Precision measurement of neutrino oscillation parameters with NOvA

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Joint Institute for Nuclear Research

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Neutrino oscillation

Flavors are expressed as linear combinations of the mass eigenstates through the mixing matrix.

Flavor basis | accelerator, atmospheric | accelerator, short baseline reactor | solar, long baseline reactor | Mass basis

$$\begin{vmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{matrix}\Bigg\rangle = \begin{pmatrix}1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{vmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{matrix}\Bigg\rangle$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, where $c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

Oscillation probability

$$P(\nu_\alpha \to \nu_\beta) = \left|\sum_{i=1}^{n}\sum_{j=1}^{n} U^*_{\alpha i}U_{\beta j}\langle\nu_j \mid \nu_i(t)\rangle\right|^2$$

Parameters:

- three mixing angles θ_{12}, θ_{13}, θ_{23}
- CP violating phase δ_{CP}
- mass splittings $\Delta m^2_{ij} = m^2_i - m^2_j$:
  Δm^2_{21}, Δm^2_{32}, $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$

Current status of neutrino oscillation parameter measurements

Parameters (PDG2024)

$\sin^2\theta_{12} \approx 0.3$ $(\pm 3.9\%)$

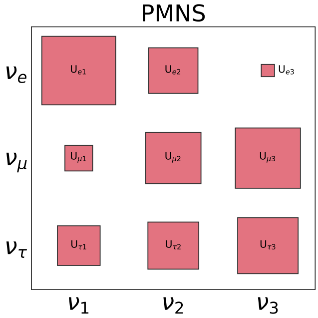
$\sin^2\theta_{13} \approx 0.02$ $(\pm 3.3\%)$

$\sin^2\theta_{23} \approx 0.5$ $(\pm 4.5\%)$

$\delta_{CP} \approx 1.2\pi$ $(\pm 20\%)$

$\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ $(\pm 2.5\%)$

$\Delta m^2_{32} \approx 2.45 \times 10^{-3}$ $(\pm 1.1\%)$ [NO]



Open questions:

- Neutrino mass ordering (NMO):
  normal $\Delta m^2_{32} > 0$ [NO] or inverted $\Delta m^2_{32} < 0$ [IO]
- θ_{23} octant:
  upper $\theta_{23} > 45°$ [UO] or lower $\theta_{23} < 45°$ [LO]
- Is charge-parity symmetry violated in lepton sector?

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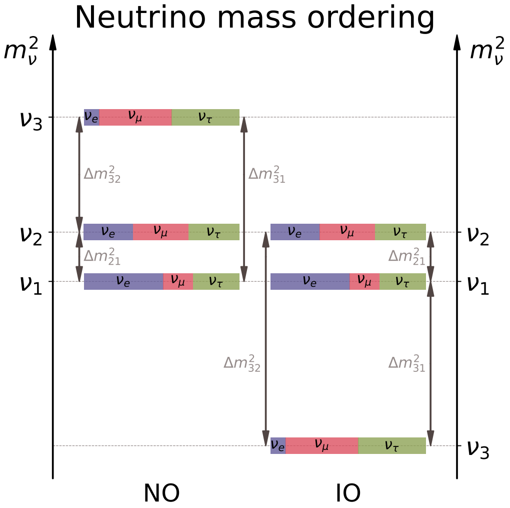
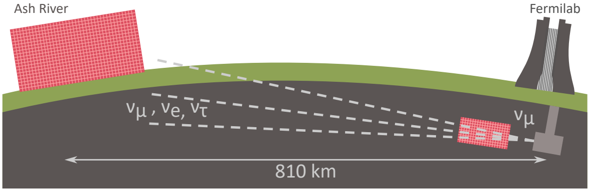


NuMI Off-axis ν_e Appearance Experiment (NOvA)



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- Neutrino source is Fermilab's Megawatt-capable NuMI beam.
- Two functionally identical, finely granulated detectors, filled with liquid scintillator.

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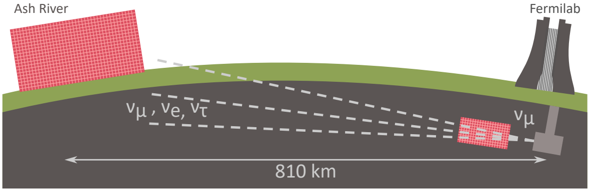

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- Neutrino source is Fermilab's Megawatt-capable NuMI beam.

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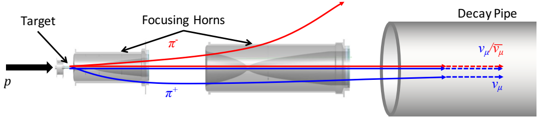
- Typical beam power of ~ 900 kW, record of 1018 kW in June 2024



- Beam purity:
  ν beam (FHC): 94% ν_μ, 5% $\bar{\nu}_\mu$, 1% $\nu_e/\bar{\nu}_e$
  $\bar{\nu}$ beam (RHC): 93% $\bar{\nu}_\mu$, 6% ν_μ, 1% $\nu_e/\bar{\nu}_e$

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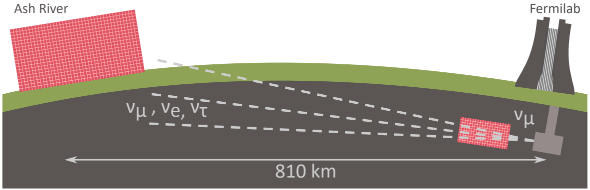

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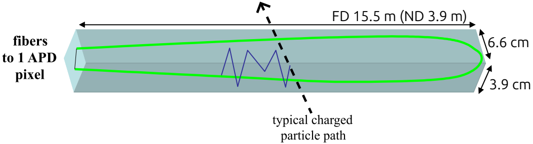
- Both detectors are composed of PVC cells, which are assembled into planes, alternating between vertical and horizontal orientations $\Rightarrow$ 3D event reconstruction

- Near (ND) ~ 300 t underground
- Far (FD) ~ 14 kt on the surface
- Centered 14.6 mrad off the beam axis



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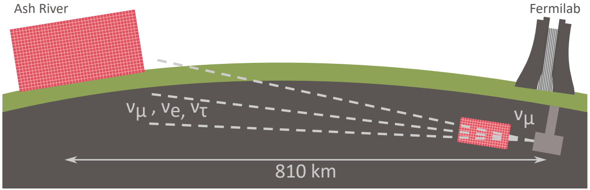

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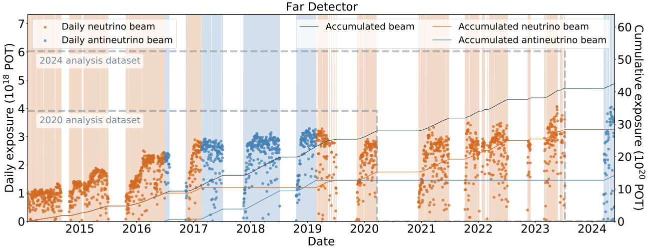
10 Years of NOvA data

- ν beam: 26.61×10^{20} POT (doubled from 2020 analysis)
- $\bar{\nu}$ beam: 12.50×10^{20} POT

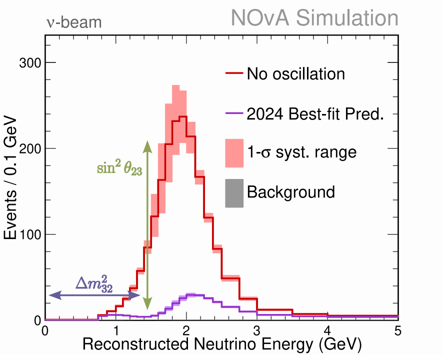


3 Flavor Physics at NOvA

$\nu_\mu(\bar{\nu}_\mu)$ disappearance

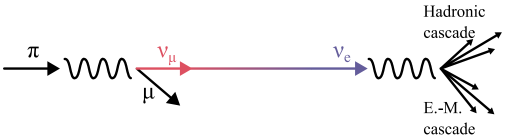
- measurement of Δm^2_{32}
- mixing angle θ_{23}

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

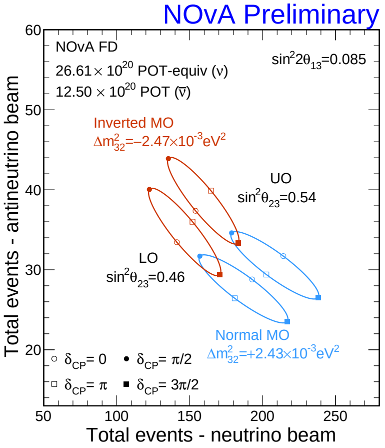


3 Flavor Physics at NOvA

$\nu_e(\bar{\nu}_e)$ appearance



- neutrino mass ordering
- CP violating phase
- θ_{23} octant
- mixing angle θ_{13}



$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha\tilde{J}\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

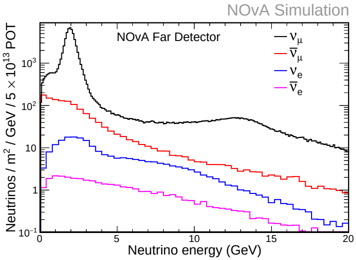
matter effect and mass ordering

ν or $\bar{\nu}$

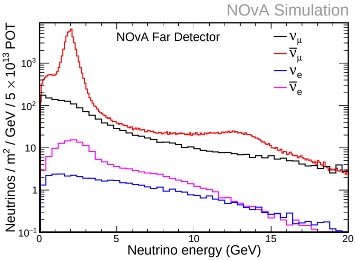
Simulation and Predictions

- **Flux**: Geant4 (v4.10) + PPTF[1] ⇒ particle production and transport through the beamline
- **Interactions**: custom model configuration of Genie 3.0.6
- **Detectors**: Geant4 and a custom readout simulation[2]
- **Particle identification and Energy reconstruction**: CVN[3] + BDT + classical algorithms
- **Extrapolation**: ND Data/MC ratios are used to correct the FD predictions.

Neutrino beam



Antineutrino beam



[1] Phys. Rev. D 94, 092005, [2] J. Phys. Conf. Ser. 664, 072002, [3] Phys. Rev. D 100, 073005

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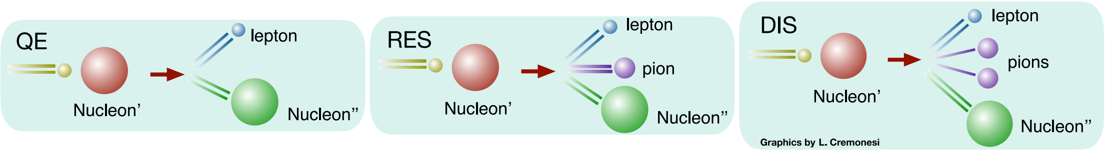

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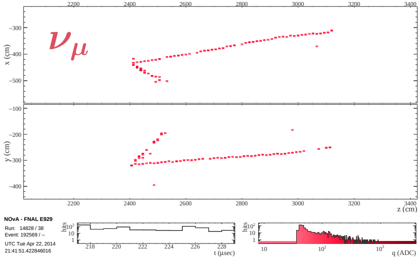
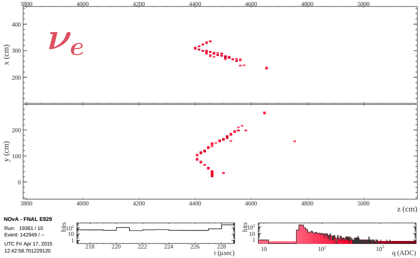


← Top view →

← Side view →



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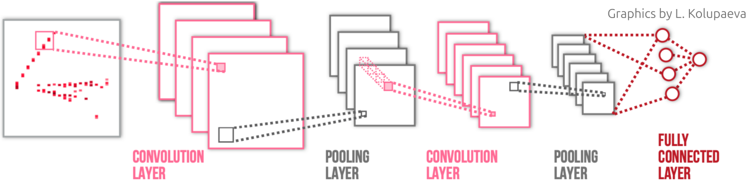

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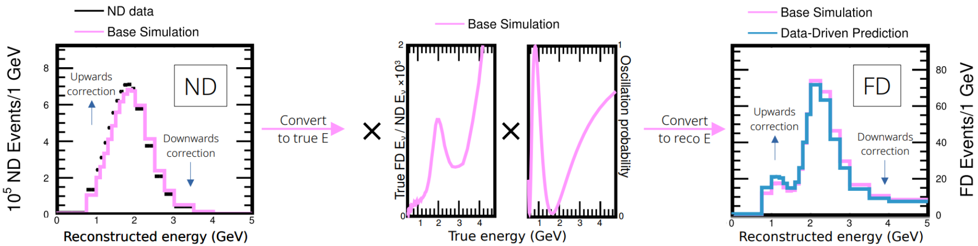

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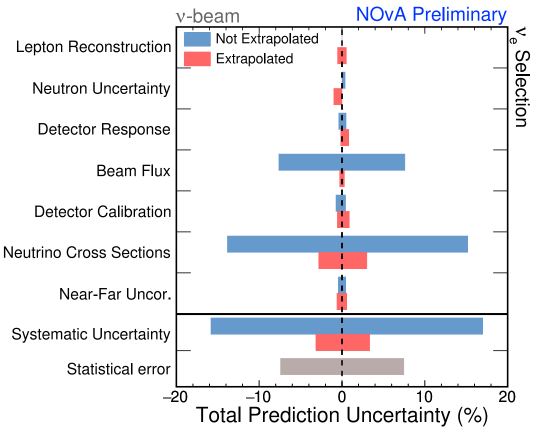
Systematic uncertainties

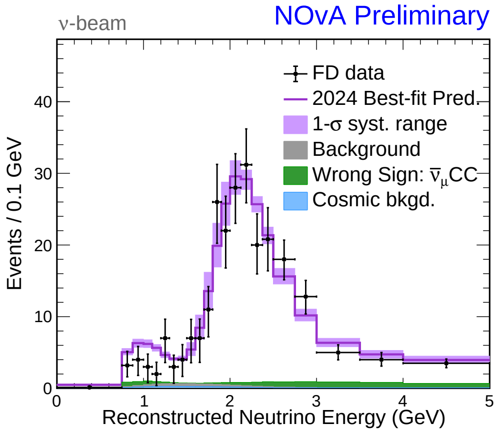


Systematic uncertainties are evaluated by varying model parameters in the simulation.

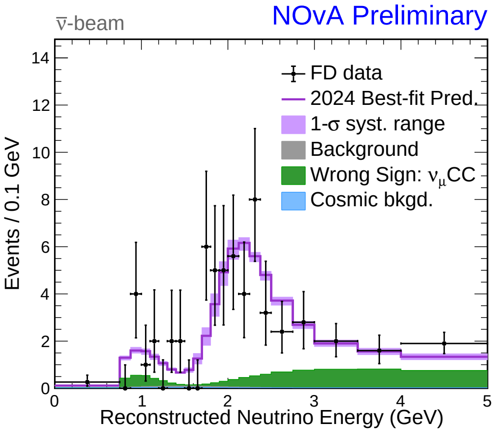
- Most uncertainty estimates are unchanged from the previous analysis[1]
- New in accounting of pion production, neutron interaction, light model
- Extrapolation reduces the impact of systematic uncertainties that are correlated between the detectors from 12–18% to 3–6.5%
- Statistical errors become the dominant contribution

[1] Phys. Rev. D 106, 032004

ν_μ far detector observations

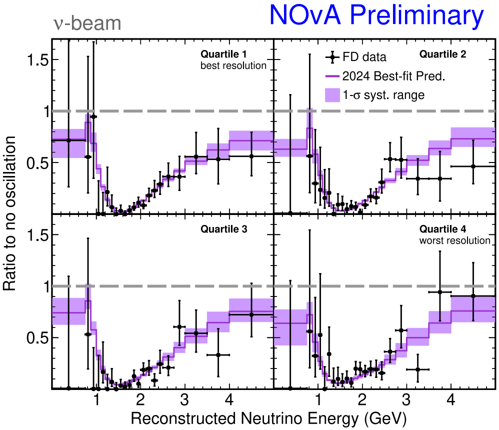


384 ν_μ candidates (expected total bkg 11.0)



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

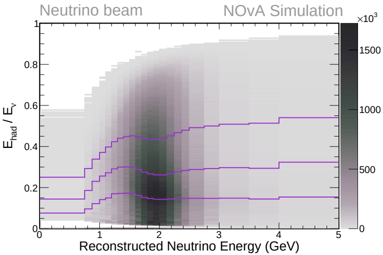
ν_μ far detector observations



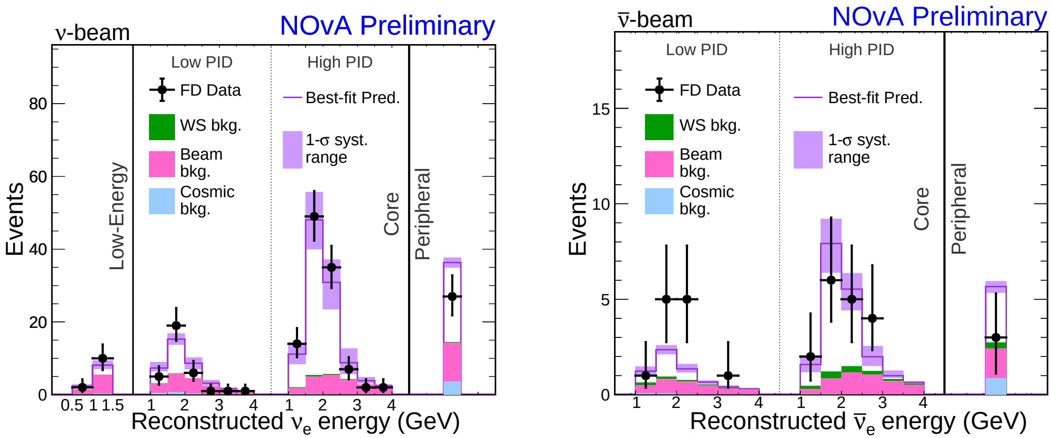
384 ν_μ candidates (expected total bkg 11.0)

NOvA's disappearance sensitivity depends on resolving the position and depth of the oscillation minimum. To improve sensitivity:

- finer energy bins near the dip
- divide the samples into bins of hadronic energy fraction (E_{had}/E_ν) and muon transverse momentum (p_T)



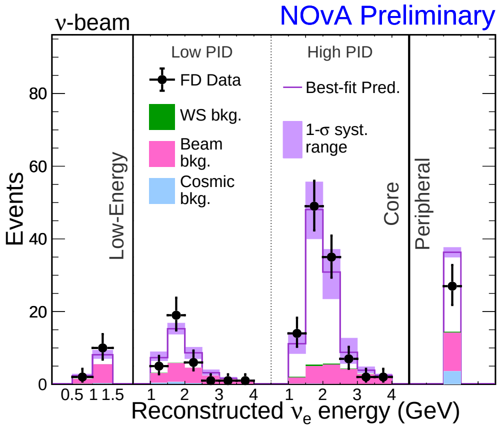
ν_e far detector observations



181 ν_e candidates (expected total bkg 62.5)

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

ν_e far detector observations



181 ν_e candidates (expected total bkg 62.5)

NOvA's appearance sensitivity relies on the ability to separate signal and background. To improve sensitivity:

- **Core**: bins of differing purities (High and Low particle identification score)
- **Peripheral**: high-confidence events with vertices outside the fiducial volume to improve sensitivity to δ_{CP}
- **Low-energy**: a brand new, independent sample "reclaims" low energy events and slightly improves sensitivity to NMO

Far detector fitting procedure

15 samples

4 $\boldsymbol{\nu_\mu}$ and 4 $\boldsymbol{\bar{\nu}_\mu}$ quartiles

+

ν_e and $\bar{\nu}_e$

Low PID, High PID, Peripheral

+

ν_e low energy sample

↓

Frequentist χ^2 minimization

profiled Feldman-Cousins[1]

Frequentist confidence regions

↓

$\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2 2\theta_{13}, \delta_{CP}$

NMO, octant θ_{23}

Constrain option:

1. NOvA only
2. 1D Reactor

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

3. 2D Daya Bay[3]

χ^2 map of $(\Delta m^2_{32}, \sin^2 2\theta_{13})$

Fixed parameters[4]:

$\sin^2\theta_{12} = 0.307$

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

- Poisson log-likelihood ratio
- 2 complementary analyses
- 3 options of external θ_{13} constraints
- 4 oscillation parameters with both hypotheses of NMO

[1] JINST 20 T02001, [2] Phys. Rev. D 110, 012005, [3] Phys. Rev. Lett. 130, 161802, [4] PDG 2023

Far detector fitting procedure

15 samples

4 $\boldsymbol{\nu_\mu}$ and 4 $\boldsymbol{\bar{\nu}_\mu}$ quartiles

$+$

ν_e and $\bar{\nu}_e$

Low PID, High PID, Peripheral

$+$

ν_e low energy sample

Bayesian
Markov Chain Monte Carlo
marginalization[2]
Bayesian credible regions

$\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2 2\theta_{13}, \delta_{CP}$
NMO, octant θ_{23}

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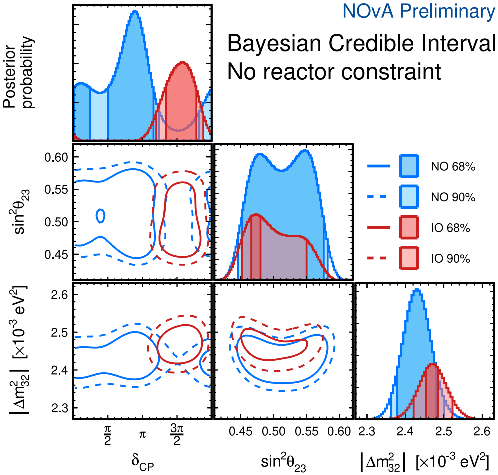
Oscillation analysis results



- Posterior-predictive p-values: 0.48
- δ_{CP}: no clear preference for either CP violation or conservation
- θ_{23}: the data favor regions of parameter space close to maximal mixing, with no significant preference for octant
- Δm^2_{32}: improved precision provides an additional lever for probing the NMO

These results are consistent with previous NOvA analyses[1] and other experiments

[1] Phys. Rev. D 106, 032004, Phys. Rev. D 110, 012005

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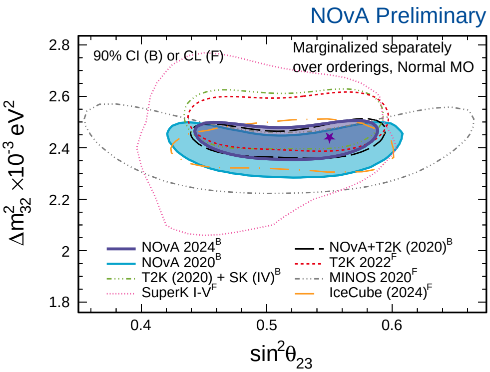

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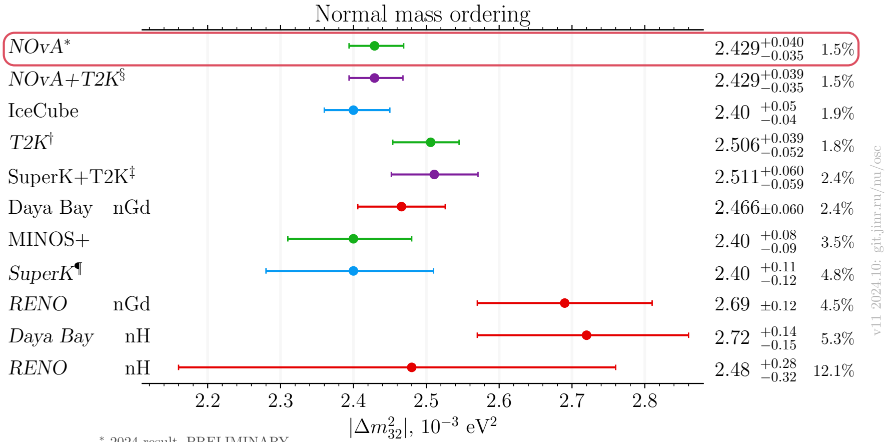
The most precisely known oscillation parameter

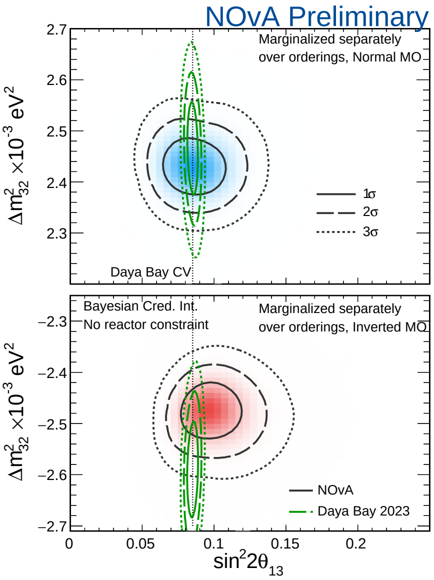
NOvA's new result gives the most precise single experiment measurements of Δm^2_{32}, achieving a fractional uncertainty of 1.5%.



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

The synergy between reactor and long-baseline accelerator experiments



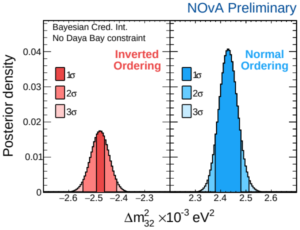
- Reactor and long-baseline accelerator measurements of Δm^2_{32} should agree[1] only under the correct NMO hypothesis.
- Daya Bay[2] and NOvA have better agreement in the Normal mass ordering.

[1] Phys. Rev. D 72, 013009, [2] Phys. Rev. Lett. 130, 161802

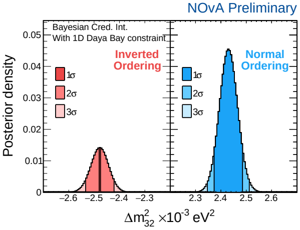
External θ_{13} constraints

Normal mass ordering preference

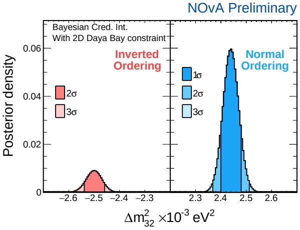
NOvA only



1D Reactor



2D Daya Bay



Bayes factor: 2.4 (70%) 3.3 (77%) 6.6 (87%)

- NOvA data show a slight preference for Normal mass ordering.
- The preference increases with adding external constraints on θ_{13}.
- Bayes factor is the ratio of likelihoods under two hypotheses

Conclusion

- The **NOvA 2024 3 Flavor Analysis** includes:
  - 10 years of data collection
  - a doubled exposure with neutrino beam: 26.61×10^{20} POT
  - updated simulation and event selection
- **2 complementary analyses**: Frequentist and Bayesian techniques yield similar results
- The **best fit point** is in the NO, the IO is rejected at 1.4σ (CL)
- Bayesian MCMC results (1D Reactor constraint):

$$\Delta m^2_{32} = 2.429^{+0.040}_{-0.034} \times 10^{-3}\text{eV}^2, \qquad \delta_{CP} = 0.93^{+0.21}_{-0.89}\,\pi, \qquad \sin^2\theta_{23} = 0.55^{+0.016}_{-0.066}$$

- Most precise single-experiment measurement of Δm^2_{32} (1.5% uncertainty)
- Strong synergy with Daya Bay measurements

NOvA's latest publications

- Explanation of the seasonal variation of cosmic multiple muon events observed with the NOvA Near Detector, arXiv:2508.04434
- Search for Accelerator-Produced Sub-GeV Dark Matter with the NOvA Near Detector, arXiv:2507.10754
- Measurement of $d^2\sigma/d|\vec{q}|dE_{\text{avail}}$ in charged current ν_μ-nucleus interactions at $<E_\nu> = 1.86\ \text{GeV}$ using the NOvA Near Detector, Phys. Rev. D 111, 052009
- Measurement of the double-differential cross section of muon-neutrino charged-current interactions with low hadronic energy in the NOvA Near Detector, arXiv.2410.10222
- Dual-Baseline Search for Active-to-Sterile Neutrino Oscillations in NOvA, Phys. Rev. Lett. 134, 081804
- Search for CP-Violating Neutrino Nonstandard Interactions with the NOvA Experiment, Phys. Rev. Lett. 133, 201802
- See more here

Backup

$\nu_e(\bar{\nu}_e)$ appearance oscillation probability

For accelerator neutrinos, the $\nu_\mu \to \nu_e$ appearance probability in matter[3], expanded to second order in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$:

$$\begin{aligned}\mathrm{P}\left(\nu_\mu \to \nu_e\right) \approx & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} \\ & +\alpha\tilde{J}\cos\left(\Delta \pm \delta_{CP}\right)\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)} \\ & +\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}\end{aligned}$$

where:

- $A = \pm 2\sqrt{2}G_F n_e E/\Delta m^2_{31}$ is positive (negative) for neutrinos (antineutrinos).
- $\Delta = \Delta m^2_{31}L/4E$
- $\tilde{J} = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}$

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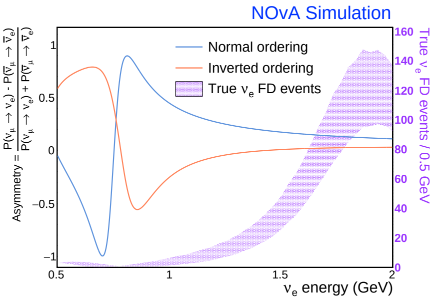
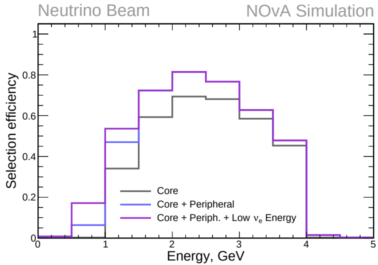
[3] Phys. Rev. Lett. 112, 191801

New Low Energy ν_e sample

- The sample covers the 0.5 to 1.5 GeV energy range.
- The low-energy region has significant sensitivity to the NMO.
- The primary background is neutral current interactions.
- Any candidate that fails the core selection is passed through a BDT optimized to identify events with low-energy electromagnetic showers from primary electrons.
- FHC: 12 ν_e additional candidates were observed, with expected background 7.1.

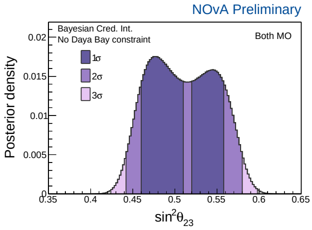




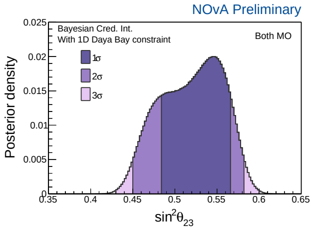
External θ_{13} constraints

θ_{23} upper octant preference

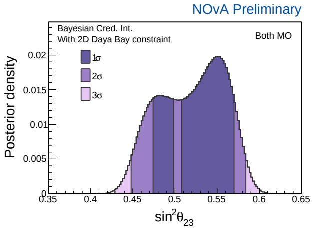
NOvA only



1D Reactor



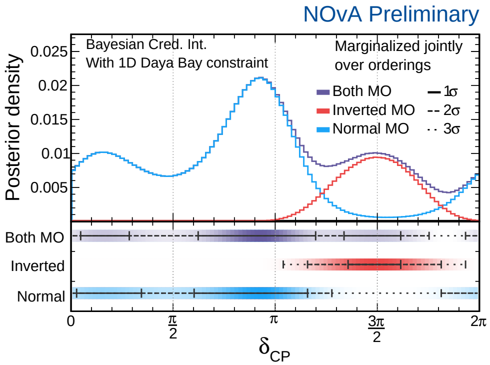
2D Daya Bay



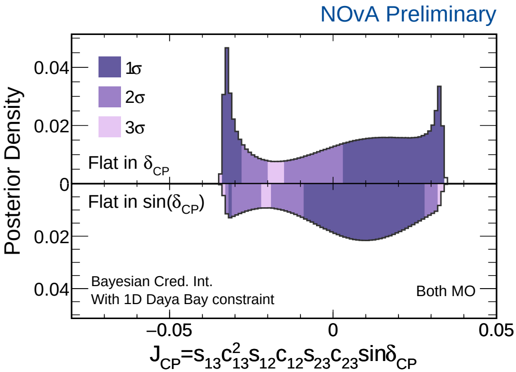
Bayes factor: 1.3 (56%) 2.1 (68%) 2.0 (66%)

- NOvA data show a slight preference for upper octant of θ_{23}.
- The preference increases with adding 1D Daya Bay constraint on θ_{13}.

δ_{CP} and neutrino mass ordering



- **NO**: disfavors maximal CP violating points $\pi/2$ at $> 1\sigma$ and $3\pi/2$ at $> 2\sigma$.
- **IO**: rejects CP conserving points 0 and π, and CP violating points $\pi/2$ at $> 3\sigma$.



The preference of CP violation over CP conservation ($J_{CP} = 0$)

- **NO**: Bayes factor 1.1 (56%)
- **IO**: Bayes factor 4.3 (81%)