Results from the NOvA Experiment

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

September 30th, 2025
Padua, Italy

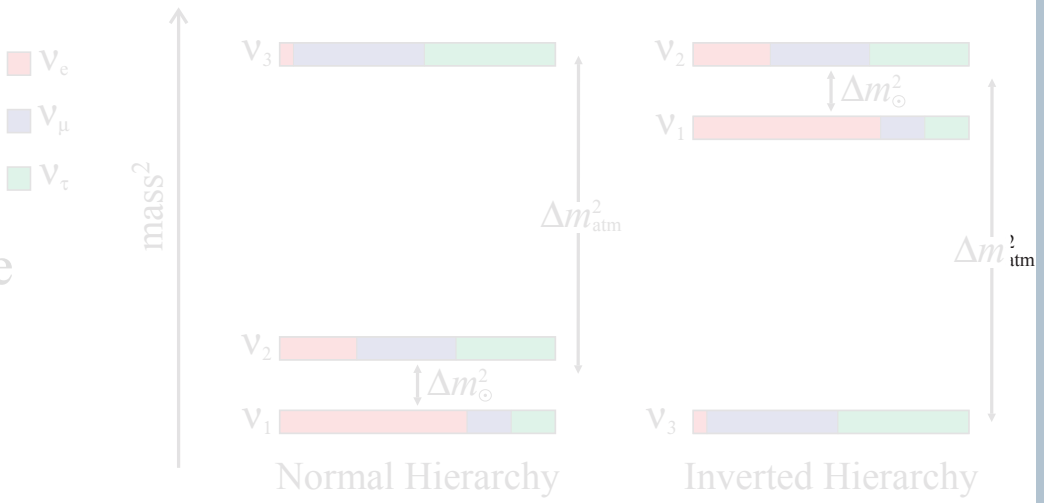
UNIVERSITY OF SOUTH ALABAMA

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

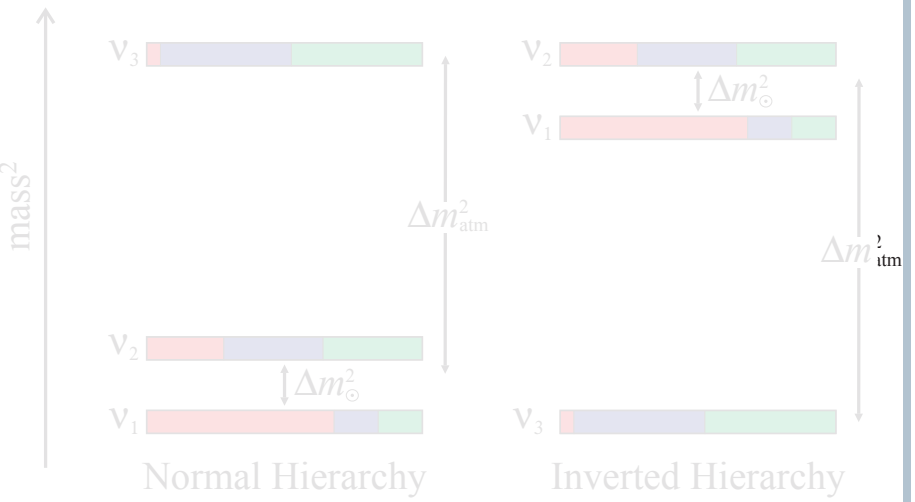


Introduction

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

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

- 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

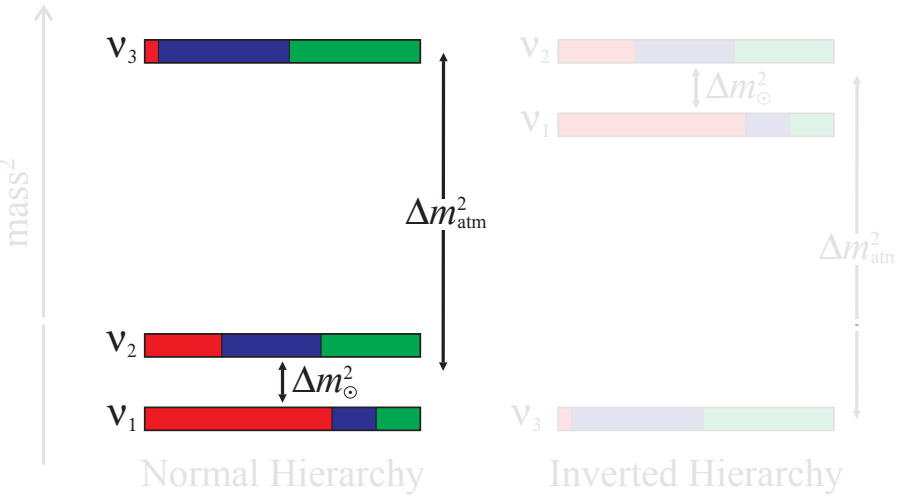


Introduction

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

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

- 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

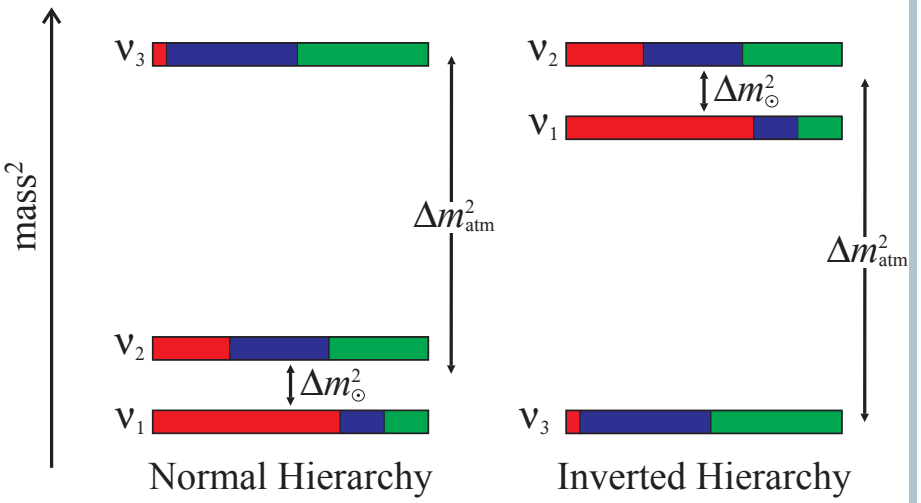


Introduction

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

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

- 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

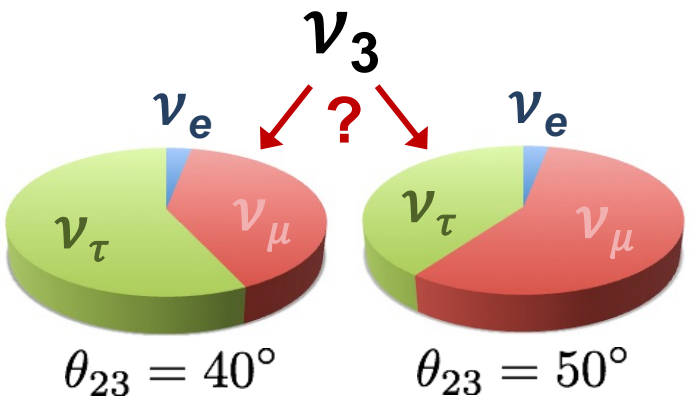


Introduction

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

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

- 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



Introduction

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

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

- 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

Beyond Oscillation Physics

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

Introduction

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

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

- Physics Goals:
  - Search for magnetic monopoles
  - New results hot off the press today!

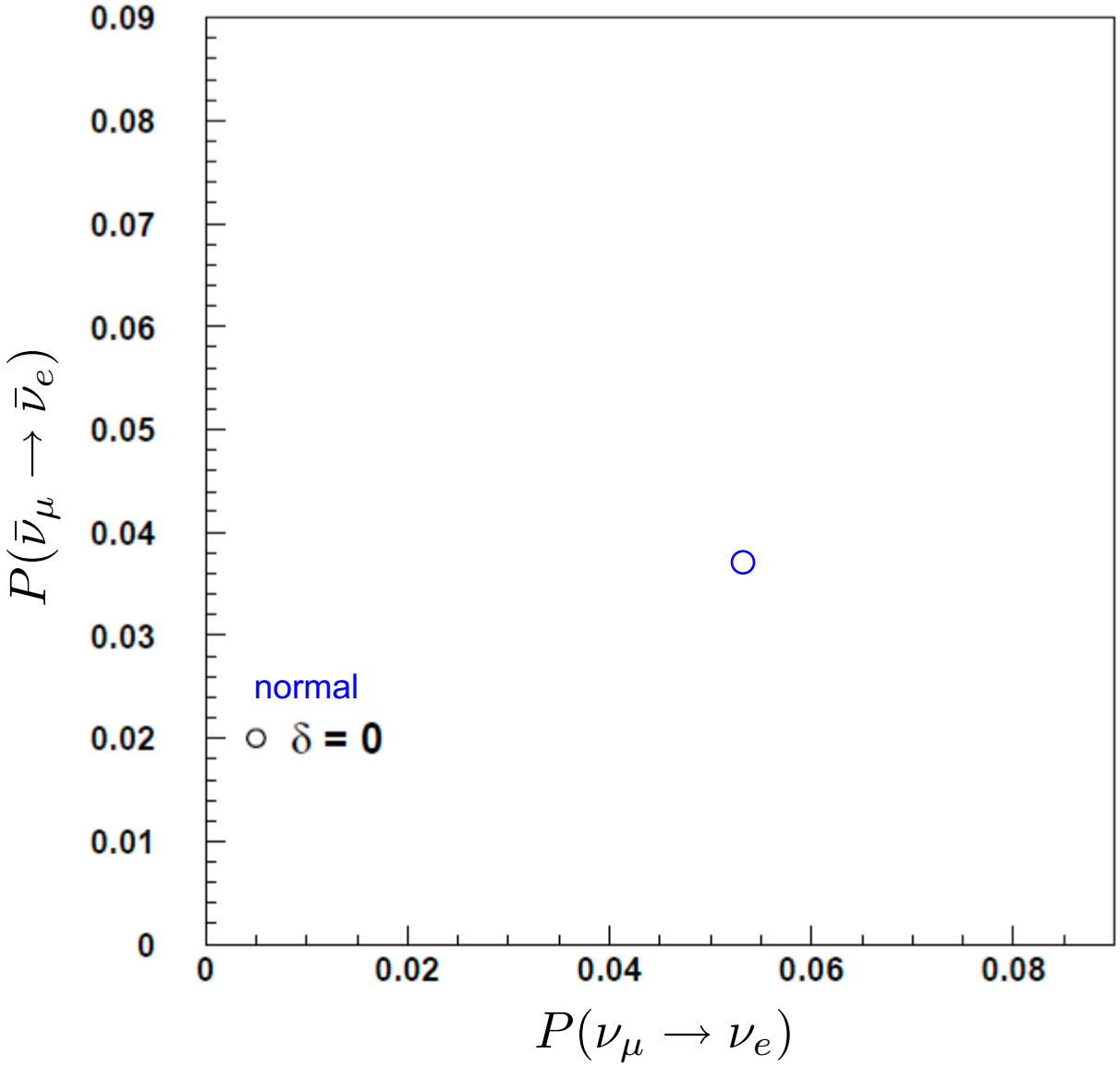
Beyond Oscillation Physics

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

XXI Workshop on Neutrino Telescopes

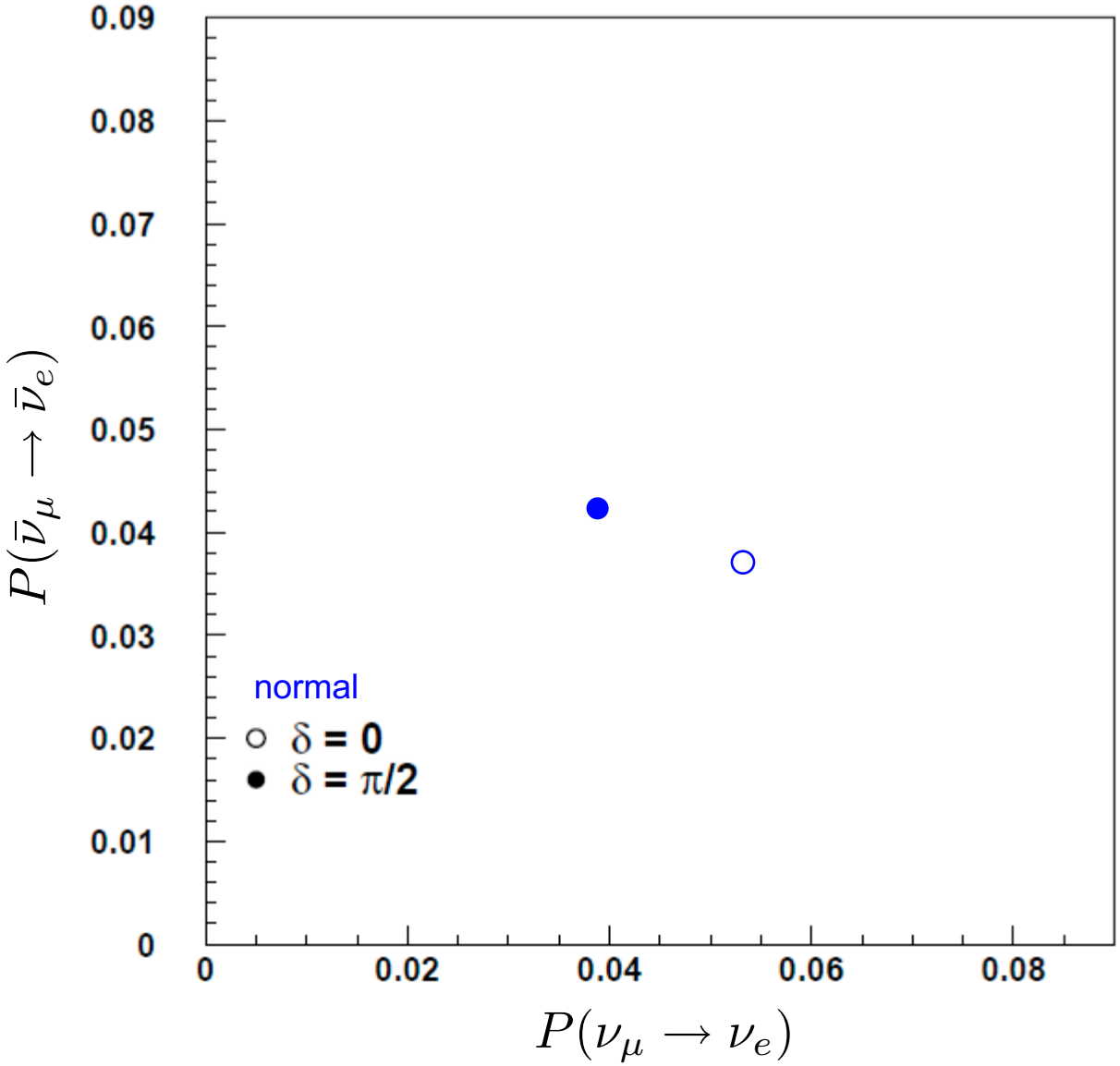
Neutrino Oscillation Results

Extracting Nature's Parameters



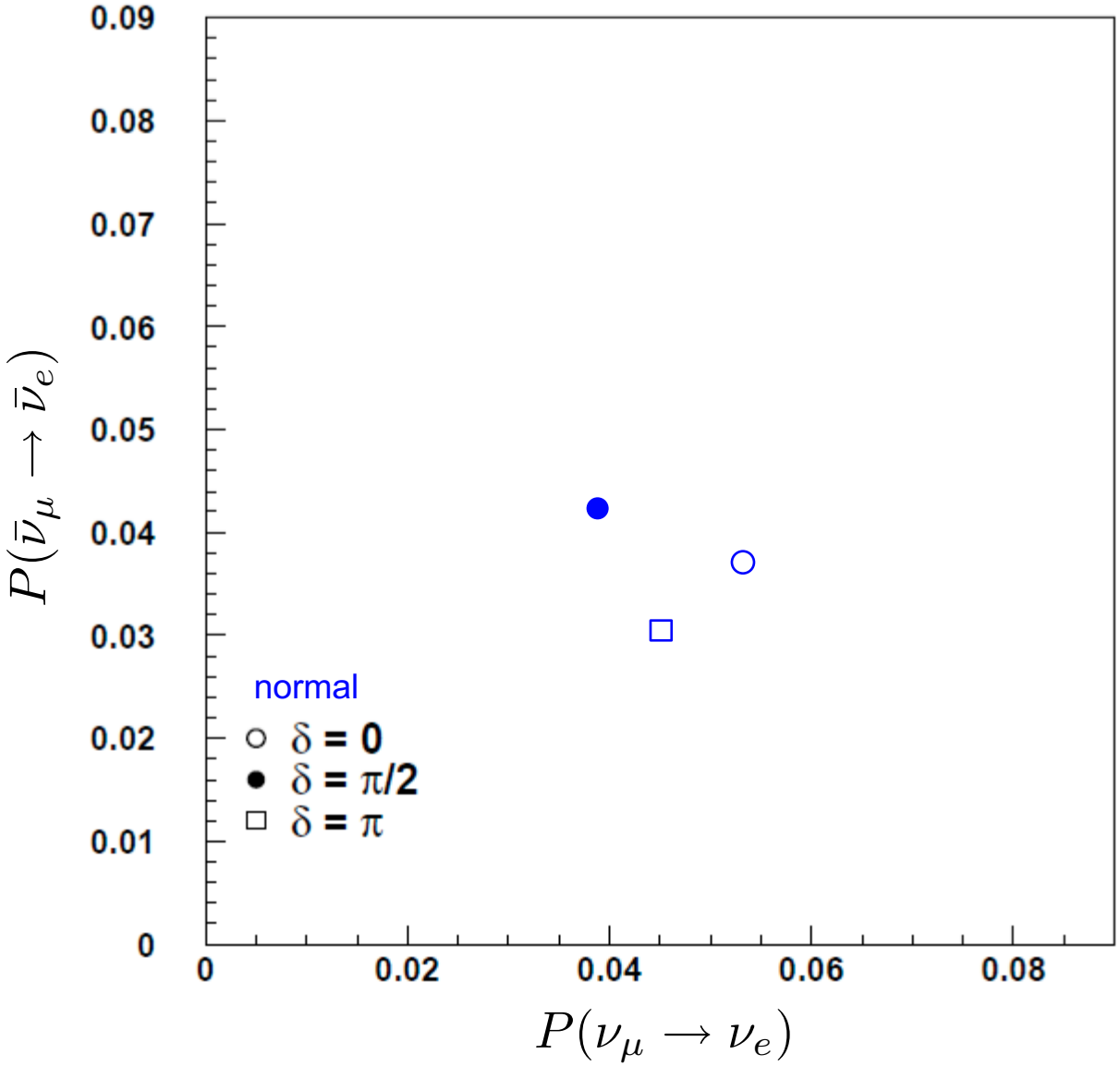
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.

Extracting Nature's Parameters



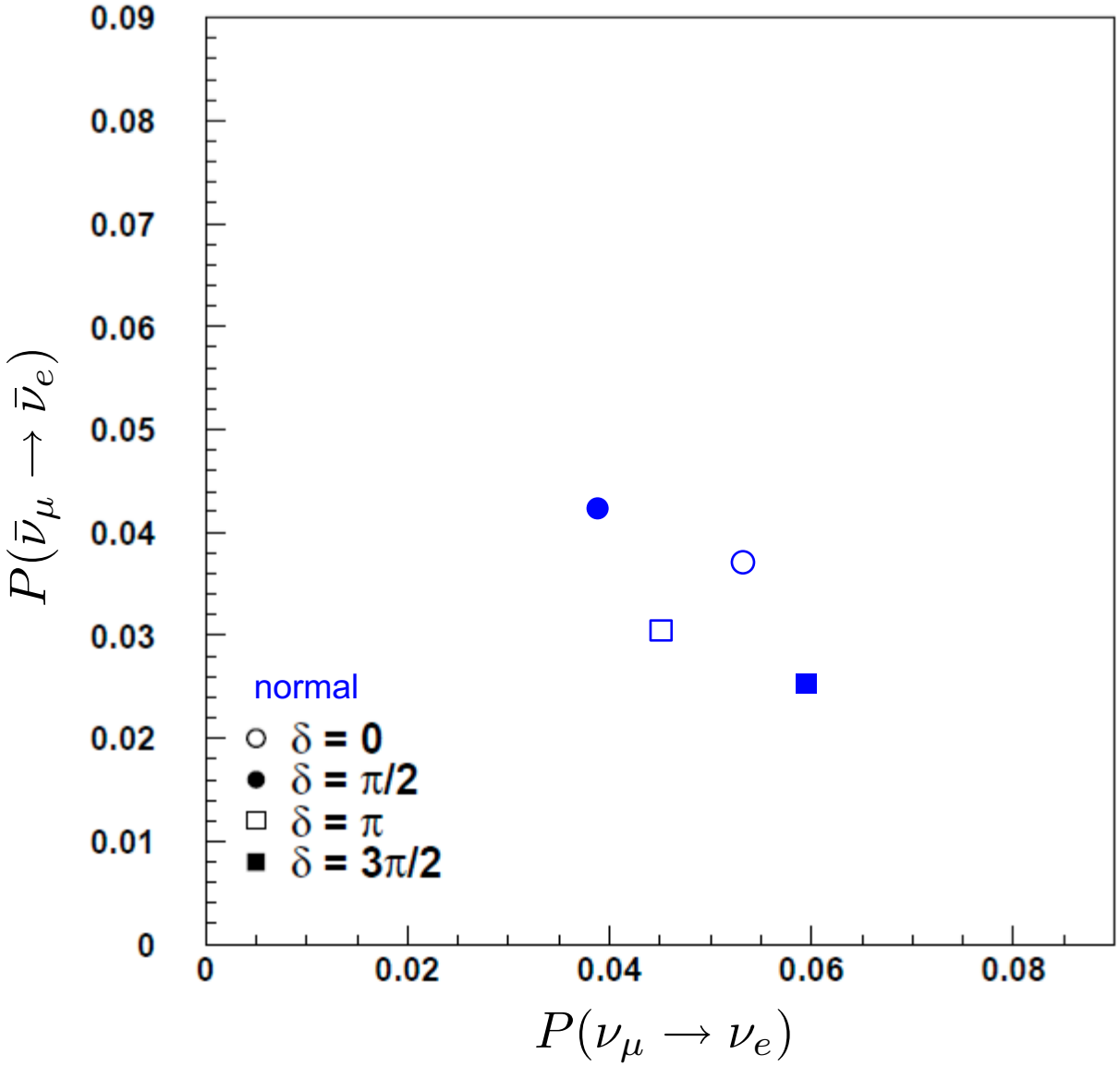
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.

Extracting Nature's Parameters



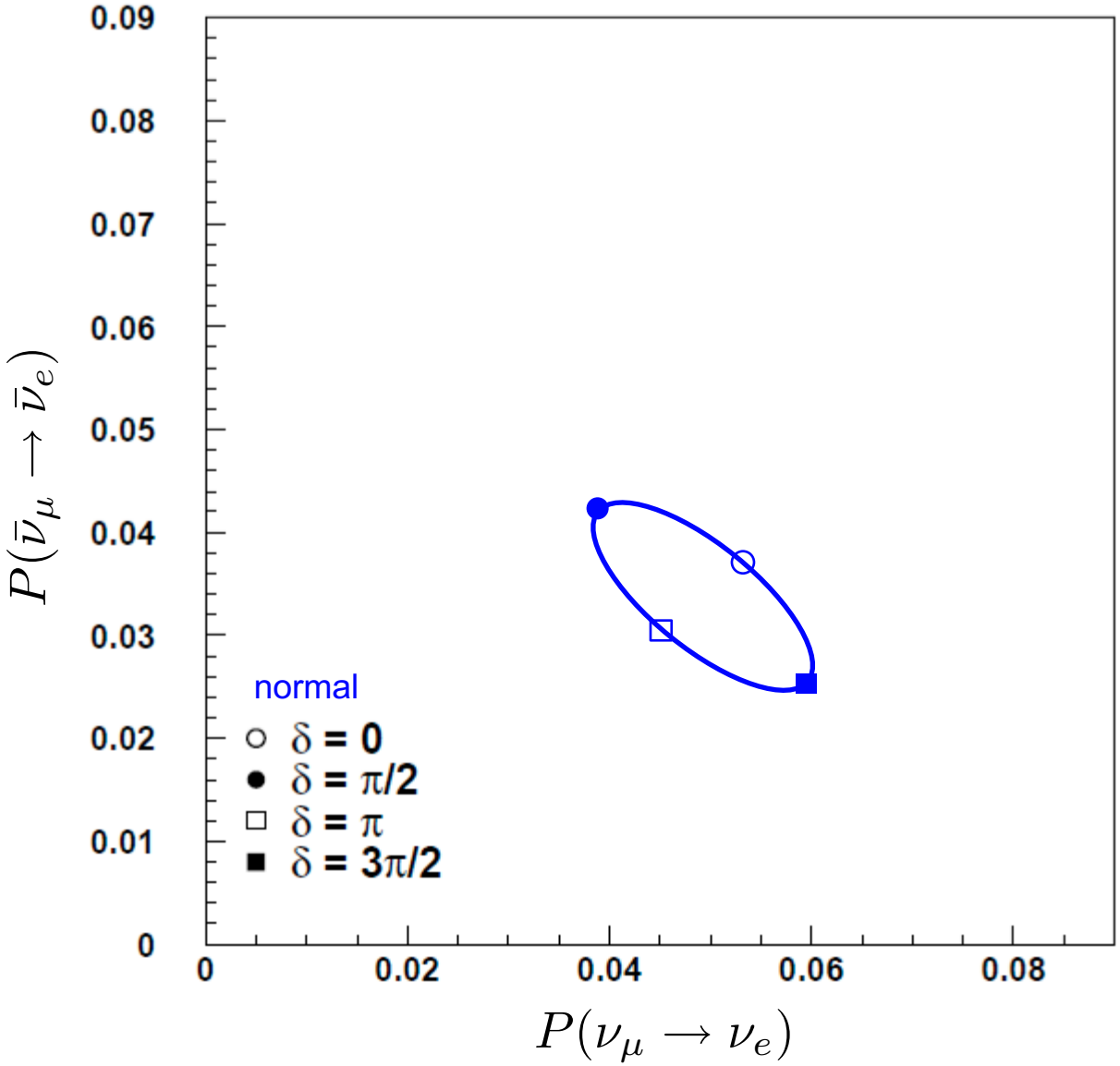
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.

Extracting Nature's Parameters



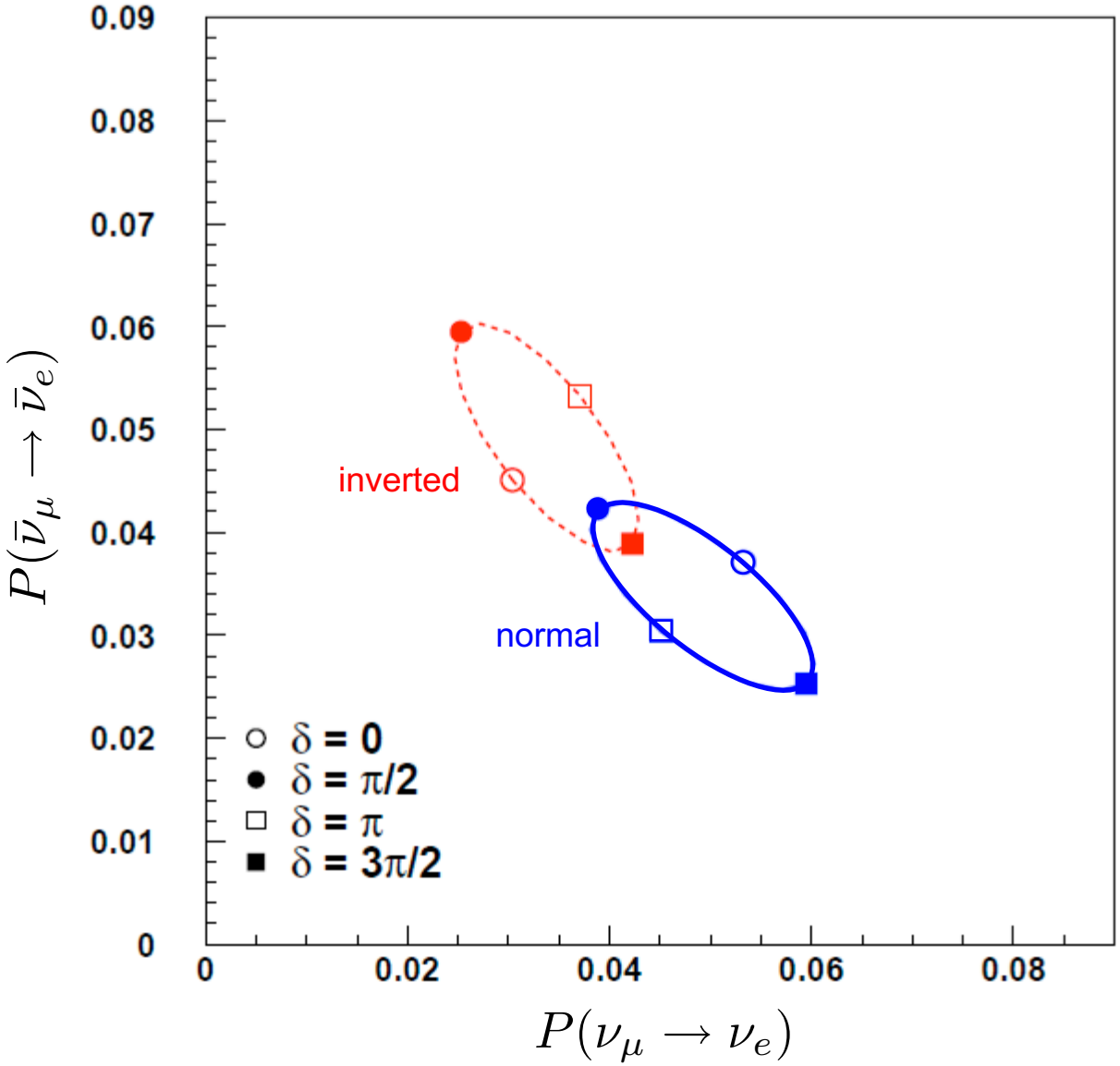
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.

Extracting Nature's Parameters



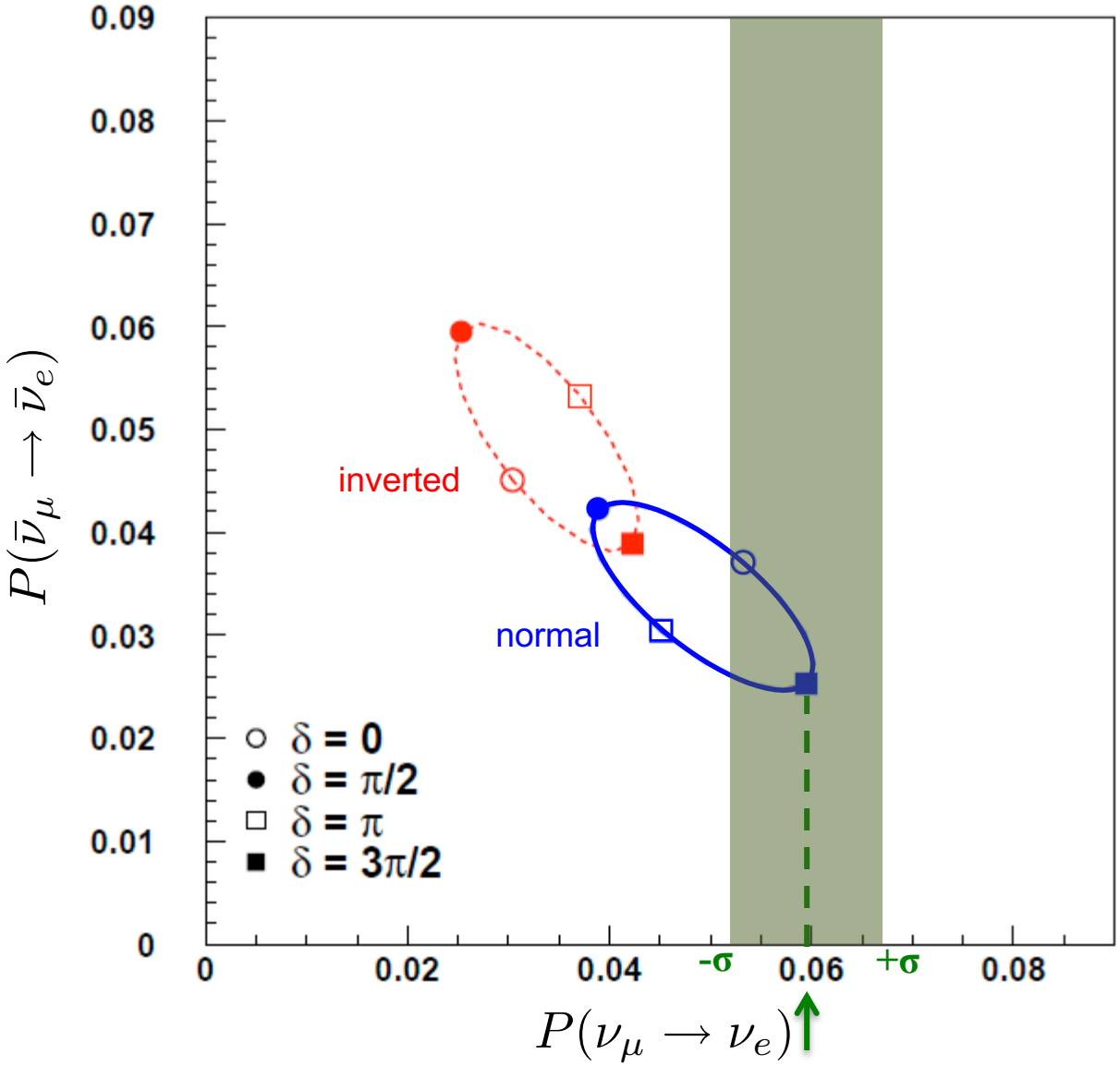
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.

Extracting Nature's Parameters



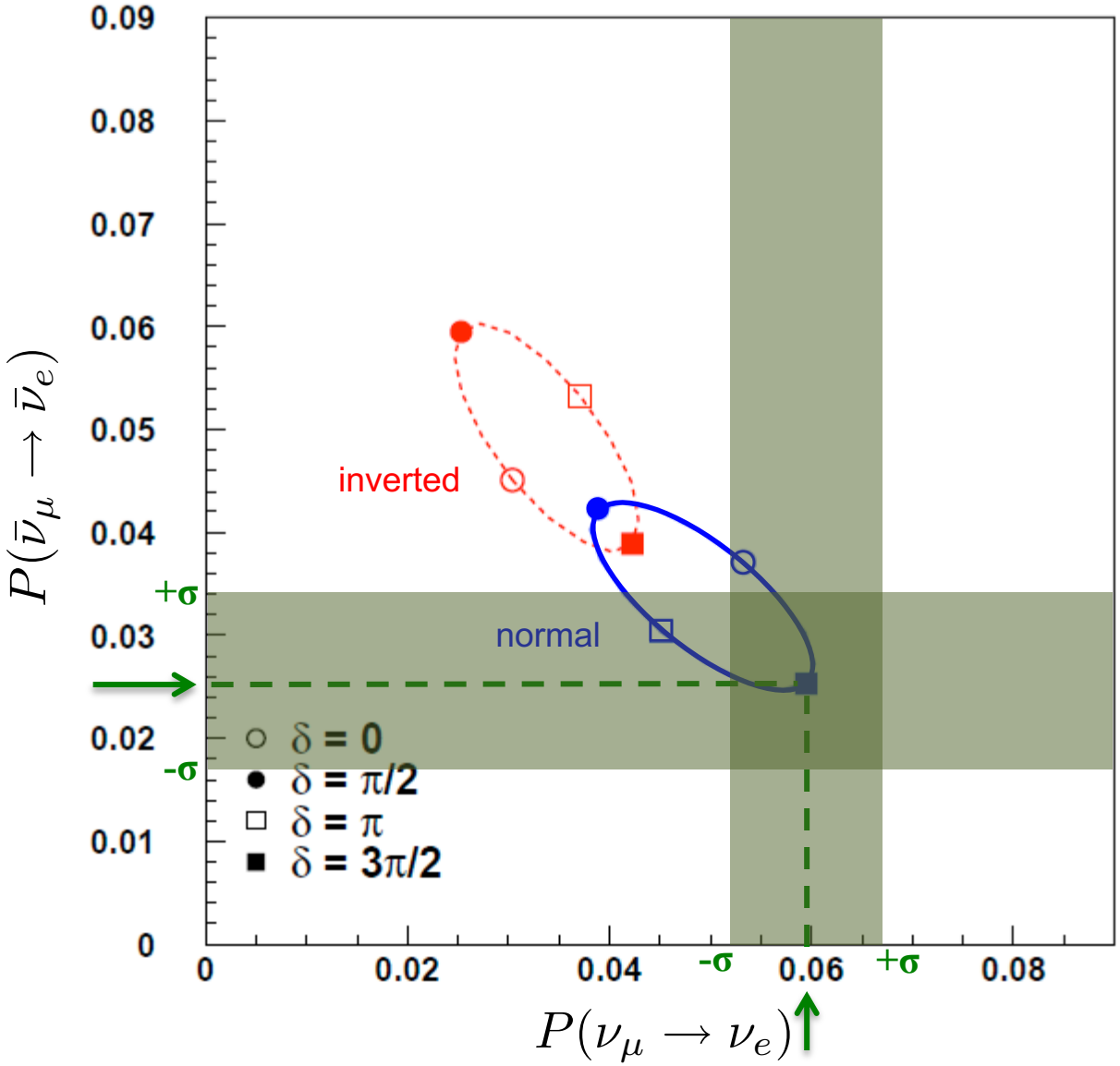
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.

Extracting Nature's Parameters

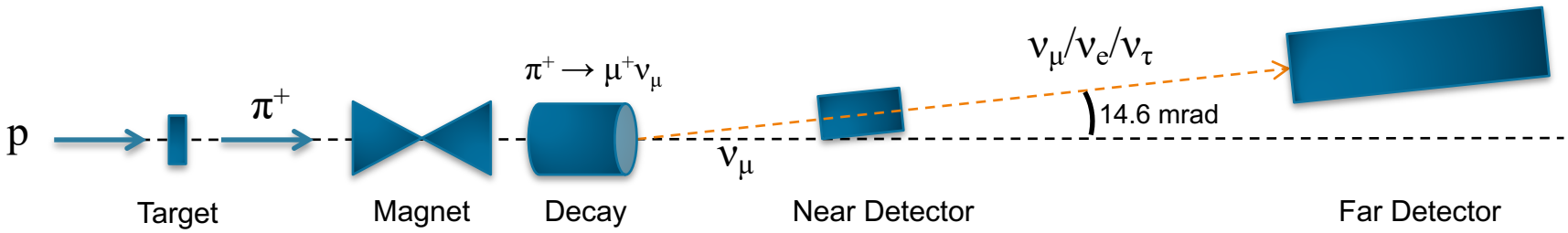


- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Here is an example measurement NOνA might make.

Extracting Nature's Parameters



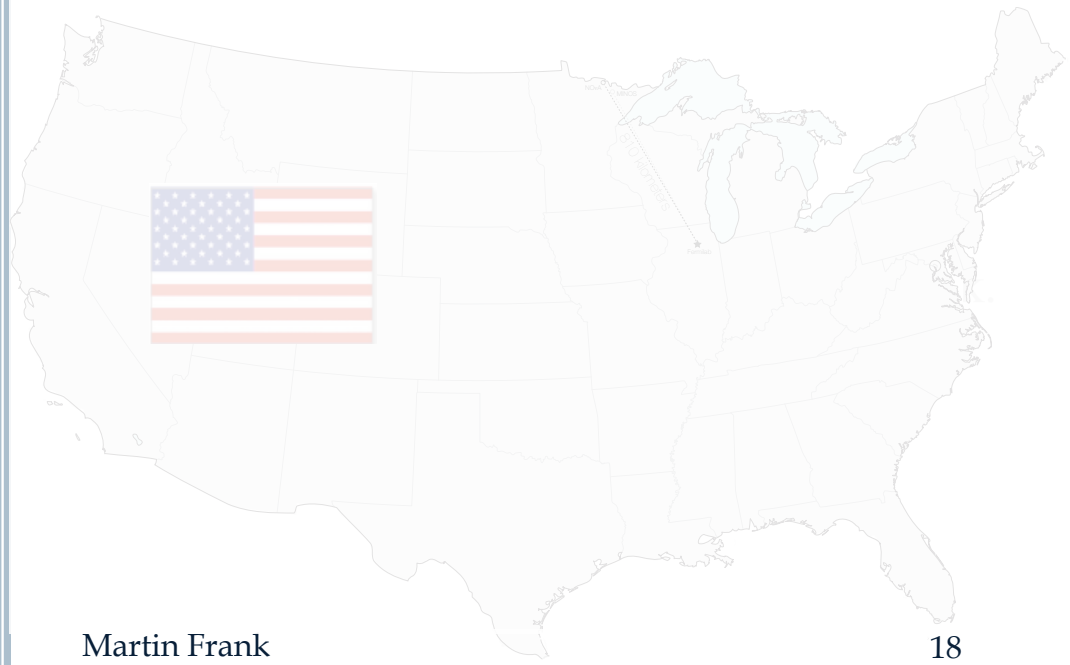
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Here is an example measurement NOνA might make.

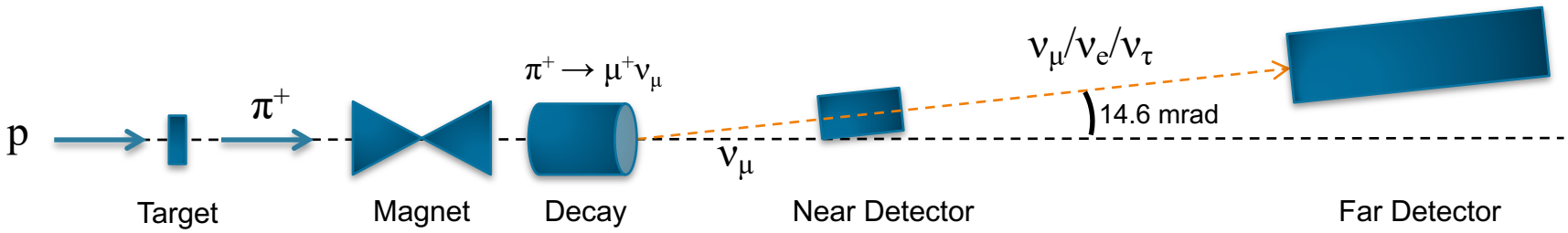


Neutrino Beam

Baseline (L = 810 km)

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

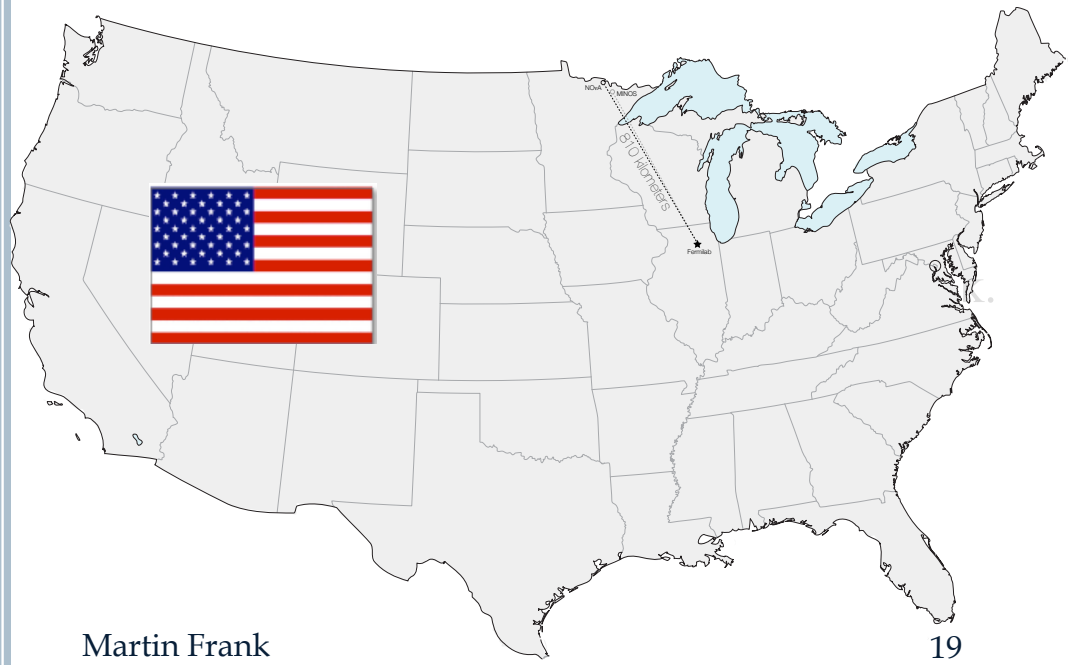


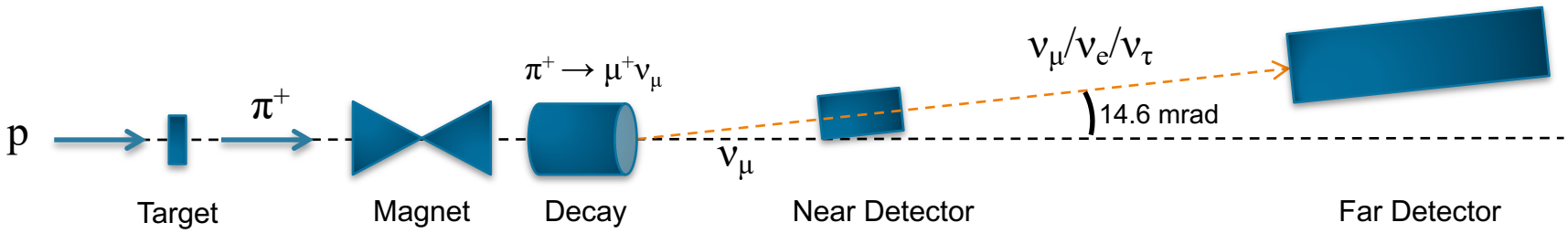


Neutrino Beam

Baseline (L = 810 km)

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

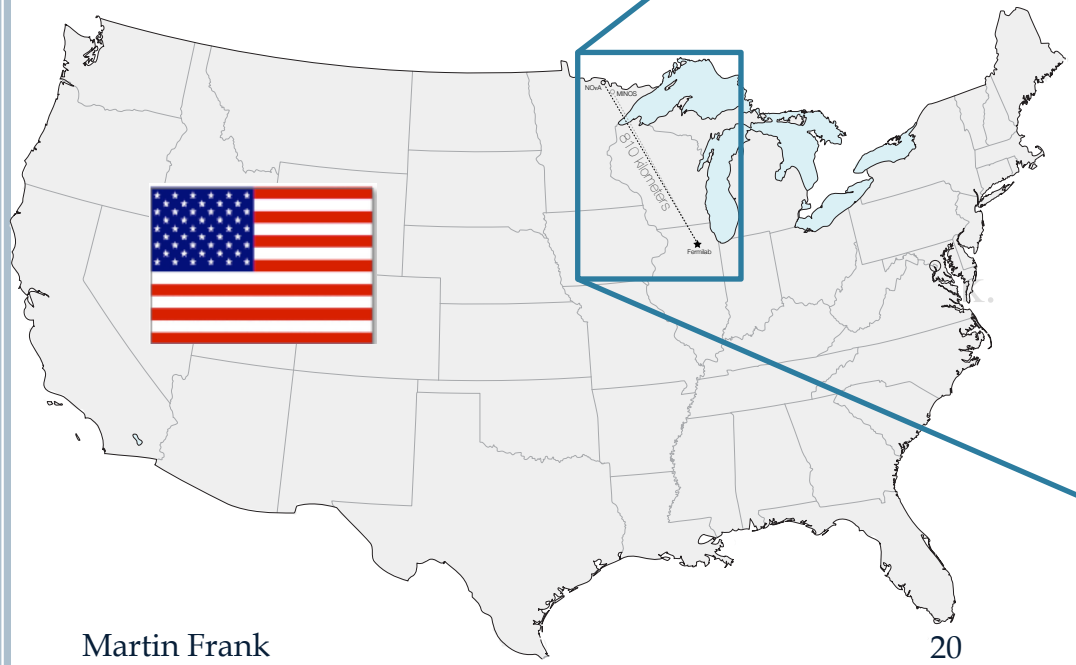


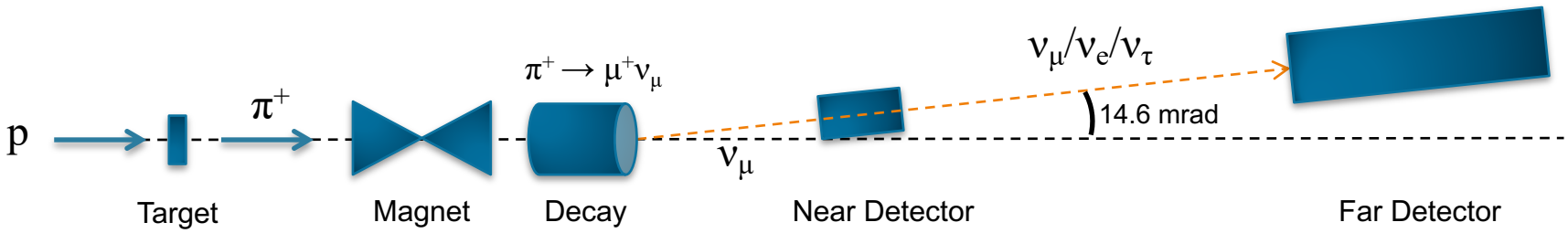


Neutrino Beam

Baseline (L = 810 km)

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





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)

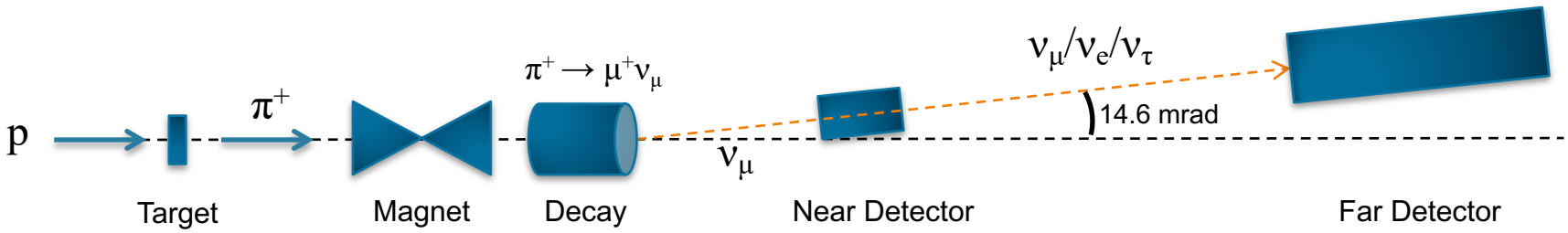
We can achieve a narrowly distributed neutrino energy by placing the detectors 14.6 mrad off the beam axis.

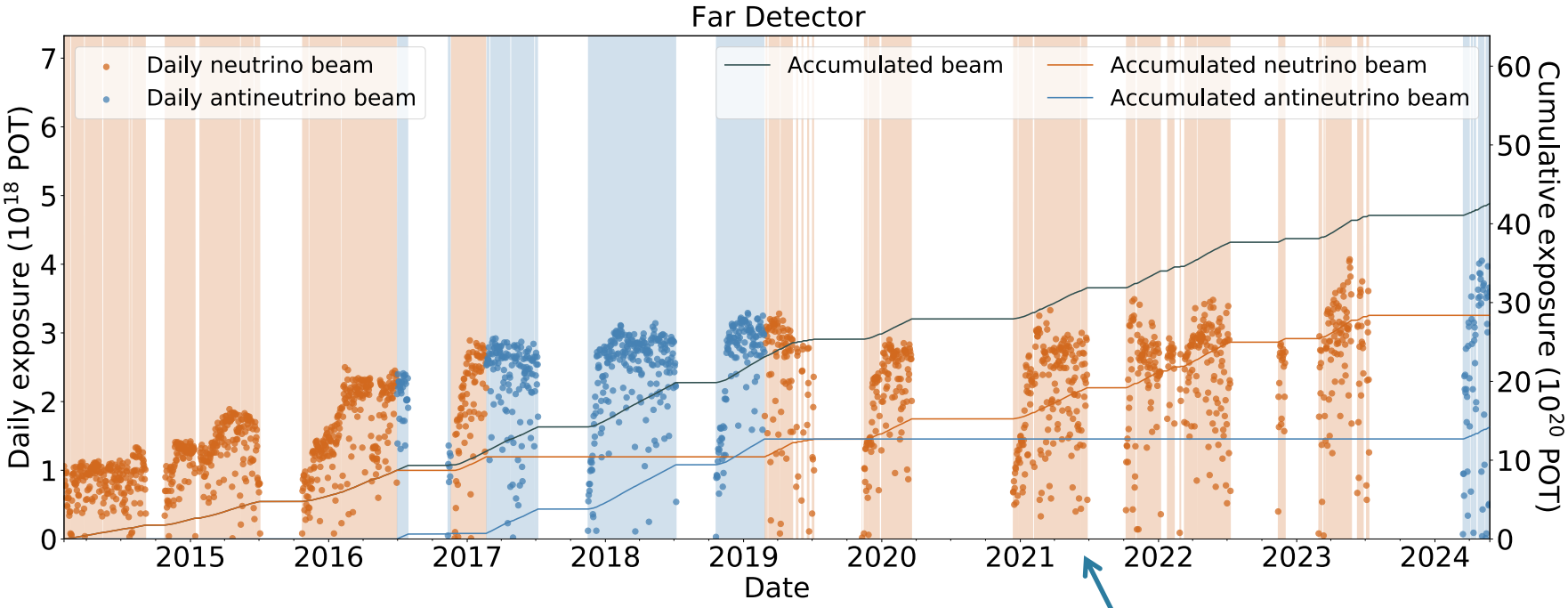
This is also the $\nu_\mu \rightarrow \nu_e$ oscillation peak.

Protons on Target (POT)

26.6×10^{20} POT: neutrino mode

12.5×10^{20} POT: antineutrino mode





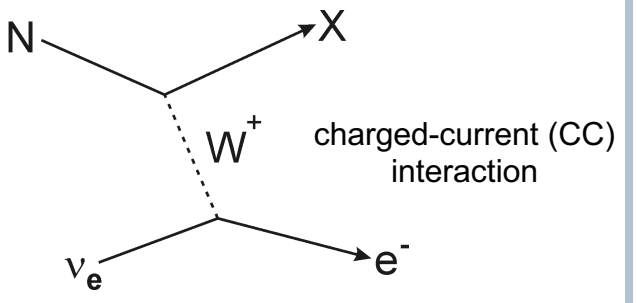
Protons on Target (POT)

26.6 x 10^{20} POT: neutrino mode

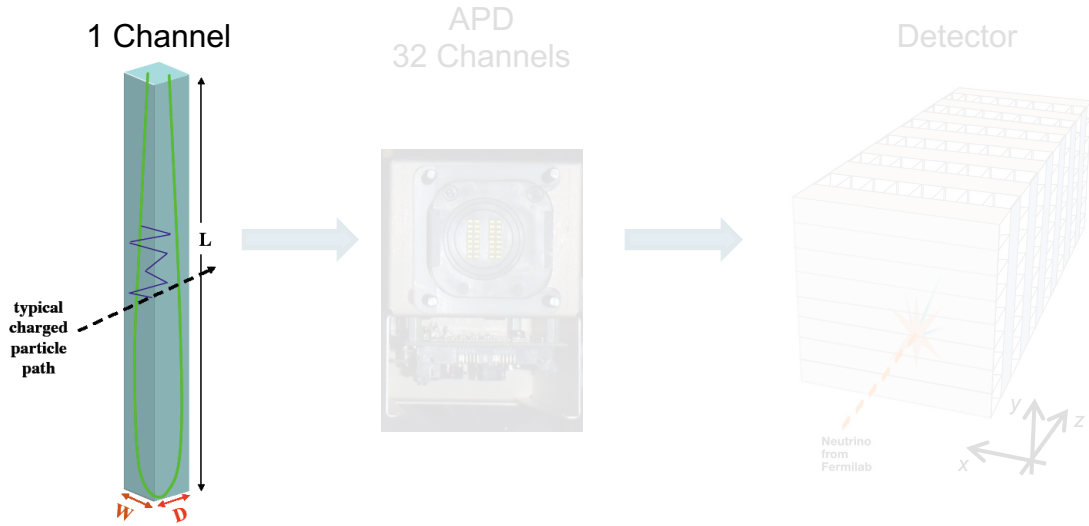
12.5 x 10^{20} POT: antineutrino mode

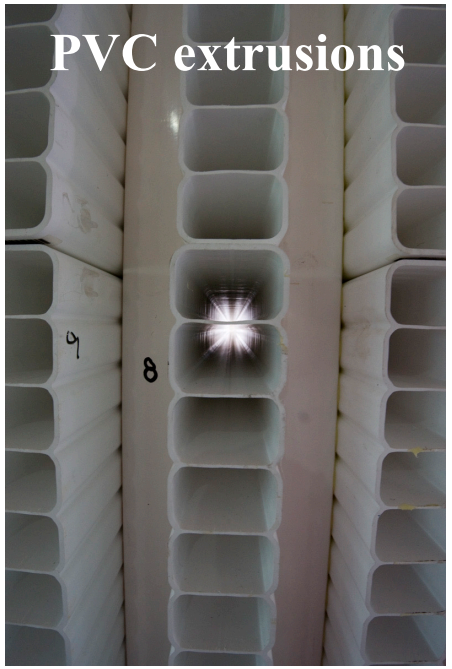
10 years of beam!
2014 - 2024

Neutrino Detection

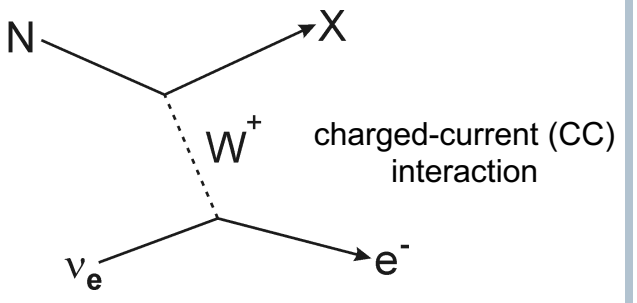


- We want to detect electron neutrinos (ν_e):
  - This requires a large detector mass and good electron identification.
- NOvA is a rectangular tracking calorimeter.
  - low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides 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)

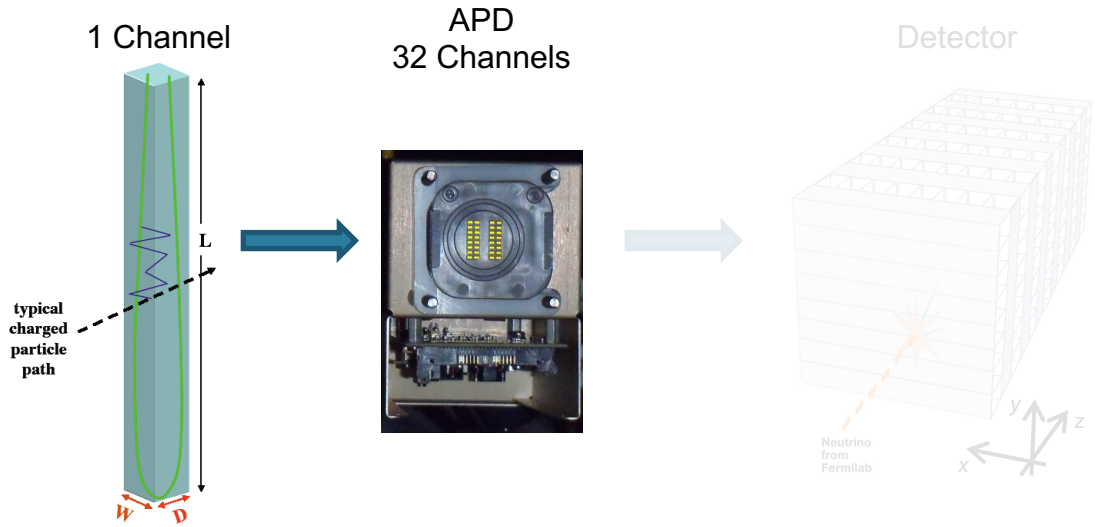


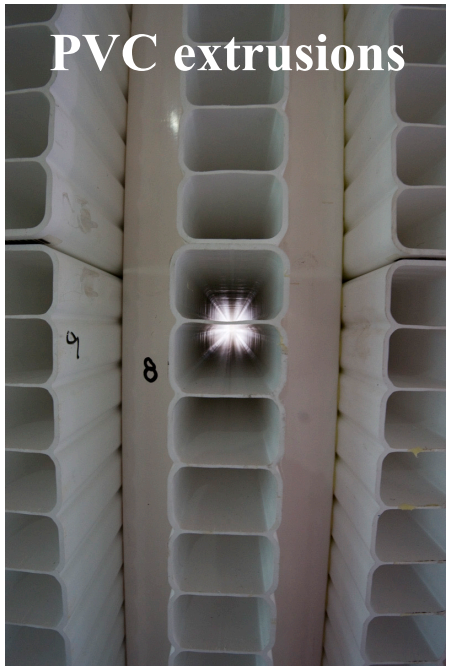


Neutrino Detection

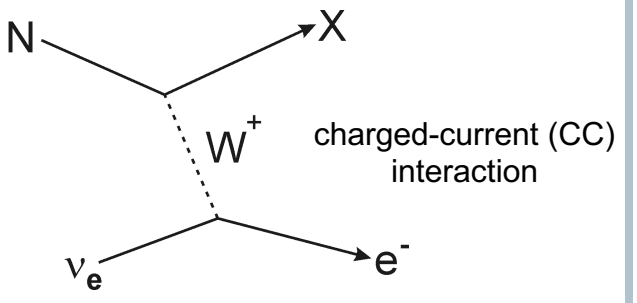


- We want to detect electron neutrinos (ν_e):
  - This requires a large detector mass and good electron identification.
- NOvA is a rectangular tracking calorimeter.
  - low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides 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)

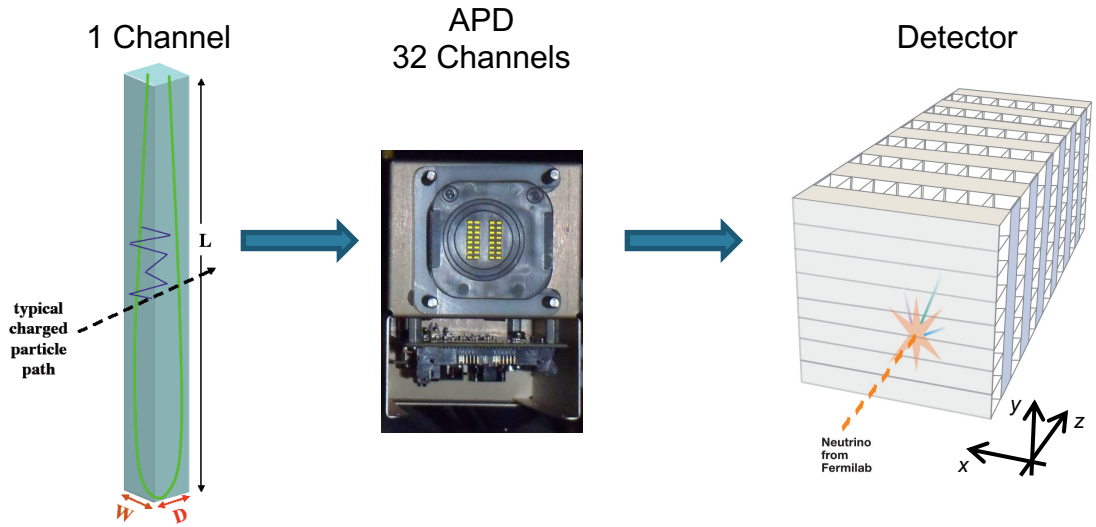


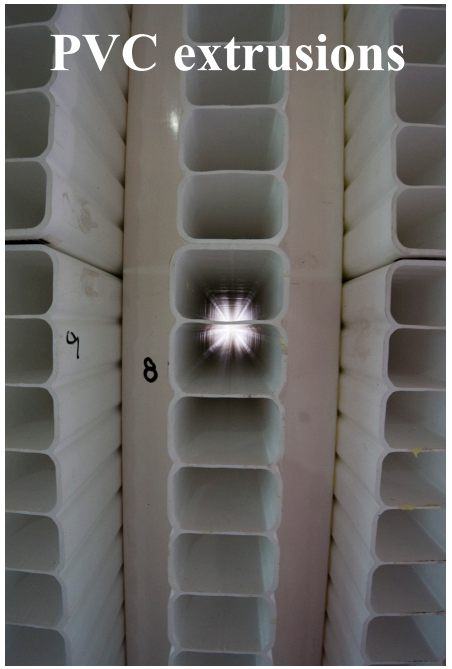


Neutrino Detection

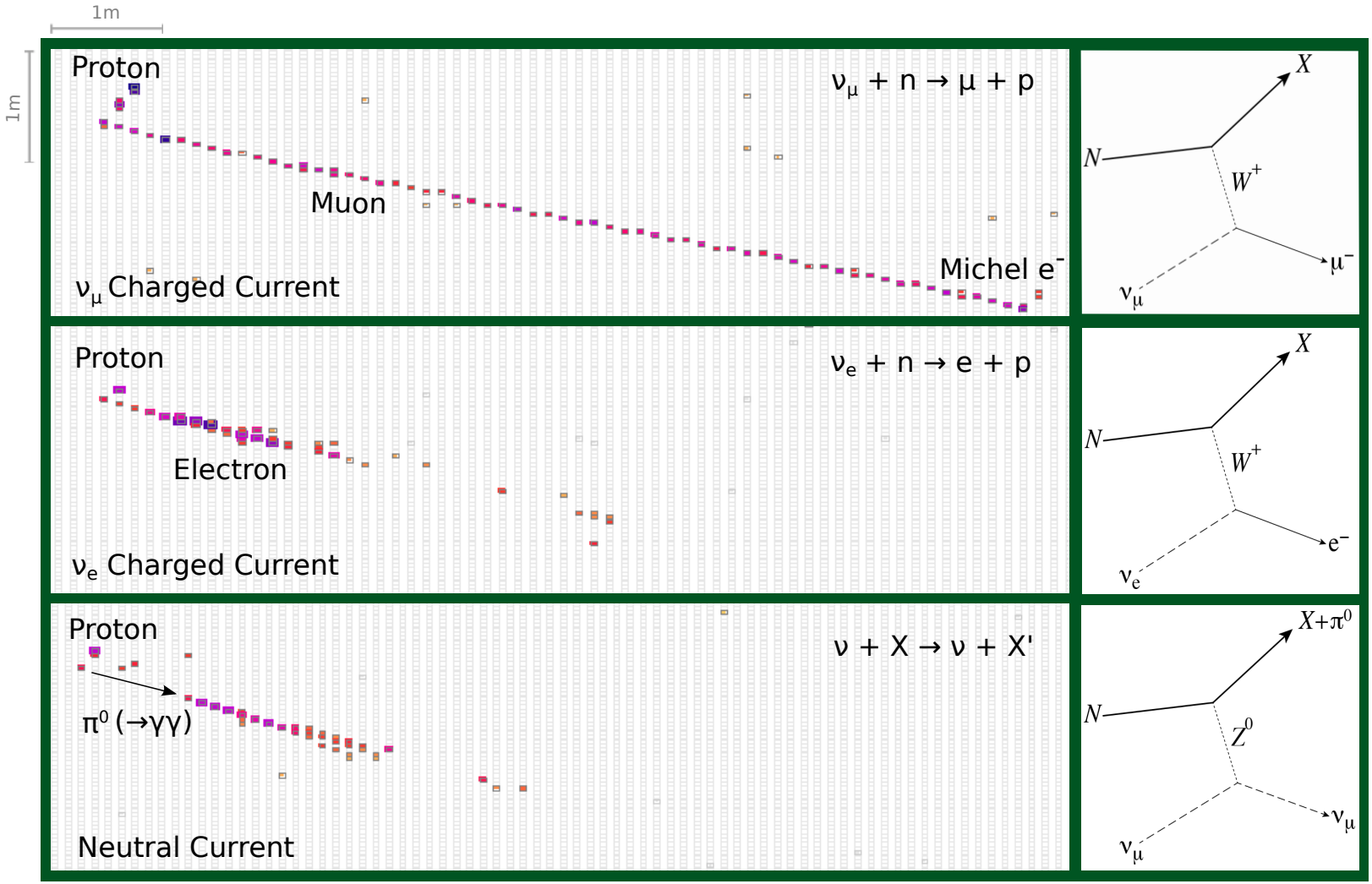


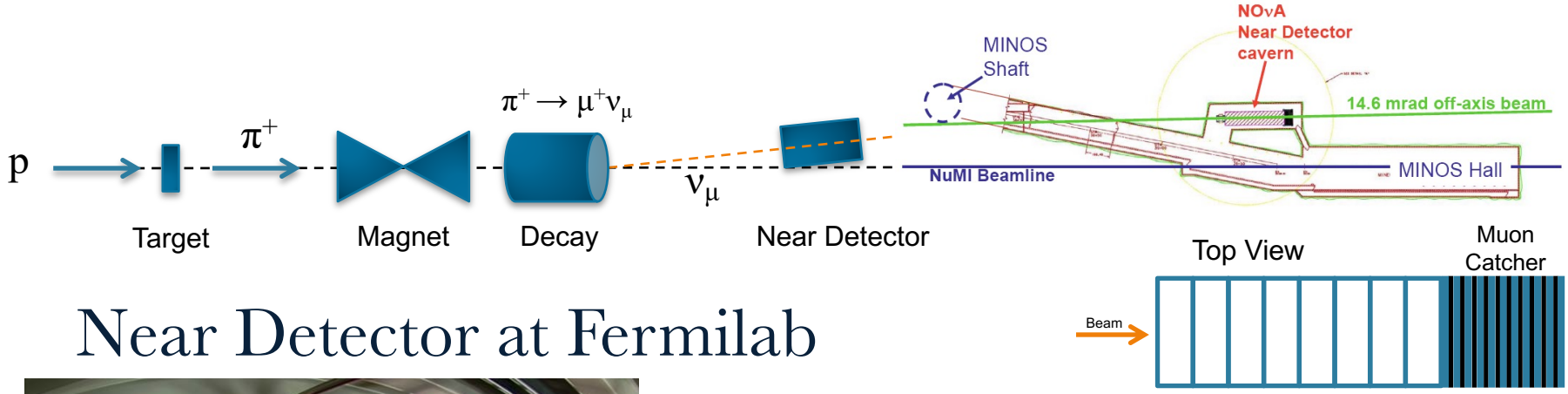
- We want to detect electron neutrinos (ν_e):
  - This requires a large detector mass and good electron identification.
- NOvA is a rectangular tracking calorimeter.
  - low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides 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)



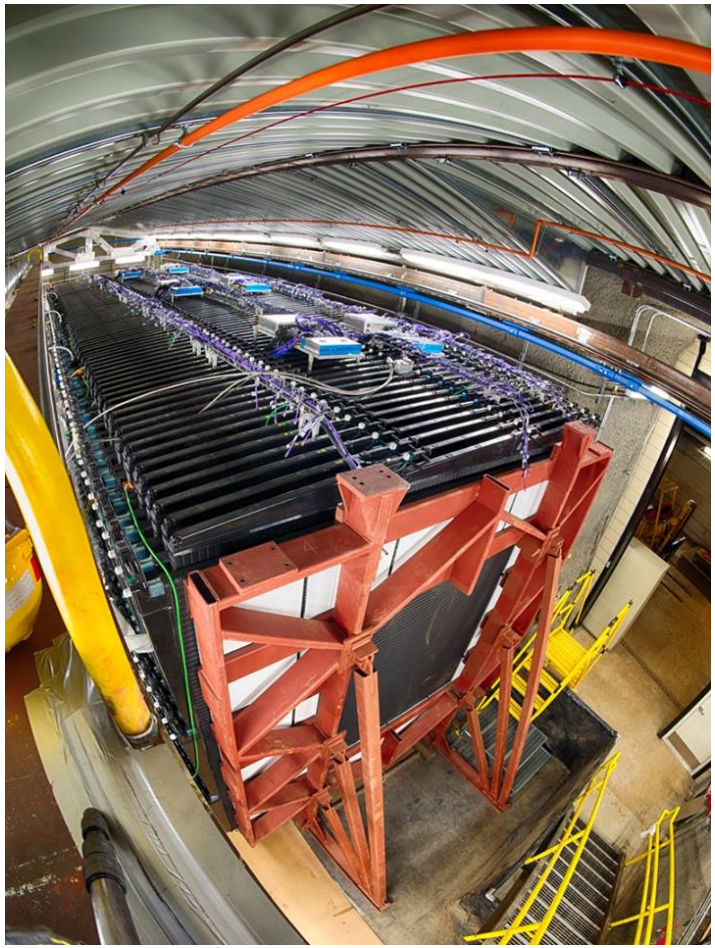


Simulated Event Display

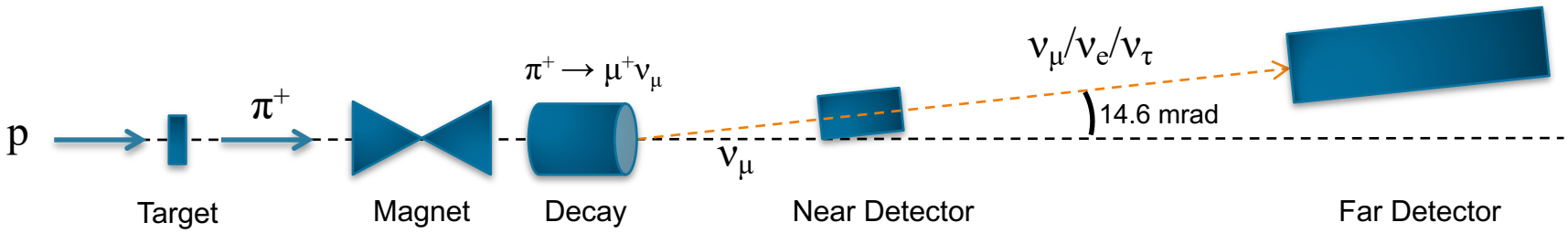




Near Detector at Fermilab



- 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

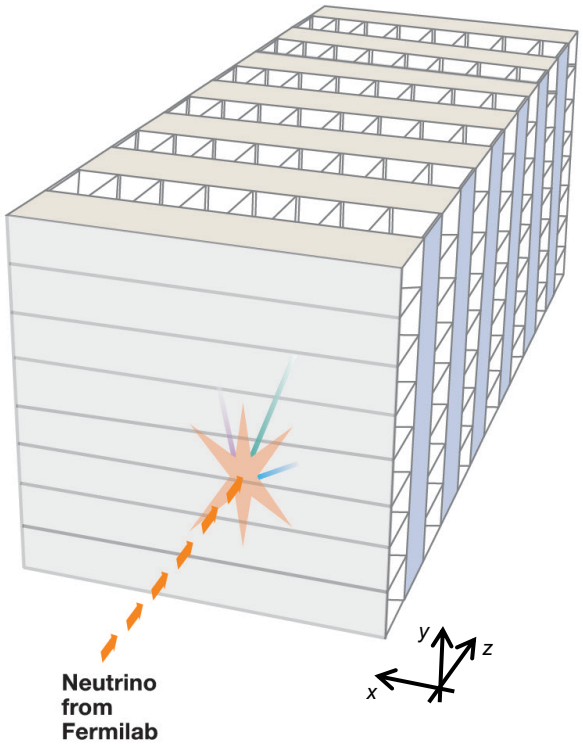


Far Detector in Ash River, MN

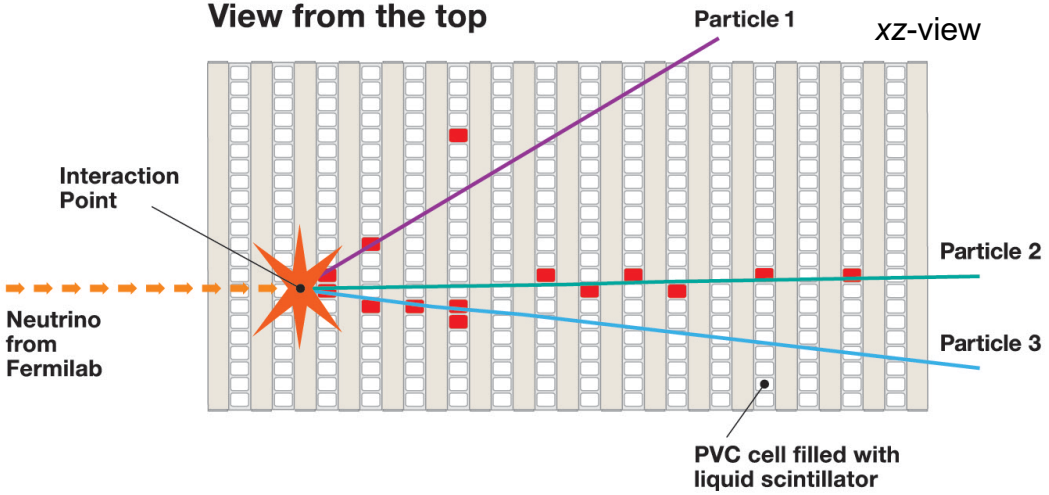
- 810 km downstream from NuMI target
- On the surface
- 14,000 tons
- 15 m × 15 m × 60 m
- Instrumented with 344k channels
- Few neutrino interactions per year
- ~130,000 cosmic ray muons per second

Neutrino Detection

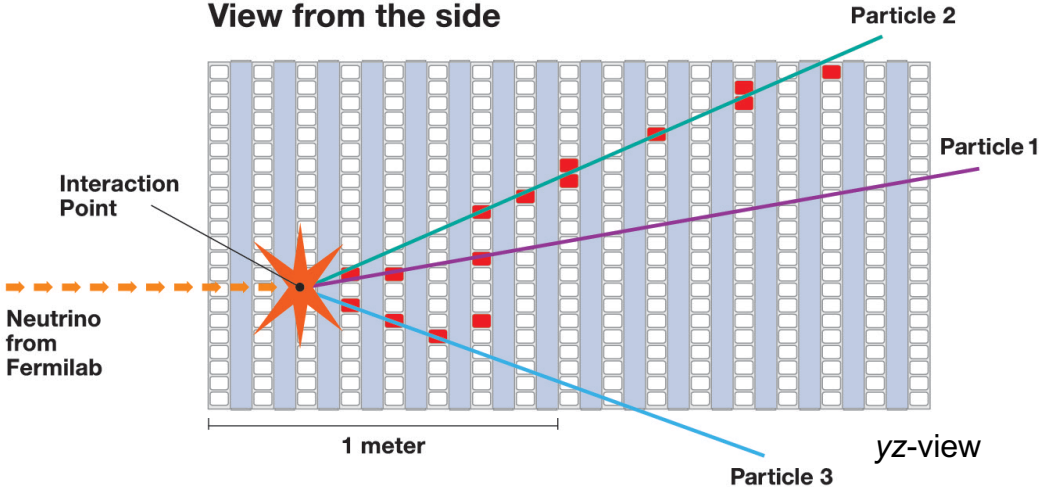
3D schematic of NOvA particle detector



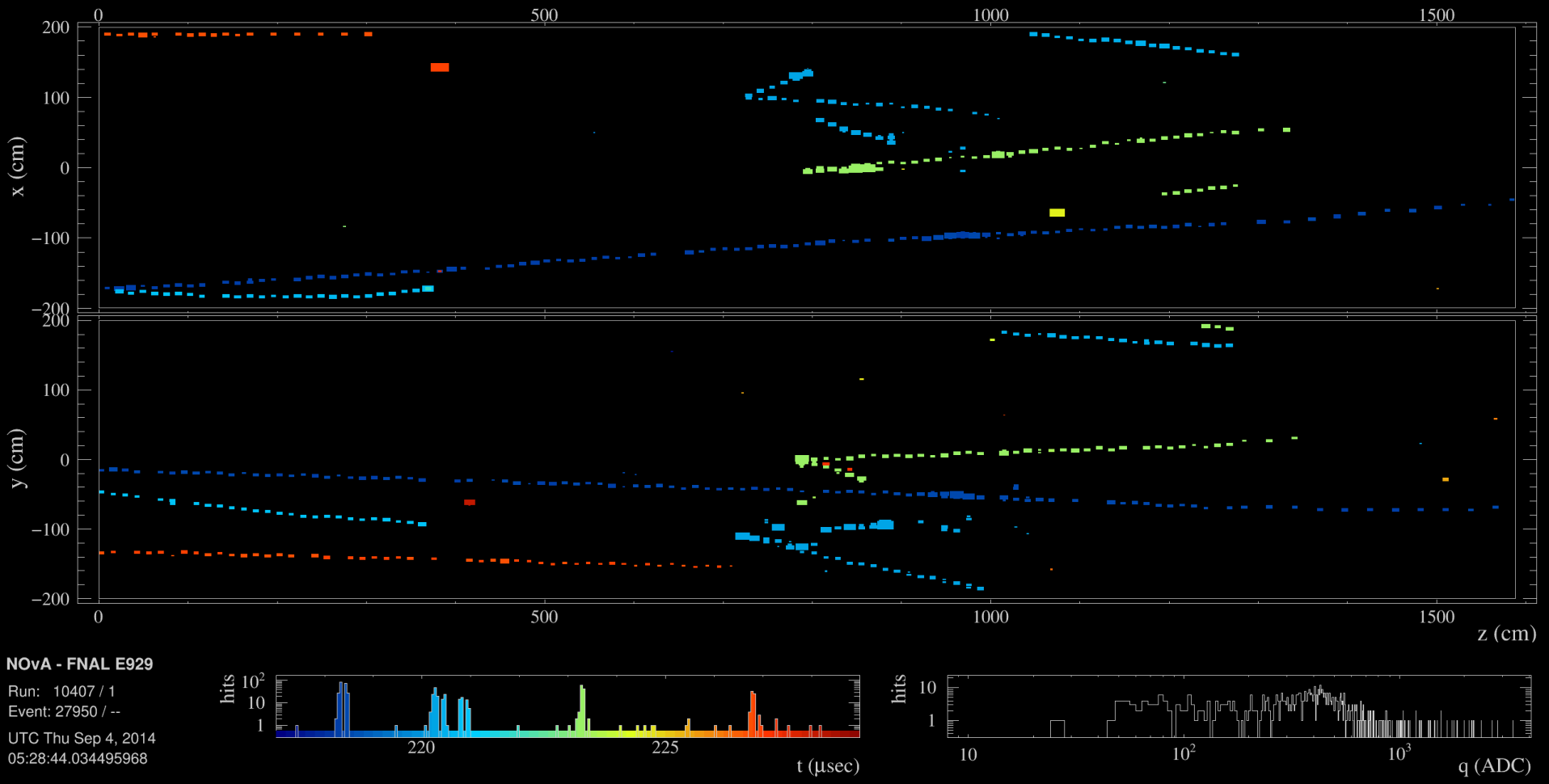
View from the top



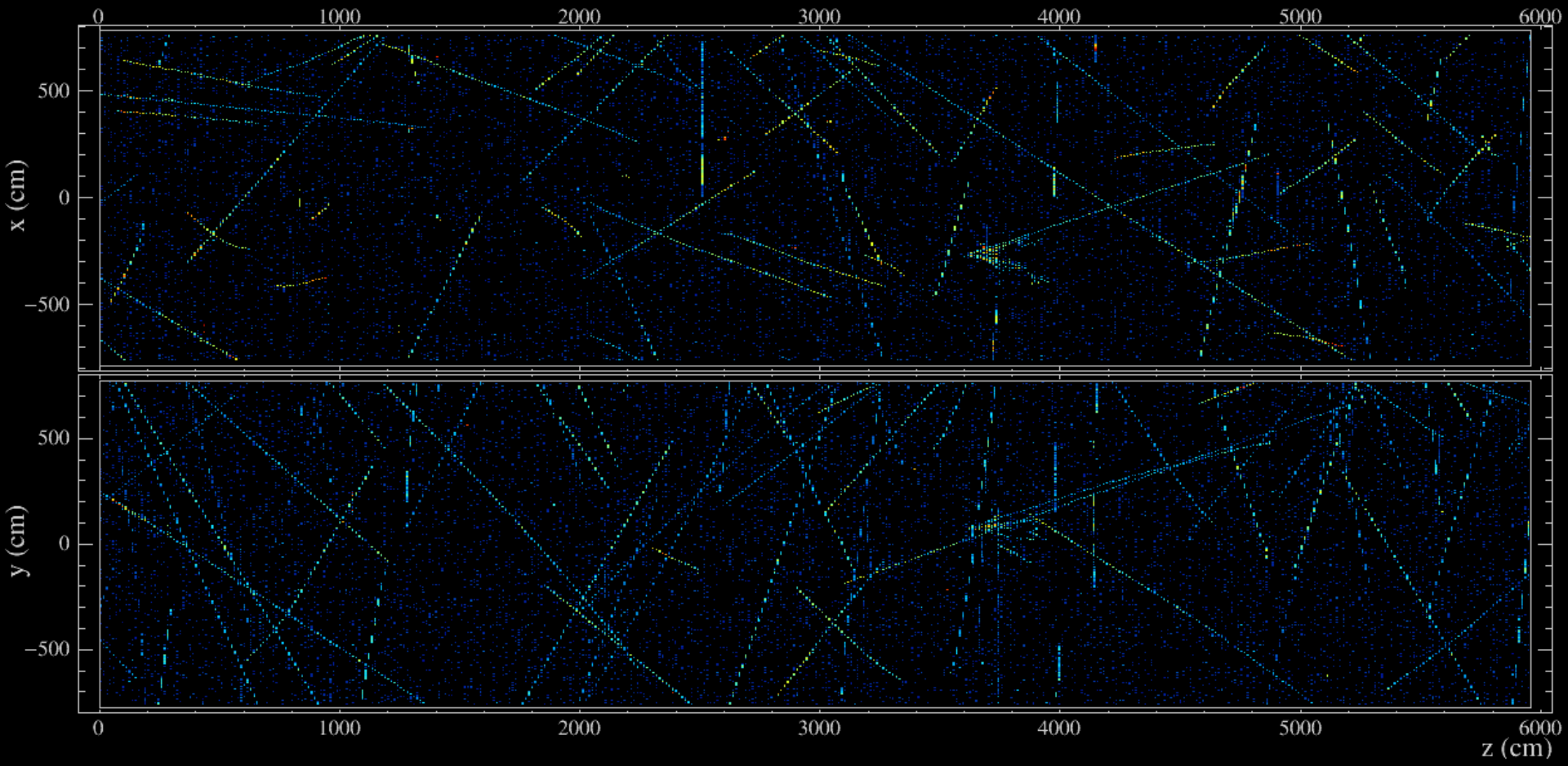
View from the side



Near Detector Event Display



Far Detector Event Display



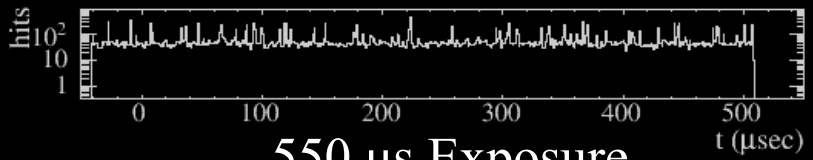
NOvA - FNAL E929

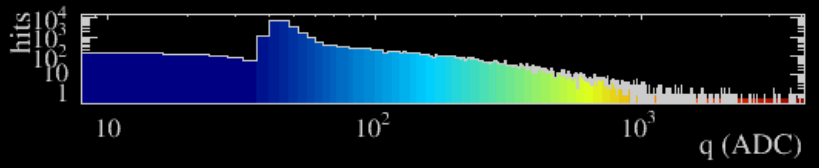
Run: 18620 / 13

Event: 178402 / --

UTC Fri Jan 9, 2015

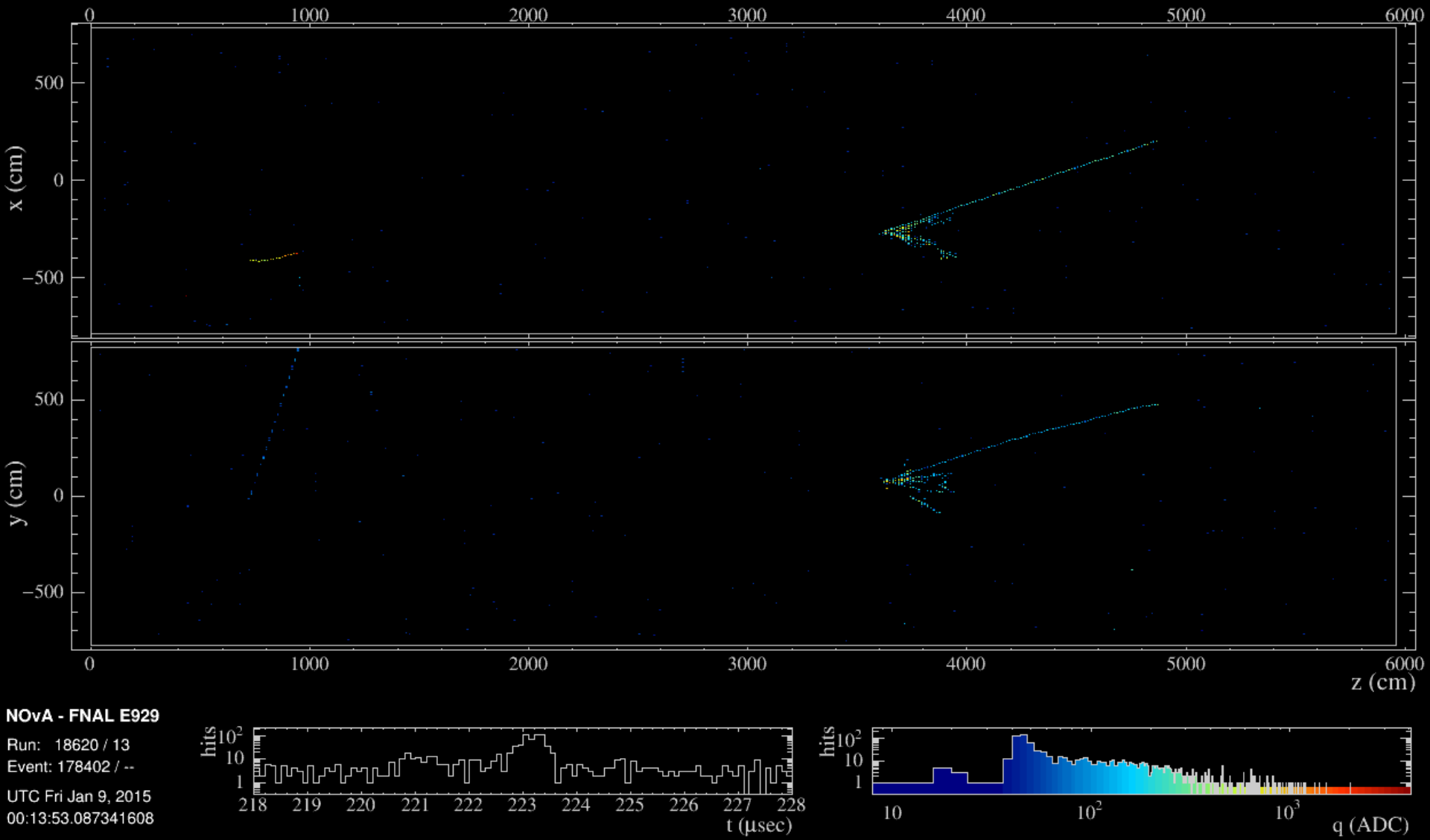
00:13:53.087341608





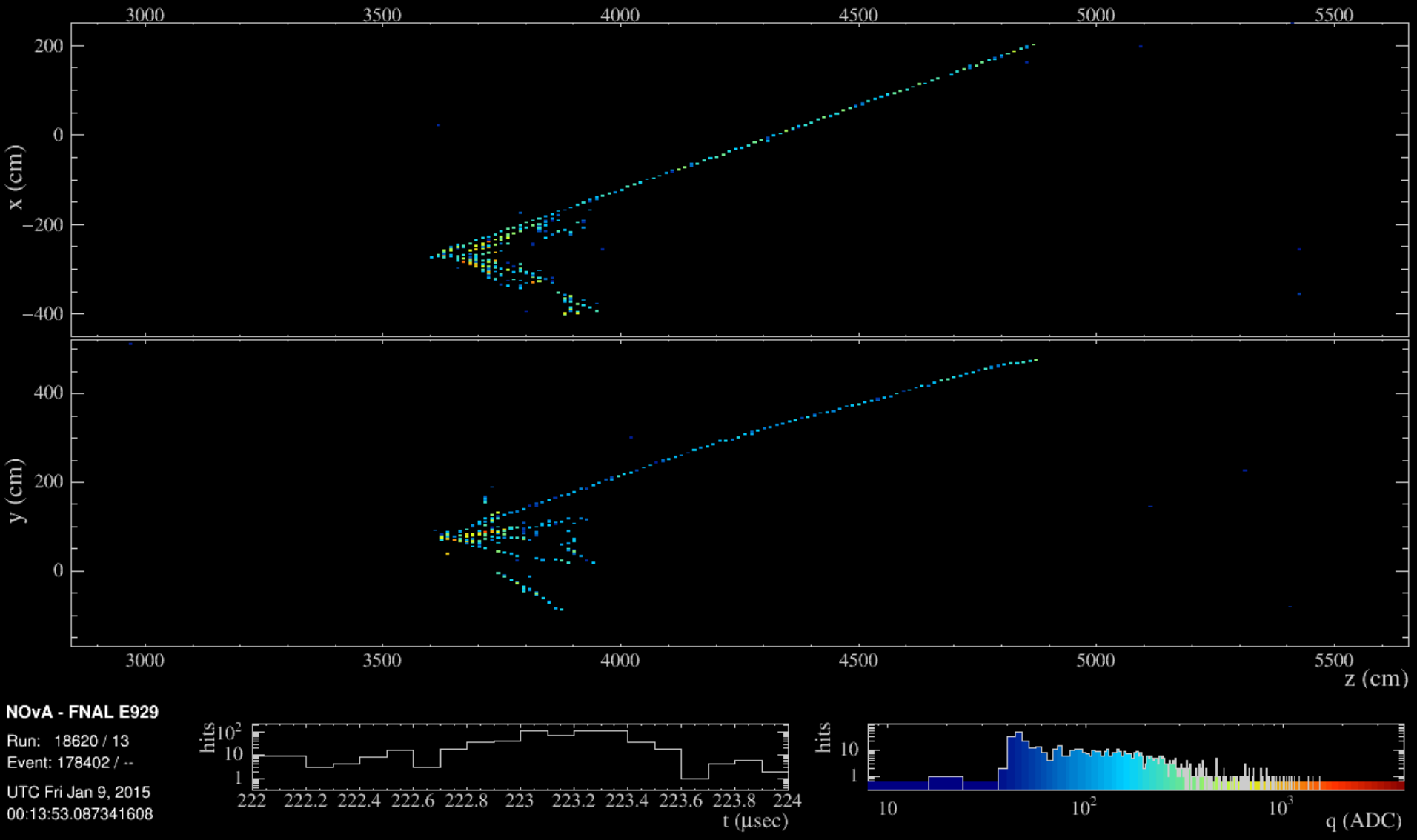
550 μs Exposure

Time Zoom on NuMI Beam Pulse



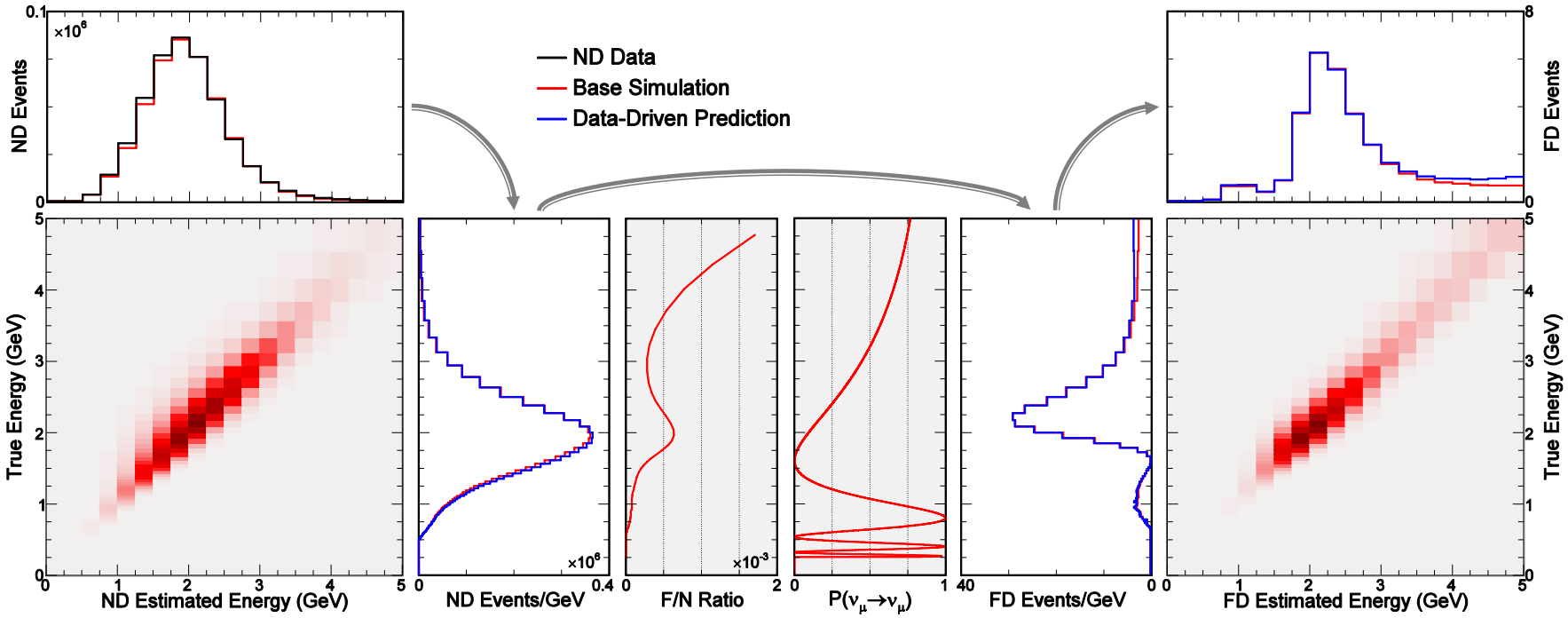
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608

Close-Up of Neutrino Interaction

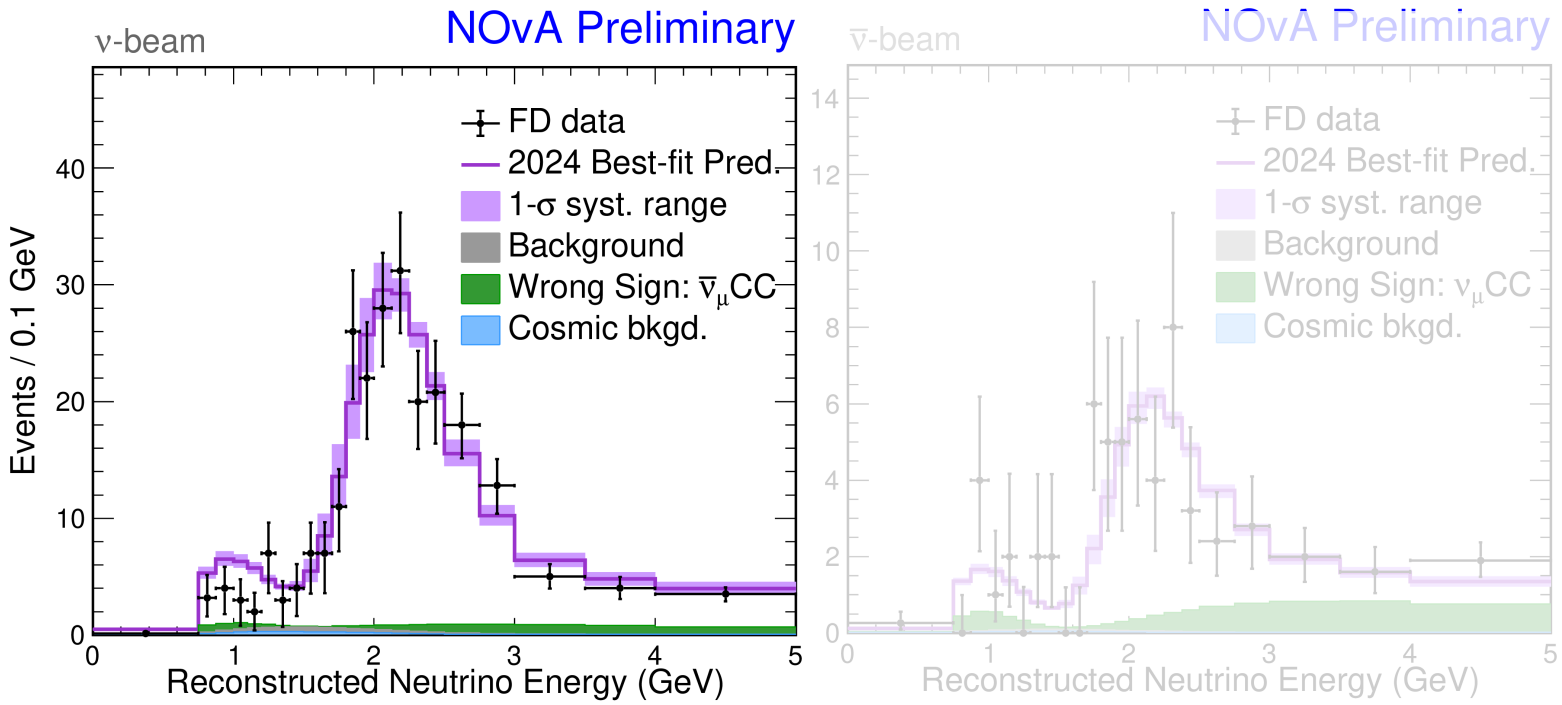


Far Detector Neutrino Prediction

- 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

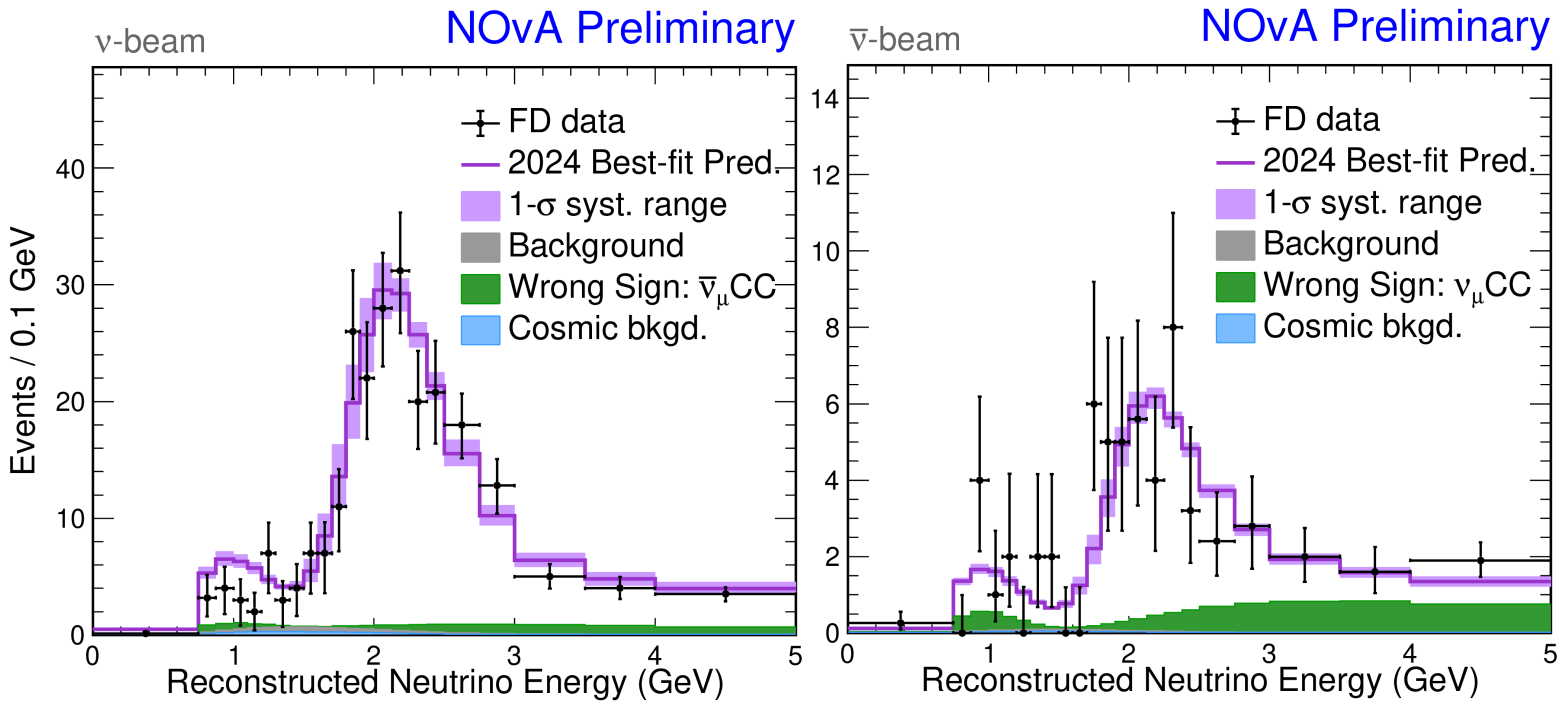


Muon Neutrino Events



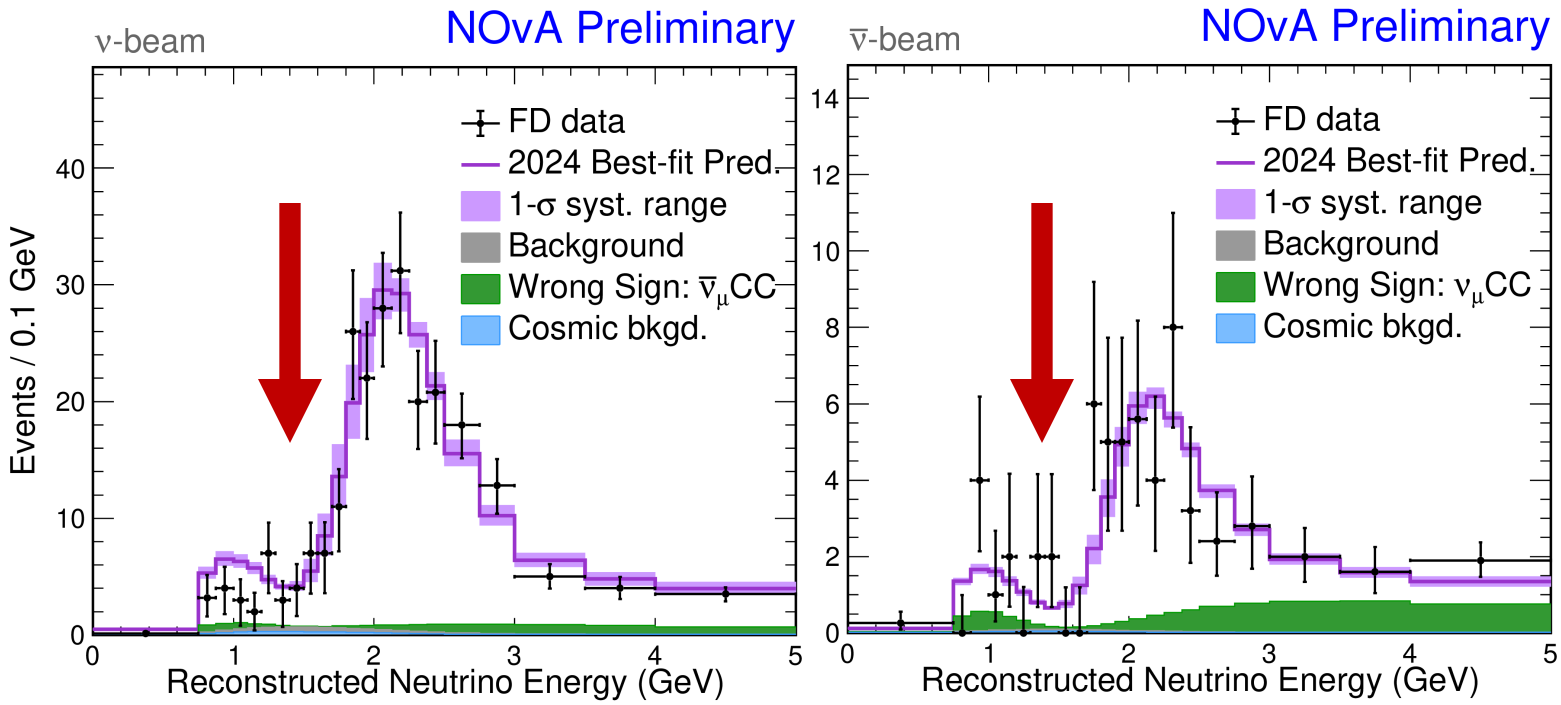
- Muon neutrino event counts:
  - 384 ν_μ candidates (beam: 26.6 x 10^{20} POT)
  - 106 anti-ν_μ candidates (beam: 12.5 x 10^{20} POT)
- Note the dip in the energy spectra indicating the disappearance of muon neutrinos

Muon Neutrino Events



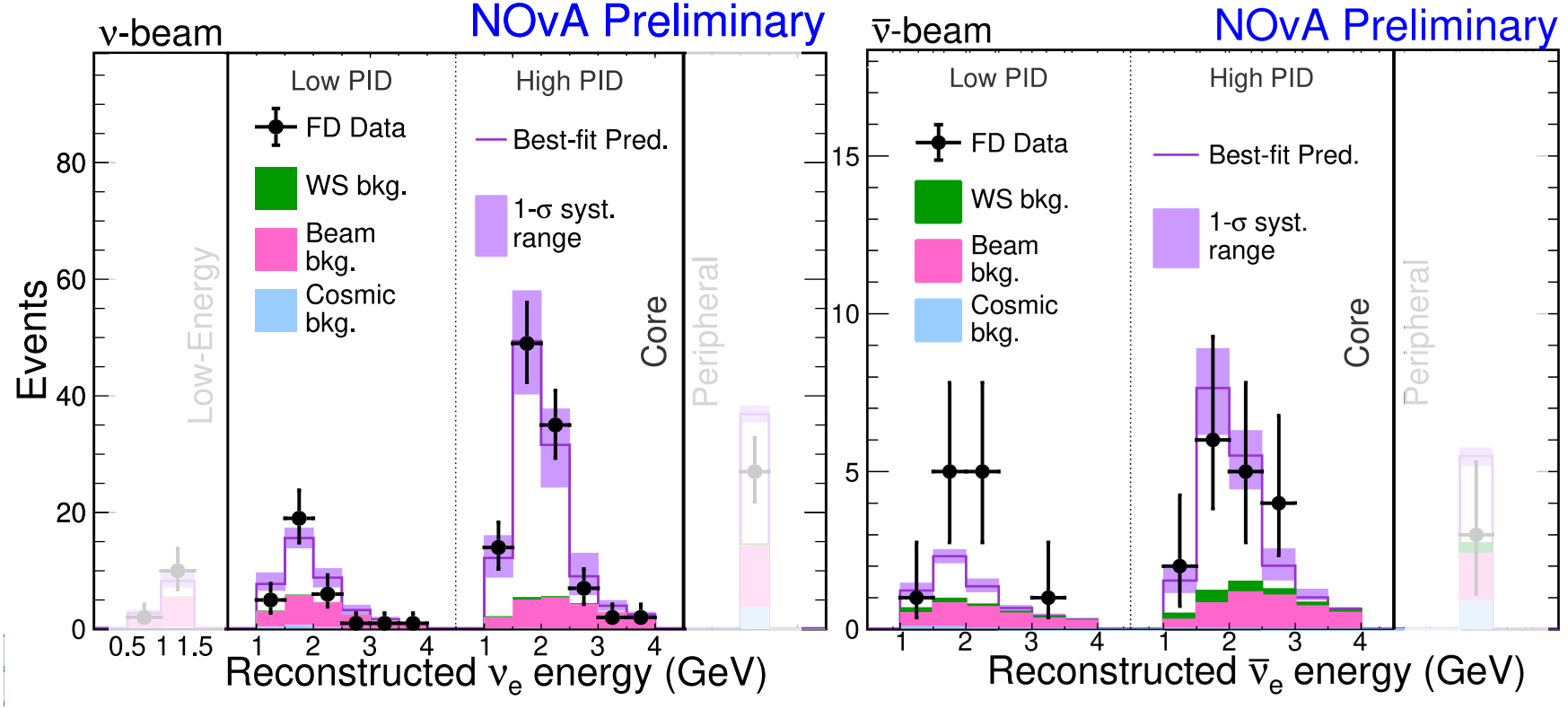
- Muon neutrino event counts:
  - 384 ν_μ candidates (beam: 26.6 x 10^{20} POT)
  - 106 anti-ν_μ candidates (beam: 12.5 x 10^{20} POT)
- Note the dip in the energy spectra indicating the disappearance of muon neutrinos

Muon Neutrino Events



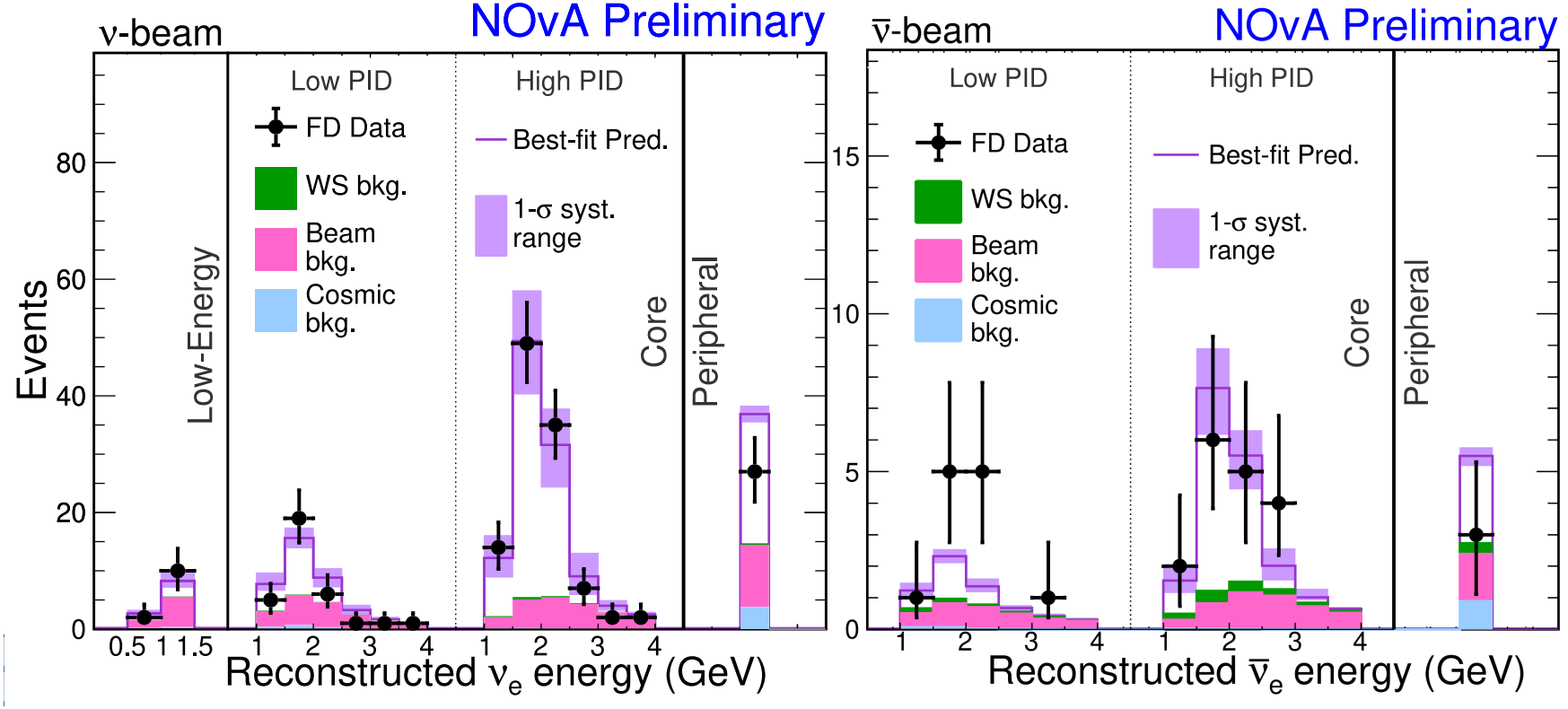
- Muon neutrino event counts:
  - 384 ν_μ candidates (beam: 26.6 x 10^{20} POT)
  - 106 anti-ν_μ candidates (beam: 12.5 x 10^{20} POT)
- Note the dip in the energy spectra indicating the disappearance of muon neutrinos

Electron Neutrino Events



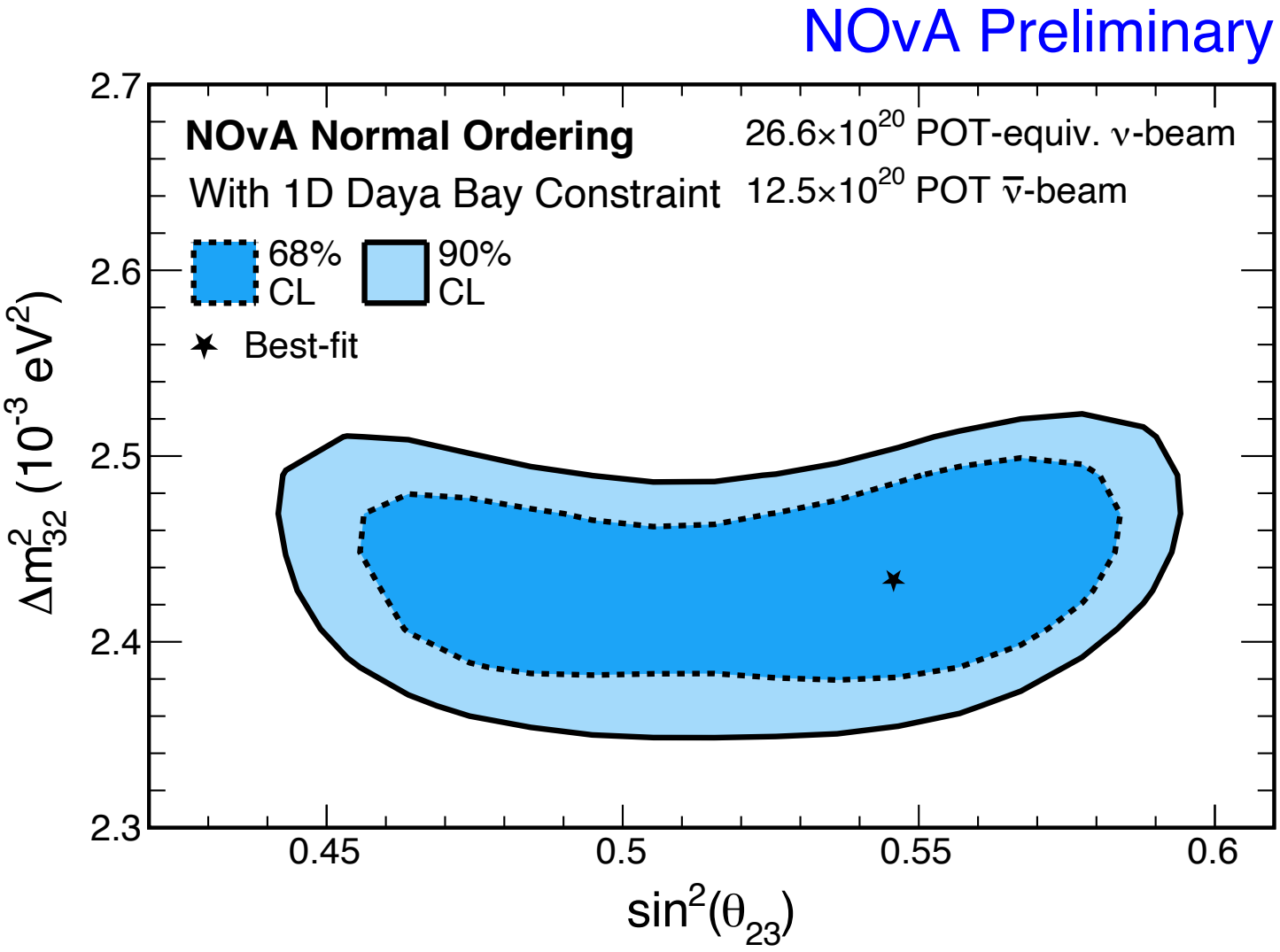
- Electron neutrino event counts
  - 181 ν_e candidates (beam: 26.6 x 10^{20} POT)
  - 32 anti-ν_e candidates (beam: 12.5 x 10^{20} POT)
- Samples divided into four selections:
  - Low-Energy, Low Particle ID (PID), High PID and Peripheral

Electron Neutrino Events

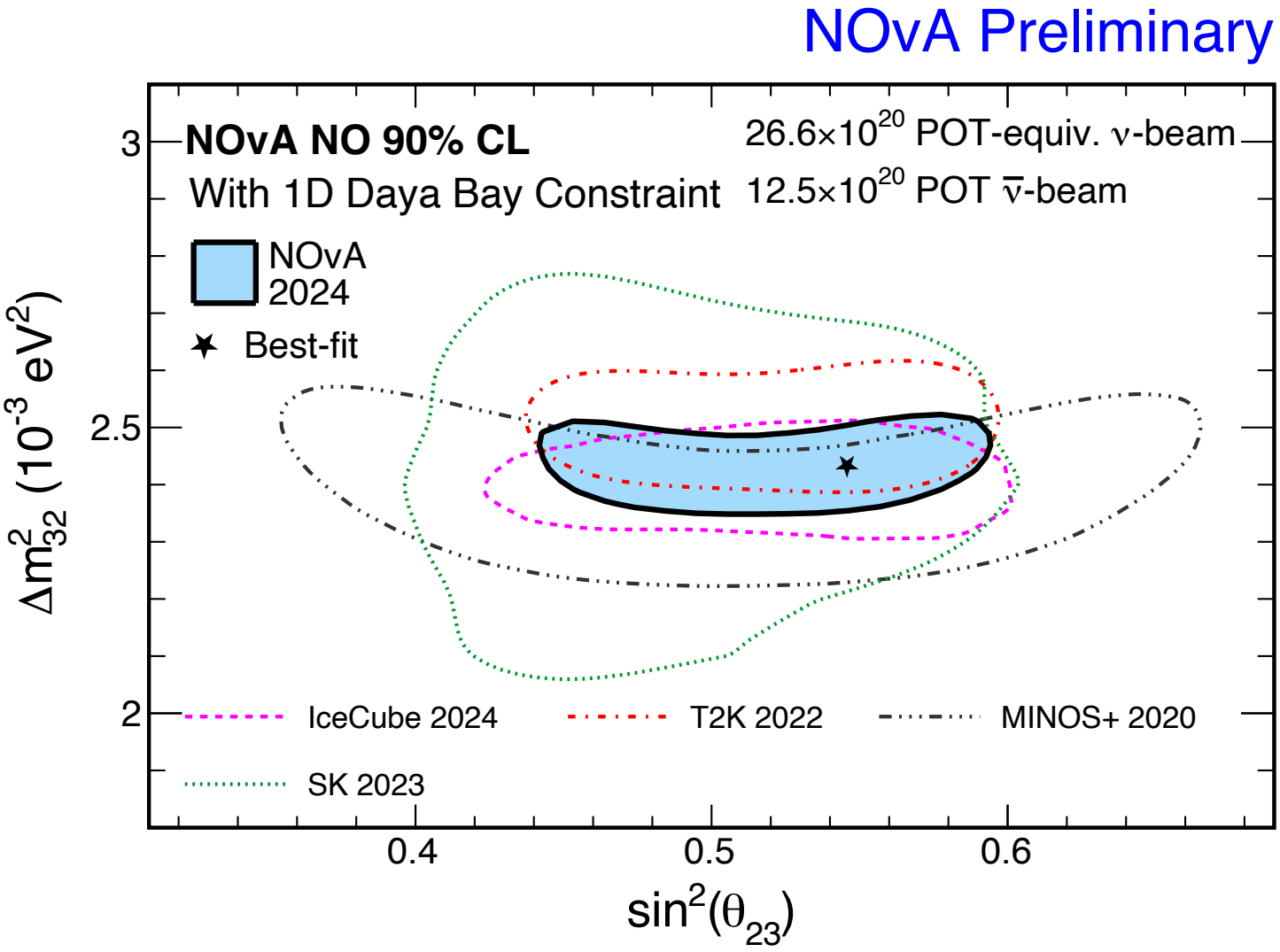


- Electron neutrino event counts
  - 181 ν_e candidates (beam: 26.6 x 10^{20} POT)
  - 32 anti-ν_e candidates (beam: 12.5 x 10^{20} POT)
- Samples divided into four selections:
  - Low-Energy, Low Particle ID (PID), High PID and Peripheral

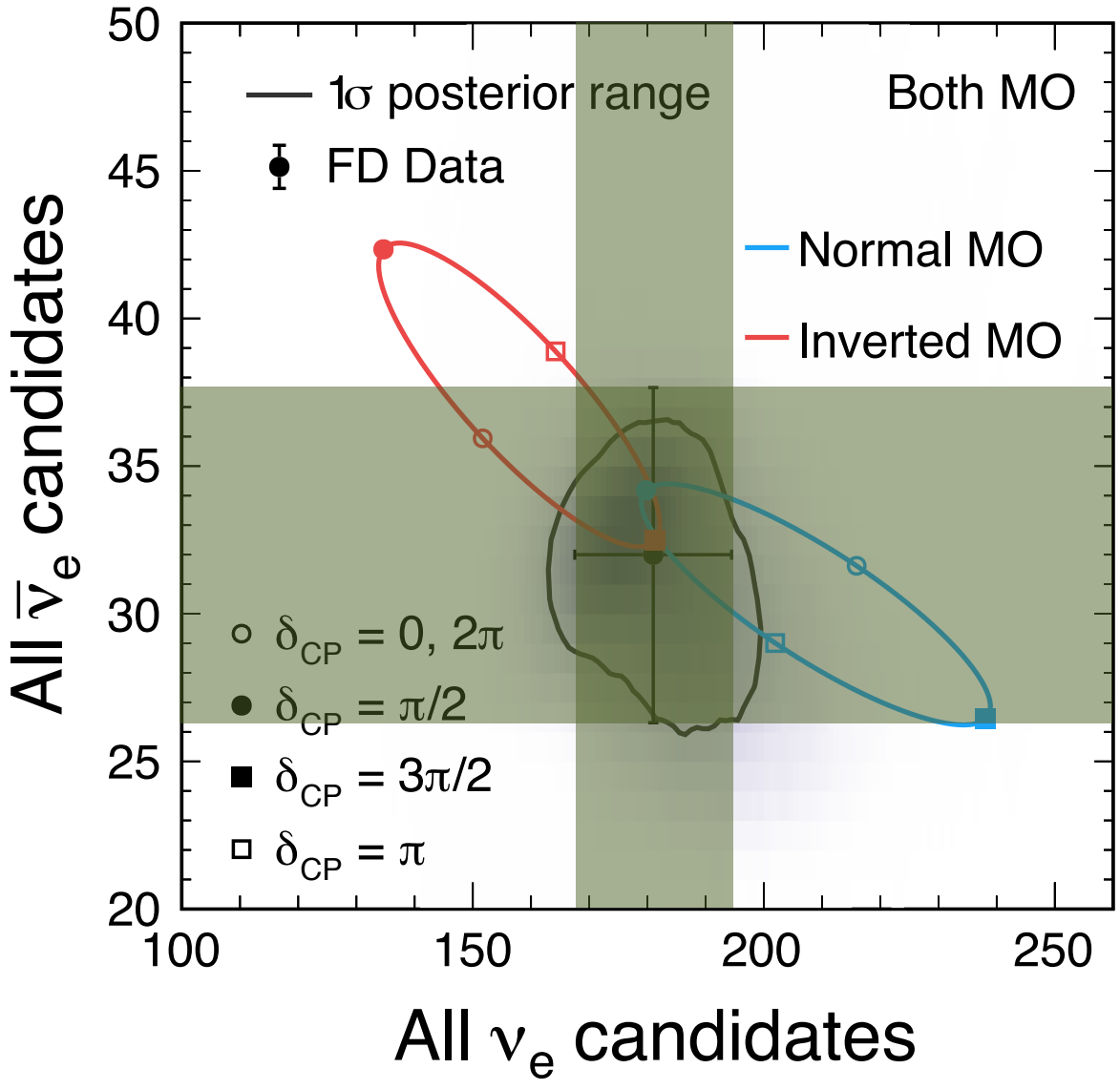
Extract Nature's Parameters



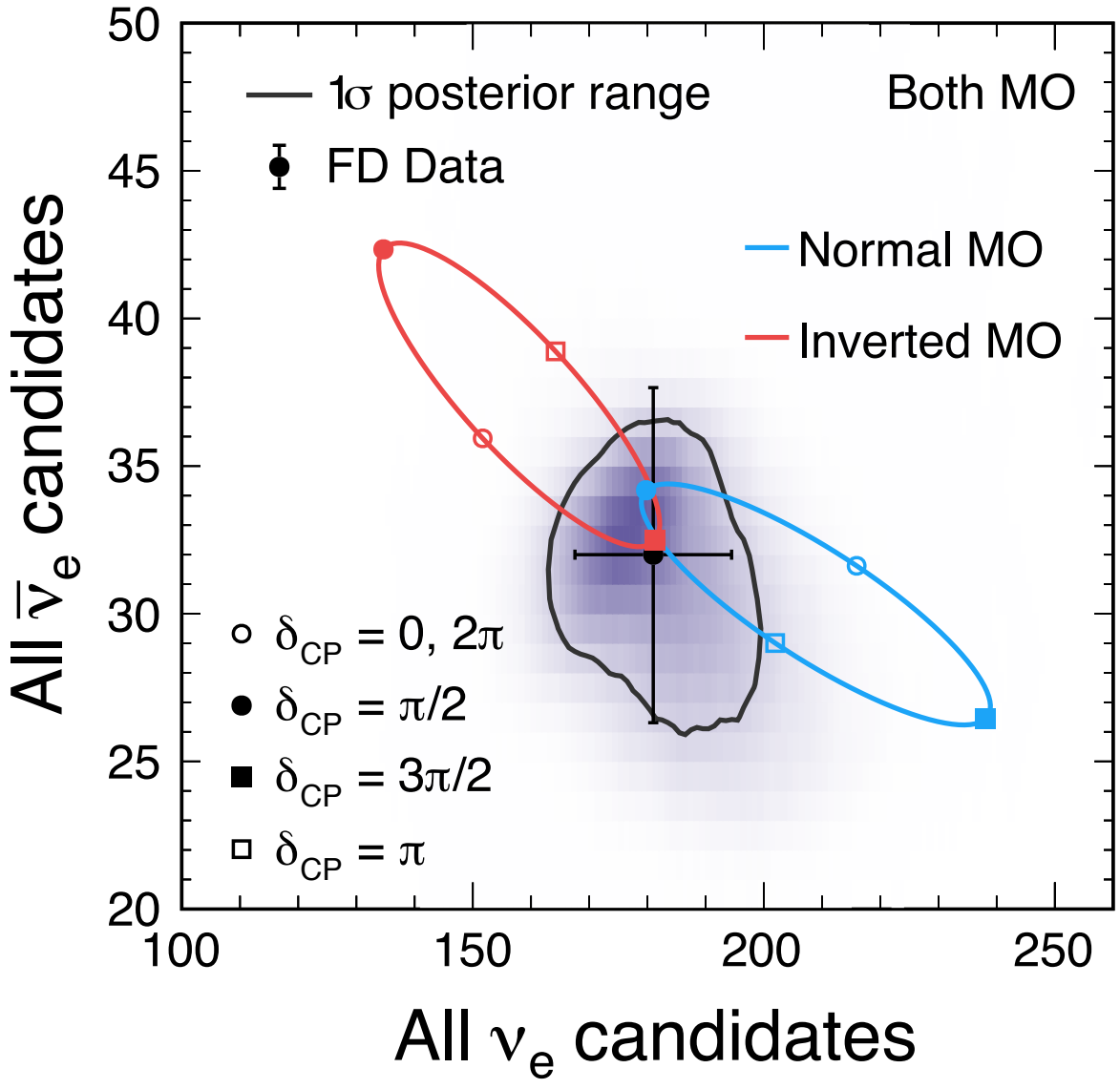
Extract Nature's Parameters



Extract Nature's Parameters

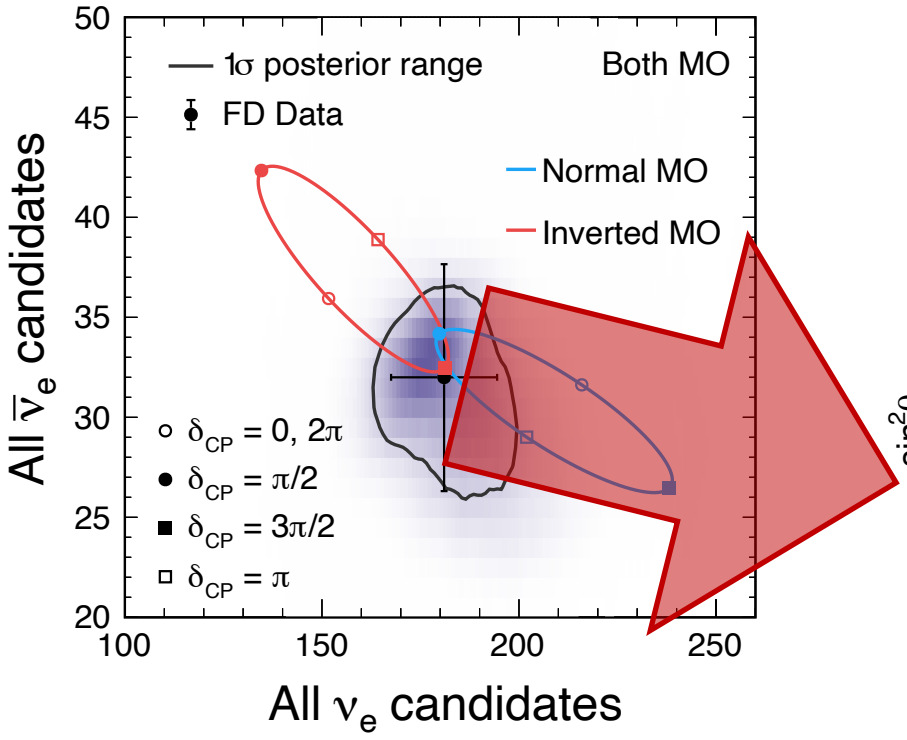


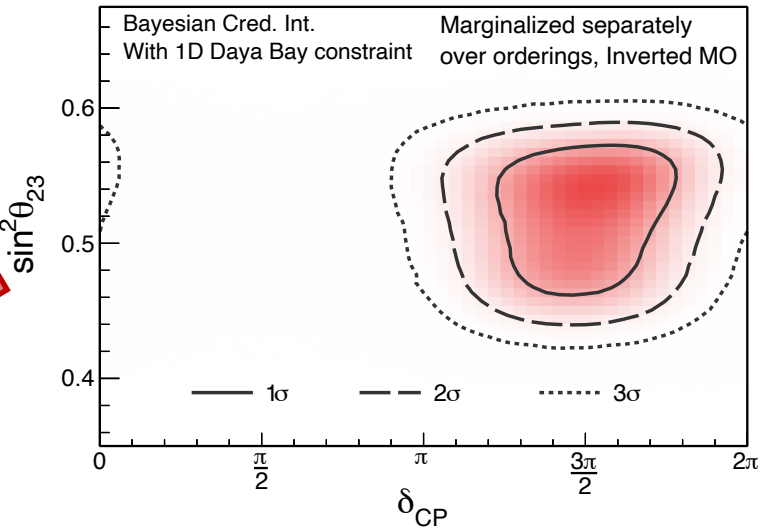
Extract Nature's Parameters



Extract Nature's Parameters

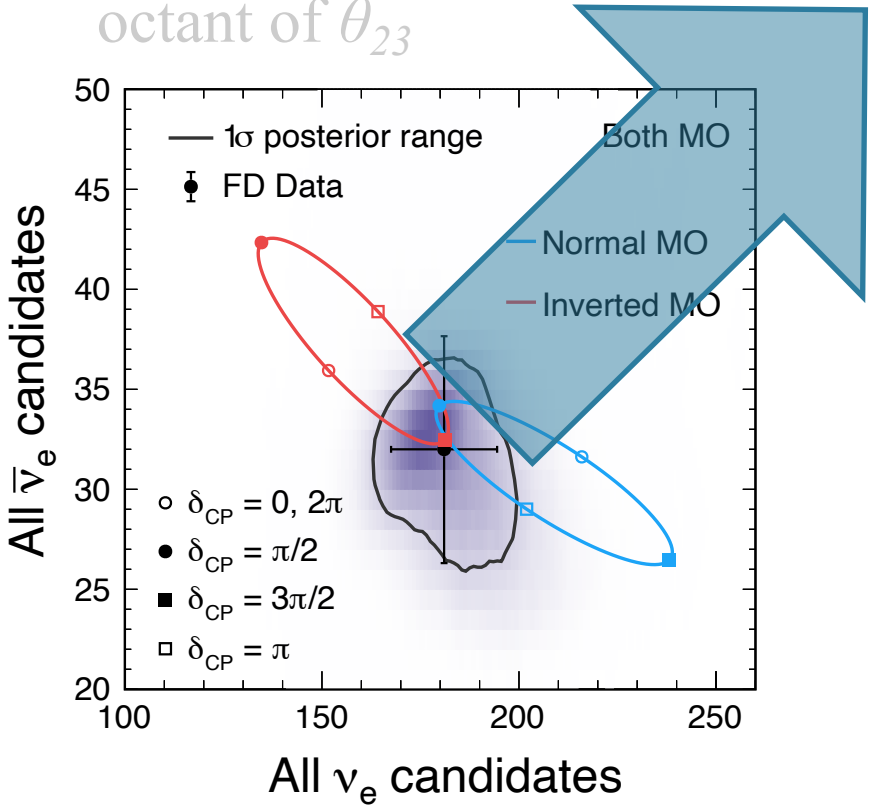
- Mild preference for normal ordering
- Mild preference for upper octant of θ_{23}

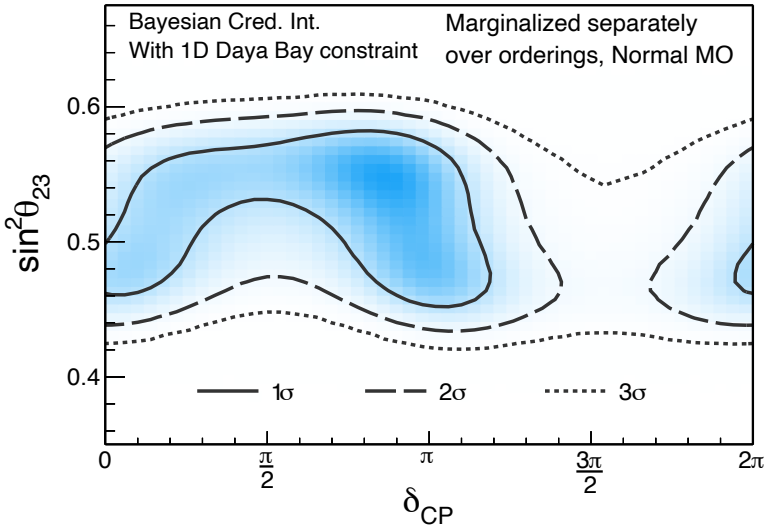


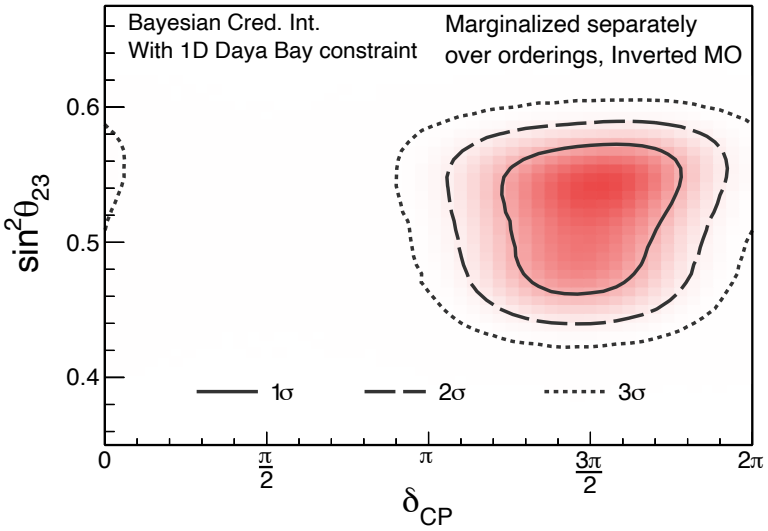


Extract Nature's Parameters

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

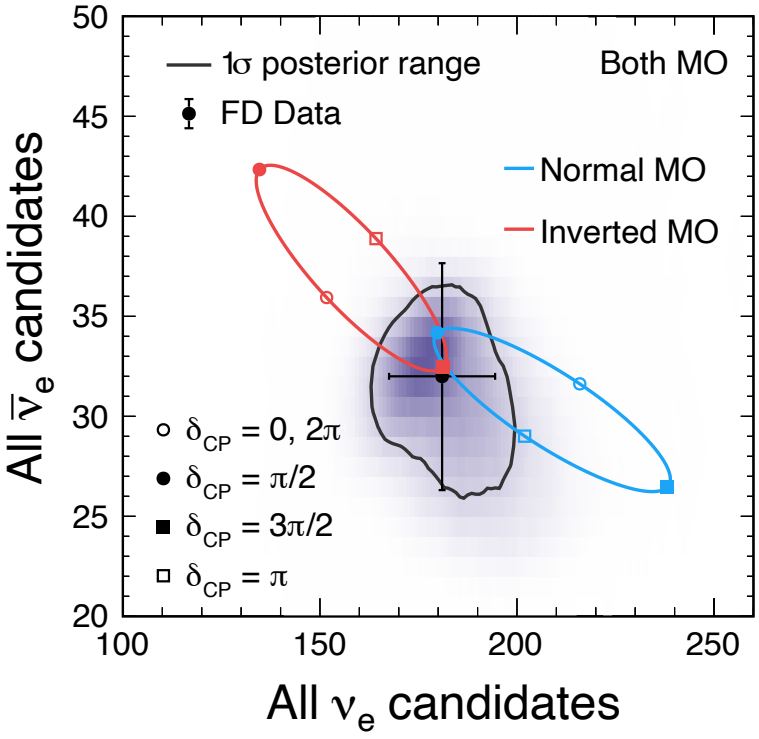


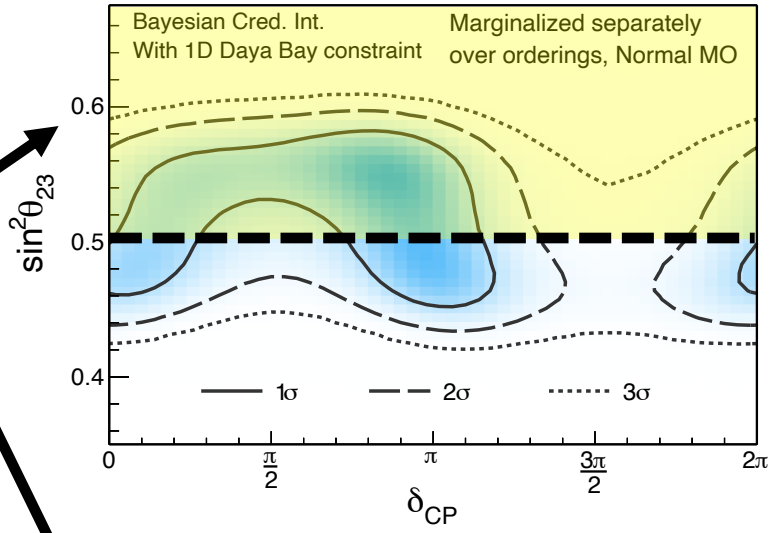


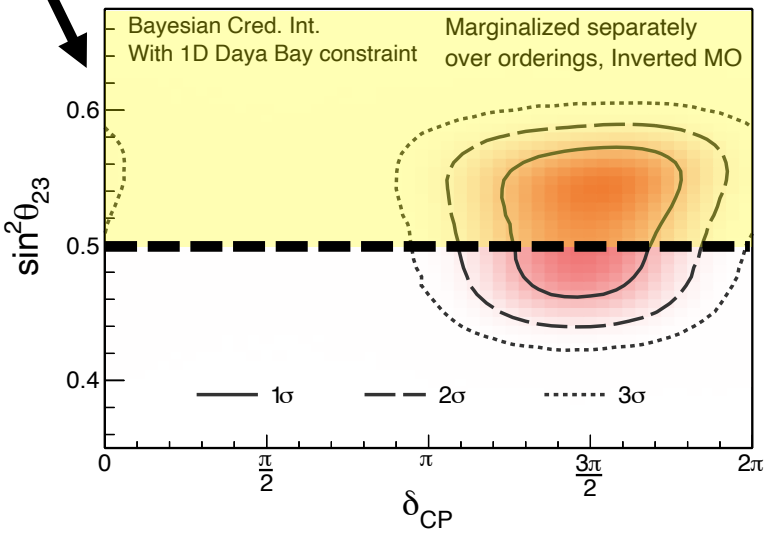


Extract Nature's Parameters

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

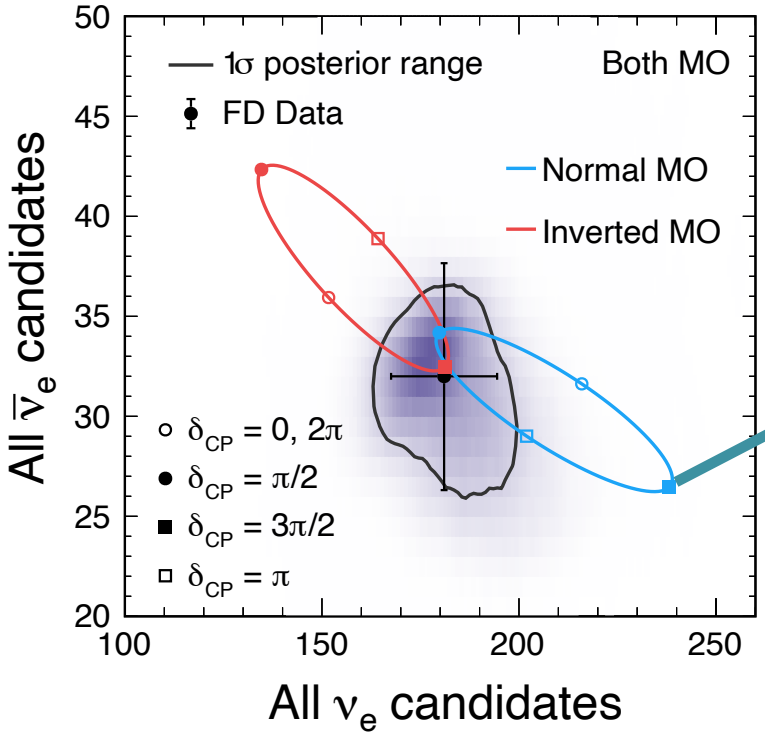


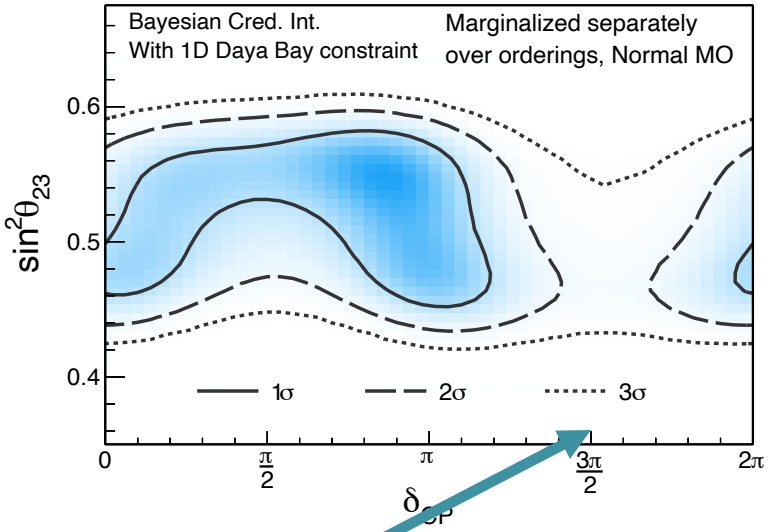


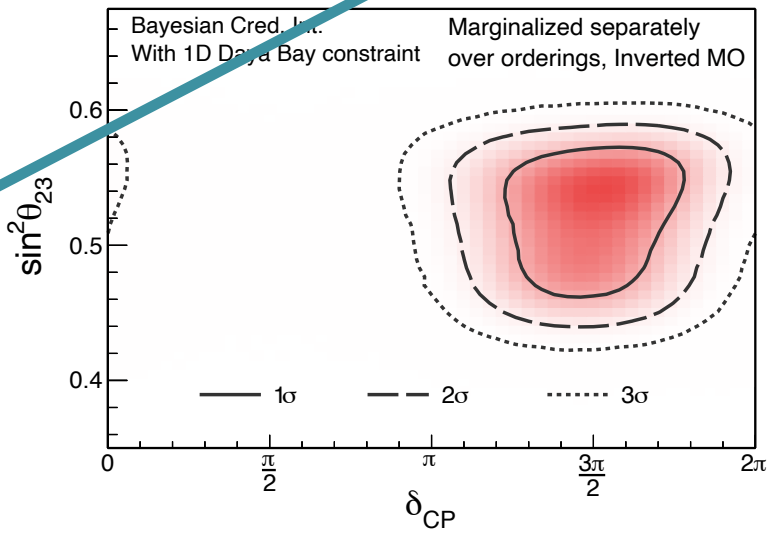


Extract Nature's Parameters

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

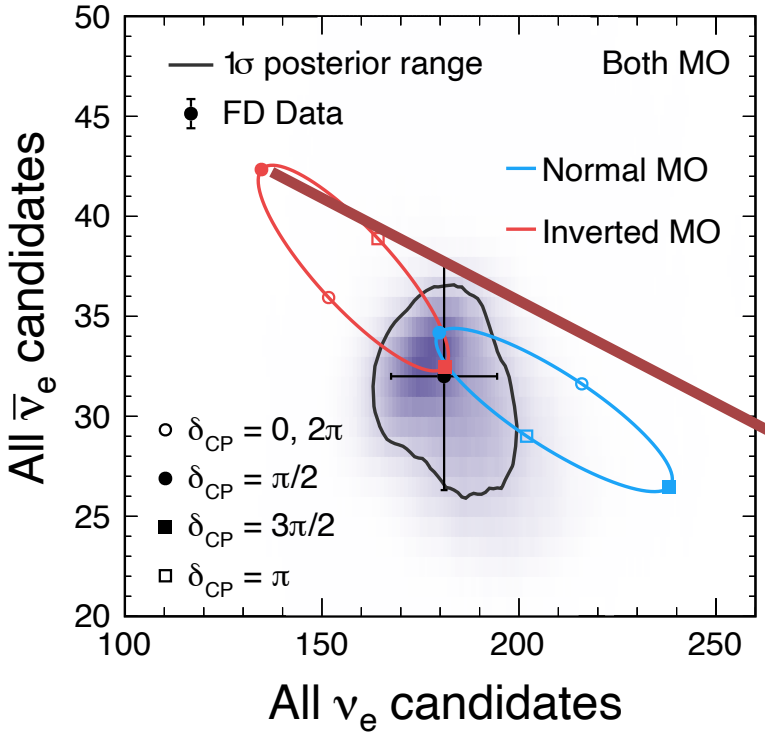


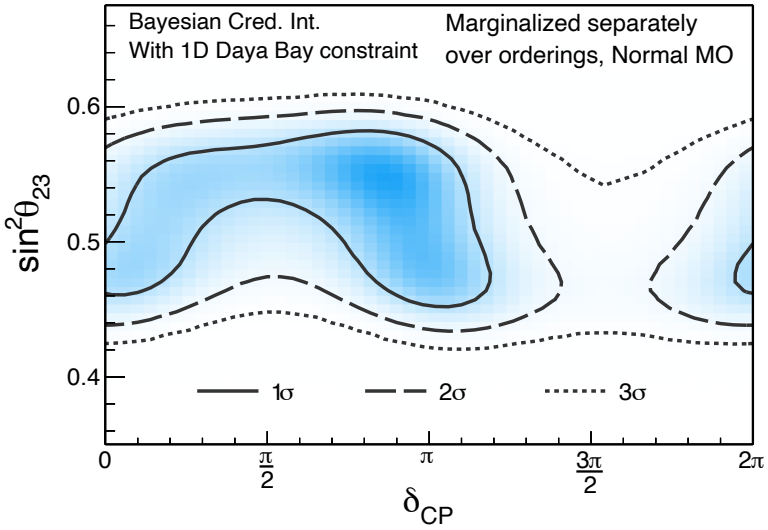


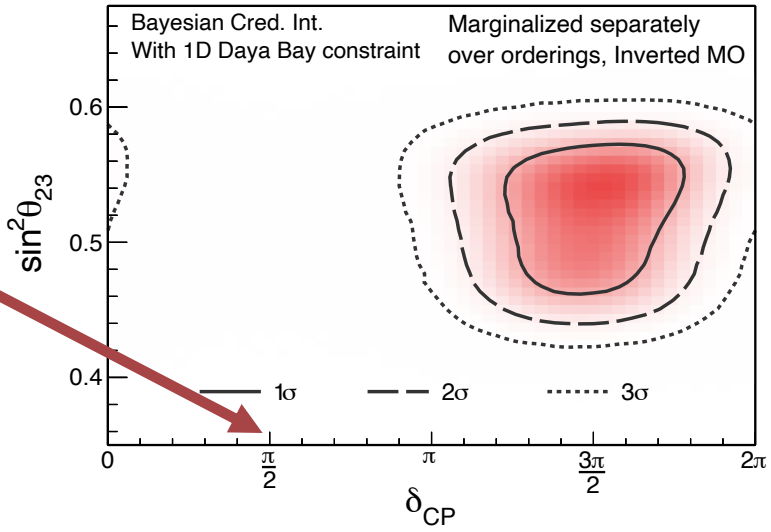


Extract Nature's Parameters

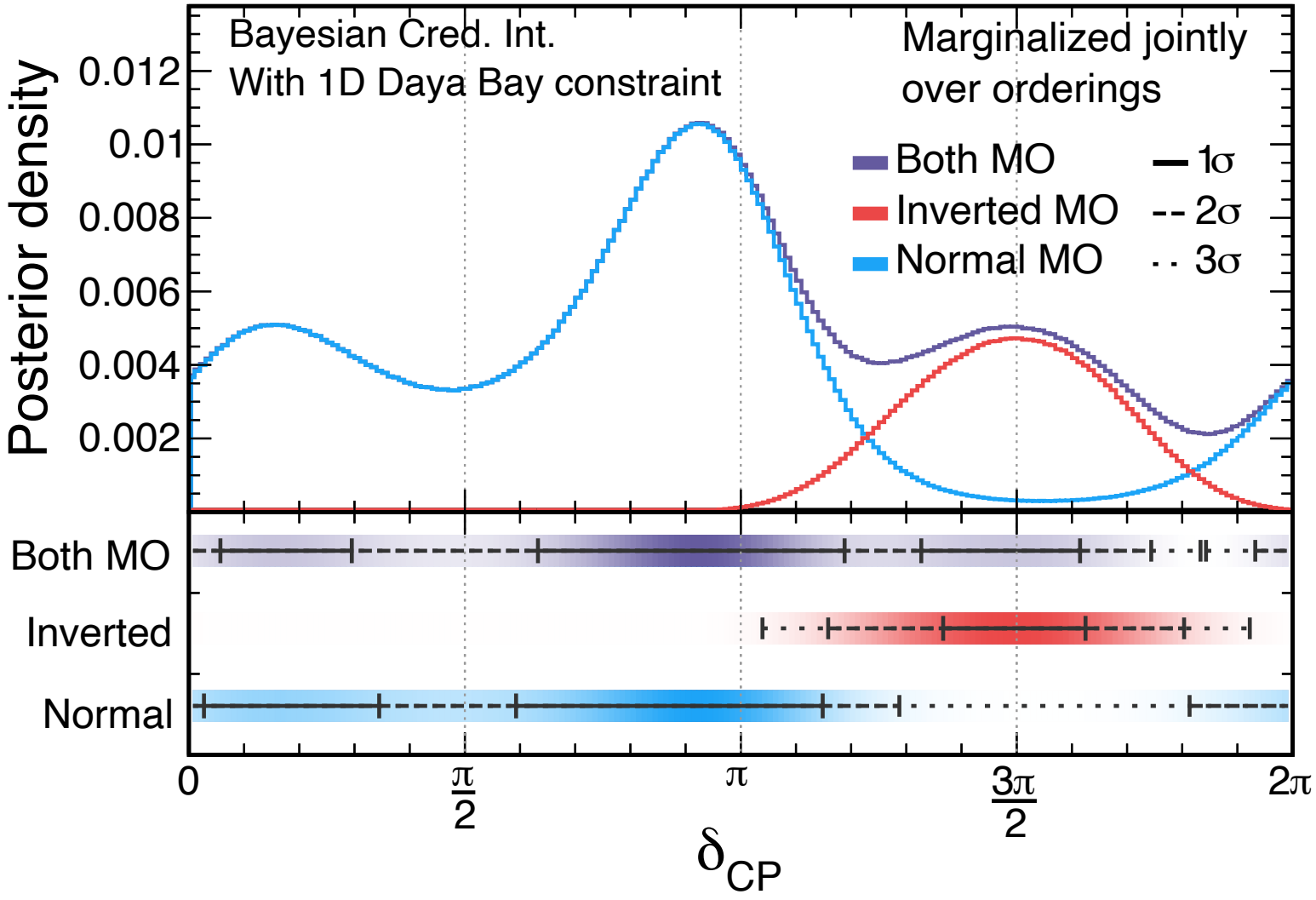
- Mild preference for normal ordering
- Mild preference for upper octant of θ_{23}







Extract Nature's Parameters



Neutrino Oscillation Results

- We measured the most precise single-experiment constraint on the atmospheric neutrino mass-splitting!

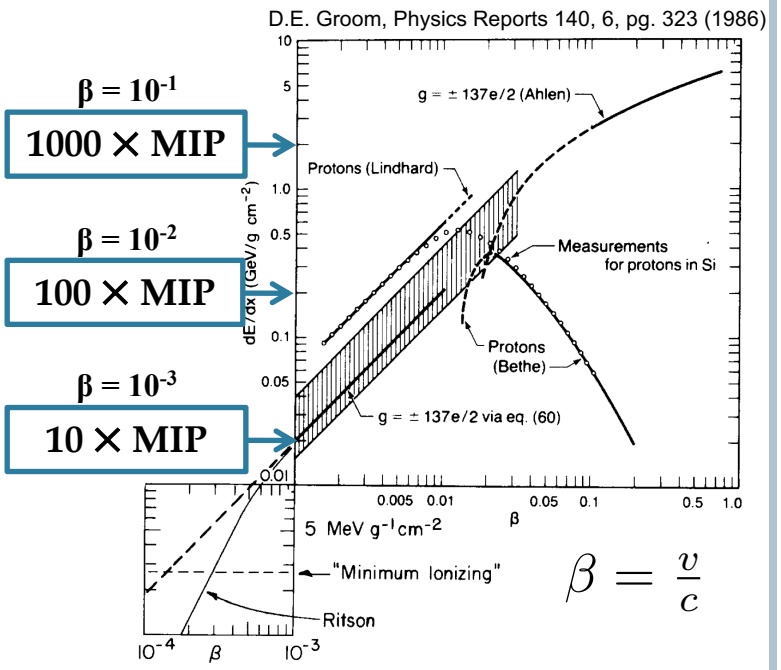
Parameter	Best-fit	Normal Ordering Preference (σ)	
$\sin^2(\theta_{23})$	$0.546^{+0.032}_{-0.075}$	W/ 1D Daya Bay constraint	p-value 0.1731 $1.36\,\sigma$
$\Delta m^2_{32}\ (10^{-3}\,\mathrm{eV}^2)$	$2.433^{+0.035}_{-0.036}$	W/ 2D Daya Bay constraint	p-value 0.1158 $1.57\,\sigma$
$\delta_{CP}\ (\pi)$	0.875		

XXI Workshop on Neutrino Telescopes

Magnetic Monopole Search

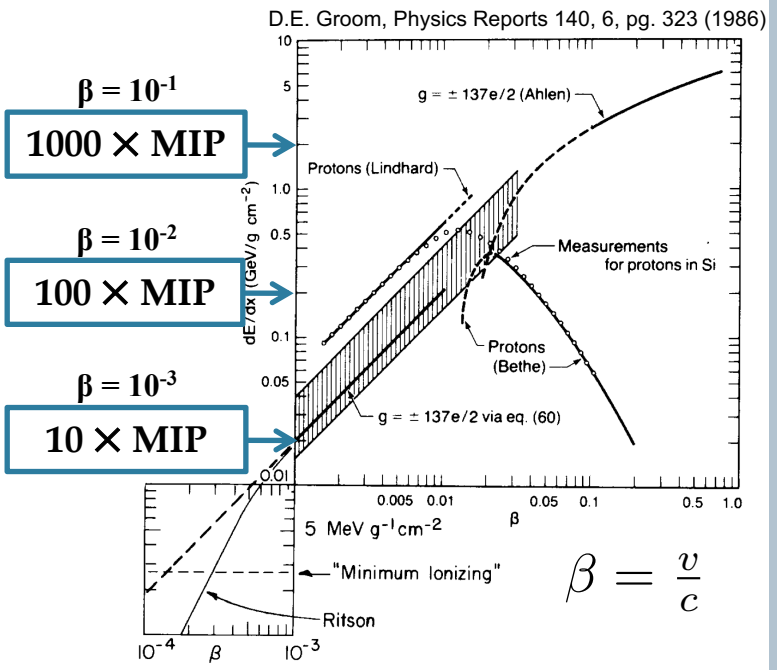
Magnetic Monopole Search

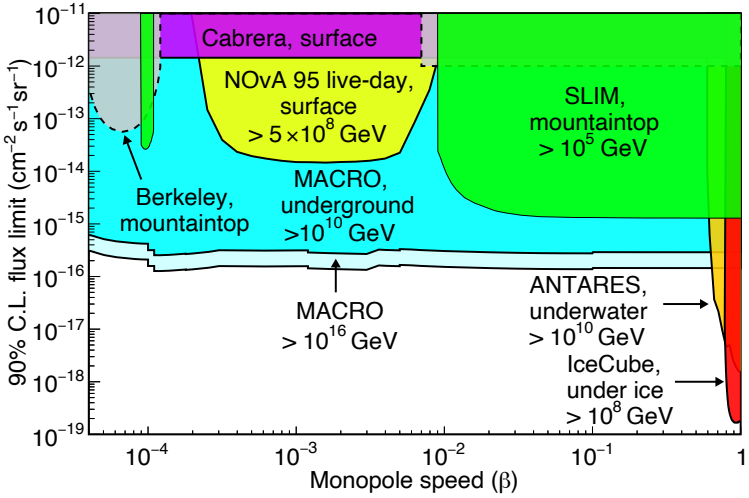
- **"The magnetic monopole is the most venerable member of the mythological bestiary of physics."**
  – Don Groom
- We search for magnetic monopoles.
- If they exist, they will deposit energy in our detector.
- NOνA has the unique potential to probe a new region of phase space:
  - due to our large surface area
  - and our location on the surface.
- NOνA has dedicated triggers to write out monopole-like events.
- First search published in 2021.



Magnetic Monopole Search

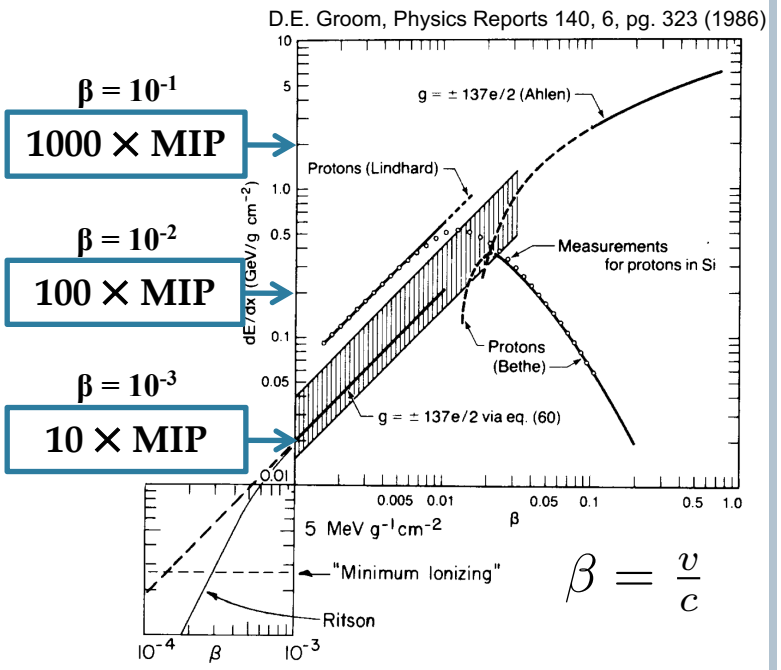
- **"The magnetic monopole is the most venerable member of the mythological bestiary of physics."**
  – Don Groom
- We search for magnetic monopoles.
- If they exist, they will deposit energy in our detector.
- NO*ν*A has the unique potential to probe a new region of phase space:
  - due to our large surface area
  - and our location on the surface.
- NO*ν*A has dedicated triggers to write out monopole-like events.
- First search published in 2021.

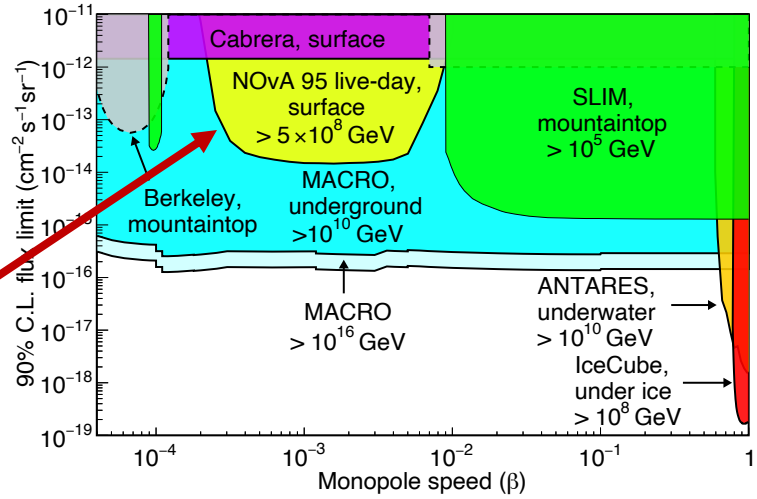




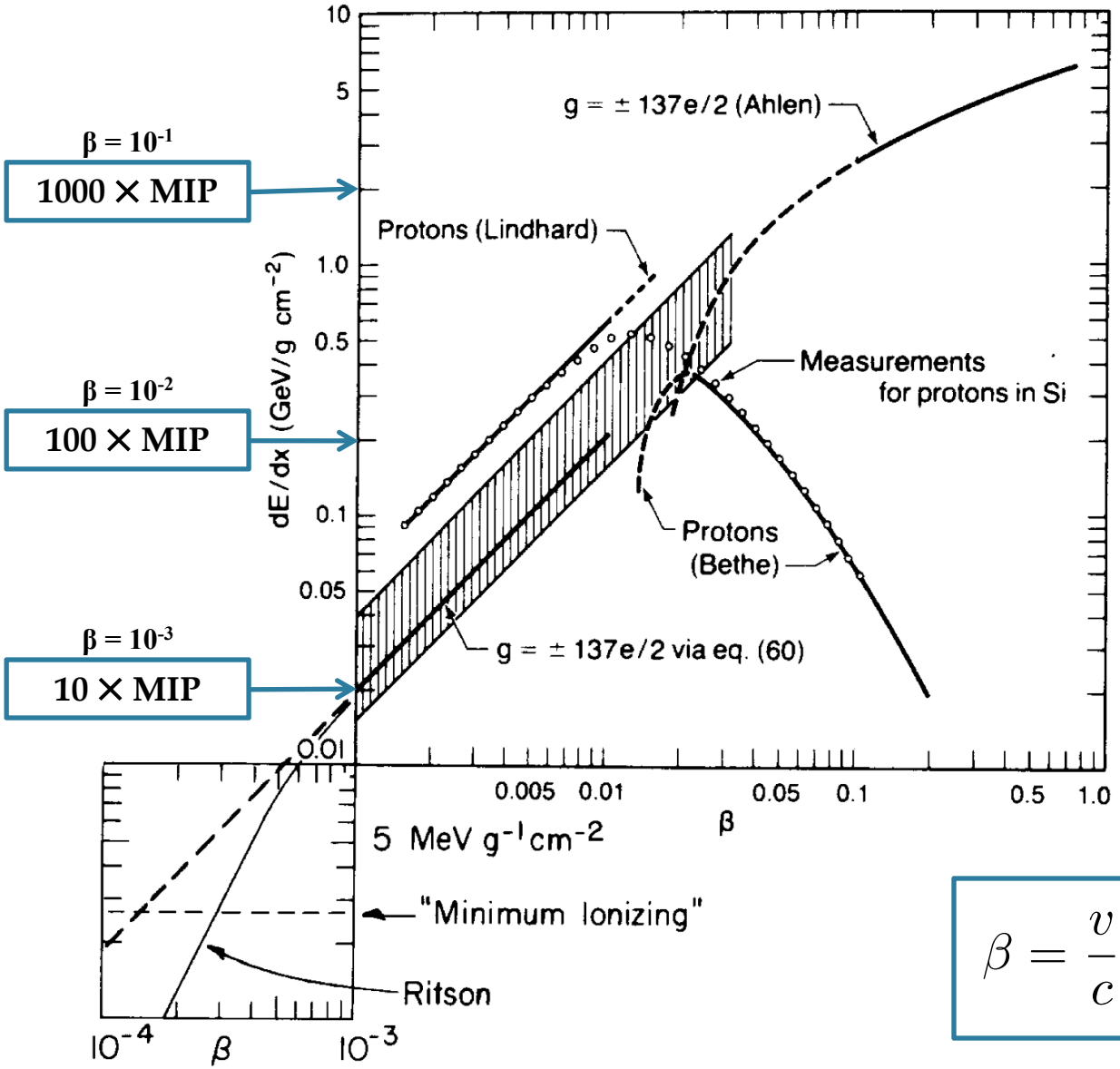
Magnetic Monopole Search

- **"The magnetic monopole is the most venerable member of the mythological bestiary of physics."**
  – Don Groom
- We search for magnetic monopoles.
- If they exist, they will deposit energy in our detector.
- NO*v*A has the unique potential to probe a new region of phase space:
  - due to our large surface area
  - and our location on the surface.
- NO*v*A has dedicated triggers to write out monopole-like events.
- First search published in 2021.





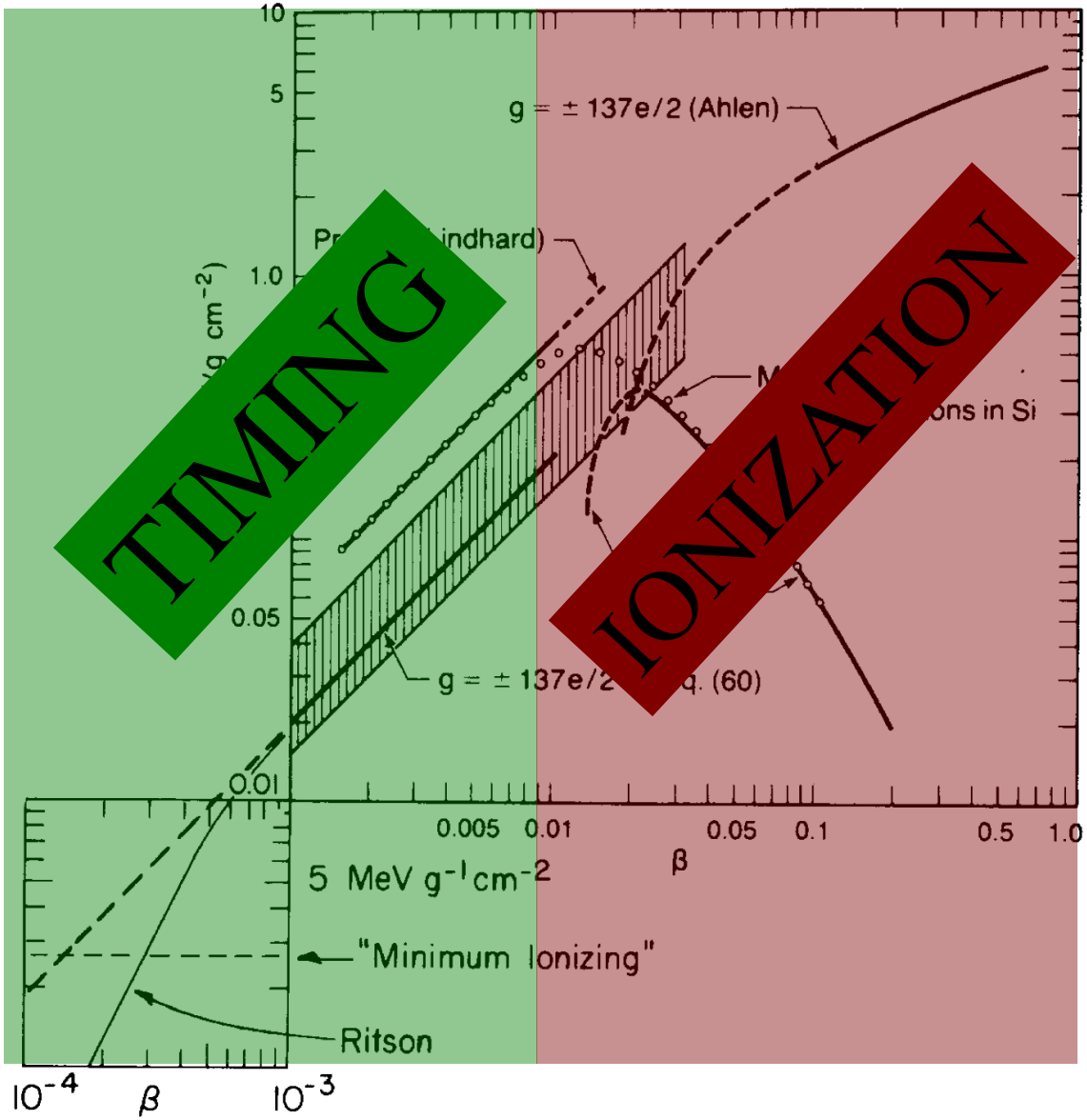
Magnetic Monopole Energy Deposition



- Groom's summary of the magnetic monopole energy deposition as calculated from EM.
- Monopole interaction is similar to particle with charge Z = 69 at high β.

$$\beta = \frac{v}{c} = \frac{\text{velocity}}{\text{speed of light}}$$

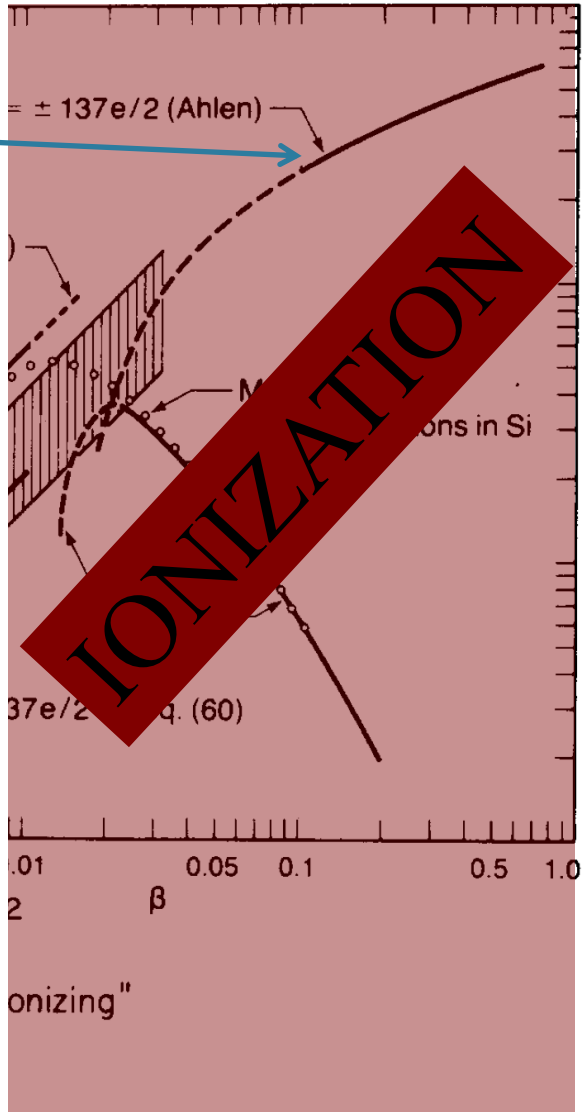
Analysis Strategy



- We divide the magnetic monopole searches into two broad categories based on:
  A. Ionization
  B. Timing

Analysis Strategy

Large energy deposition is suppressed through Birks effect.

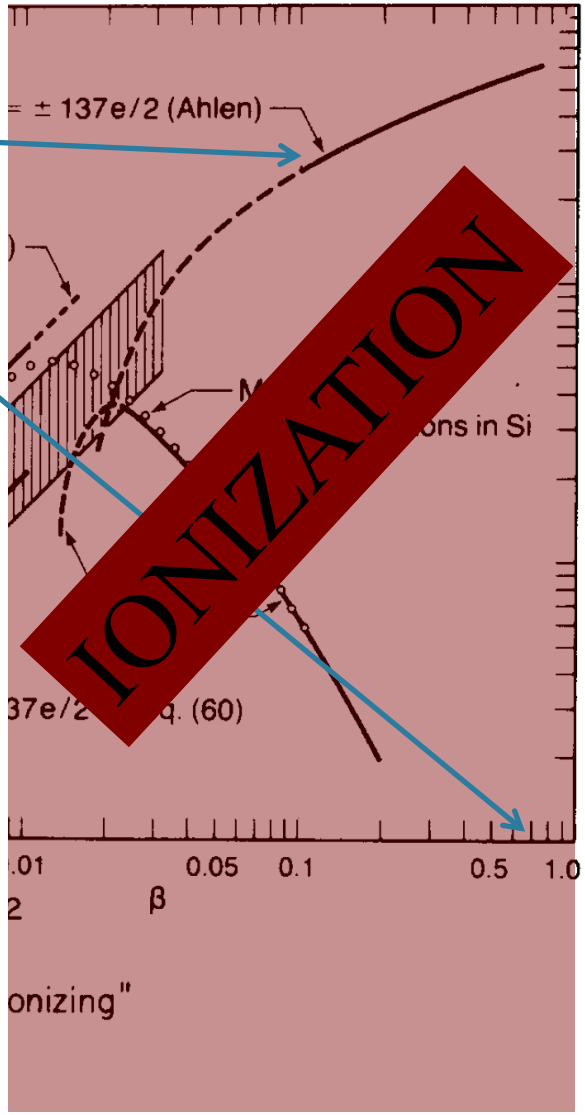


- A lot of work went into verifying that these effects were properly accounted for in our simulation.

Analysis Strategy

Large energy deposition is suppressed through Birks effect.

Fast monopoles ($\beta \gtrsim 0.7$) produce Cherenkov light.

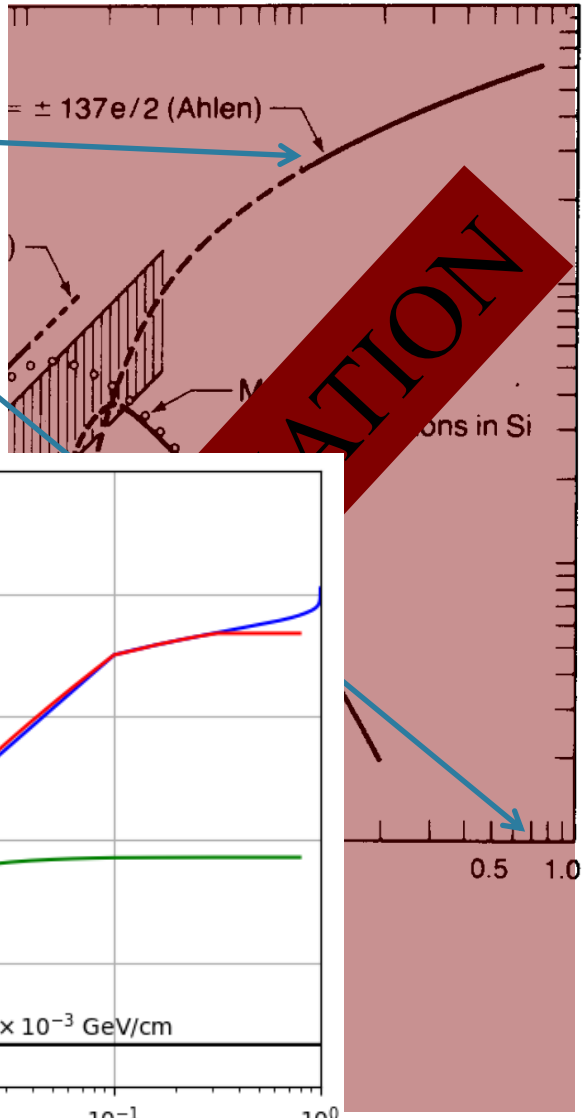


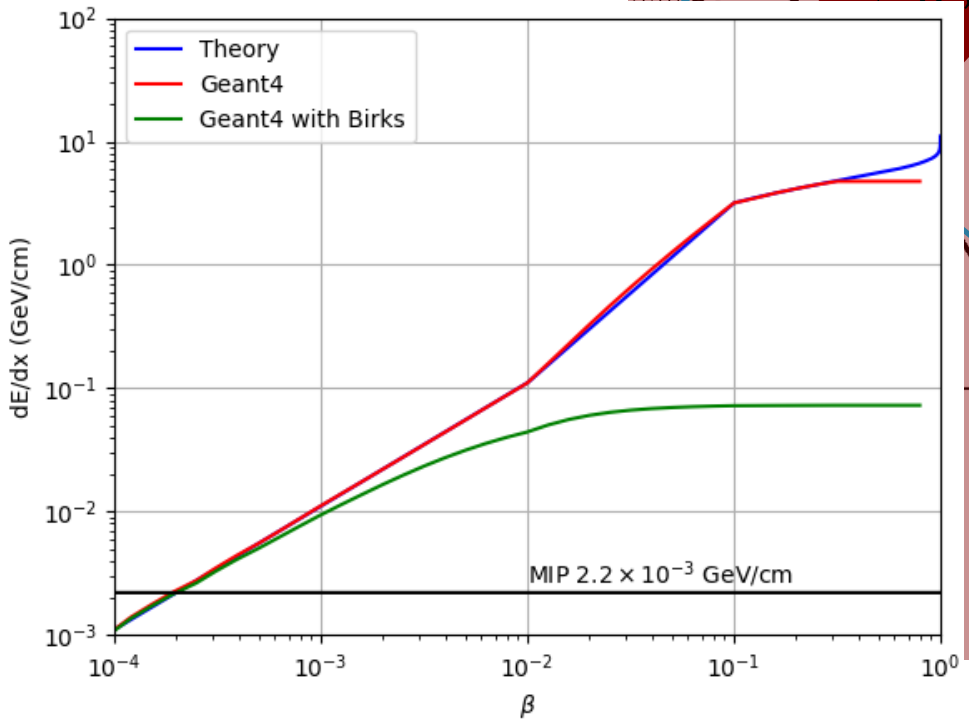
- A lot of work went into verifying that these effects were properly accounted for in our simulation.

Analysis Strategy

Large energy deposition is suppressed through Birks effect.

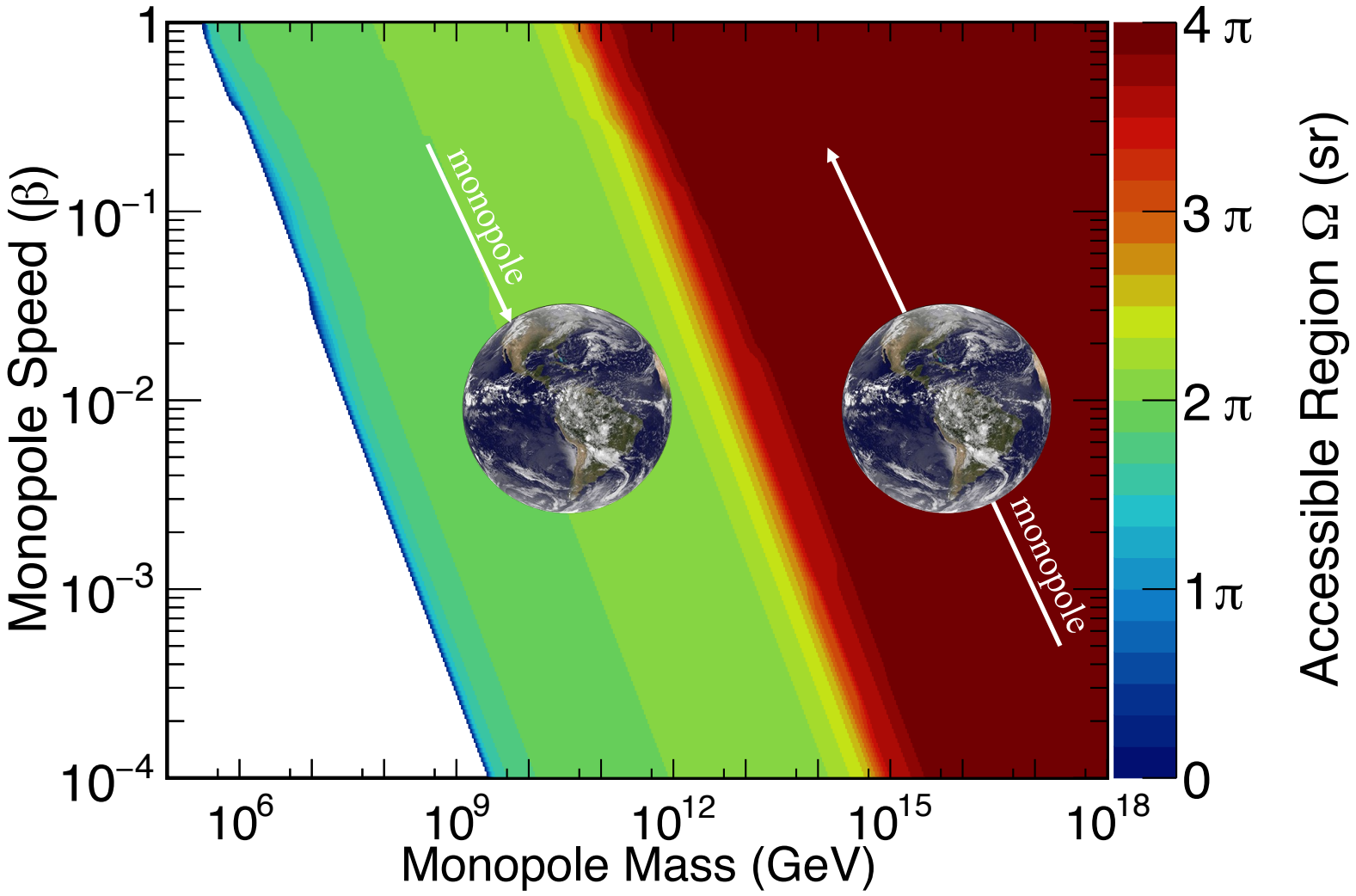
Fast monopoles ($\beta \gtrsim 0.7$) produce Cherenkov light.





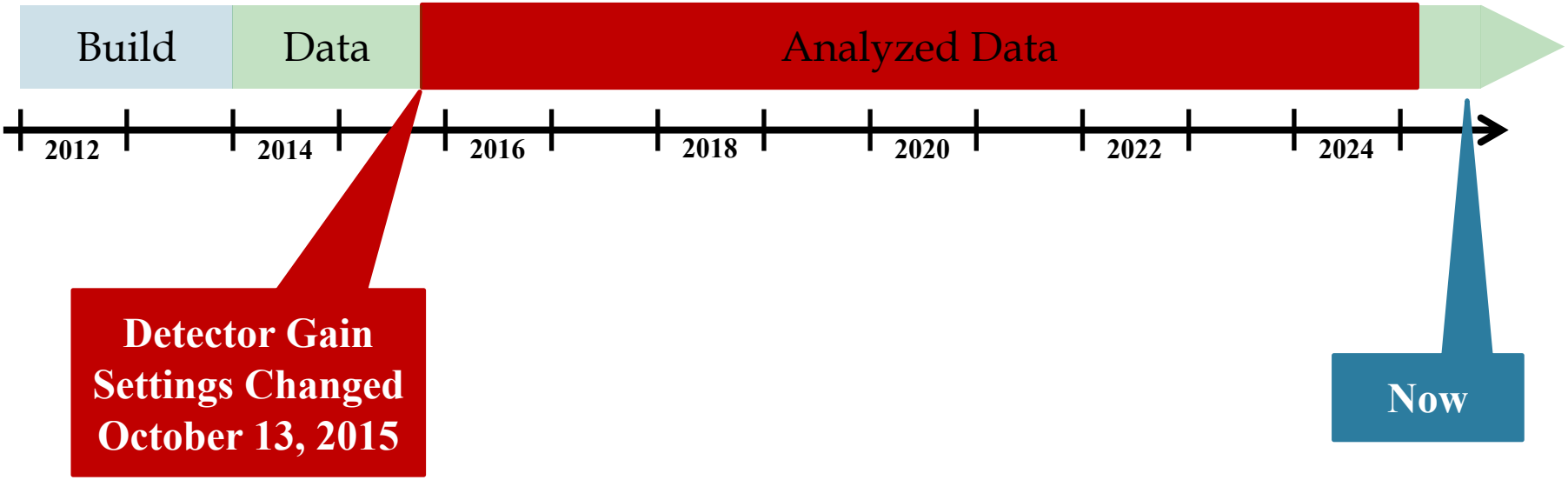
- A lot of work went into verifying that these effects were properly accounted for in our simulation.

Acceptance Region



Data Samples

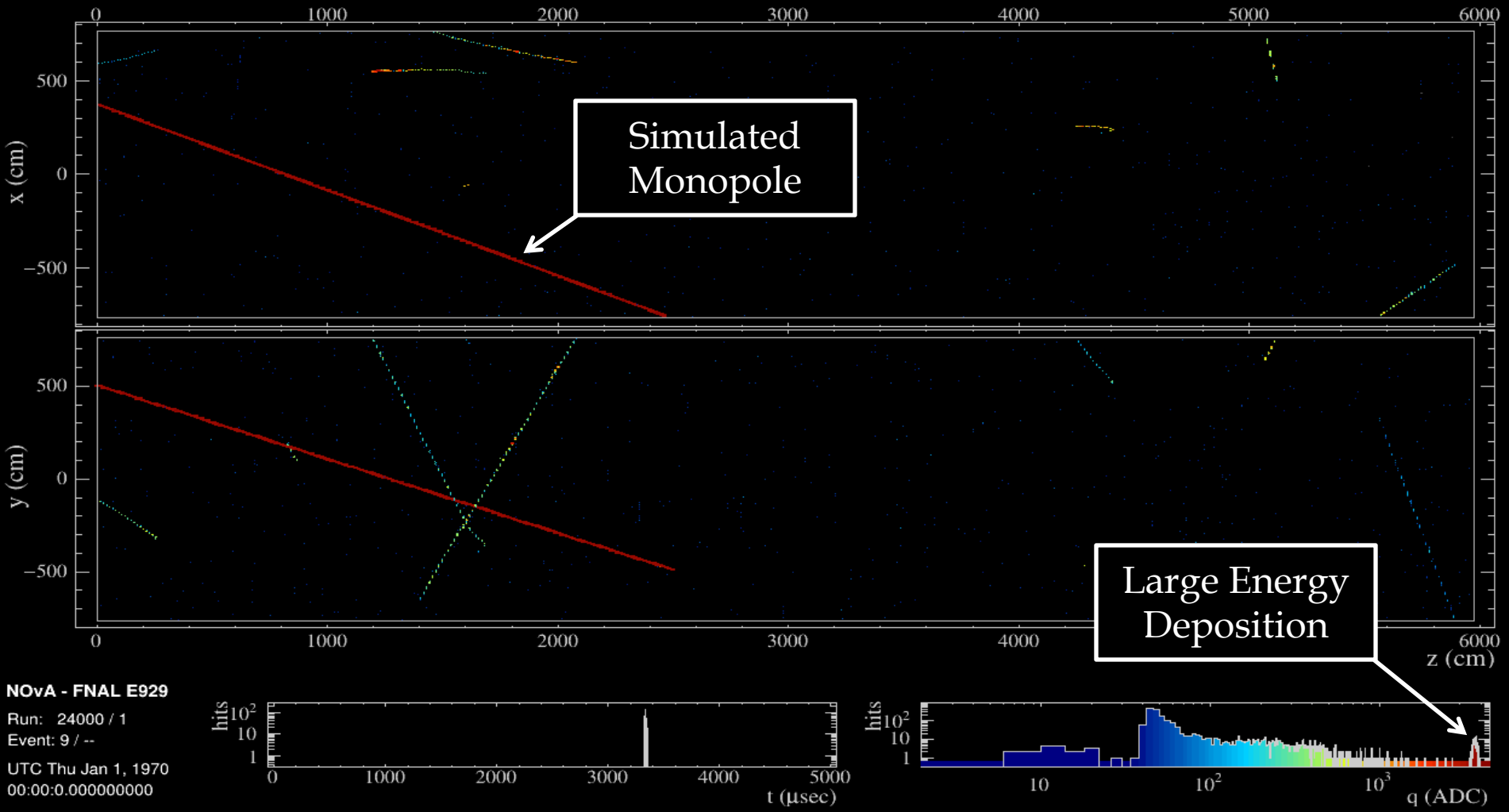
- Ionization Search:
  - October 2015 – February 2025
  - 2,904 days (2,713 days marked as good)
- Timing Search:
  - February 2016 – October 2024
  - 2,985 days (2,743 days marked as good)



XXI Workshop on Neutrino Telescopes

Ionization Magnetic Monopole Search

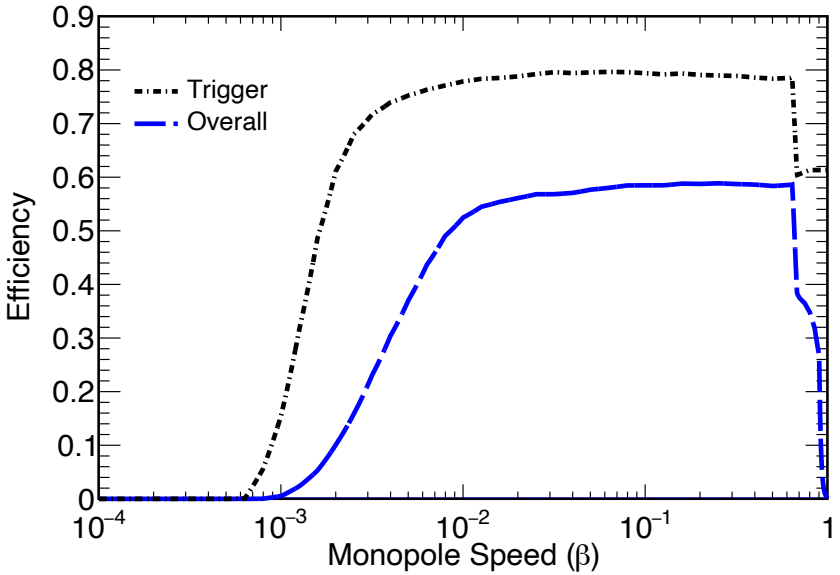
Raw Data with Simulated Monopole

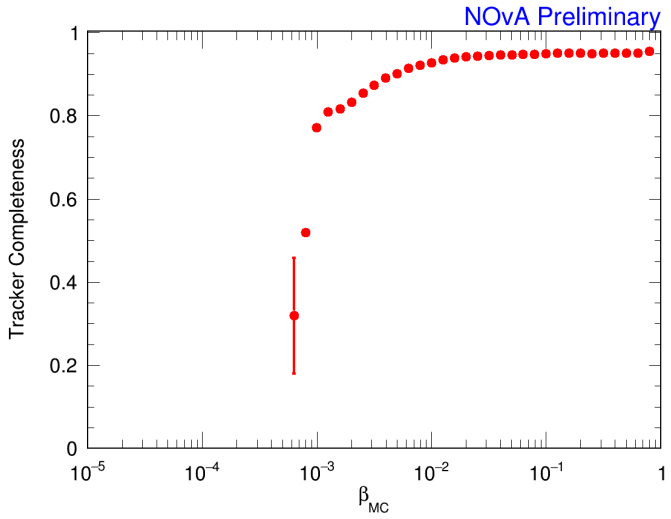


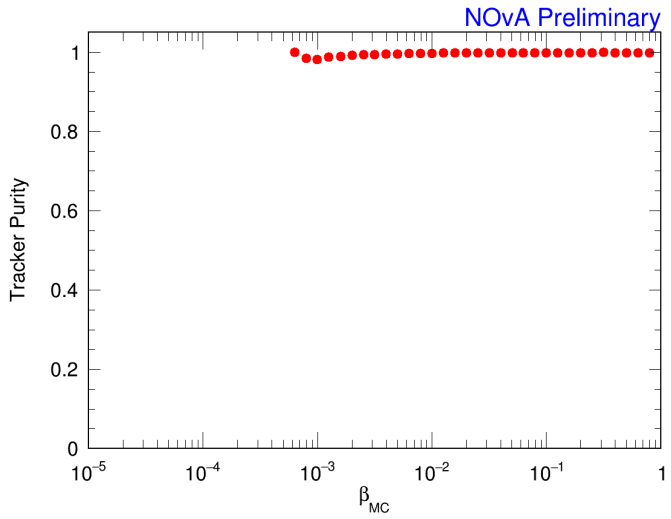
50 μs Exposure

Analysis Strategy

1. Trigger on monopole-like patterns with high energy depositions in live data stream.
2. Reconstruct event kinematics offline.
   - ~100% track purity for $\beta > 10^{-3}$
   - ~90% track completeness for $\beta > 10^{-2}$

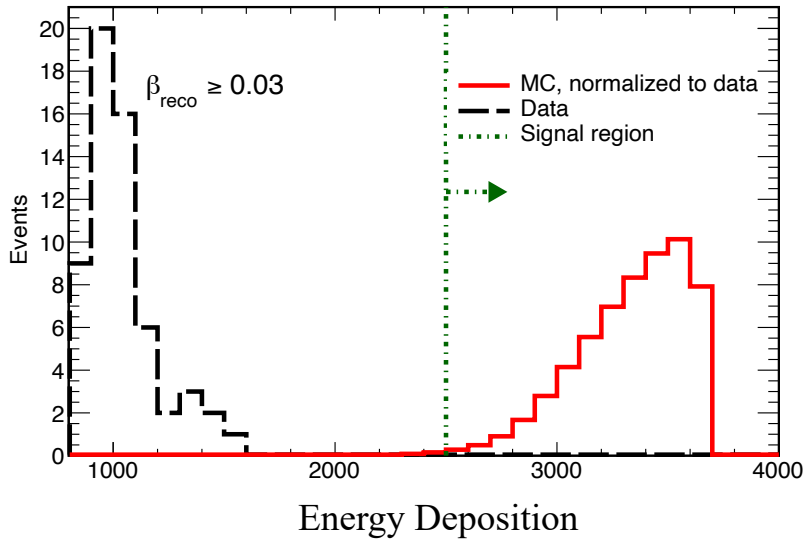






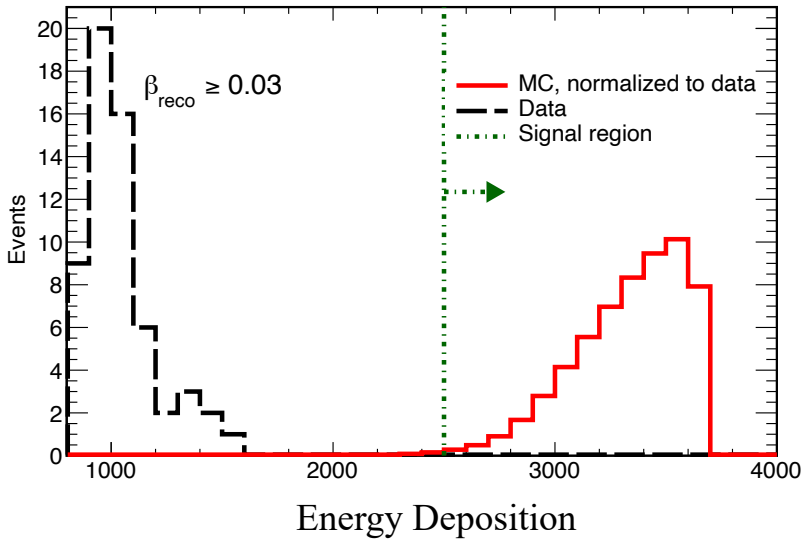
Offline Analysis Strategy

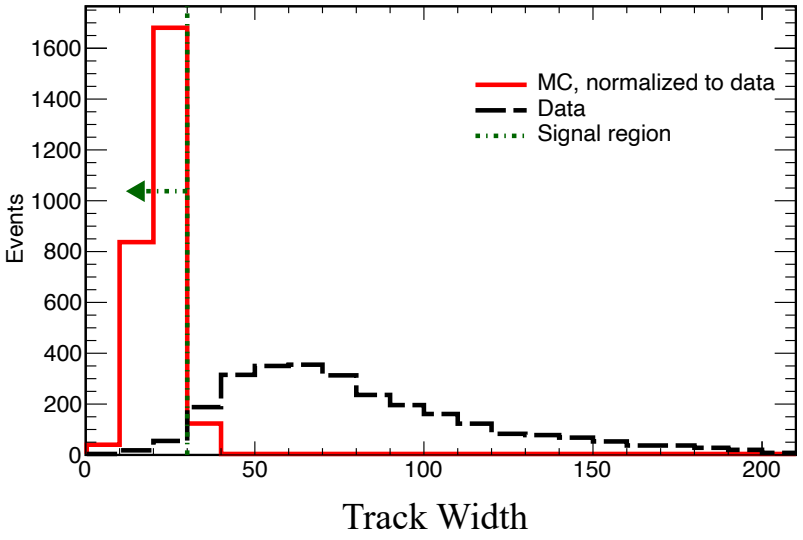
- Data:
  - Triggered by ionizing monopole algorithm
- MC:
  - Simulated monopole overlaid with cosmic data
- Select events with high energy deposition
- Select narrow events:
  - Removes energetic showering muons that tend to be wider

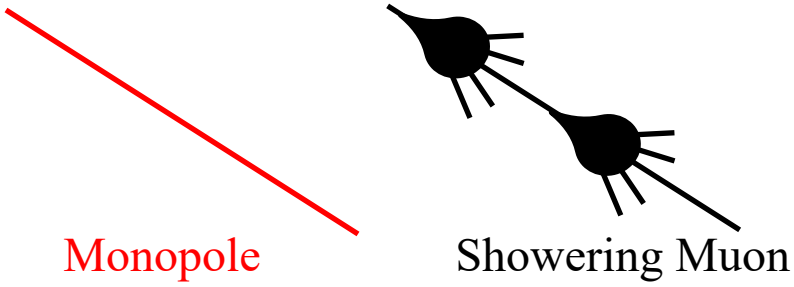


Offline Analysis Strategy

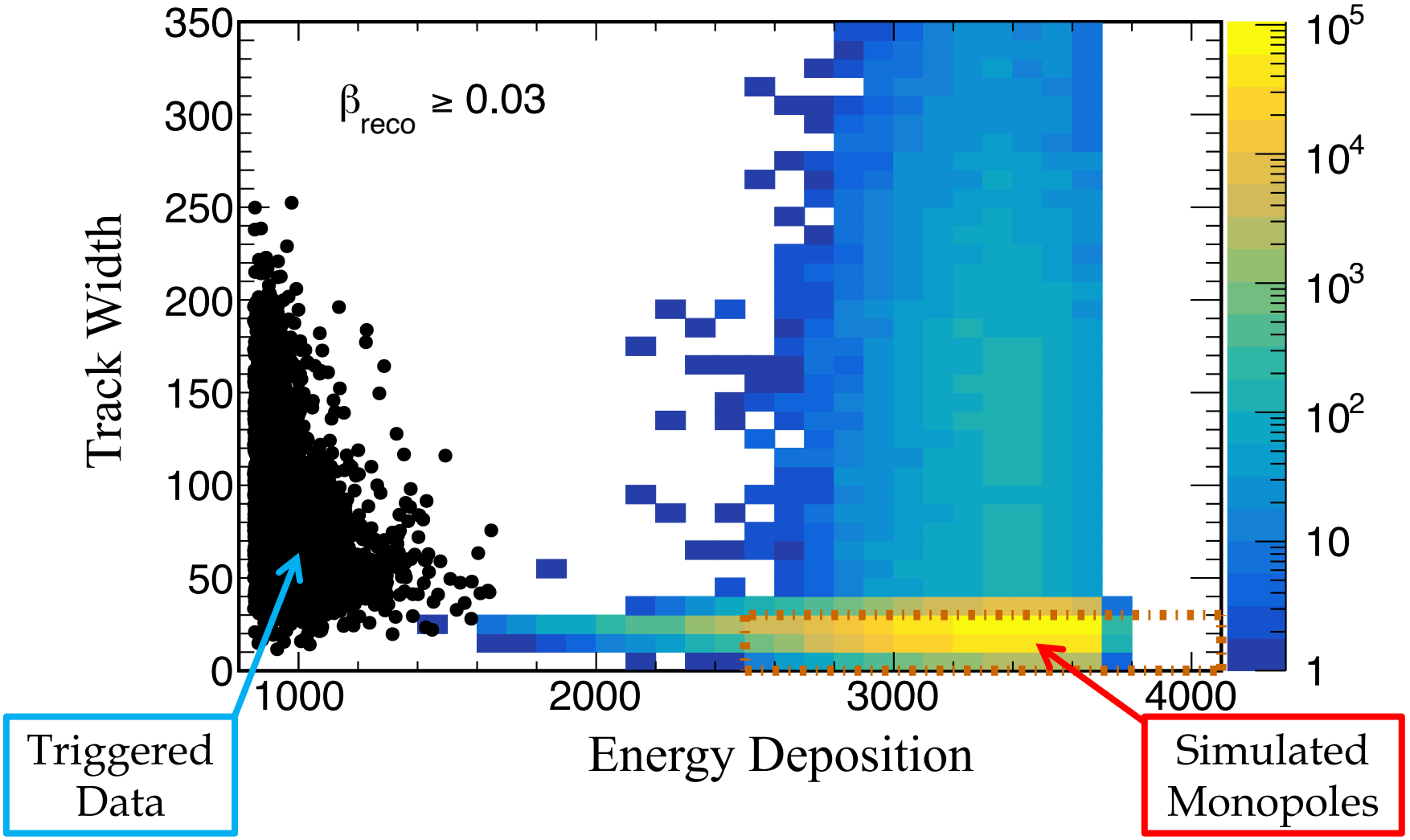
- Data:
  - Triggered by ionizing monopole algorithm
- MC:
  - Simulated monopole overlaid with cosmic data
- Select events with high energy deposition
- Select narrow events:
  - Removes energetic showering muons that tend to be wider





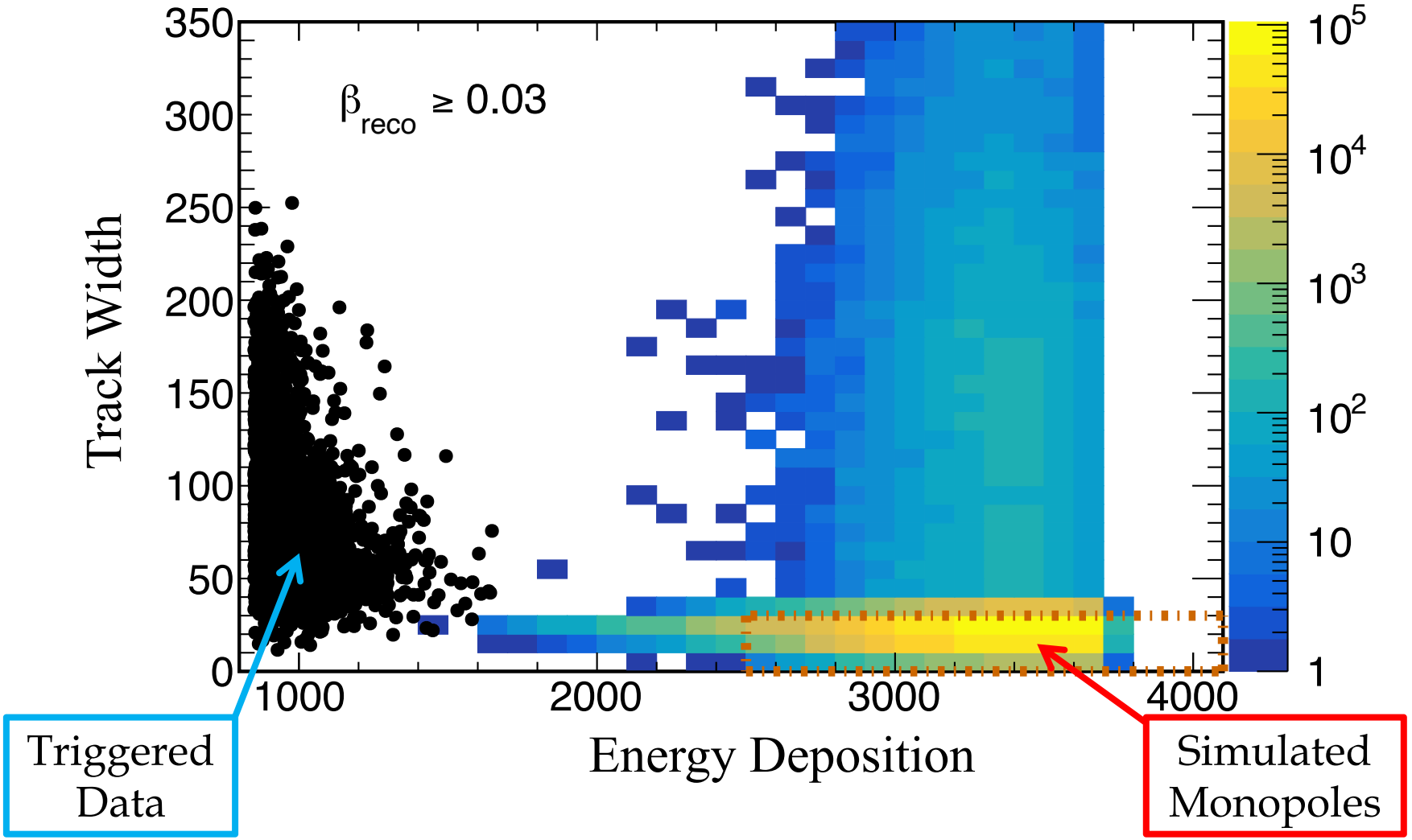


Signal Search

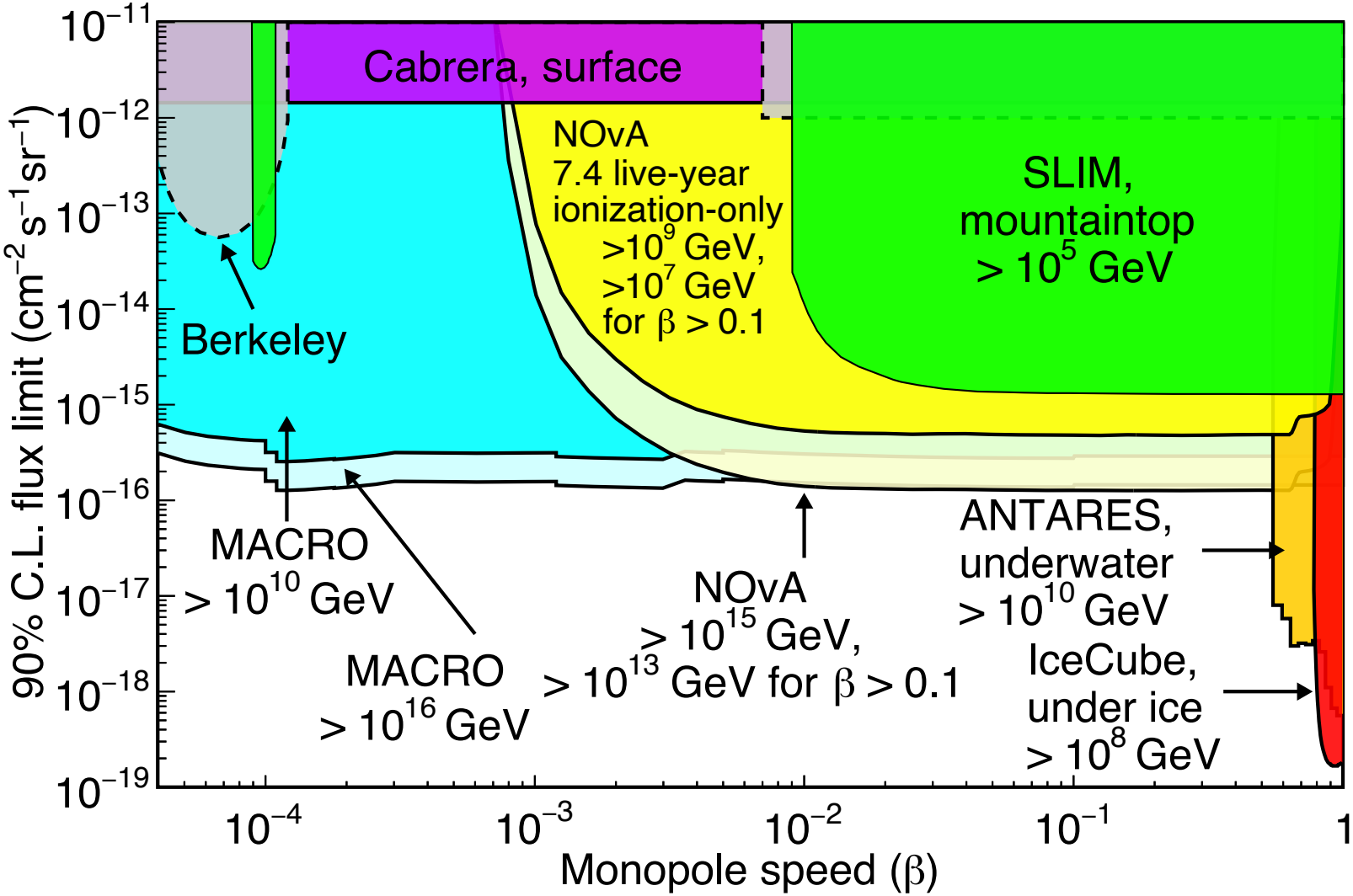


Signal Search

No Magnetic Monopole Event Found!



Magnetic Monopole Flux Limits



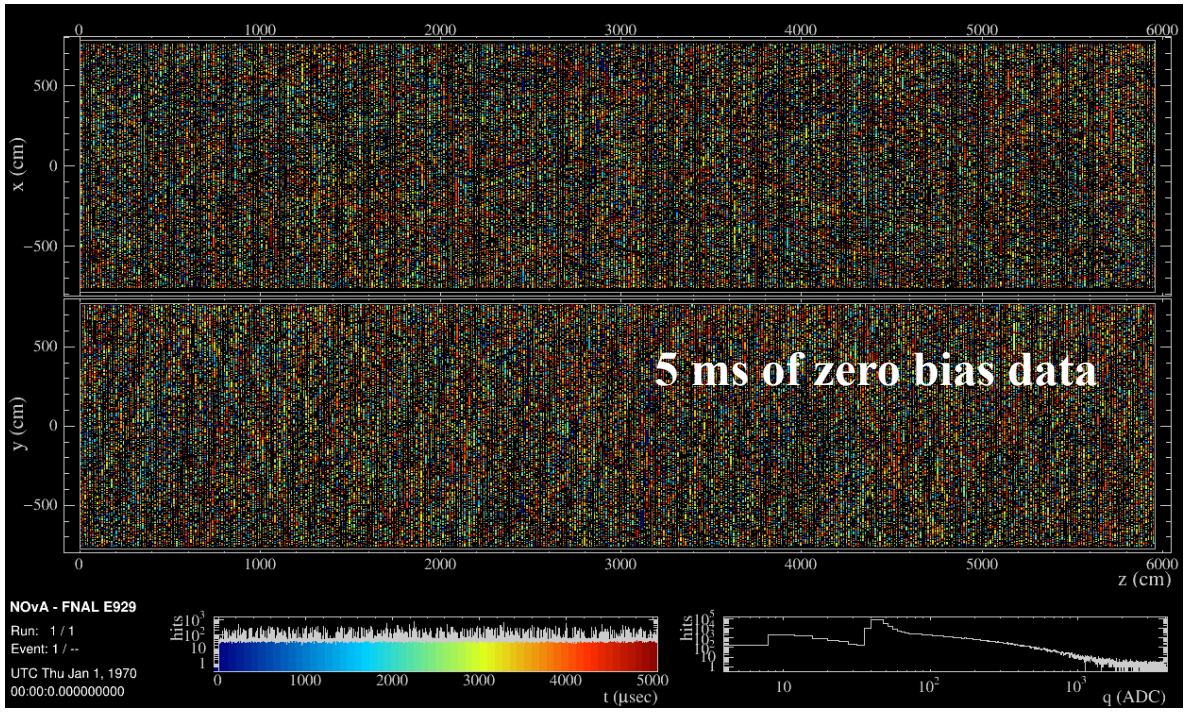
Timing Magnetic Monopole Search

Monopole Simulation

- We used simulation to determine the efficiency of selecting monopole tracks for $10^{-4} < \beta < 10^{-2}$.
- The monopoles were simulated using an isotropic flux.
- Each simulated monopole was combined with 5 ms of zero bias data (i.e. data with typical running conditions).

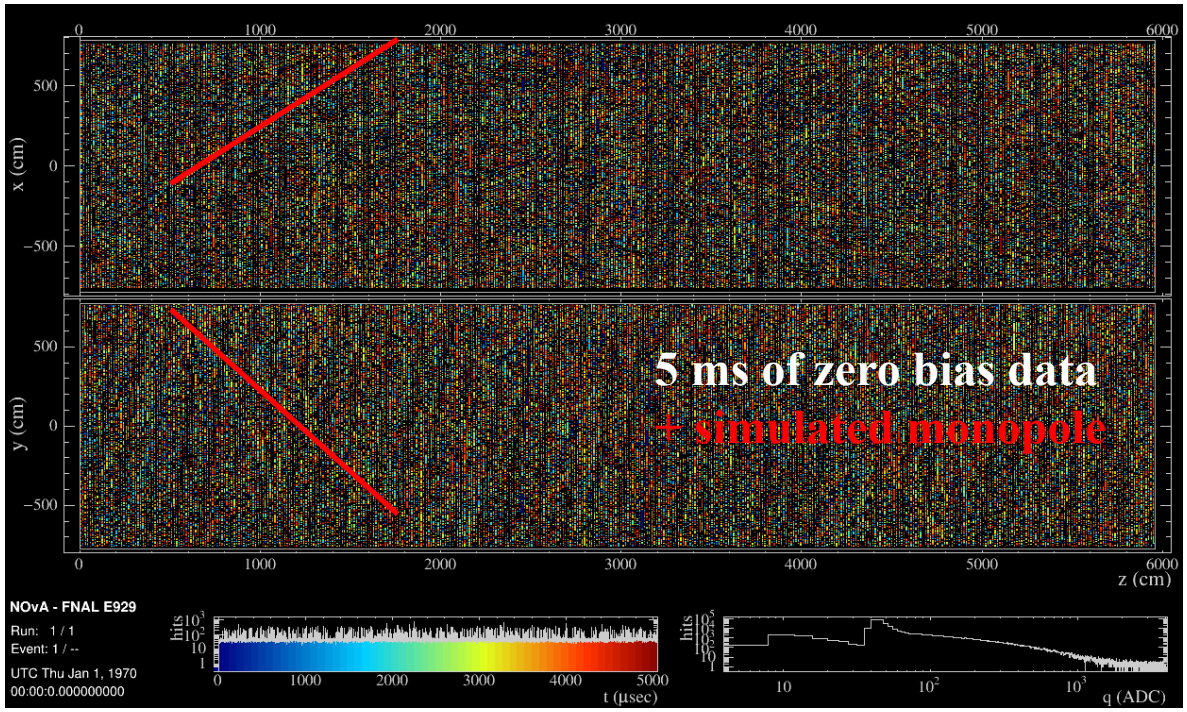
Monopole Simulation

- We used simulation to determine the efficiency of selecting monopole tracks for $10^{-4} < \beta < 10^{-2}$.
- The monopoles were simulated using an isotropic flux.
- Each simulated monopole was combined with 5 ms of zero bias data (i.e. data with typical running conditions).



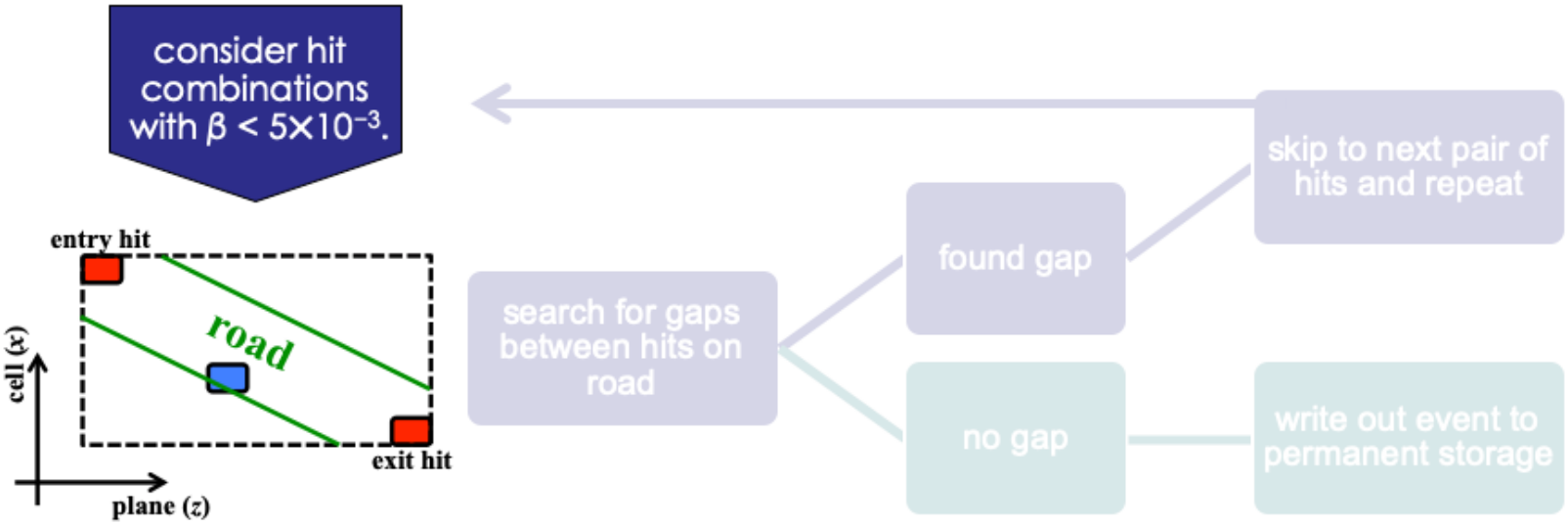
Monopole Simulation

- We used simulation to determine the efficiency of selecting monopole tracks for $10^{-4} < \beta < 10^{-2}$.
- The monopoles were simulated using an isotropic flux.
- Each simulated monopole was combined with 5 ms of zero bias data (i.e. data with typical running conditions).



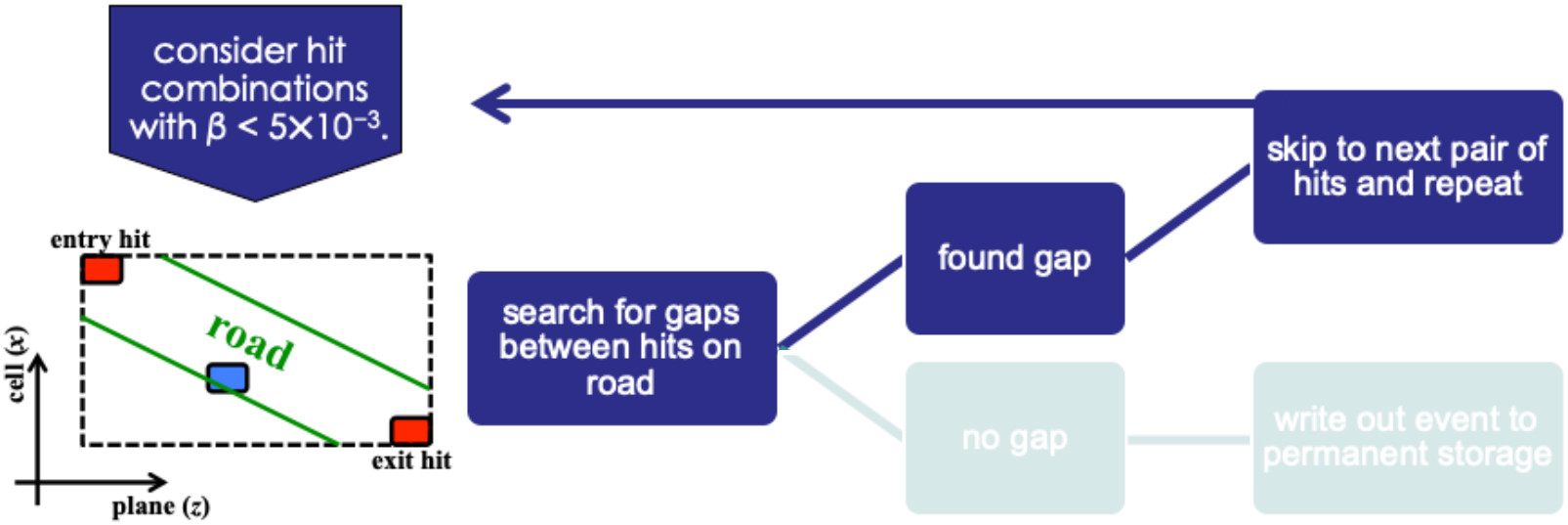
Analysis Strategy – Trigger

- The NOvA detectors are equipped with a data-driven trigger (DDT) system that continuously examines the live data stream on over 100 computing nodes.
- The monopole trigger algorithm examines pairs of hits on the surface of the detector for each event (5 ms).



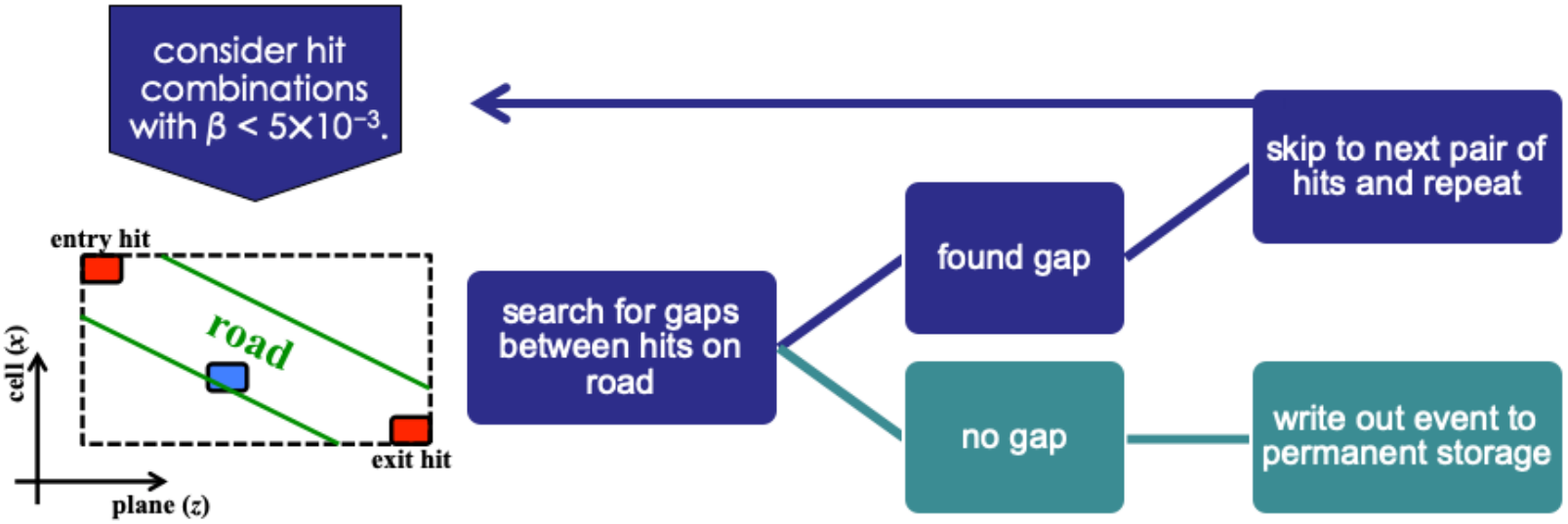
Analysis Strategy – Trigger

- The NOvA detectors are equipped with a data-driven trigger (DDT) system that continuously examines the live data stream on over 100 computing nodes.
- The monopole trigger algorithm examines pairs of hits on the surface of the detector for each event (5 ms).



Analysis Strategy – Trigger

- The NOvA detectors are equipped with a data-driven trigger (DDT) system that continuously examines the live data stream on over 100 computing nodes.
- The monopole trigger algorithm examines pairs of hits on the surface of the detector for each event (5 ms).

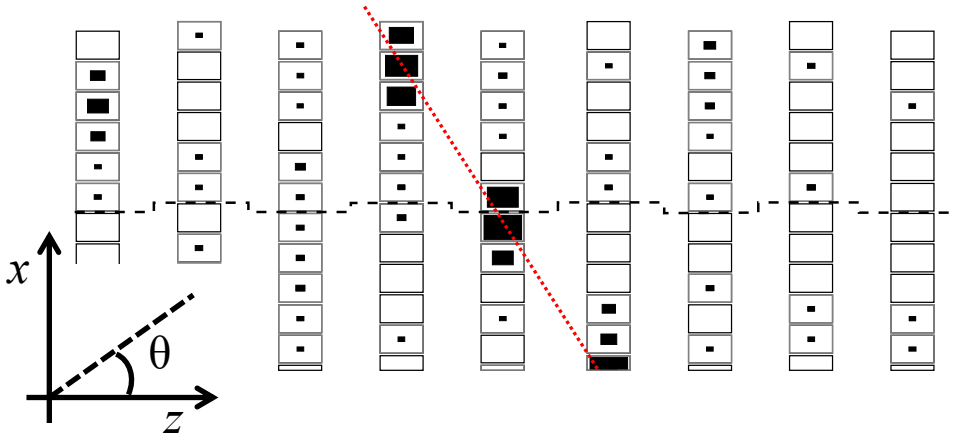


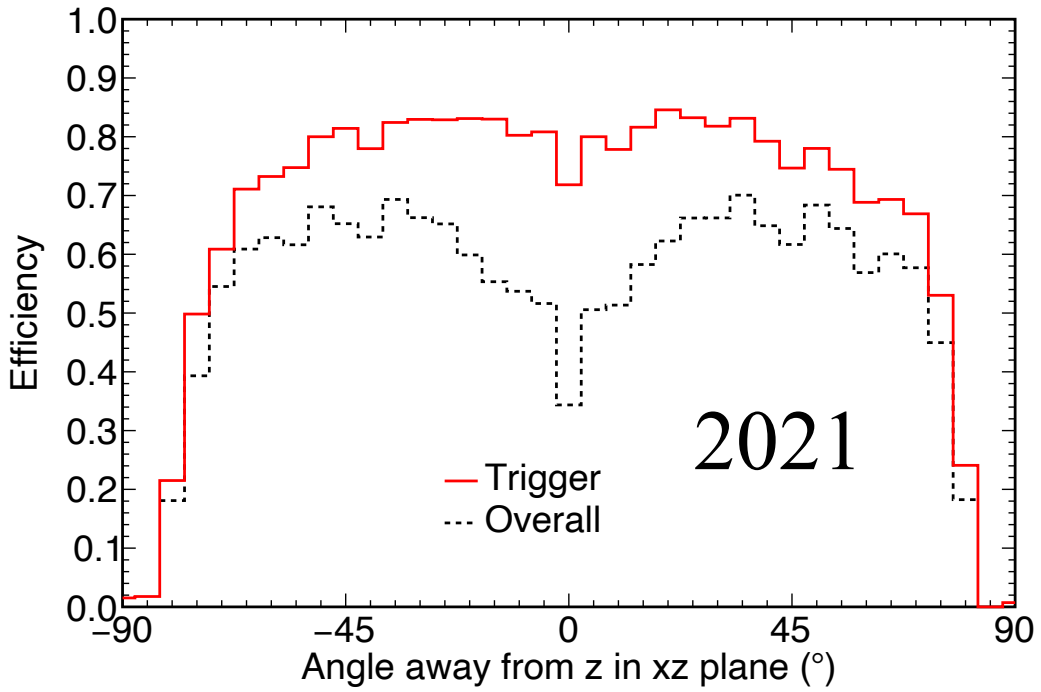
Trigger and Reconstruction Efficiencies

- Efficiency constant:
  - from $\beta \sim 5\text{x}10^{-4}$
  - to $\beta \sim 5\text{x}10^{-3}$
- Some efficiency lost due to tracks parallel to the detector planes.
  - $|\theta| \sim 90°$
- Improvements in the trigger and offline reconstruction algorithms have increased efficiency since the 2021 result!

Trigger and Reconstruction Efficiencies

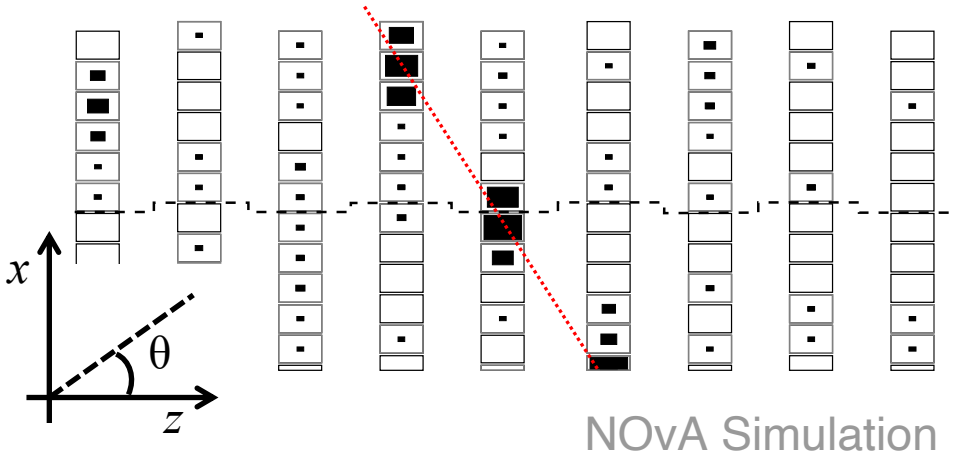
- Efficiency constant:
  - from $\beta \sim 5\text{x}10^{-4}$
  - to $\beta \sim 5\text{x}10^{-3}$
- Some efficiency lost due to tracks parallel to the detector planes.
  - $|\theta| \sim 90°$
- Improvements in the trigger and offline reconstruction algorithms have increased efficiency since the 2021 result!

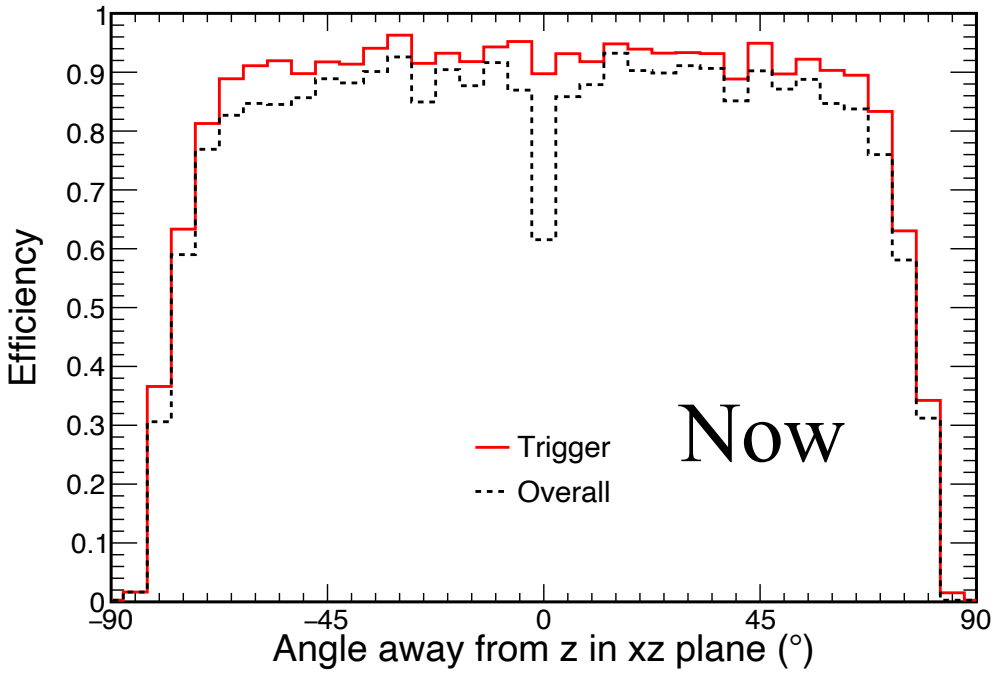




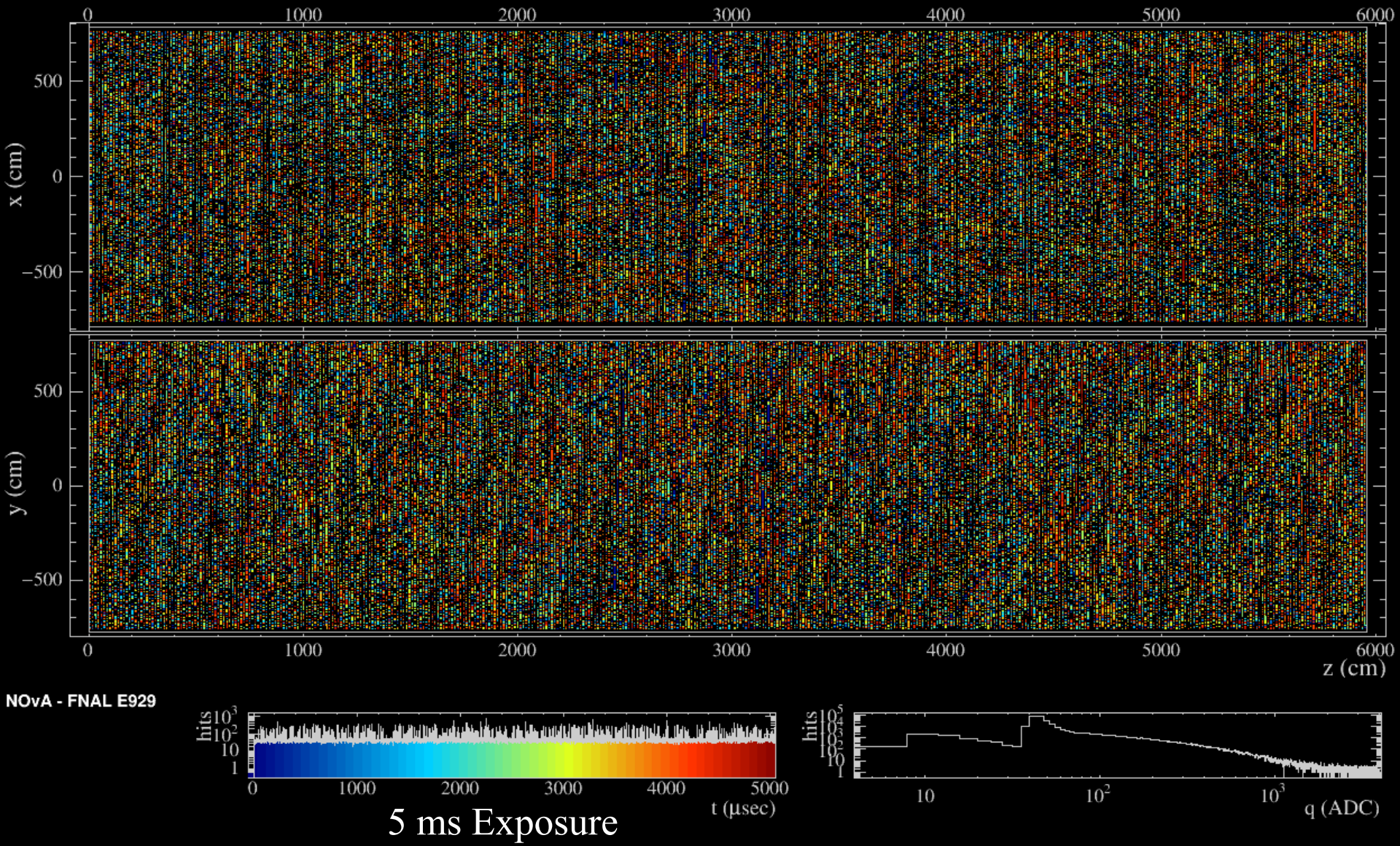
Trigger and Reconstruction Efficiencies

- Efficiency constant:
  - from $\beta \sim 5\text{x}10^{-4}$
  - to $\beta \sim 5\text{x}10^{-3}$
- Some efficiency lost due to tracks parallel to the detector planes.
  - $|\theta| \sim 90°$
- Improvements in the trigger and offline reconstruction algorithms have increased efficiency since the 2021 result!



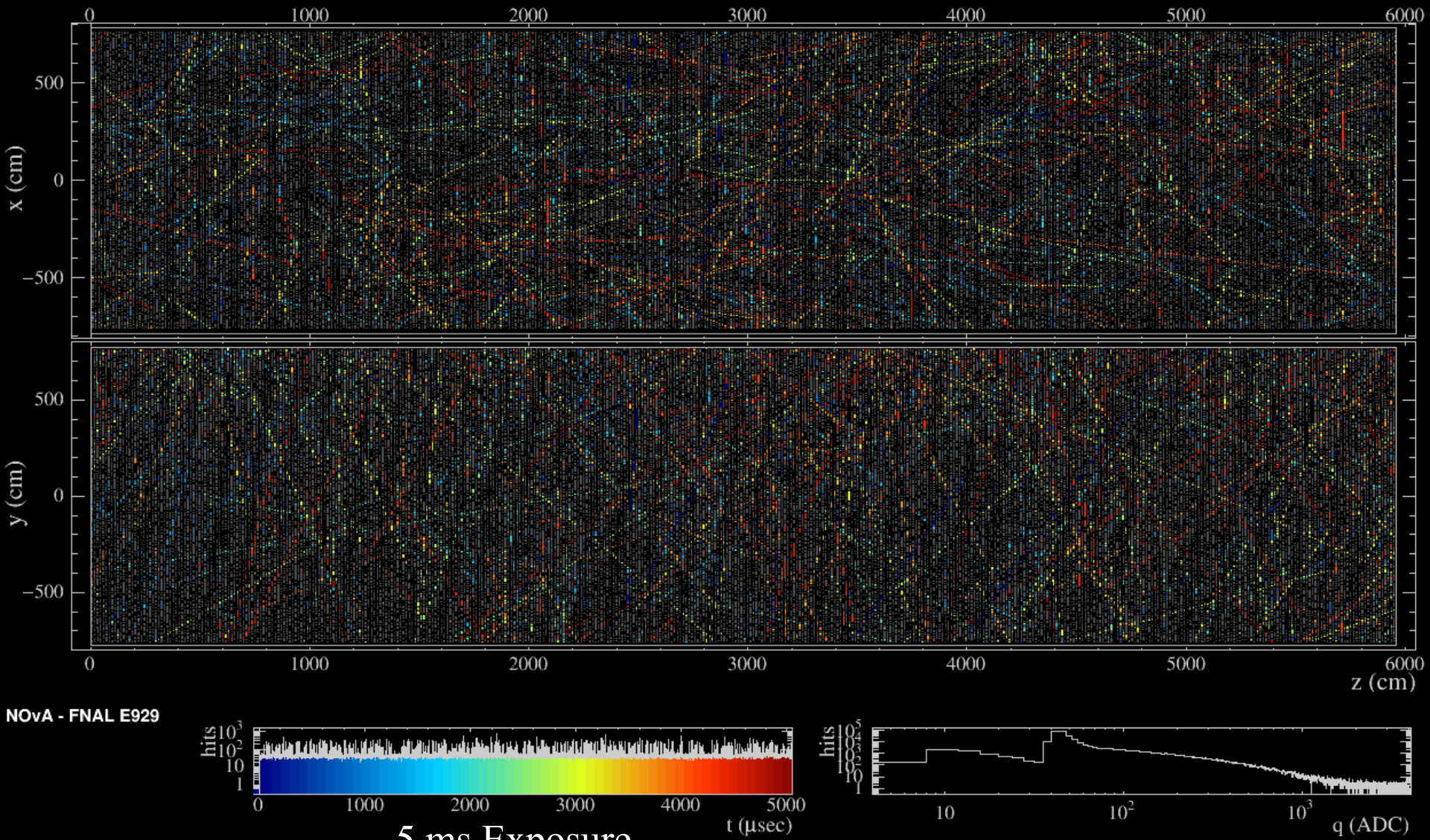


Offline Reconstruction



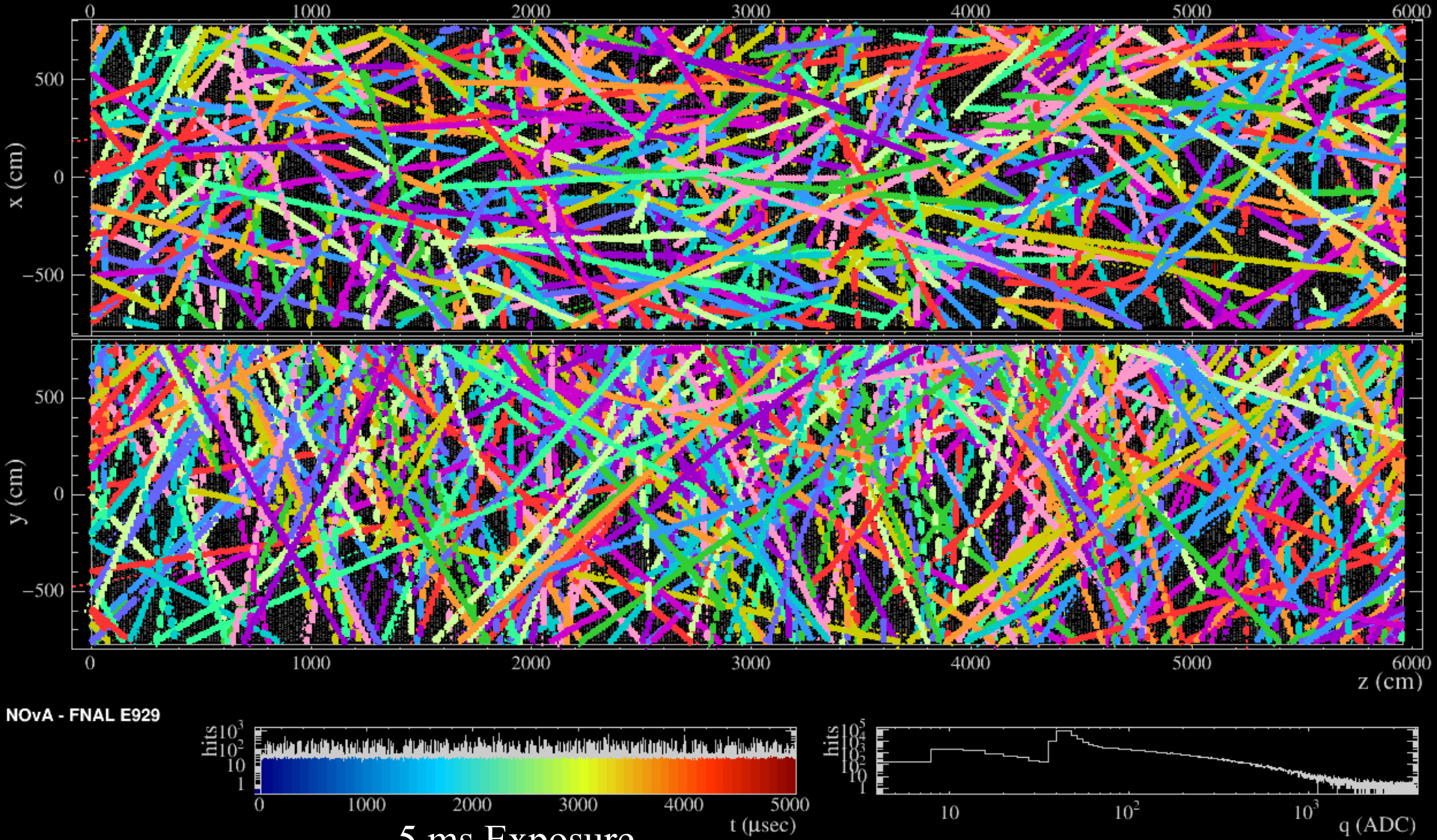
5 ms Exposure

Remove Low Energy Hits



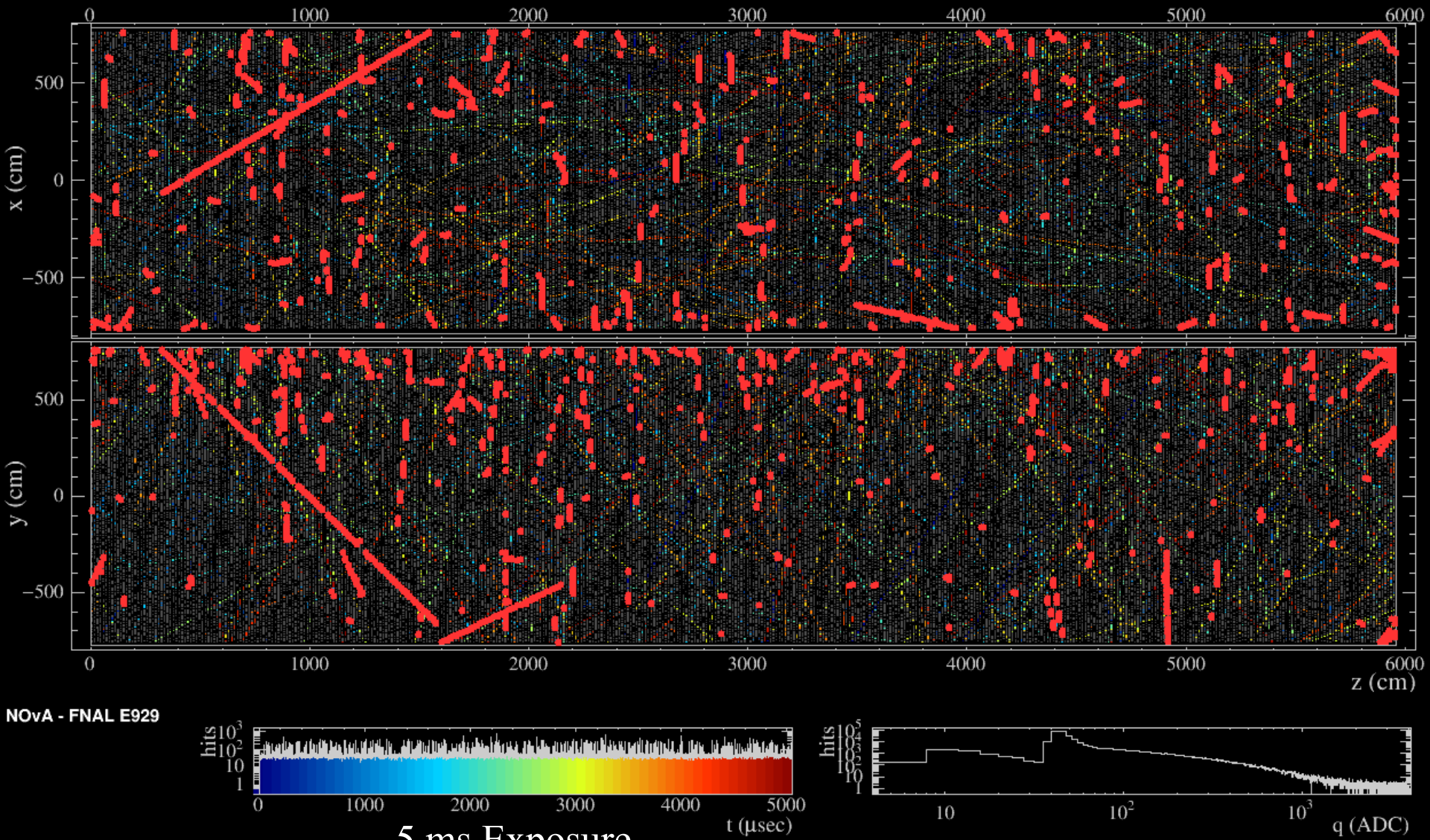
5 ms Exposure

Identify Cosmic Rays



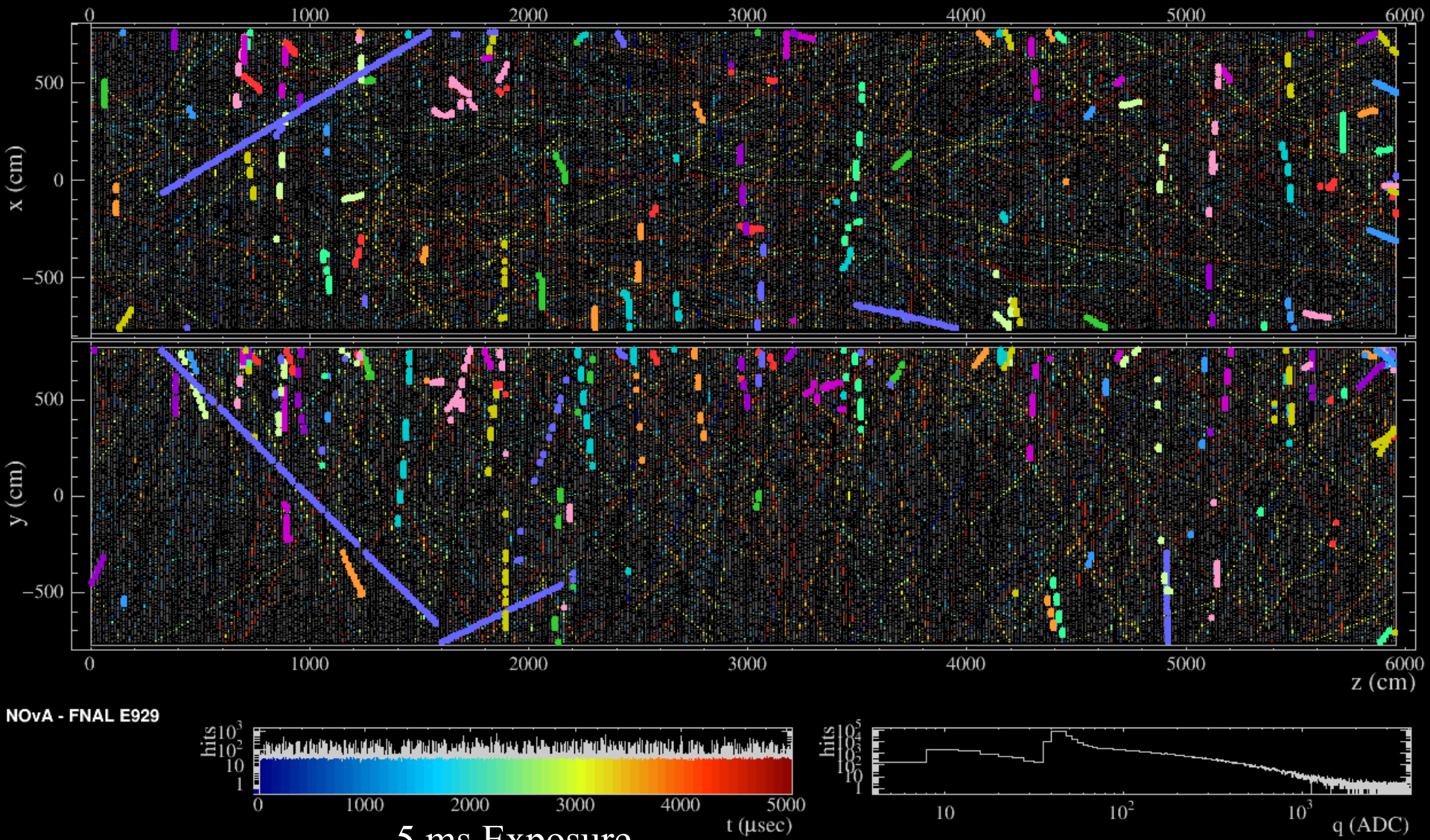
5 ms Exposure

Remove Cosmic Rays



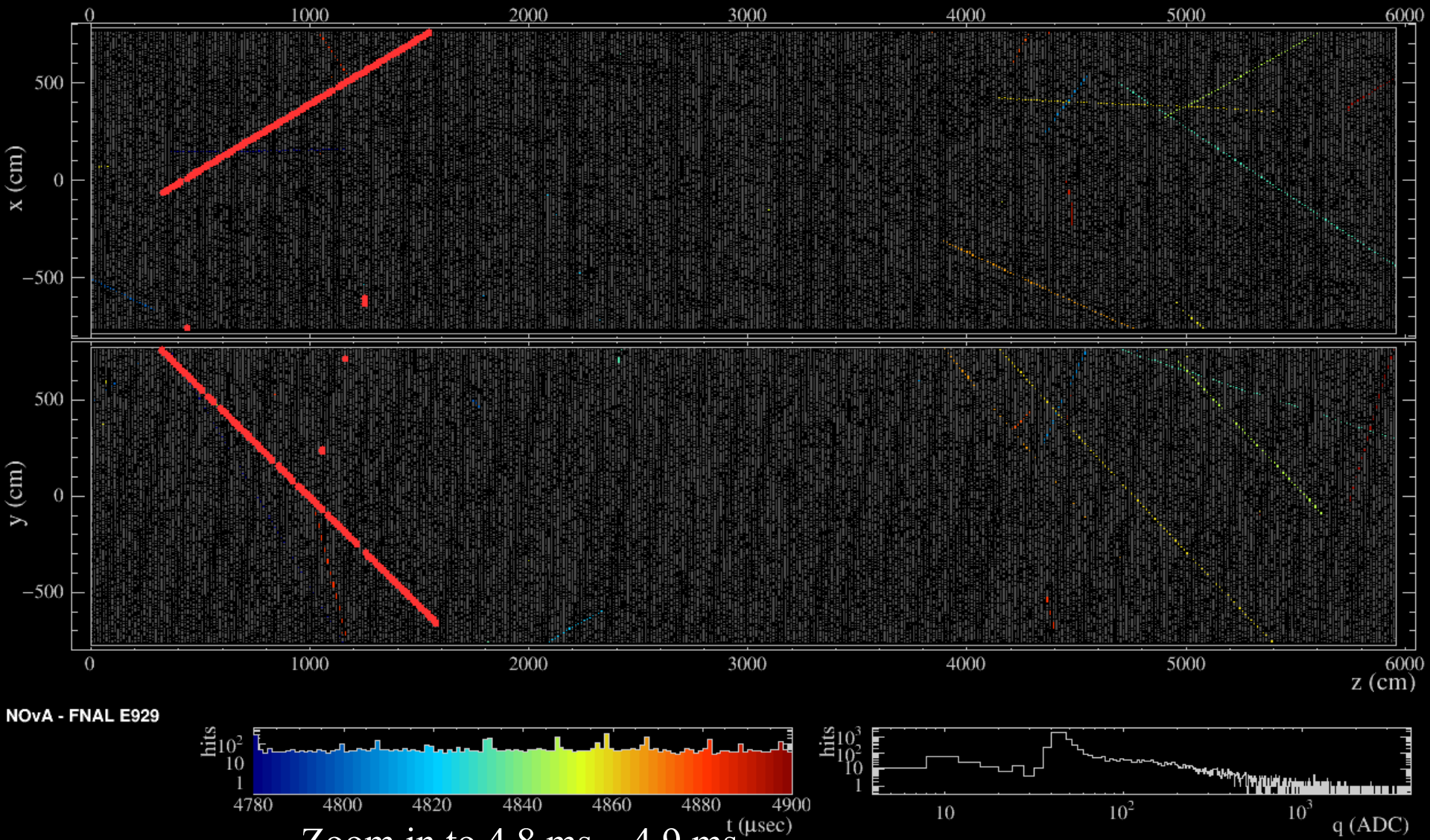
5 ms Exposure

Identify Groups of Correlated Hits



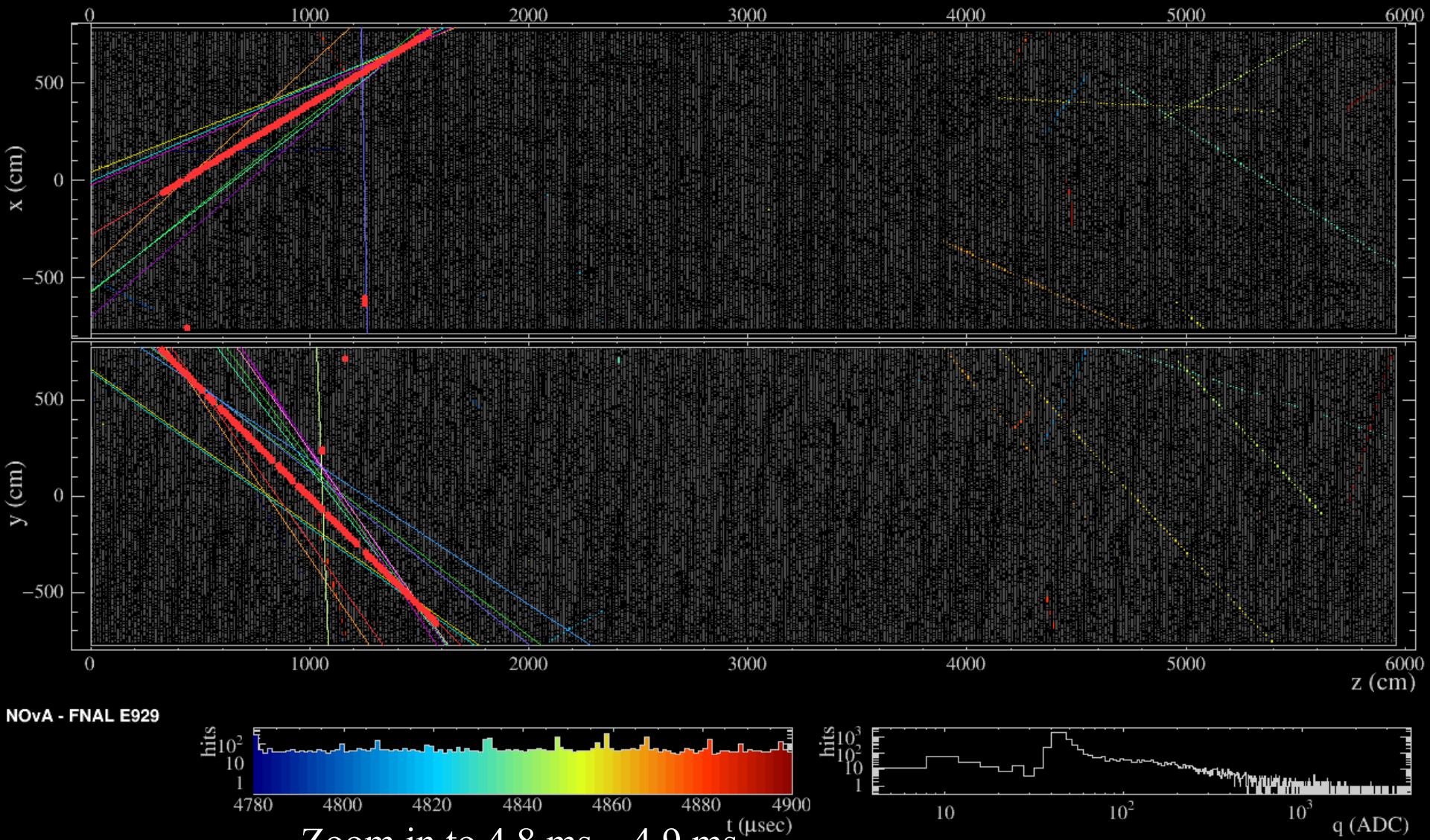
5 ms Exposure

Time Zoom on Monopole Group of Hits



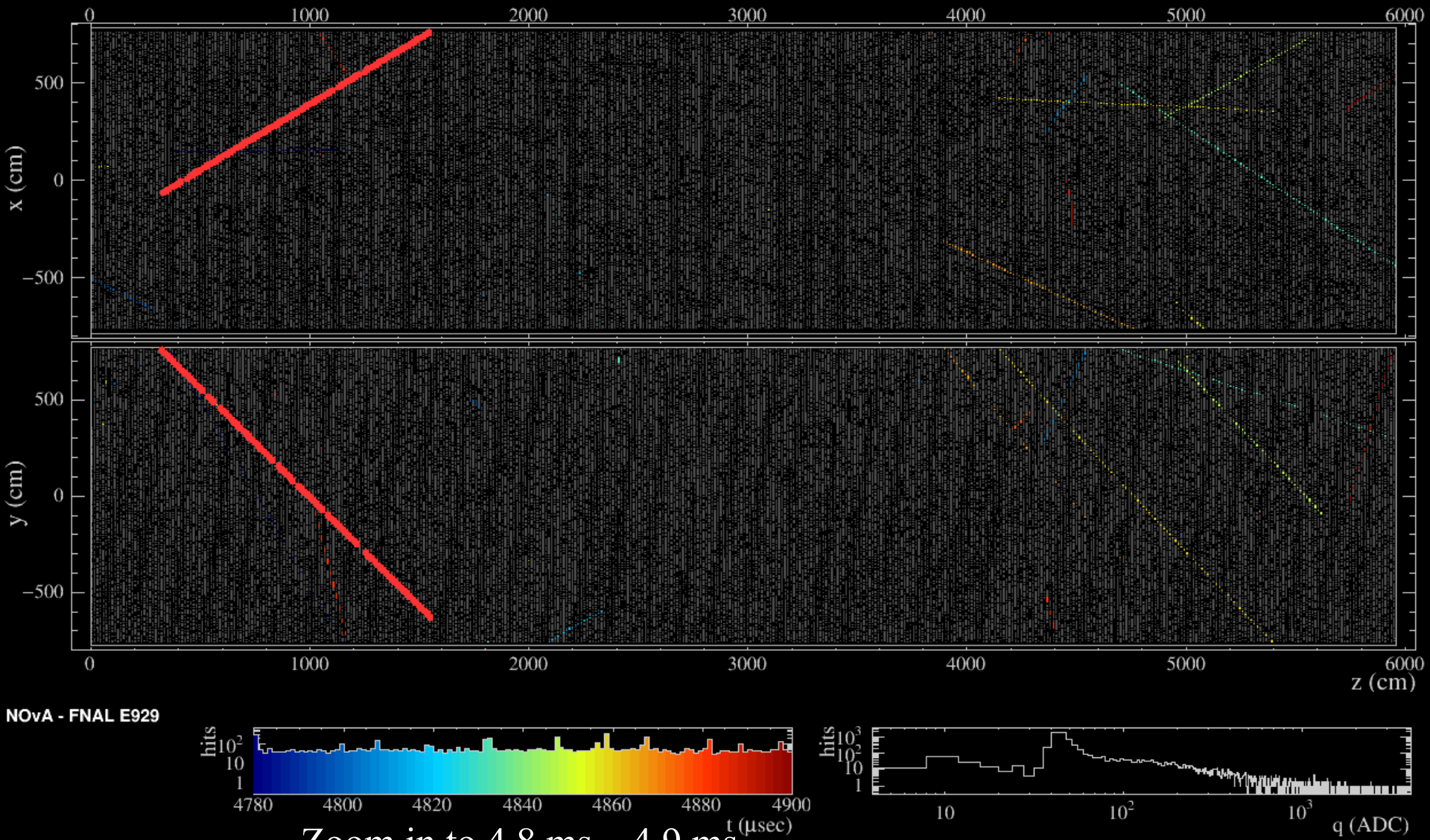
Zoom in to 4.8 ms – 4.9 ms

Identify Straight Line Features (Hough Tracking)



Zoom in to 4.8 ms – 4.9 ms

Identify Monopole Track



Zoom in to 4.8 ms – 4.9 ms

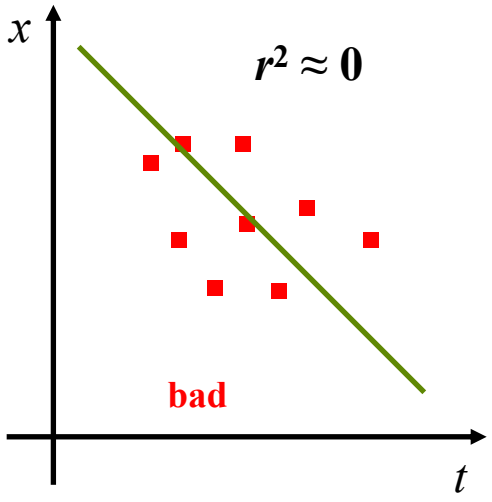
Analysis Strategy – Offline

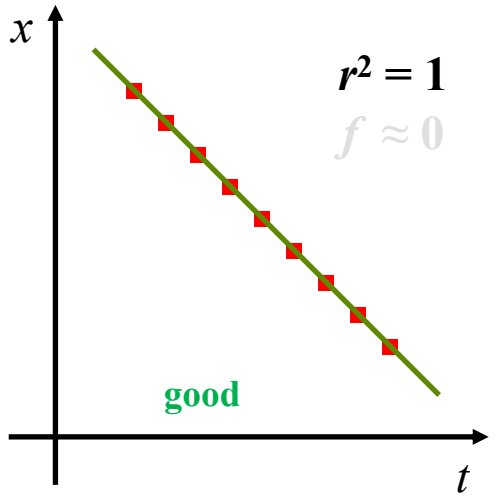
- We want to identify straight line tracks.
- Two powerful discriminators:
  - Correlation coefficient: r^2

$$r = \frac{\sum_j^n (t_j - \bar{t})(x_j - \bar{x})}{\sum_j^n (t_j - \bar{t}) \sum_j^n (x_j - \bar{x})}$$

  - Time gap fraction: f

$$f = \frac{\Delta t_{\max}}{\Delta t_{\text{track}}}$$





Selection Cuts
$r^2 > 0.95$

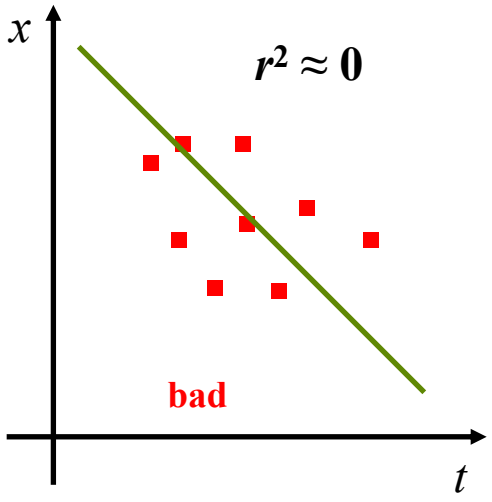
Analysis Strategy – Offline

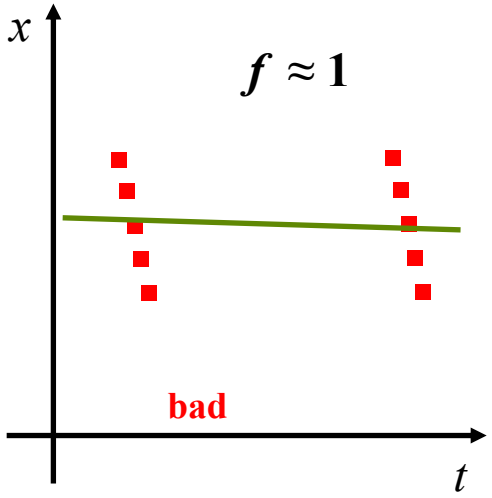
- We want to identify straight line tracks.
- Two powerful discriminators:
  - Correlation coefficient: r^2

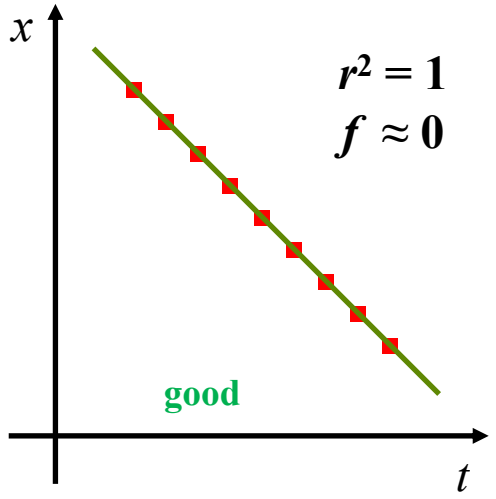
$$r = \frac{\sum_j^n (t_j - \bar{t})(x_j - \bar{x})}{\sum_j^n (t_j - \bar{t}) \sum_j^n (x_j - \bar{x})}$$

  - Time gap fraction: f

$$f = \frac{\Delta t_{\max}}{\Delta t_{\text{track}}}$$





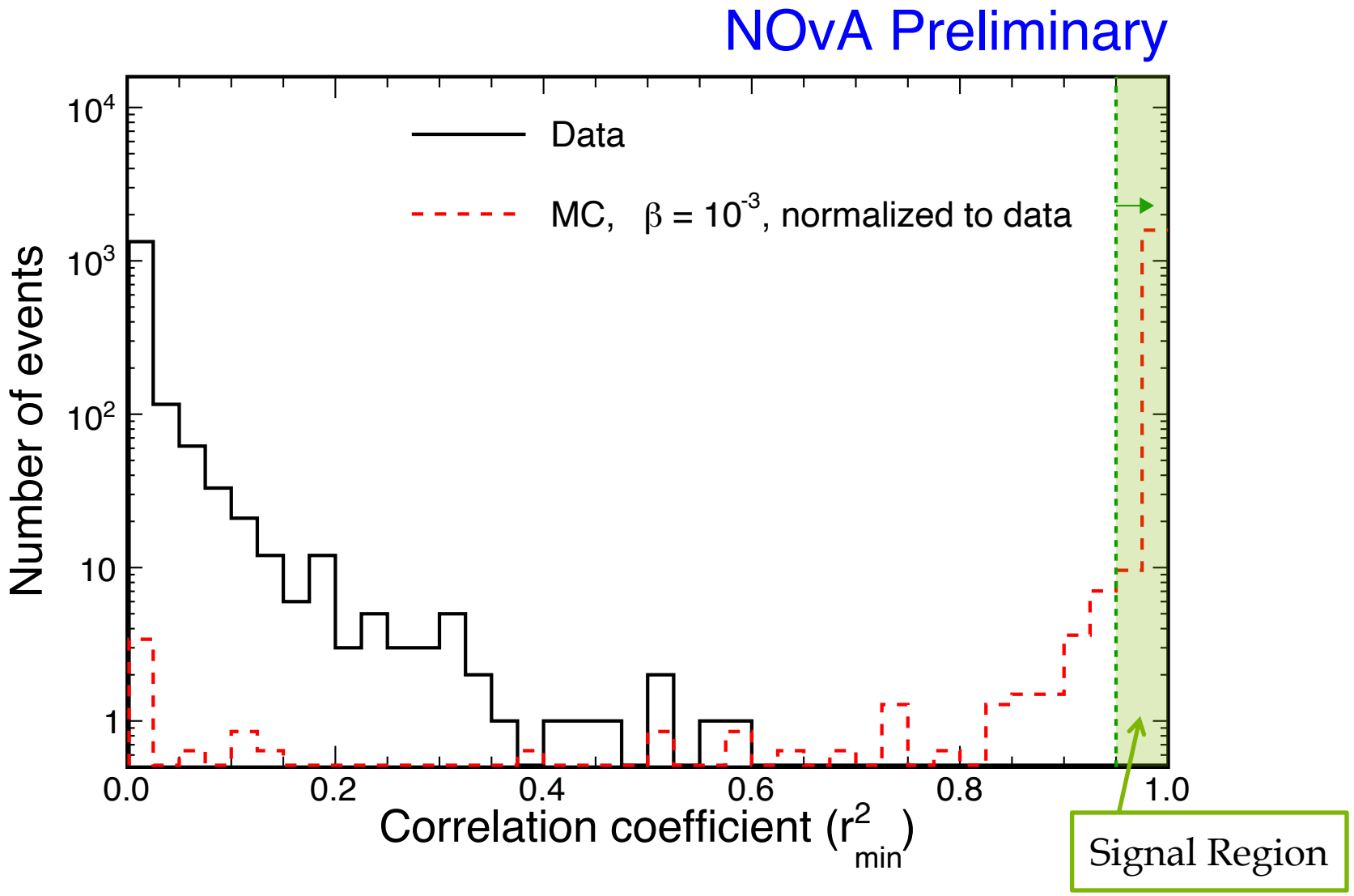


Selection Cuts

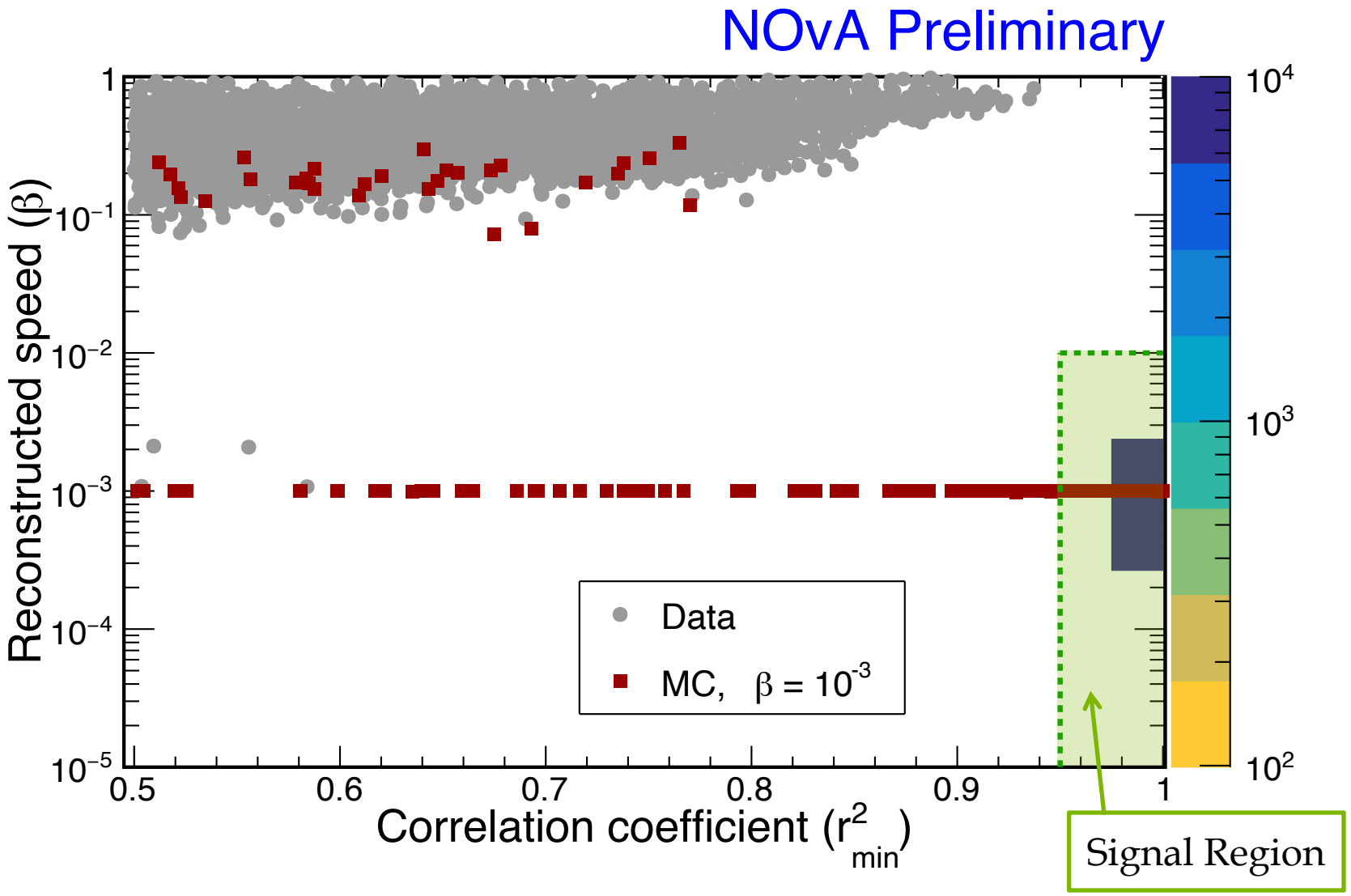
$r^2 > 0.95$

$f < 0.2$

Correlation Coefficient

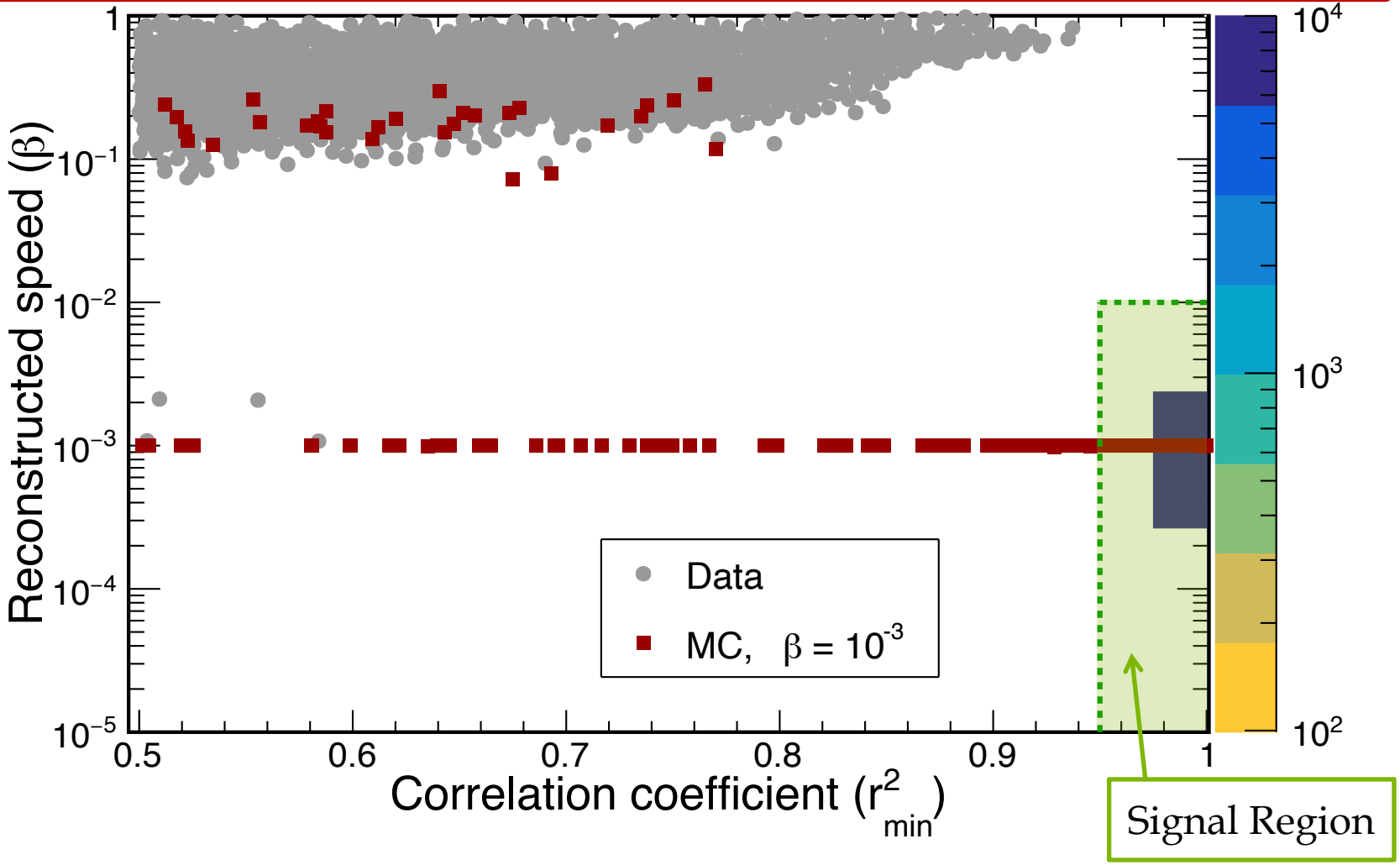


Signal Search



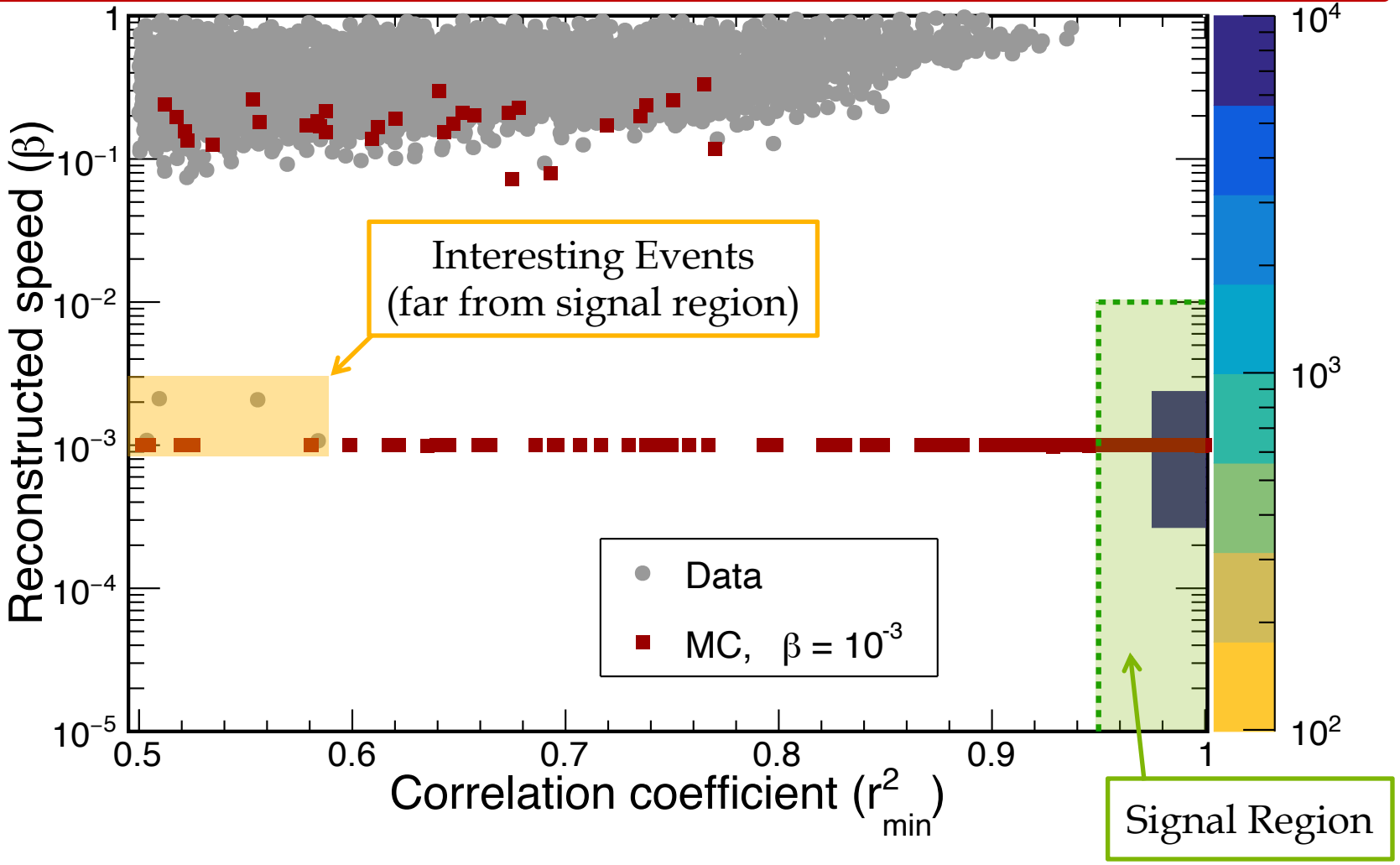
Signal Search

No Magnetic Monopole Event Found!

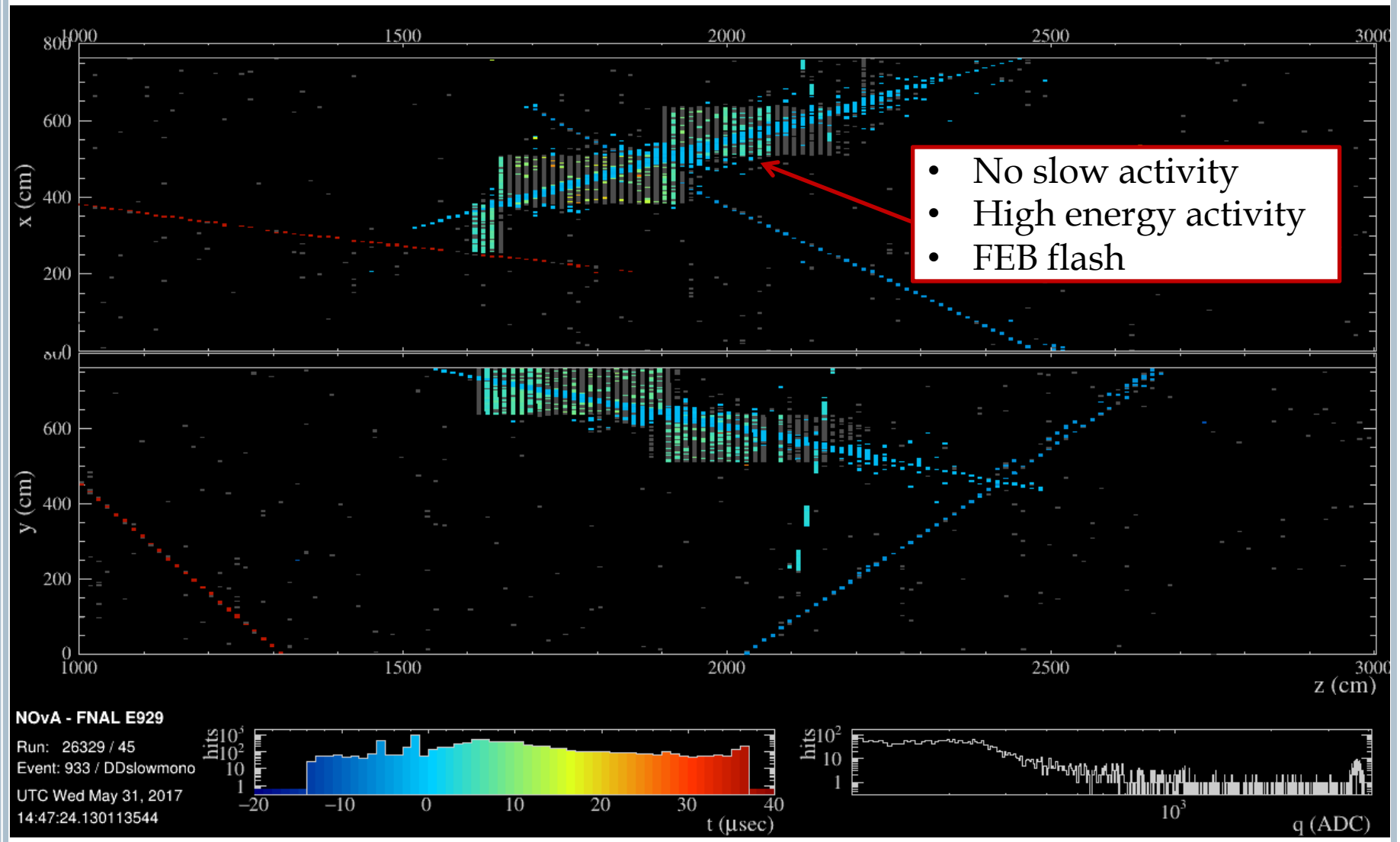


Signal Search

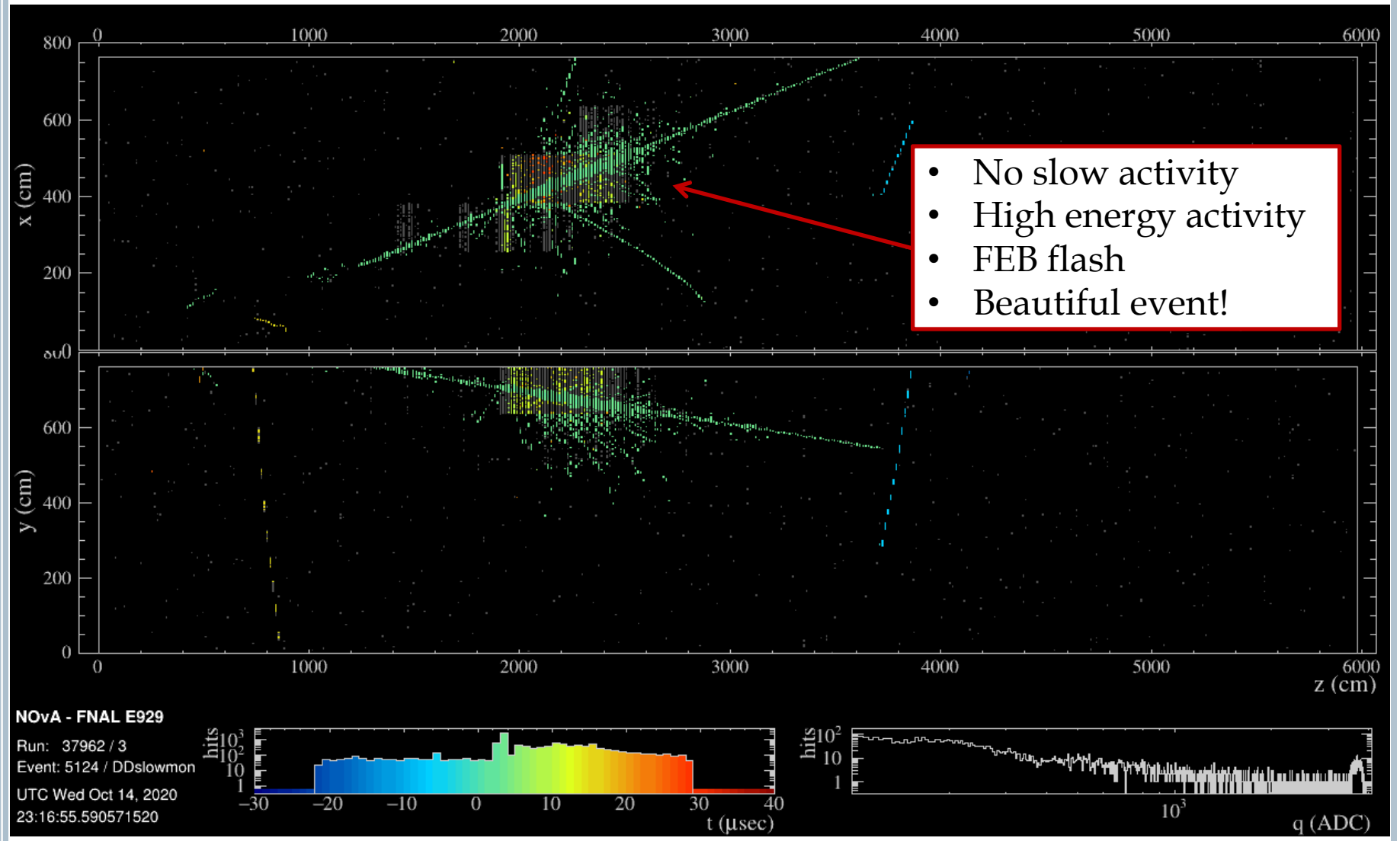
No Magnetic Monopole Event Found!



Interesting Event 1 – Timing Search

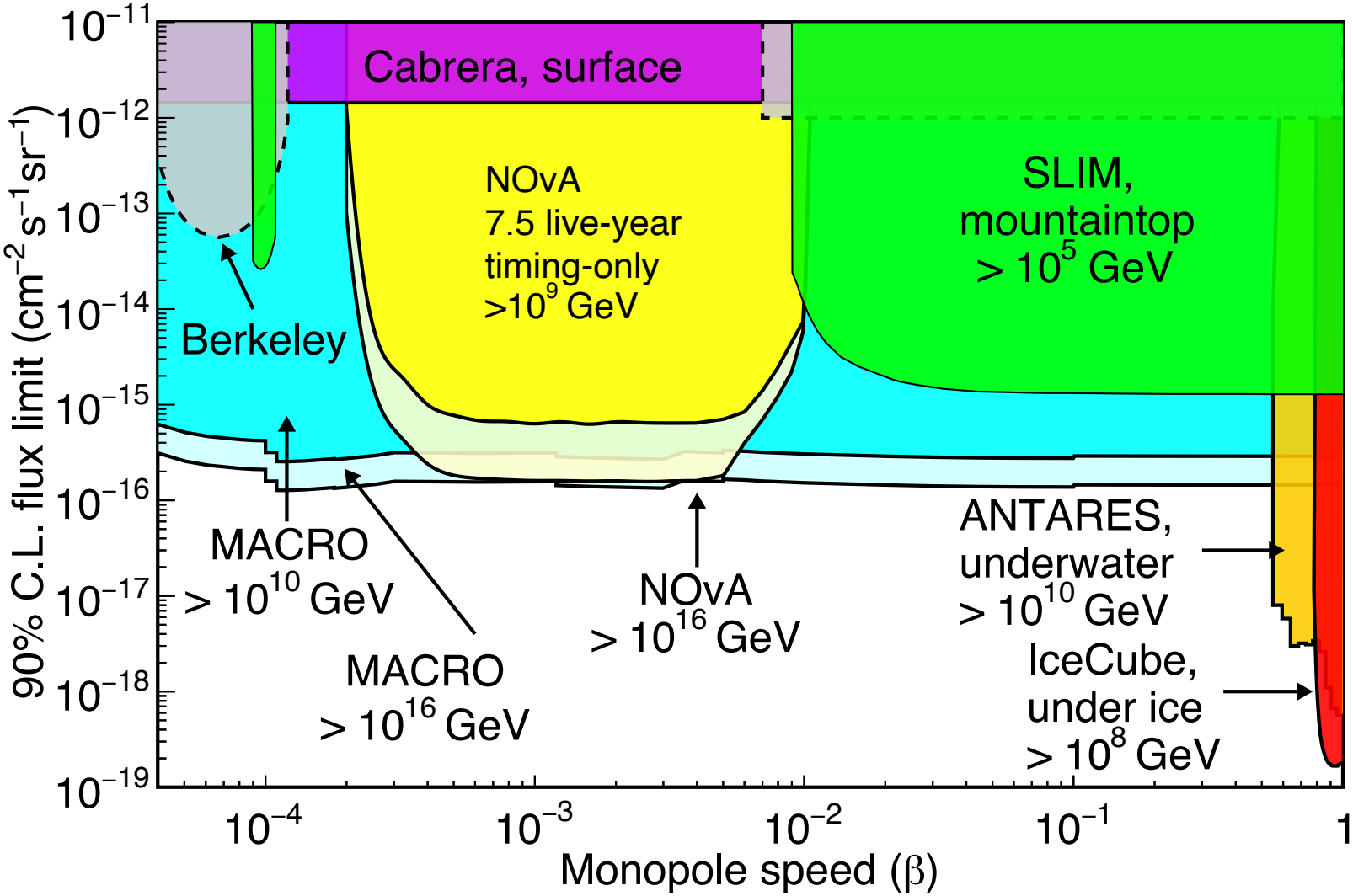


Interesting Event 2 – Timing Search

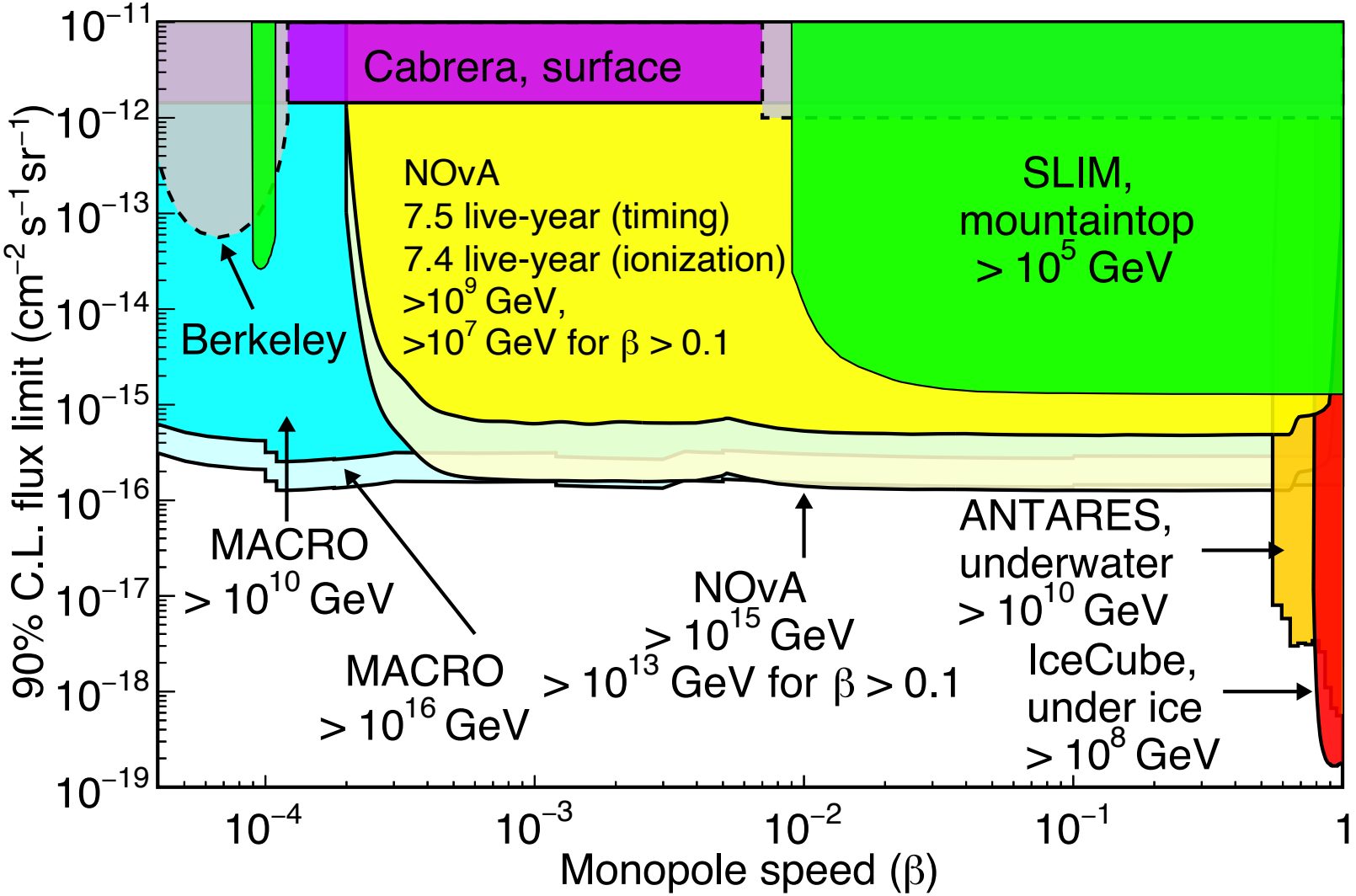


- No slow activity
- High energy activity
- FEB flash
- Beautiful event!

Magnetic Monopole Flux Limits



Magnetic Monopole Flux Limits



Summary

- We continue to untangle the oscillation parameter phase space.
  - Stay tuned for our combined results with T2K (up next)!
- We searched for magnetic monopoles. In the absence of any signal, we set limits as low as 2×10^{-16} $cm^{-2}s^{-1}sr^{-1}$.
- Thanks to the NOvA Collaboration!
- Thanks to our funding agencies for supporting the NOvA experiment (see next slide) and my work (NSF-2412236).

>266 scientists and engineers from 51 institutions from 8 countries

Acknowledgements

This document was prepared by the NOvA collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002. This work was supported by the U.S. Department of Energy; the U.S. National Science Foundation; the Department of Science and Technology, India; the European Research Council; the MSMT CR, GA UK, Czech Republic; the RAS, the Ministry of Science and Higher Education, and RFBR, Russia; CNPq and FAPEG, Brazil; UKRI, STFC and the Royal Society, United Kingdom; and the state and University of Minnesota. We are grateful for the contributions of the staffs of the University of Minnesota at the Ash River Laboratory, and of Fermilab.

Signal Search – L > 20 m