NOvA recent results of three-flavor oscillation analysis

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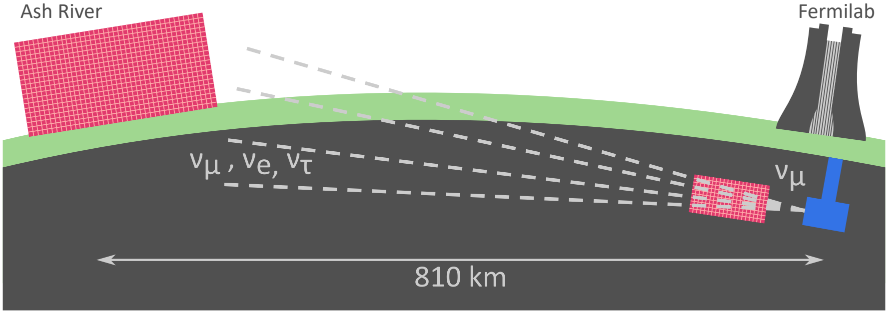
NuMI Off-axis ν_e Appearance Experiment (NOvA)

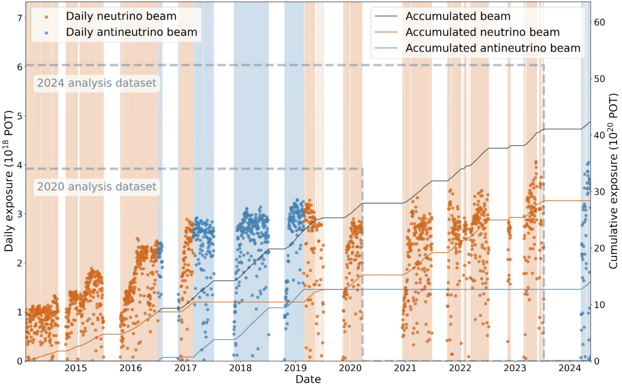


- NOvA is a long-baseline off-axis neutrino oscillation experiment at US.
- Neutrino source is Fermilab's Megawatt-capable NuMI beam.
- Two functionally identical, finely granulated detectors, filled with liquid scintillator.

New data and beam power

New results comprise 10 Years of NOvA data (2014-2023)

- Typical beam power of $\sim$ 900 kW, record of 1018 kW in June 2024.
- Beam purity:
  FHC: 95% ν_μ, 4% $\bar{\nu}_\mu$, 1% $\nu_e/\bar{\nu}_e$
  RHC: 93% $\bar{\nu}_\mu$, 6% ν_μ, 1% $\nu_e/\bar{\nu}_e$
- 26.61×10^{20} POT neutrino mode (doubled from 2020 analysis).
- 12.50×10^{20} POT antineutrino mode.



3 Flavor Physics at NOvA

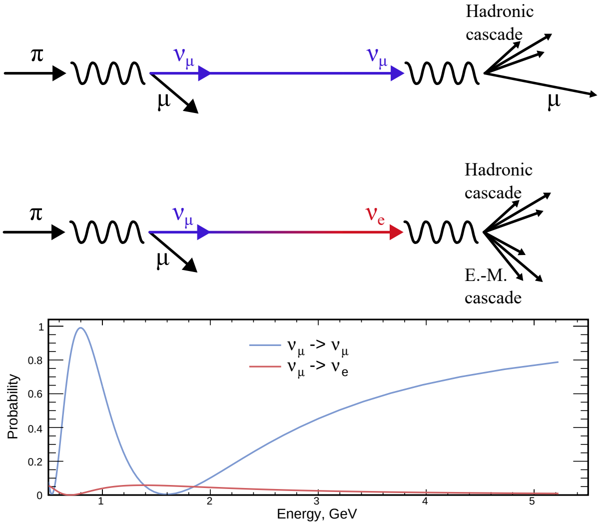
Primary goals:

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

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

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

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



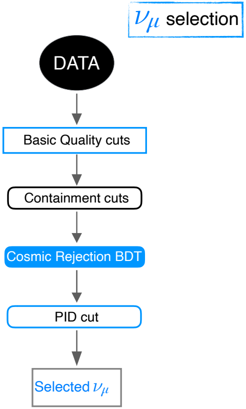
Event selection

The full Far Detector selection includes a set of selection cuts: quality, containment, cosmic rejection, and the event-classifier.

Enhancing sensitivity by samples splitting

ν_μ selection:

- the sensitivity depends primarily on the shape of the energy spectrum
- dataset is divided into 4 quartiles by hadronic energy fraction



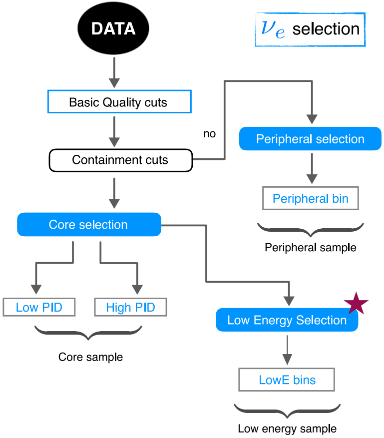
Event selection

The full Far Detector selection includes a set of selection cuts: quality, containment, cosmic rejection, and the event-classifier.

Enhancing sensitivity by samples splitting

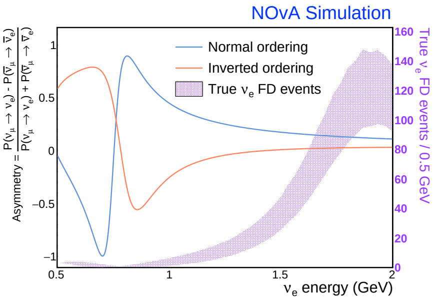
ν_e selection:

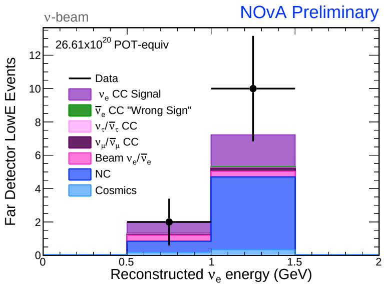
- the sensitivity depends primarily on separating signal from background
- A new selection was developed to retain lower energy ν_e candidates.



New Low Energy ν_e sample

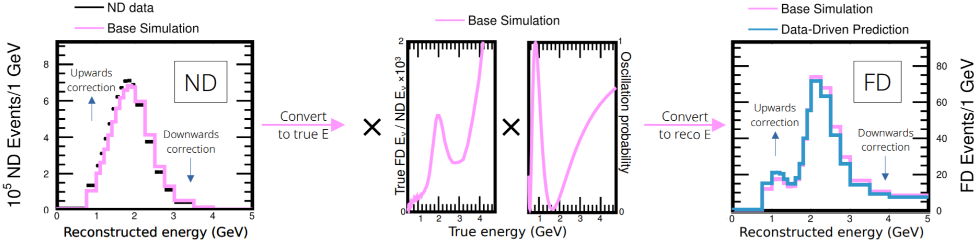
- Previous analysis had a cut $E_{reco}(\nu) \geq 1$ GeV
- Maximum ordering sensitivity from asymmetry at lower E_ν
- Improves sensitivity to mass orderings by few percent (depending on the oscillation parameters)
- No low energy events for the antineutrino beam mode





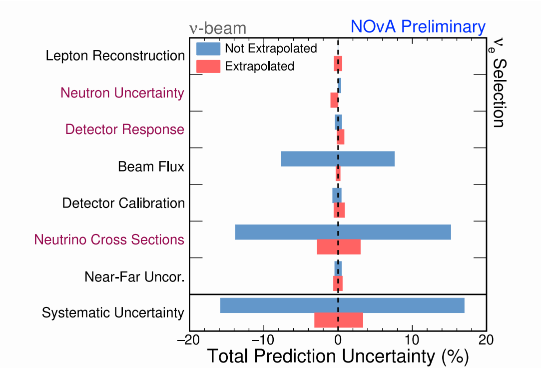
Extrapolation

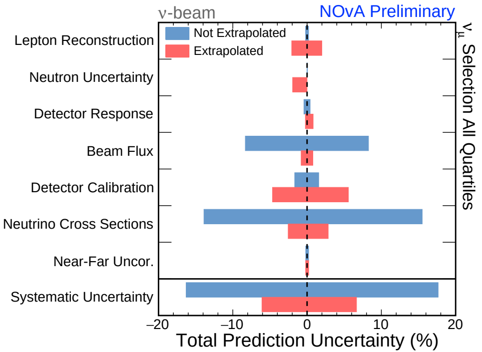
The Near Detector (ND) Data/MC ratios are used to correct the Far Detector (FD) predictions.



- ND ν_μ-like samples are used to correct the FD $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ signal predictions.
- ND ν_e-like samples are used to correct the FD ν_e background predictions.
- Far-to-near transformation accounts for well understood effects like beam divergence, and detector acceptance differences.
- The resulting constrained FD predictions are highly correlated with the ND corrections.

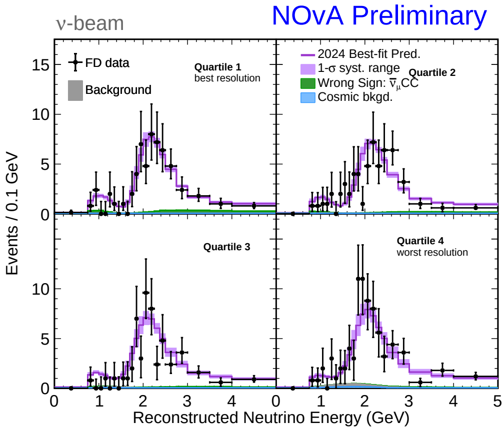
Systematic uncertainties

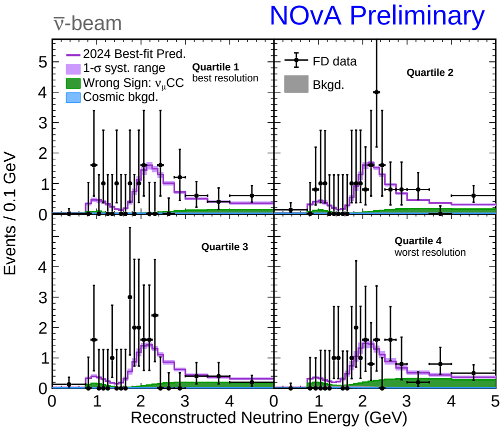




- 2024 improvements: new pion-production systematic uncertainties, improved light response model and neutron propagation uncertainty.
- ND constraints reduce the systematic uncertainties in the FD predictions from 18% to 4%. Statistical uncertainties are dominant in the oscillation measurement.

ν_μ far detector observations

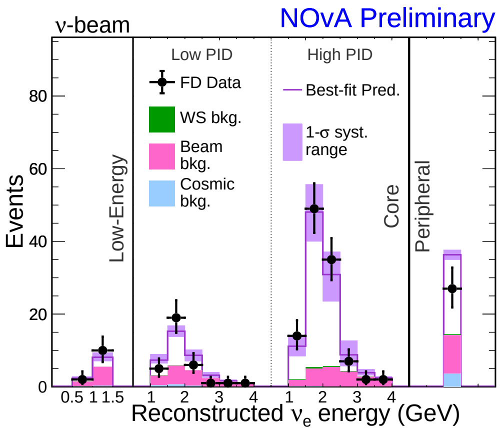




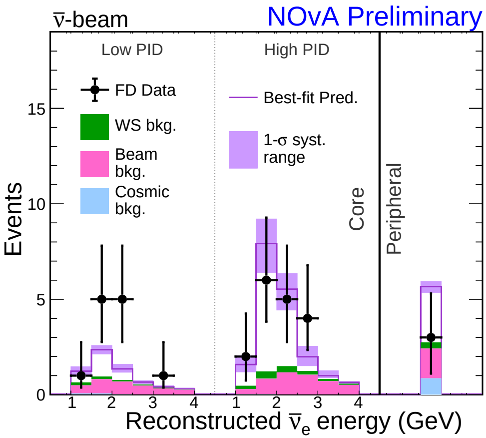
384 ν_μ candidates (expected total bkg 11.0)

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

ν_e far detector observations



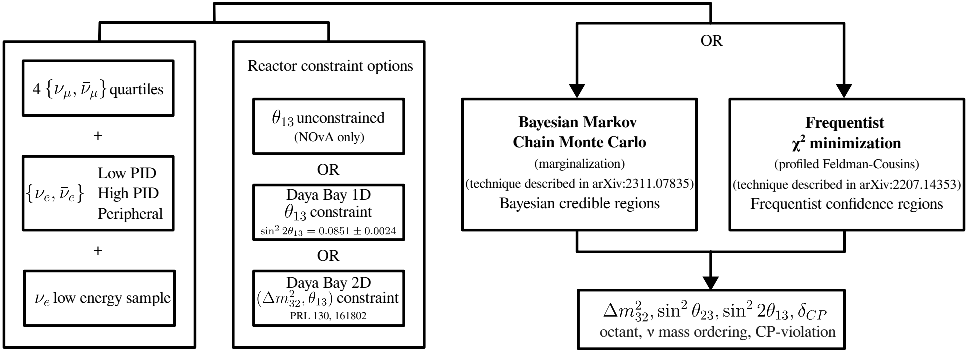
181 ν_e candidates (expected total bkg 62.5)



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

Far detector fitting procedure

- a simultaneous fit of all samples is performed, using Bayesian or Frequentist techniques
- external constraints are used for the solar parameters and optionally reactor constraint on θ_{13}



Other mixing parameters:
$\sin^2\theta_{12} = 0.307$ (PDG 2023), $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2 (PDG 2023), $\rho = 2.74$ g/cm^2 (CRUST 1.0)

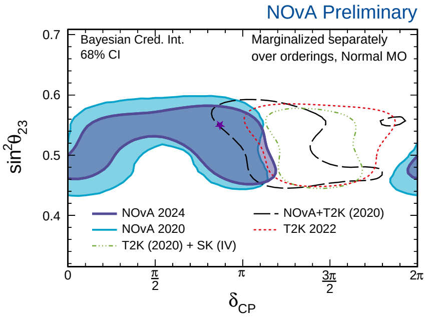
Oscillation parameter results

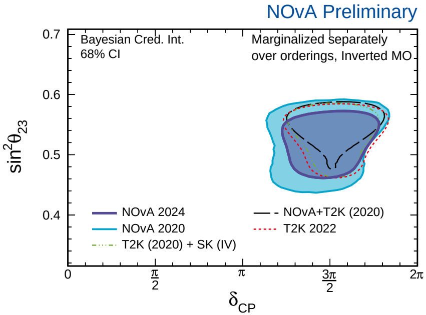
Frequentist results

(with Daya Bay 1D θ_{13} constraint)

Parameter	Normal MO	Inverted MO
$\Delta m^2_{32}/10^{-3}\text{eV}^2$	$+2.433^{+0.035}_{-0.036}$	$-2.473^{+0.035}_{-0.035}$
$\sin^2\theta_{23}$	$0.546^{+0.032}_{-0.075}$	$0.539^{+0.028}_{-0.075}$
δ_{CP}	$0.88\ \pi$	$1.51\ \pi$
Rejection significance (σ)		1.36

- The new NOvA result is consistent with previous one.
- The data disfavor asymmetry combinations NO:$\delta = 3\pi/2$, and IO: $\delta = \pi/2$.





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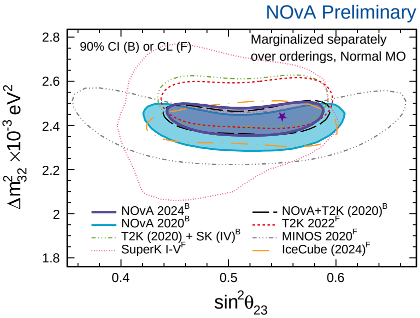
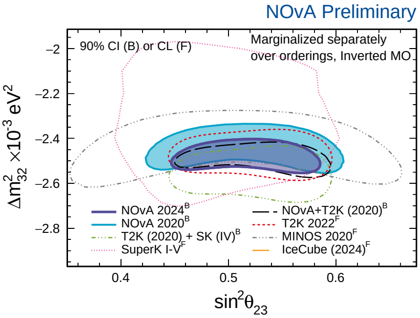
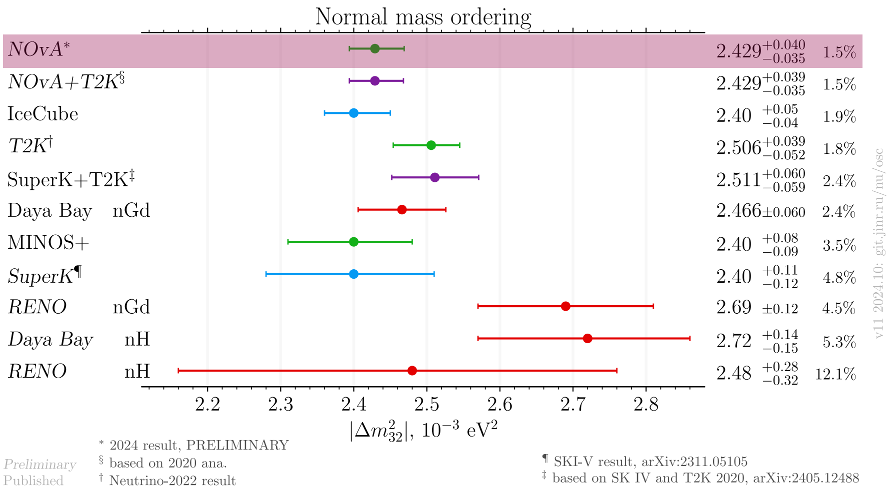
- The new NOvA result is consistent with previous one.
- In the $\nu_2 - \nu_3$ sector, NOvA's measurements are consistent with accelerator, atmospheric, and joint results.







Δm^2_{32} is now the most precisely know PMNS parameter.

NOvA's new result gives the most precise single experiment measurement (1.5% unc.).

Conclusion

- The NOvA 2024 analysis includes:
  - 10 years of data collection
  - a doubled neutrino mode exposure compared to 2020 analysis
  - updated simulation and event selection
- Results are consistent with previous analysis.
- Both Frequentist and Bayesian techniques yield similar results on our data.
- Most precise single-experiment measurement of Δm^2_{32} (1.5% uncertainty).
- Slight preference for normal mass ordering (6.8 Bayes Factor, 1.6σ), Upper Octant θ_{23}, CP-conserving δ_{CP} values.
- Data disfavor regions with large $\nu_e/\bar{\nu}_e$ asymmetry.

The NOvA future goal is doubling of antineutrino data before 2027.

crucial to clarify Neutrino Mass Ordering and CP-violation