# Results from NOvA

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for the NOvA Collaboration

NuFact 2021
Sept. 6th 2021

# Outline

- Physics goals
- How NOvA works
- Oscillation measurements
- Cross-section measurements
- Sterile-neutrino search
- “Exotics” (astrophysics & BSM) studies
- Test Beam program
- Joint analysis with T2K
- Summary & conclusions

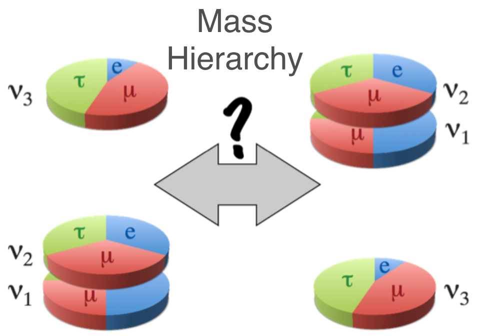
# Main Goals

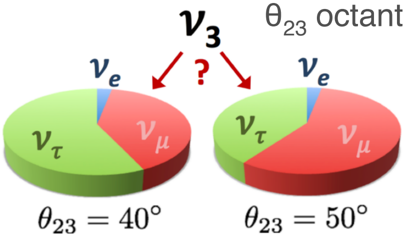
- **NOvA: long-baseline neutrino oscillation** experiment (Fermilab to northern Minnesota, 810 km)
- Addresses open questions:
  - **sign** of $\Delta m^2_{32}$: Normal or Inverted Hierarchy?
  - **value** of $\theta_{23}$: Maximal Mixing ($\nu_\mu/\nu_\tau$ symmetry)?
  - does neutrino oscillation **violate CP**?

…via $\nu_\mu$, $\overline{\nu}_\mu$ disappearance & $\nu_e$, $\overline{\nu}_e$ appearance

7 NOvA NuFact presentations:

Matt Strait WG1 talk



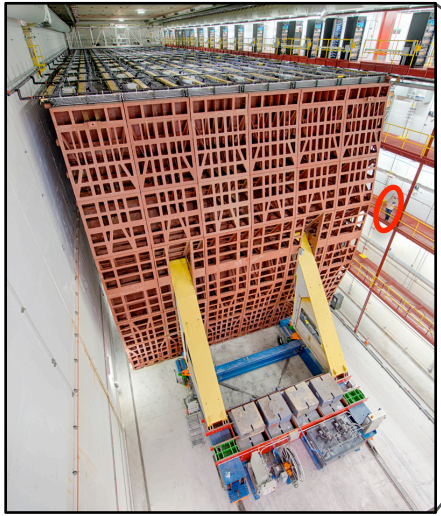




$\delta_{CP} = ?$

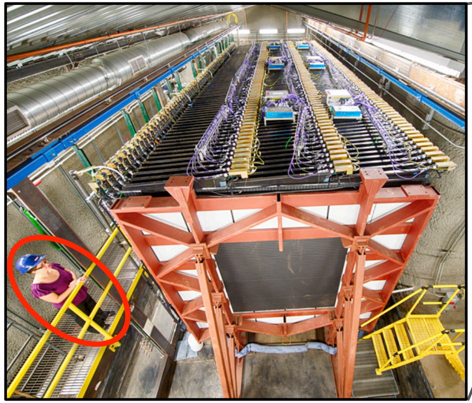
- Also rich broader physics program:
  - **neutrino cross-section** measurements — Leo Aliaga, Bryan Ramson WG2 talks, Wenjie Wu poster
  - search for **sterile neutrinos** — Jeremy Hewes WG5 talk
  - investigation of **astrophysical** and **BSM** phenomena

also "Modeling issues in NOvA" — Greg Pawloski, joint WG1&2 talk
and "NuMI beam modeling" — Yiding Yu poster

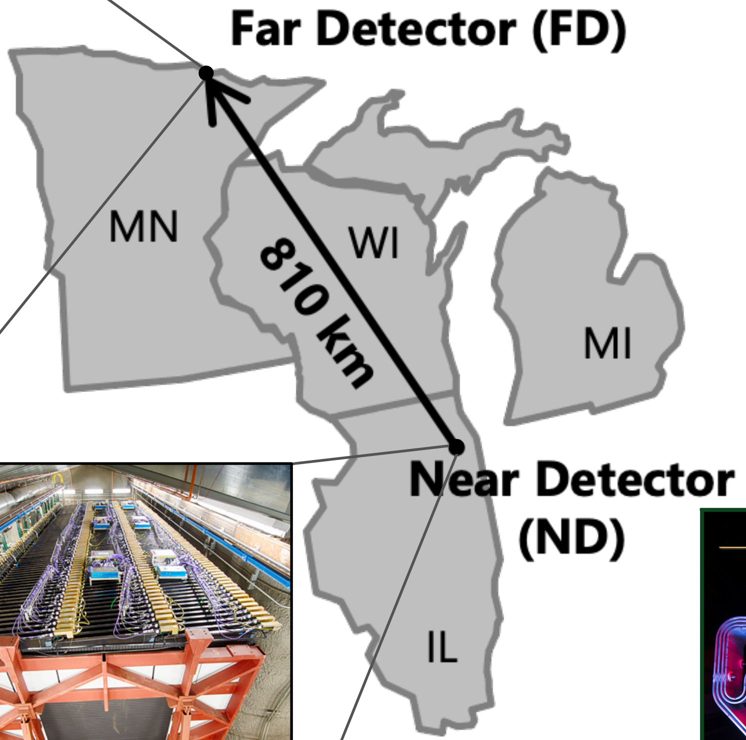
# NOvA Layout

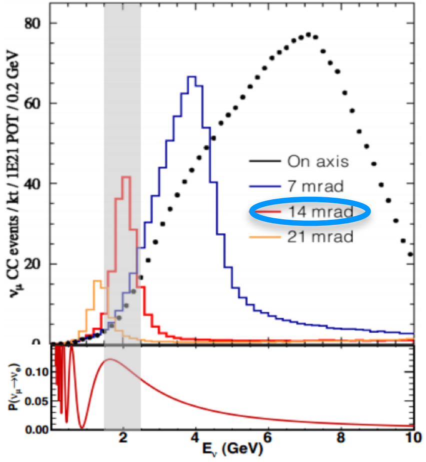


**14 kt Far Detector**
(on surface)

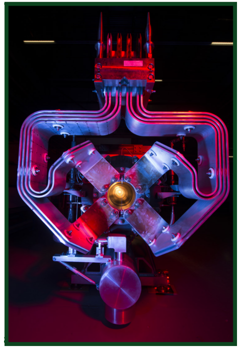


**0.3 kt Near Detector**
(105 m underground)



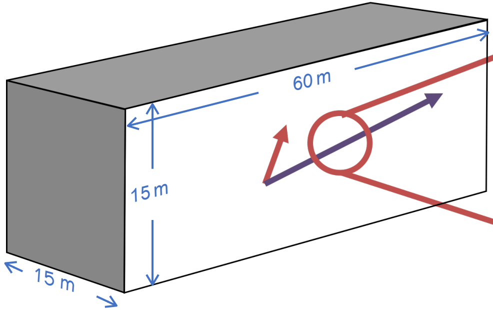

Maximizes flux at 1.8 GeV oscillation peak

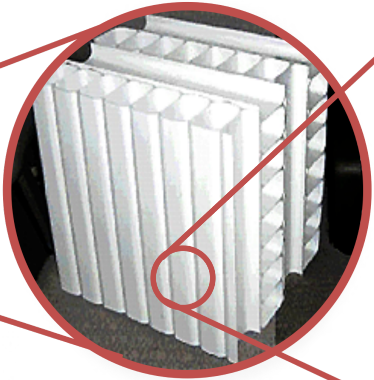


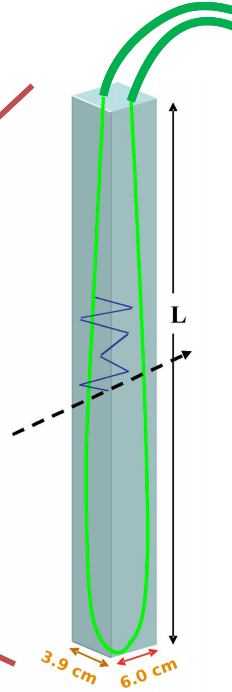
**NuMI beam**
(viewed @ 14.6 mrad off-axis)

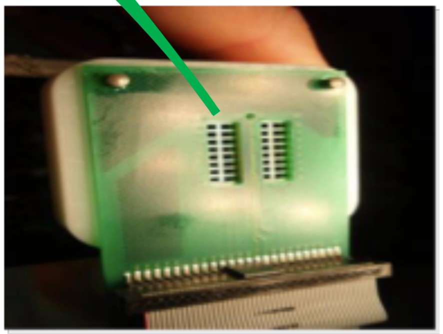
# NOvA Detectors: Construction & Principle

- Alternating horizontal & vertical planes of small extruded PVC **cells** filled with **liquid scintillator**





  - **NOvA FD:** *world's largest self-supporting plastic structure?*

- **Charged particles** deposit energy
  → **scintillation & Cherenkov light**, collected by **wavelength-shifting fibers**

- **Avalanche PhotoDiode** transduces **light signal** to electrical pulse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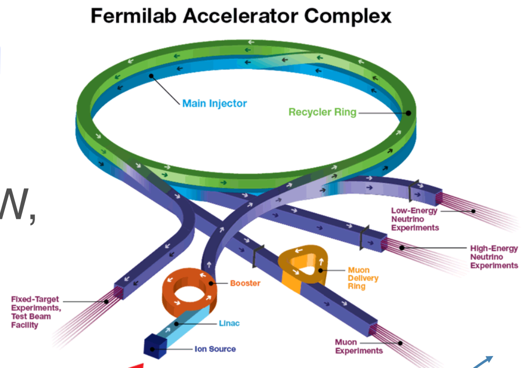
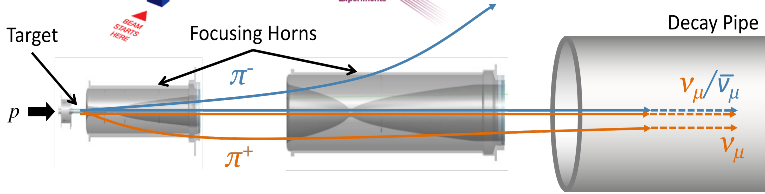
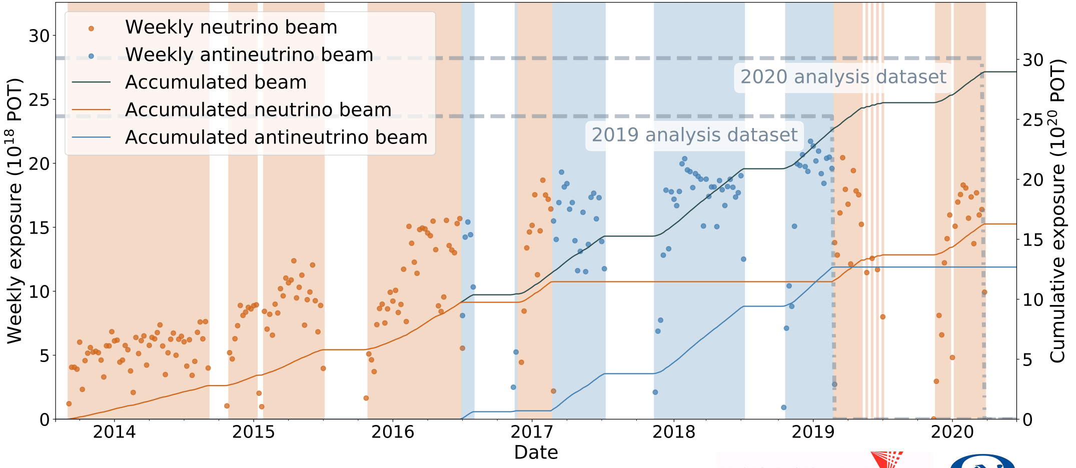
# NuMI Beam




- **World's most intense accelerator neutrino beam:**
  - typical proton-beam power 680 kW (with peaks > 800 kW, e.g., 843 kW for an hour on 15 June)
- Neutrinos/antineutrinos selected via focusing-horn magnetic-field direction
- **+54%** increase in **neutrino** exposure over 2019 analysis
- **Upgrades** in place for **1 MW**, early PIP-II Booster improvements should allow >900 kW via faster cycle



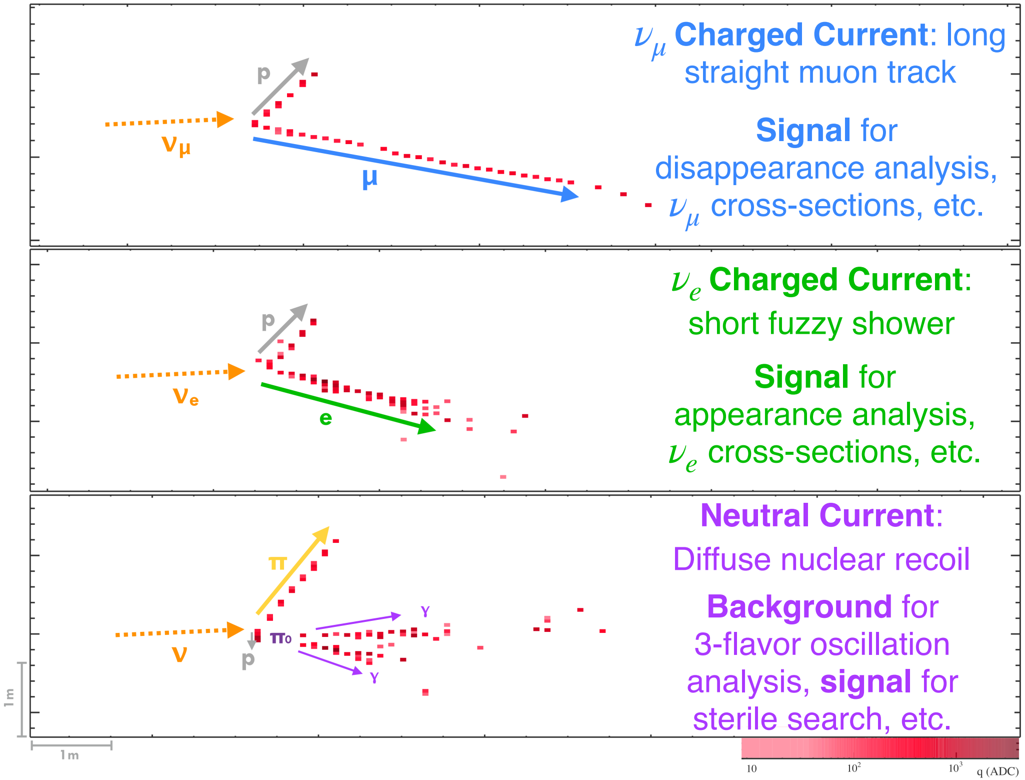





MW-capable target

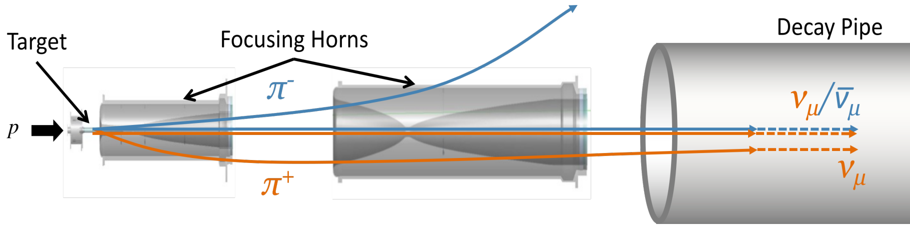

MW-capable horn

# Event Topologies



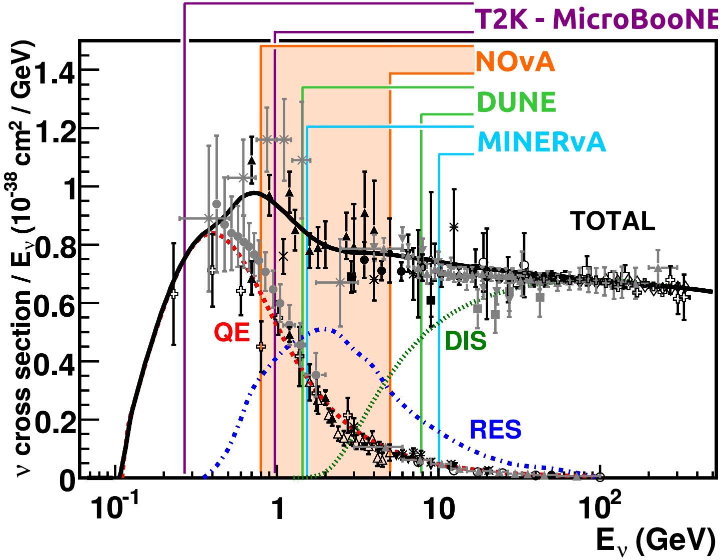

- Use **Machine Learning** techniques to **select** and **classify** neutrino interactions:
  - convolutional neural network (**CNN**)
- Excellent cosmic-ray rejection using CNN and Boosted Decision Trees (BDTs)

# Simulation Chain




- Geant4 simulation of **beam transport**
- **Neutrino flux**:
  - hadron production model constrained with external thin-target measurements

    → ~10% normalization uncertainty (MINERvA technique, Phys.Rev. D **94**, 092005)
- **Neutrino interaction** model: GENIE simulation tuned on NOvA ND and external data
  - NOvA: crossover region where multiple processes contribute
  - adjust **MEC** & **FSI** (GENIE 3)
- Geant4 simulation of **detector response**




Adapted from J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. **84**, 1307 (2012)

# Measuring Neutrino Oscillation Parameters

- $\nu_\mu$ & $\overline{\nu}_\mu$ **disappearance** rates constrain $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\cos^4(\theta_{13})\sin^2(2\theta_{23}) + \sin^2(2\theta_{13})\sin^2(\theta_{23})\right)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

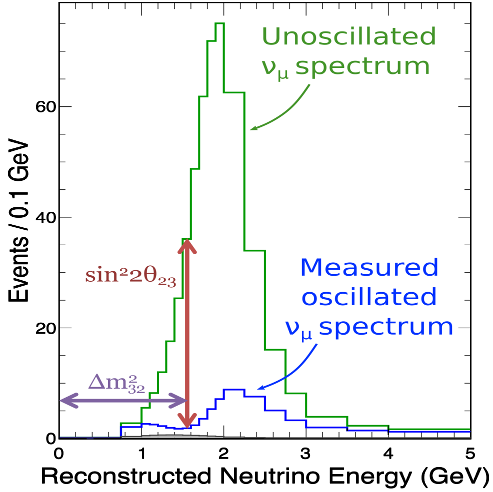
- $\nu_\mu \to \nu_e$ & $\overline{\nu}_\mu \to \overline{\nu}_e$ **appearance** rates constrain $\sin^2\theta_{23}$, $\Delta m^2_{32}$ & $\delta_{CP}$:

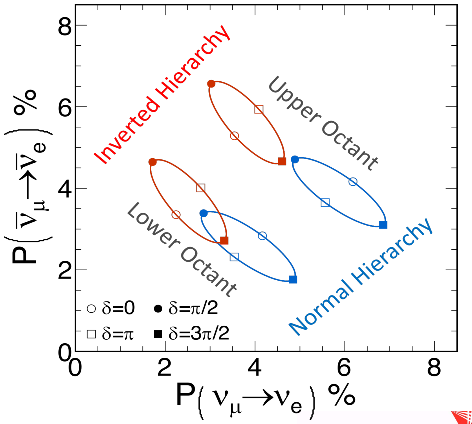
$$P(\nu_\mu \to \nu_e) \approx \left|\sqrt{P_{\rm atm}}e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}}\right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\,(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP})$$

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL}\Delta_{31}$$

- Simultaneous fit to $\nu$ & $\overline{\nu}$ **appearance** & **disappearance spectra** → optimal sensitivity





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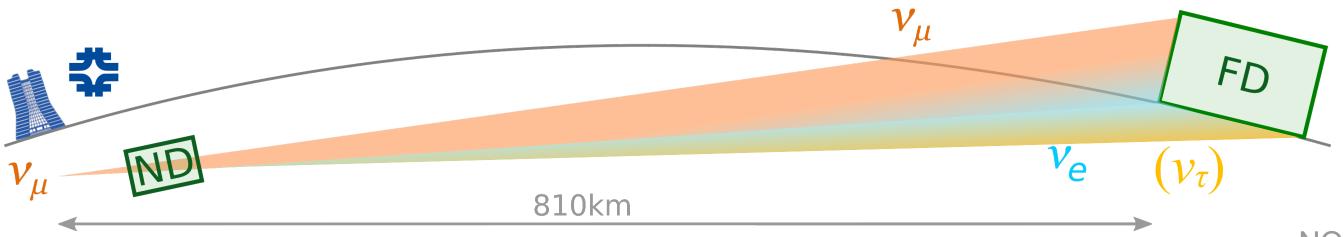
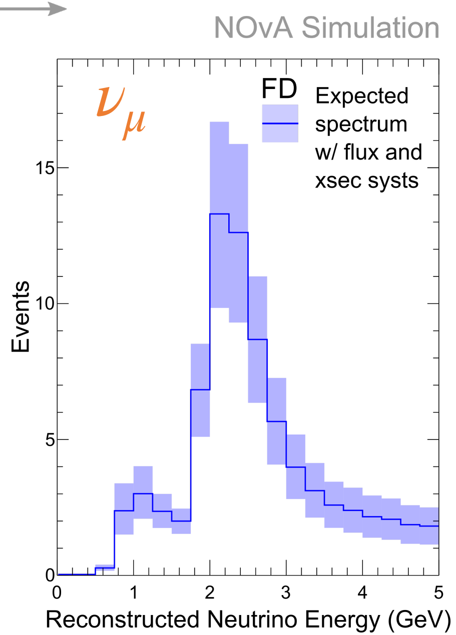
# Minimizing Effects of Cross-Section Uncertainty




- Measure $\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$ energy spectra in FD
- Large flux and cross-section uncertainties



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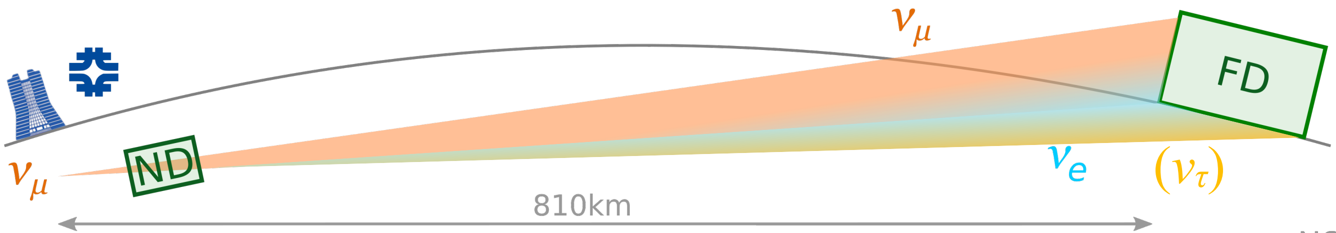


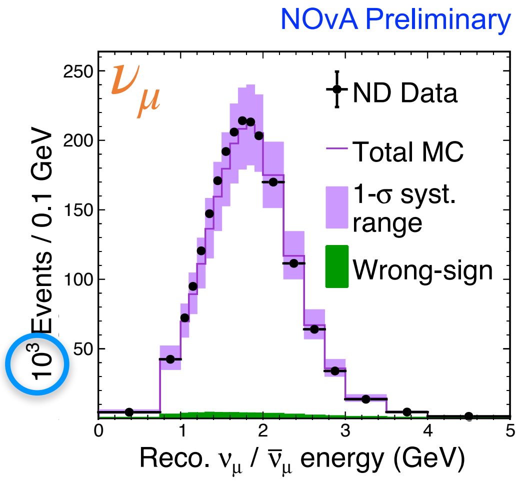


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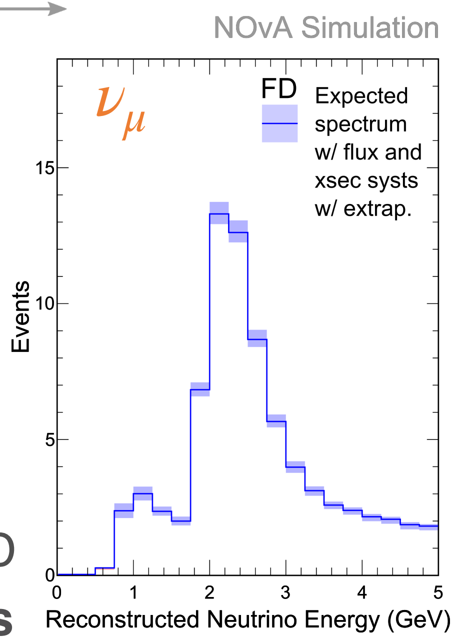
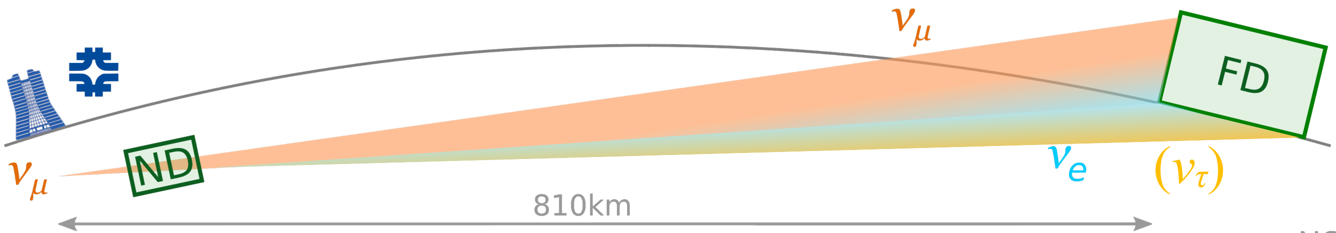
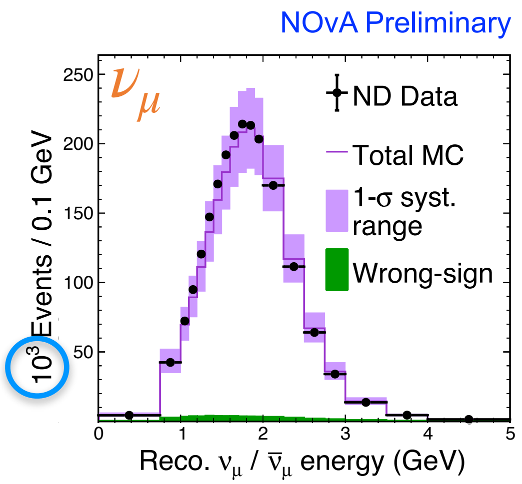


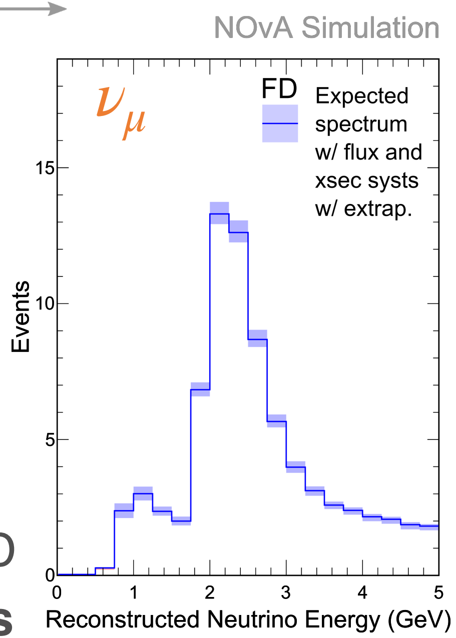

- Measure (high-stats) $\nu_\mu/\bar{\nu}_\mu$ spectra in ND, **extrapolate** to FD
  - substantially **cancels flux** & **cross-section uncertainties**

# Minimizing Effects of Cross-Section Uncertainty




- Measure $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ energy spectra in FD
- Important analysis details:
  - adjust GENIE simulation to better match ND data
  - new: extrapolate in bins of $E_\nu$ and $p_{t,\ell}$ → smaller systematics




- Measure (high-stats) $\nu_\mu/\bar{\nu}_\mu$ spectra in ND, **extrapolate** to FD
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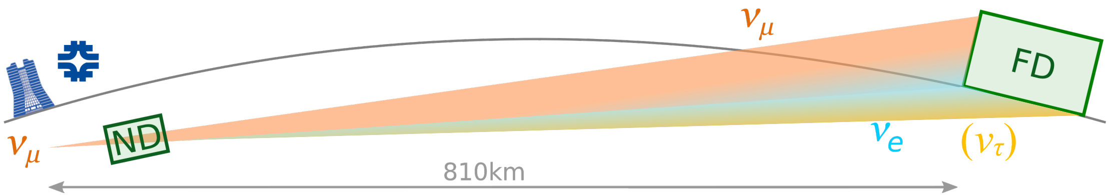
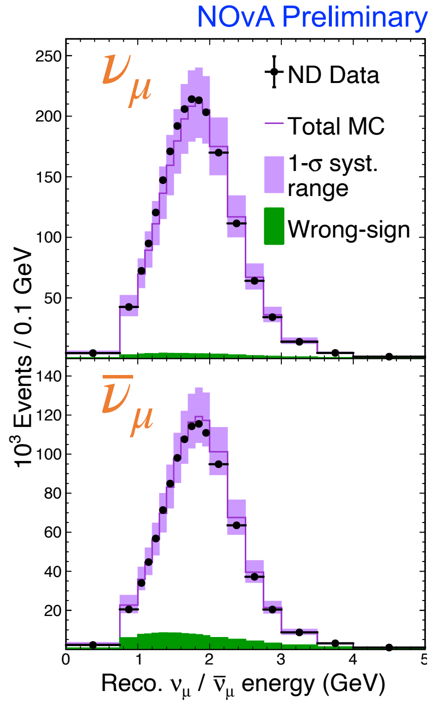
# Oscillation Results



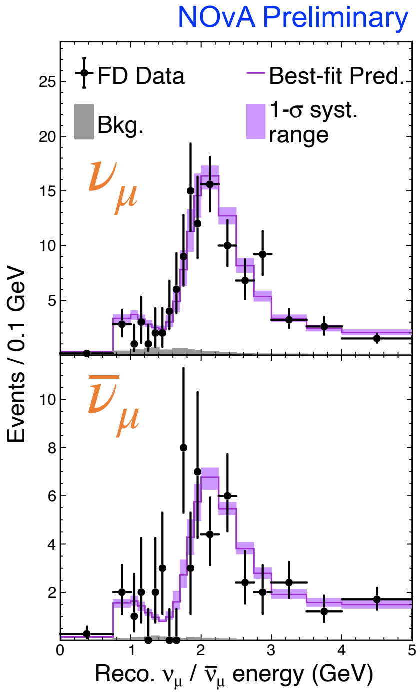

- (Dis)appearance at FD:
  - 211 $\nu_\mu$ candidates
  - 105 $\bar{\nu}_\mu$ candidates
  - 82 $\nu_e$ candidates
  - 33 $\bar{\nu}_e$ candidates

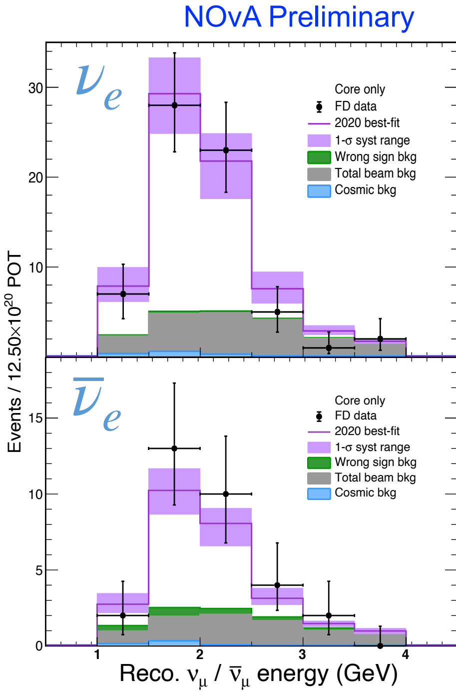
Simultaneous fit to $\nu$ & $\bar{\nu}$ appearance & disappearance → **best fit point:**

$\Delta m^2_{32}$ = **2.41×10$^{-3}$ eV$^2$**

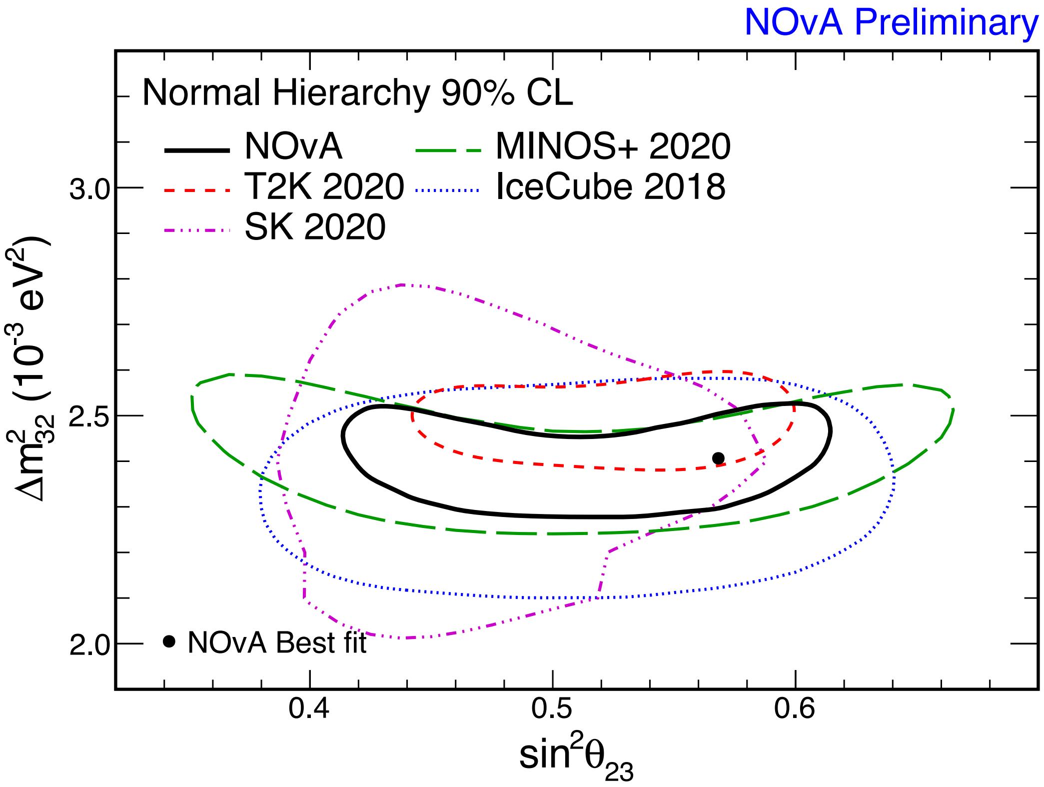
$\sin^2\theta_{23}$ = **0.57**

$\delta_{CP}$ = **0.82π**



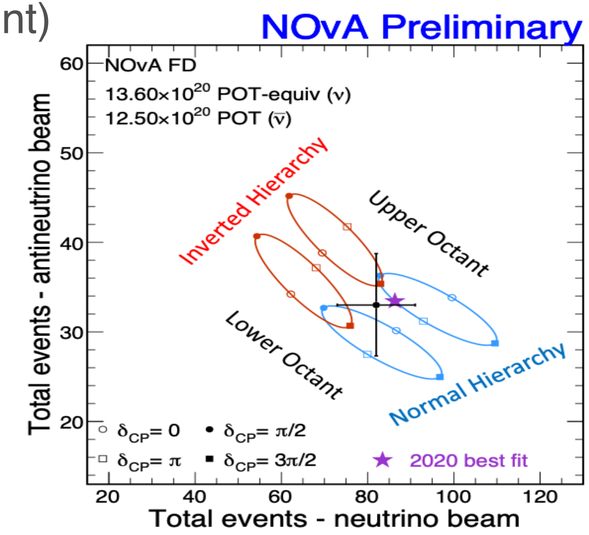
# Oscillation Results

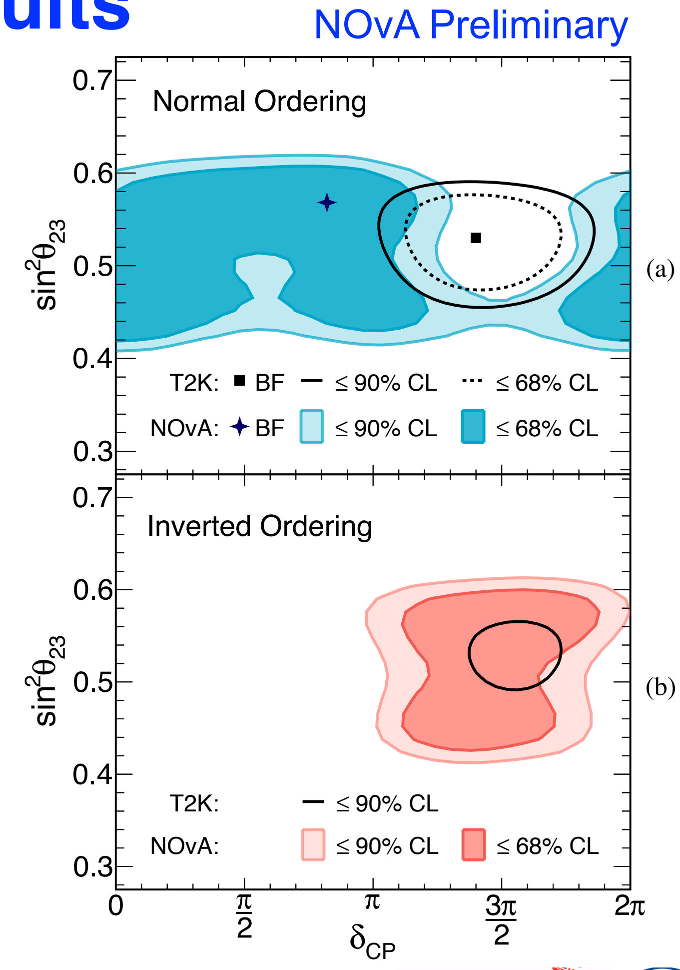



- Statistical & systemic uncertainties via Feldman–Cousins (frequentist) approach
- **Precision measurements**:
  - $\Delta m^2_{32} = 2.41 \pm 0.07 \times 10^{-3}$ eV$^2$ (3%)
  - $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$ (6%)
- Best fit point: **Normal Hierarchy** and **Upper Octant** ($\theta_{23} > 45^o$)

# Oscillation Results

- **Constraints** on $\delta_{CP}$:
  - NH:
    - $\delta_{CP}$ = 3π/2 disfavored at ~2σ
    - at 90% confidence level, entire range of $\delta_{CP}$ allowed
  - IH: $\delta_{CP}$ = π/2 disfavored at >3σ
  - tension (but consistent) with T2K
  - we see no strong $\nu_e/\overline{\nu}_e$ asymmetry

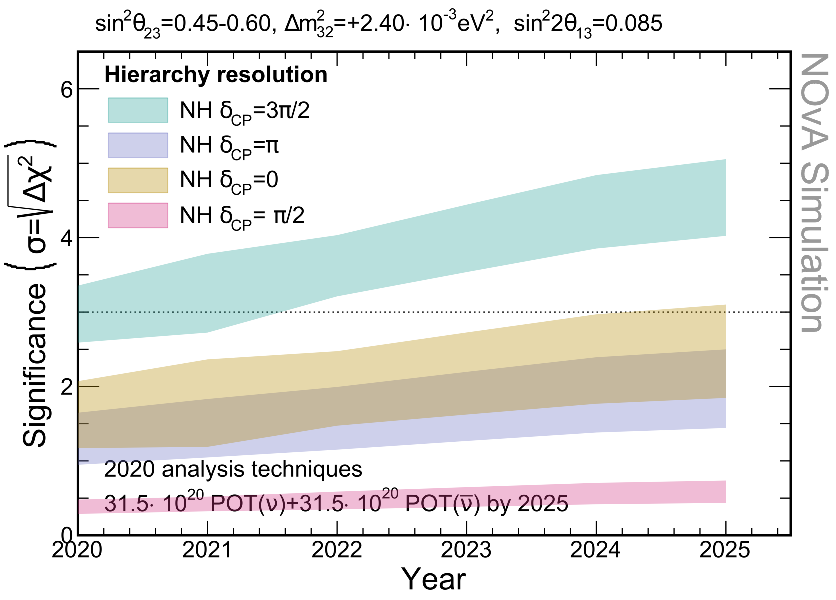


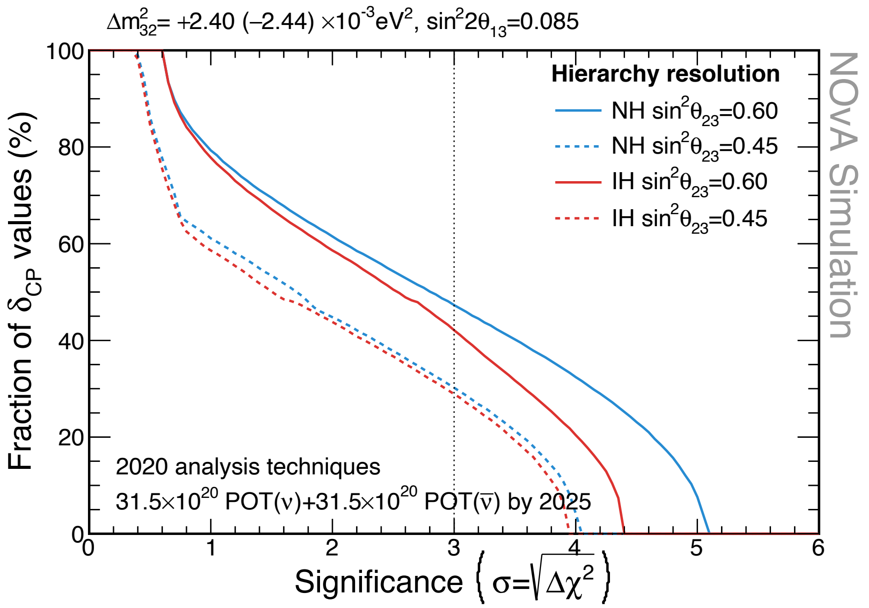




[T2K: Nature 580 (2020) 339]

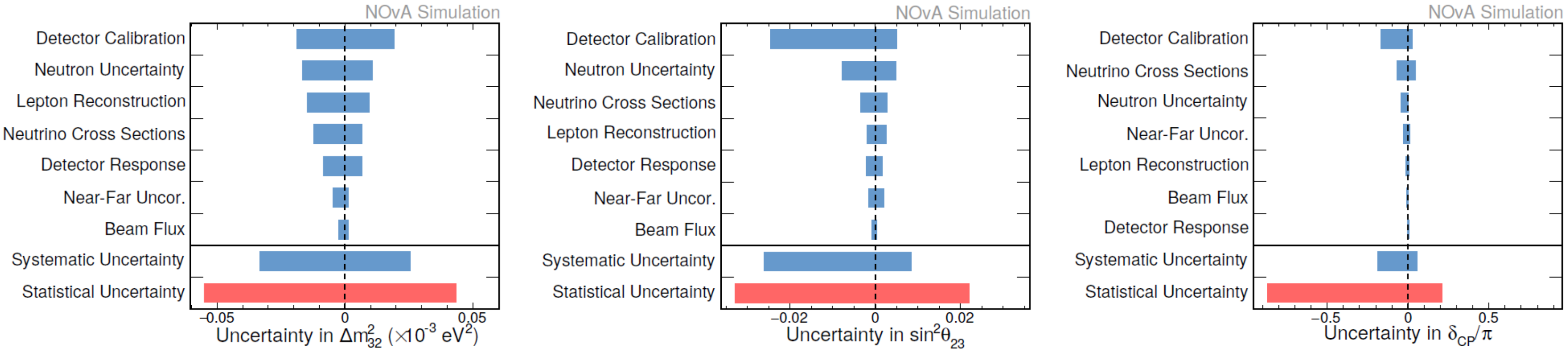
# Future Oscillation Reach

- Expect to run through **2026**, accumulating **>6 × 10[21] protons on target** (POT)
- Could reach **≥4σ sensitivity** to **Mass Hierarchy, >3σ** for 30–50% of $\delta_{CP}$ values
- Probe the majority of $\delta_{CP}$ values at **≥2σ level**



# Oscillation Parameter Uncertainties




- **Leading** systematic: detector calibration uncertainty
- **Subleading**: neutron calibration uncertainty
  or
  neutrino interaction model
  or
  lepton reconstruction uncertainty

} Depending on parameter being measured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# Neutrino Scattering & Oscillation

- **Neutrino interaction model:** an important oscillation systematic
  ⇒ worth measuring neutrino scattering cross sections ourselves
  & valuable for future experiments (e.g., DUNE)

- Also valuable in itself: probe of interesting strong-interaction dynamics
- NOvA ND provides **high-statistics** neutrino-interaction samples
  - can make new, improved cross-section measurements

- Published so far:
  - Measurement of neutrino-induced neutral-current coherent $\pi^0$ production in the NOvA near detector, Phys. Rev. D **102** (2020) 012004

- Cross-section analyses (in progress) reported at this Workshop:
  - $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ charged-current (CC) inclusive cross sections
  - $\nu_\mu$ CC with low hadronic activity ("MEC-enhanced")
  - $\nu$ and $\overline{\nu}$ scattering with final-state EM showers
  - $\nu + e$ elastic scattering

# Studies of/Searches for Astro or BSM Phenomena

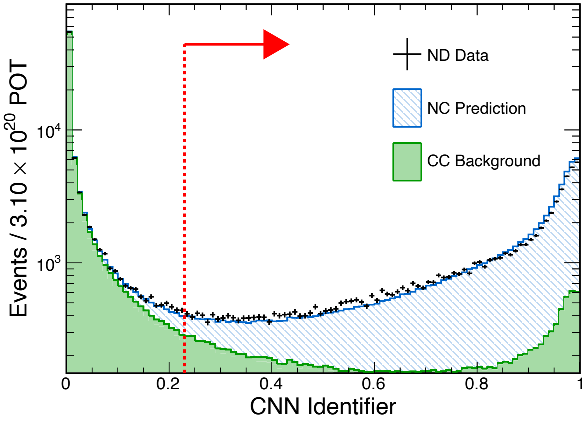
- Already (or soon to be) published in journals:
  - Extended search for supernova-like neutrinos in NOvA coincident with LIGO/Virgo detections, accepted by Phys. Rev. D, 2106.06035
  - Seasonal variation of multiple-muon cosmic ray air showers observed in the NOvA detector on the surface, Phys. Rev. D **104** (2021) 012014
  - Search for slow magnetic monopoles with the NOvA detector on the surface, Phys. Rev. D **103** (2021) 012007
  - Supernova neutrino detection in NOvA, JCAP **10** (2020) 014
  - Search for multimessenger signals in NOvA coincident with LIGO/Virgo detections, Phys. Rev. D **101** (2020) 112006
- Searches/studies in progress:
  - neutrino magnetic moment
  - magnetic monopoles
  - dark matter
  - $n\bar{n}$ oscillations

# Sterile Neutrino Search

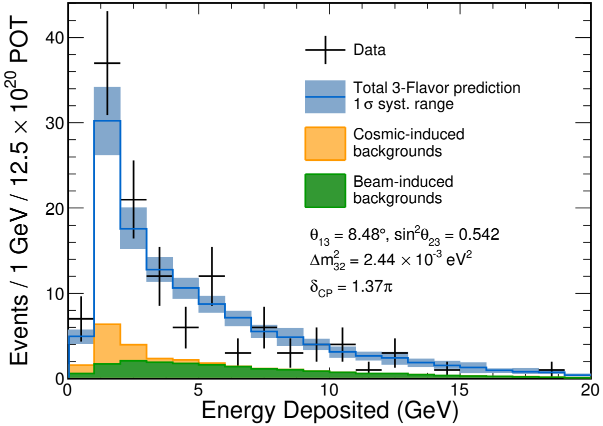
- Search for sterile-active mixing in $12.51 \times 10^{20}$ POT **antineutrino** sample obtained June 2016 – Feb 2019
  - LSND and MiniBooNE saw effects in **antineutrinos**
- Analysis looks for NC disappearance from ND to FD
- 1st result using **long-baseline** accelerator **antineutrinos**
  - 121 NC events observed, $122 \pm 11 \pm 15$ expected

  $\Rightarrow$ 90% CL limits: $\theta_{24} < 25°$ and $\theta_{34} < 32°$ in 3+1 model ($0.05\text{eV}^2 \leq \Delta m^2_{41} \leq 0.5\ \text{eV}^2$)
    - this analysis insensitive to larger $\Delta m^2_{41}$ (oscillations would occur within ND)
- Submitted for publication: arXiv:2106.04673

NOvA Preliminary

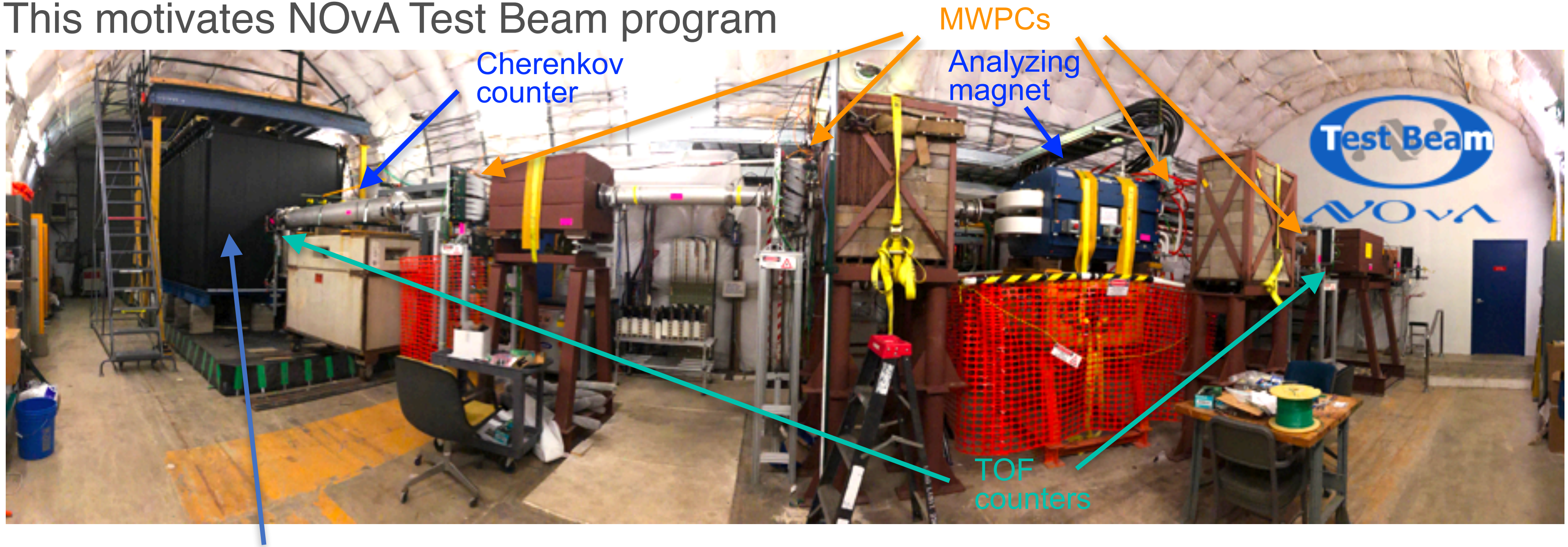



NOvA Preliminary



# Test Beam Program

- Detector calibration: leading uncertainty in NOvA
  - important to reduce it as statistical errors shrink
- This motivates NOvA Test Beam program




  - mini-NOvA detector illuminated by narrow-band, particle-identified, momentum-analyzed charged-particle beam

# Test Beam Program

- Data accumulated so far: thousands of identified electrons, protons, pions
- More running planned in next FNAL run cycle
- Planning possible DT (14 MeV) neutron-generator calibration as well

# NOvA–T2K Joint Analysis

- Two most precise long-baseline oscillation measurements are NOvA's & T2K's
  - as we've seen, in some tension
- Desirable to perform joint fit
  - somewhat challenging due to differing approaches and models used
    - frequentist vs. Bayesian, GENIE vs. NEUT, etc…
- Joint NOvA–T2K working group analysis in progress
  - aiming for result in 2021–22

# Summary

- **Updated oscillation results:**
  - among world's **most precise measurements** of:
    - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$
    - $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
  - exclude **IH** $\delta_{CP} = \pi/2$ **at > 3σ** and **NH** $\delta_{CP} = 3\pi/2$ **at 2σ**
- **Cross-section** measurements
- Searches for/investigations of **astro phenomena**: monopoles, neutrinos in coincidence with gravitational-wave events, multi-muon cosmic-ray events,…
- 1st long-baseline accelerator antineutrino **sterile neutrino limits**
- **Test Beam** in progress to improve calibration systematics
- See **WG1, 2,** and **5 NOvA talks** and **posters** for more details

# Questions?

MAY 2020