Latest NOvA Oscillation Results from 10 Years of Data

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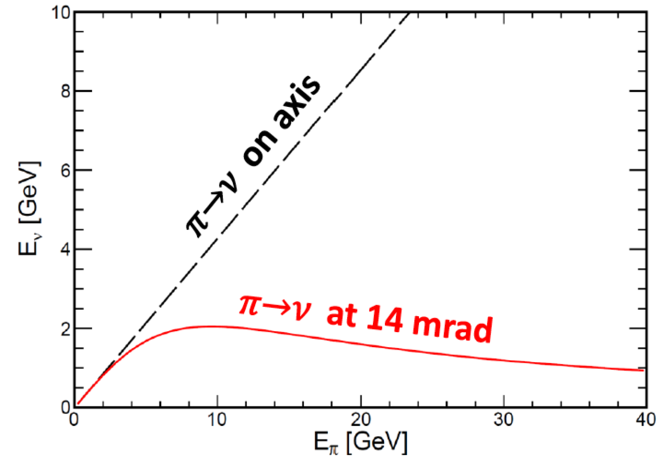
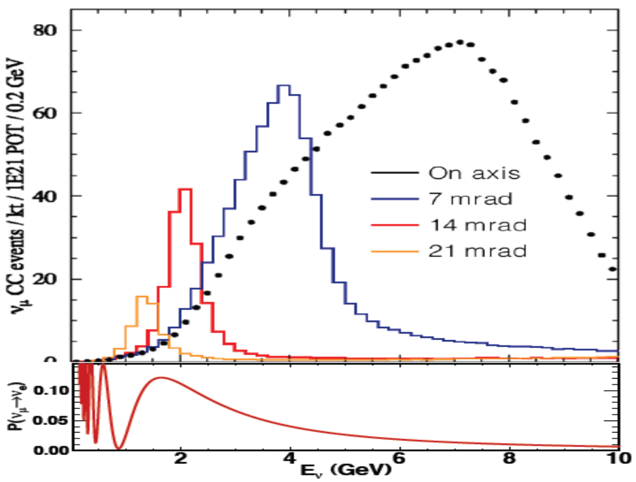
NuMI Off-Axis ν_e Appearance Experiment (NOvA)

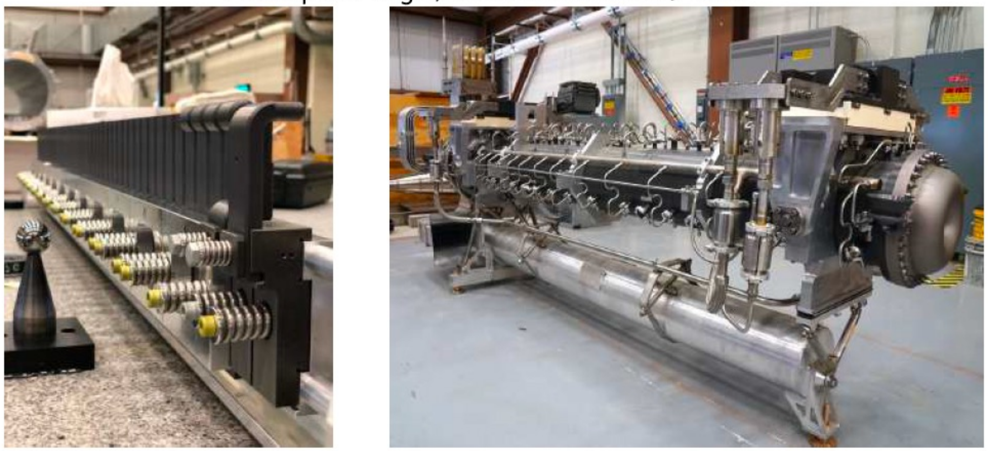




- Muon neutrino beam at Fermilab near Chicago
- Longest baseline in operation (810 km), large matter effect, sensitive to mass ordering
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum

Neutrino Beam Performance

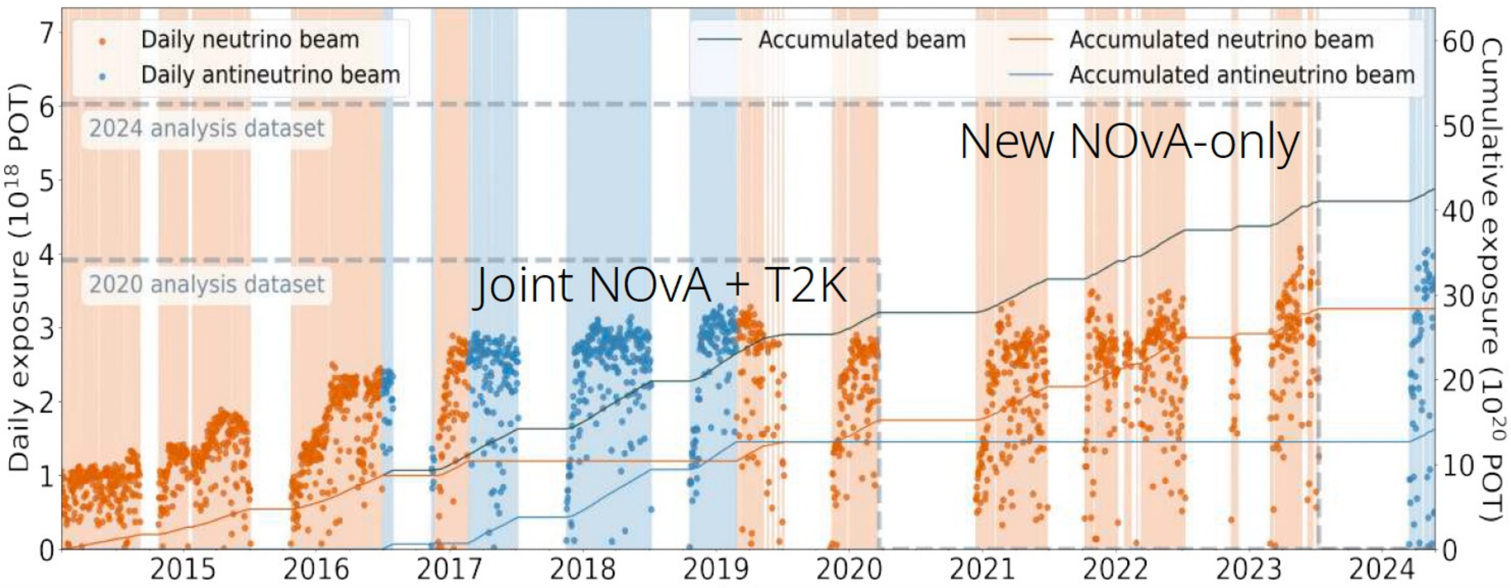
MW capable target, horn installed in 2019-2020



Upgraded beamline targets, horns and accelerator

~megawatt beam achieved:

- Regular ~900 kW
- Record 959 kW



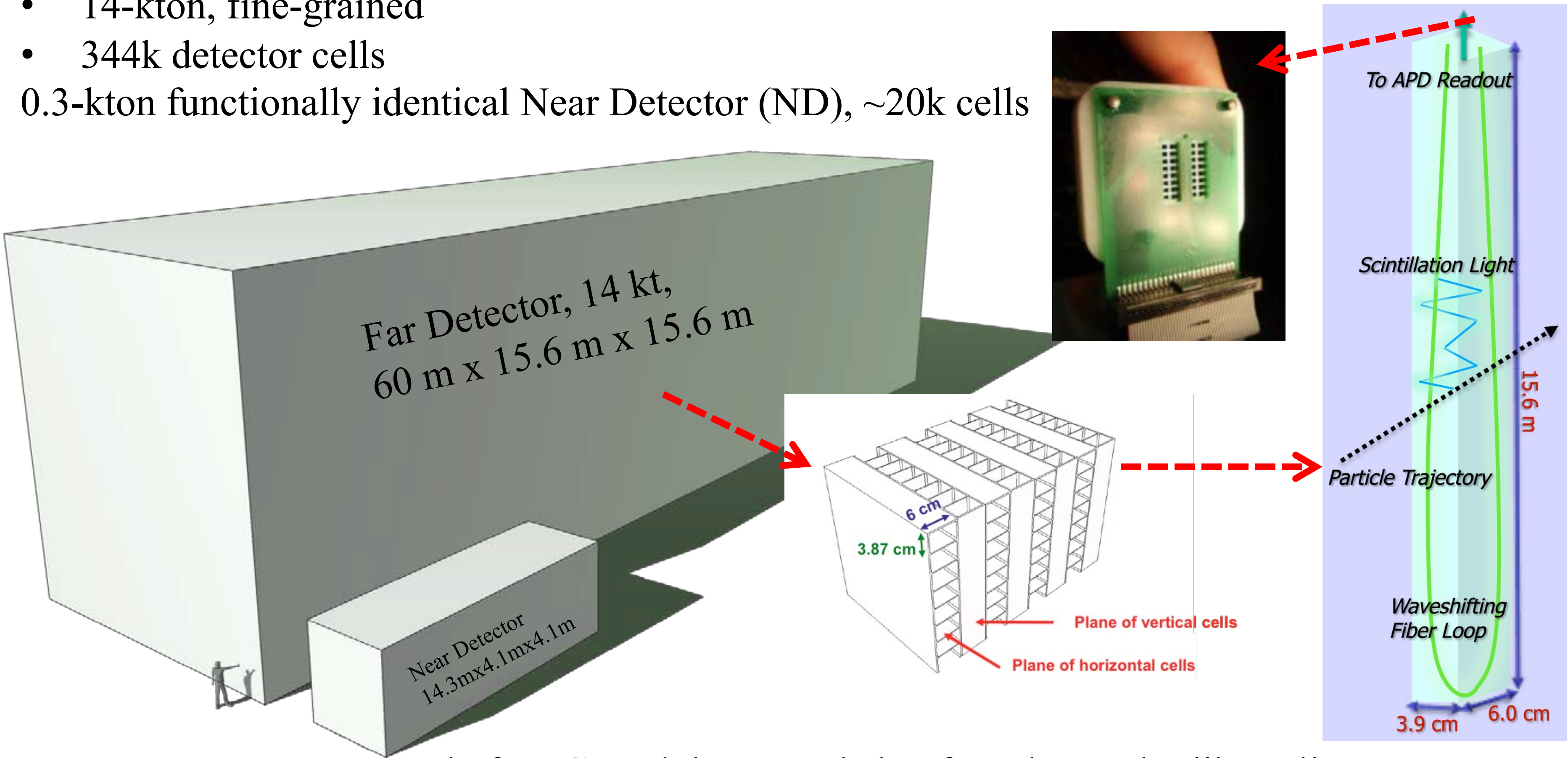
- 2014-2023: 10 years of beam to NOvA
- Neutrino beam data: 26.6x10^{20} Protons on Target (POT), (+96%)
- Antineutrino data: 12.5 x 10^{20} POT

NOvA Detectors

Far Detector (FD):

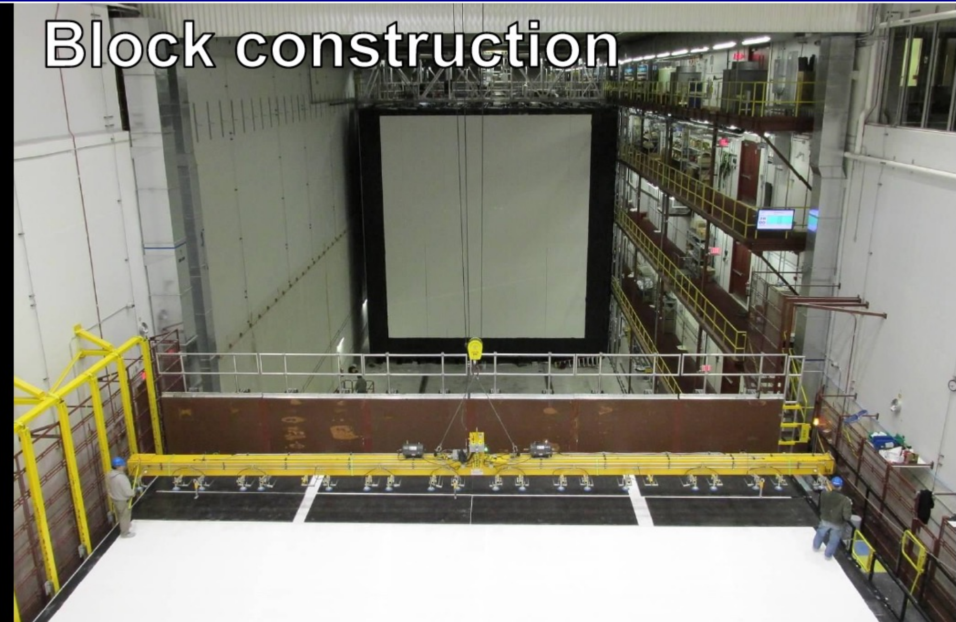
- 14-kton, fine-grained
- 344k detector cells

0.3-kton functionally identical Near Detector (ND), ~20k cells



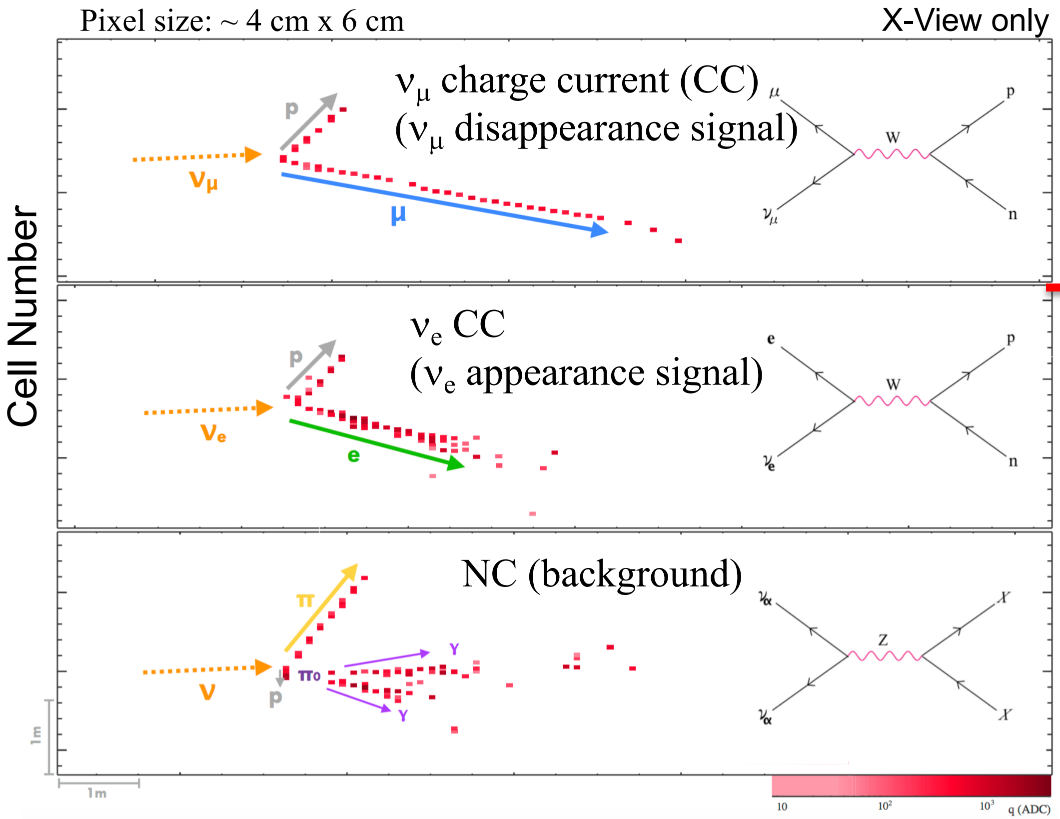
- Detectors are composed of PVC modules extruded to form long tube-like cells
- Each cell: filled with liquid scintillator, has wavelength-shifting fiber (WLS) routed to Avalanche Photodiode (APD)
- Cells arranged in planes, assembled in alternating vertical and horizontal directions → 3-D information of neutrino interactions

NOνA Detectors

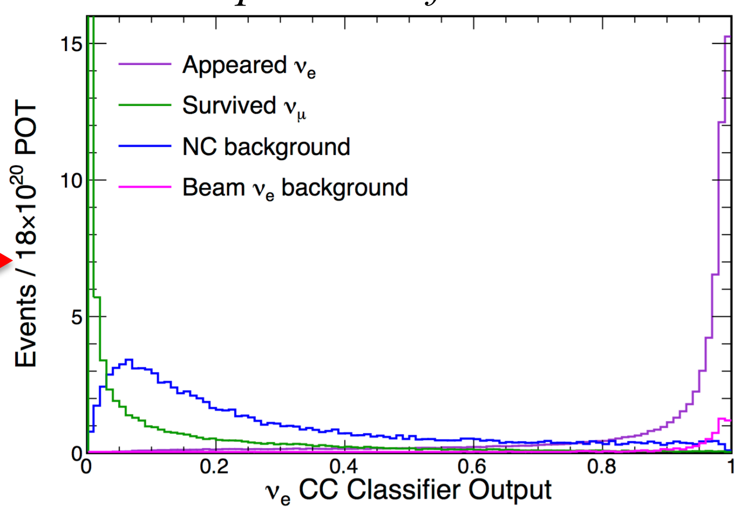


Deep-Learning based neutrino classifier (PID)

- CVN: a convolutional neural network (CNN), based on modern image recognition technology, A. Aurisano et. al, JINST 11, P09001 (2016)
- Extract features directly from pixel maps
- **New cosmic rejection CVN used for 2024 analysis**



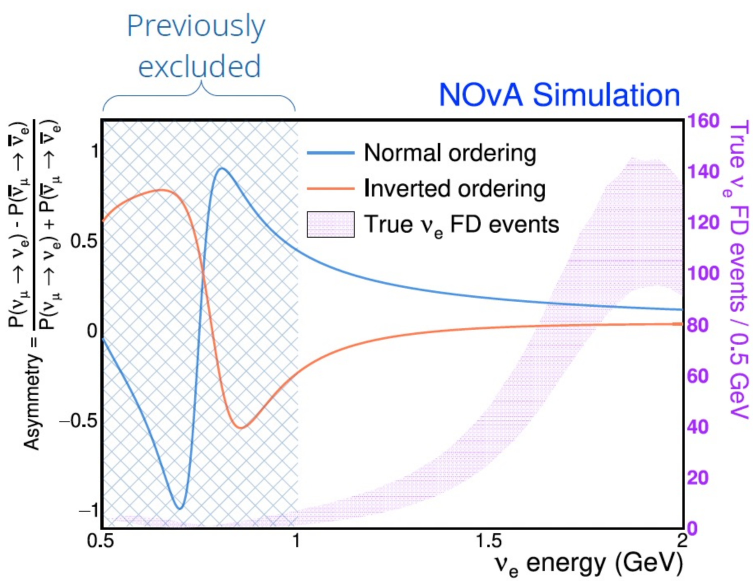
CVN output in the far detector MC

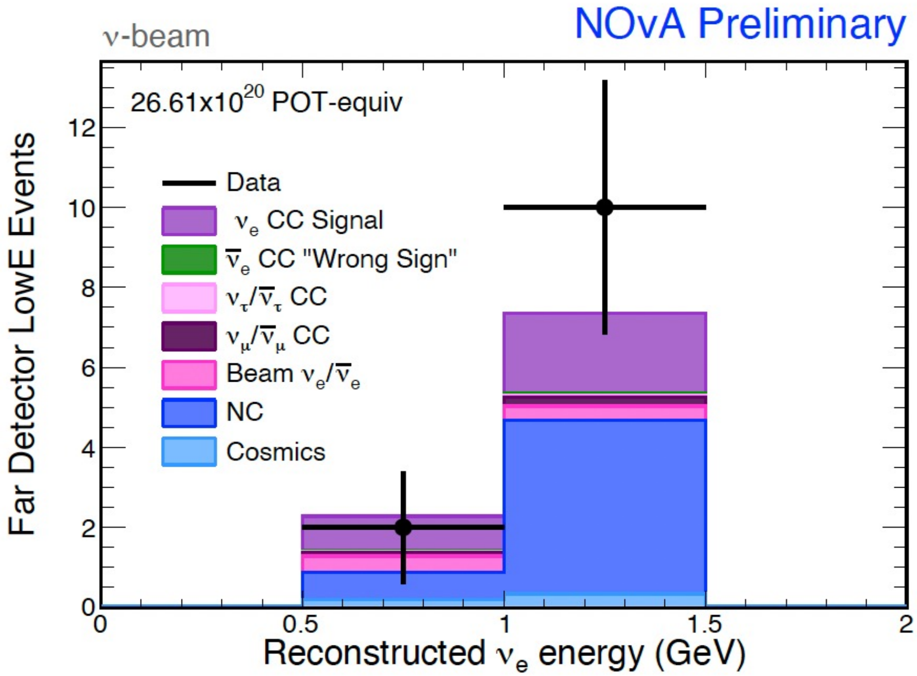


A. Aurisano et. al, JINST 11, P09001 (2016)

Select ν_μ ($\bar{\nu}_\mu$) CC and ν_e ($\bar{\nu}_e$) CC candidates from neutrino (antineutrino) beam with CVN in Near Detector (ND) and Far Detector (FD)

Expanding ν_e selection



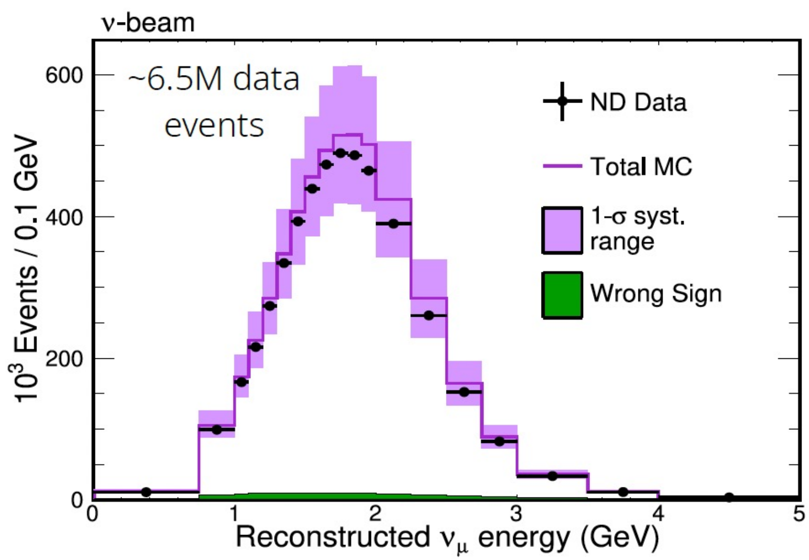


Maximum mass ordering sensitivity from ν_e-$\bar{\nu}_e$ asymmetry in low energy region (E<1GeV), previously removed

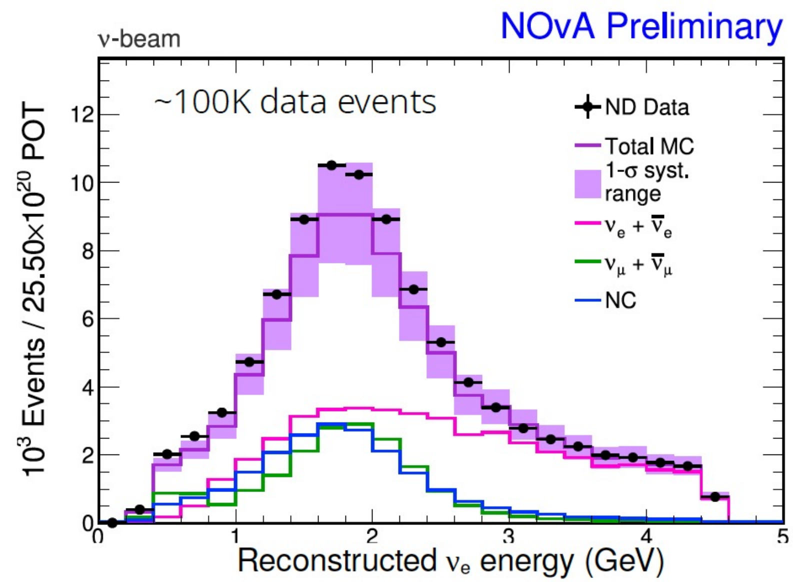
- New BDT to retrain low energy ν_e events, neutrino (FHC) only for now
- Increases mass ordering sensitivity by ~few%

Near detector observations

ND spectra reflect *unoscillated* beam



ν_μ candidates

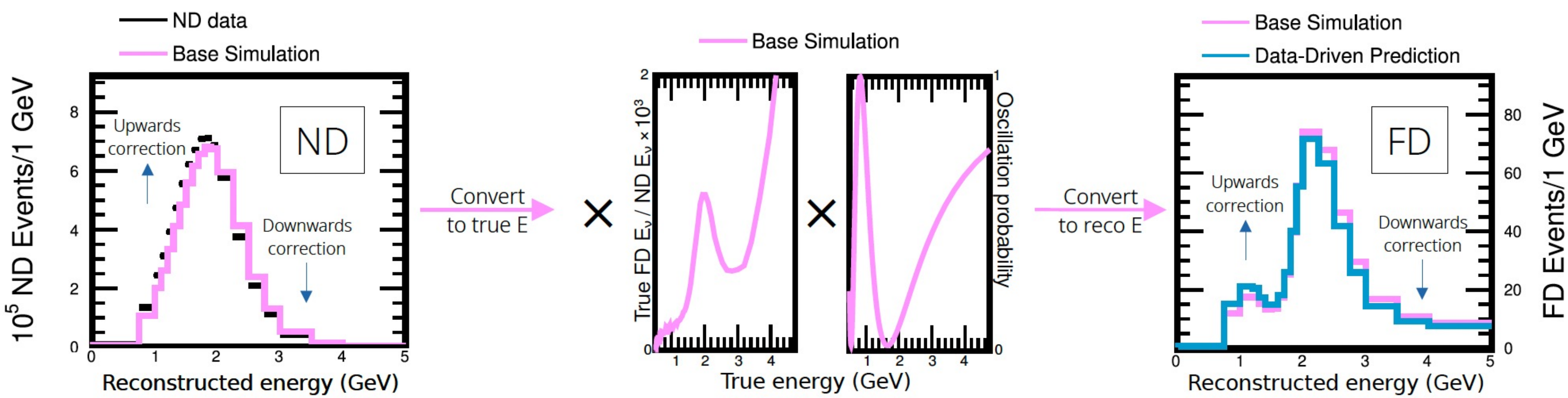


ν_e candidates

Extrapolate to FD for $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance signals

Extrapolate to FD to constrain dominant (50%/70%) beam backgrounds in $\nu_e/\bar{\nu}_e$ appearance

Far/Near detector extrapolation

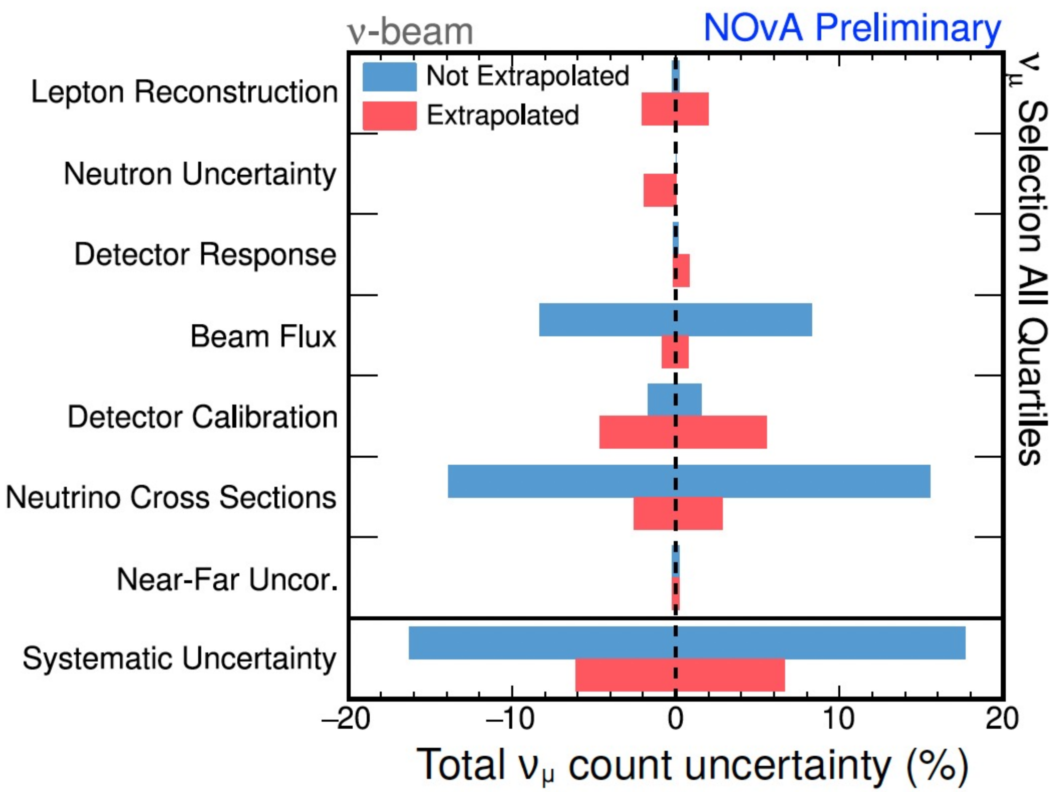


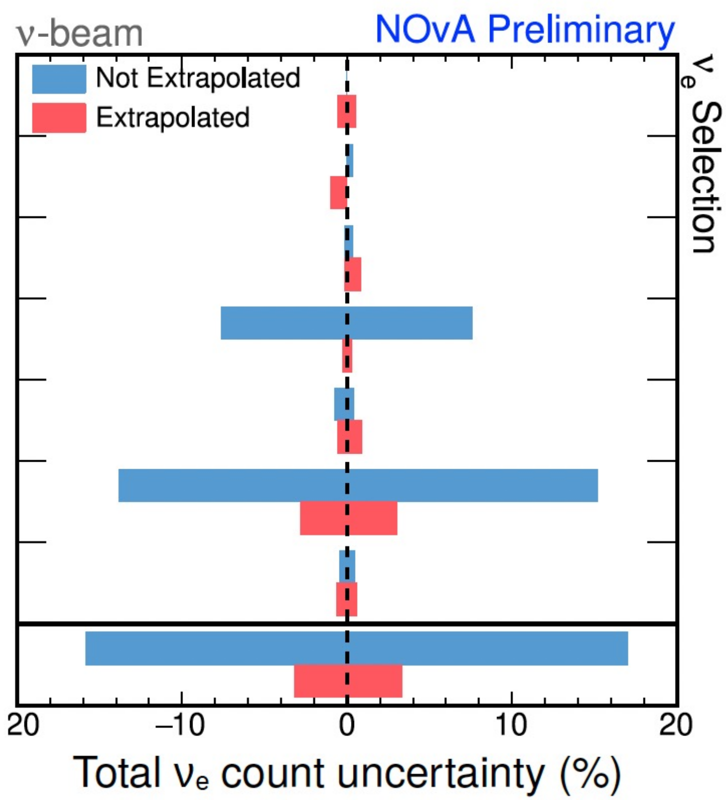
Correct ND simulation with data

Far/Near extrapolation: adjust for beam divergence, detector acceptance; apply oscillations

FD prediction

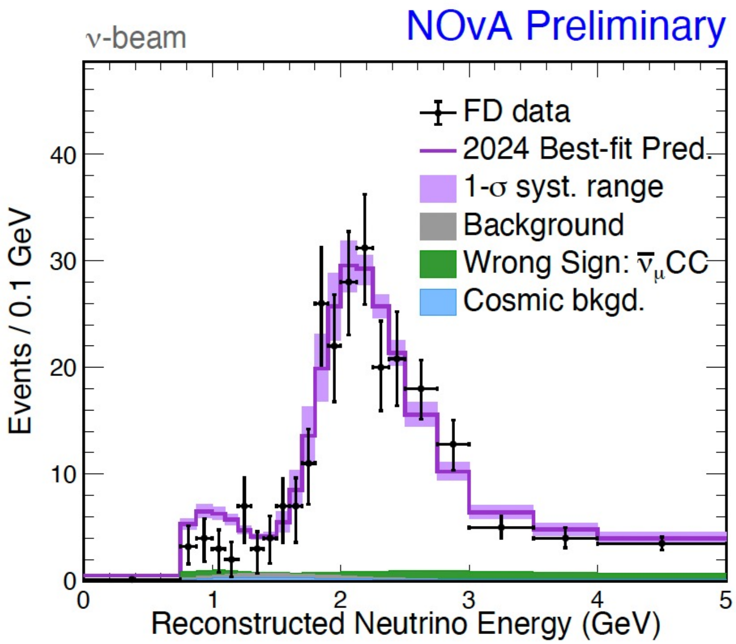
Systematic uncertainties



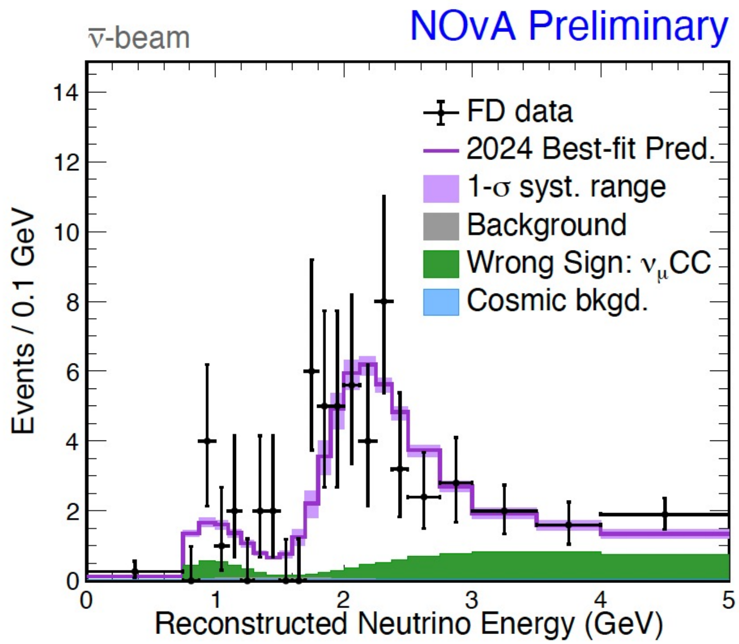


Far Detector $\nu_\mu(\overline{\nu}_\mu)$ Observations

- Observed $\nu_\mu(\overline{\nu}_\mu)$ candidates from 10 years of NOvA Data (neutrino beam exposure of 26.6×10^{20} POT and anti-neutrino beam exposure of 12.5×10^{20} POT)



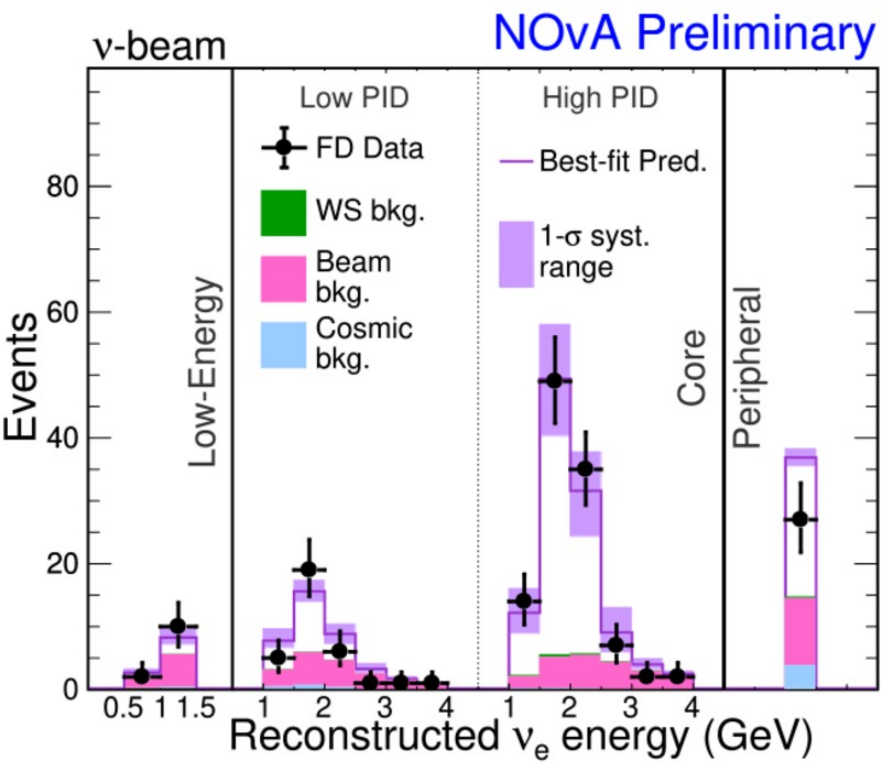
384 ν_μ data candidates (11.3 background)



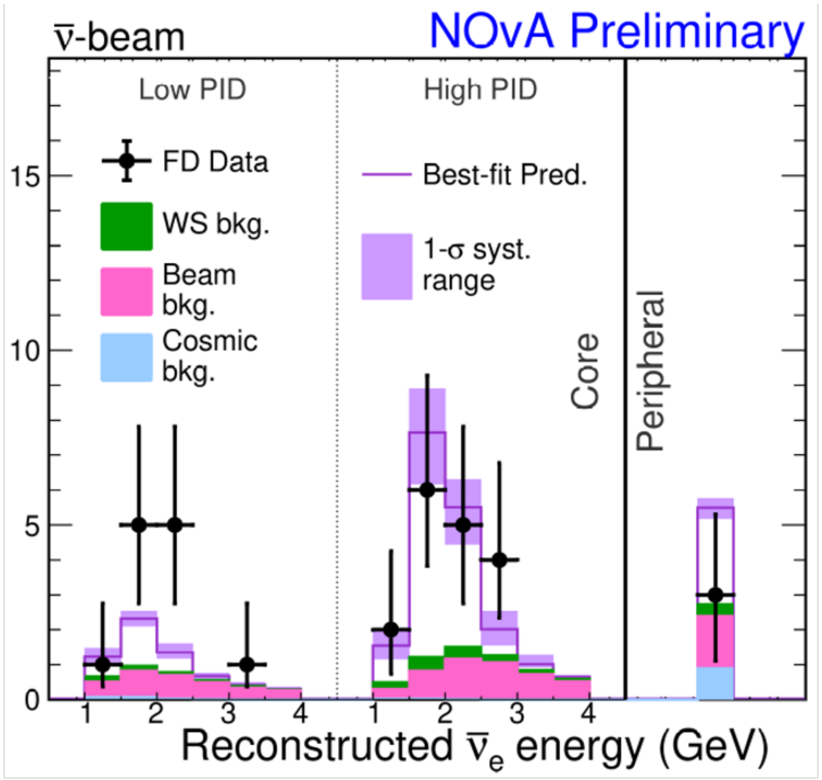
106 data $\overline{\nu}_\mu$ candidates (1.7 background)

Far Detector $\nu_e(\bar{\nu}_e)$ Observations

- Observed $\nu_e(\bar{\nu}_e)$ candidates from 10 years of NOvA Data (neutrino beam exposure of 26.6×10^{20} POT and anti-neutrino beam exposure of 12.5×10^{20} POT)



181 ν_e data candidates (61.7 background)

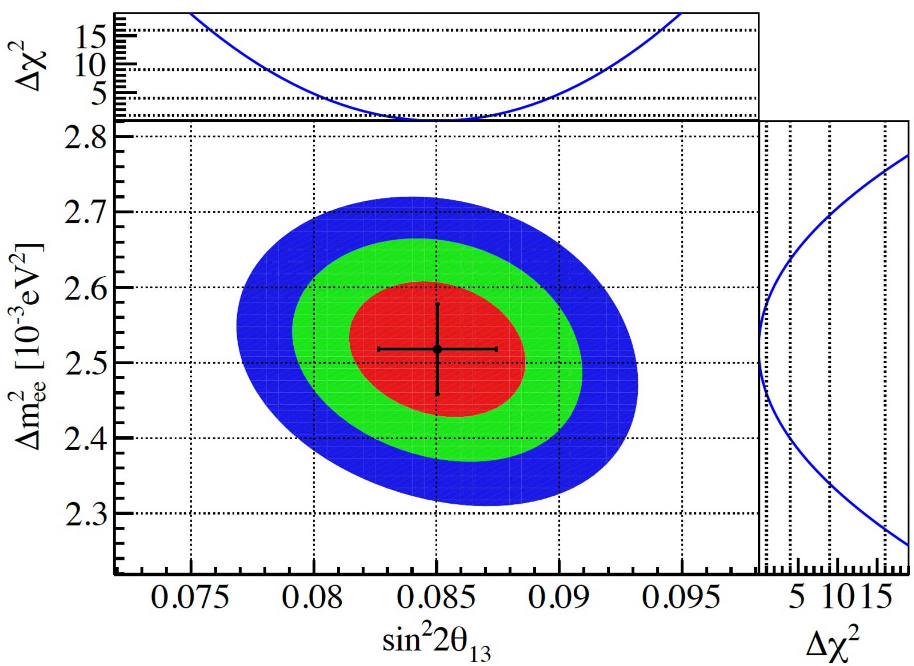


32 data $\bar{\nu}_e$ candidates (12.7 background)

Extracting Oscillation parameters

- Joint fit to $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance to extract:
  Δm^2_{32}, $\sin^2 2\theta_{23}$, δ_{CP}, Mass Hierarchy, octant of θ_{23}
- Solar parameters Δm^2_{12}, θ_{23} : constrained to PDG values
- Reactor constraints:
  - Unconstrained
  - Daya Bay 1D constraint: $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$
  - Daya Bay 2D constraints: Δm^2_{32}, θ_{13}

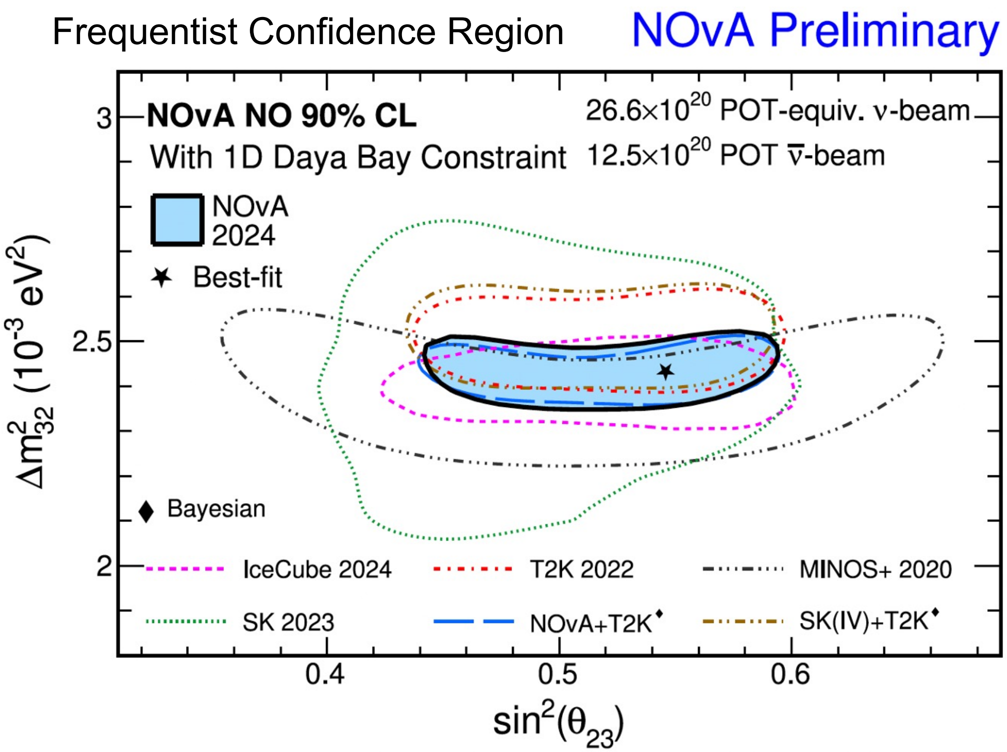
Phys. Rev. Lett. 130, 161802

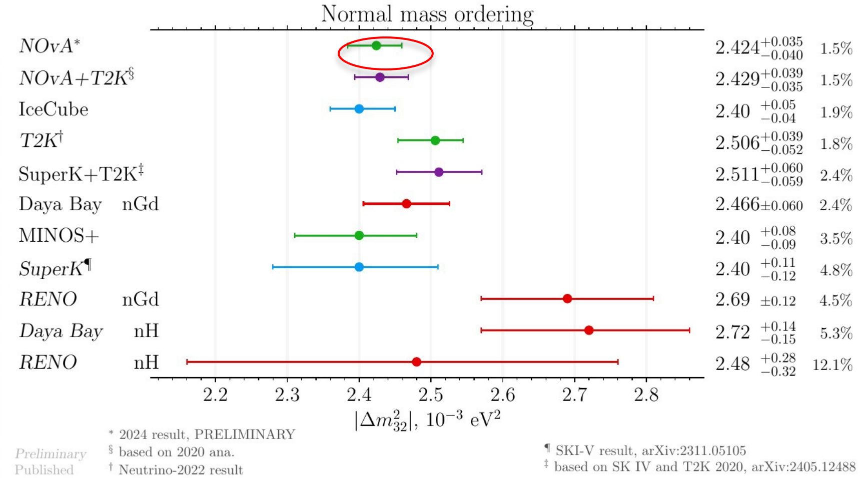


Statistical methods：

- Bayesian: Markov Chain Monte Carlo for marginalization arXiv:2311.07835
- Frequentist: minimum χ^2 test with profiled Feldman-Cousins method, arXiv:2207.14353

ν2 – ν3 mixing





(Frequentist) best fit:

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

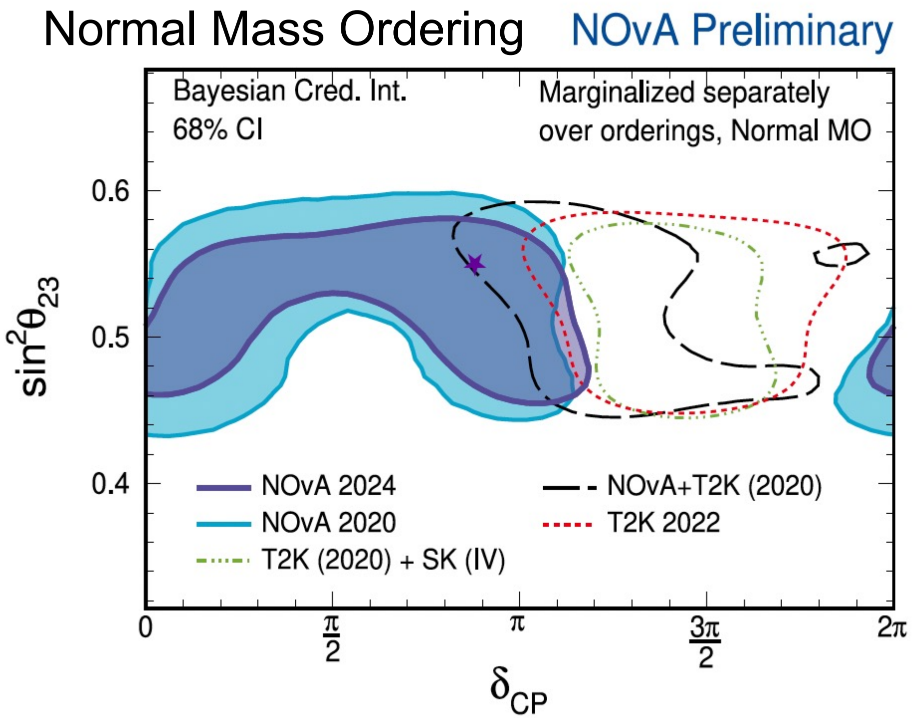
$$\sin^2\theta_{23} = 0.546^{+0.032}_{-0.075}$$

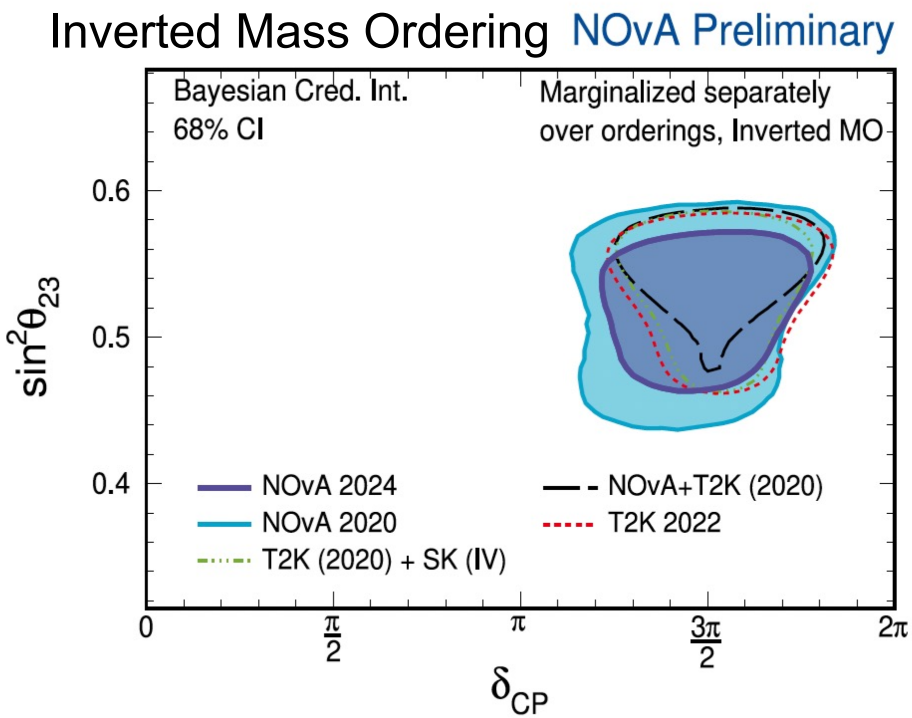
Mild Upper Octant preference

(69% prob; Bayes factor = 2.2)

- NOvA's measurements consistent with the rest of the accelerator and atmospheric experiments
- Δm^2_{32} best-fit lies in the normal mass ordering (NO)
- $\sin^2(\theta_{23})$ best-fit value lies in the upper octant

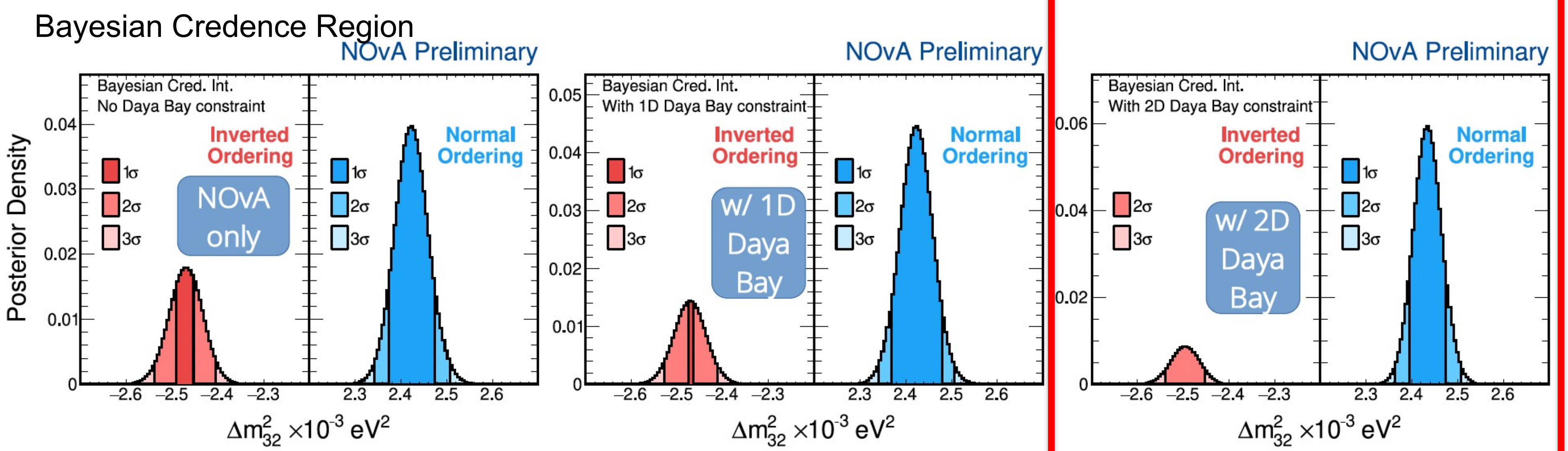
Mass ordering and CPV





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

Mass ordering and CPV



No reactor constraint	Daya Bay $\sin^2 2\theta_{13}$ only	Daya Bay ($\sin^2 2\theta_{13}$, Δm^2_{32})
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

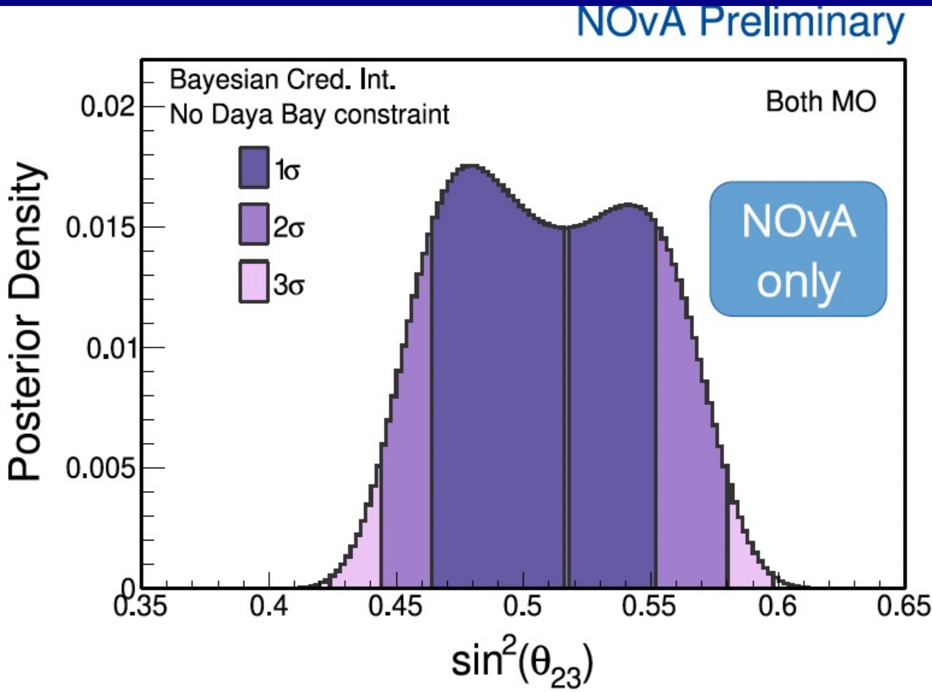
Summary and Prospect

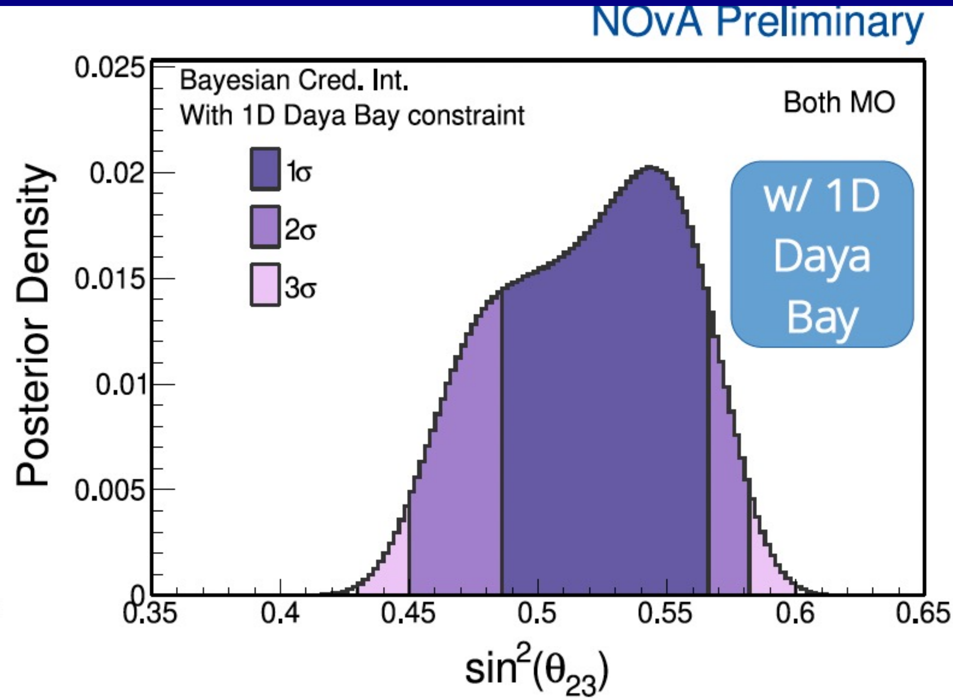
- NOvA 2024 results: First new NOvA neutrino oscillation measurement since 2020, with doubled neutrino beam dataset
- Most precise single-experiment measurement of Δm^2_{32} (1.5%)
- With reactor constraints on θ_{13} and Δm^2_{32} :
  - Upper Octant preference to 69% odds
  - Normal Ordering preference to 87% odds.
- Aim to double of antineutrino data before 2027 – crucial to clarify MO/CPV
- Test beam constraints on energy scales expected in near future

Thank you!

Backup

ν2 – ν3 mixing





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 <1σ