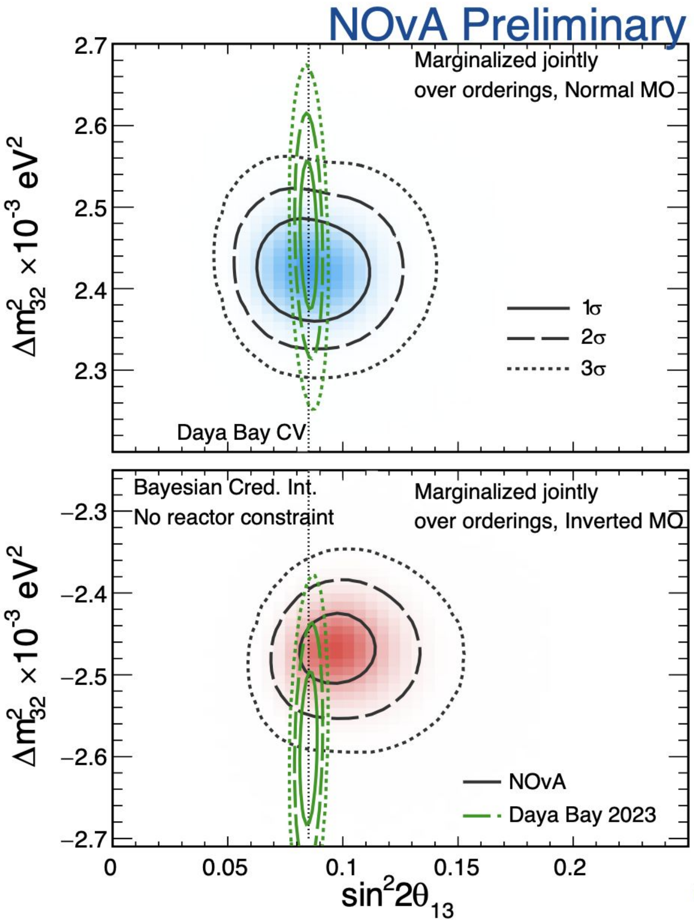
2024 Results: θ_{23}

Mild preference for upper octant (69% probability) that emerges from applying the reactor constraint

Maximal mixing is allowed at <1σ

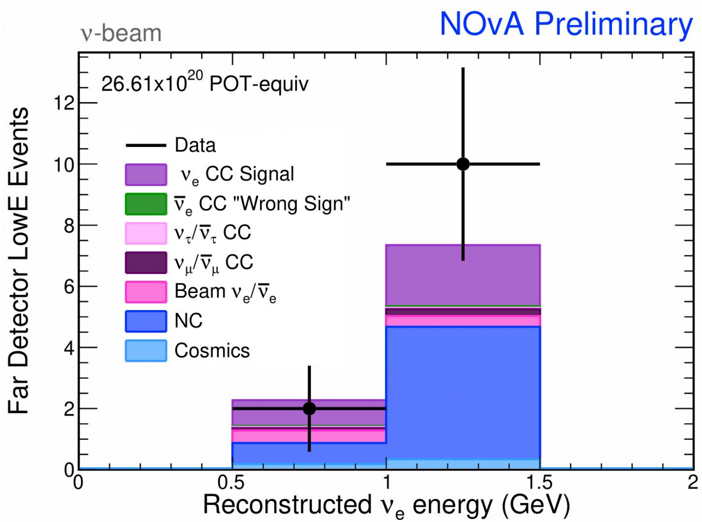


2D Daya Bay

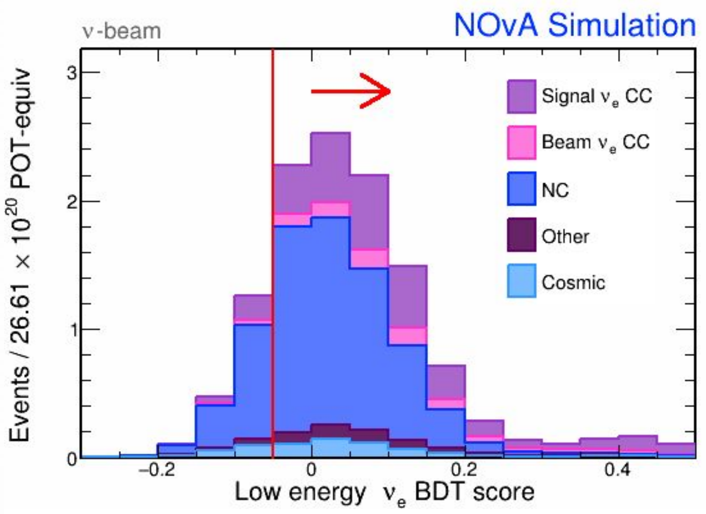


Daya Bay 2D (Δm^2_{32}, θ_{13}) constraint (PRL 130, 161802)

Low E Sample



ν-beam
NOvA Preliminary
26.61x10^20 POT-equiv
Far Detector LowE Events
Data
ν_e CC Signal
ν̄_e CC "Wrong Sign"
ν_τ/ν̄_τ CC
ν_μ/ν̄_μ CC
Beam ν_e/ν̄_e
NC
Cosmics
Reconstructed ν_e energy (GeV)

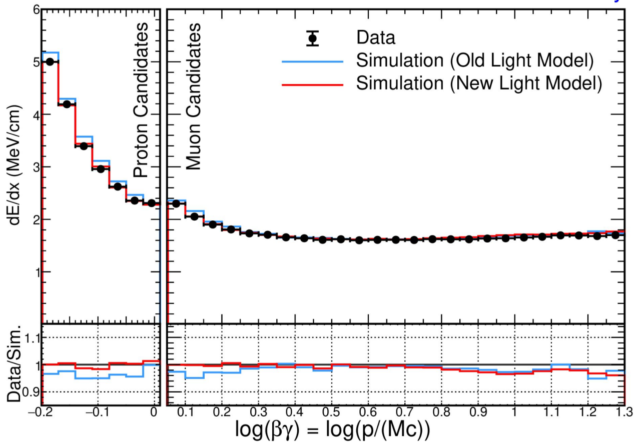


ν-beam
NOvA Simulation
Events / 26.61 × 10^20 POT-equiv
Signal ν_e CC
Beam ν_e CC
NC
Other
Cosmic
Low energy ν_e BDT score

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

Detector Characterization

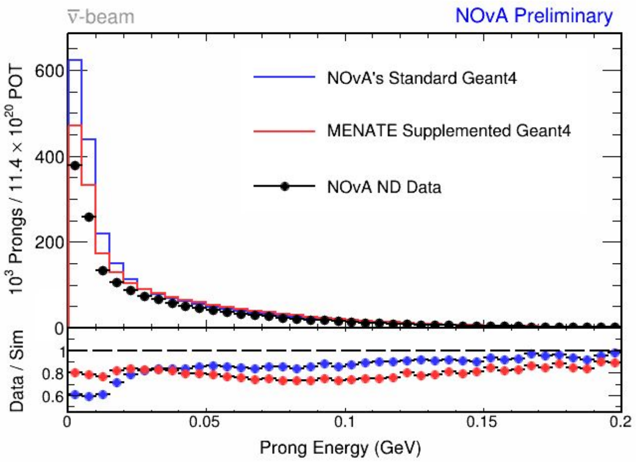
Improved Light Production Model



Better modeling of **Cherenkov and Scintillation light in both ND and FD.**

Dedicated bench measurements & in situ stopping muon and proton tracks

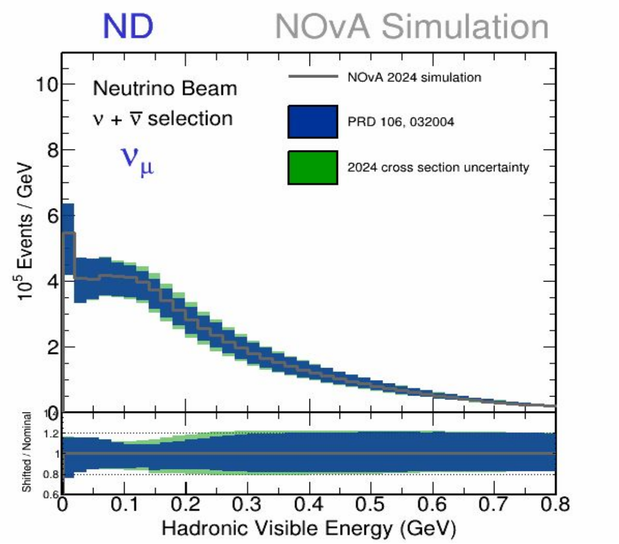
Improved n-C Scattering Model

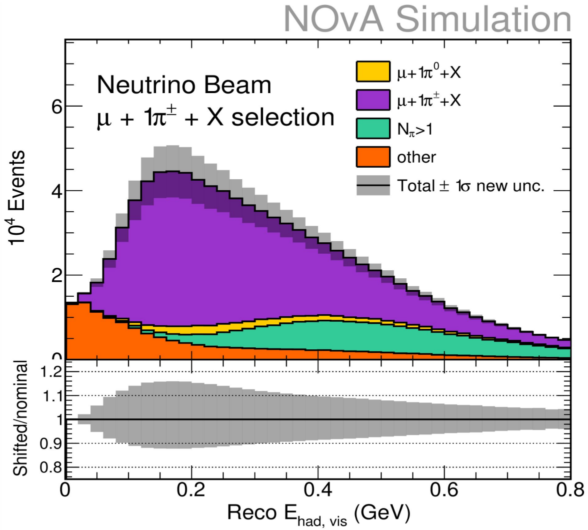


Difference between MENATE_R* and default Geant4.10.4 informs systematic uncertainty.

Cross Section Modeling

Additional Systematic Uncertainties for Pion Production





New cross section uncertainties on resonance and deep inelastic scattering interactions. Increases uncertainty on pion production around peak hadronic visible energy; modest impact on overall CC Inclusive selections.

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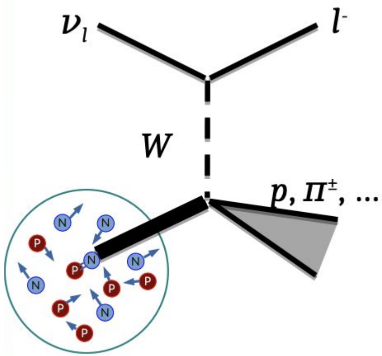
Cross section model



Base simulation: GENIE 3.0.6

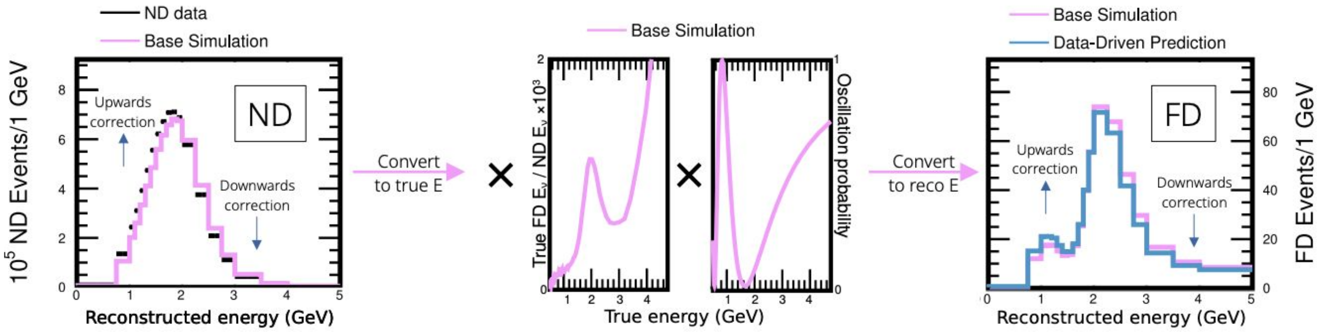
- No stock comprehensive model configuration (CMC) agrees well with data
- We choose a "theory-driven" set of models* and make *post hoc* adjustments to improve agreement

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 (Multinucleon and FSI)
(see following slides)

* We call our model collection **N1810j_00_000.** It is built by starting with GENIE's G1810b_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.

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

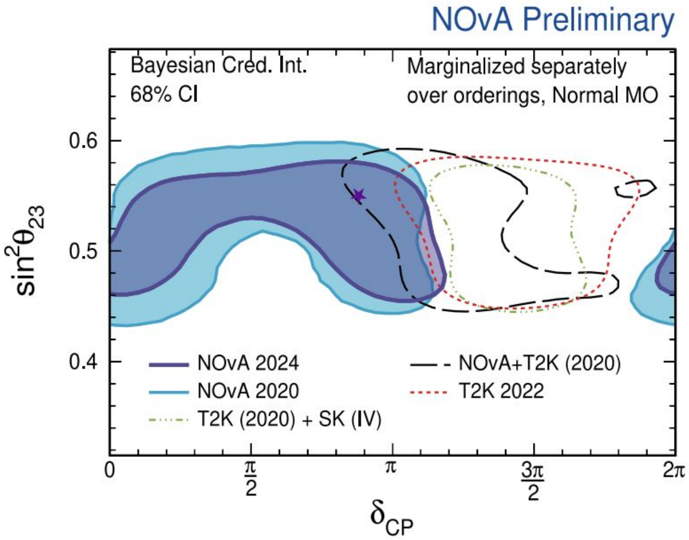
Constrain nominal prediction *and* effect of systematic uncertainties

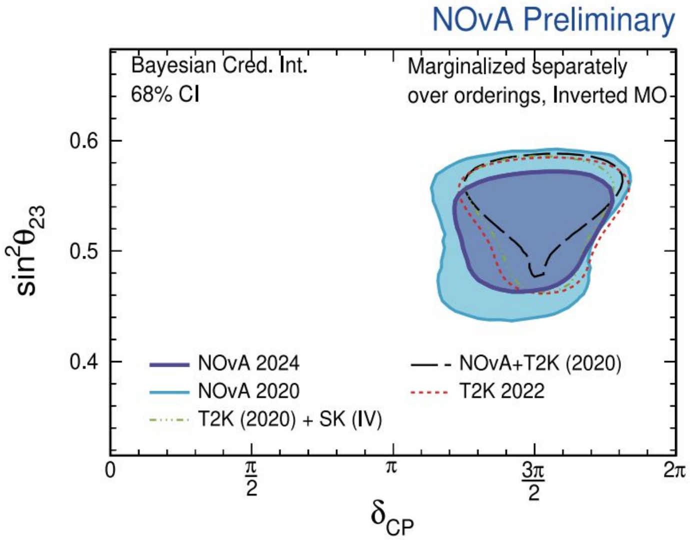
- Shift *all* elements of sim., then redo constraint
- Since post-correction all variations forced to agree at ND, spread at FD is reduced
- Effects that are not shared between detectors unaffected, or increase in some cases (e.g.: calibration)

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)

Comparisons to NOvA+T2K





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}

Alternate CCQE model: cRPA (1)

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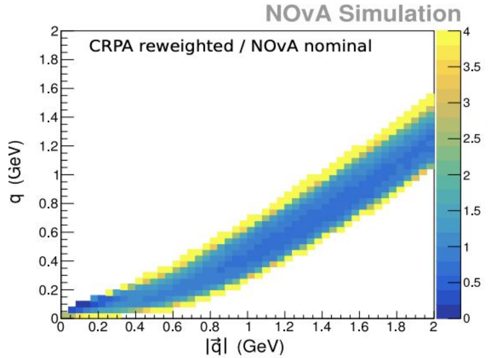
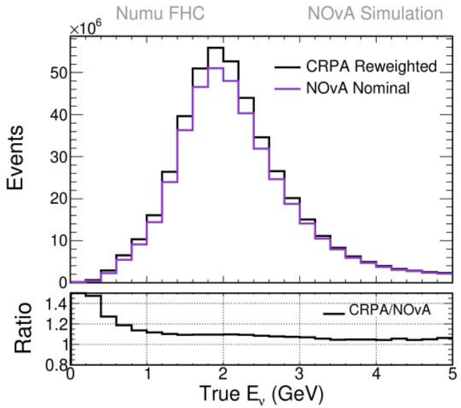
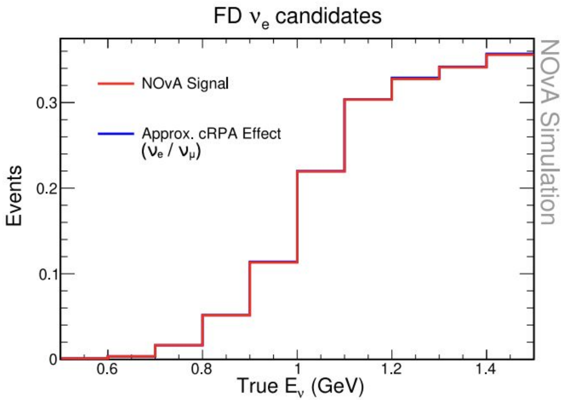


- Continuum Random Phase Approximation (CRPA) CCQE model*
  - Improved treatment of low-momentum-transfer nuclear dynamics
  - Opens additional phase space at edges of kinematically allowed region relative to base NOvA model (València)
  - Affects lowest neutrino energies most
- Studied impact on NOvA 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 ν_μ ($\bar{\nu}_\mu$) everywhere

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





Alternate CCQE model: cRPA (2)

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- 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 (except in LowE, where stat uncertainty is enormous anyway)
  - 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%