WILLIAM & MARY
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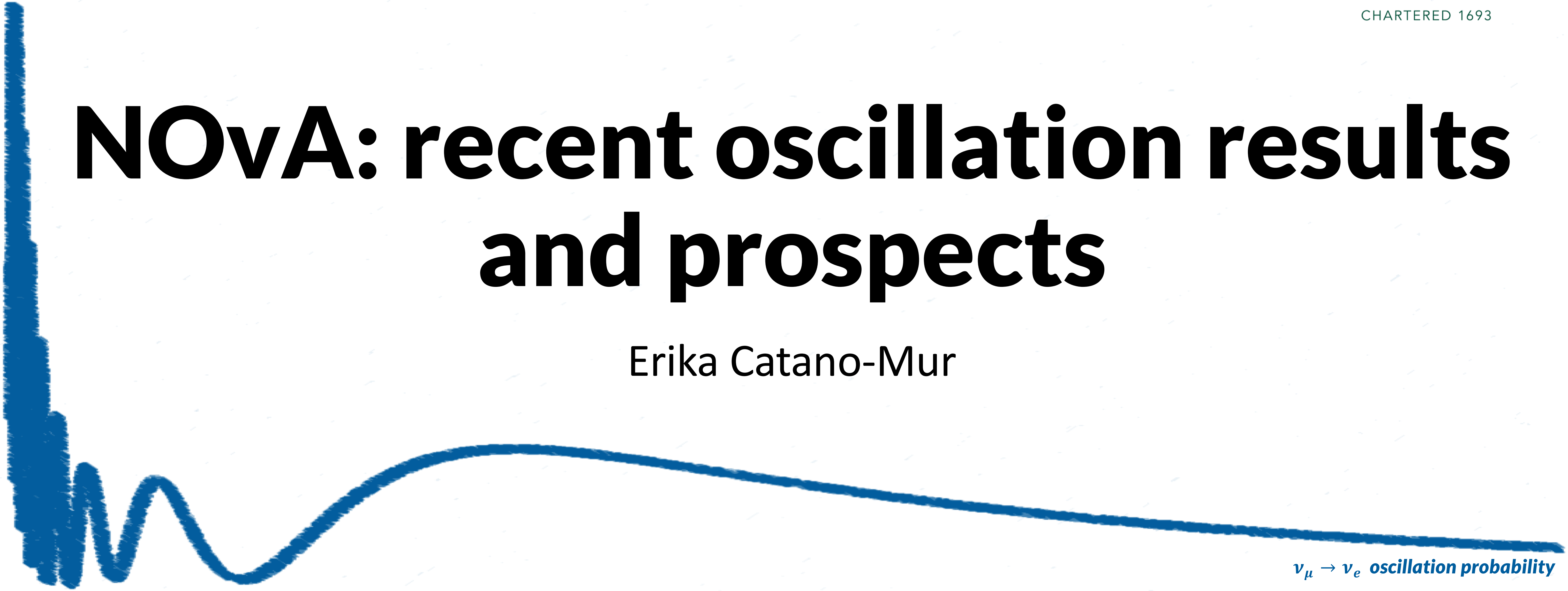
NOvA: recent oscillation results and prospects

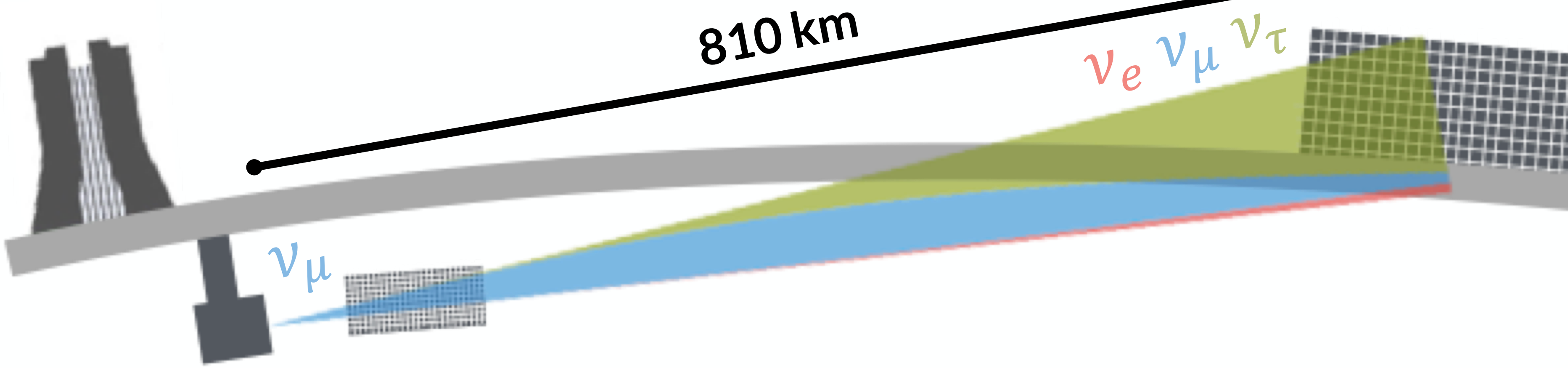
Erika Catano-Mur

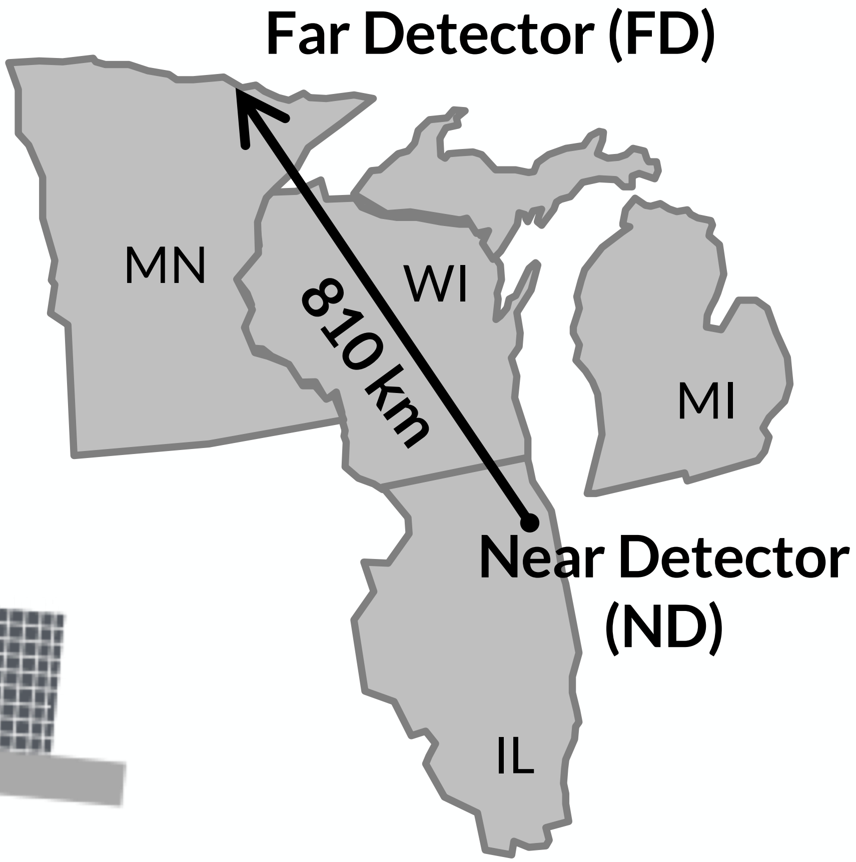


54th Fermilab Users (Virtual) Meeting. August 4th 2021

The NOvA Experiment

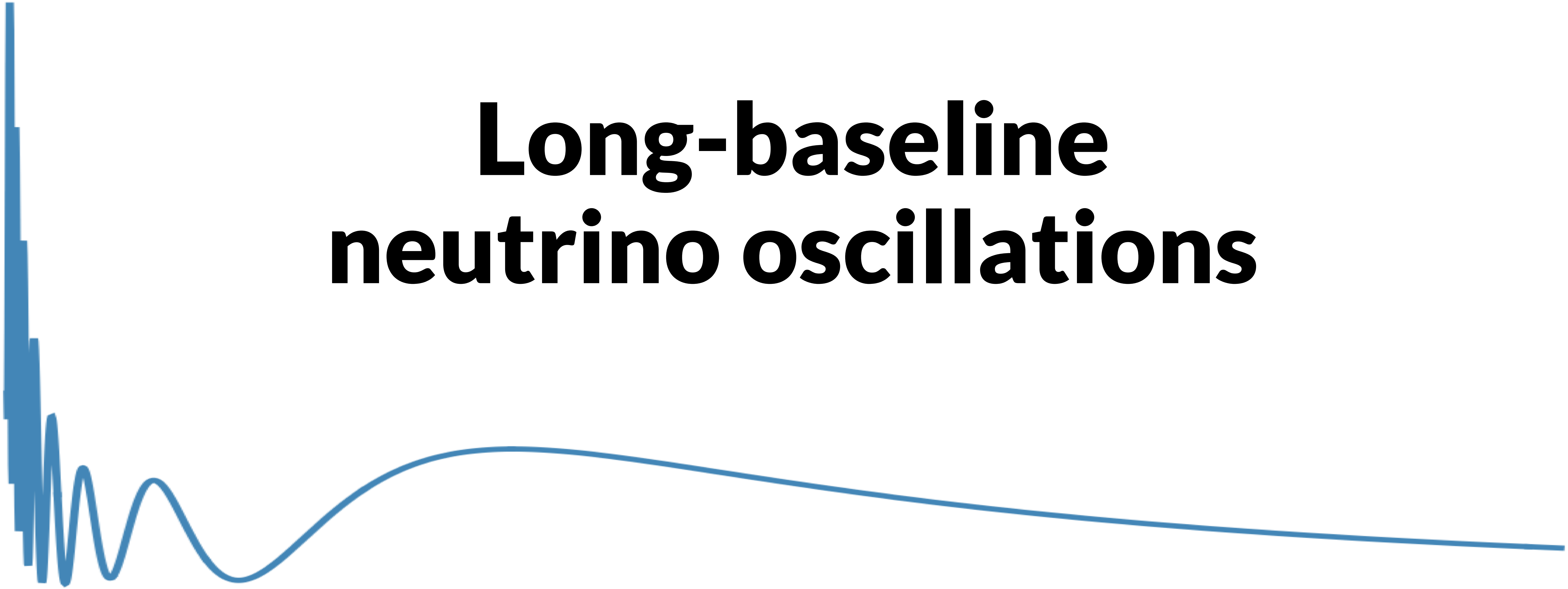
- NOvA is a **long-baseline** accelerator neutrino oscillation experiment
  - Using the **NuMI** muon neutrino (or anti-neutrino) beam from Fermilab.
- It consists of **two detectors** (Near, Far)
  - Identical technology
  - Different size and location





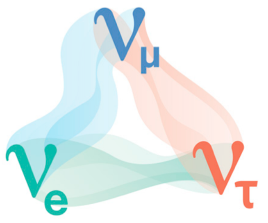
- Its primary goal is to **constrain neutrino oscillation parameters** by measuring
  - Electron (anti) neutrino appearance
  - Muon (anti) neutrino disappearance

Long-baseline neutrino oscillations



3-flavor neutrino oscillations

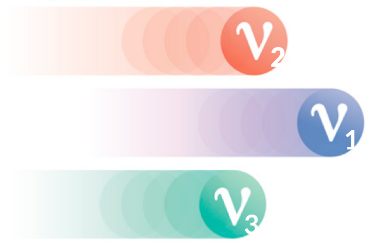
- 3-flavor neutrino oscillations are **transitions in-flight between the flavor neutrinos** $\nu_e\ \nu_\mu\ \nu_\tau$
  - Caused by non-zero neutrino masses and neutrino mixing.



Flavor states
(interaction)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

Mixing
matrix



Mass states
(propagation)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left|\sum_i U^*_{\alpha i}\, e^{-i\frac{m_i^2 L}{2E}}\, U_{\beta i}\right|^2$$

- The **oscillation probabilities** depend on:
  - Neutrino energy (E_ν)
  - Distance between the source and the detector ("baseline" L)
  - Mass squared differences ($\Delta m^2_{21}, \Delta m^2_{32}$)
  - Parameters of the mixing matrix: 3 angles and 1 phase ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)

Experimental "settings"

What we want to measure

* See: David Caratelli, "Introduction to neutrinos at Fermilab"

Oscillation experiments

- Neutrino energy + baseline → which parameters can be measured in an experiment

Source	Type of ν	E [MeV]	L [km]	$\min(\Delta m^2)$[eV^2]
Reactor	$\overline{\nu}_e$	~1	1	~10^{-3}
Reactor	$\overline{\nu}_e$	~1	100	~10^{-5}
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	~10^3	1	~1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	~10^3	1000	~10^{-3}
Atmospheric	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	~10^3	10^4	~10^{-4}
Solar	ν_e	~1	1.5x10^8	~10^{-11}

- Our current knowledge:

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\sin^2(\theta_{13}) = 0.0220 \pm 0.0007$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \mathrm{eV}^2$$

Solar

Reactor

$$\sin^2(\theta_{23}) = 0.546 \pm 0.021$$
$$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3} \mathrm{eV}^2$$

Accelerator

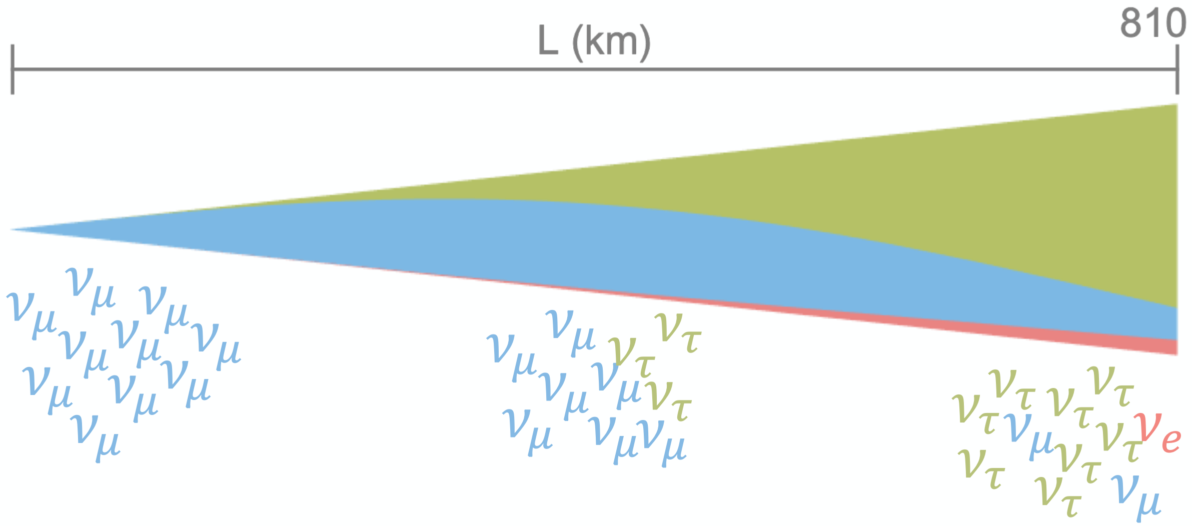
Atmospheric

Source: PDG, 2021 update

NOvA physics goals

- **Atmospheric sector** oscillations: Δm^2_{32}, $\sin^2\vartheta_{23}$, δ_{CP}
- **Key open questions** in oscillations:
  - Is the **neutrino mass hierarchy** normal or inverted?
  - Is **CP** violated in the neutrino sector?
    - Charge-Parity symmetry $\nu_\mu \rightarrow \nu_e \overset{\text{CP}}{\Longleftrightarrow} \bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Is $\boldsymbol{\vartheta_{23}}$ mixing maximal?
    - ν_μ-ν_τ symmetry
    - If not, what is the octant of ϑ_{23}?
- Disentangle by measuring…
  - disappearance $P(\nu_\mu \rightarrow \nu_\mu)$ and appearance $P(\nu_\mu \rightarrow \nu_e)$
  - in neutrinos and antineutrinos
  - over a 810 km baseline

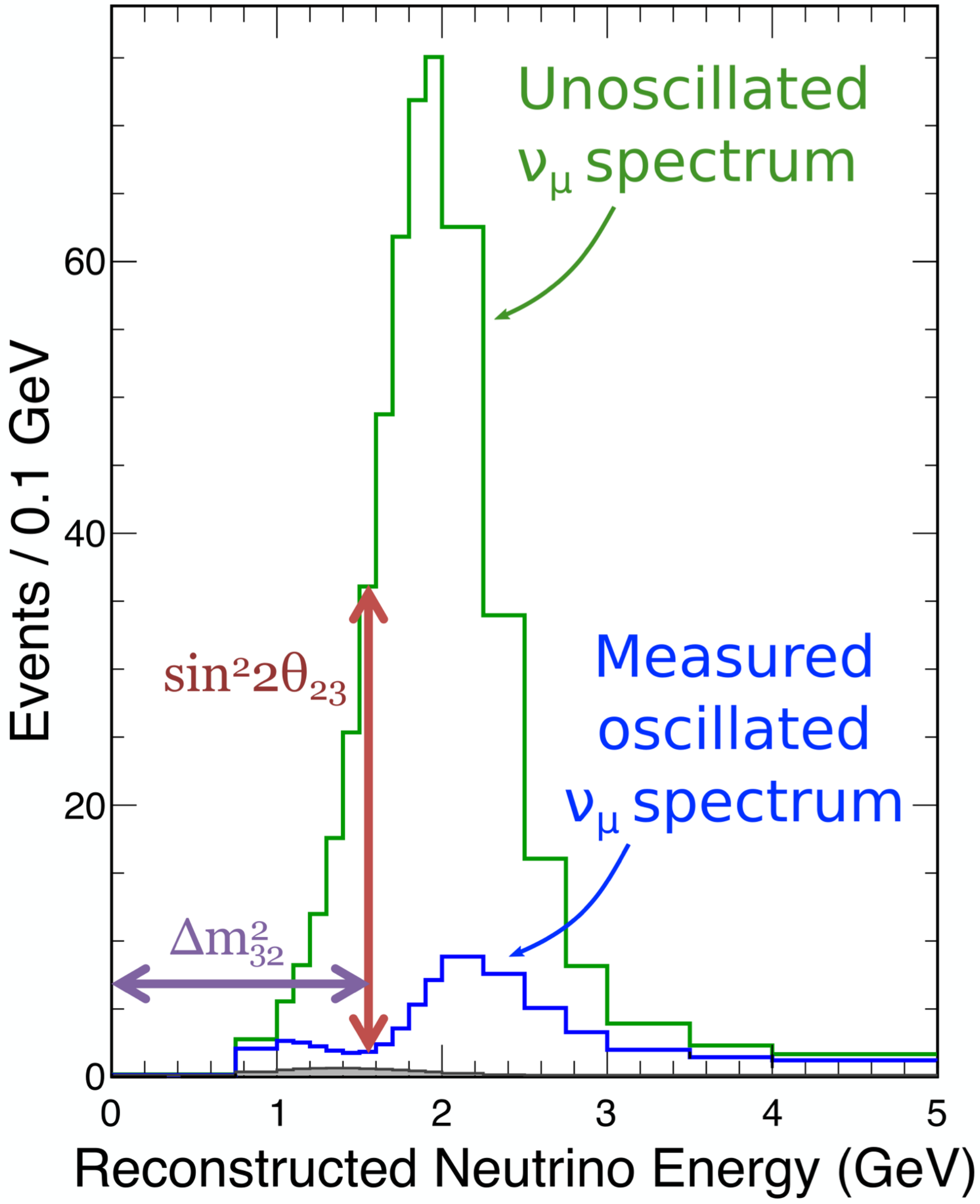
Lightest to heaviest: 1,2,3? Or 3,1,2?



$\nu_\mu \rightarrow \nu_\mu$ oscillations

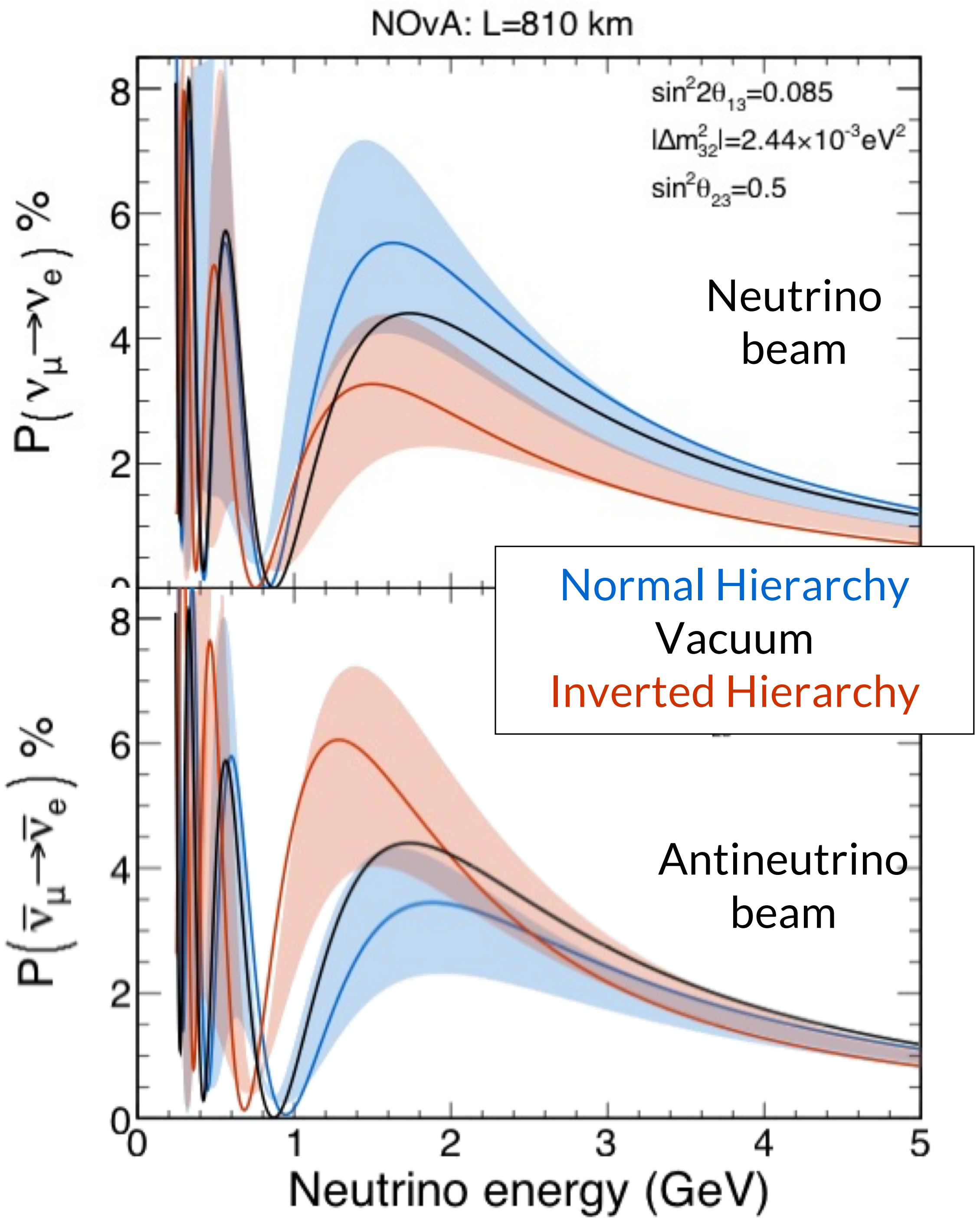
- $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ disappearance can constrain **$\sin^2 2\theta_{23}$ and $|\Delta m^2{}_{32}|$**

- Strategy:
  - Identify muon neutrinos
  - Reconstruct their energy
  - Compare the data with the unoscillated prediction
    - "Dip" location → $|\Delta m^2{}_{32}|$
    - Amplitude → $\sin^2 2\theta_{23}$



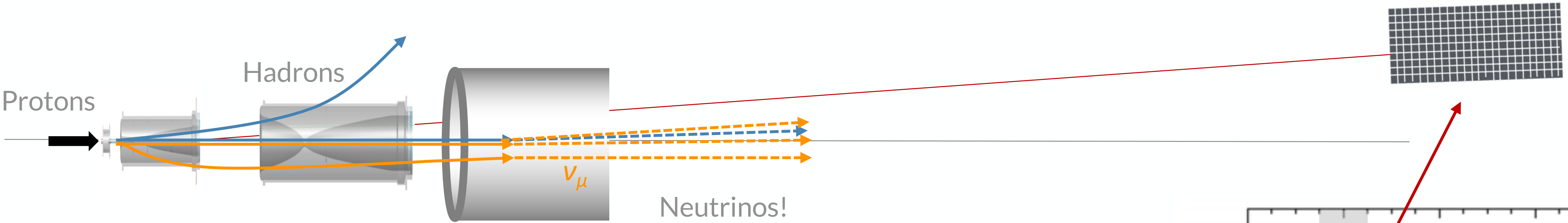
$\nu_\mu \rightarrow \nu_e$ oscillations

- $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance depend on **$\sin^2\vartheta_{23}$, Δm^2_{32} and δ_{CP}**
- Strategy:
  - Identify electron neutrinos
  - Analyze neutrino and antineutrino beam data simultaneously
  - Use the **relative (a)symmetries** between ν_e and $\overline{\nu}_e$ appearance rates to set constraints



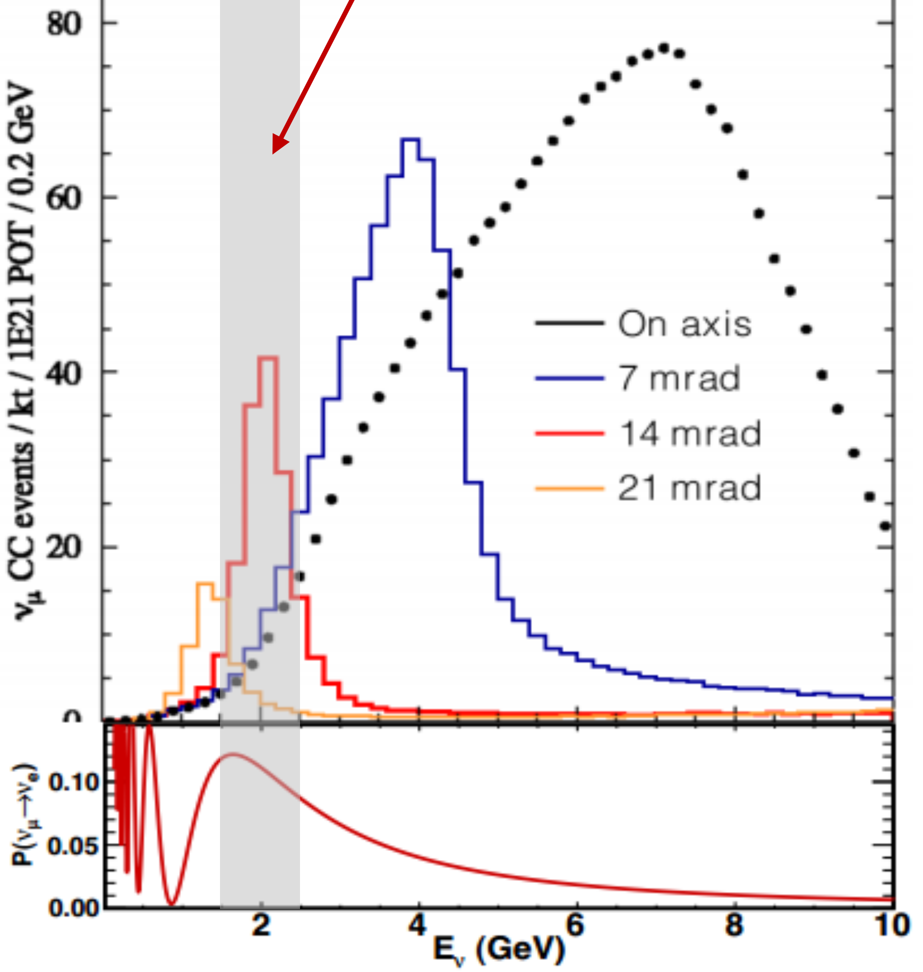
Finding neutrino events with the NOvA detectors

The NuMI muon neutrino beam



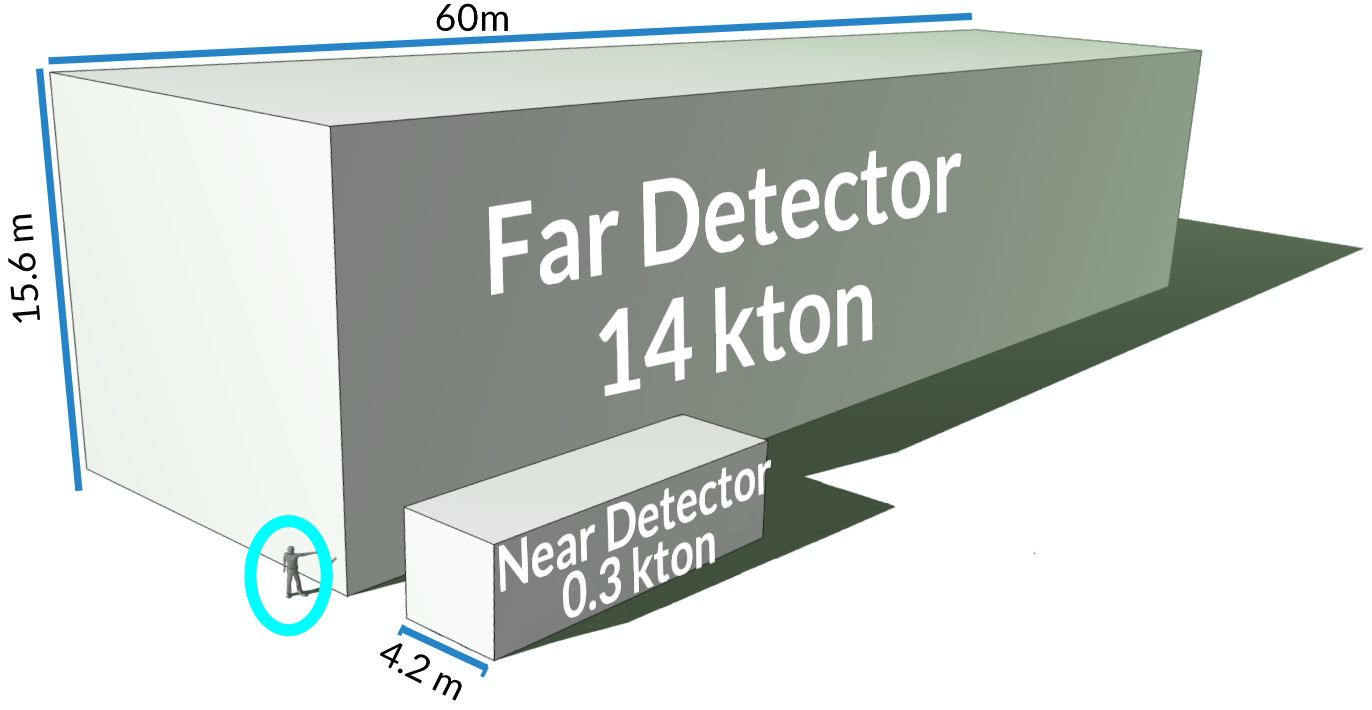
- NuMI: Neutrinos from the Main Injector
    - Part of the Fermilab Accelerator Complex*
- **Two running configurations:**
    - Neutrino beam (ν_μ)
    - Antineutrino beam ($\bar{\nu}_\mu$)

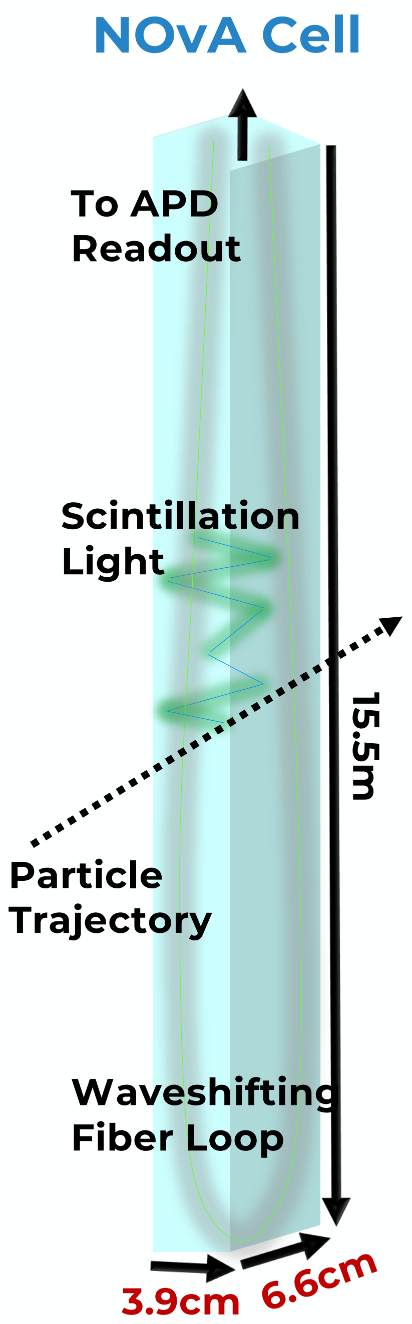
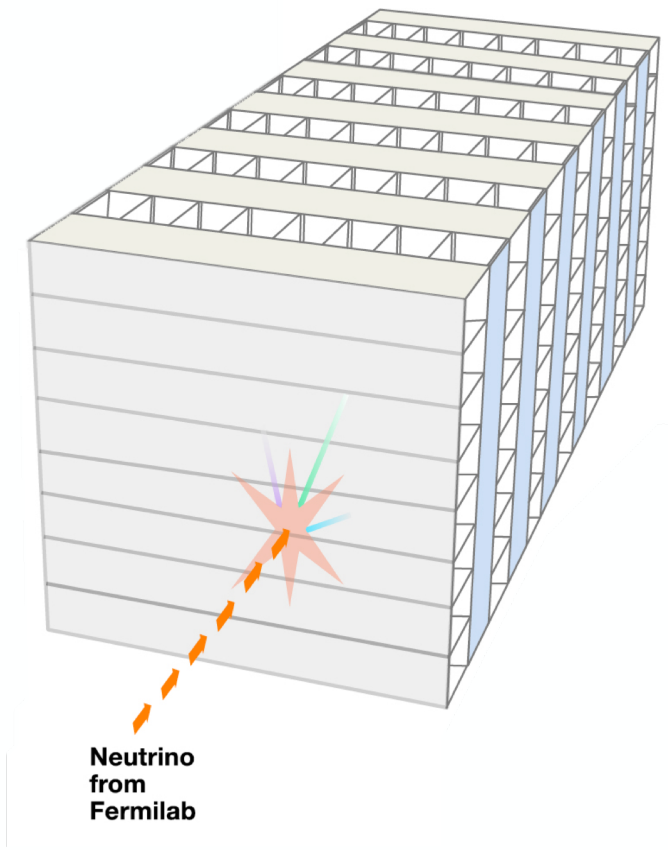
- The NOvA detectors are located **off-axis**.
- At a 14.6 mrad offset, the flux is narrower and peaked around 2 GeV.
- Small contamination: wrong sign, ν_e

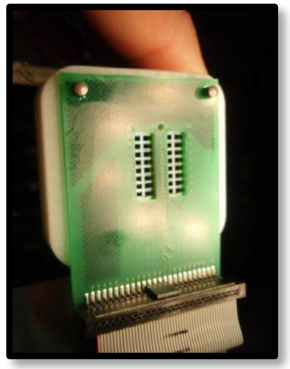


See: Jason St. John, "Introduction to Fermilab's Accelerators and Beams" (link).
David Caratelli, "Introduction to neutrinos at Fermilab"

The NOvA detectors



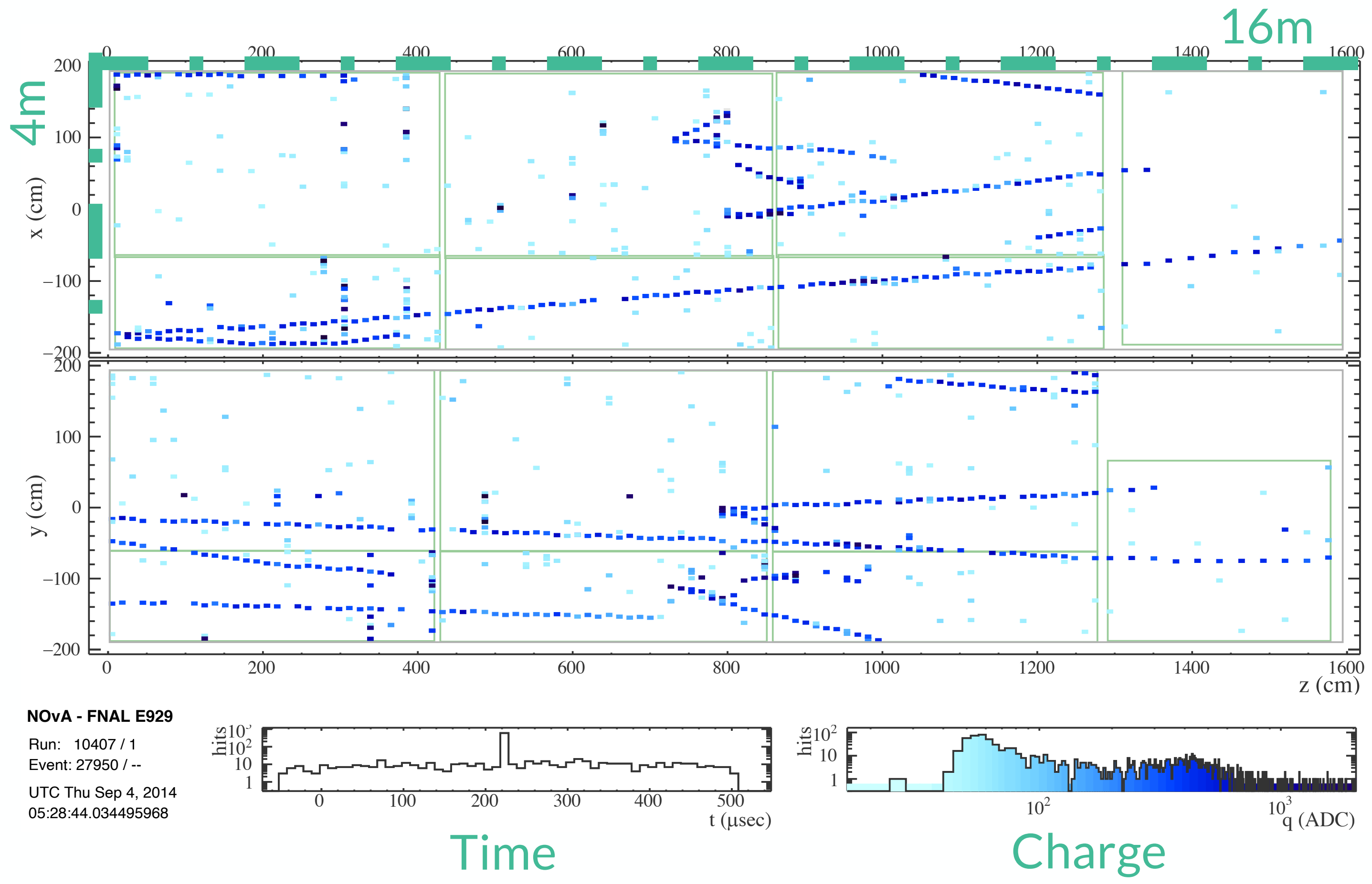


- Detectors are fine-grained, low-Z, highly-actively tracking calorimeters
- **Cells are PVC, filled with liquid scintillator**
- Read out via wavelength shifting fiber to APD
- **Orthogonal layers of cells → top and side view for each event**

Collecting neutrinos

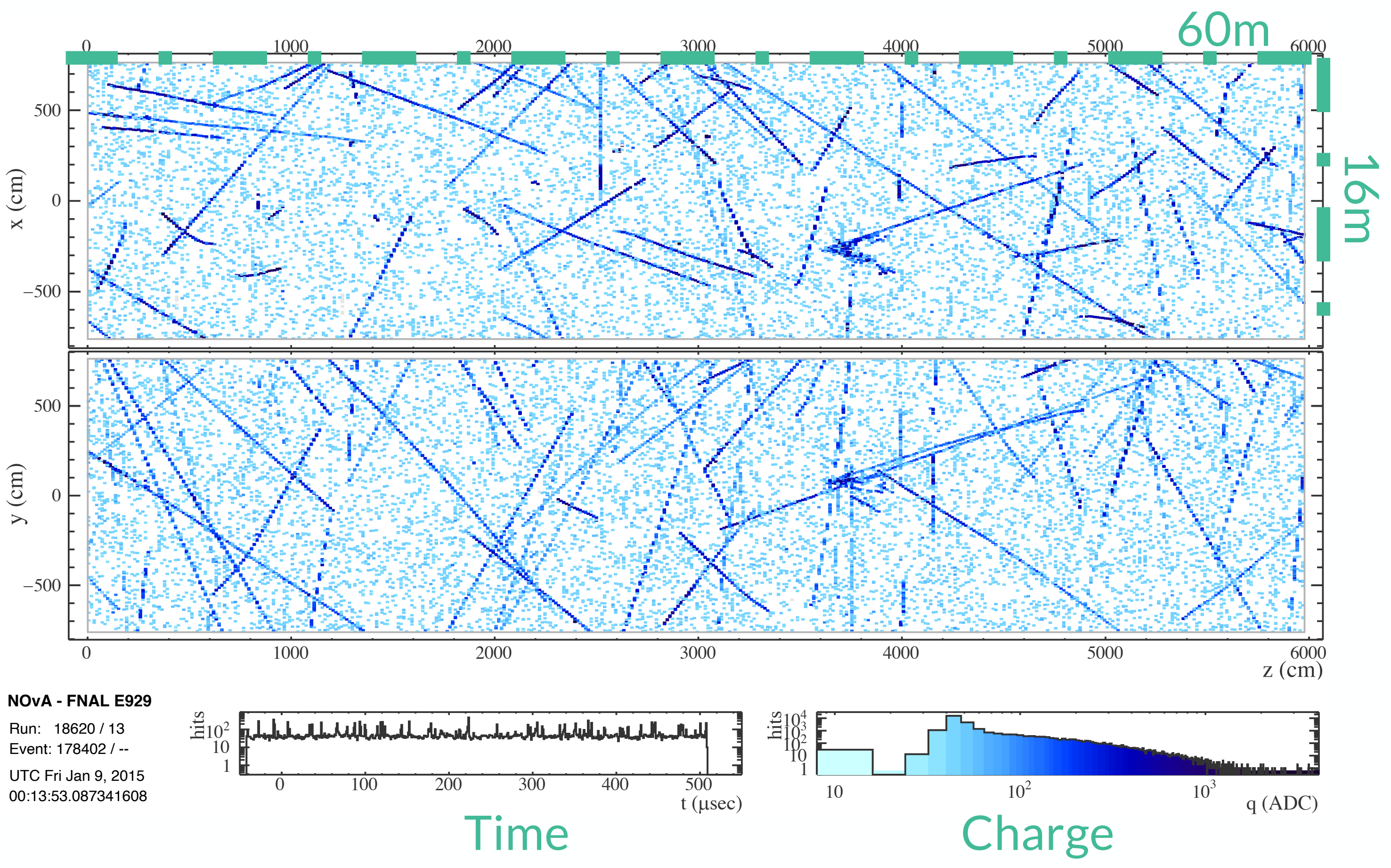
Near detector

20193 channels. 1 km from beam source
~5 contained neutrino events per beam pulse (every 1.33 sec)
Negligible cosmic background (underground)



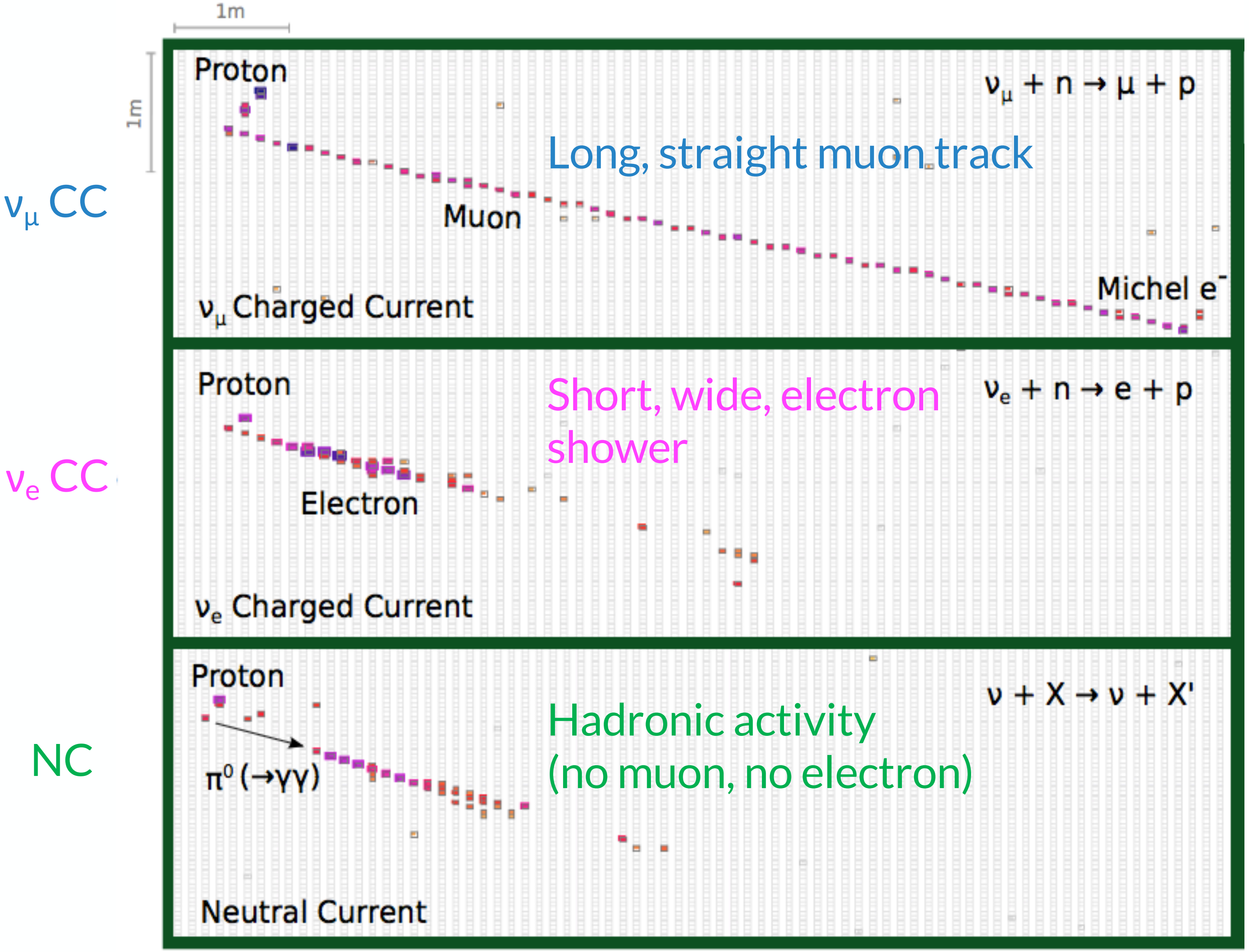
Far detector

344064 channels. 810 km from source
<1 neutrino event per day
130 kHz cosmic ray background



Beam direction

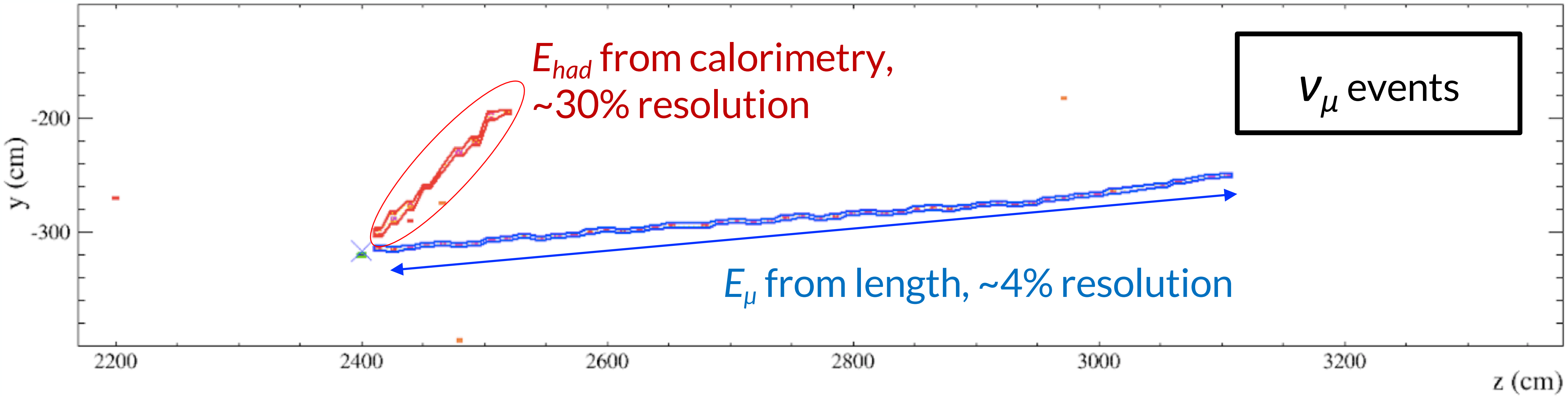
Identifying neutrino events



- Neutrino interaction candidates are identified using a **convolutional neural network (CNN)**
  - A deep-learning technique from computer vision
  - New, faster network for 2020.

- In addition to the event CNN selection:
  - Events are contained in the detector
  - In-time with the beam
  - CC ν_μ require a well-reconstructed μ track
  - Reject cosmic rays with BDTs

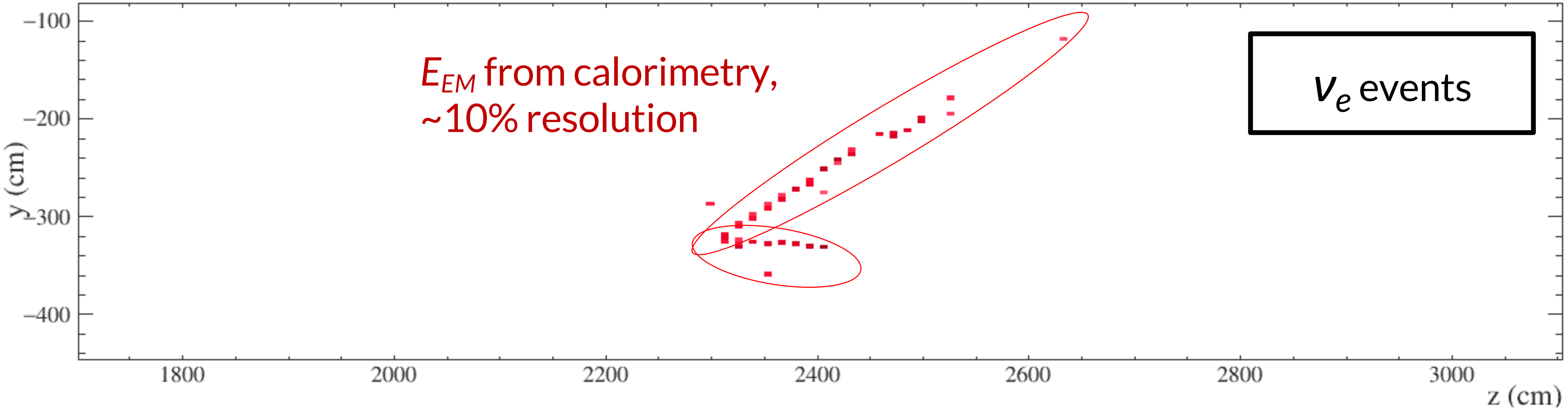
Estimating the neutrino energy



E_{had} from calorimetry, ~30% resolution

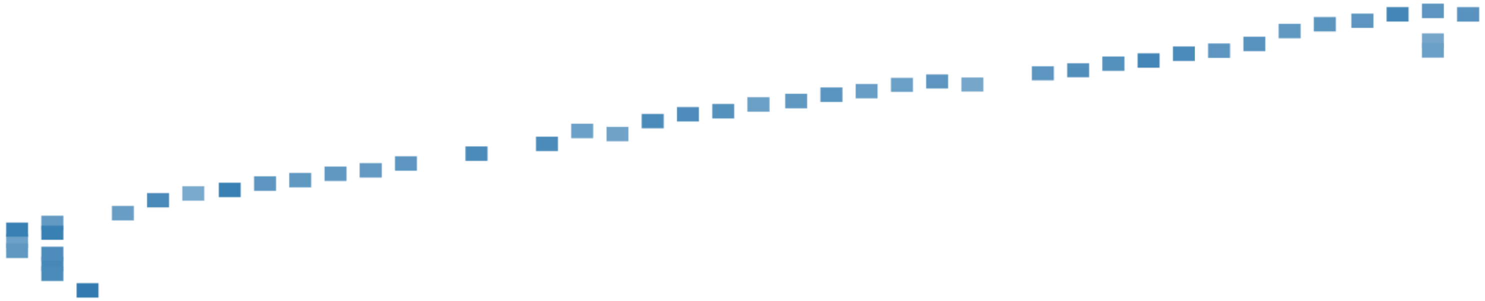
E_μ from length, ~4% resolution

ν_μ events



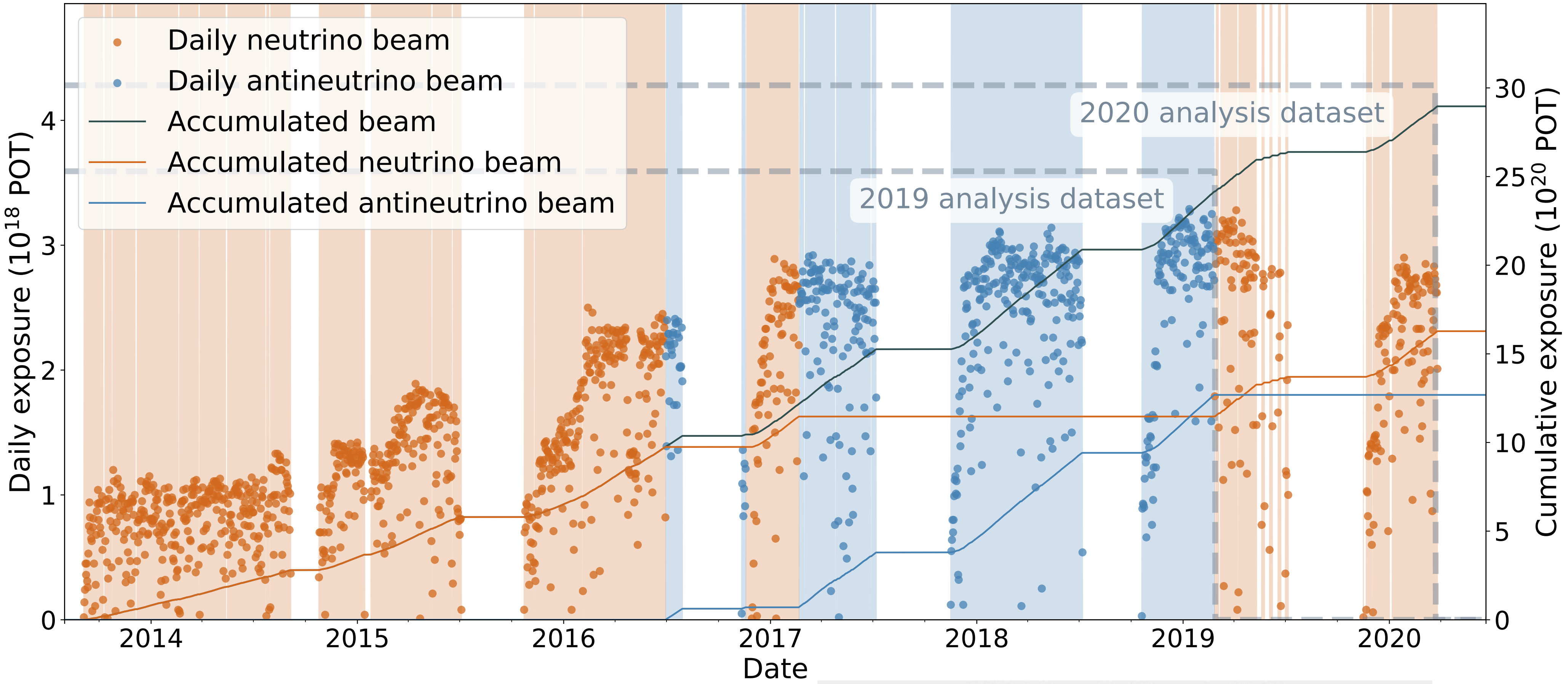
E_{EM} from calorimetry, ~10% resolution

ν_e events



3-flavor neutrino oscillation analysis

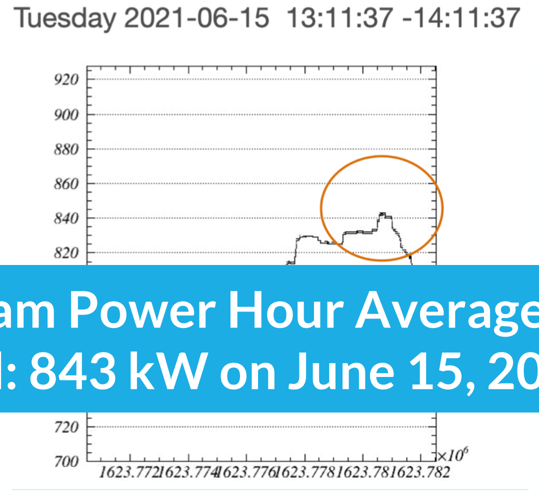
The NuMI beam dataset



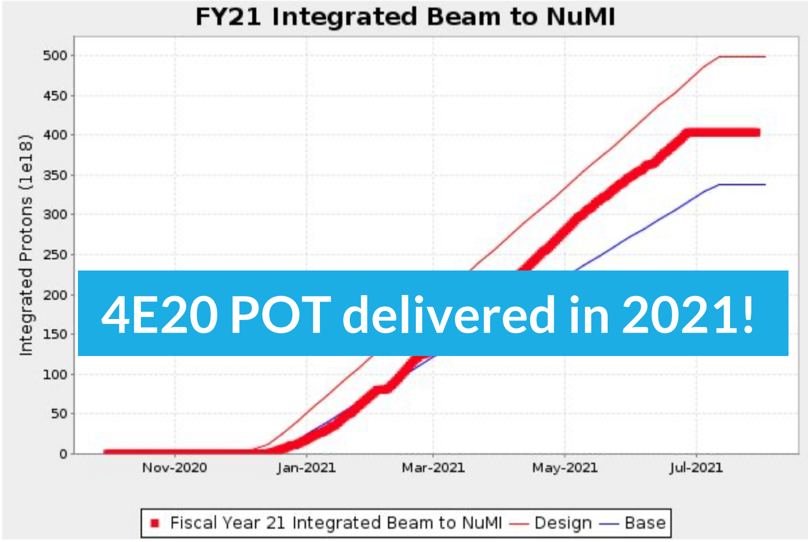
13.6×10^{20} POT neutrino + 12.5×10^{20} POT antineutrino beam mode

(2014-2020)

See: Jason St. John, "Introduction to Fermilab's Accelerators and Beams" (link).



MI Beam Power Hour Average record: 843 kW on June 15, 2021!



4E20 POT delivered in 2021!

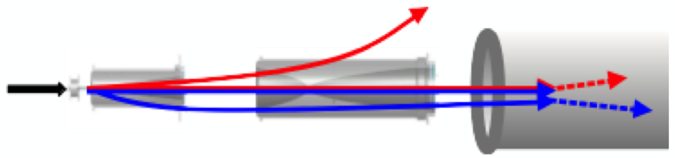
NuMI Target System Upgraded for Megawatt Beam Operation!

Analysis strategy

1. Simulated predictions
2. Data-driven improvements
3. Comparisons with FD data
4. Constraints on oscillation parameters

1. Simulated predictions

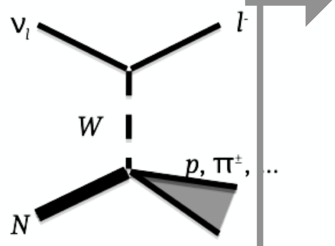
Neutrino flux



GEANT4-based simulations of particle production and transport.

Reweighted to incorporate external measurements (“PPFX”)

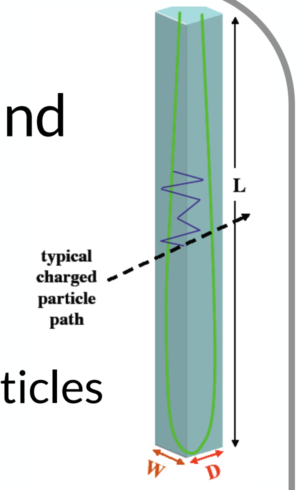
Neutrino interactions on detector materials



Simulated with GENIE 3.0.6*.

Use a custom configuration, tuned to external data and NOvA ND Data.

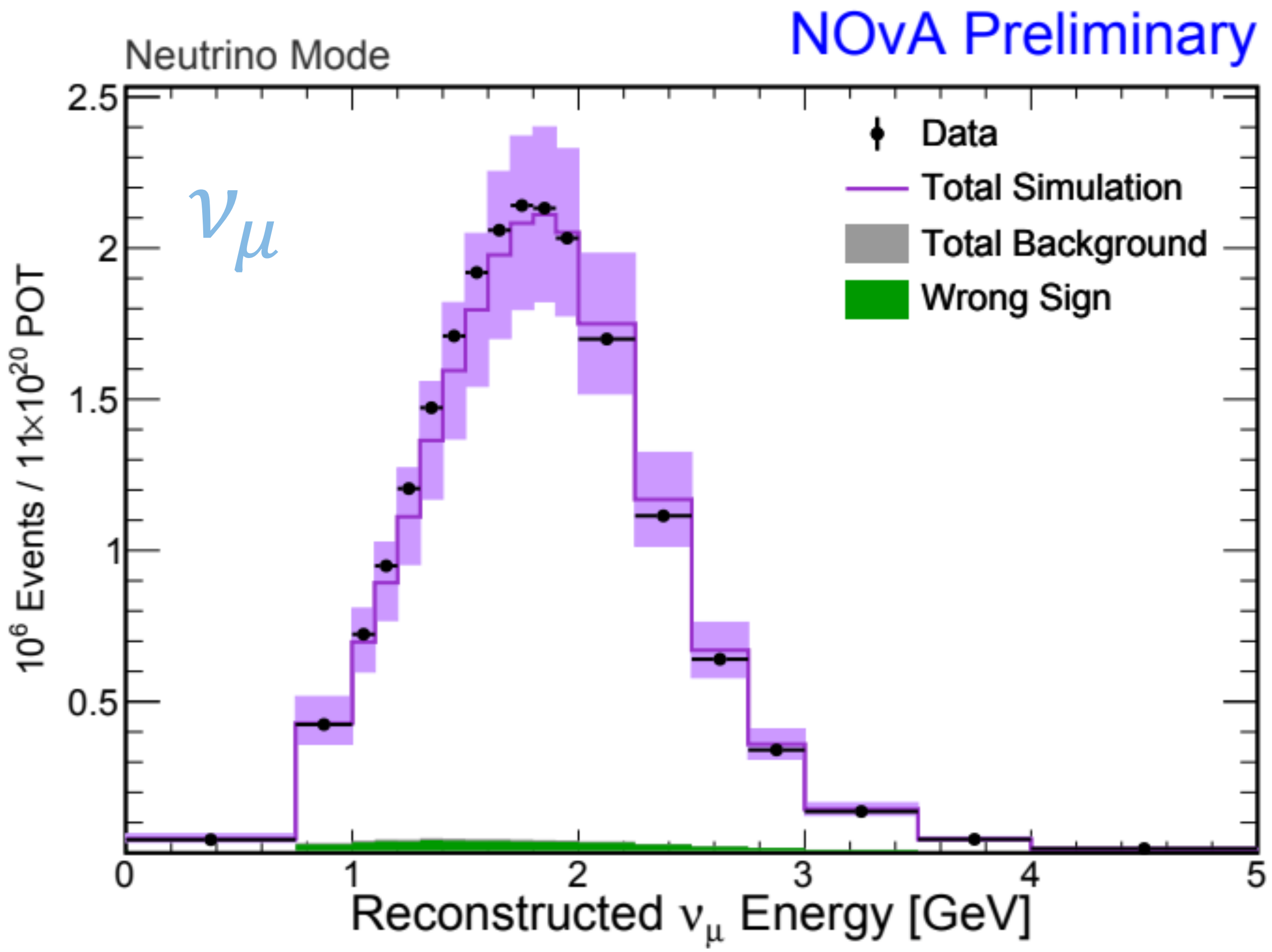
Detector response to charged particles and **light propagation**

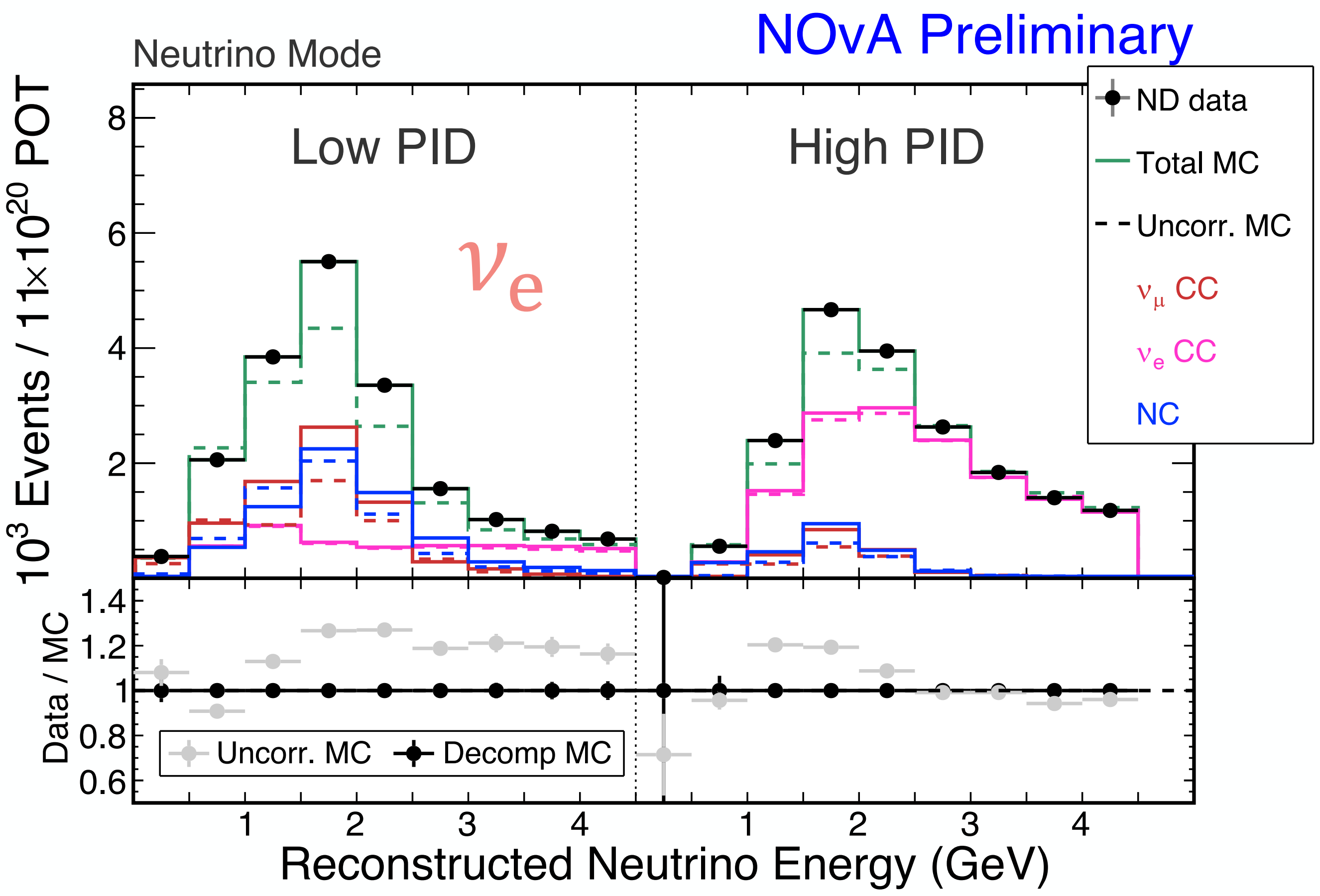


Propagation of final state particles simulated with GEANT4*.
Light readout and front-end electronics use a custom simulation.

* Updated for this analysis

Constraints using ND data



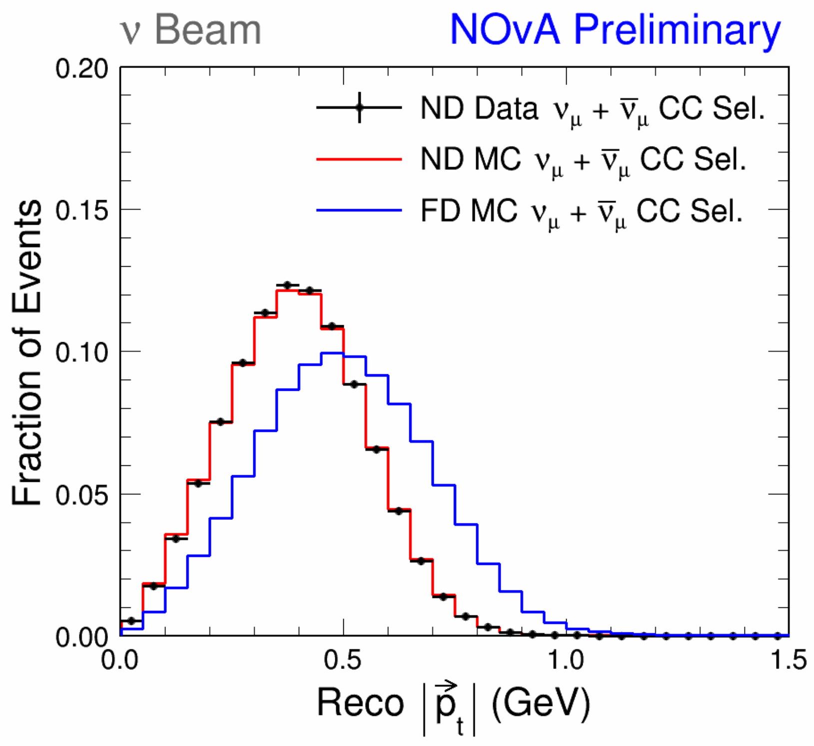


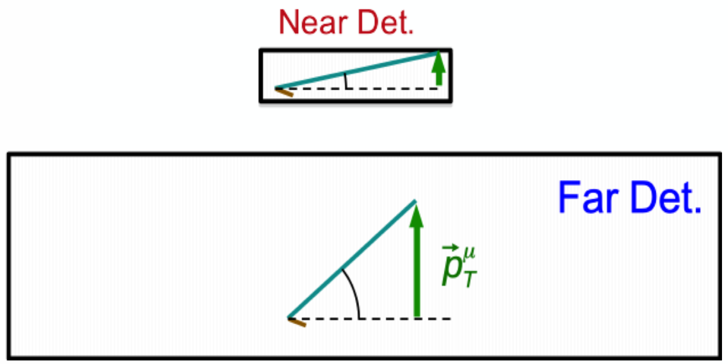
ND ν_μ-like samples are used to correct the FD $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ **signal** predictions

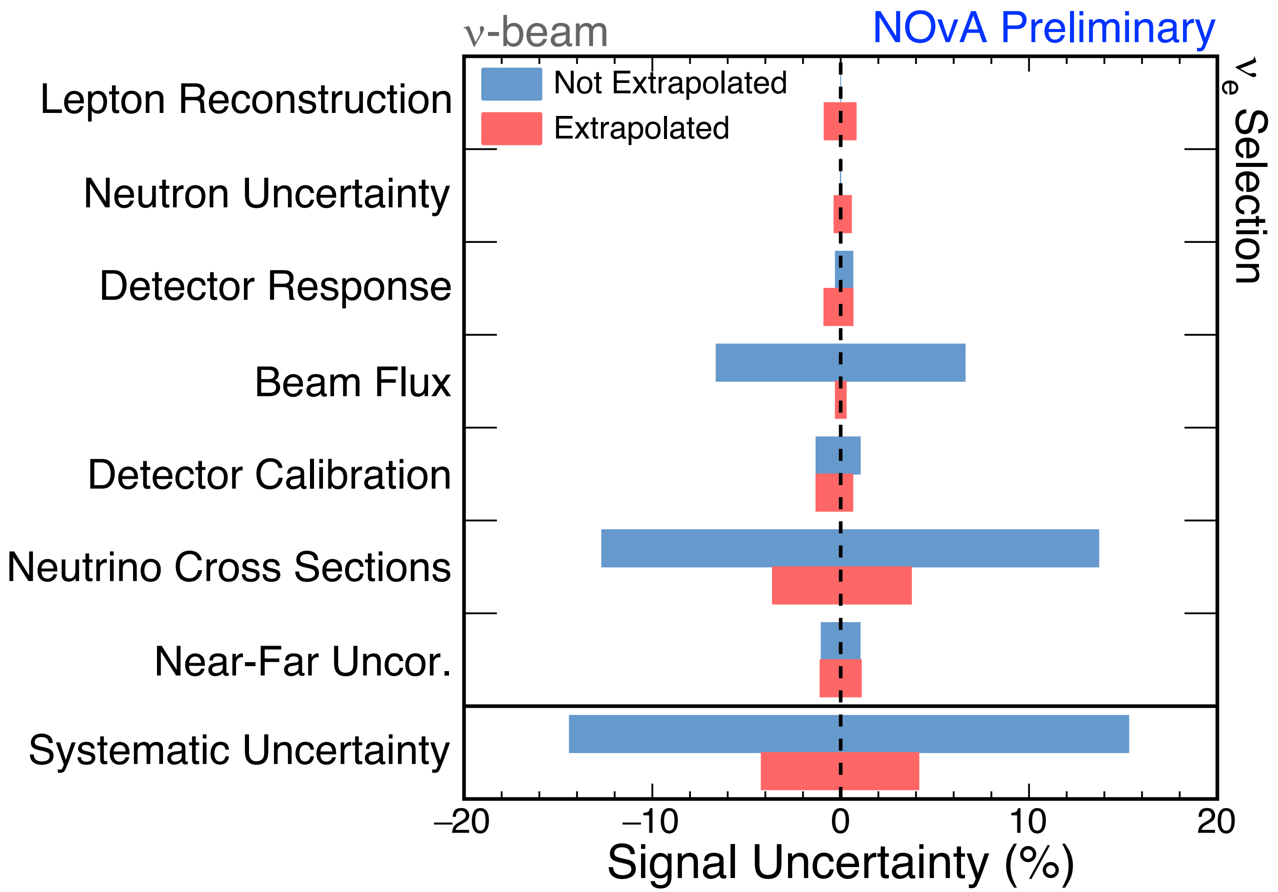
ND ν_e-like samples are used to correct the FD $\boldsymbol{\nu_e}$ **background** predictions

Constraints using ND data

- Choice of binning / subsamples → additional power to control systematic uncertainties
- **p_T binning (lepton transverse momentum)**
  - "Rebalance" ND/FD kinematics



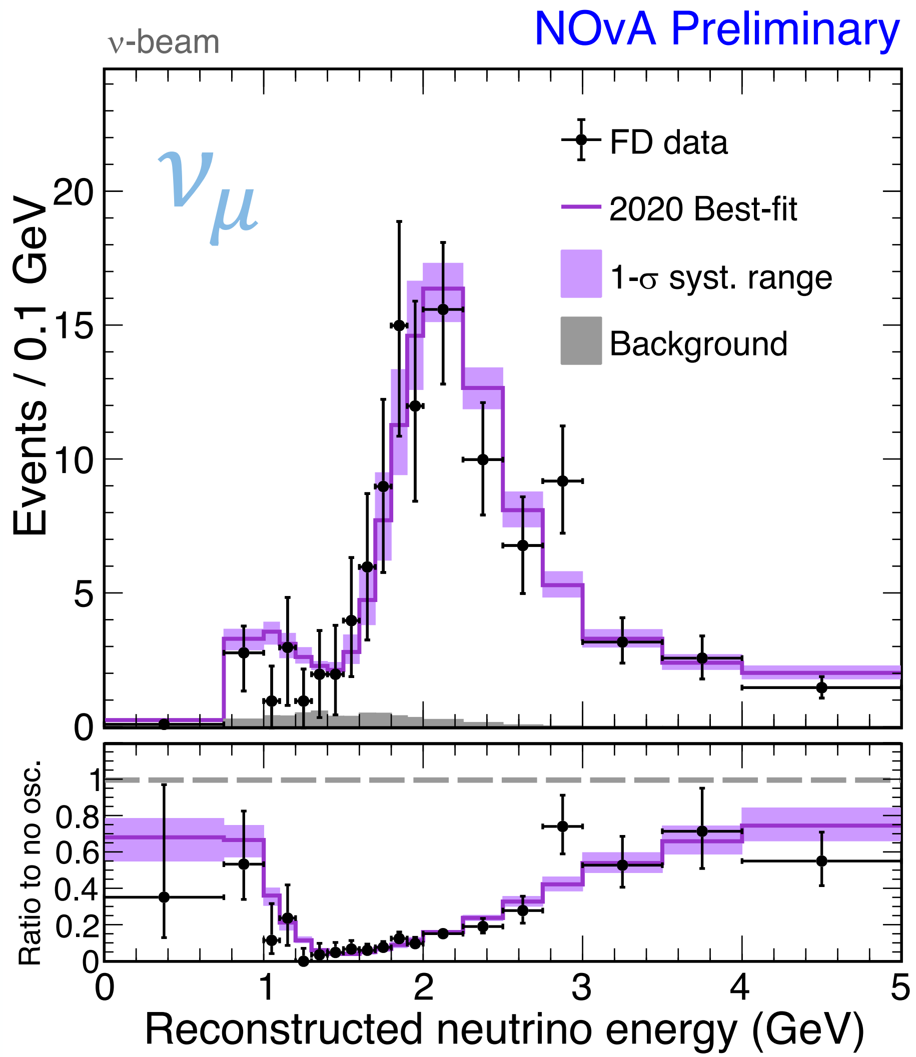




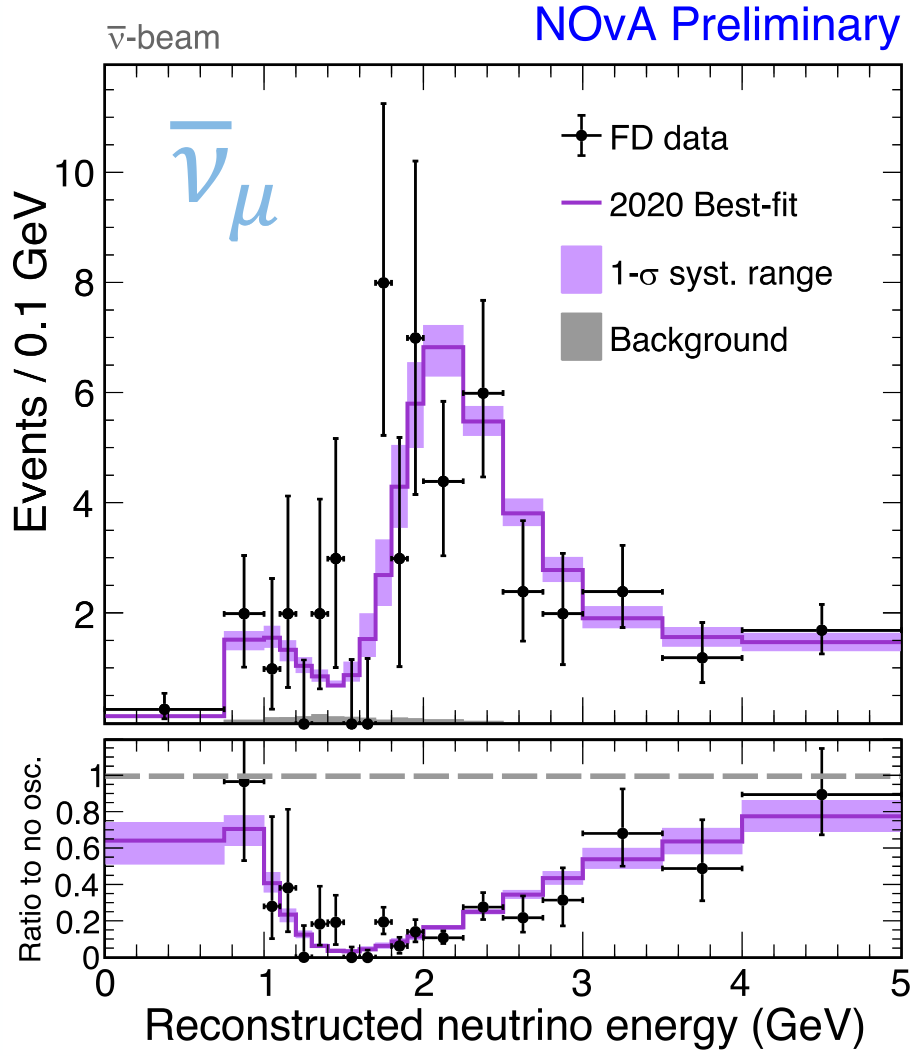
ND constraints reduce systematic uncertainties in the FD prediction from >15% to 4-5%

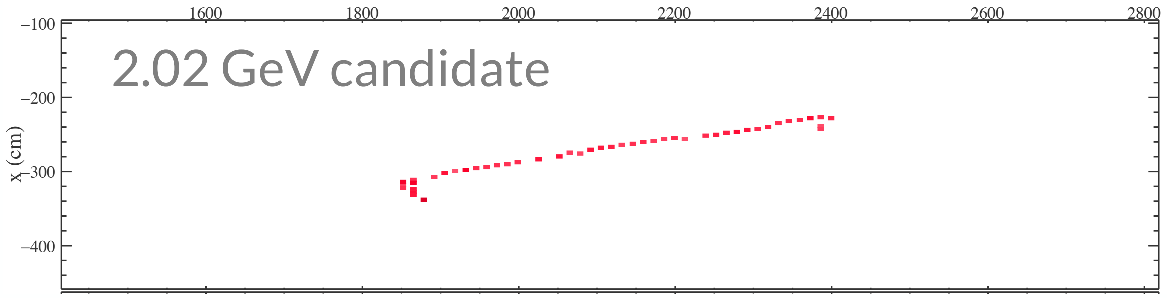
- ν_μ binning optimized to see the "dip" in the energy spectrum
- ν_e binning optimized to separate signal/background

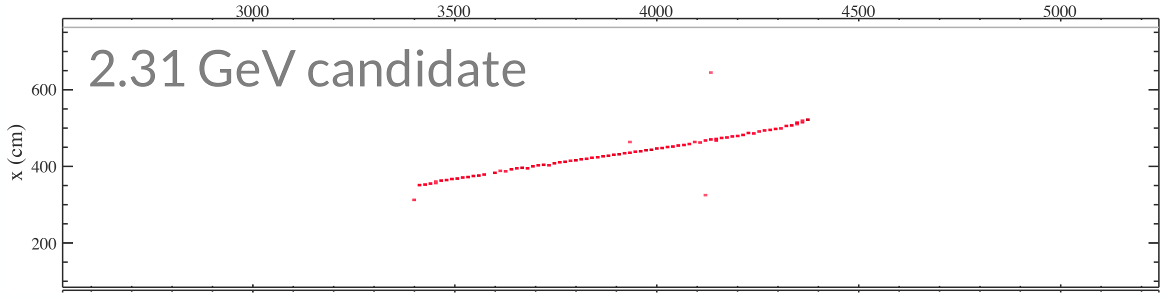
ν_μ and $\bar{\nu}_\mu$ data at the Far Det.



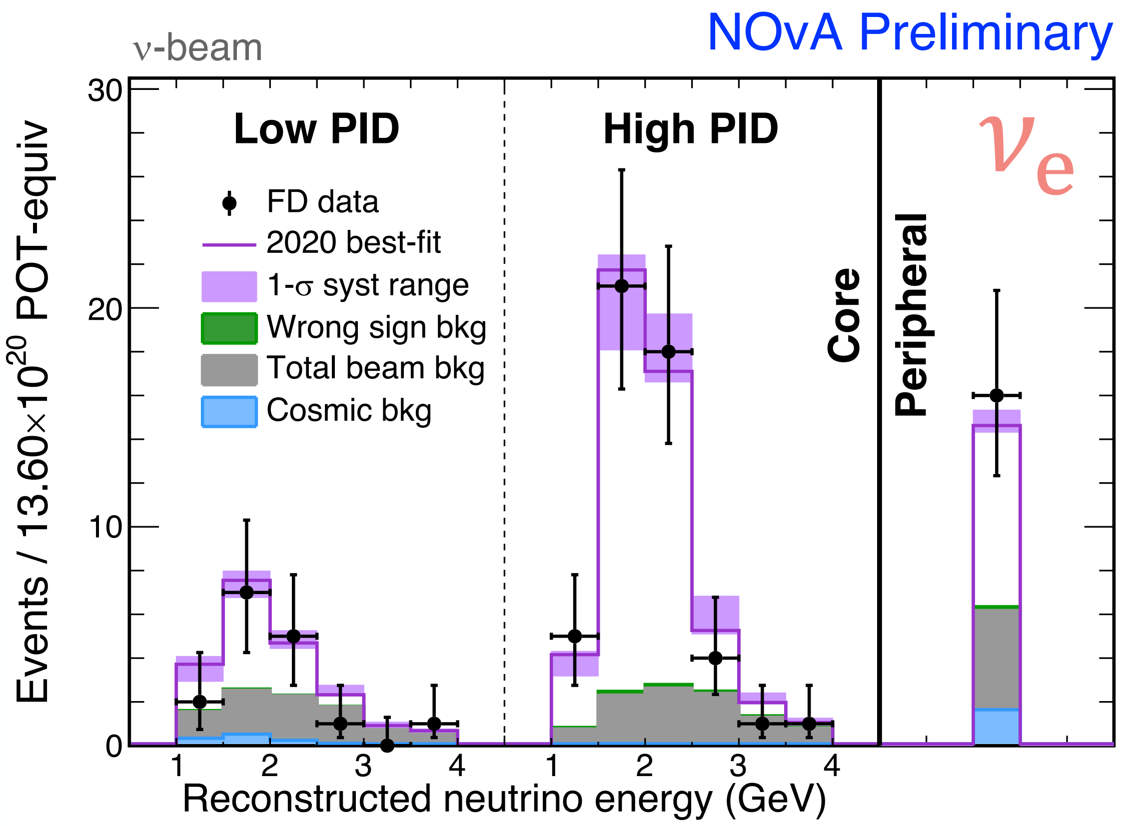
Observed	211 ν_μ	105 $\bar{\nu}_\mu$
Best fit pred.	222.3	105.4
Signal	$214.1^{+14.4}_{-14.0}$	$103.4^{+7.1}_{-7.0}$
Background	$8.2^{+1.9}_{-1.7}$	$2.1^{+0.7}_{-0.7}$

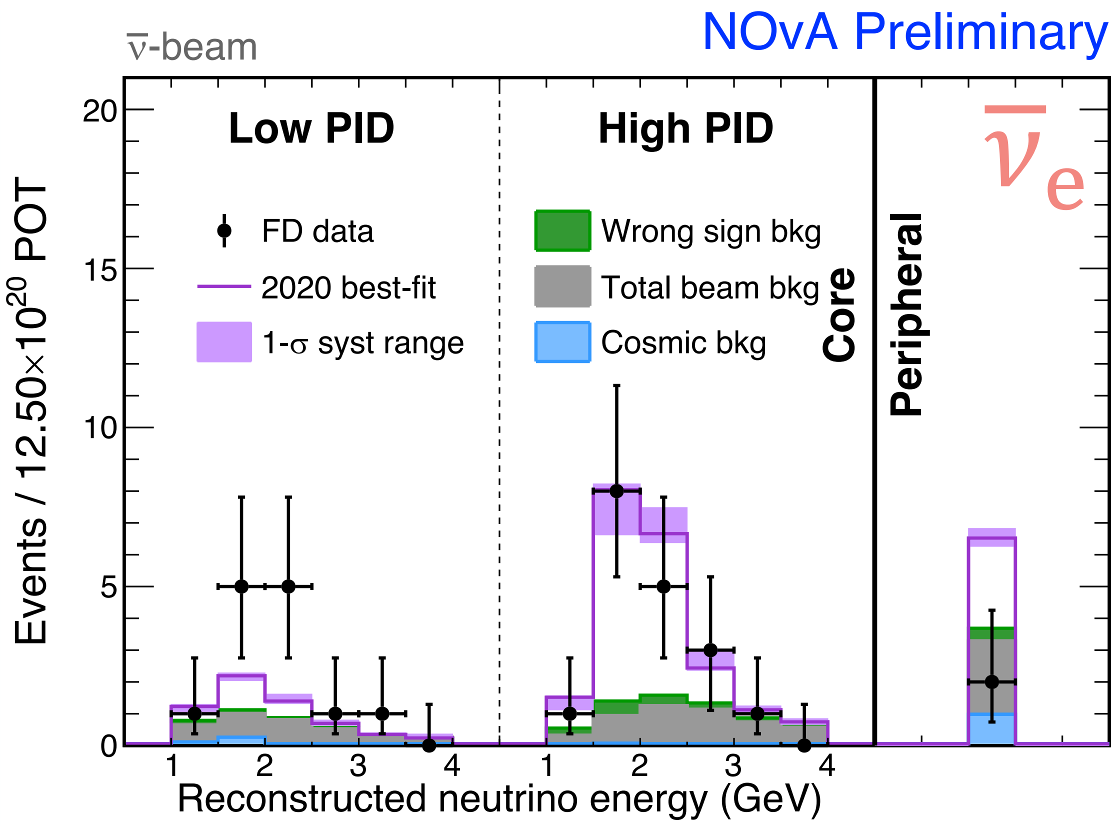


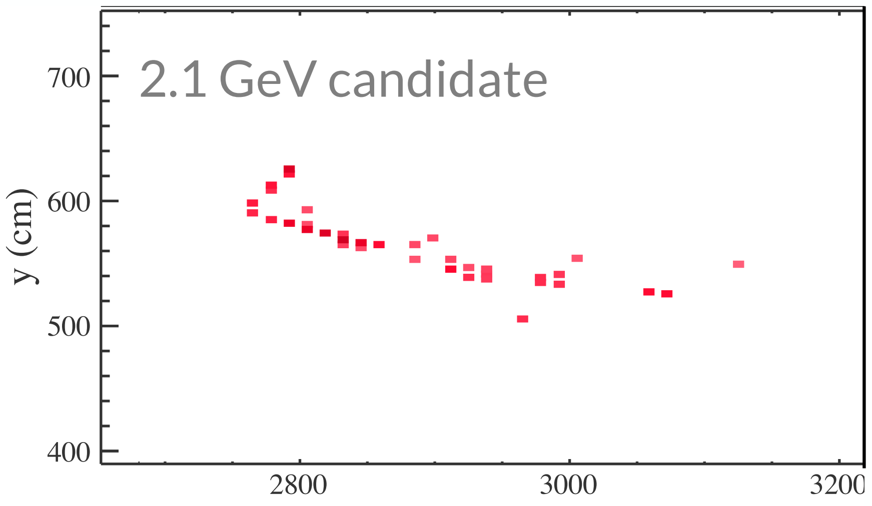

2.02 GeV candidate


2.31 GeV candidate

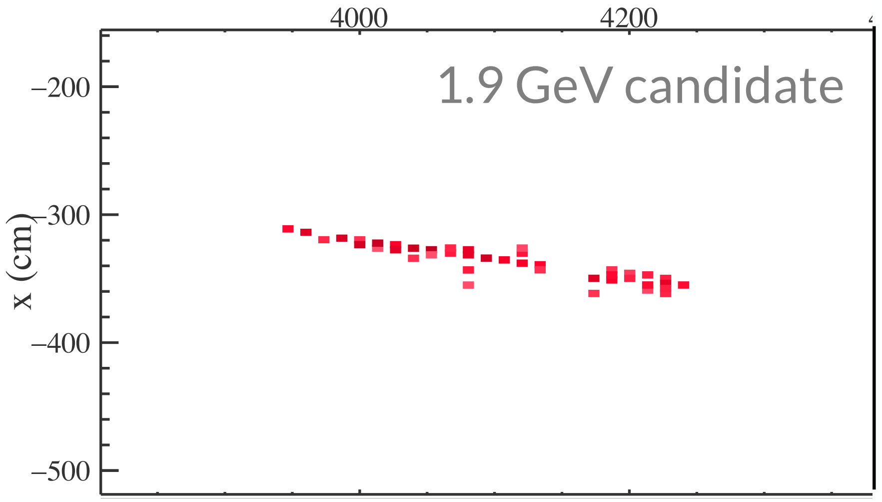
ν_e and $\bar{\nu}_e$ data at the Far Det.







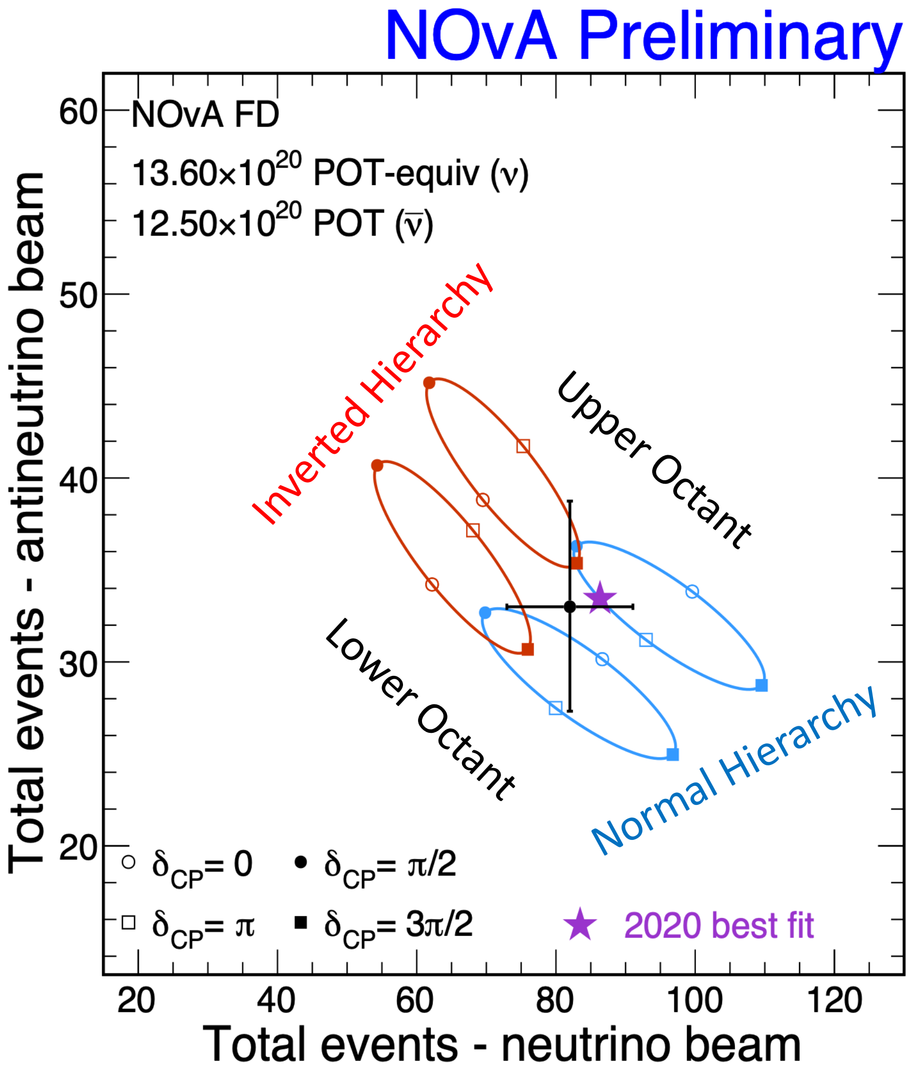
Observed	82 ν_e	33 $\bar{\nu}_e$
Best fit prediction	85.8	33.2
Signal	$59.0^{+2.5}_{-2.5}$	$19.2^{+0.6}_{-0.7}$
Background	$26.8^{+1.6}_{-1.7}$	$14.0^{+0.9}_{-1.0}$



$\nu_e / \bar{\nu}_e$ appearance + asymmetry

82 candidates (27 bkgd.) → $\boldsymbol{\nu_e}$ **appearance ✓**

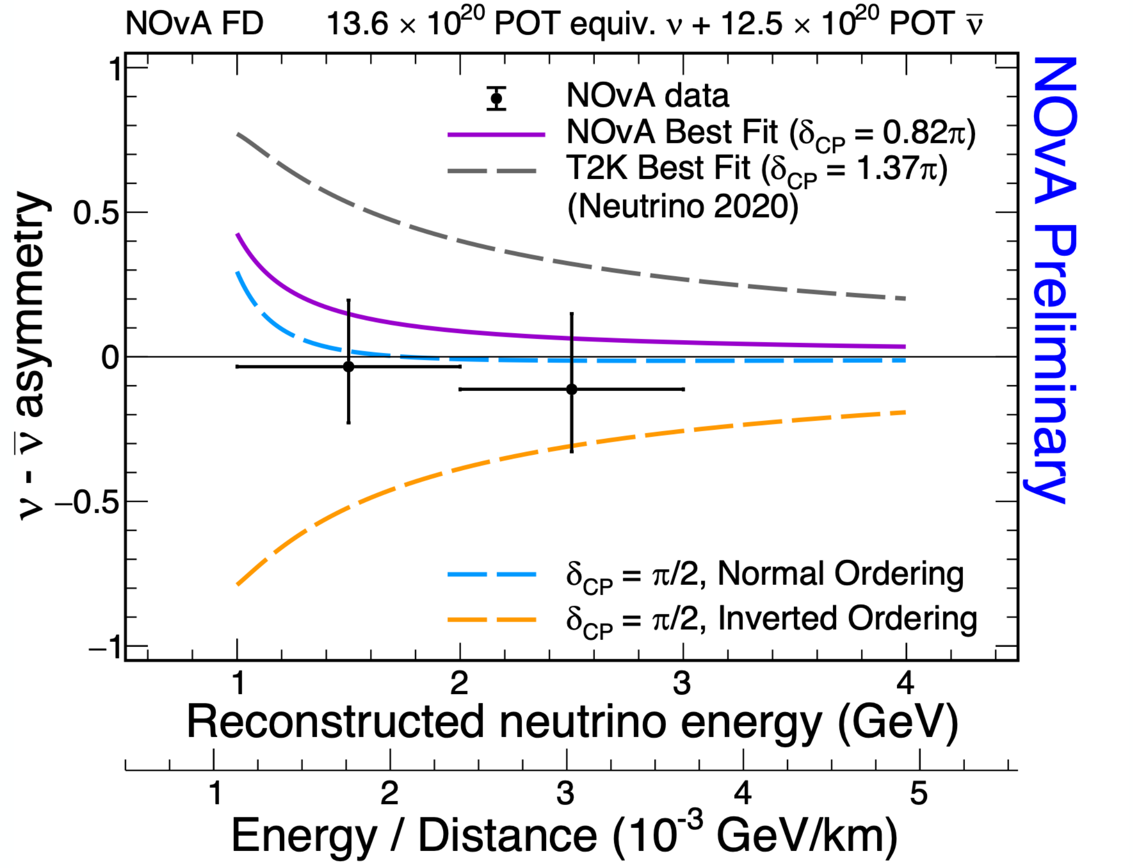
33 candidates (14 bkgd.) → $\boldsymbol{\bar{\nu}_e}$ **appearance ✓**



We don't see a strong asymmetry between $\boldsymbol{\nu_e}$ and $\boldsymbol{\bar{\nu}_e}$ appearance rates

→Exclude IH δ = π/2 at >3σ

→Disfavor NH δ = 3π/2 at ~2σ



Constraints on Δm^2_{32} and $\sin^2\vartheta_{23}$

- Best fit:

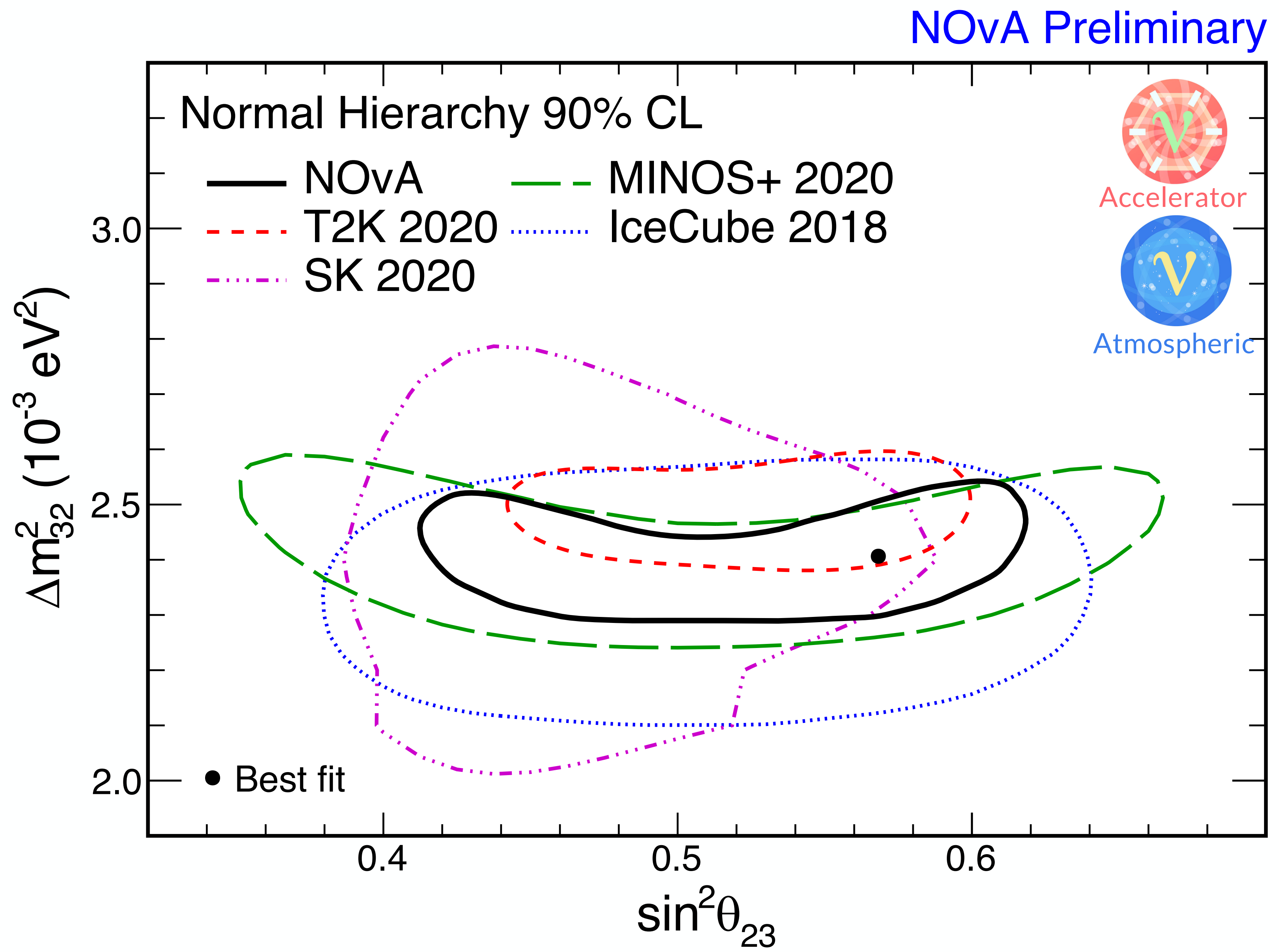
  Normal hierarchy

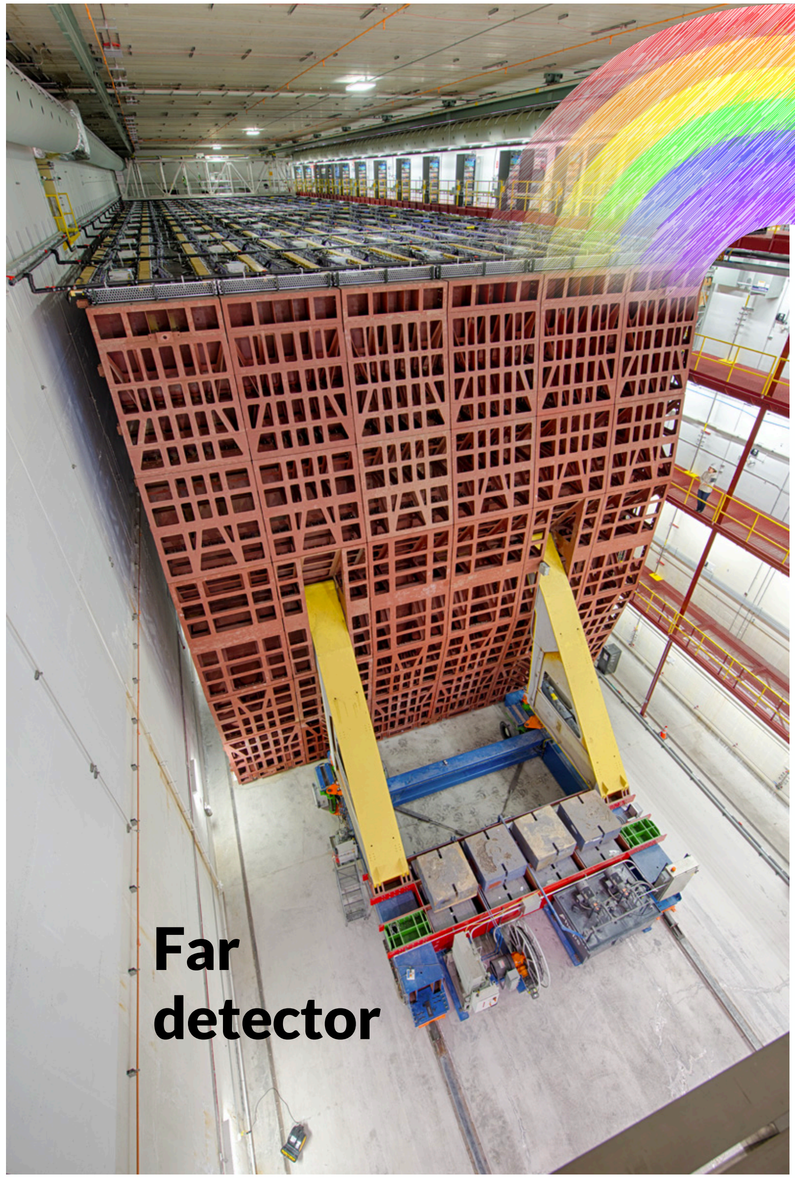
  Δm^2_{32} = (2.41±0.07)×10^{-3} eV^2

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

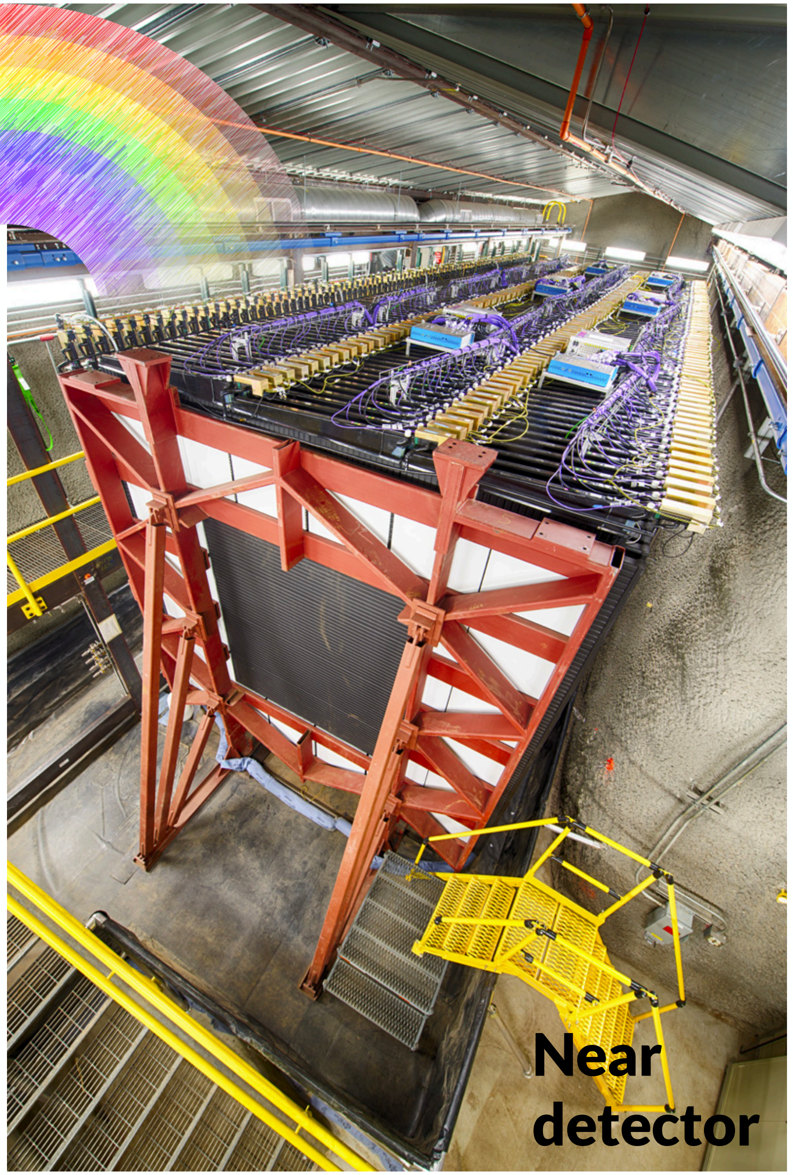
  δ_{CP}=0.82π

- **Precision measurements of Δm^2_{32} (3%) and $\sin^2\vartheta_{23}$ (6%)**





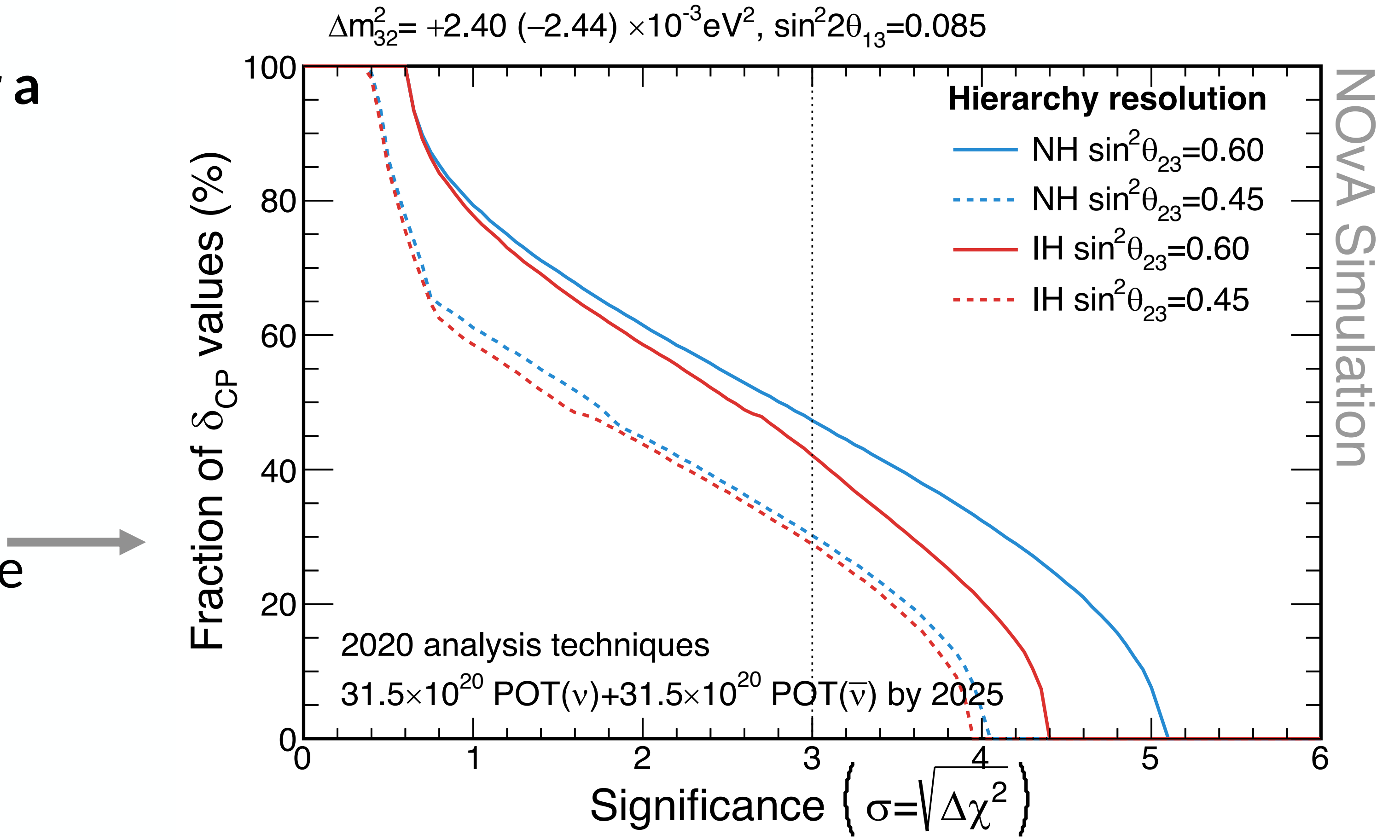
The horizon



Future 3-flavor measurements

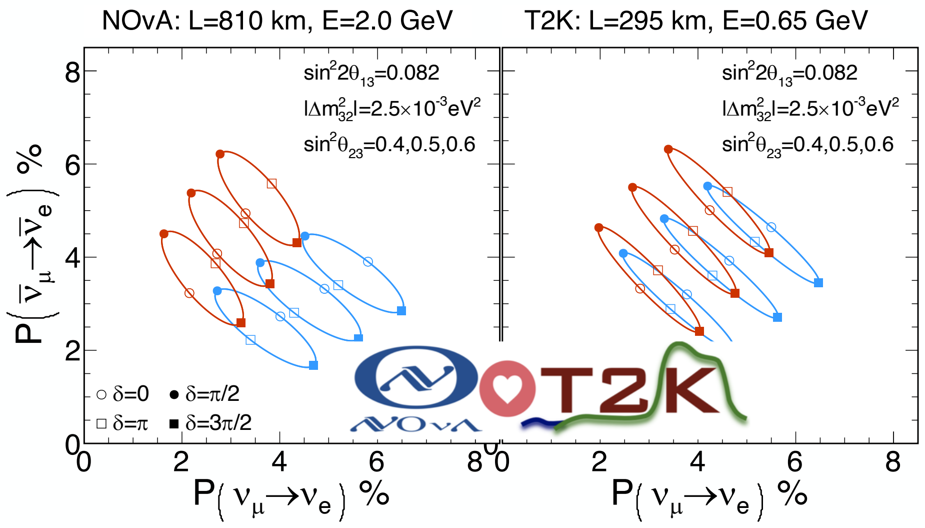
- Upcoming 3-flavor analyses:
  - Additional beam data (FY 2021-2022)
  - Improvements to the simulation, reconstruction, and analysis techniques

- **NOvA is expected to take data through 2026, for a projected total of 60-70 ×10^{20} POT**
  - We're half way there!
  - Expect increasingly precise measurements of Δm^2_{32} and $\sin^2\vartheta_{23}$.
  - We can reach 3σ hierarchy sensitivity for 30-50% of *δ* values, and ~5σ in the most favorable case.
  - We can also reach a ~2σ determination of CP violation.

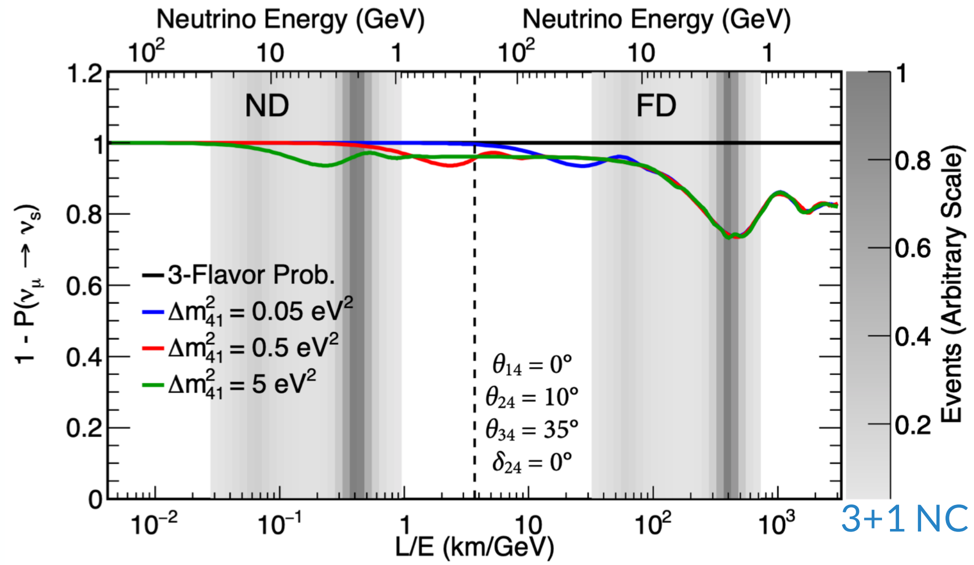


NOvA: a rich physics program!

NOvA + T2K joint analysis

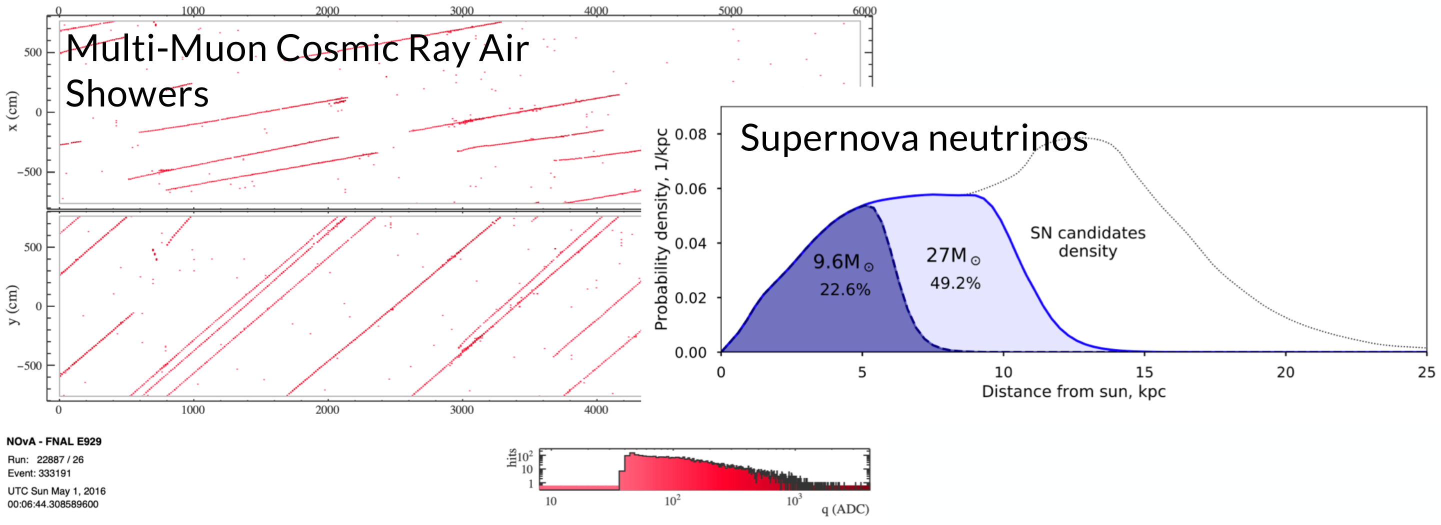


Sterile neutrino searches



3+1 NC oscillations

Cosmic ray physics and exotics



Multi-Muon Cosmic Ray Air Showers

Supernova neutrinos

Cross-section measurements

TOMORROW (session 16)
Wenjie Wu, "NOvA cross-section measurements"

Learn more: NOvA publications. Snowmass LOI: NOvA+T2K, Steriles , Exotics, Cross-sections

NOvA Test Beam

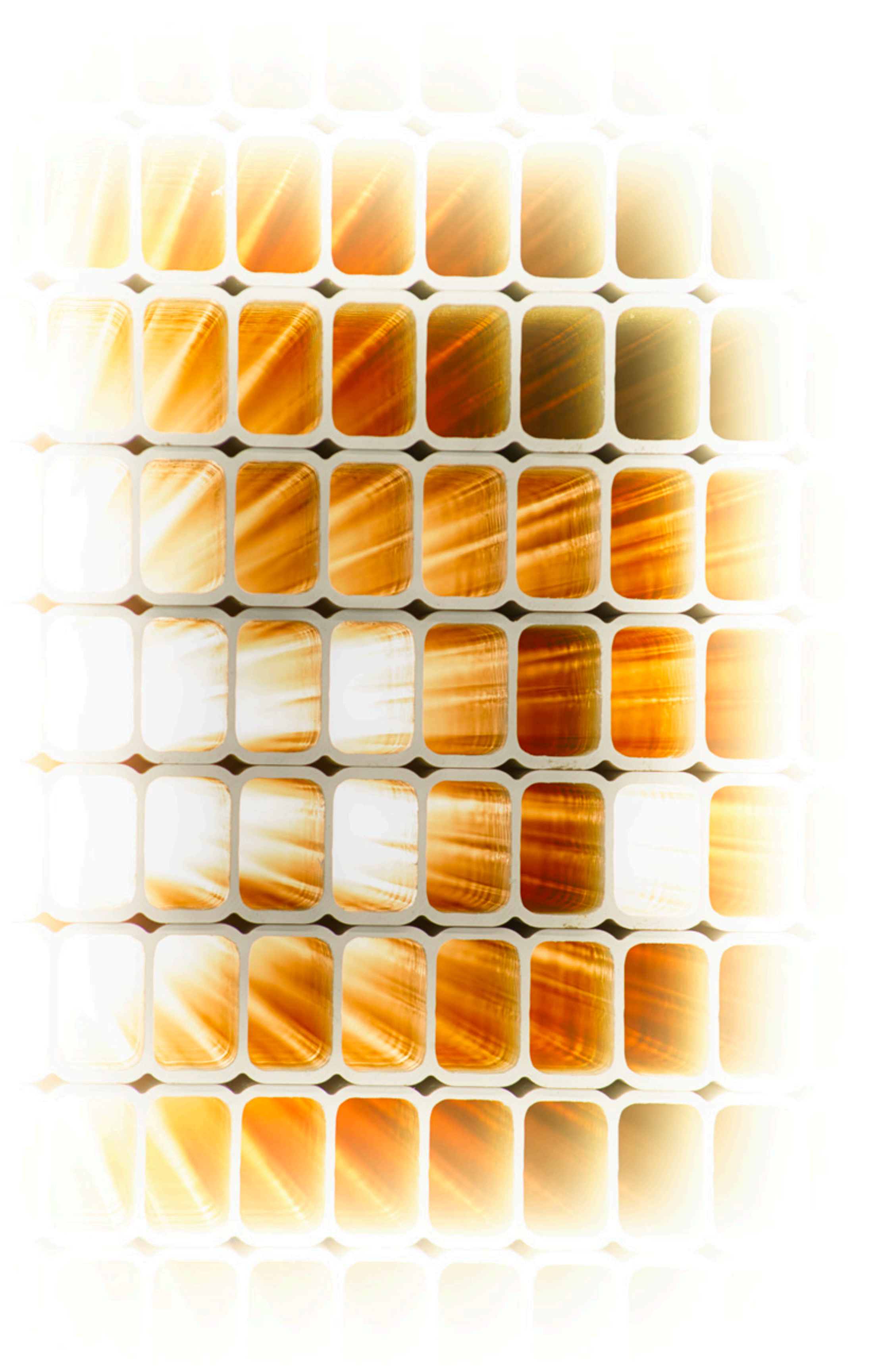
- A scaled- down 30-ton NOvA detector
- **Deployed at the Fermilab Test Beam Facility**
- Analyzes tagged charged particles from a tertiary beamline (protons, pions, muons, electrons and kaons) in the 0.2 — 2.0 GeV/c momentum range
- Results could **address some of the largest systematic uncertainties in NOvA**

NOvA TB @ MCenter

* See: Vallary Bhopatkar,
“Fermilab Test Beam Facility” (link)

Summary

- NOvA's primary goal is the study of **3-flavor neutrino oscillations**, via measurements of muon (anti)neutrino disappearance and electron (anti)neutrino appearance
- The most recent oscillation analysis results:
    - **Precision measurements of Δm^2_{32} (3%) and $\sin^2\vartheta_{23}$ (6%)**
    - **No strong asymmetry between ν_e and $\bar{\nu}_e$ appearance rates**
- The data analyzed so far corresponds to ~half of the total expected. There's still a lot to do!
- **NOvA can explore more physics**: sterile neutrino searches, cross-section measurements, exotic and cosmic-ray studies…
    - A lot of opportunities for young scientists



NOvA continued recording and analyzing data throughout 2020 and 2021.

This was made possible by the extraordinary dedication of the Fermilab community at large.

THANK YOU!! See you next year! 🤞

Feb. 2020, UC Irvine

May 2020, Online

Photo: Jason Van Hartman. FNAL news, July 2021