Latest Three-Flavor Neutrino Oscillation Results from NOvA

Martin J. Frank
University of South Alabama
on behalf of the NOvA Collaboration

EPS-HEP 2023
Hamburg, Germany

August 22nd, 2023

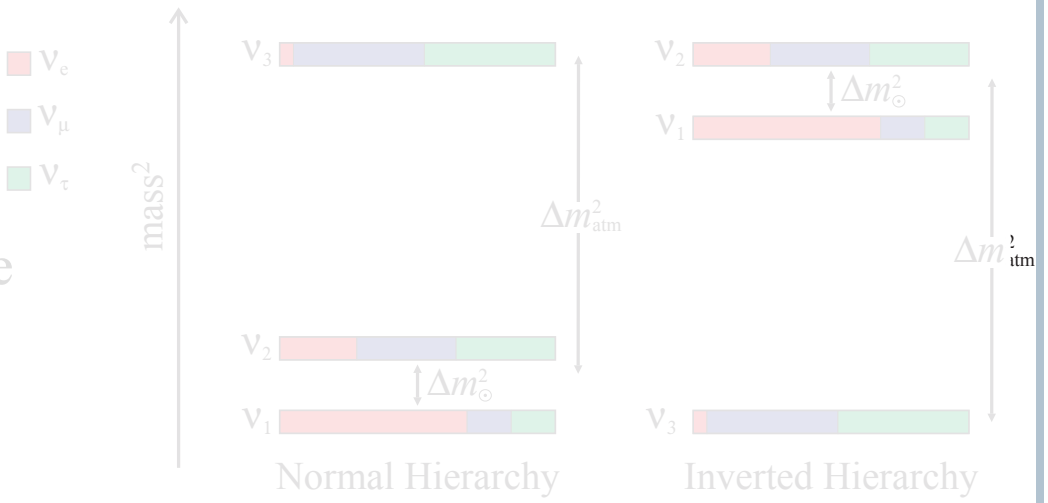
UNIVERSITY OF
SOUTH ALABAMA

Introduction

- NOνA:
  - NuMI: Neutrinos at the Main Injector (ν_μ)
  - Off-Axis: monoenergetic beam (2 GeV)
  - ν_e Appearance

$$P(\nu_\mu \rightarrow \nu_e)$$
$$P(\nu_\mu \rightarrow \nu_\mu) = f(\theta_{13}, \theta_{23}, \delta_{CP}, \text{mass hierarchy}, \ldots)$$

- Physics Goals:
  - measure $\theta_{13}, \theta_{23}, \Delta m^2_{32}$
  - measure δ_{CP}
    CP-violating phase angle
  - resolve mass hierarchy
  - resolve θ_{23} octant



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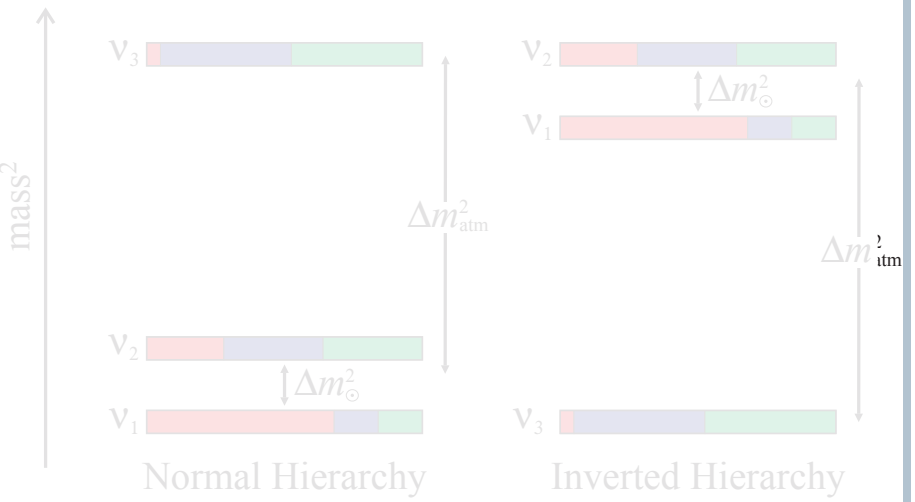

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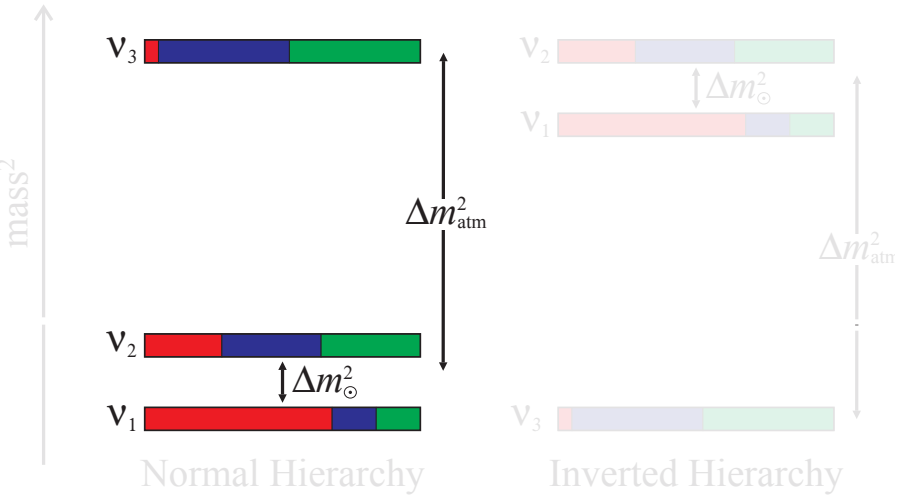

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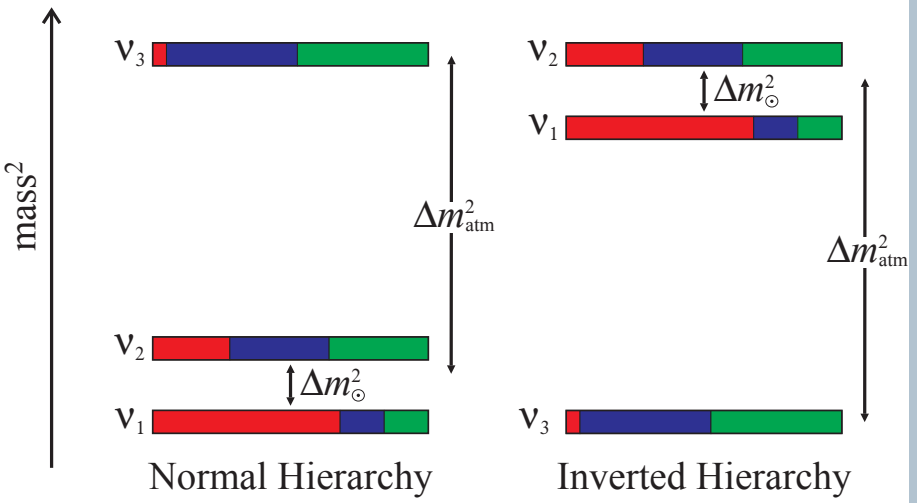

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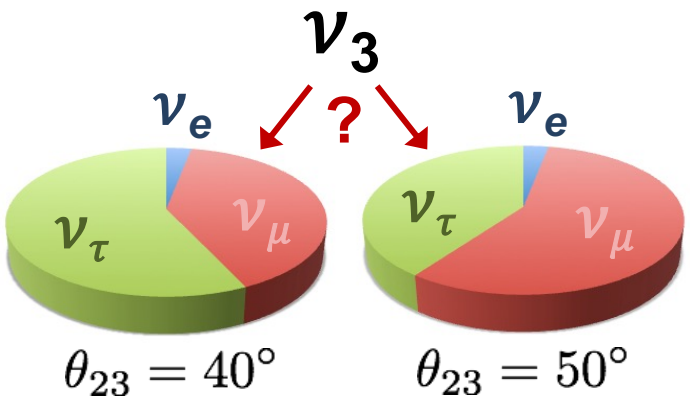

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- Non-Standard Interactions
- Neutrino Cross Sections
- Sterile Neutrinos
- Dark Matter
- Magnetic Monopoles
- Supernova
- And More!

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T03: Barnali Brahma
Friday 9:30 am
Room O221, East Wing

T10: Martin Frank
Monday 10:00 am
Hörsaal A

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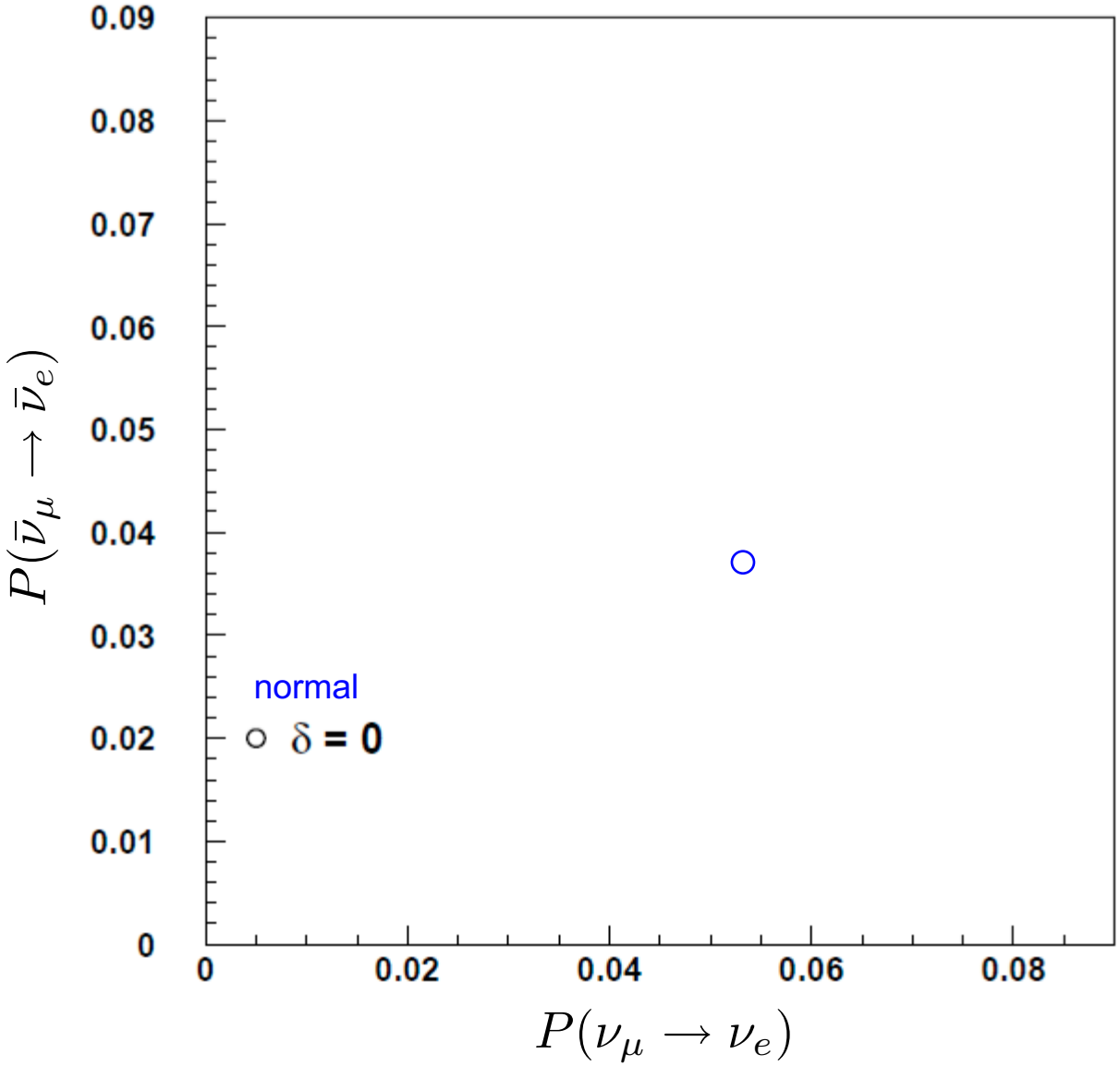
Extracting Nature's Parameters



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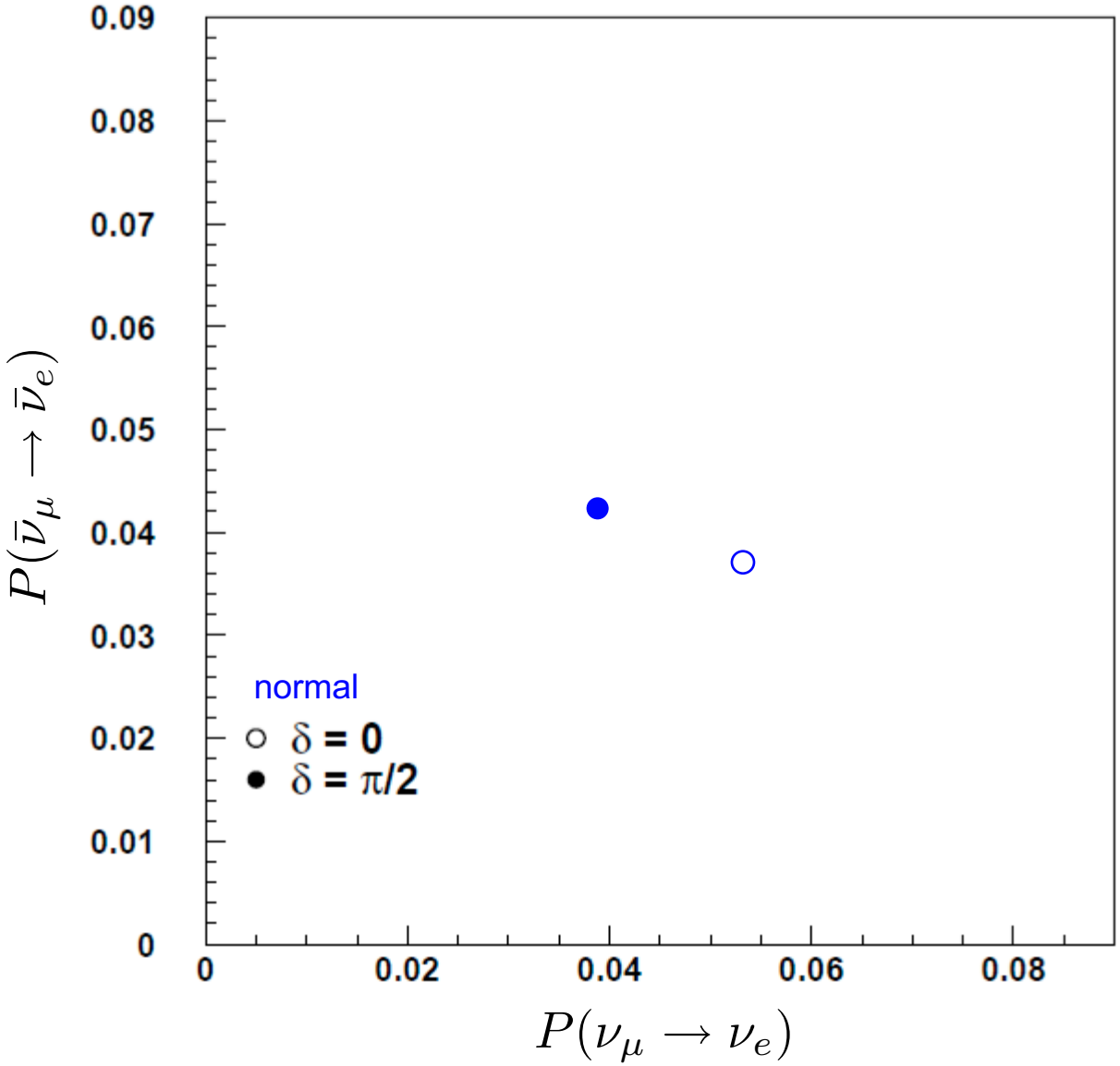

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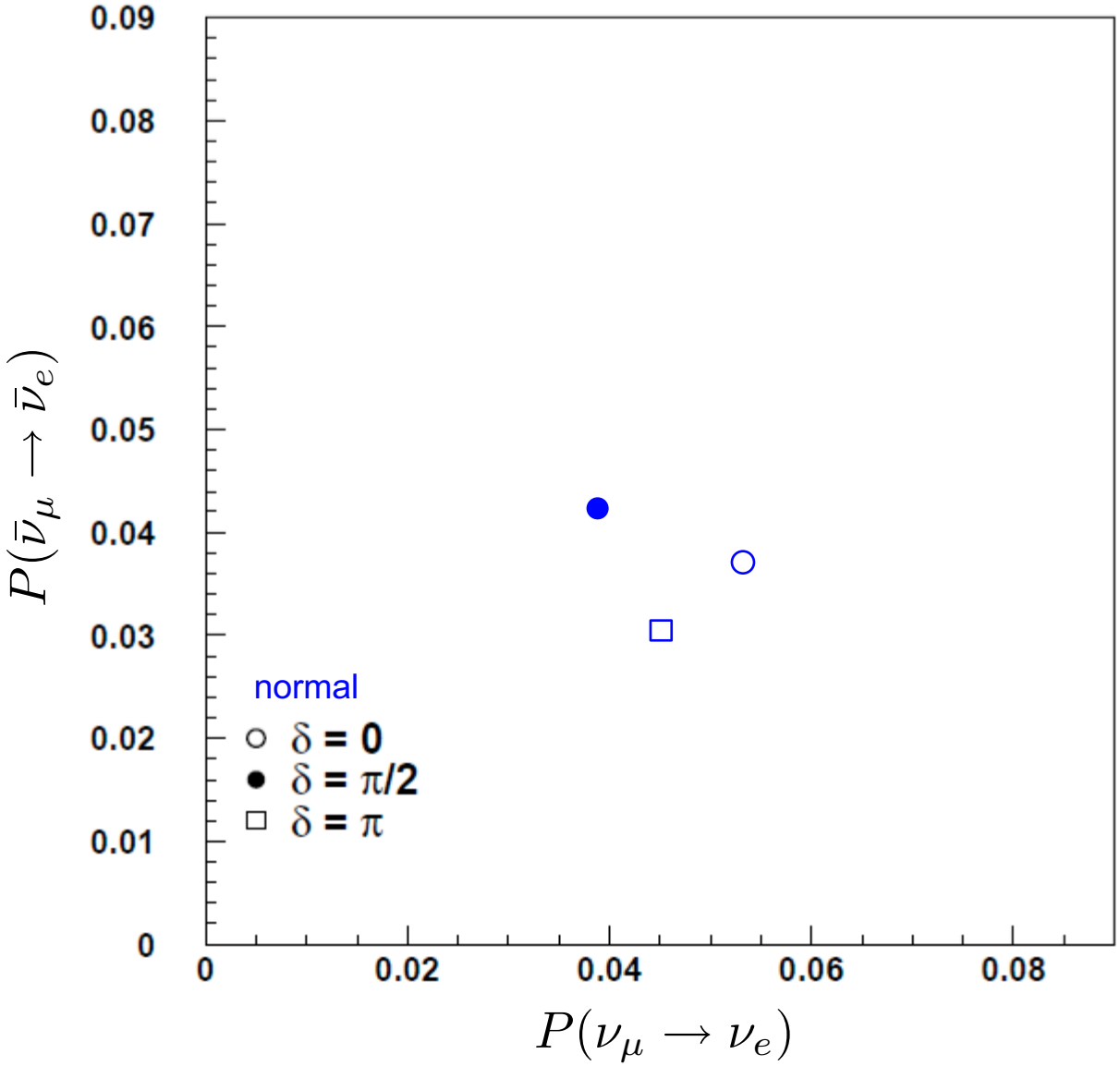

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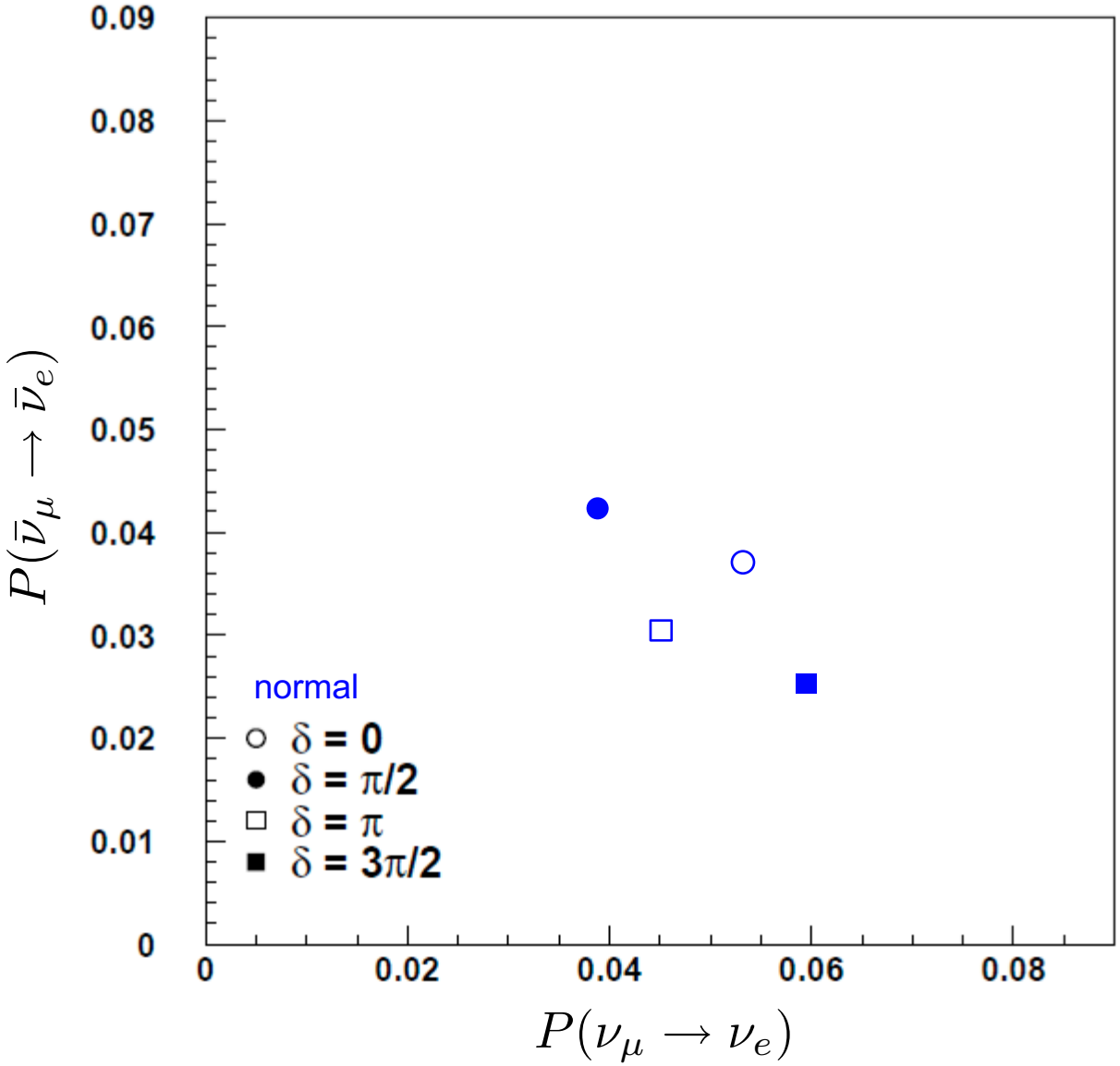

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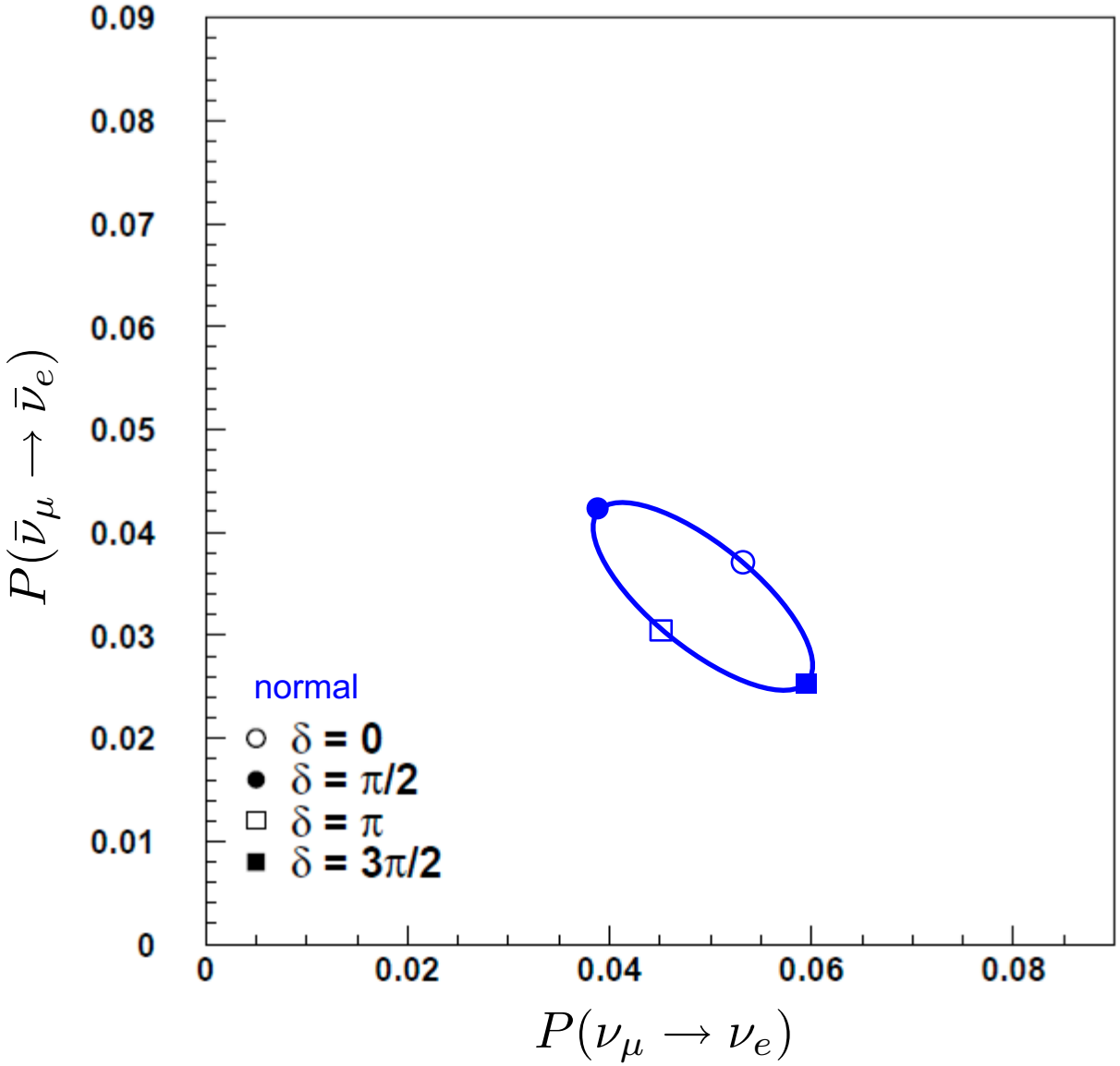

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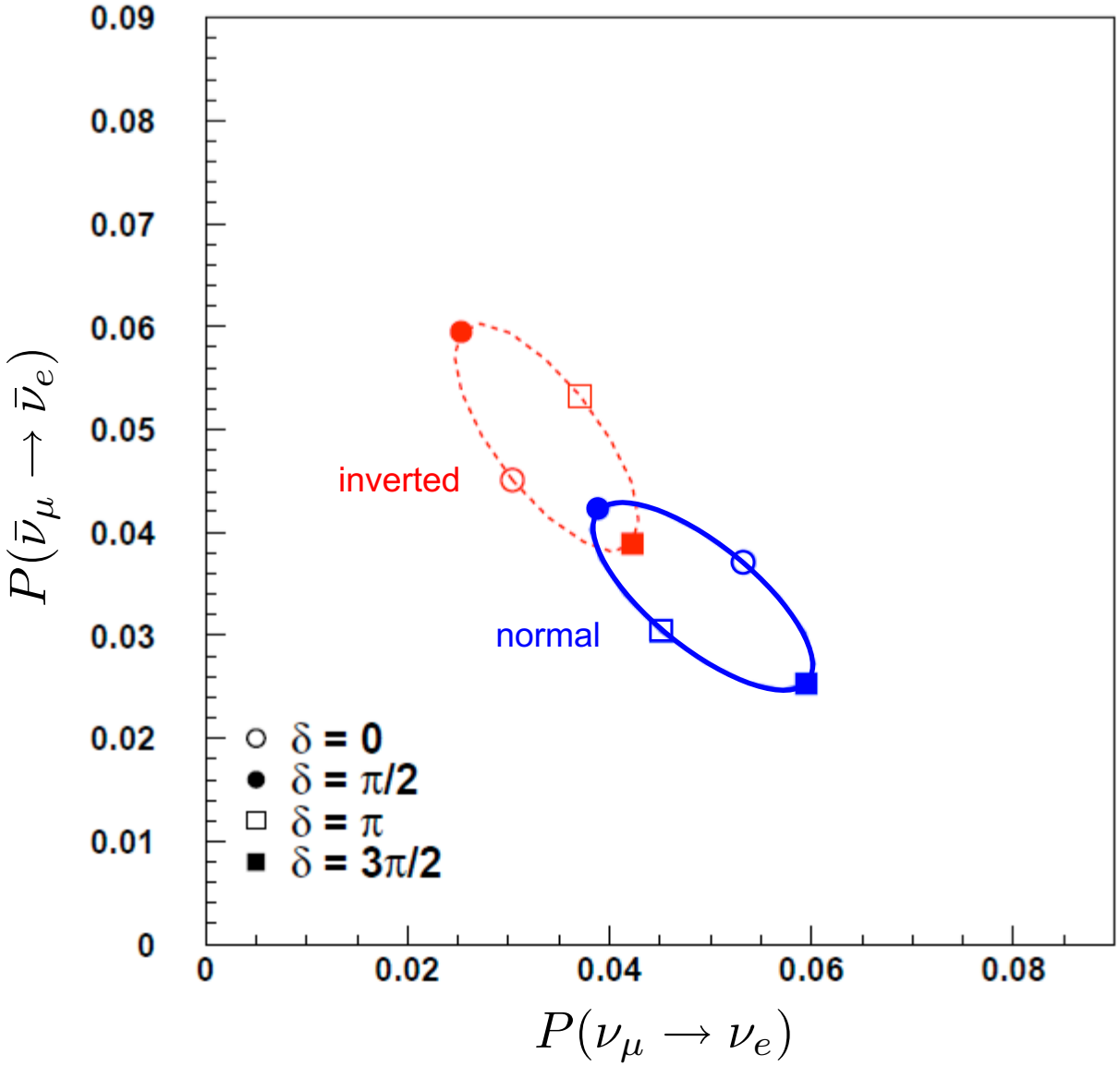

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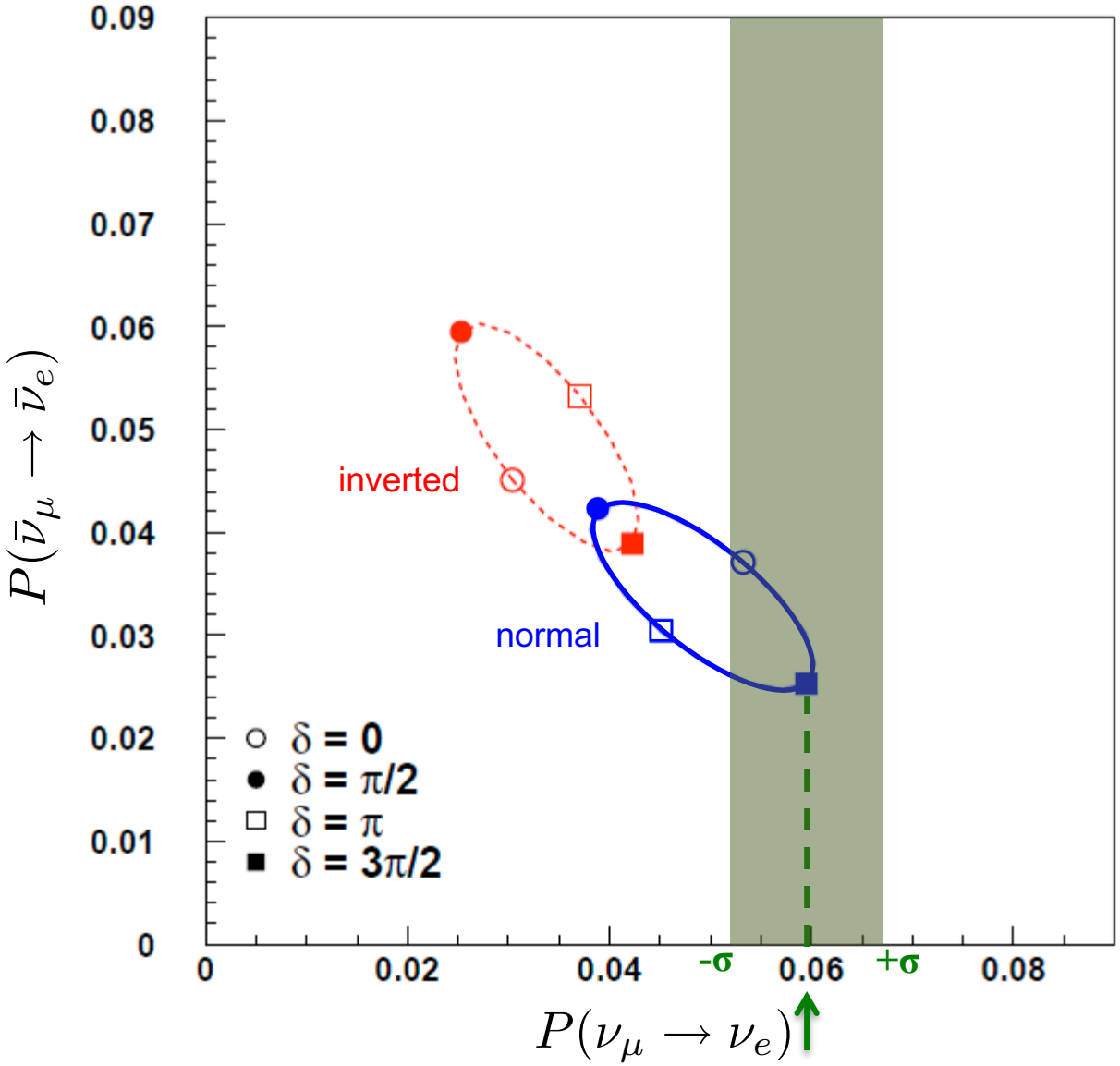

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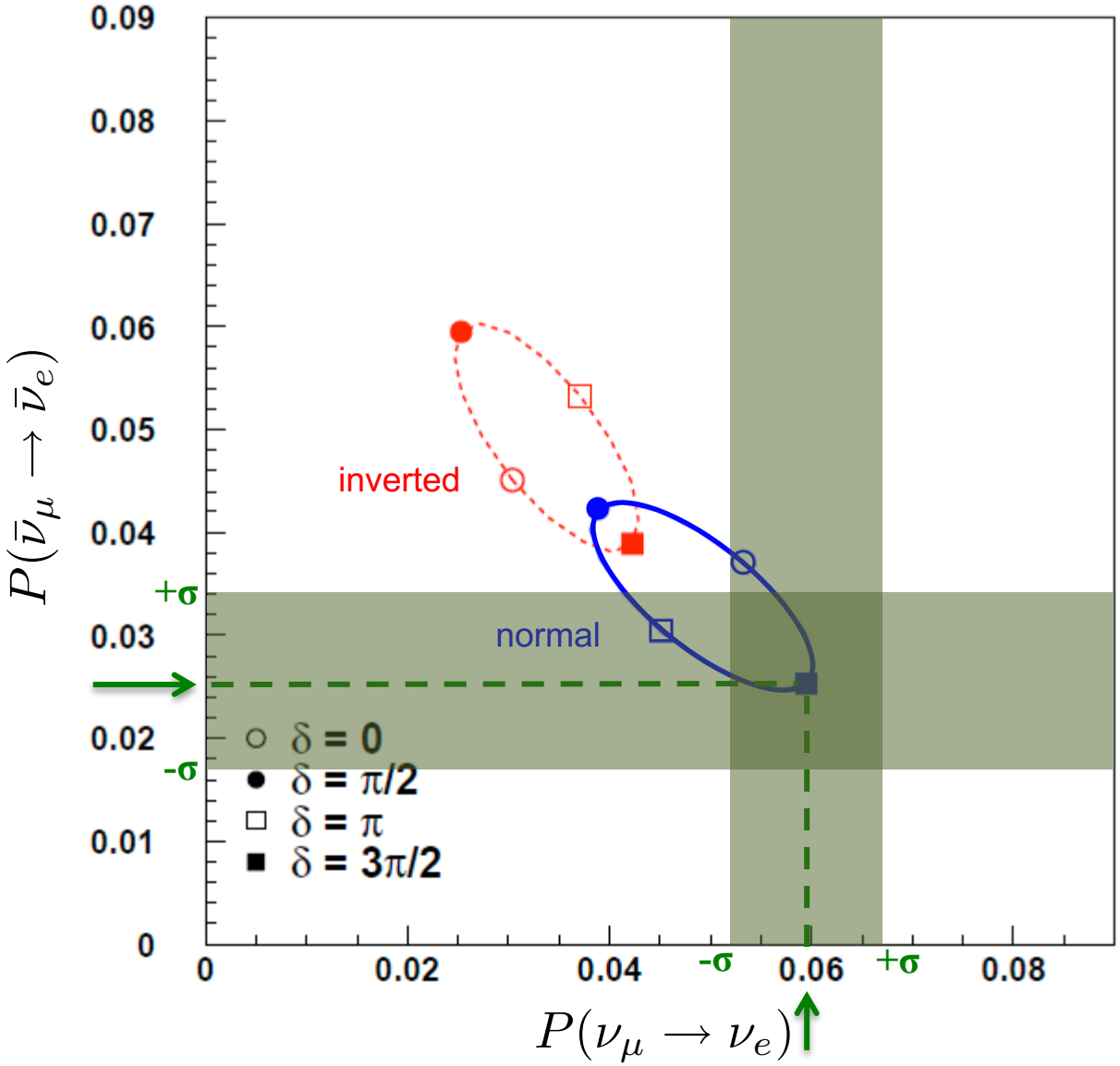

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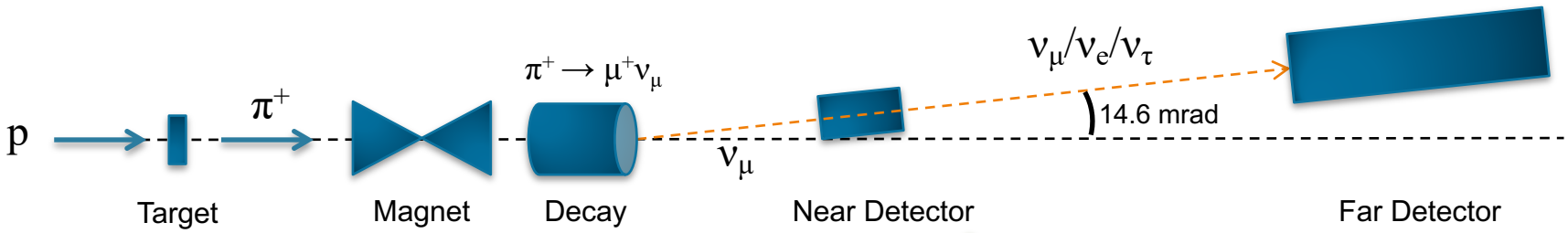


Neutrino Beam

Baseline (L = 810 km)

The neutrino beam travels from Fermilab to Ash River, MN through the earth's crust.

Energy (E_ν = 2 GeV)

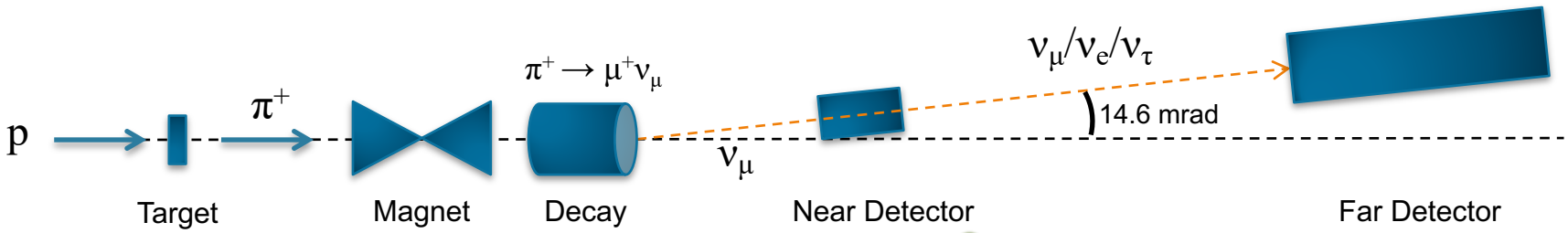
We can achieve a narrowly distributed neutrino energy by placing the detectors 14.6 mrad off the beam axis.

This is also the $\nu_\mu \rightarrow \nu_e$ oscillation peak.

Protons on Target (POT)

13.6×10^{20} POT: neutrino mode

12.5×10^{20} POT: antineutrino mode



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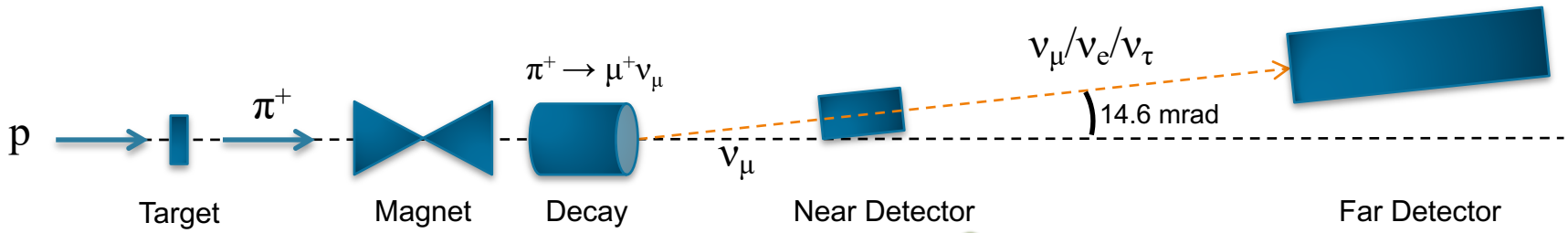

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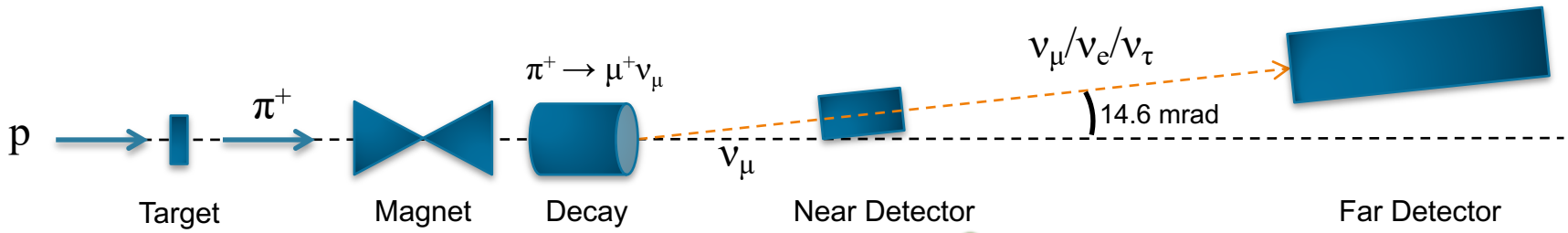

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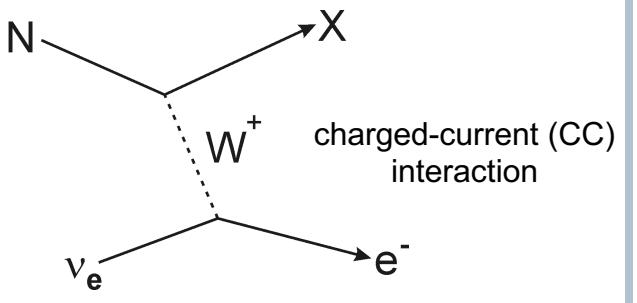
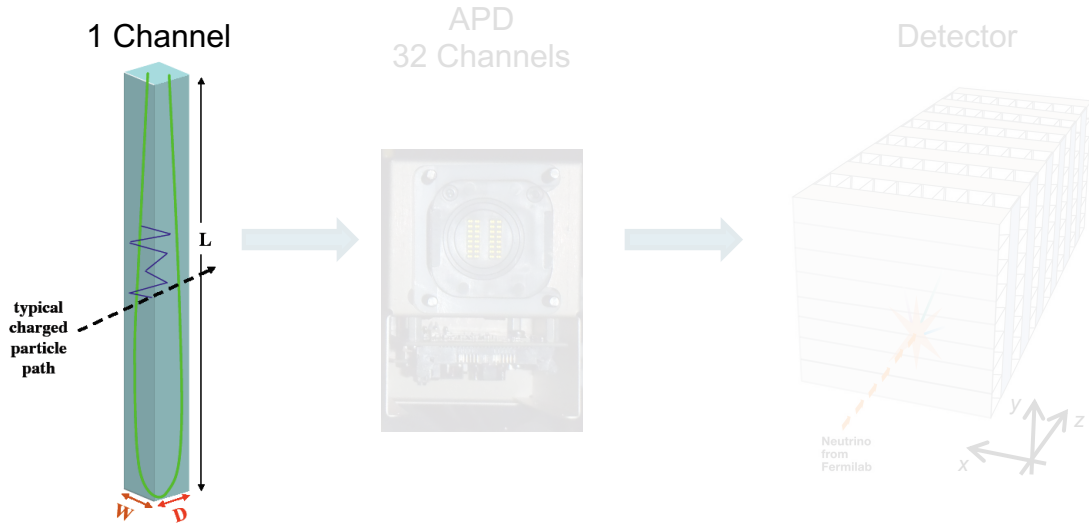
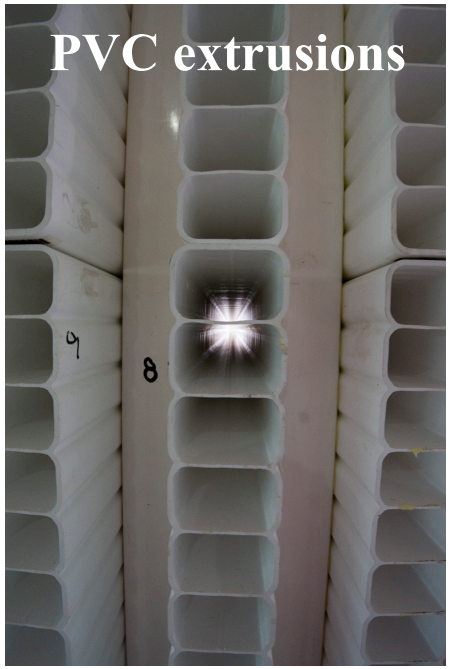


- We want to detect electron neutrinos (ν_e):
  - This requires a large detector mass and good electron identification.
- NOvA is a rectangular tracking calorimeter.
  - low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides many samples per radiation length (differentiate e^- and π^0)
  - each extrusion contains one wavelength-shifting fiber
  - ends of fiber read out by avalanche photo-diode (APD)





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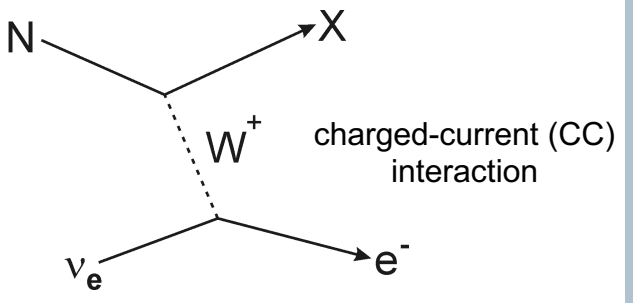

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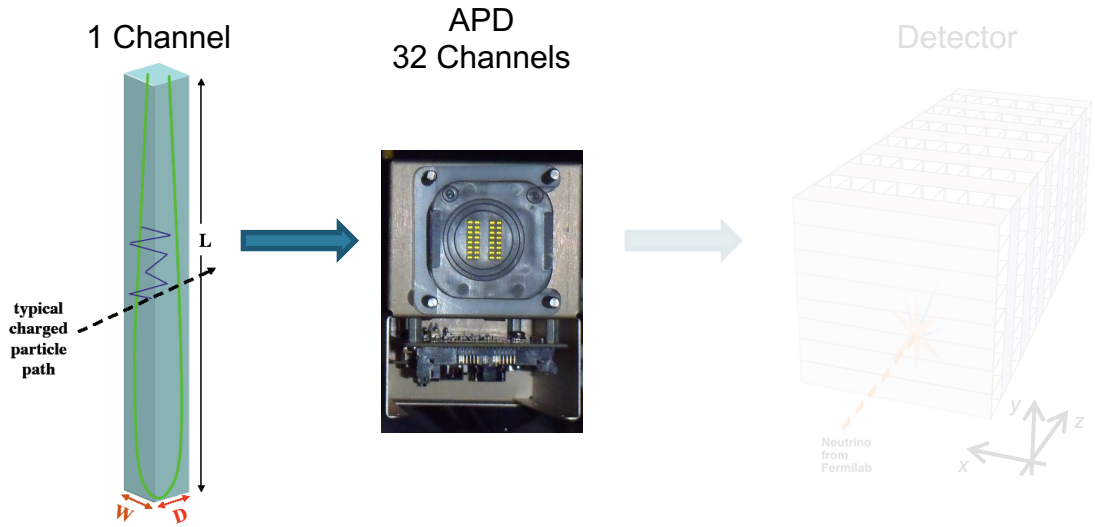

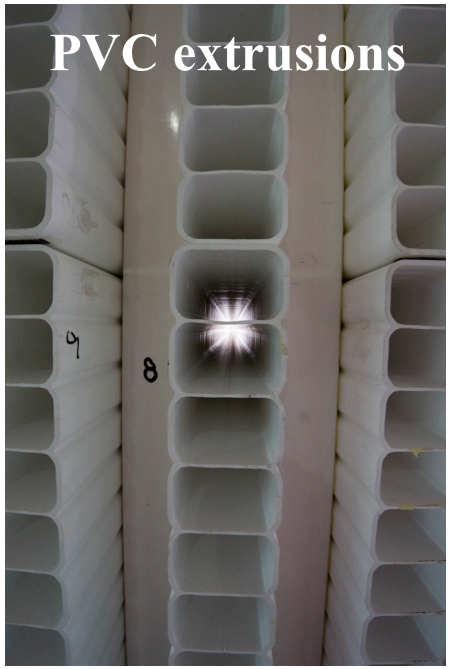

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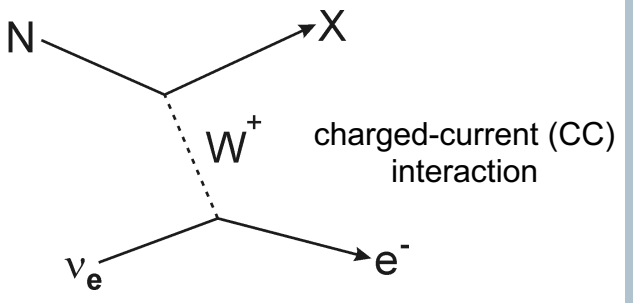

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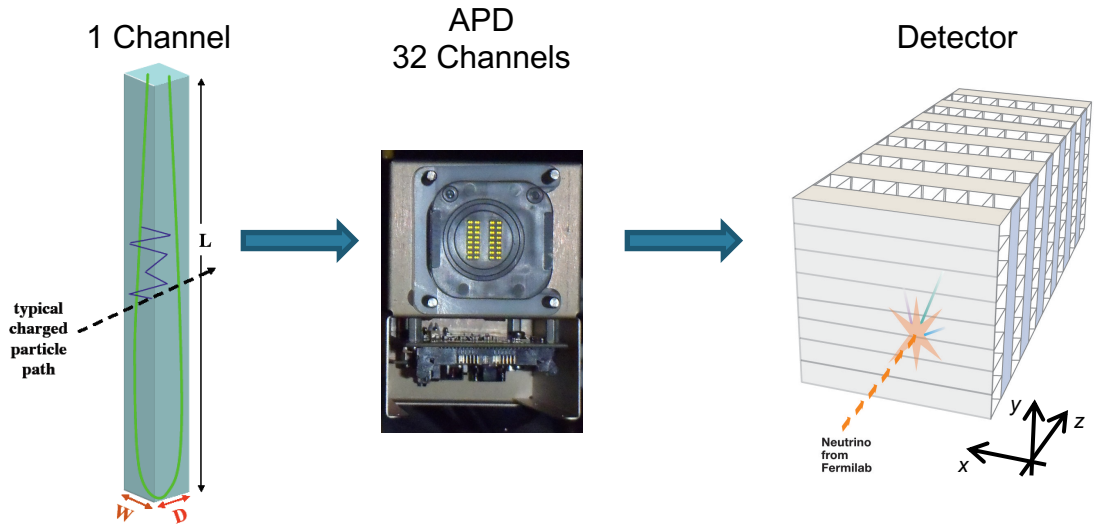
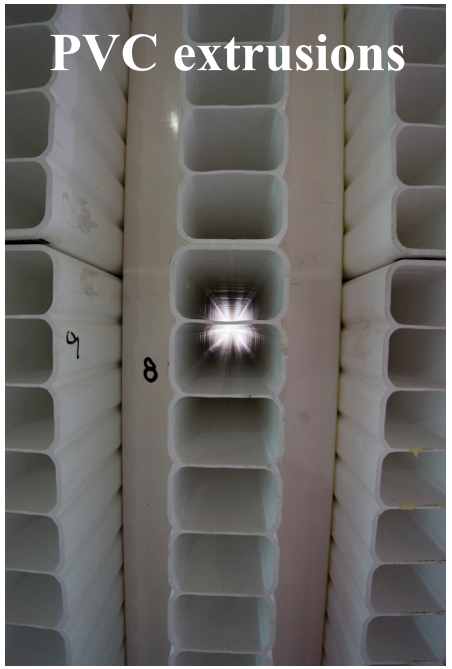
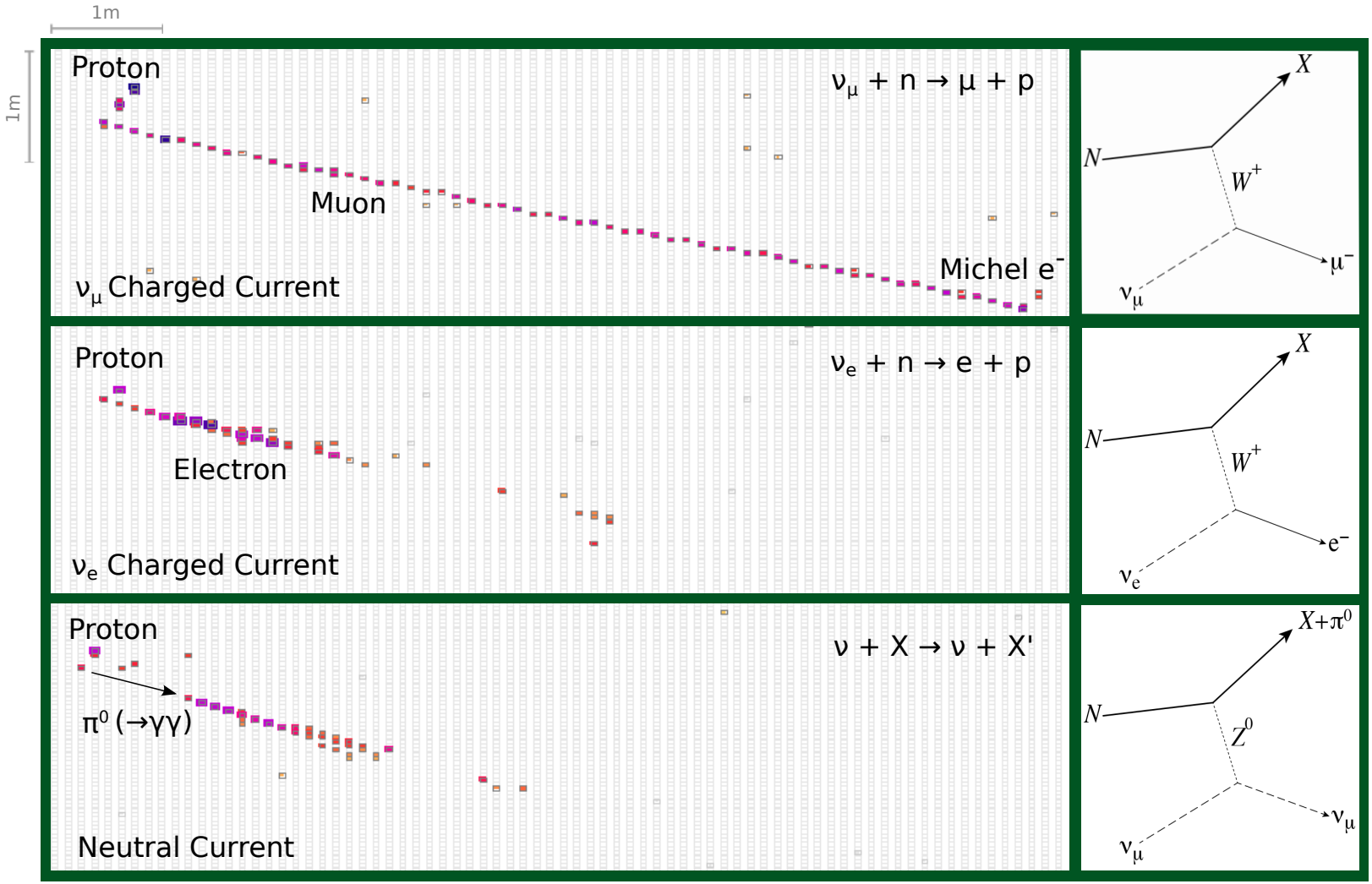
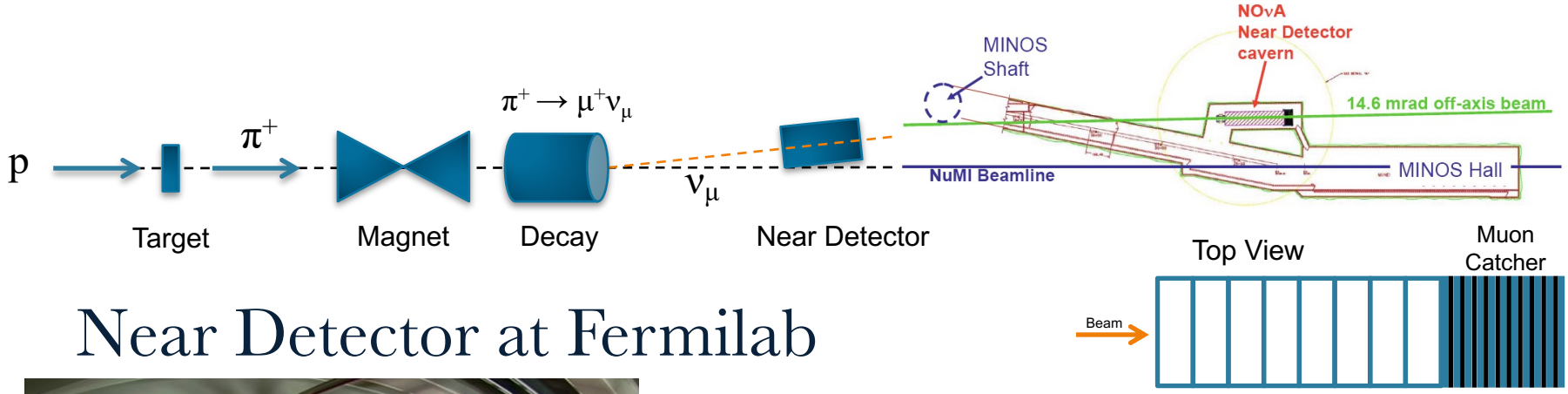


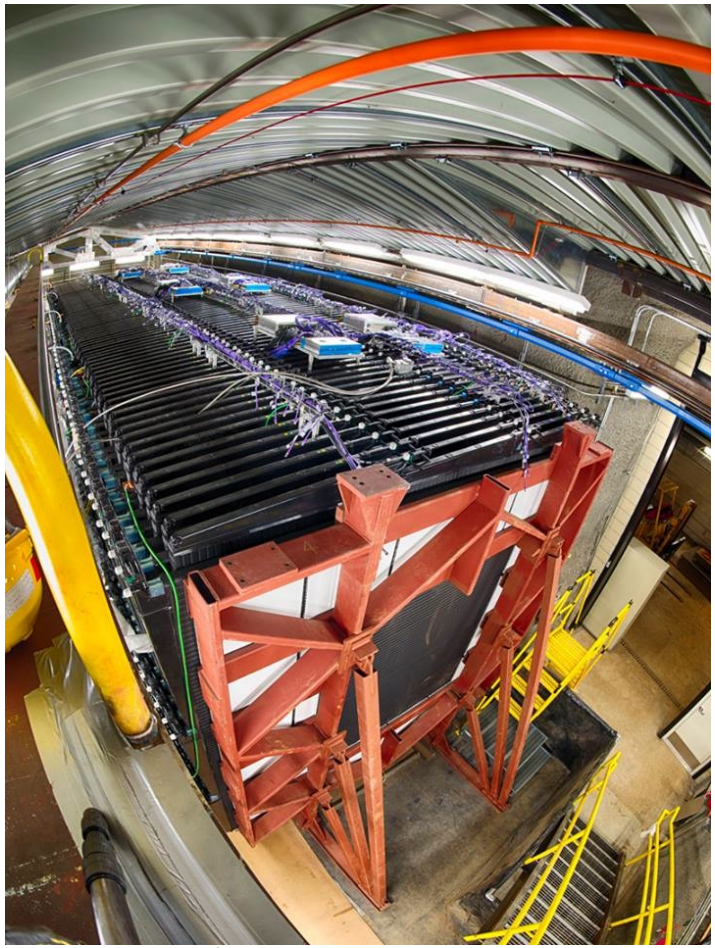


Simulated Event Display

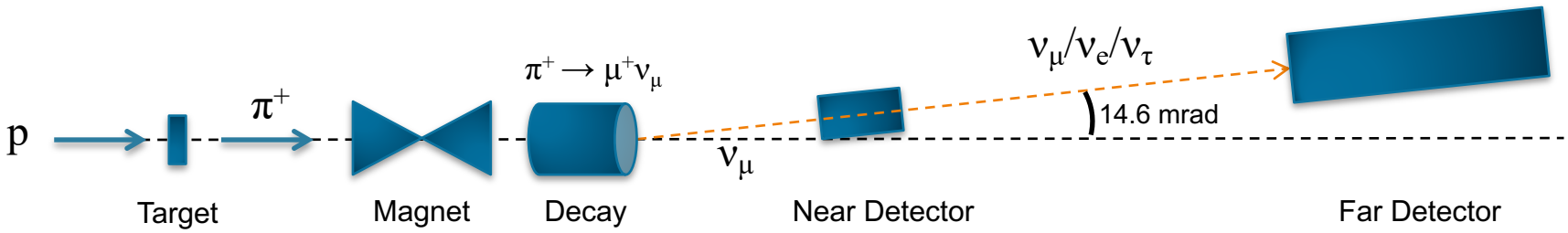




Near Detector at Fermilab



- 1 km downstream from NuMI target
- 105 m underground
- 300 tons
- 4 m × 4 m × 15 m
- Instrumented with 20k channels
- Several neutrino interactions per second
- Few cosmic ray muons per second

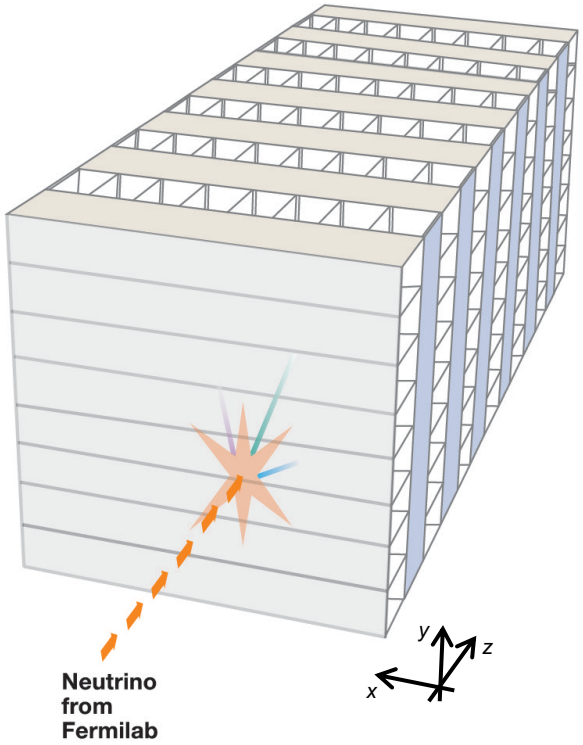


Far Detector in Ash River, MN

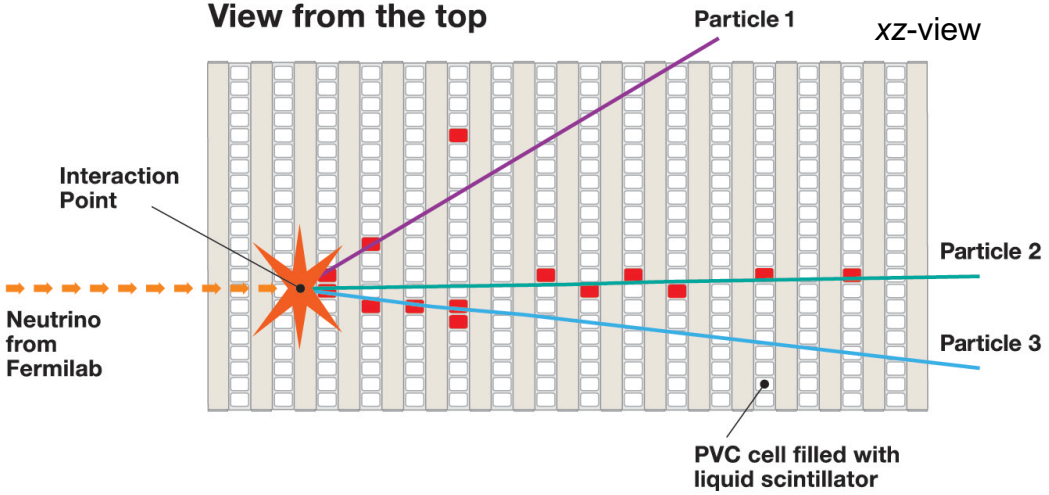
- 810 km downstream from NuMI target
- On the surface
- 14,000 tons
- 15 m × 15 m × 60 m
- Instrumented with 344k channels
- Few neutrino interactions per year
- ~130,000 cosmic ray muons per second

Neutrino Detection

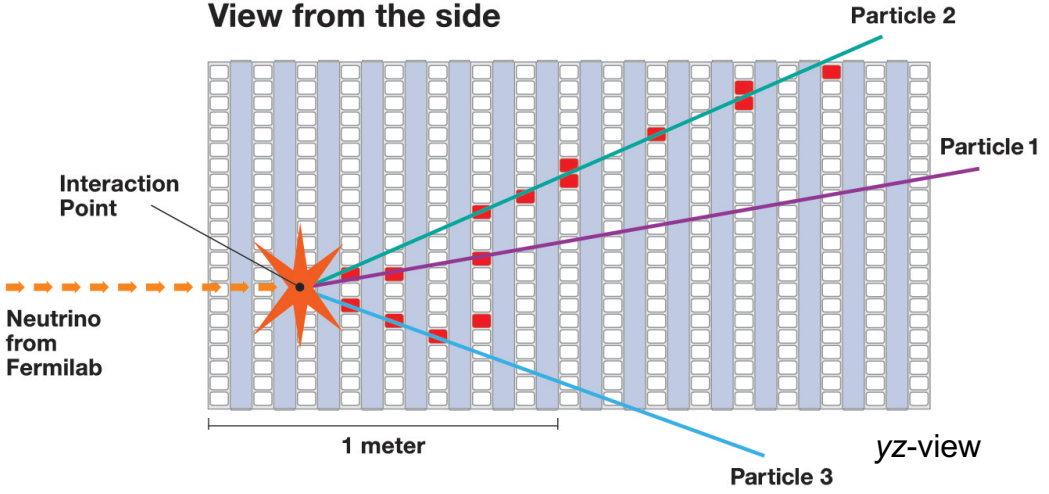
3D schematic of NOvA particle detector



View from the top



View from the side



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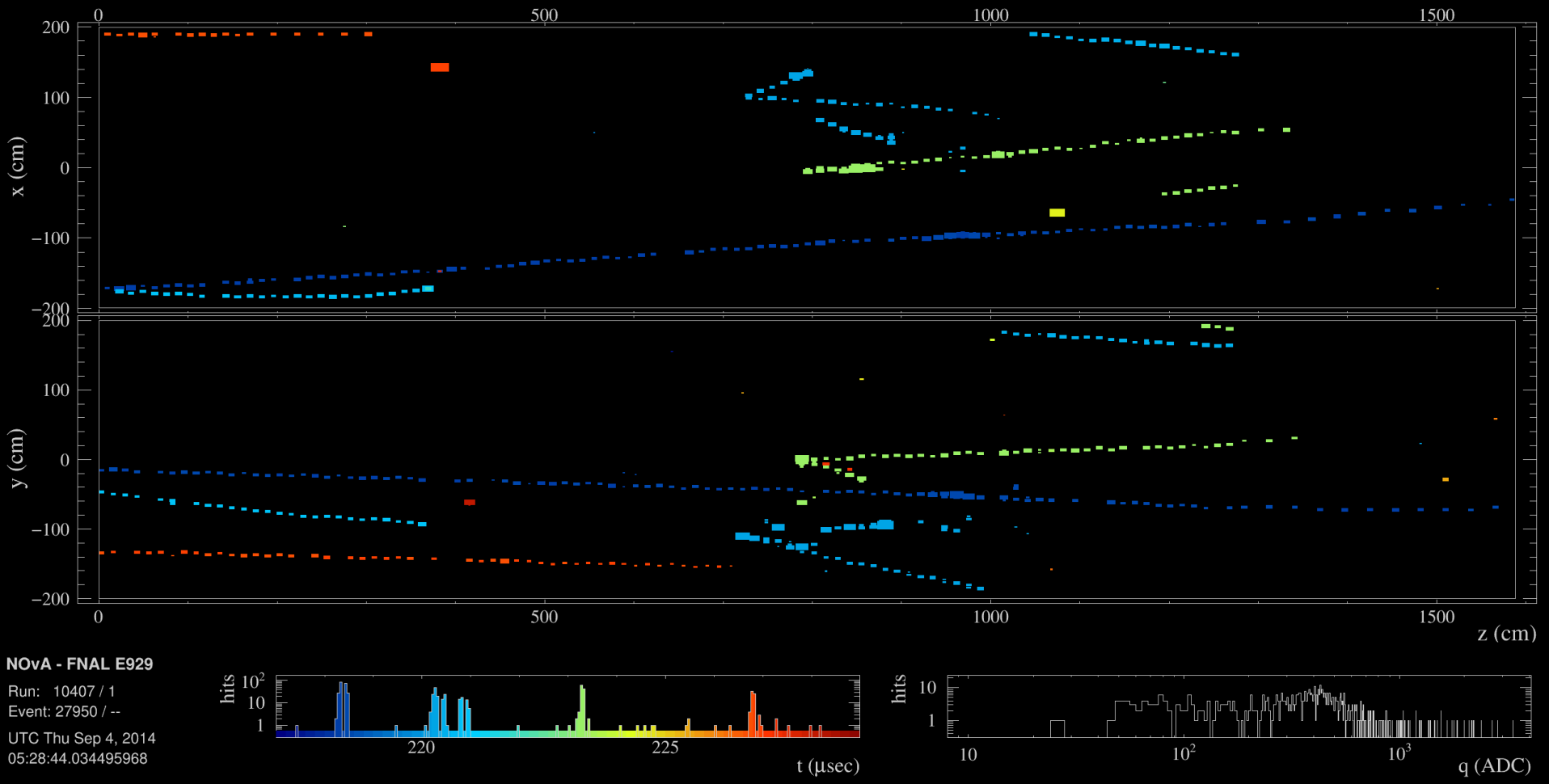

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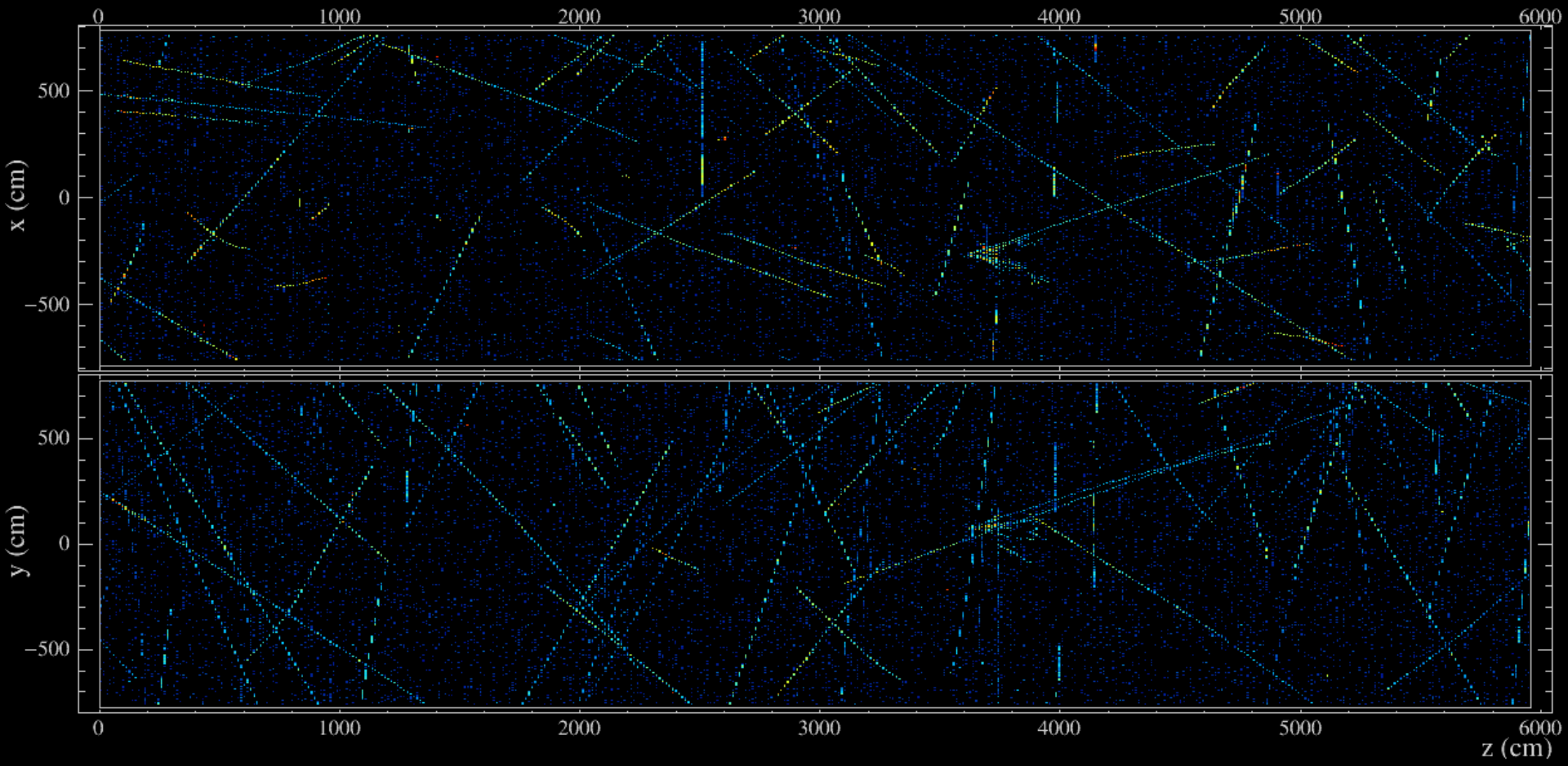
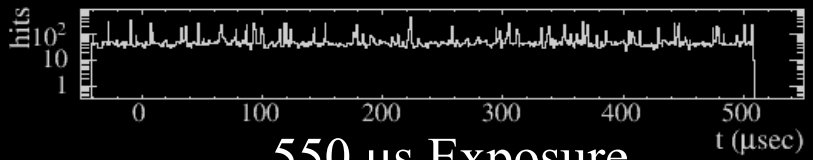
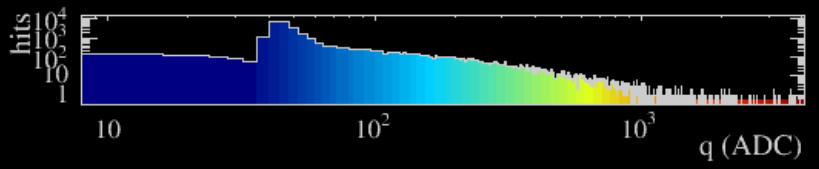


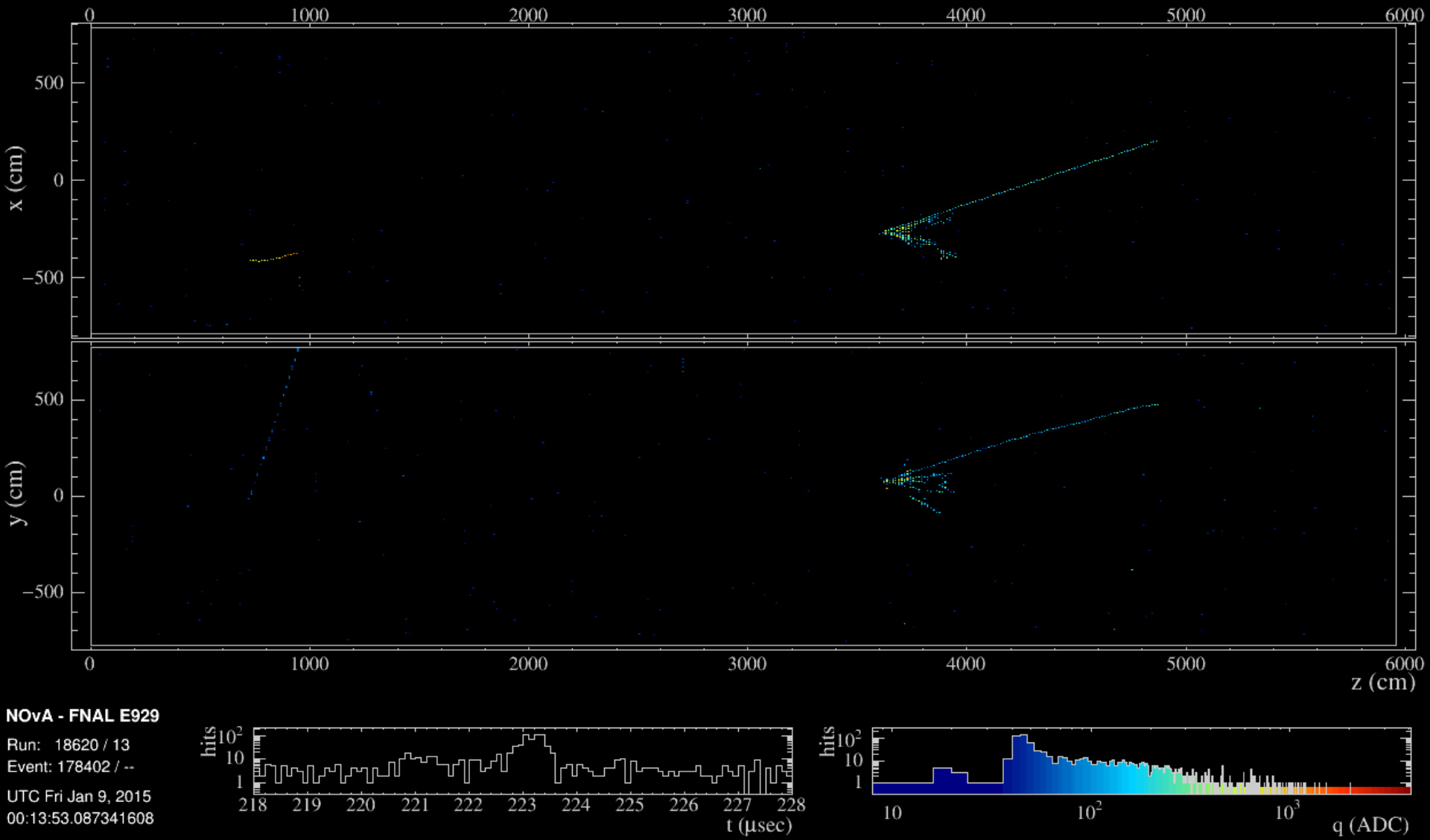
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608





550 μs Exposure

Time Zoom on NuMI Beam Pulse



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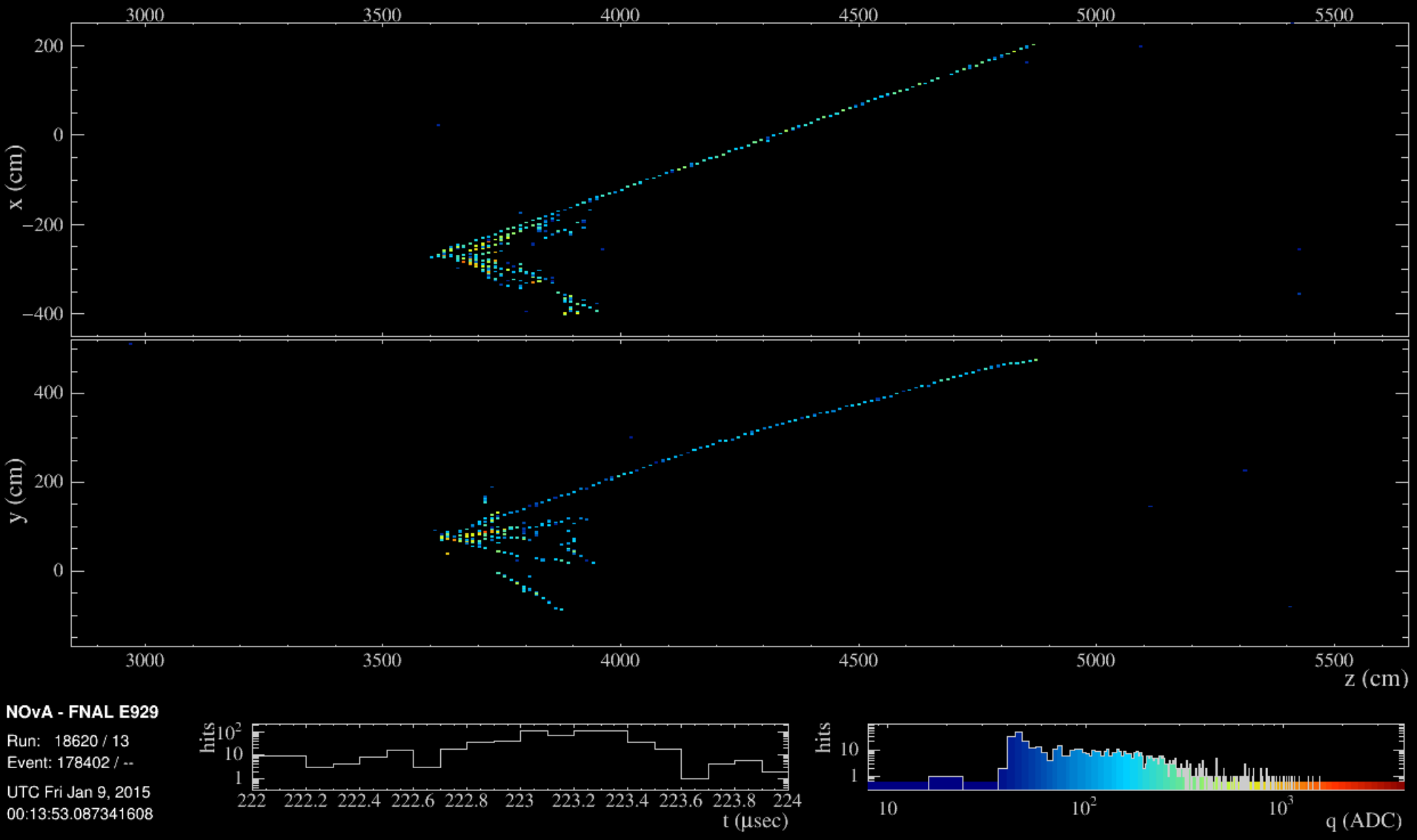
Close-Up of Neutrino Interaction



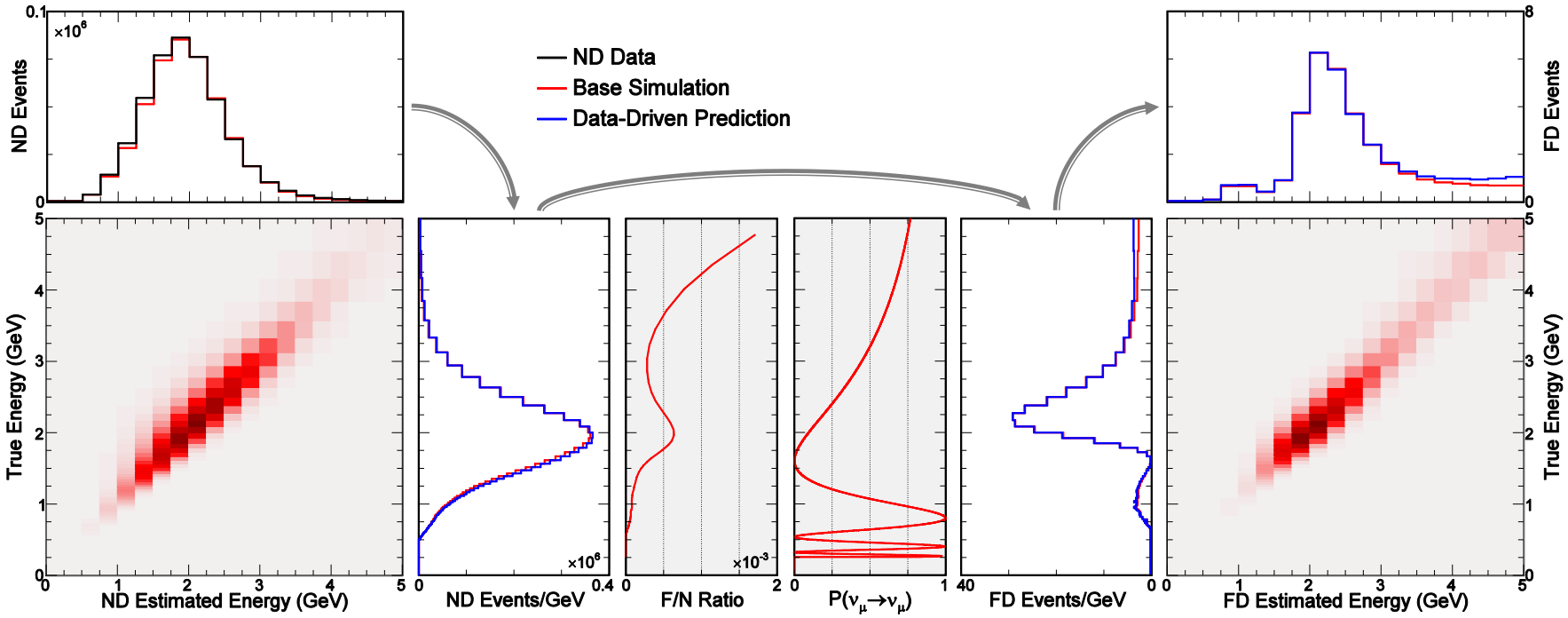
Neutrino Analysis

Alternative statistical treatment

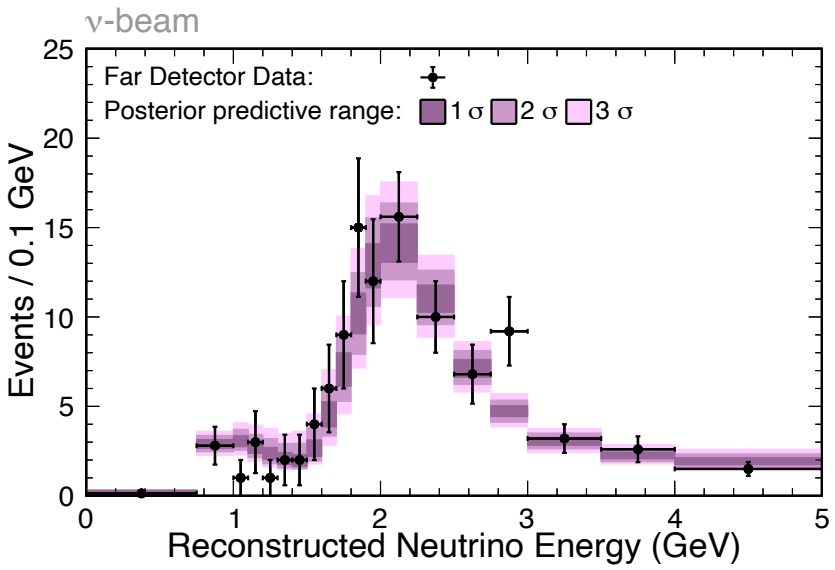
- The neutrino counts are identical to the ones from Phys. Rev. D **106**, 032004 (2022).
  - Frequentist measurement with Feldman-Cousins corrections
- We re-analyzed this data using a Bayesian Markov Chain Monte Carlo.
  - Expand measured neutrino oscillation parameters
  - Direct θ_{13} determination using NOvA only
  - Measure Jarlskog invariant (CP-violation parameter)
- Some vocabulary:
  - Prior: assumed probability distribution of input
  - Posterior: probability distribution of desired output

Far Detector Neutrino Prediction

- We use a data-driven technique to extrapolate the neutrino events in the near detector to the far detector:
  1. Estimate true energy distribution of near detector events
  2. Multiply by expected far/near event ratio and oscillation probability
  3. Convert far detector true energy into reconstructed energy

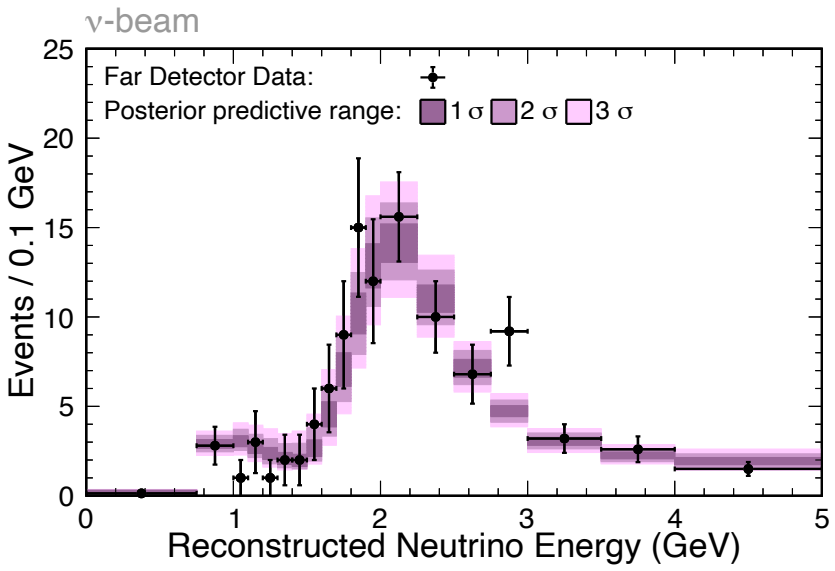


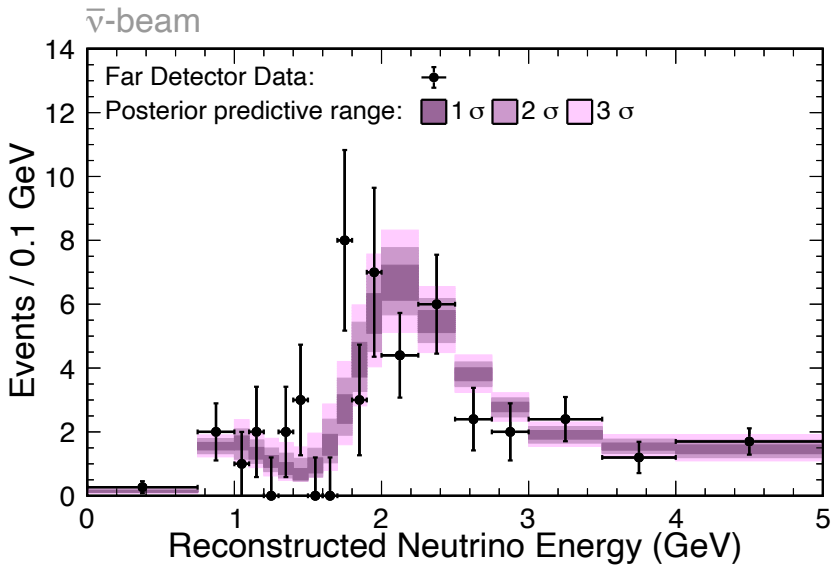
Muon Neutrino Events



- Muon neutrino event counts
- Neutrino beam (left) – 13.6 x 10^{20} POT
- Antineutrino beam (right) – 12.5 x 10^{20} POT
- Note the dip in the energy spectrum indicating the disappearance of muon neutrinos

Muon Neutrino Events





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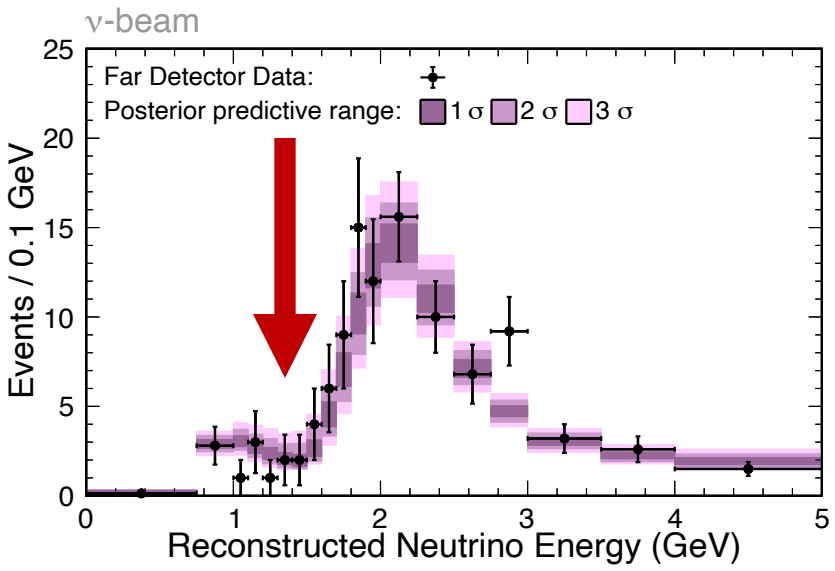

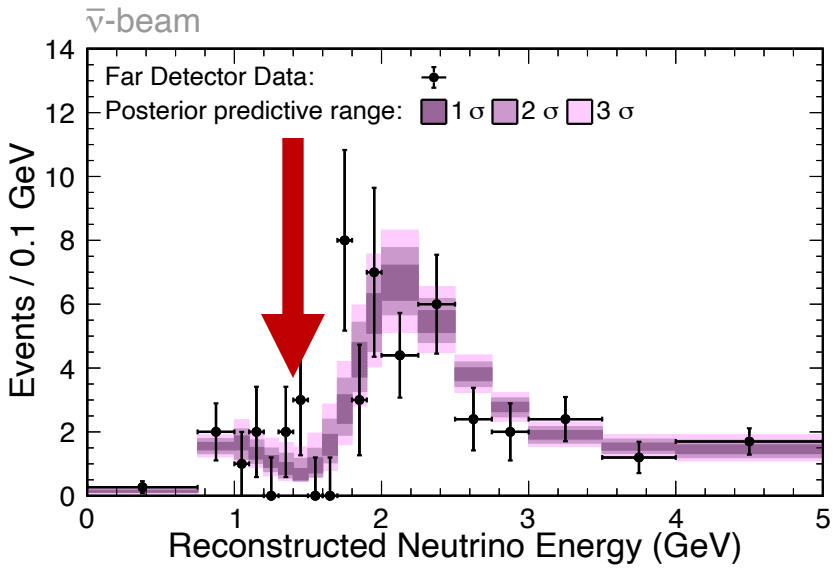

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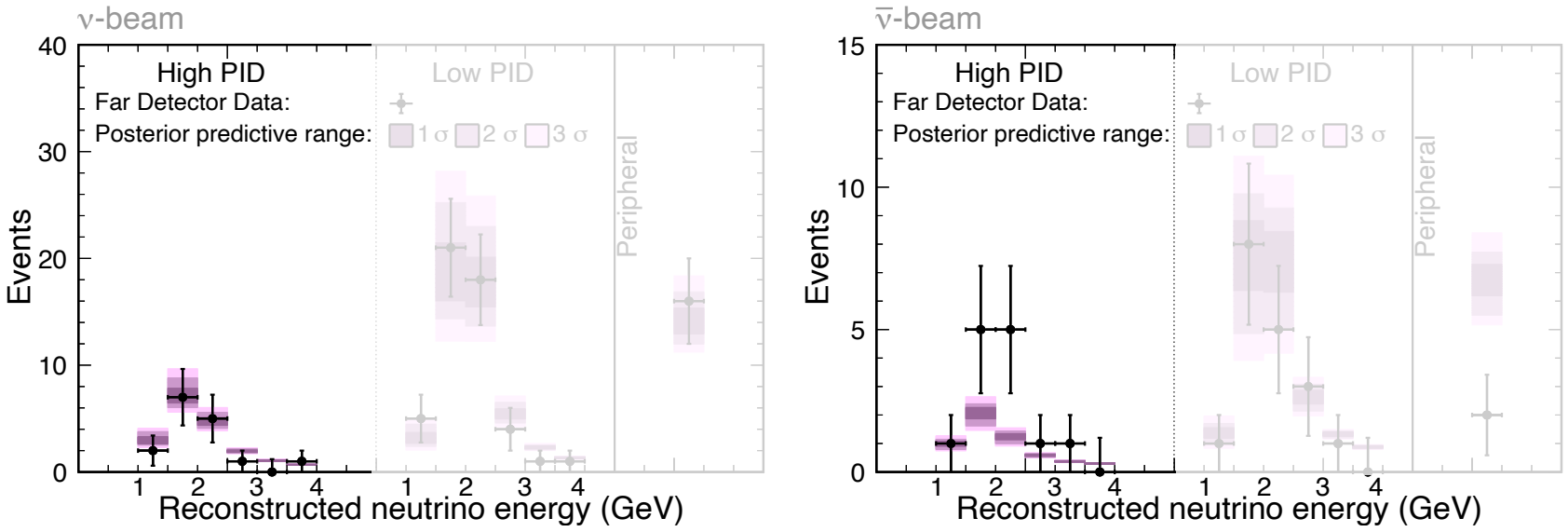
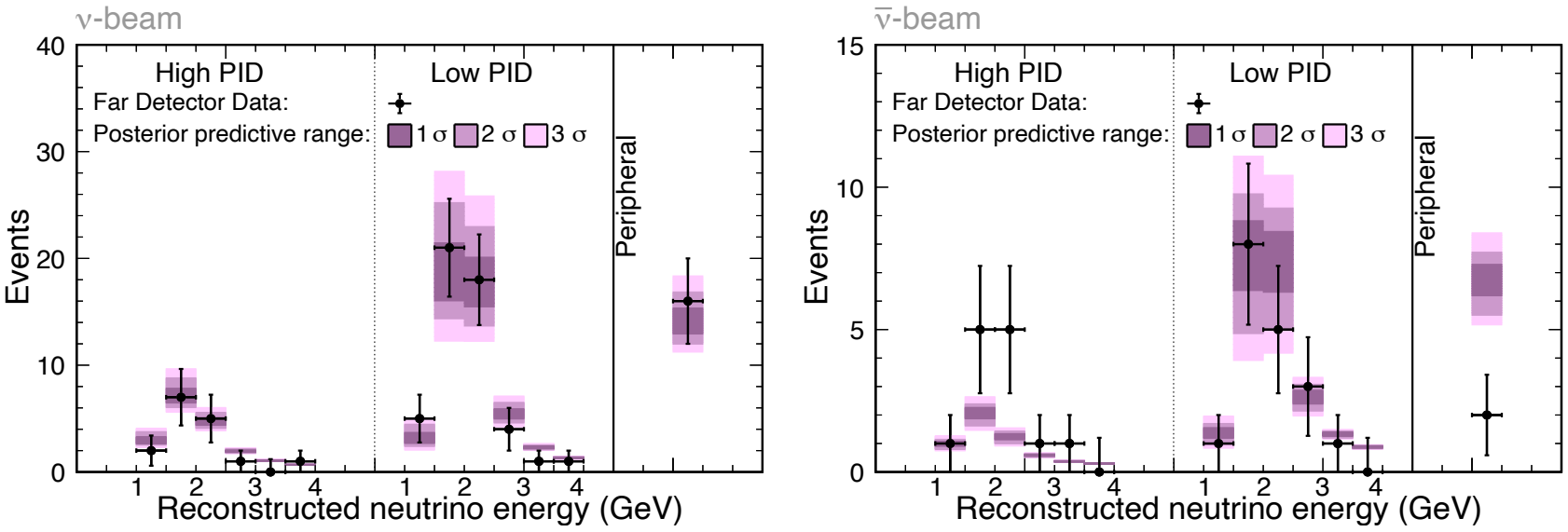
Electron Neutrino Events



- Electron neutrino event counts
- Neutrino beam (left) – 13.6 x 10^{20} POT
- Antineutrino beam (right) – 12.5 x 10^{20} POT
- Samples divided into three Particle ID (PID) categories:
  - High, Low, Peripheral

Electron Neutrino Events



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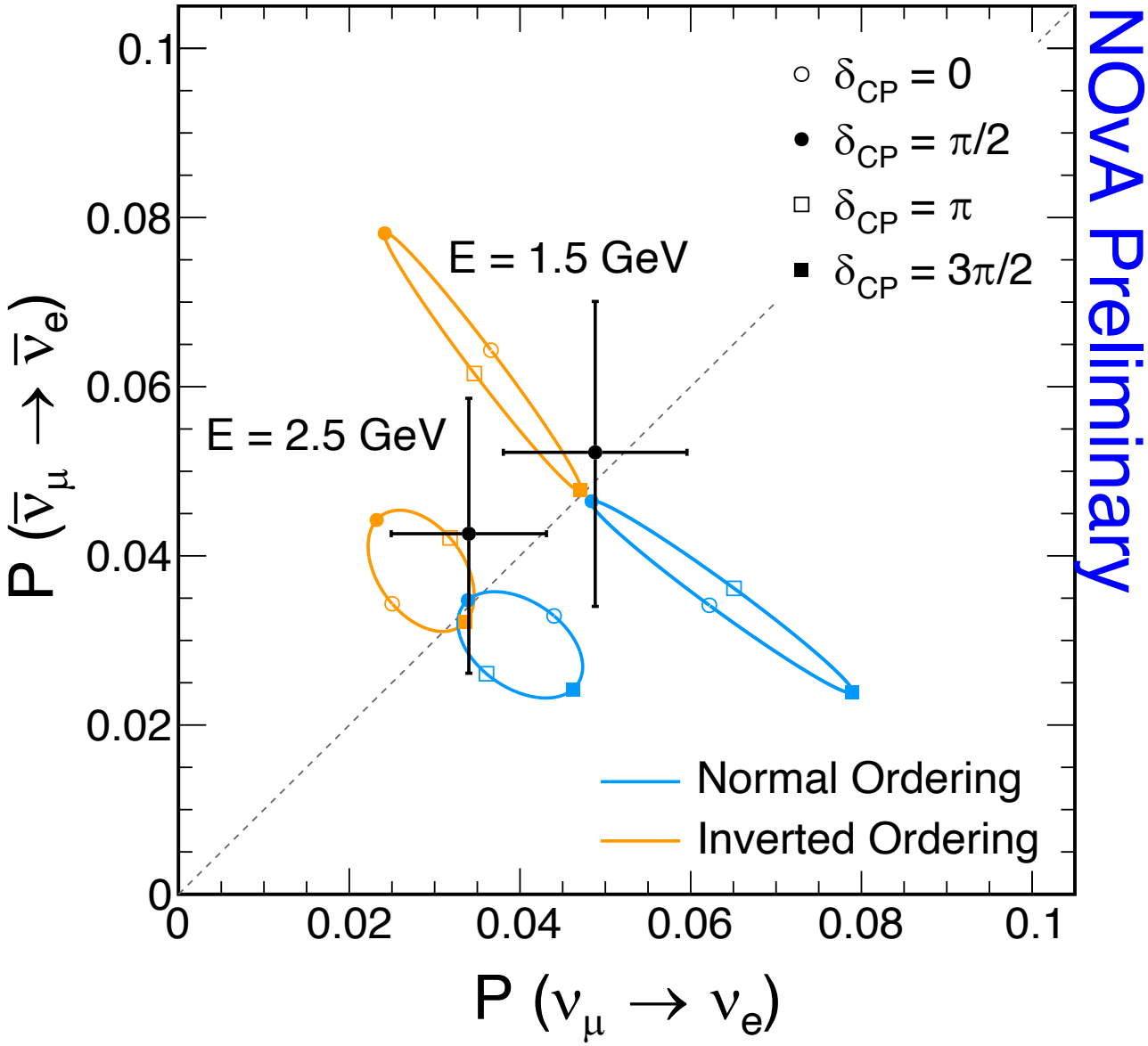
Extract Nature's Parameters



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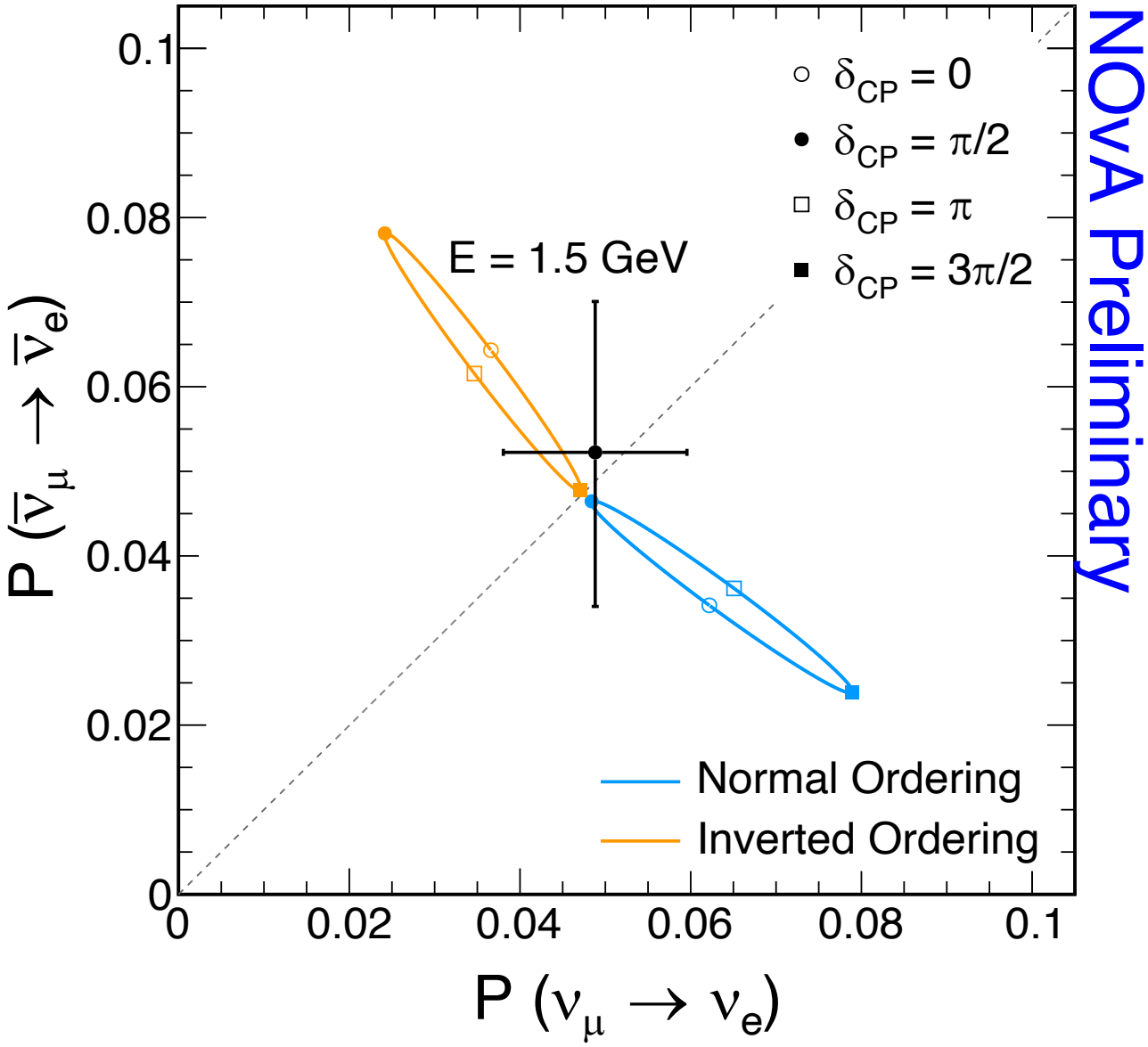

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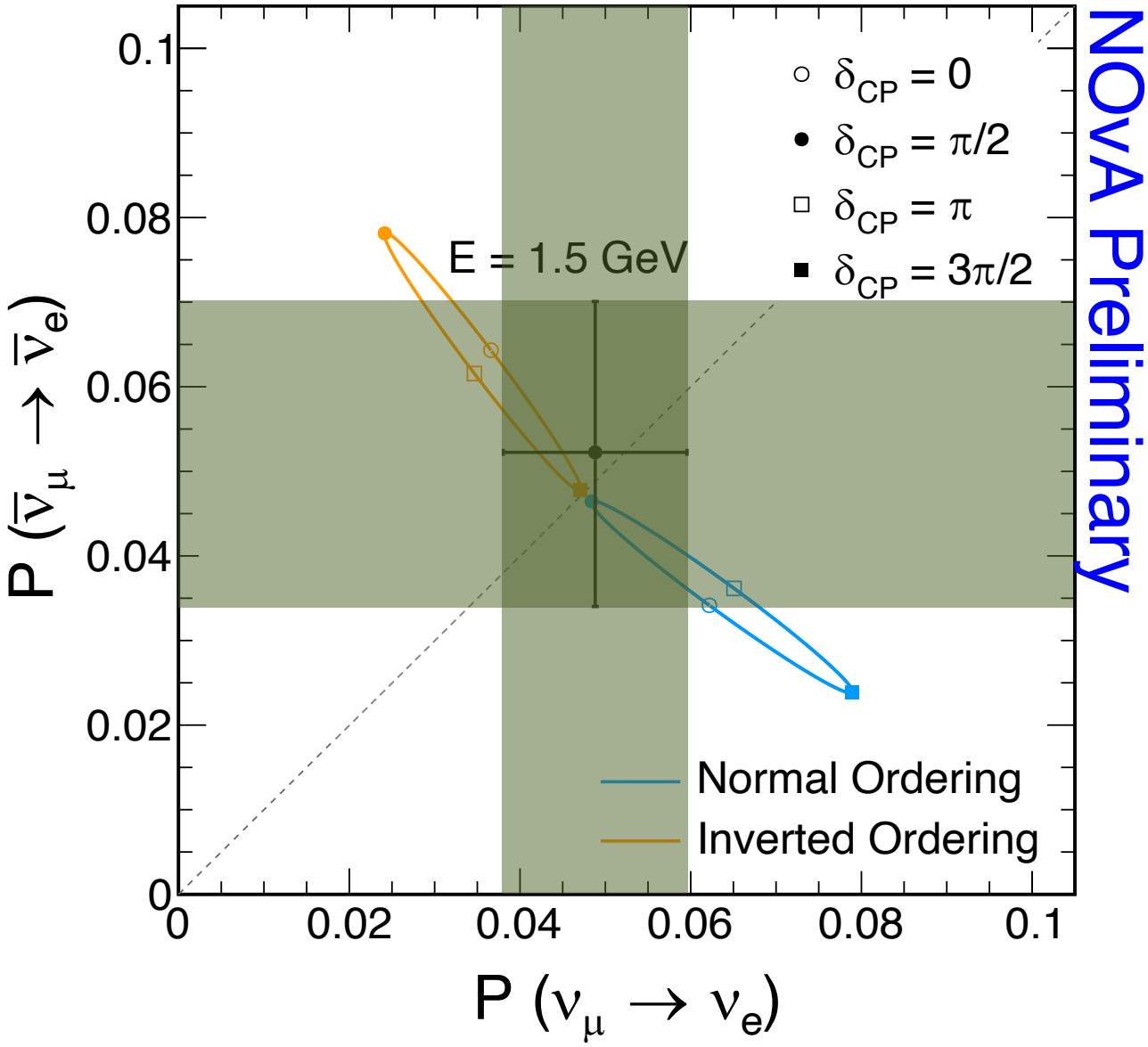
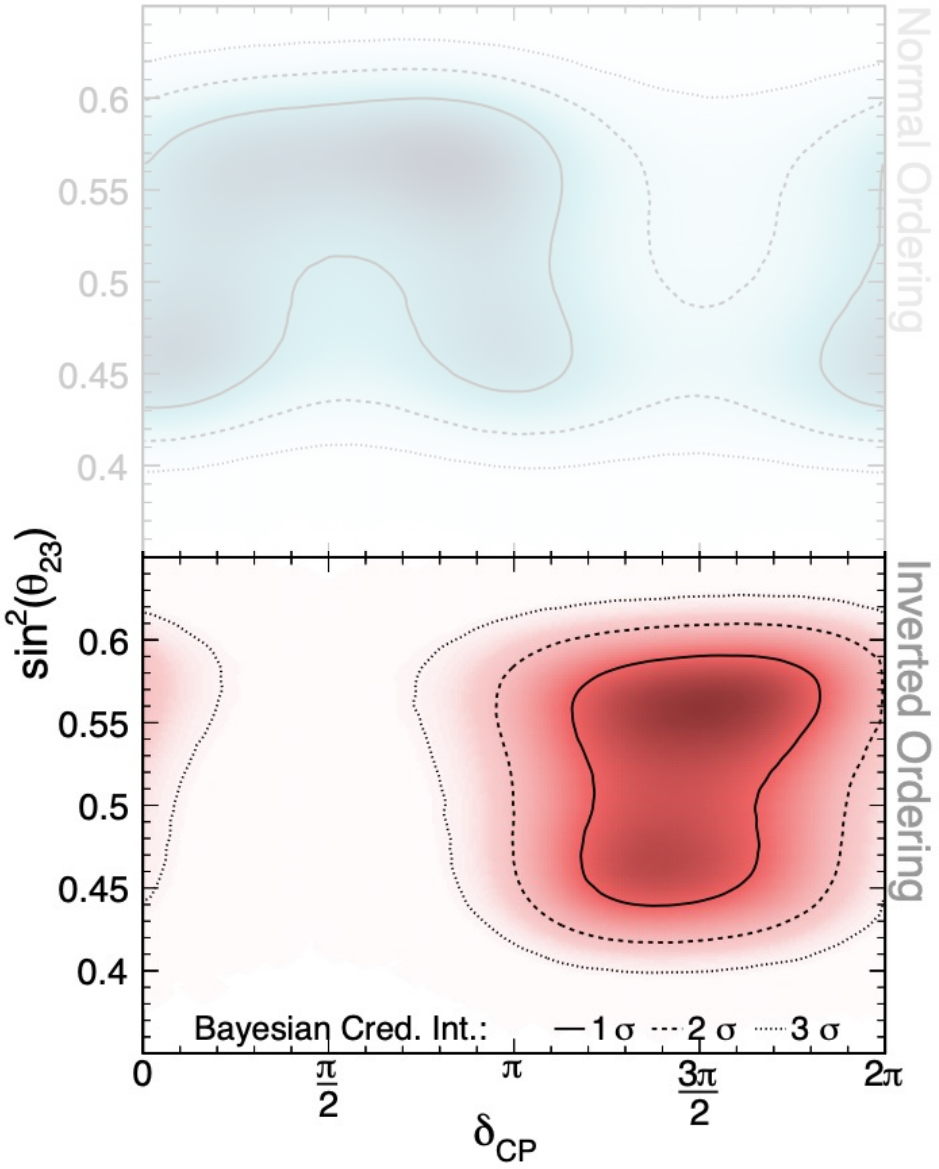


Extract Nature's Parameters

- Weak preference for normal ordering
- Weak preference for upper octant of θ_{23}



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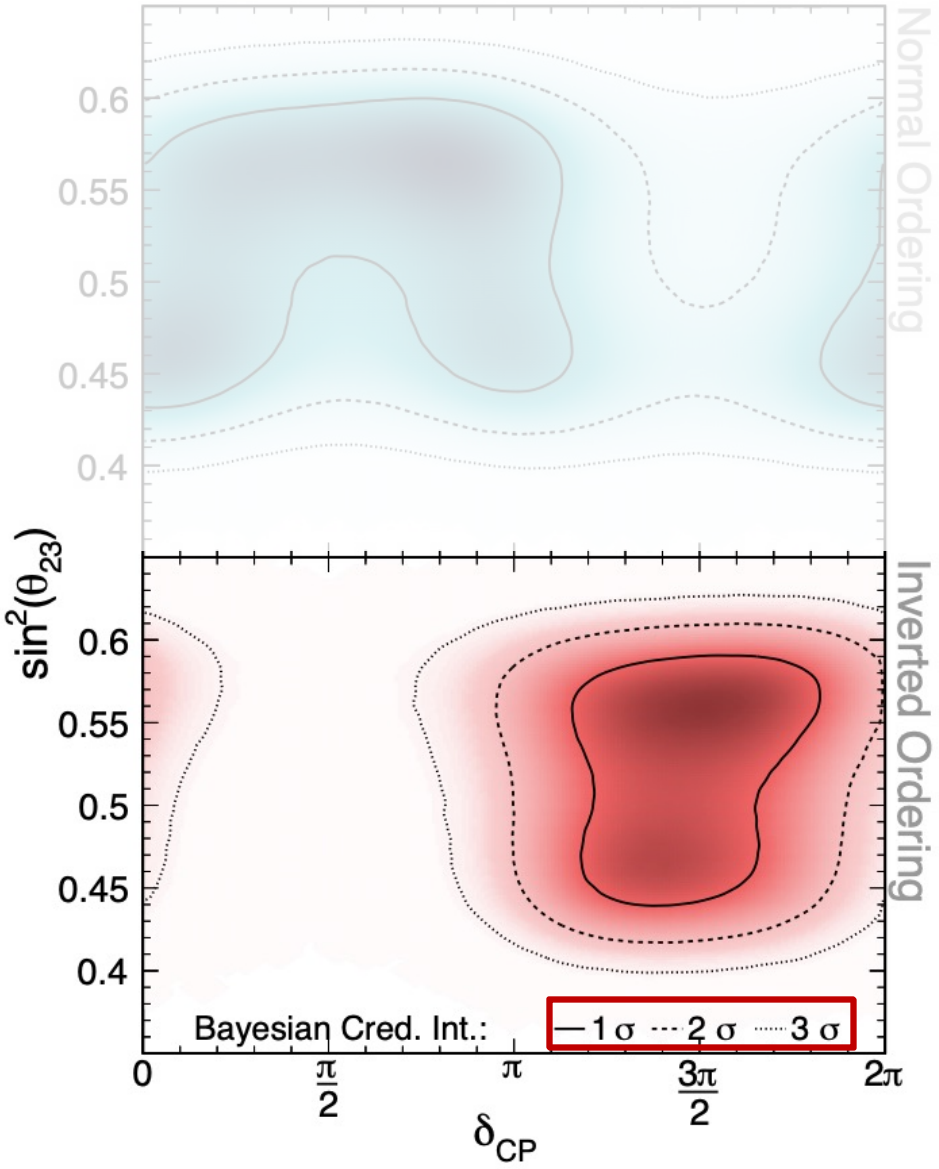

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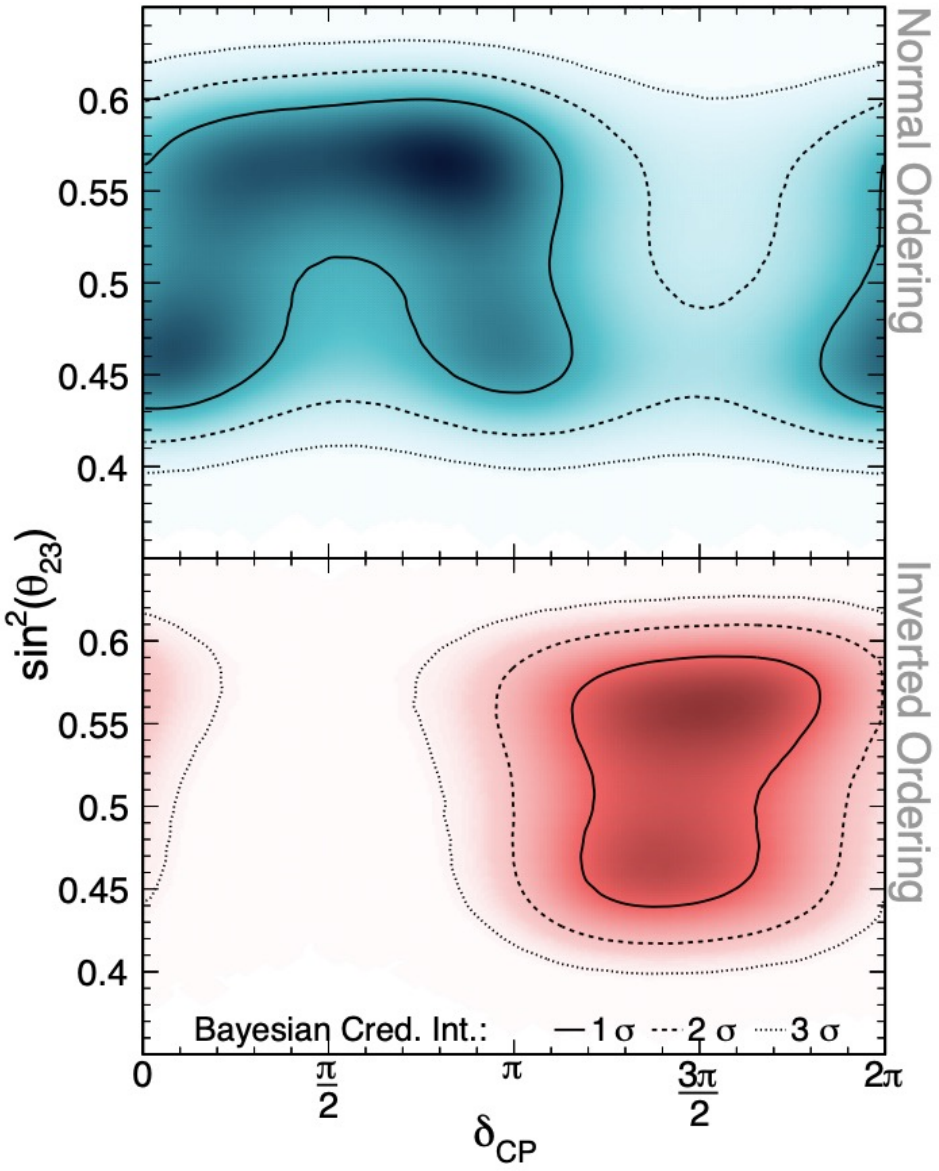

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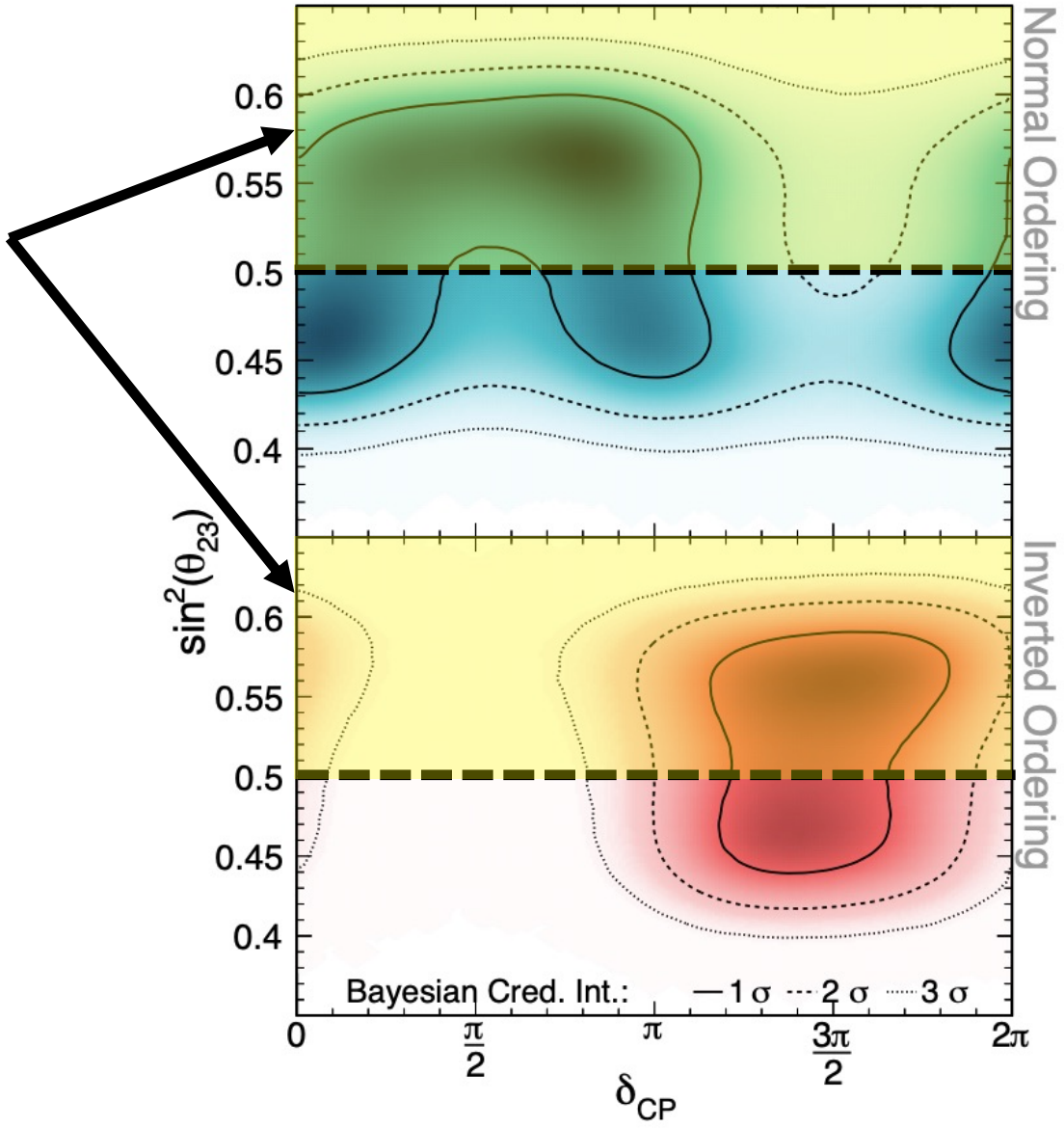

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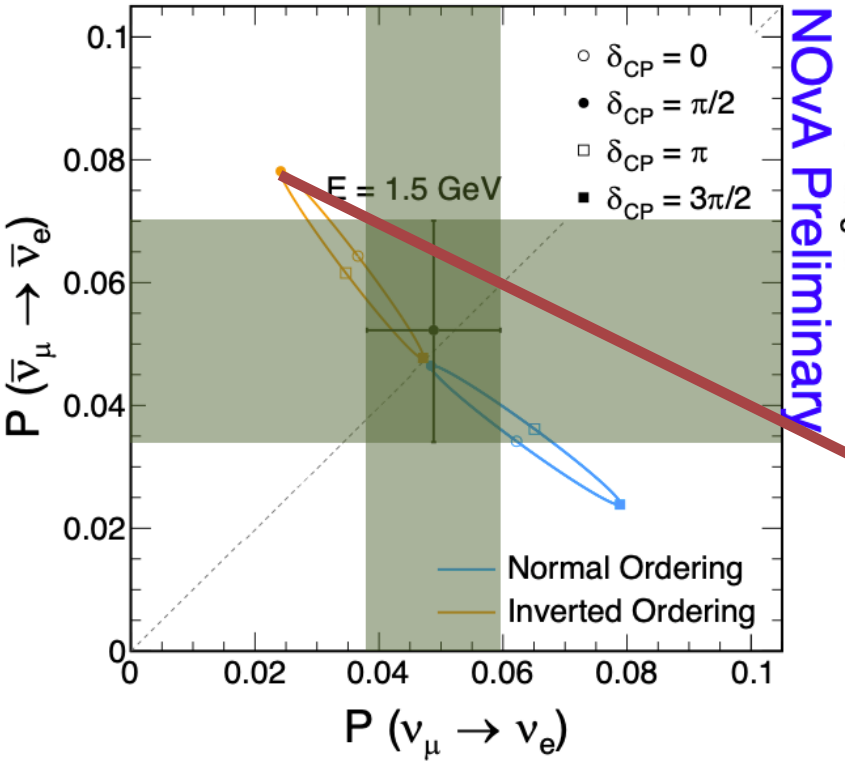

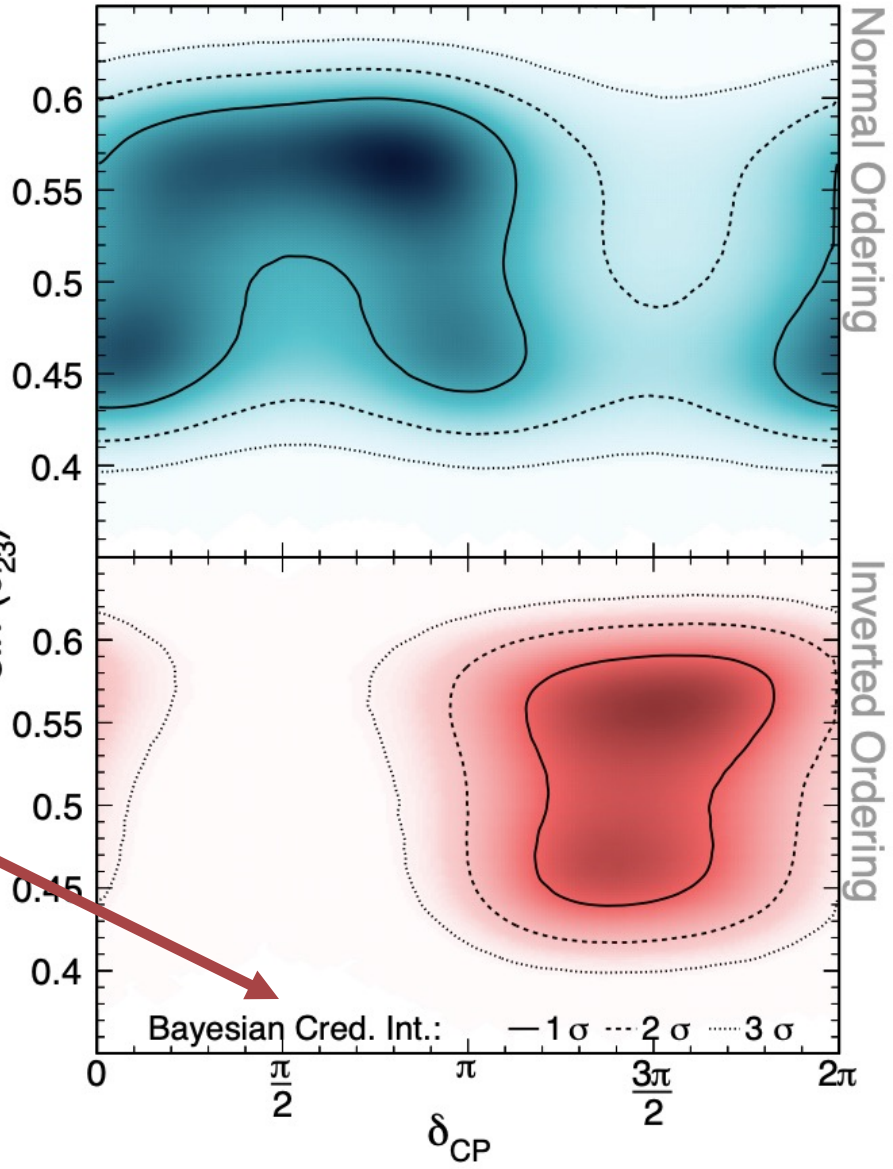

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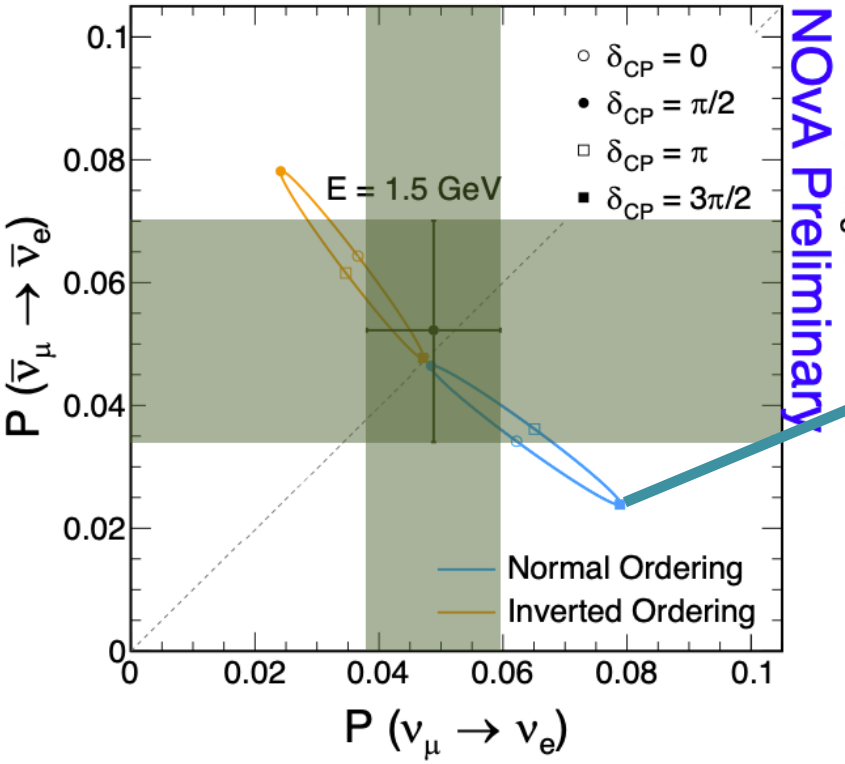
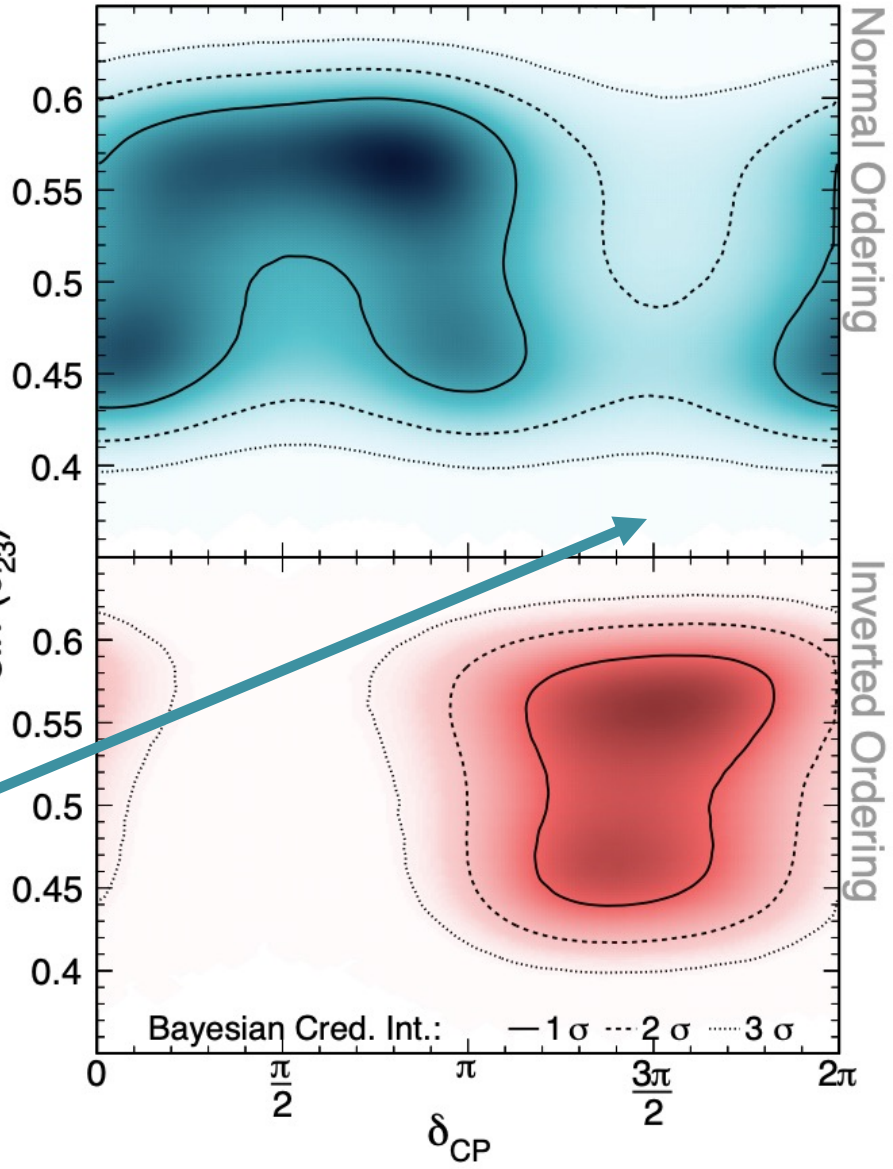
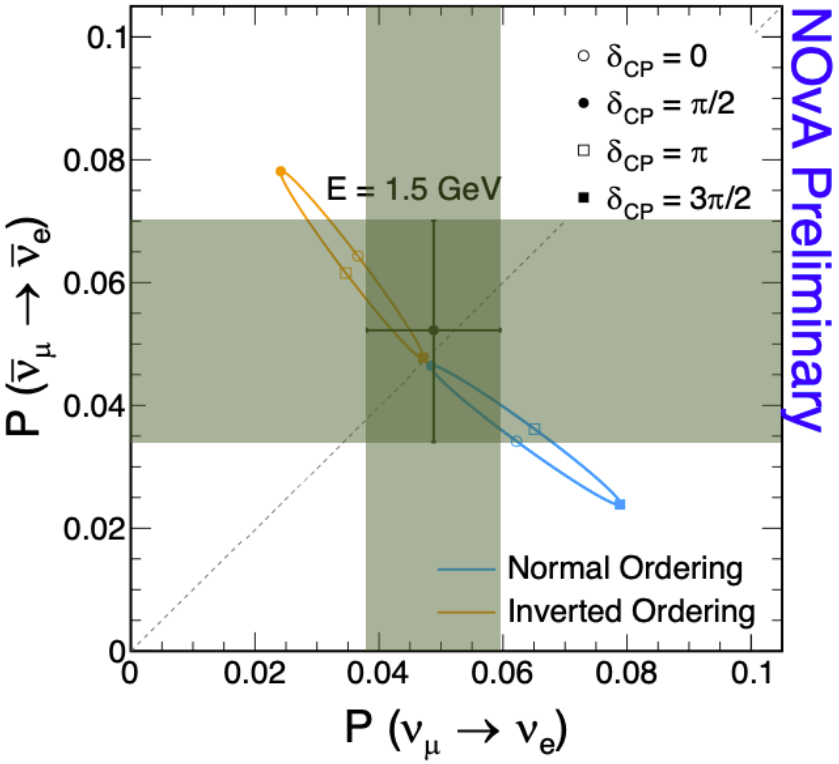


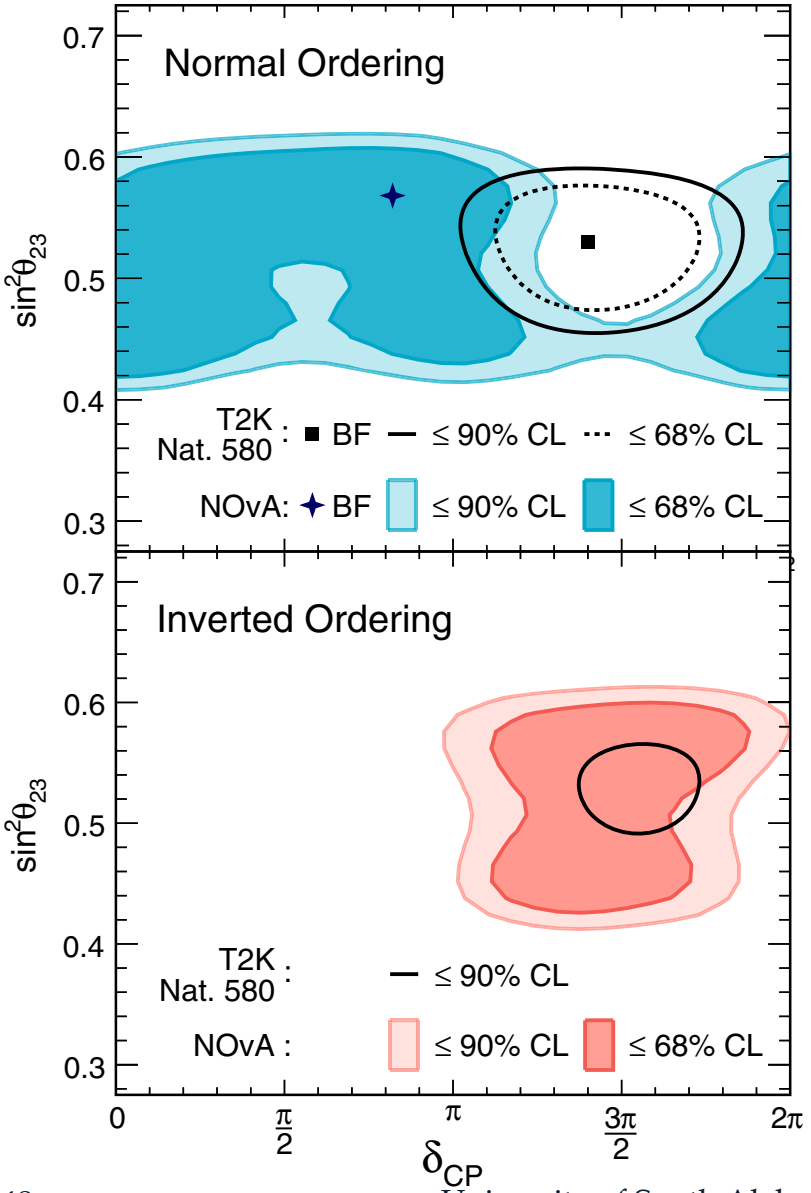
NOvA Preliminary



Extract Nature's Parameters

- Same conclusion as 2022 frequentist analysis





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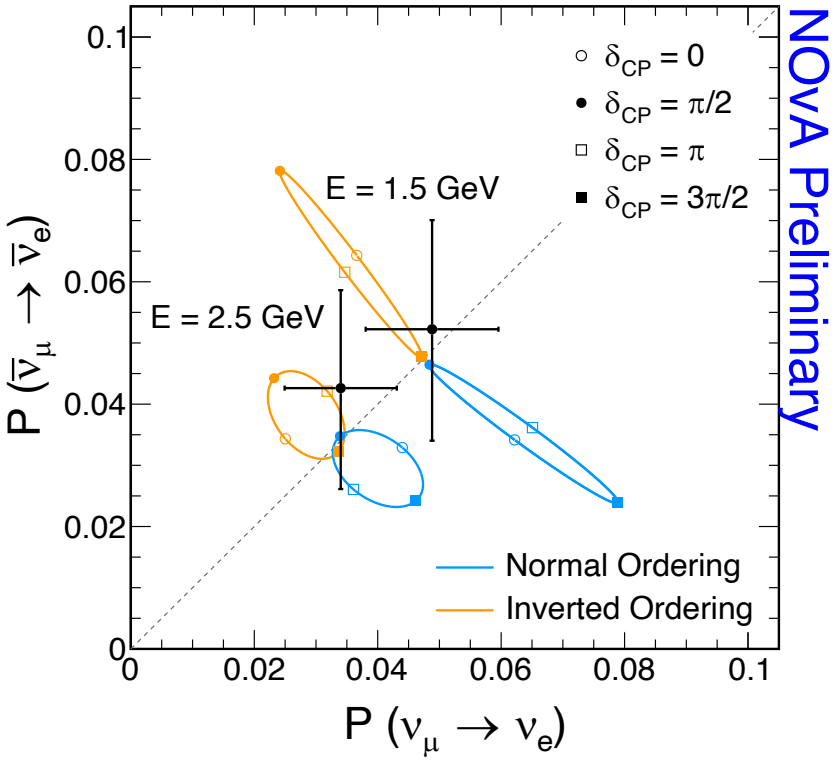
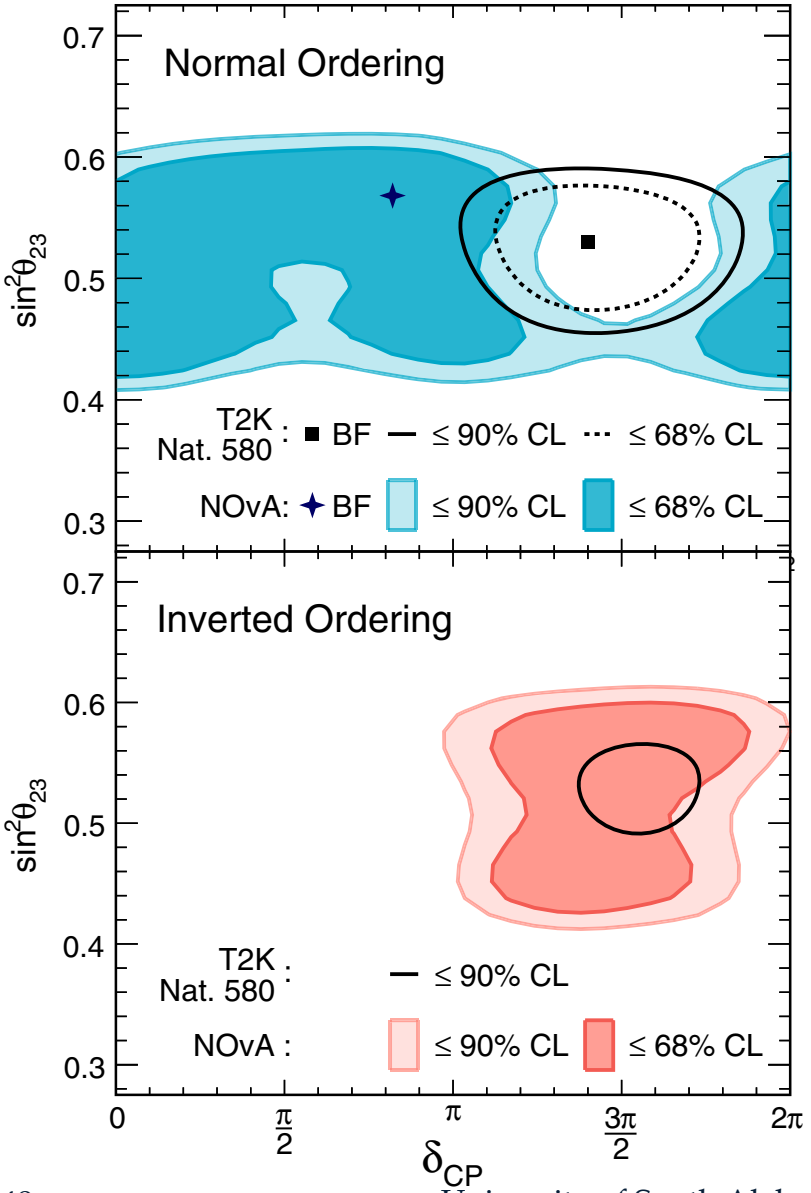
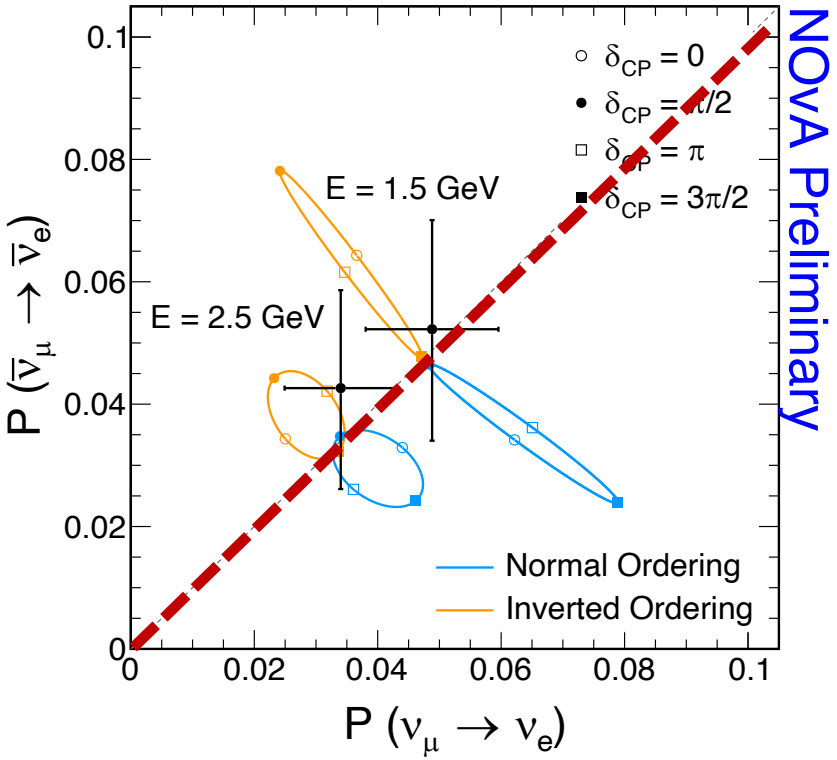
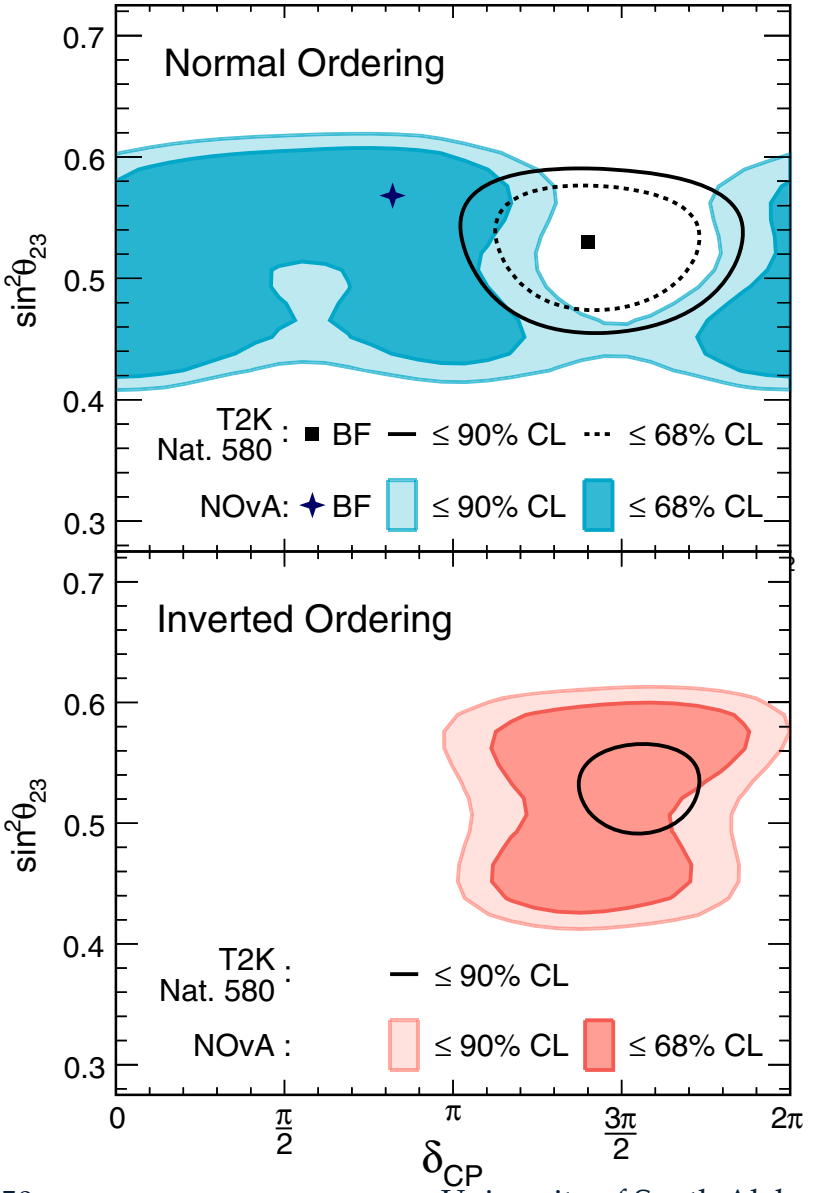




Extract Nature's Parameters

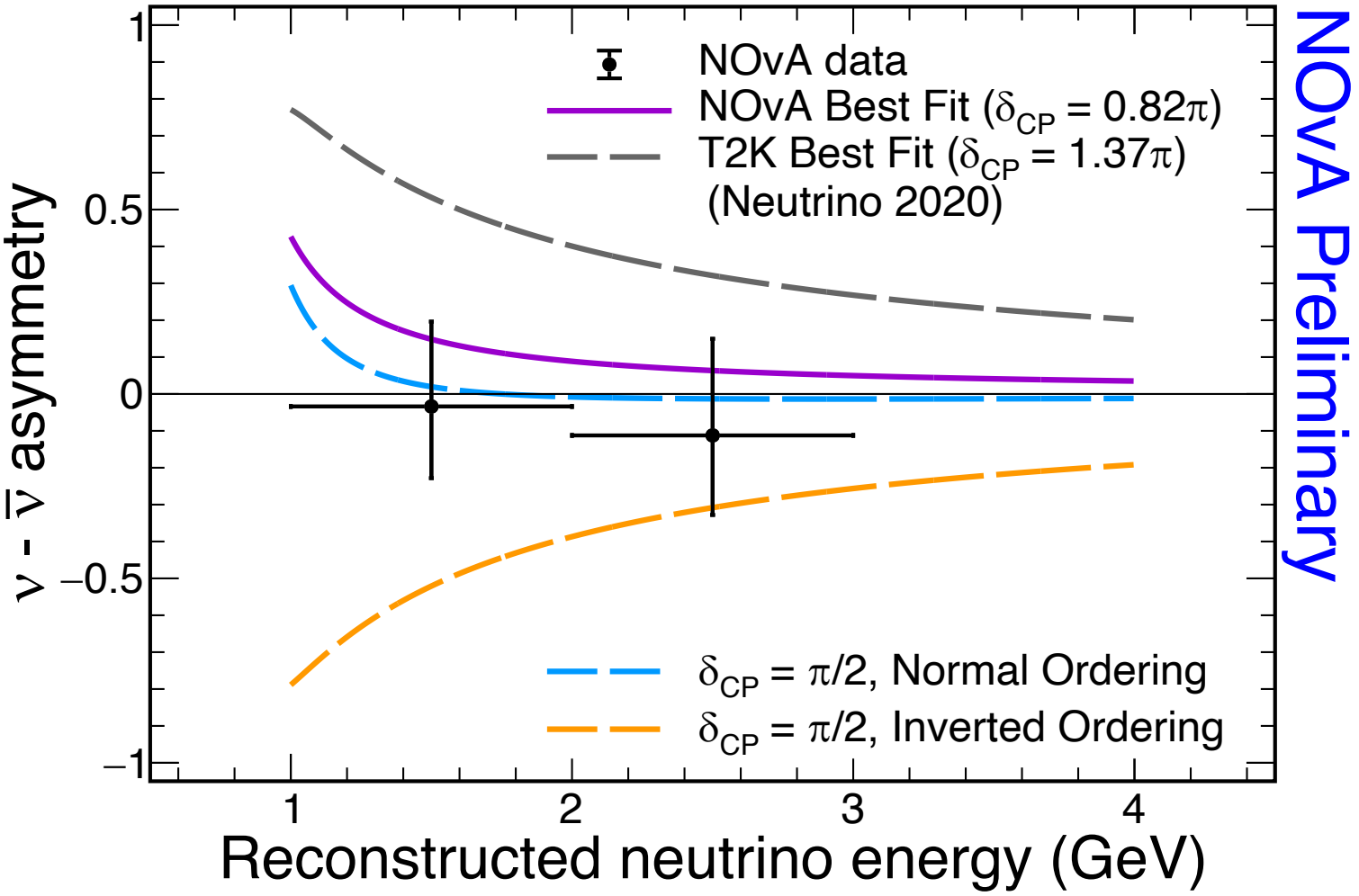
- Same conclusion as 2022 frequentist analysis
- Neutrino-antineutrino asymmetry





Extract Nature's Parameters

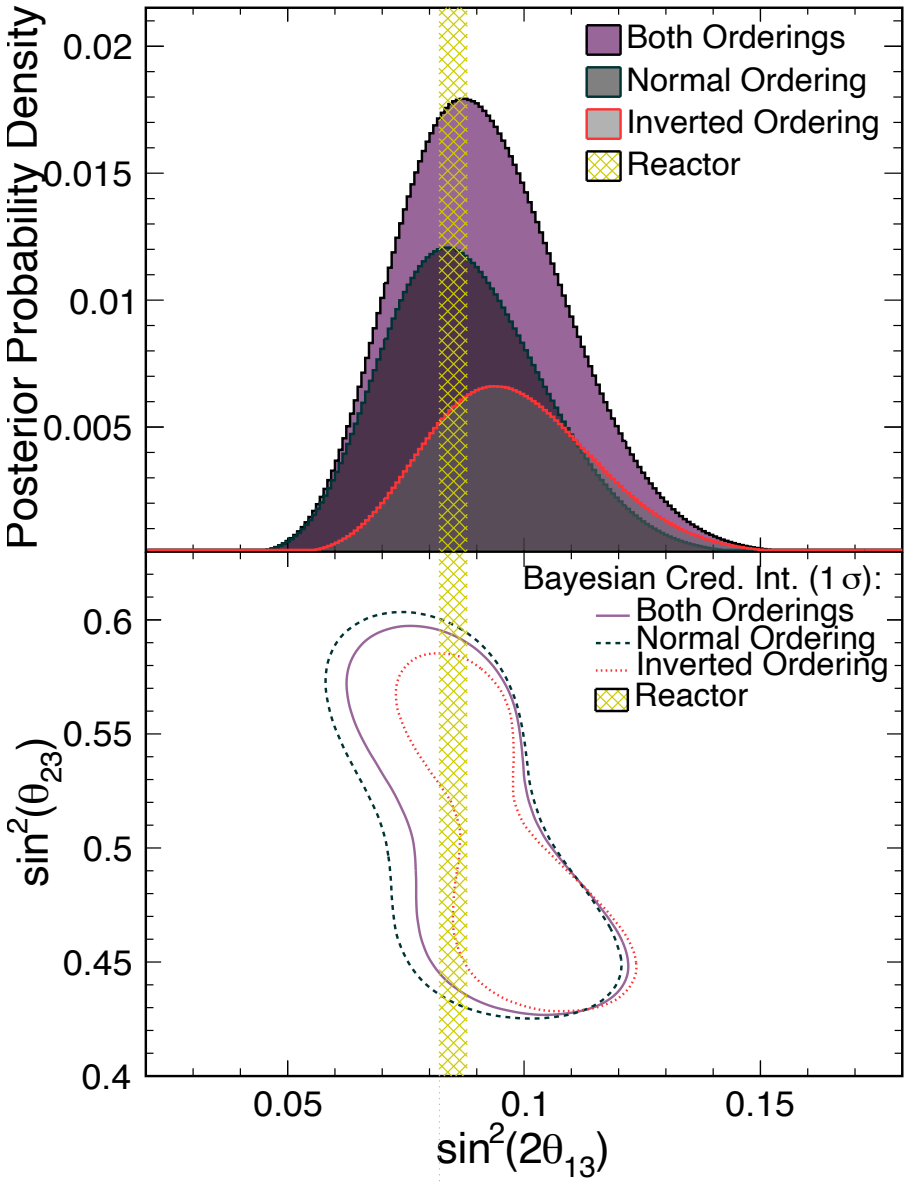
- We measure a small neutrino-antineutrino asymmetry.



Extract Nature's Parameters

- Weak preference for normal ordering
- Weak preference for upper octant of θ_{23}
- We can measure θ_{13} using NOvA only.
  - Without reactor constraint

$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$



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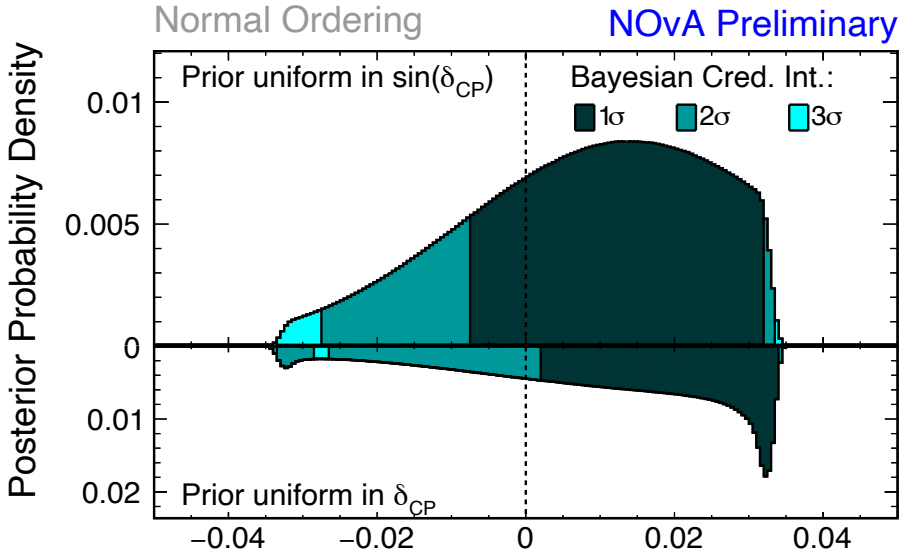
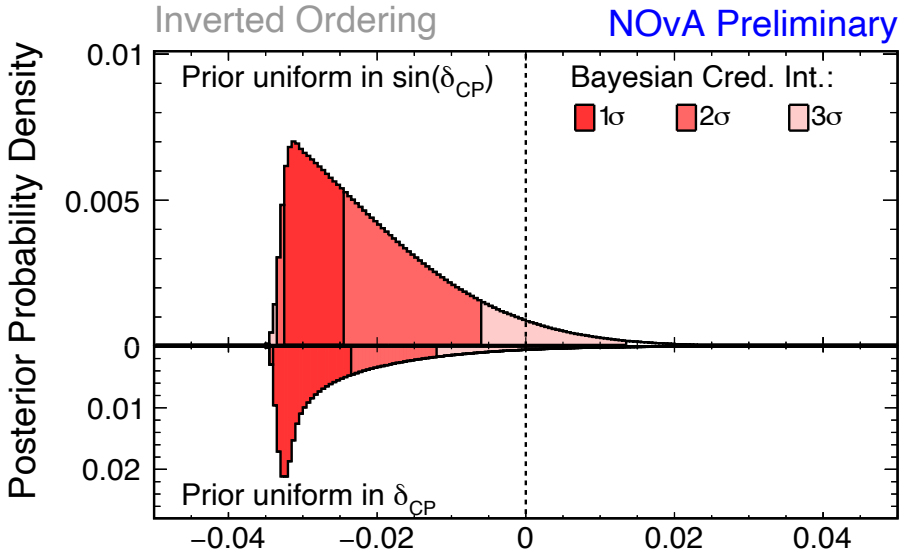
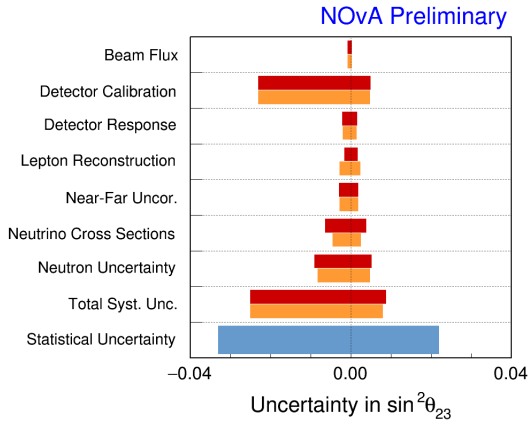
- Jarlskog invariant:
  - J = 0: CP conserved
  - J ≠ 0: CP violated

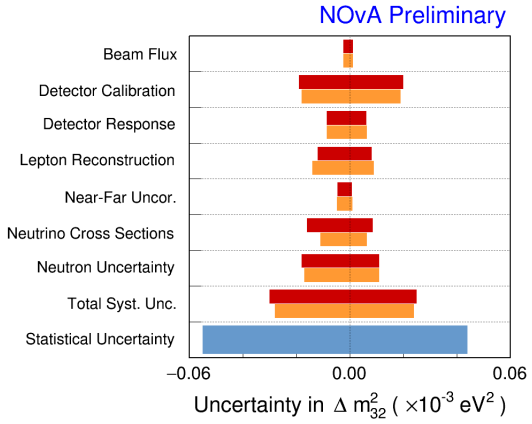


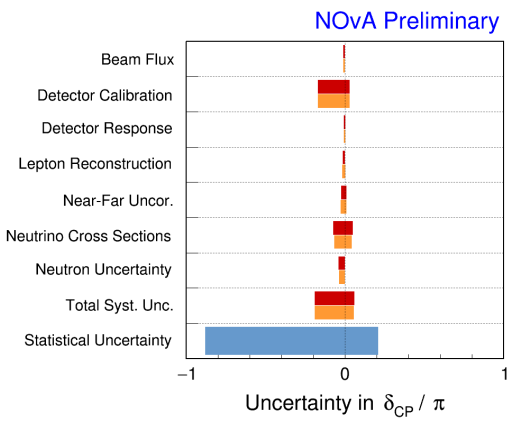


Systematic Uncertainties

- Several systematic uncertainties were considered:

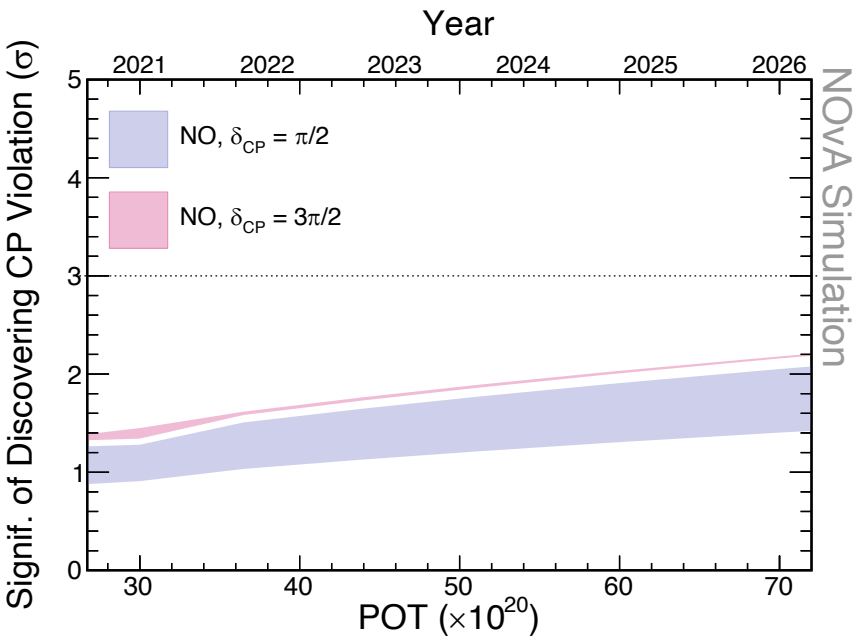


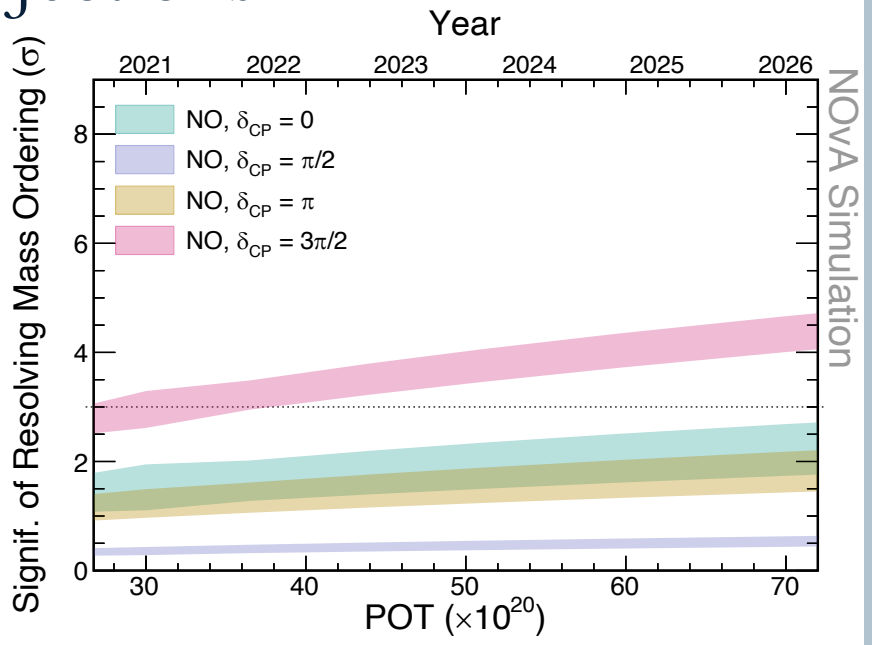




- We are still limited by statistics.
- Largest systematic uncertainties addressed by Test Beam:

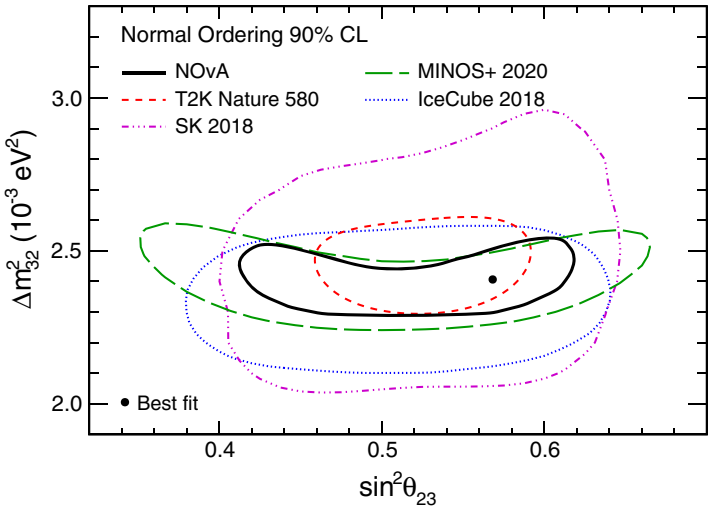
Future Projections





- NOvA is expected to run until 2026.
- Significance of discovering CP violation (left)
- Significance of resolving the mass ordering (right)
- Joint analysis between NOvA and T2K is underway.

Summary



- Current NOvA measurements:

$$\Delta m^2_{32} = 2.41 \pm 0.07 \times 10^{-3}\ \text{eV}^2$$

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

$$\delta_{\text{CP}} = 0.82\pi^{+0.27\pi}_{-0.87\pi}$$

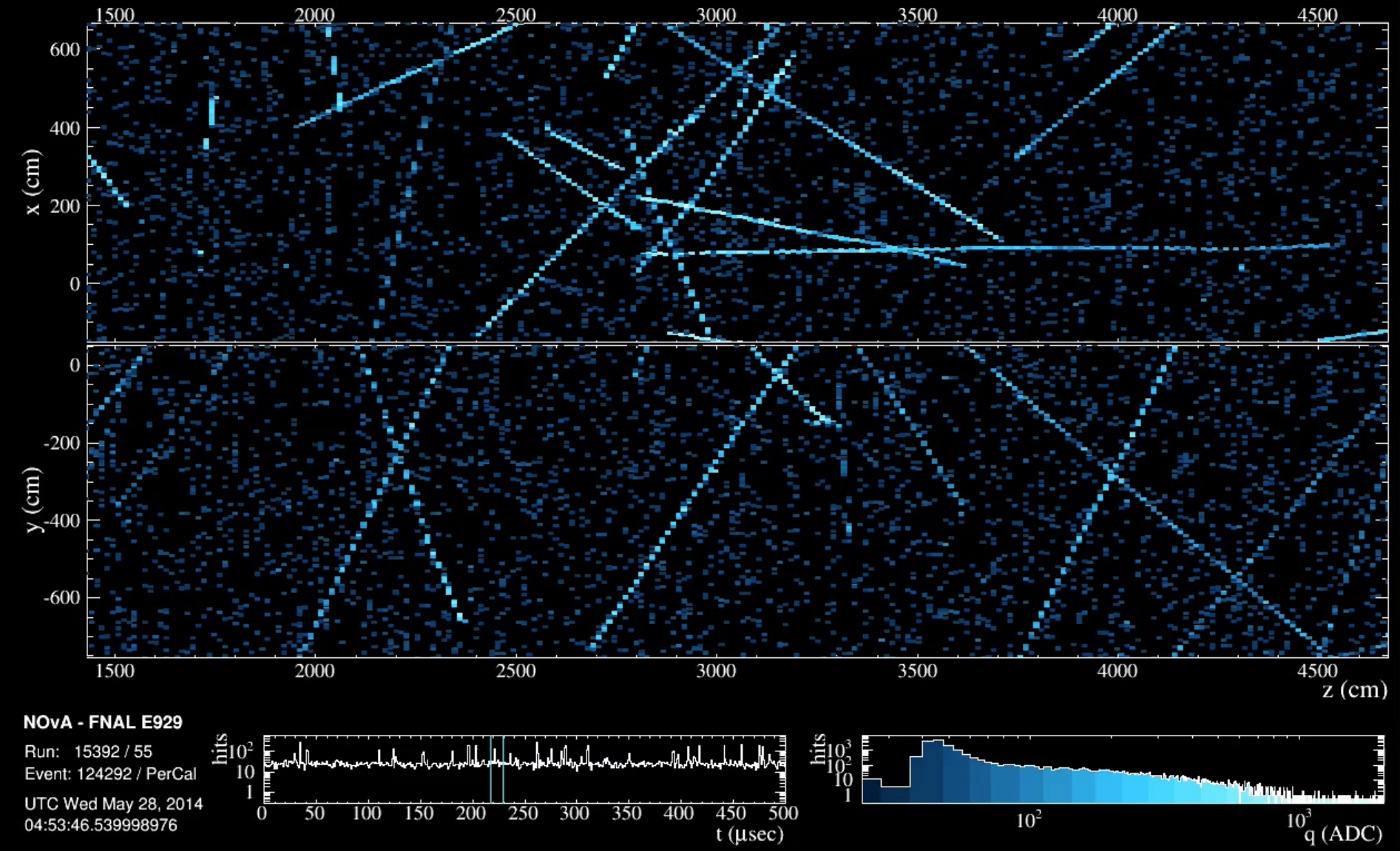
$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

- Stay tuned for our next results with more exposure and the T2K/NOvA joint analysis.
- Thanks to the NOvA Collaboration and our funding agencies!

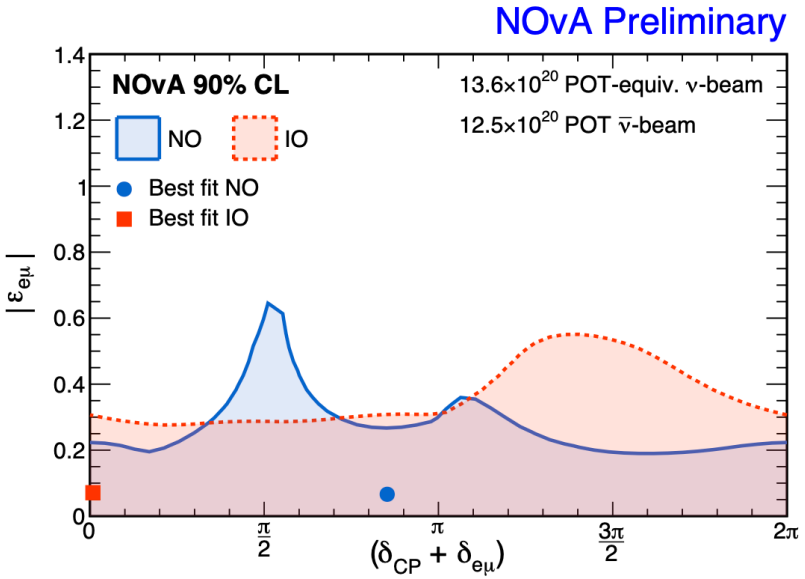
>266 scientists and engineers from 49 institutions from 8 countries

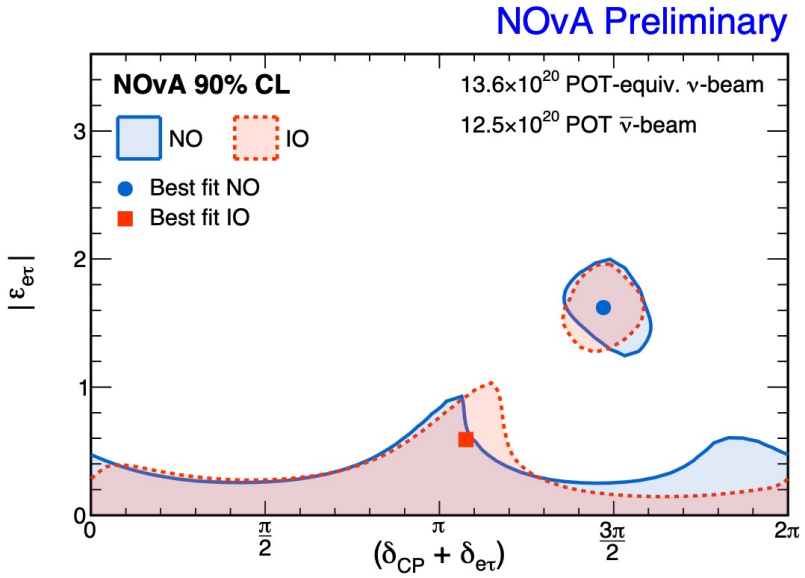
Back-Up Slides

Live Detector Activity



Non-Standard Interactions





Redefine sum of matrices to single effective matrix

$$\mathcal{H} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^{\dagger} + V \begin{pmatrix} \delta_e + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ (\varepsilon_{e\mu})^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ (\varepsilon_{e\tau})^* & (\varepsilon_{\mu\tau})^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

Where ε = 1 → same size as MSW effect
Assume all NSI comes from electrons
and correct if theory says up or down quark.