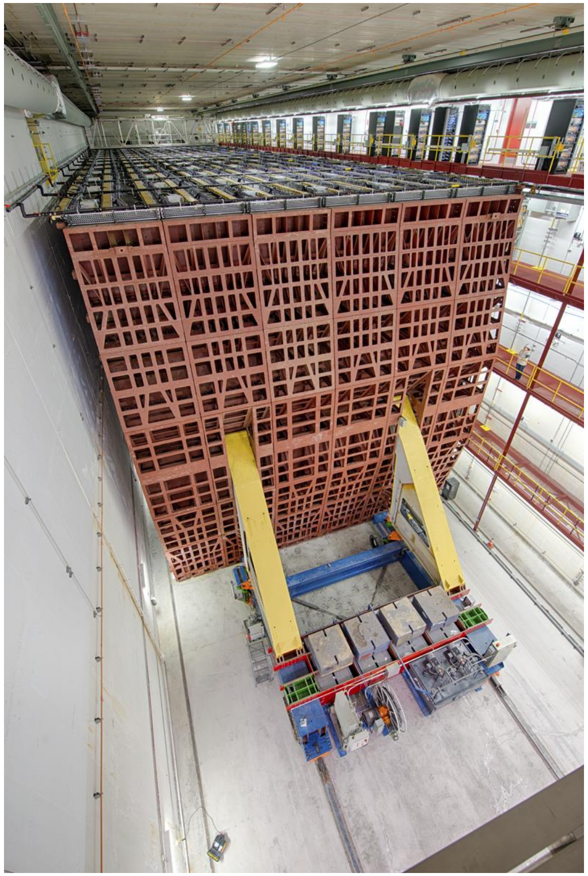
Recent Results from NOvA



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For the NOvA Collaboration

May 26, 2022

Neutrino Mixing

3x3 mixing between flavor states and mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Three mixing angles and one phase that affect neutrino oscillations

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\ e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin^2\theta_{23} = 0.573^{+0.018}_{-0.023}$ $\sin^2\theta_{13} = 0.02220^{+0.00068}_{-0.00062}$ $\sin^2\theta_{12} = 0.304^{+0.013}_{-0.012}$

1-sigma ranges from a global fit of oscillation data (solar+atmospheric+reactor+accelerator)

NuFIT 5.1 (2021), www.nu-fit.org
JHEP 09 (2020) 178 [arXiv:2007.14792]

Neutrino Oscillations

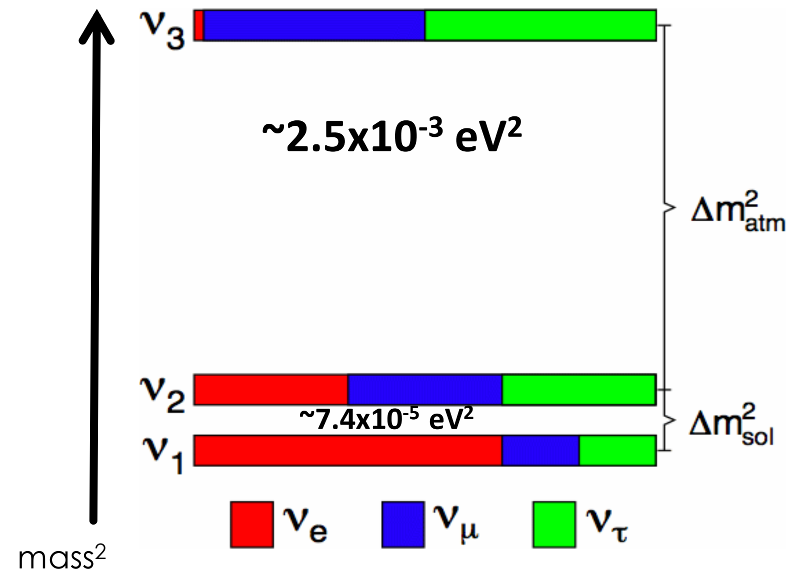
Neutrinos are created in flavor eigenstates

Mixture changes as neutrinos travel, leading to a probability that a neutrino born as flavor α will be observed later as flavor β:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*}\right)\sin^2\left(1.27\frac{\Delta m_{ij}^2 L}{E}\right) + 2\sum_{i>j} Im\left(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*}\right)\sin\left(1.27\frac{\Delta m_{ij}^2 L}{E}\right)$$

***L* = baseline in km**
***E* = neutrino energy in GeV**
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Color represents $|U_{\alpha j}|^2$



2 independent mass-squared differences

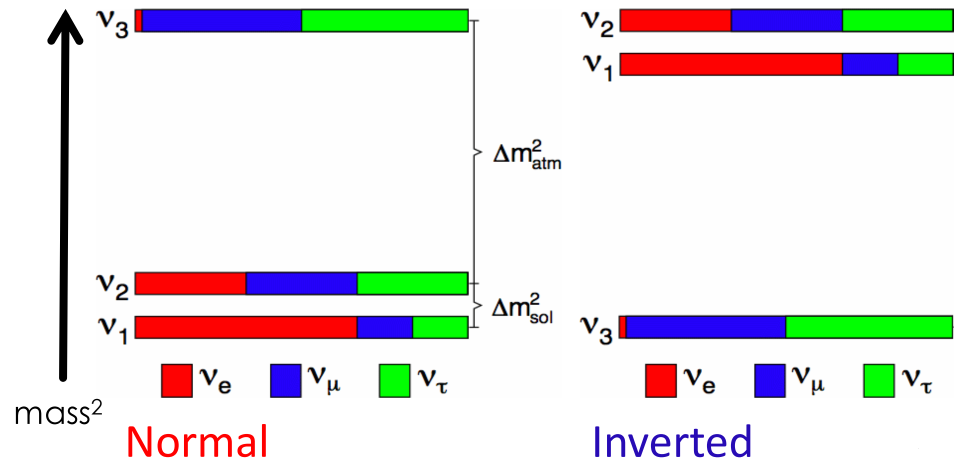
Choose L/E depending on which mass-squared difference to be probed

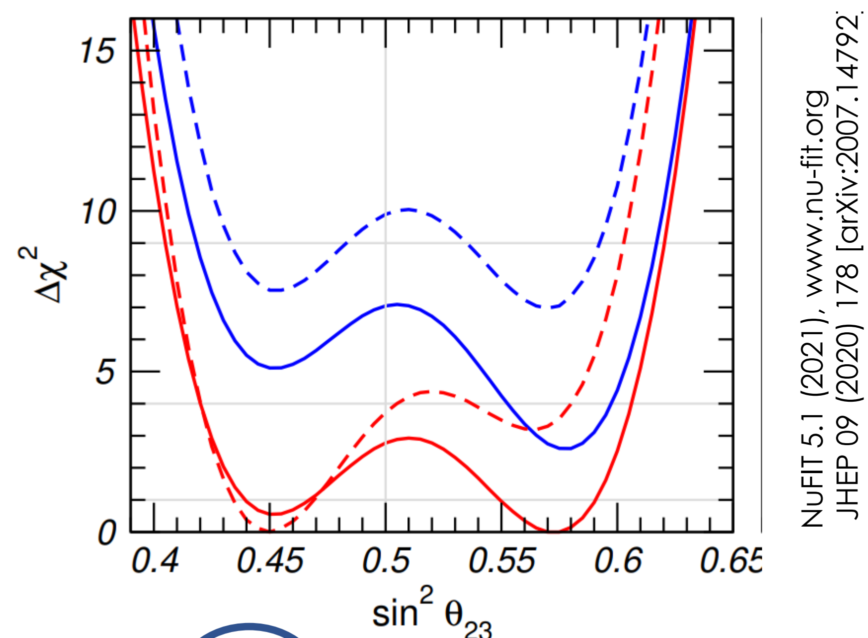
Open Questions

We have a consistent picture of 3-flavor oscillations from a >20-year experimental program!

Remaining questions we want to address with current and future long-baseline measurements:

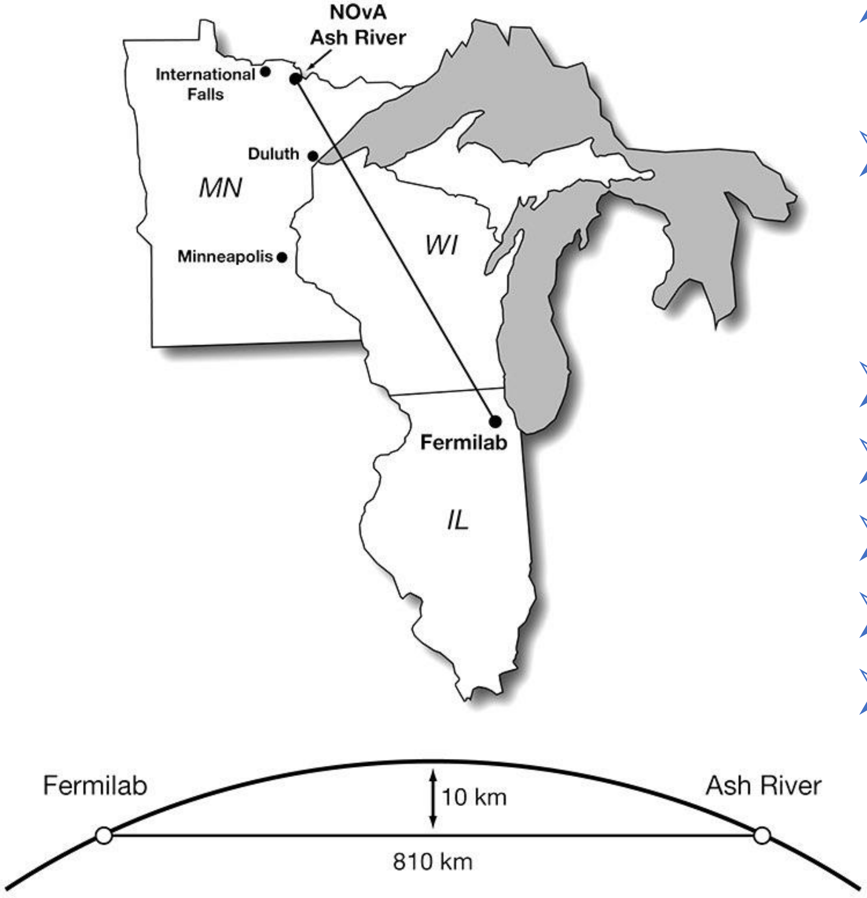
- What is the neutrino mass ordering (sign of Δm^2_{32})?
- Is CP violated in neutrino oscillations ($\delta \neq 0$ and $\delta \neq \pi$)
- Is ν_3 mostly ν_μ or ν_τ (the octant of θ_{23}; $\theta_{23} < \pi/4$ or $> \pi/4$)?





$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

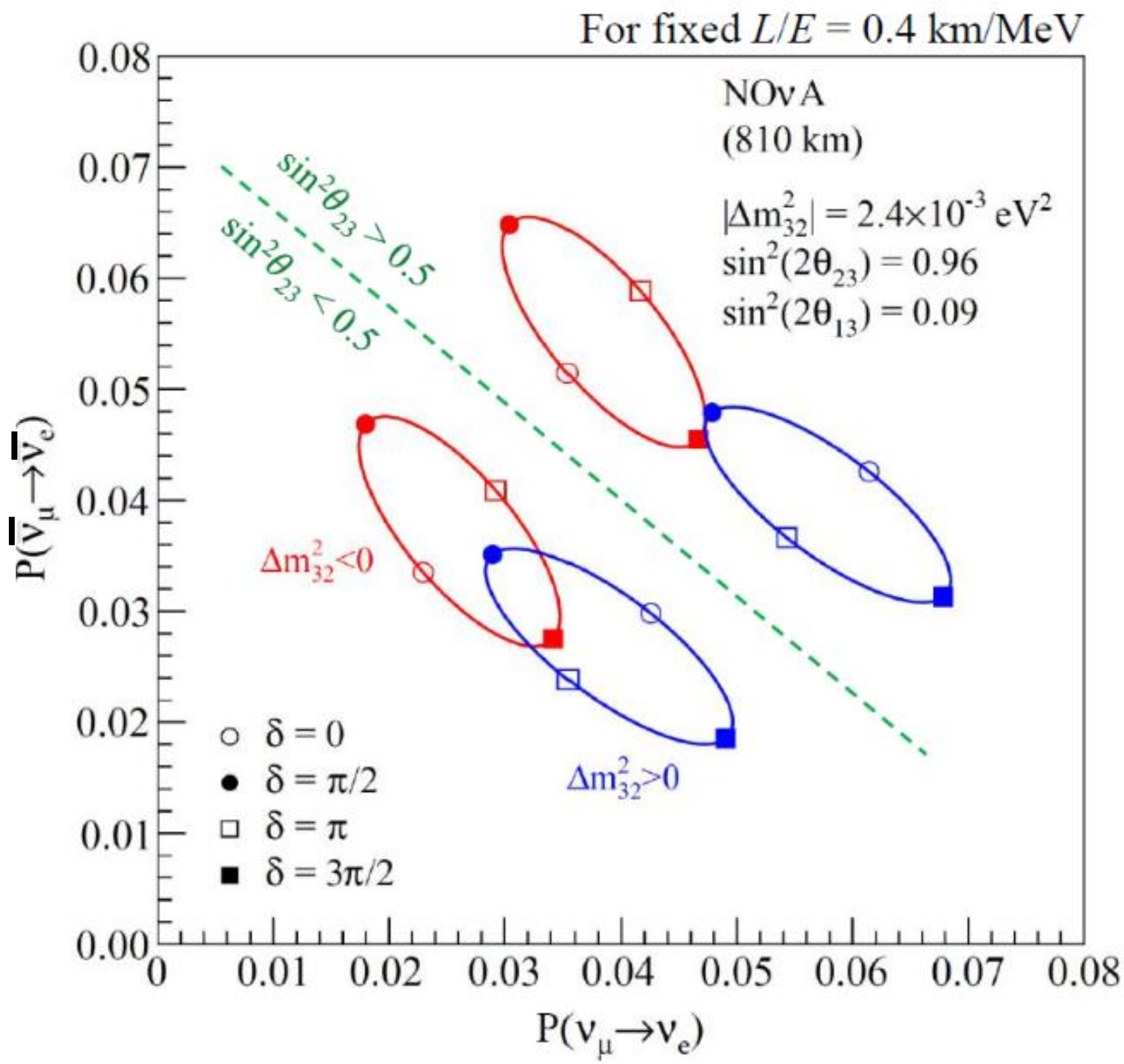
The NOvA Experiment



- Long-baseline accelerator neutrino experiment
- Muon neutrino and antineutrino beams produced at Fermilab, peak neutrino energy ~2 GeV
- Two functionally-identical detectors
- Near detector: Fermilab
- Far detector: Ash River, MN
- 810 km baseline
- With L/E ~400 km/GeV, sensitive to oscillations with larger mass splitting

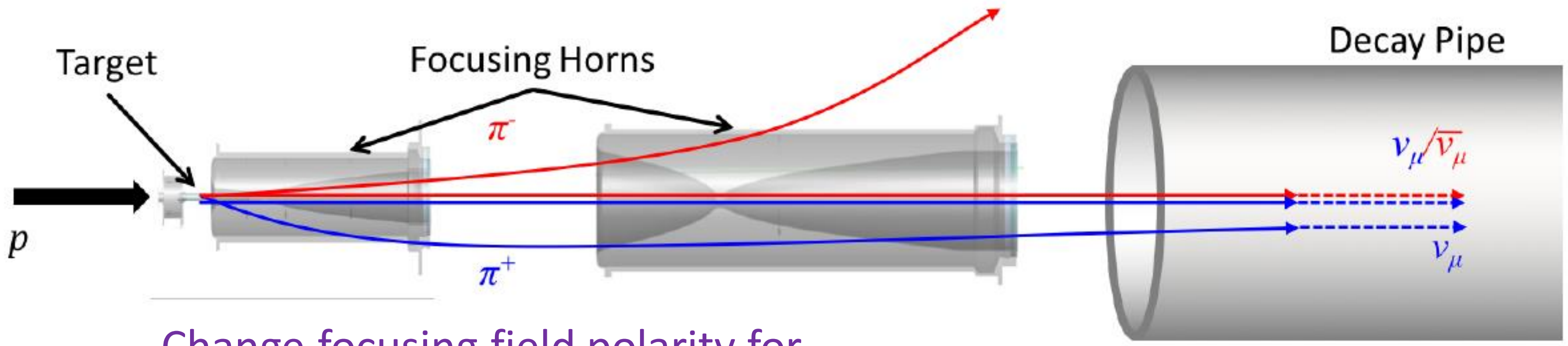
Electron Neutrino Appearance

- The CP phase leads to an asymmetry between the neutrino and antineutrino appearance probabilities
- Additionally, the matter effect causes an asymmetry, because the Earth is filled with electrons, not positrons

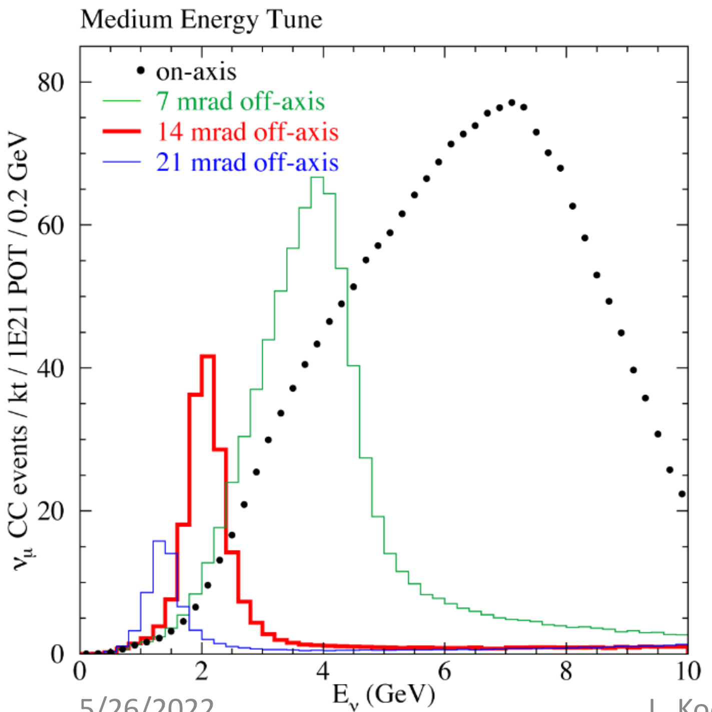


NuMI Beam

Small wrong-sign component as well as smaller electron flavor component

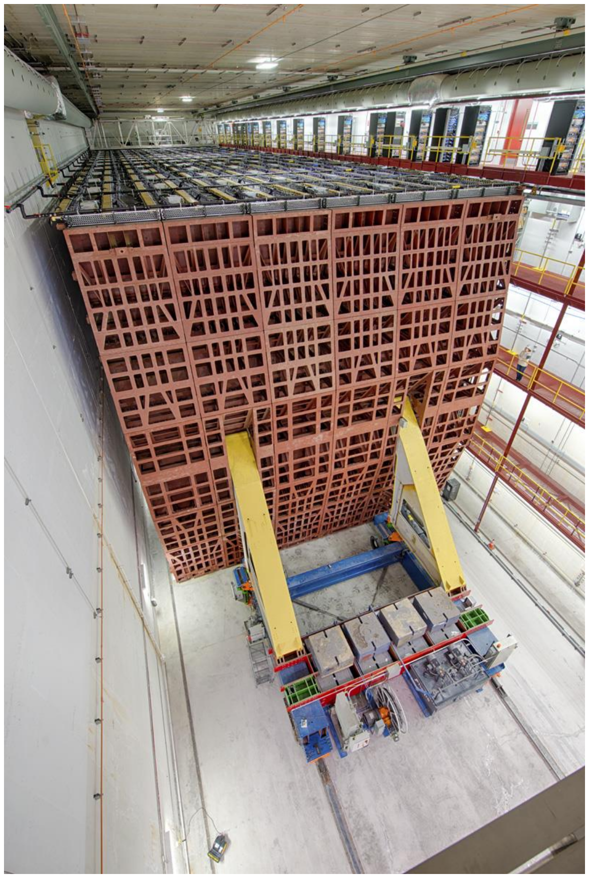


Change focusing field polarity for neutrino beam or antineutrino beam

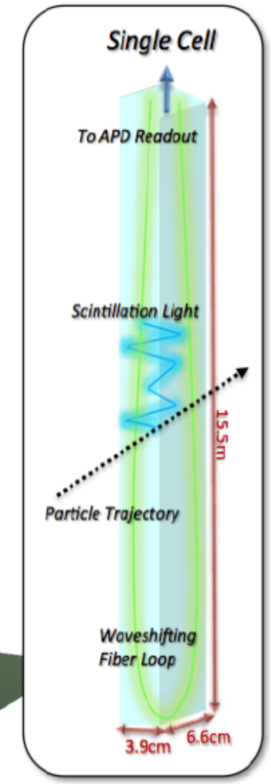


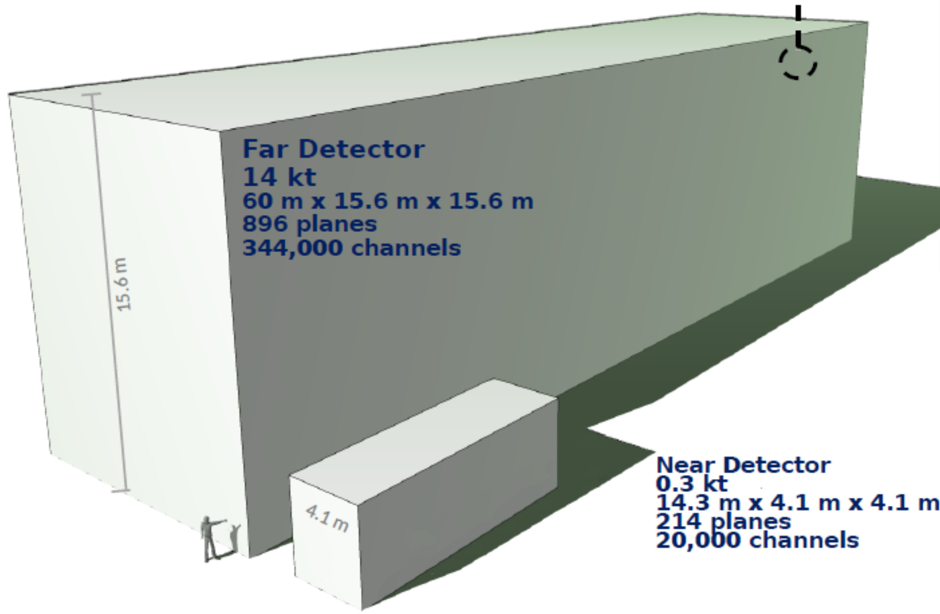
NOvA detectors are located 14 mrad off-axis with respect to beam direction

NOvA Detectors



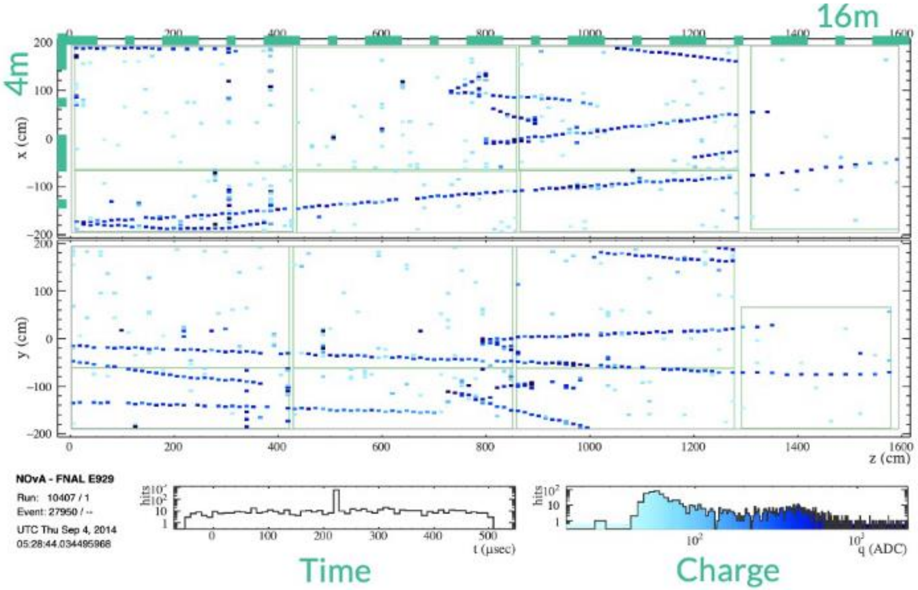
Extruded PVC cells filled with liquid scintillator instrumented with wavelength-shifting fiber and APDs



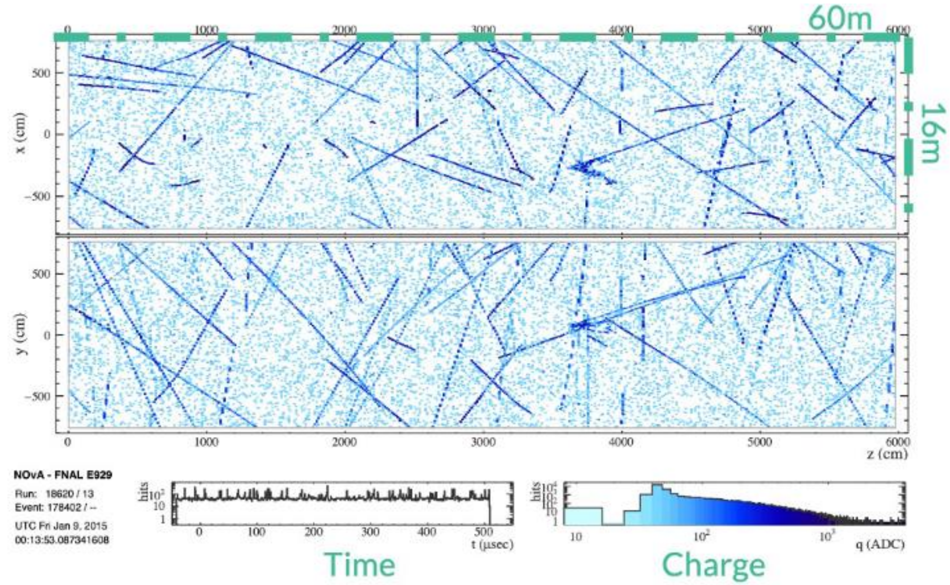


NOvA Detectors

ND



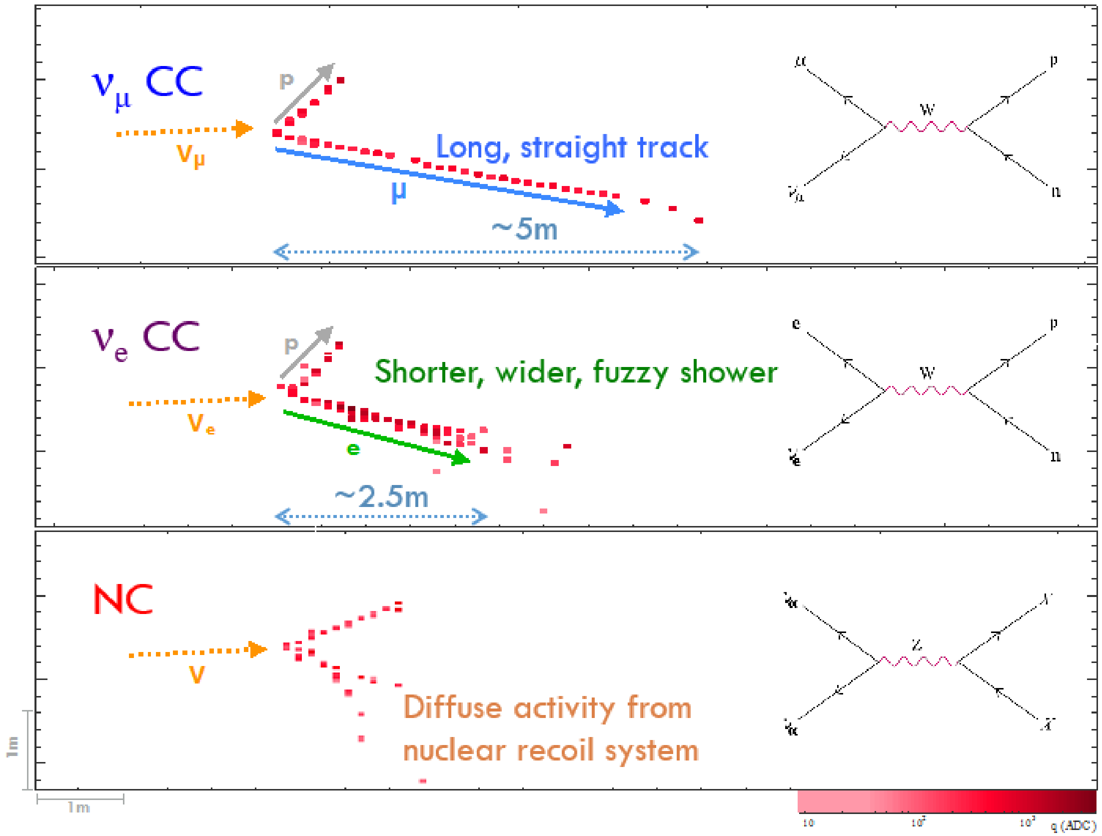
FD



~20k channels
1 km from target
100 m underground
~5 contained events for each 10 µs
beam pulse (every ~1.33 second)

~344k channels
810 km from target
On surface (~130 kHz cosmic rate)
<1 neutrino beam event per day

Event classification



Candidate events are required to:

- Be in time with the beam
- Be contained in the detector
- Pass data quality cuts

Event type identified by a convolutional neural network (CNN)

Cosmics are rejected

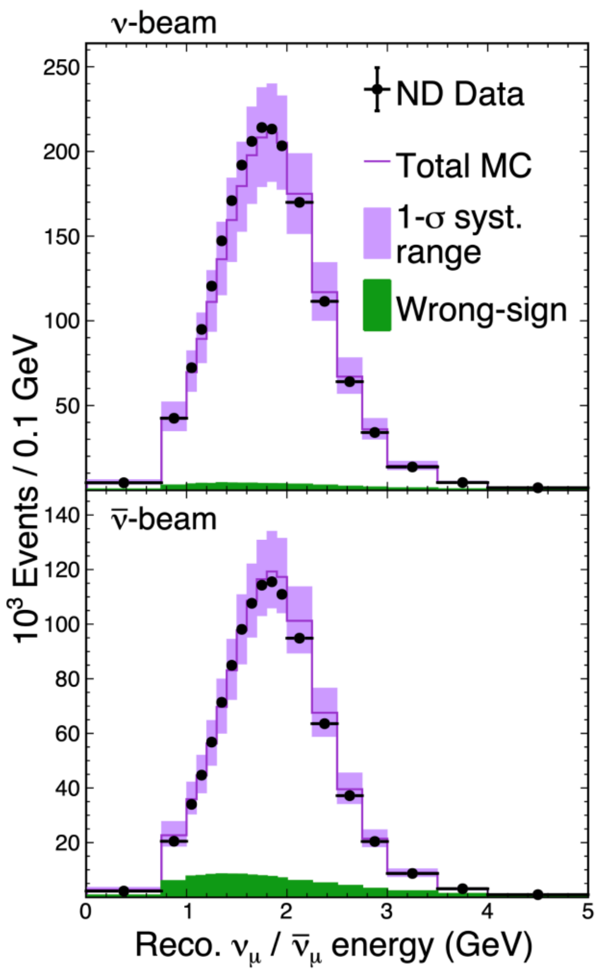
Energy reconstruction:

- Muon energy by range (3% resolution)
- Hadronic energy from calorimetry (30% resolution)
- EM energy by calorimetry (10% resolution)

ND Data

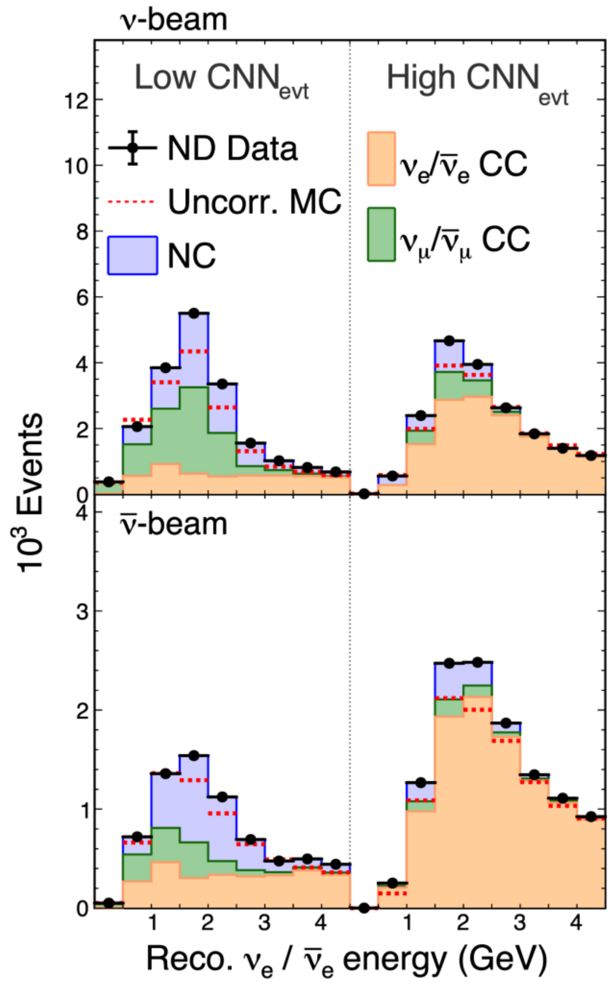
ND/FD concept: use ND data (with no oscillation effects) to make FD predictions – reduce impact of flux and cross section uncertainties

ND muon neutrino and antineutrino data:



Constrain FD $\upsilon_\mu \rightarrow \upsilon_\mu$ and $\upsilon_\mu \rightarrow \upsilon_e$ signal predictions

ND electron neutrino and antineutrino data:

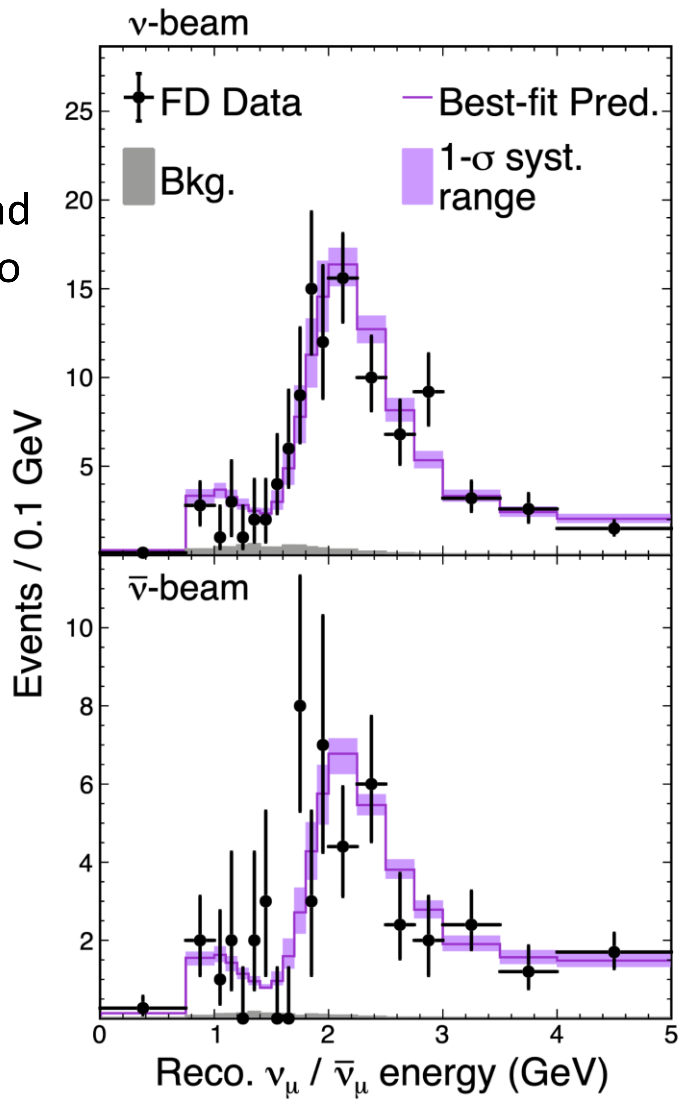


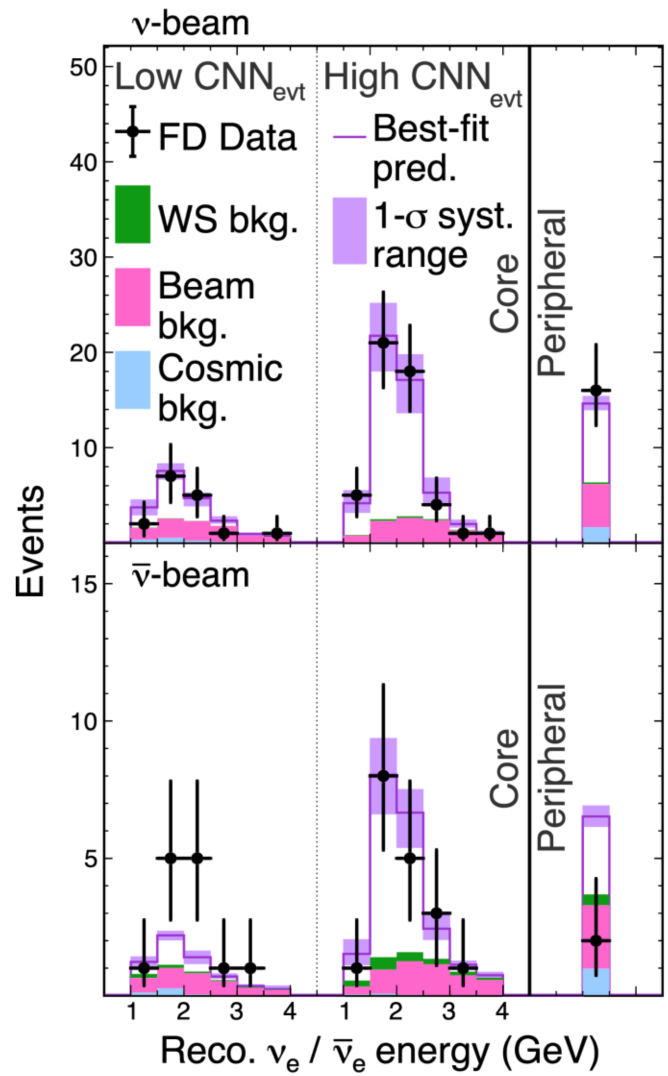
Constrain FD $\upsilon_\mu \rightarrow \upsilon_e$ background predictions

arXiv: 2108.08219

FD Data

FD muon neutrino and antineutrino data





FD electron neutrino and antineutrino data

arXiv: 2108.08219

Oscillation Results

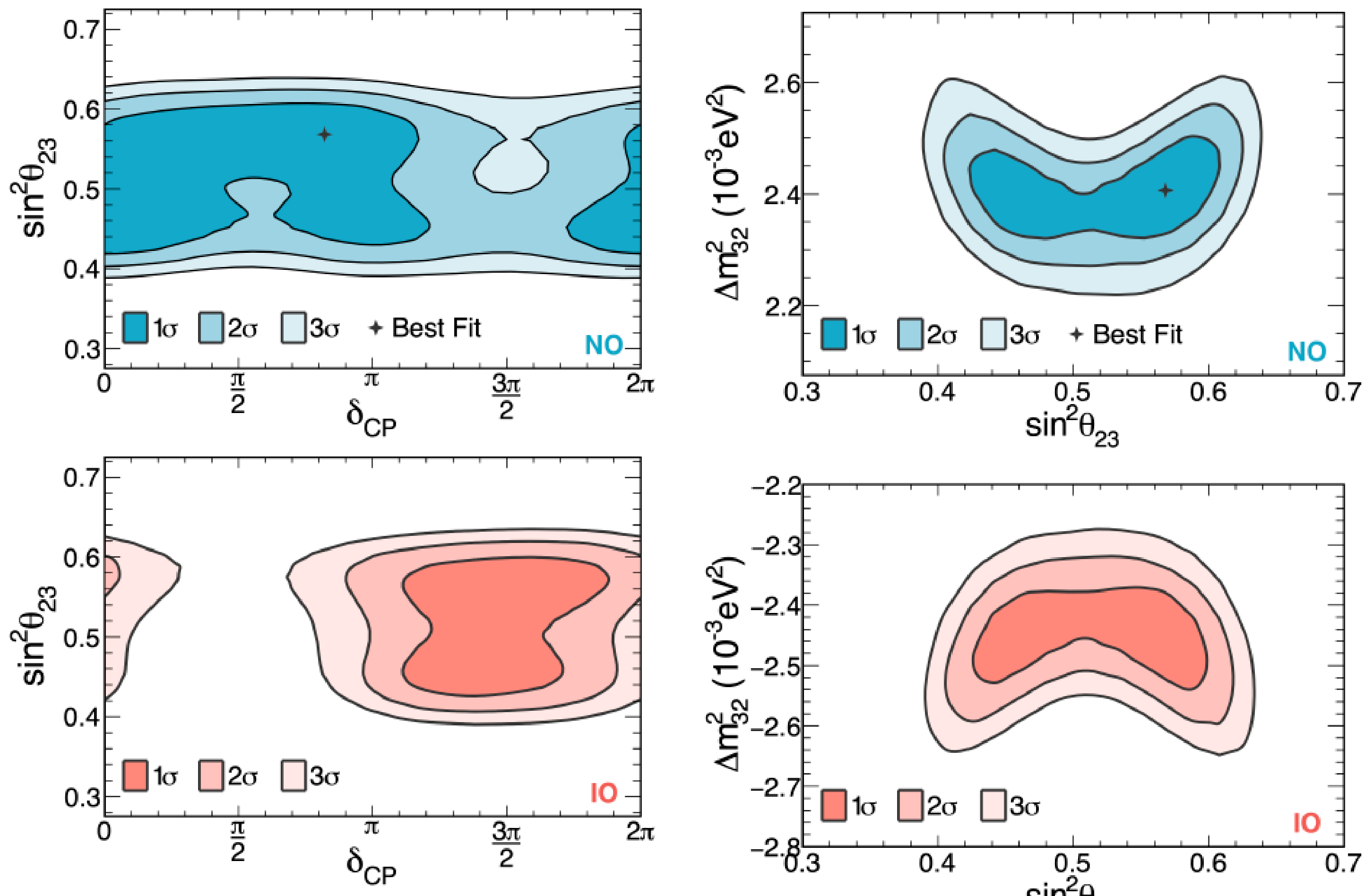
Best fit:

Normal hierarchy

Δm^2_{32} **= (2.41±0.07)×10^{-3} eV^2**

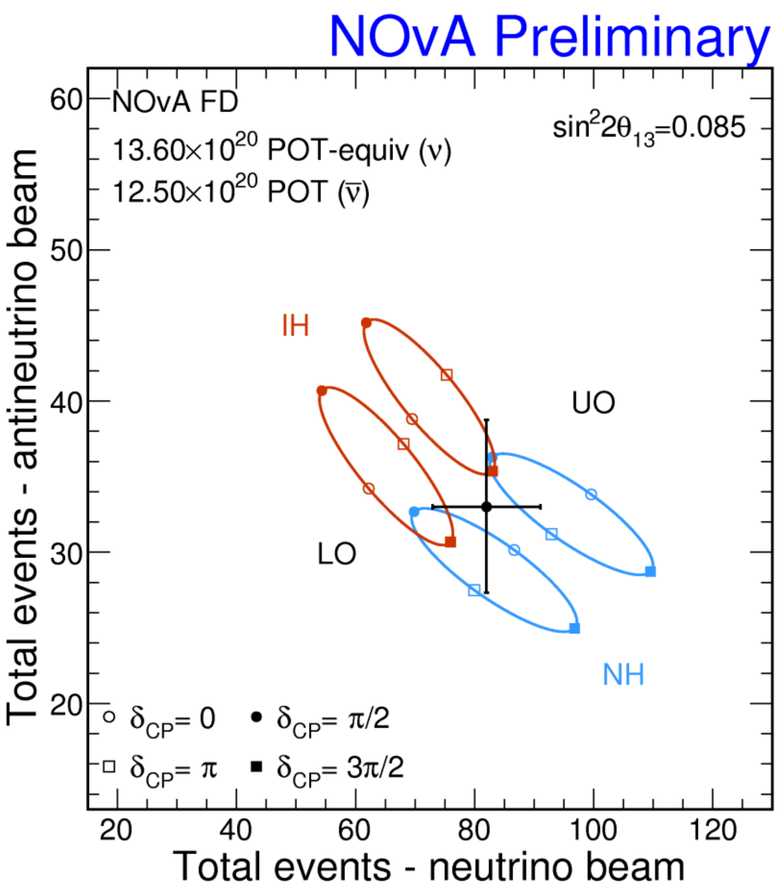
$\sin^2\theta_{23}$ **= 0.57$^{+0.04}_{-0.03}$**

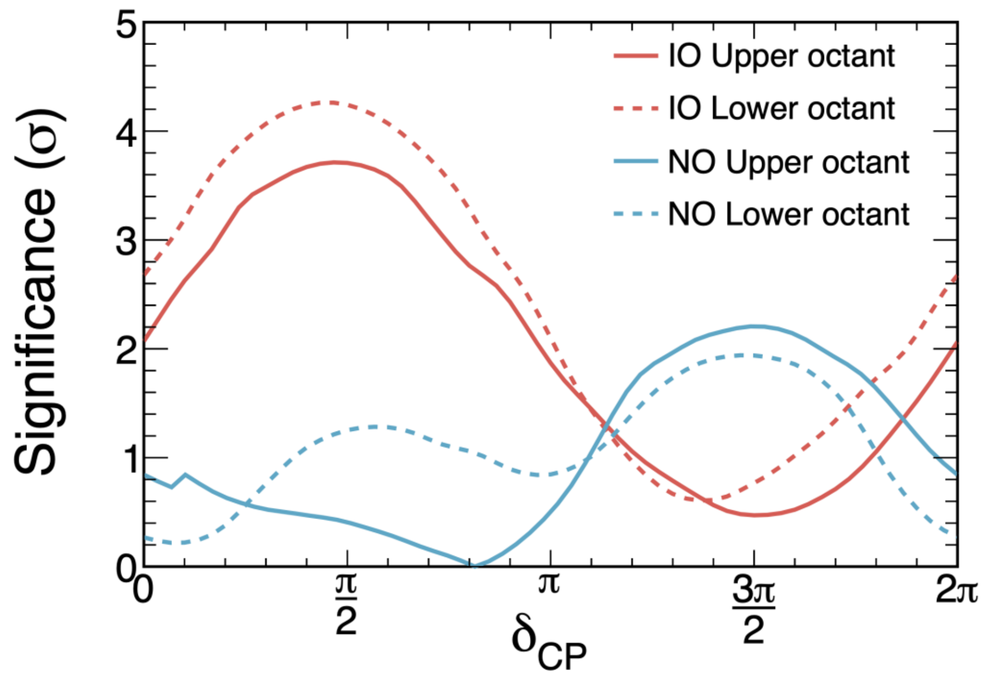
δ_{CP} =0.82π



arXiv: 2108.08219

Oscillation Results

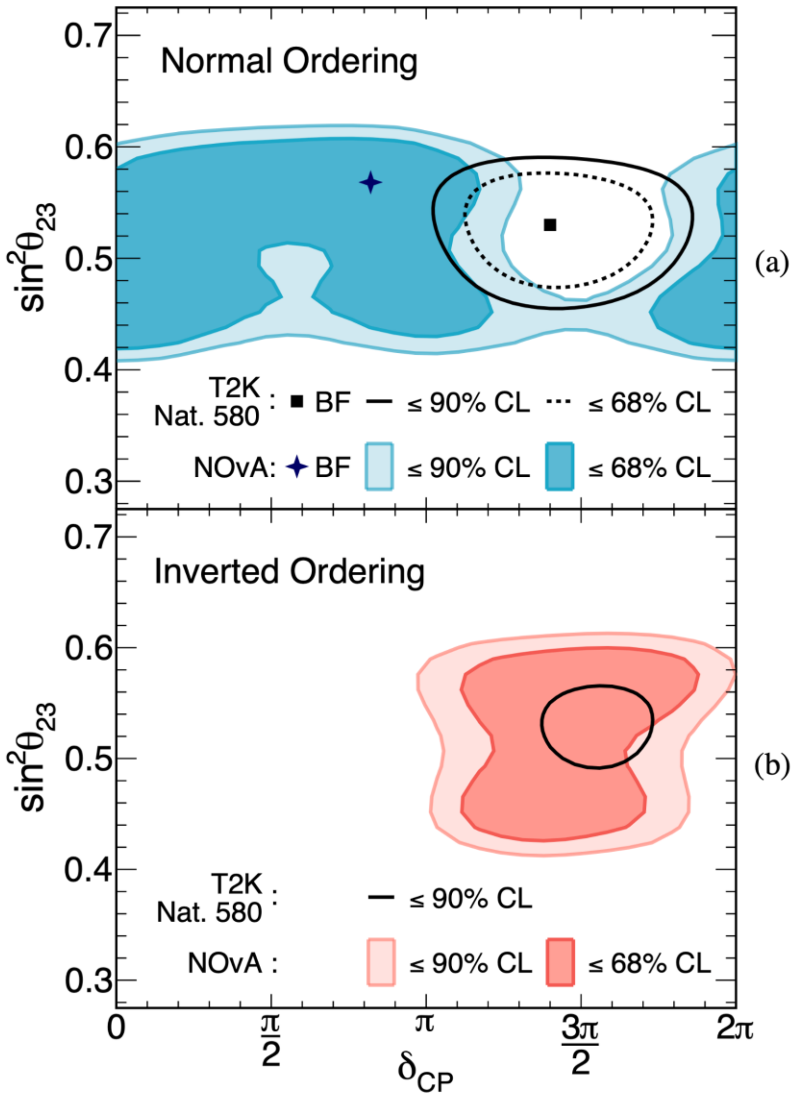


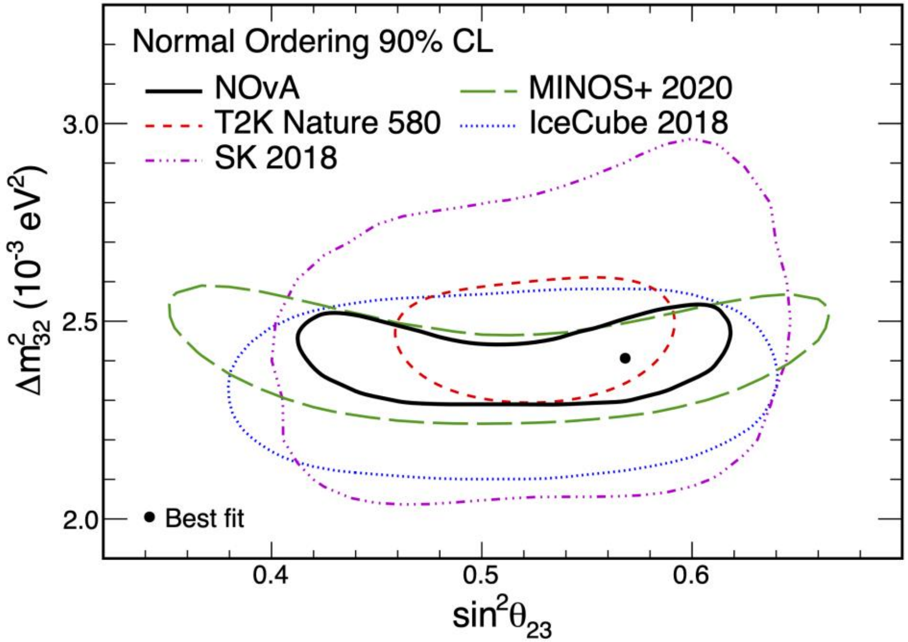


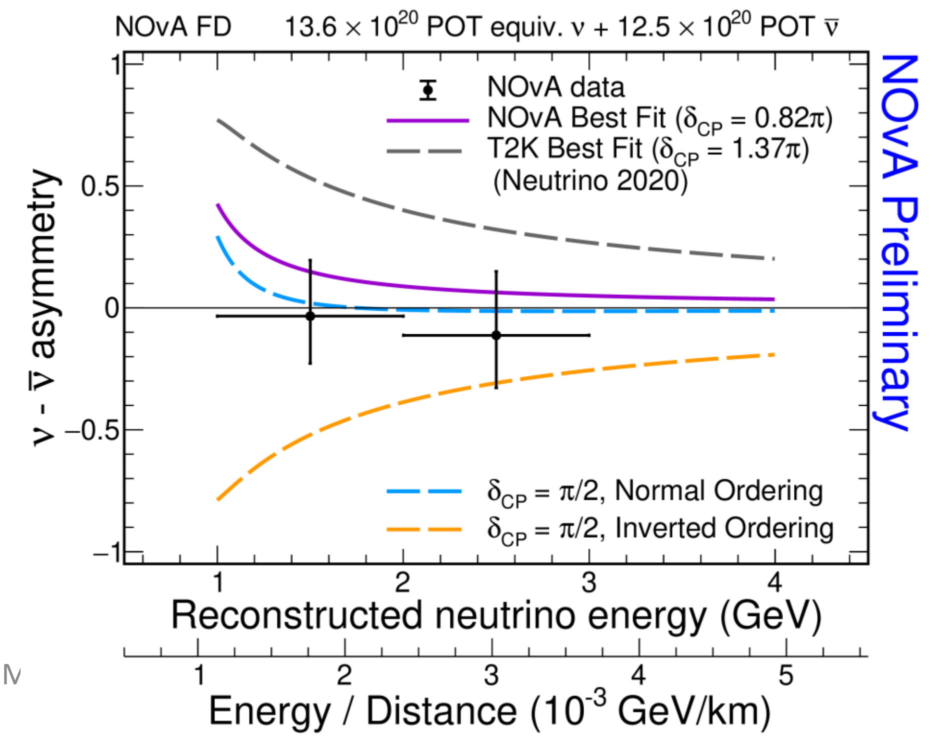
→Exclude IH $\delta = \pi/2$ at >3σ

→Disfavor NH $\delta = 3\pi/2$ at ~2σ

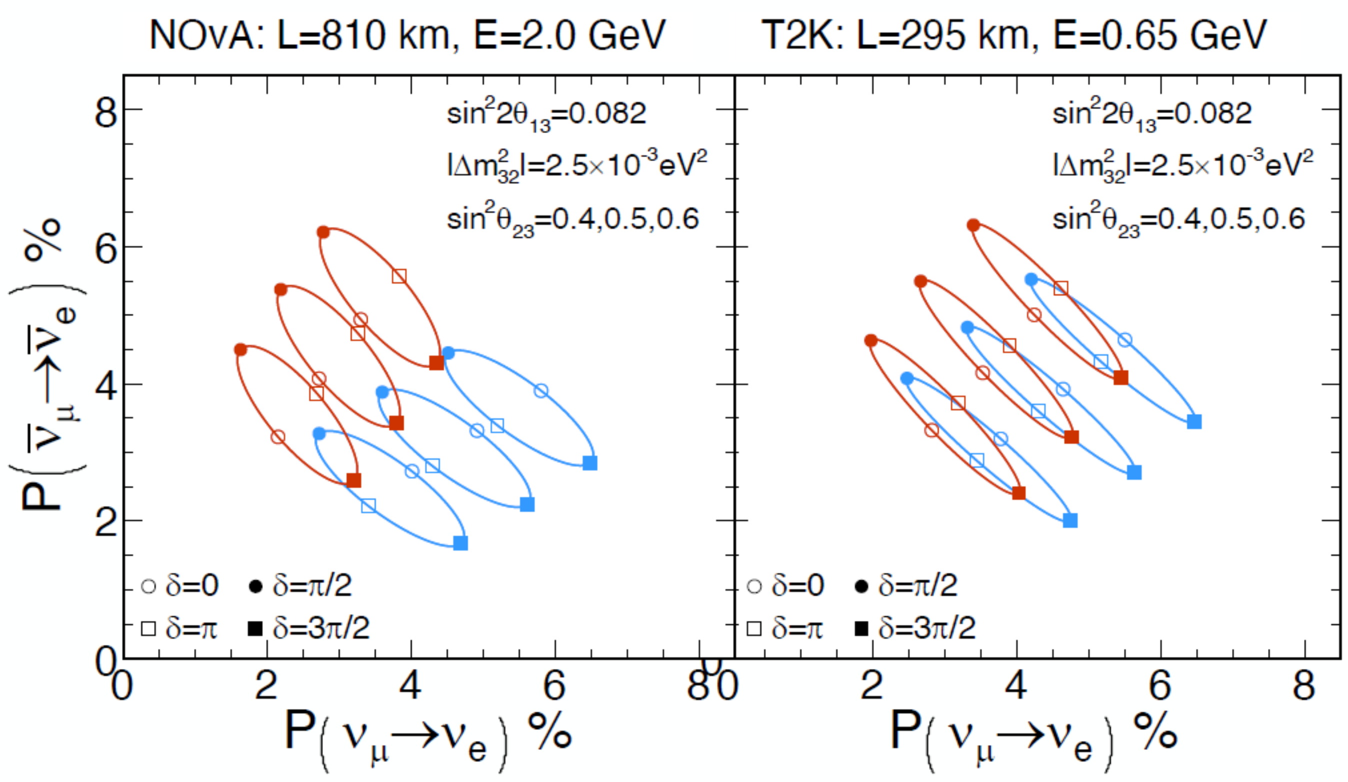
Global Picture







Future: NOvA + T2K

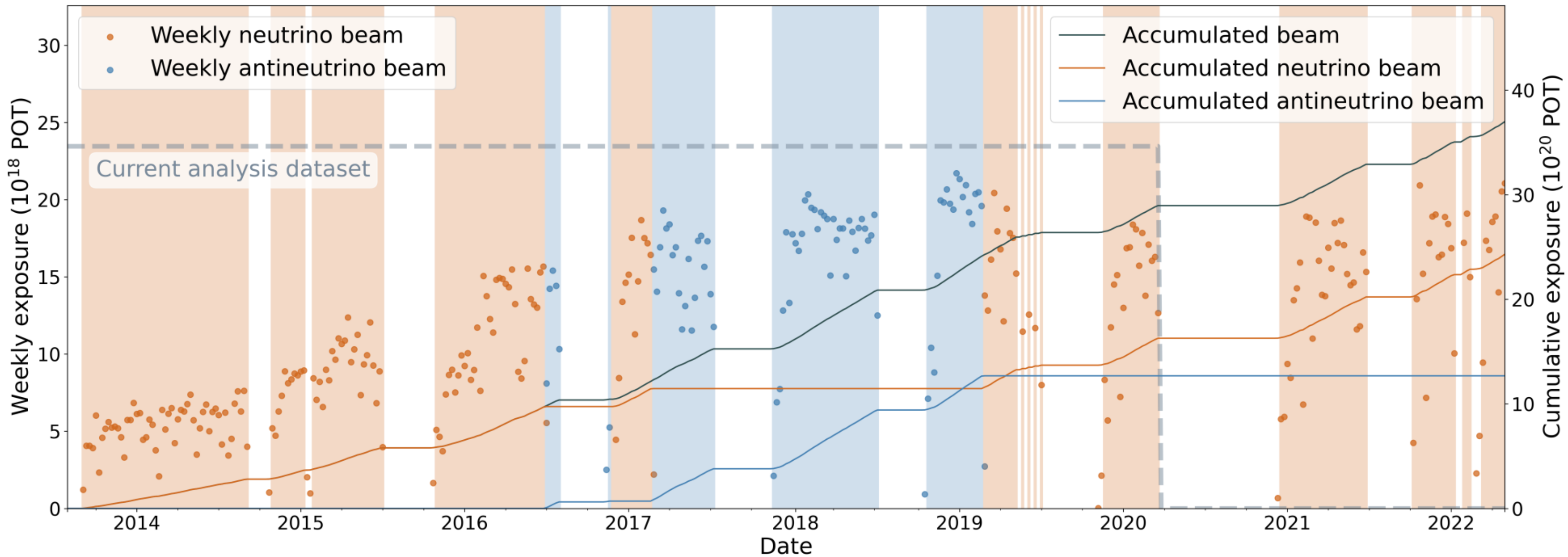


NOvA and T2K are highly complementary: different energy, different baseline → degeneracies occur at different values

Joint NOvA+T2K analysis is in progress!

NOvA: Accumulated Data

Recently set a new power record of 893 kW!

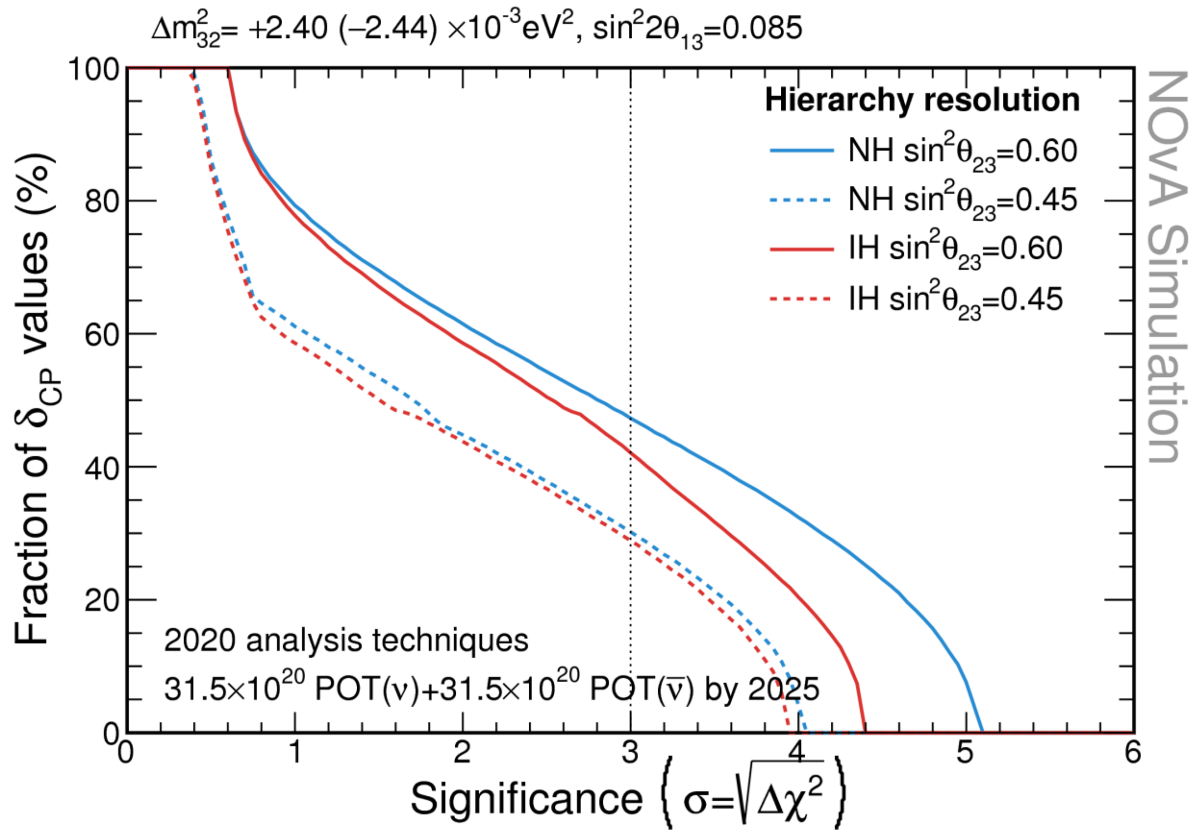


Results shown in this talk correspond to
13.60×10^{20} POT neutrino
12.5×10^{20} POT antineutrino

NOvA expects to take data through 2026, for a total of $60\text{-}70 \times 10^{20}$ POT

Future Prospects

- 3σ sensitivity in mass ordering for 30-50% of CP values
- 5σ for the most favorable value of CP-violating phase
- ~2σ sensitivity to maximal CP violation



Expect to remain statistics limited
Currently running test beam program (with 30 ton detector) to refine energy-scale systematics

Beyond 3-flavor oscillations…

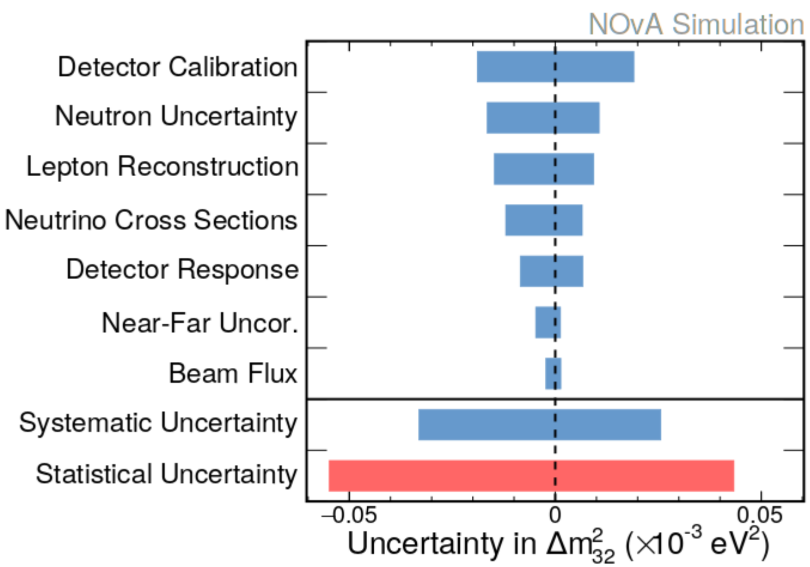
- Neutrino interactions
  - Inclusive υ_μ CC cross section (arXiv:2109.12220)
  - New υ_μ CC results next week @Neutrino 2022!
  - Soon: antineutrino cross sections
- Sterile neutrino search
  - NC channel: neutrinos (*Phys.Rev.D* 96 (2017) 7, 072006), antineutrinos (*Phys.Rev.Lett.* 127 (2021) 20, 201801)
  - New results next week @Neutrino 2022!
- Non-standard interactions (NSI): coming soon
- Cosmic ray physics
- Exotic searches:
  - Magnetic monopoles (*Phys.Rev.D* 103 (2021) 1, 012007)
- Multimessenger astronomy
  - Searches for unusual activity associated with gravitation wave alerts (*Phys.Rev.D* 101 (2020) 11, 112006; *Phys.Rev.D* 104 (2021) 6, 063024)
  - Supernova neutrinos: self-trigger, as well as induced by SNEWS alert (*JCAP* 10 (2020) 014)

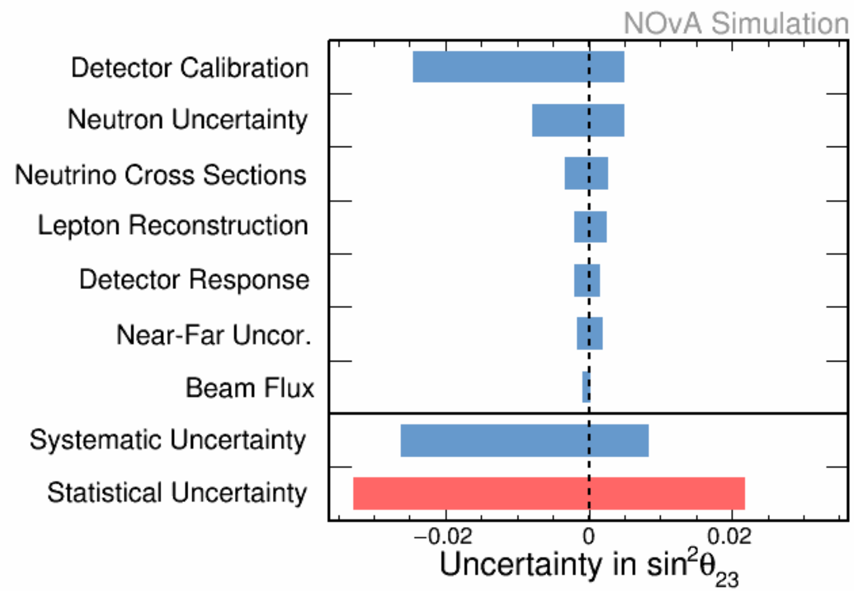
Summary

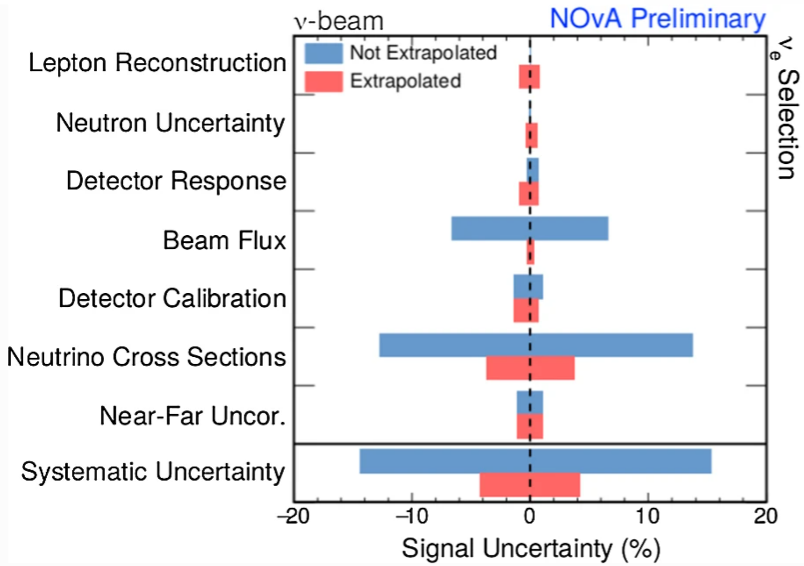
- NOvA is a long-baseline accelerator neutrino experiment studying neutrino oscillations
  - Probing mass ordering, CP violation, and octant
- Taking data since 2014 and expect to continue until 2026
- Joint analysis with T2K is in progress
- Rich physics program beyond 3-flavor oscillations
- Stay tuned for new results
  - Neutrino 2022 next week!

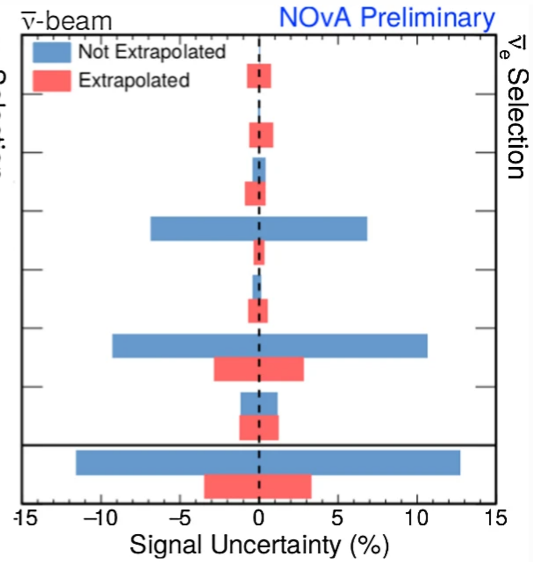
Backup

Systematic Uncertainties









Sterile Oscillations