Latest Oscillation Results from NOvA

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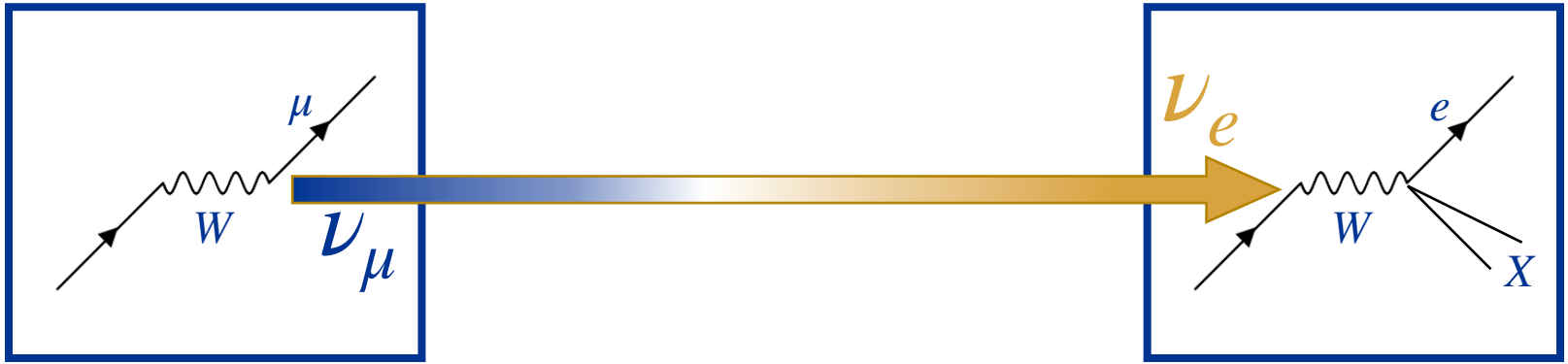
Lake Louise Winter Institute 2022

University of Pittsburgh

Neutrino Oscillations

Neutrinos are created as one flavor …

… but can be detected in another



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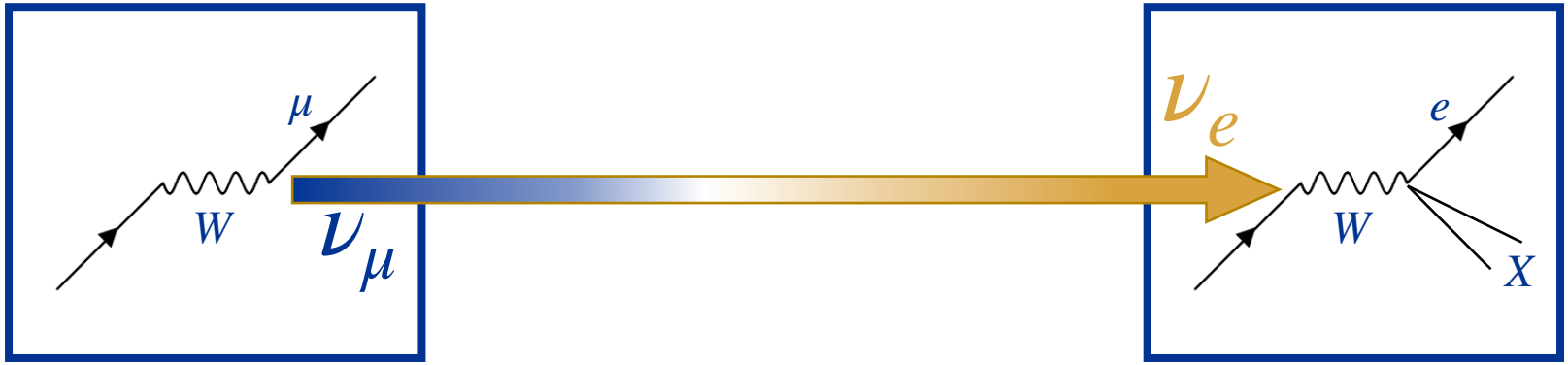


Each flavor is a linear combination of mass states:

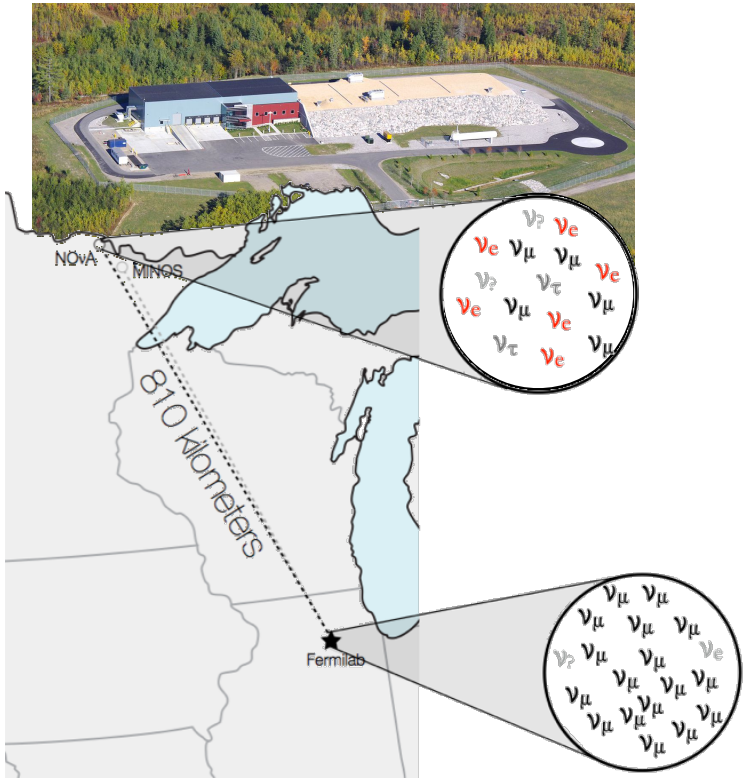
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$$

Oscillations depend on all these parameters and the differences between the mass differences!

NOvA Physics Program

- NOvA: long-baseline neutrino oscillation experiment (810 km baseline)



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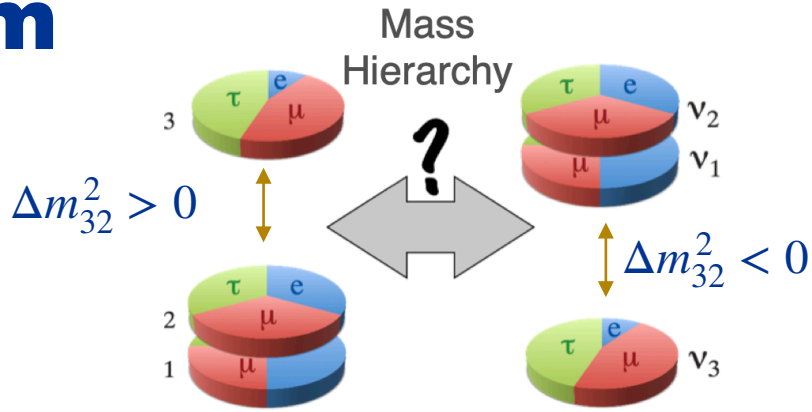
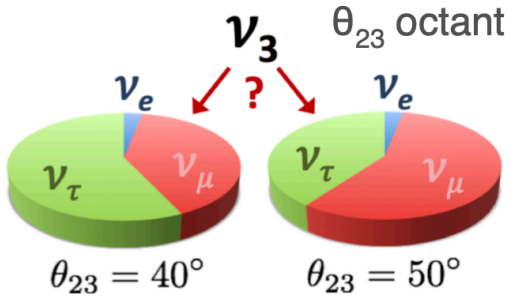
- NOvA: long-baseline neutrino oscillation experiment (810 km baseline)
- Addresses open questions:
  - Sign of Δm^2_{32}: normal or inverted hierarchy?
  - Value of θ_{23}: maximal mixing or (ν_μ/ν_τ symmetry)
  - Is there CP violation in the lepton sector?

Using $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ and antineutrino oscillations





$\delta_{CP} = ?$

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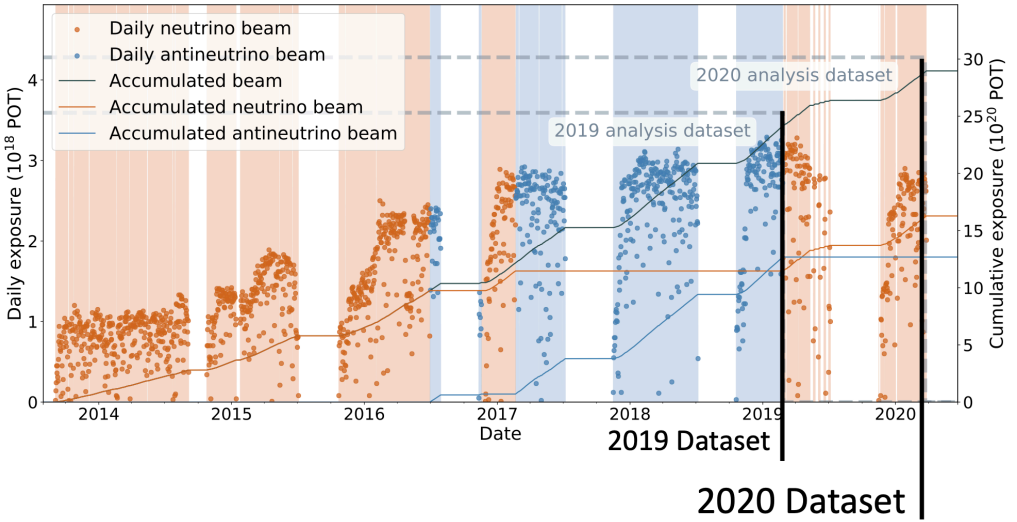
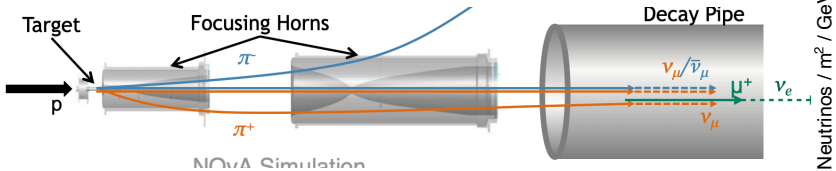
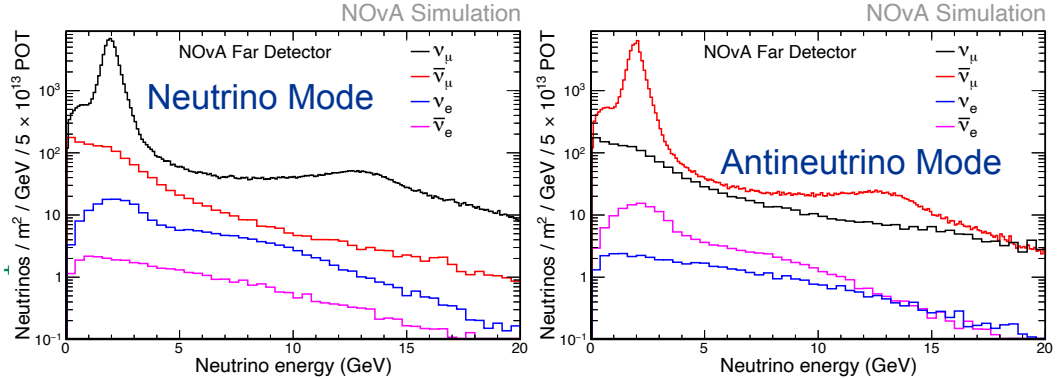
    Using $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ and antineutrino oscillations
- Broad physics program:
  - Neutrino-nucleus cross-section measurements [PRD, arXiv:1902.00558]
  - Search for sterile neutrinos [PRL, arXiv:2106.04673]
  - Astrophysics: Multi-muon air showers [PRD, arXiv:2105.03848] **And More!**

The NUMI Beam

- Typically runs ~650kW:
  - 5 near detector events / spill
  - ~1 event / day at the far detector
- Charge select pions to get 96% (83%) pure muon neutrino (antineutrino) beam
- Current datasets have:
  - ≈1 million events in the near detector for both beam modes
  - ≈100 events in the far detector for both beam modes

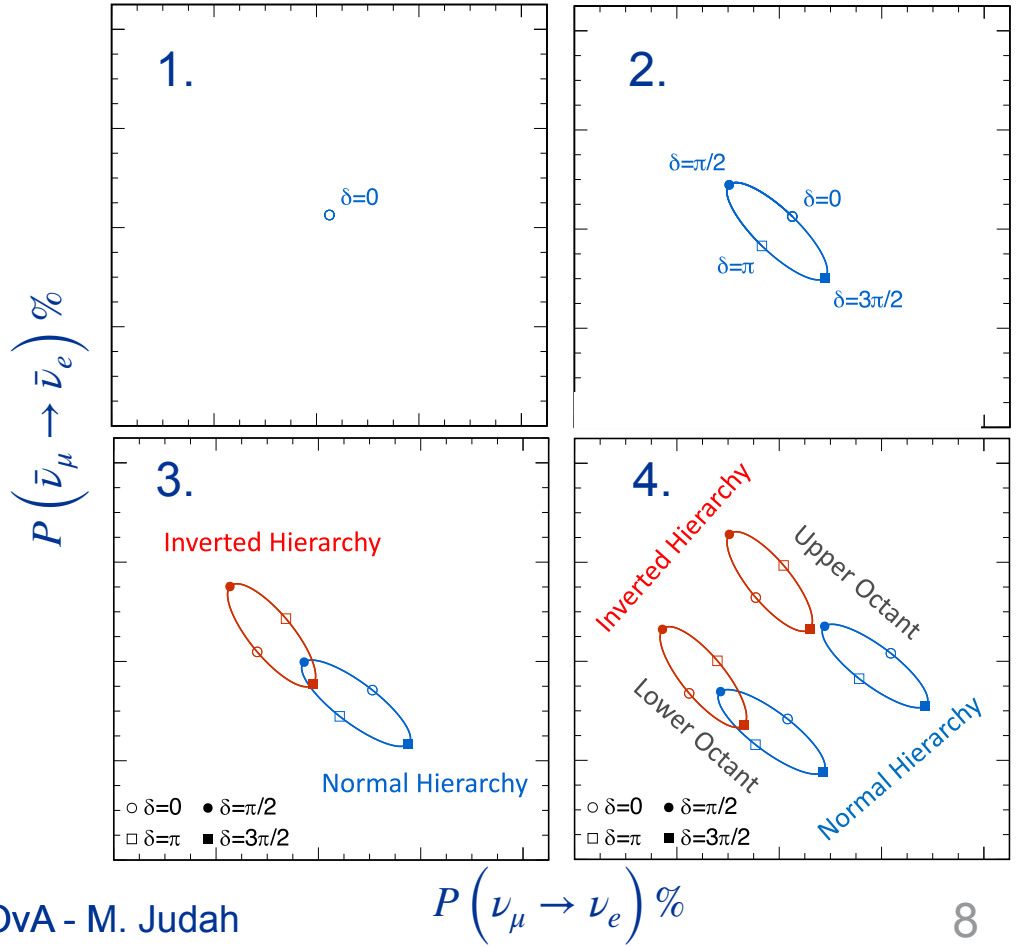






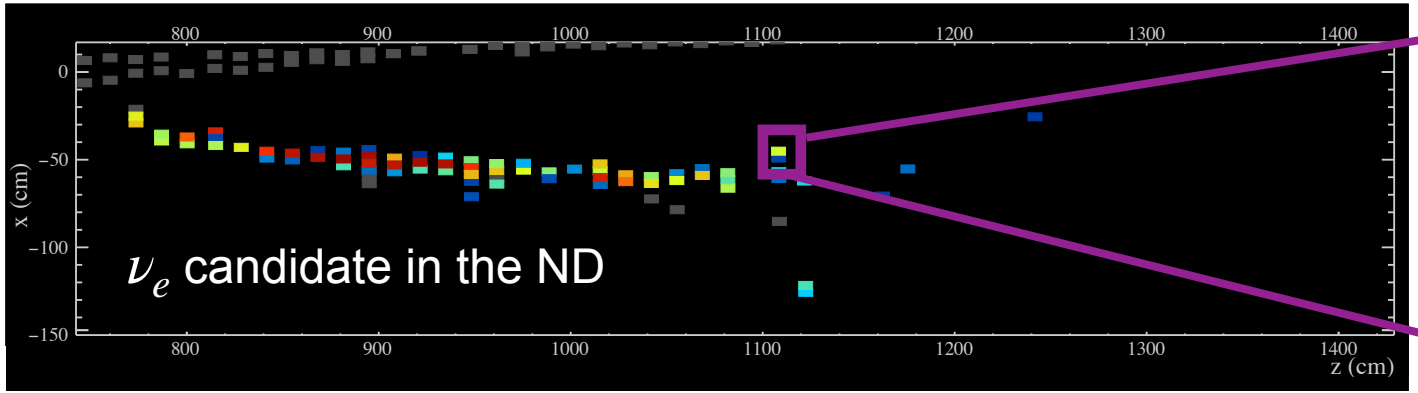
Why neutrinos and antineutrinos?

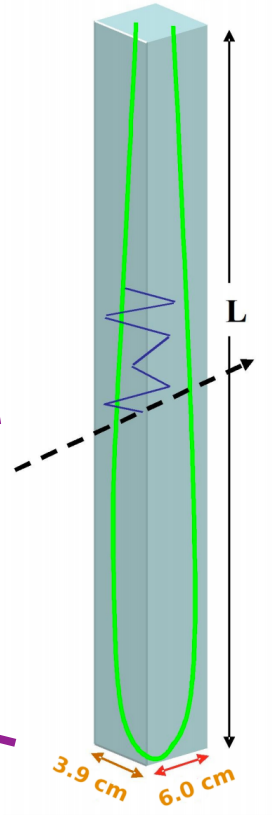
1. In vacuum and no CP-violation, ν and $\bar{\nu}$ oscillation probabilities are equal
2. **CP-violation** produces opposite effects for ν and $\bar{\nu}$ oscillation probabilities
3. **Matter effects** generate opposite effects depending on **Mass Hierarchy**
4. θ_{23} can increase or decrease oscillation probabilities



The NOvA Detectors

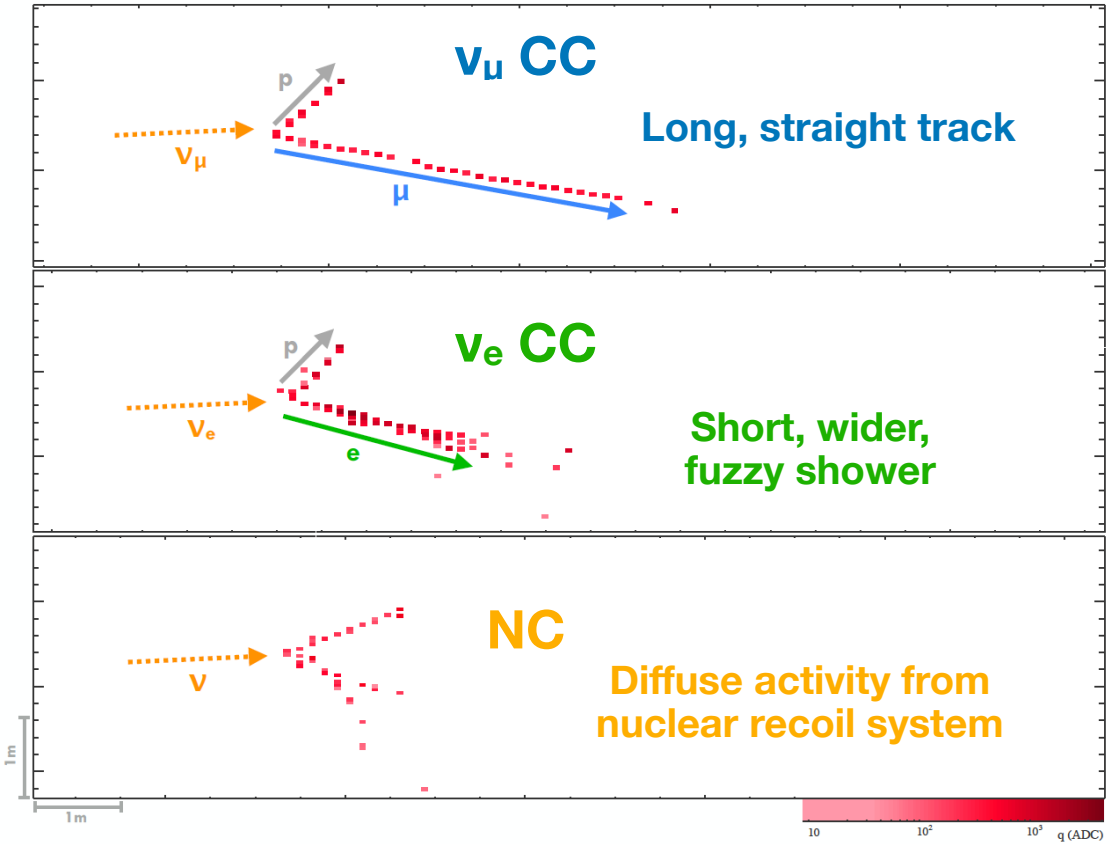
- 2 functionally identical detectors: 14 mrad off-axis and 810 km apart
- Orthogonal layers of segmented PVC filled with liquid scintillator — 3D tracking and calorimetry
- Optimized for electron showers: ~6 samples per X_0 and ~60% active
- Good time resolution (~5 ns) and spatial resolution(~few cm)
- Allows clear separation of interactions



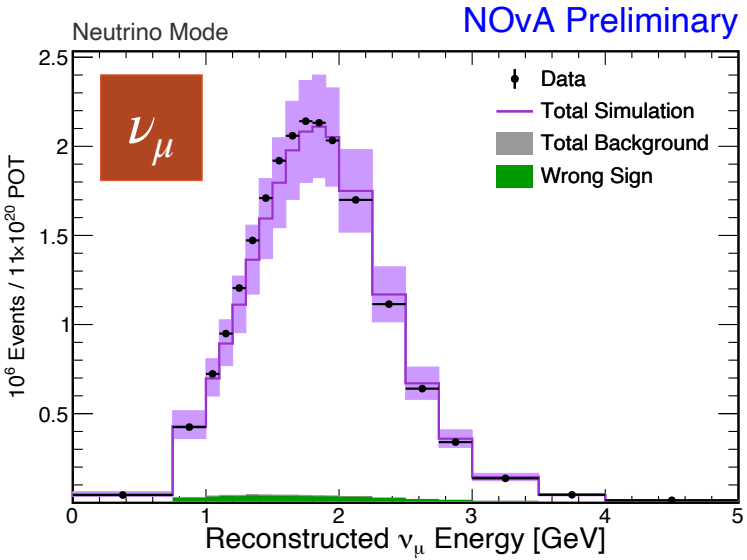


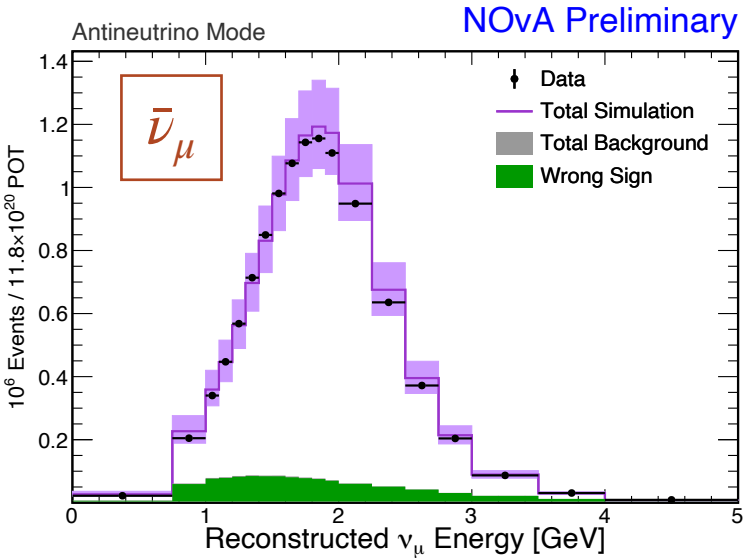
Event Selection

- Identify neutrino flavor using convolution neural network.
  - Deep-learning technique inspired by computer vision
- Before main algorithm to ID events:
  - Events are contained
  - Reject cosmic rays with BDTs



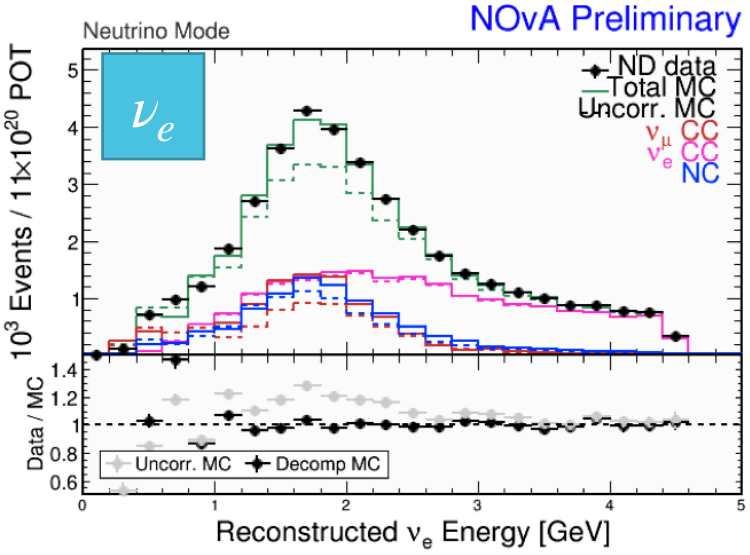
Muon Neutrinos at the ND

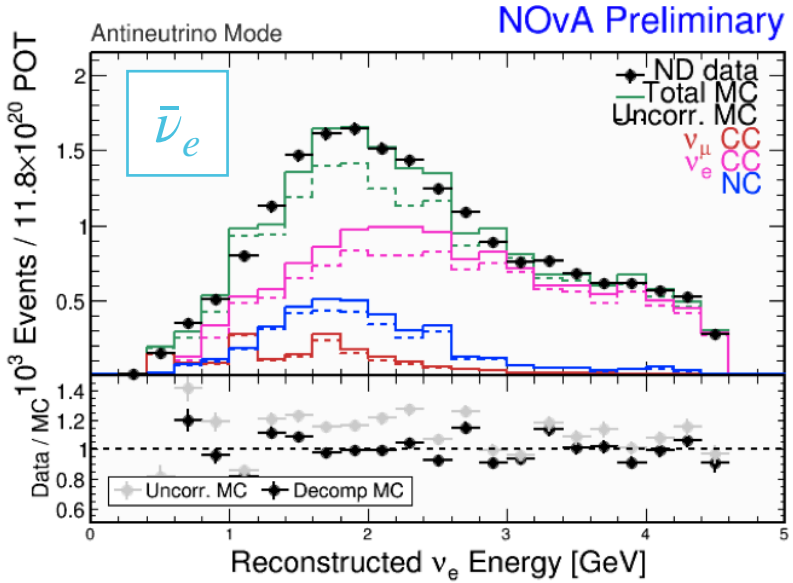




- Use ν_μ sample to predict ν_μ and ν_e signal at FD
- Dominant uncertainties from flux and $\nu - A$ interaction uncertainties

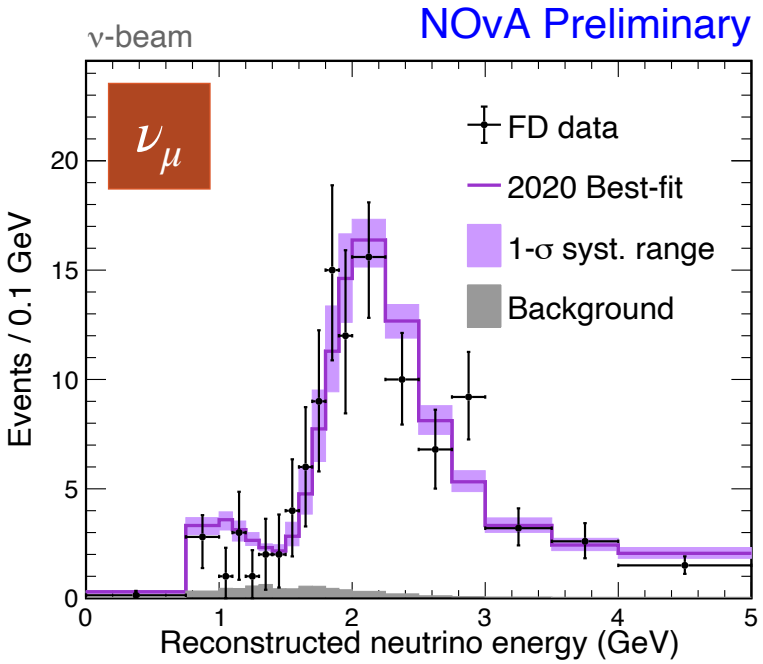
Electron Neutrinos at the ND



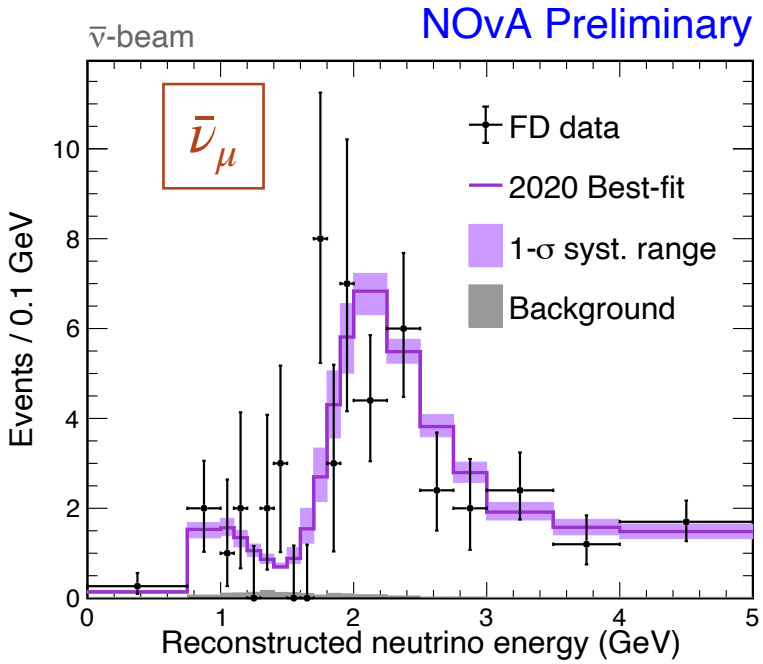


- ν_e-like spectrum shows backgrounds to the $\nu_\mu \rightarrow \nu_e$ signal
- Sample used to predict the backgrounds at the FD
- Largest background is intrinsic beam ν_e & $\bar{\nu}_e$

Far Detector ν_μ CC Spectrum

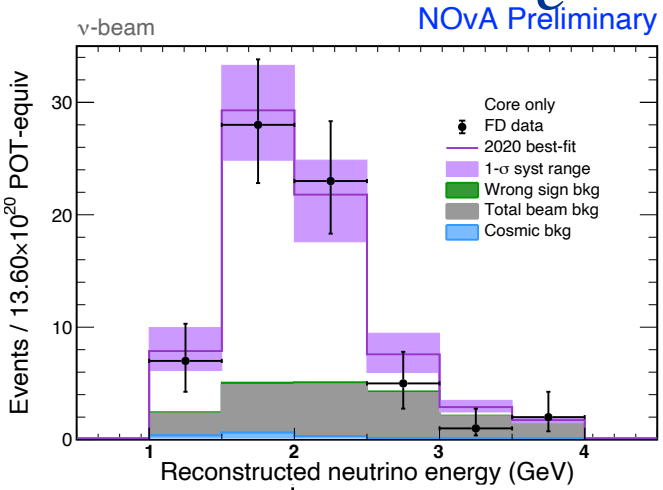


211 events, 8.2 background

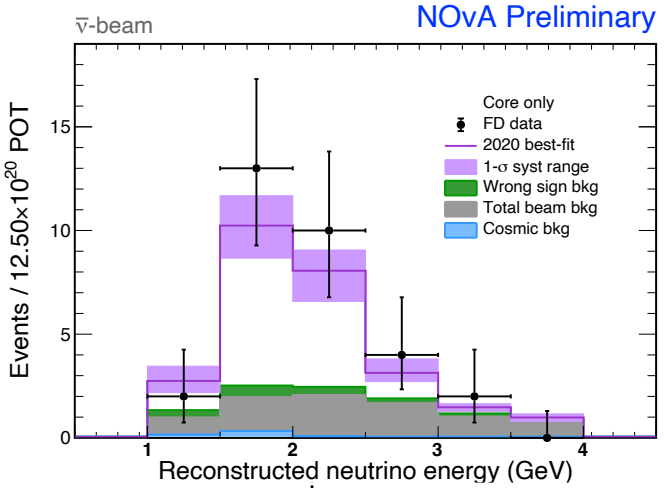


105 events, 2.1 background

Far Detector ν_e Candidates



Total Observed	82
Total Prediction	85.8
Wrong-sign	1.0
Beam Bkgd.	22.7
Cosmic Bkgd.	3.1
Total Bkgd.	26.8

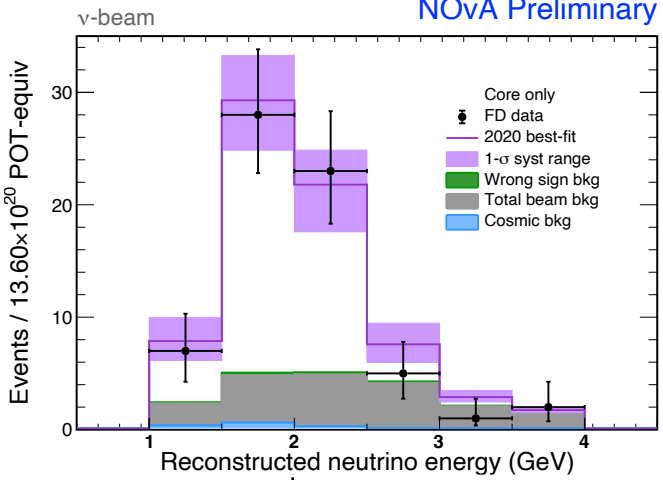


Total Observed	33
Total Prediction	33.2
Wrong-sign	2.3
Beam Bkgd.	10.2
Cosmic Bkgd.	1.6
Total Bkgd.	14.0

Far Detector ν_e Candidates

>4σ evidence of electron antineutrino appearance

NOvA Preliminary



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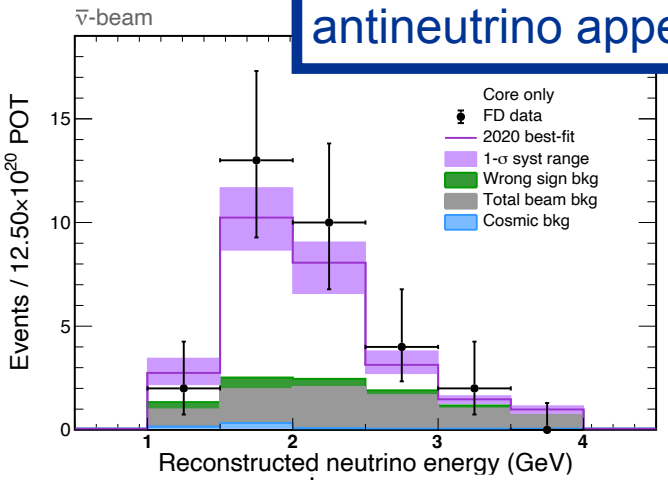

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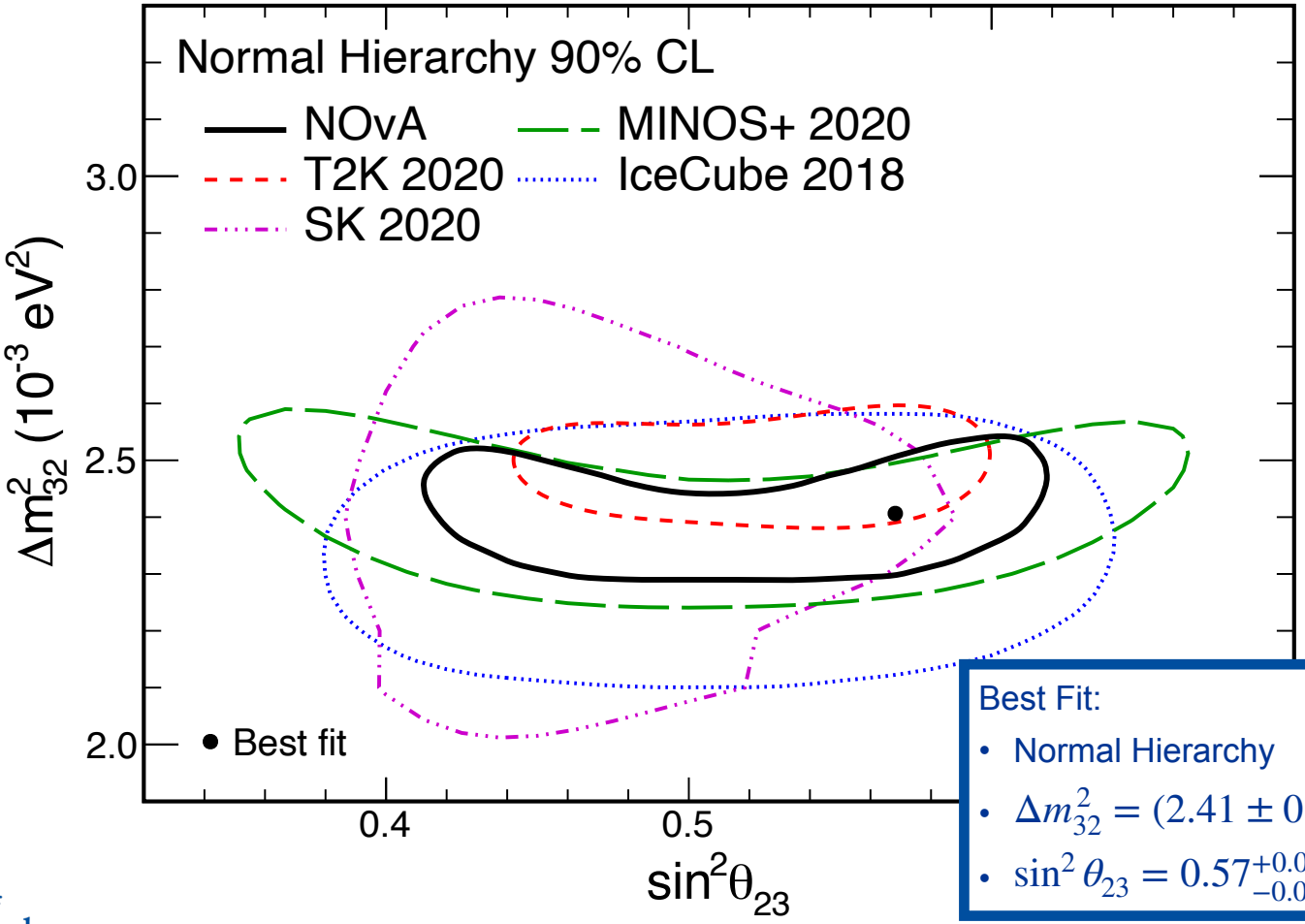

Best Fit:

- Normal Hierarchy
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2
- $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

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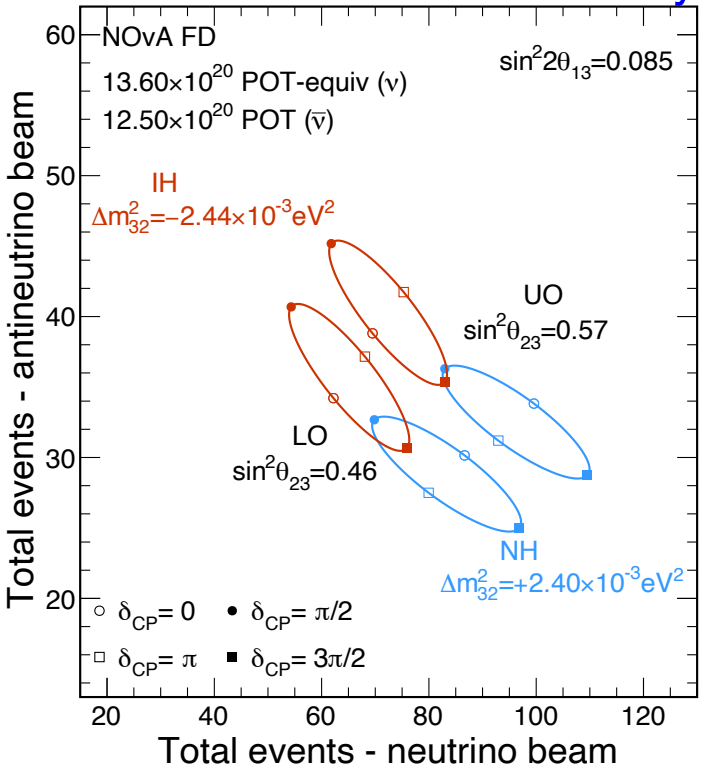

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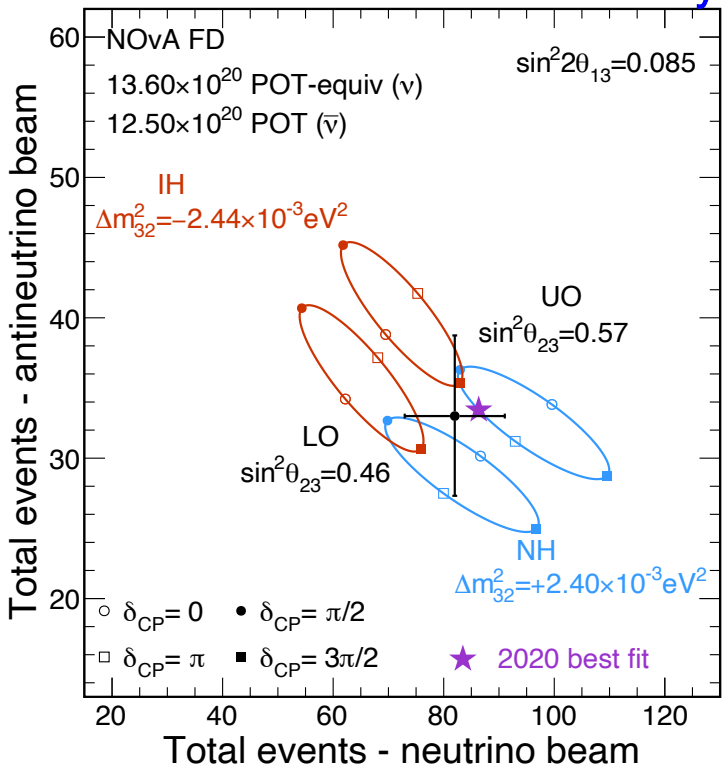
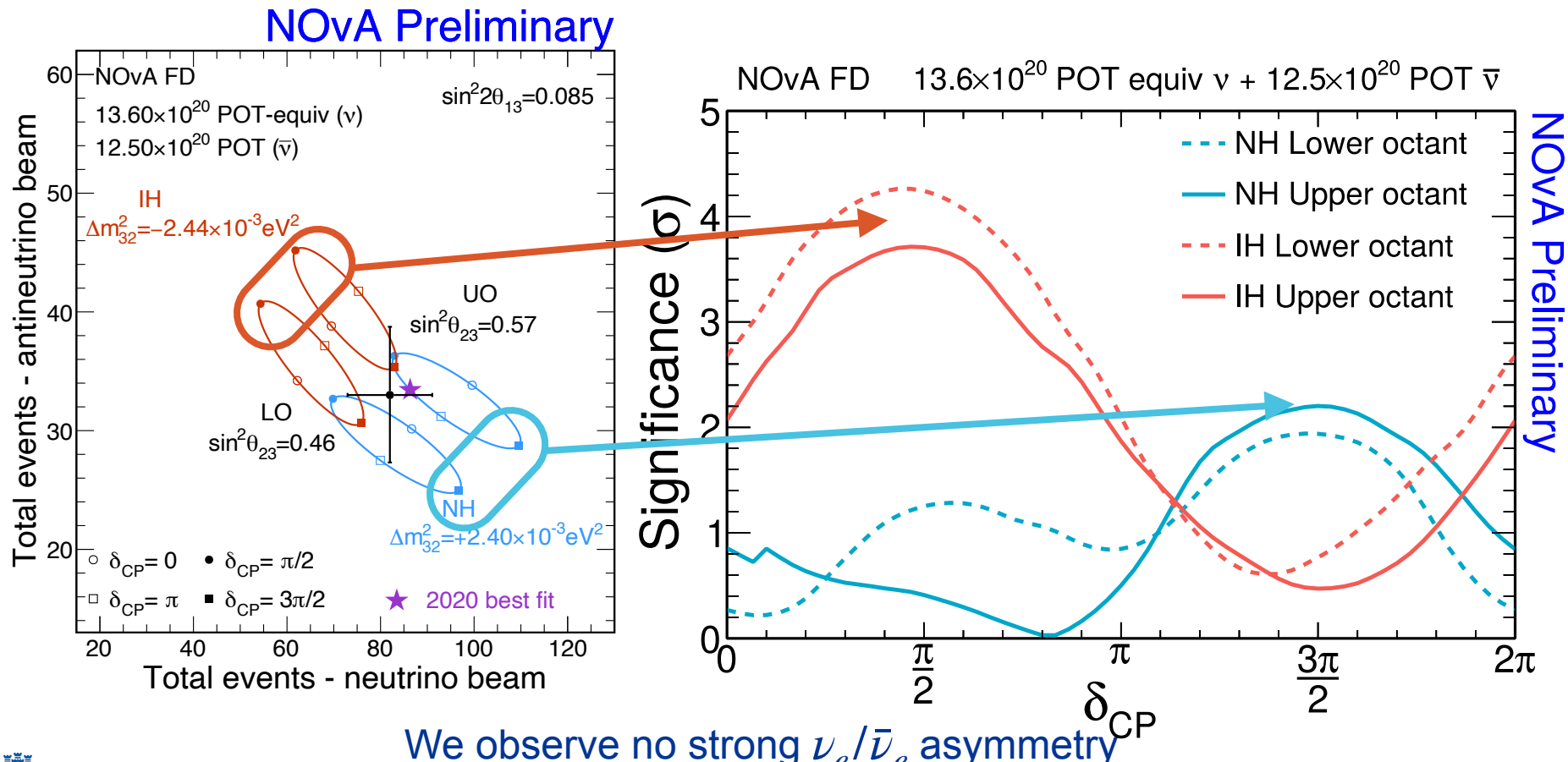


We observe no strong $\nu_e/\bar{\nu}_e$ asymmetry



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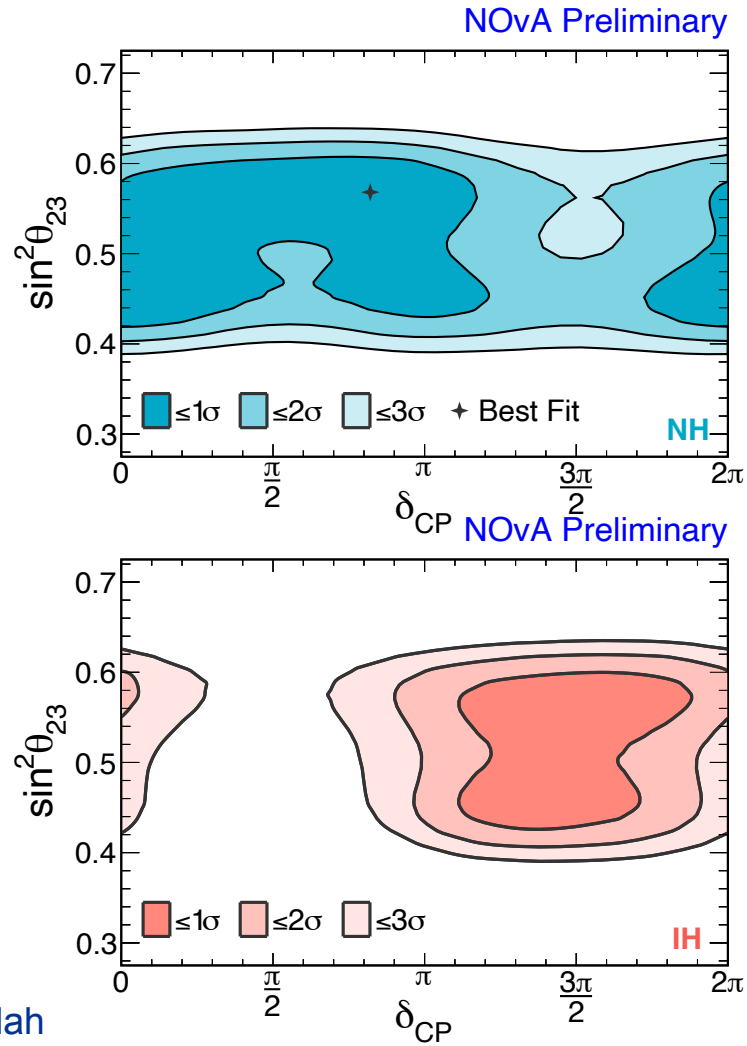
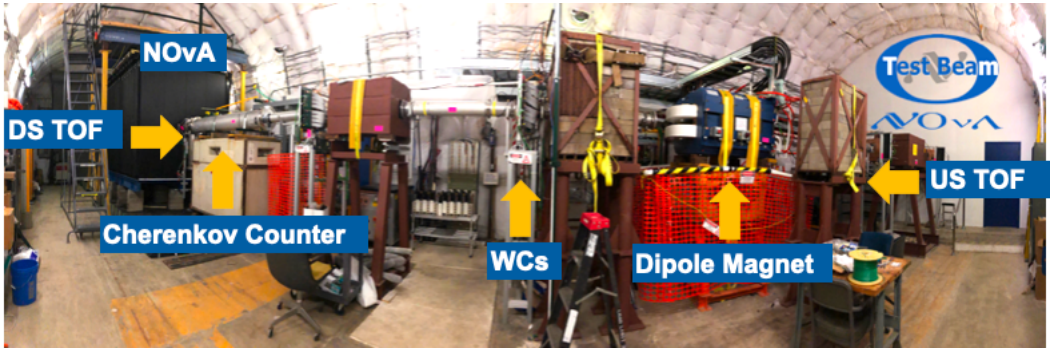
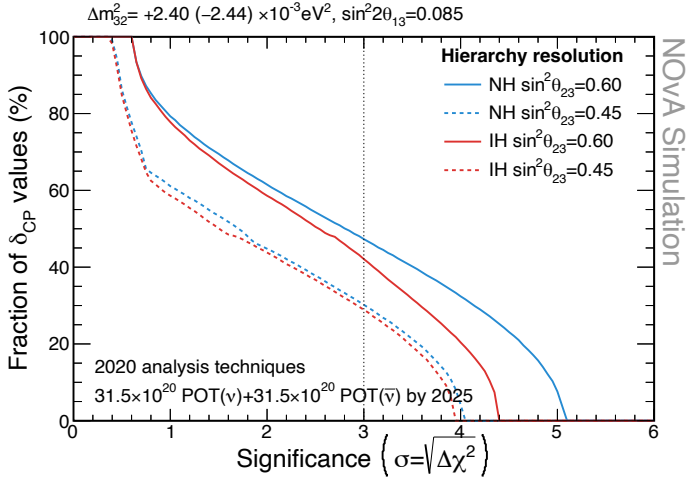
Results

- Best Fit:
  - Normal Hierarchy
  - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$
  - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
- Precision measurements of Δm^2_{32} and $\sin^2\theta_{23}$
- Constraints on δ_{CP}
  - NH: $\delta_{CP} = 3\pi/2$ disfavored at ~2σ
  - IH: $\delta_{CP} = \pi/2$ disfavored at >3σ
- **Working on a joint fit of the data from NOvA and T2K!**



The Future





- Plan to reduce the largest systematic uncertainties related to detector energy scale using our test beam experiment
- NOvA can reach 3σ hierarchy determination sensitivity for 30-50% of δ_{CP} values with full dataset and upgraded beam

Questions?