

Sub-luminal Magnetic Monopoles search results from the NOvA Experiment

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Outline

- General searching strategy
- Online Trigger algorithm
- Simulation, Overlay, Reconstruction and Selection
- False-positive signal: Muon pairs
- Results
 - ◆ Sensitivity for Magnetic Monopoles

Searching Strategy

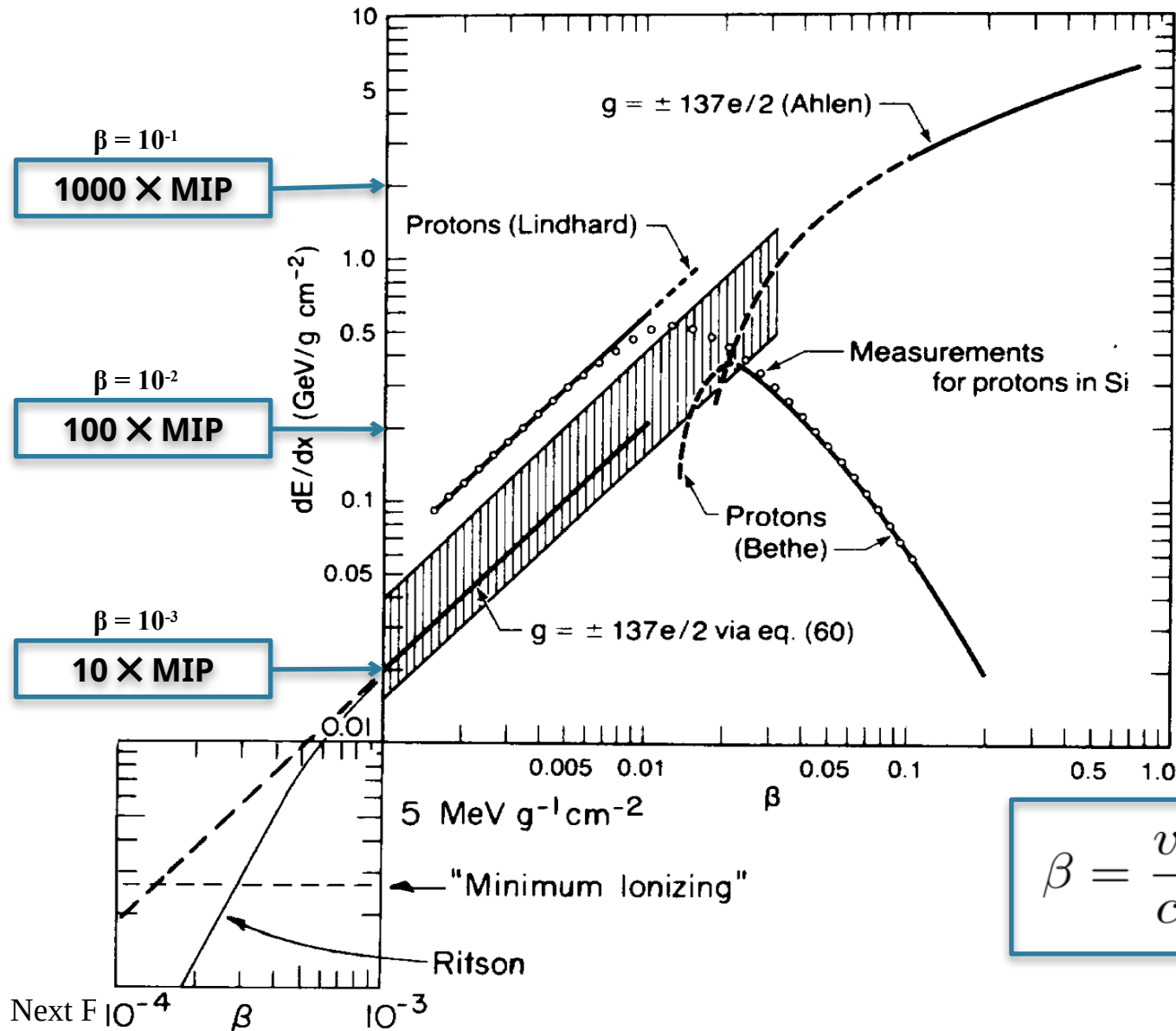
- The NOvA far detector (FD) is well suited for finding exotic particles due to its technical features. With a surface area of 4,000 m² and a location near the Earth's surface, the 14 kt FD provides unique sensitivity to potential magnetic monopoles at various betas.
- For the **timing-based** search the most distinctive aspect of the signal is the track speed. This search is expected to be background free so the flux limits scale linearly with exposure.
- Monopoles with $\beta < 10^{-2}$ and less can be identified due to their linear tracks with long transit times through the detector.
- Technically we can record tracks as slow as $\beta \approx 10^{-4}$

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

Magnetic Monopole Energy Deposition

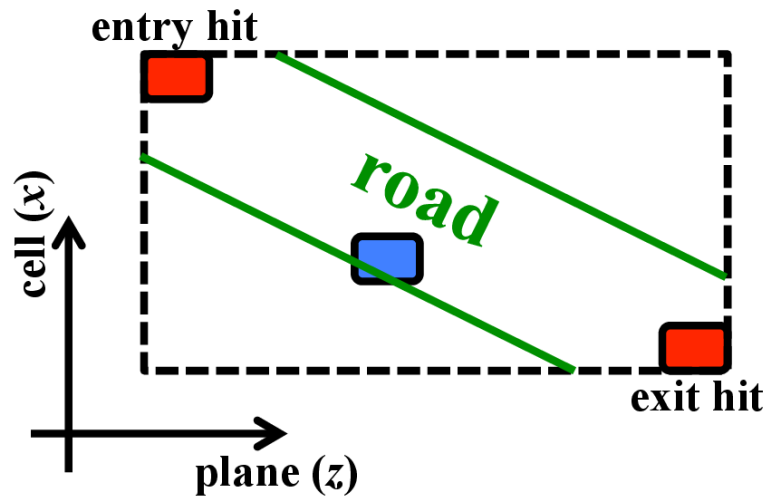


- Groom's summary of the magnetic monopole energy deposition as calculated from EM.
- Monopole interaction is similar to particle with charge $Z = 69$ at high β .

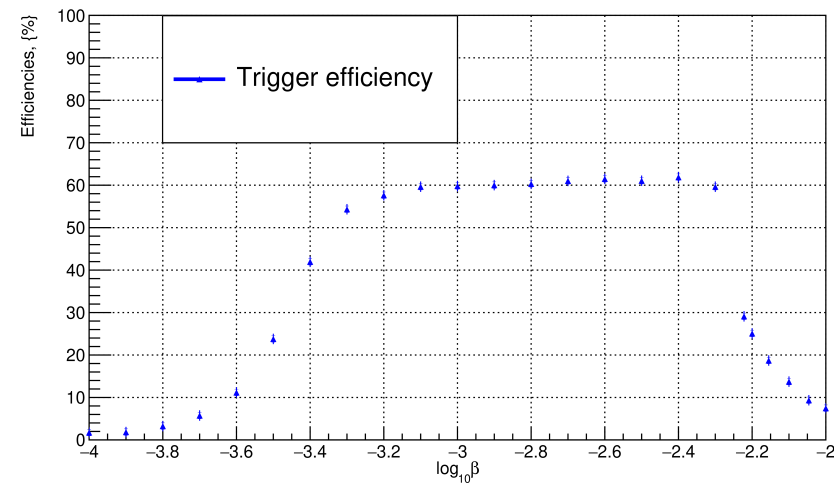
$$\beta = \frac{v}{c} = \frac{\text{velocity}}{\text{speed of light}}$$

Online Trigger algorithm

- Trigger looks at the live data and tries to identify straight lines of hits that would be consistent with a “slow” track.



Schematic depiction of the trigger algorithm

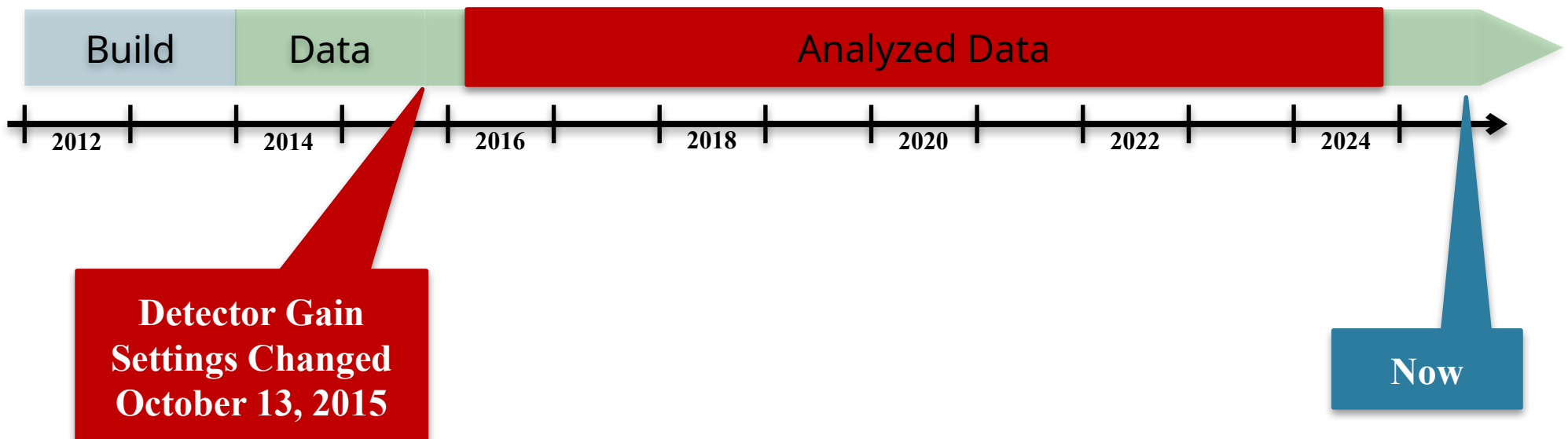


Slow monopole trigger efficiency vs. true speed

Data Sample

➤ Timing Search:

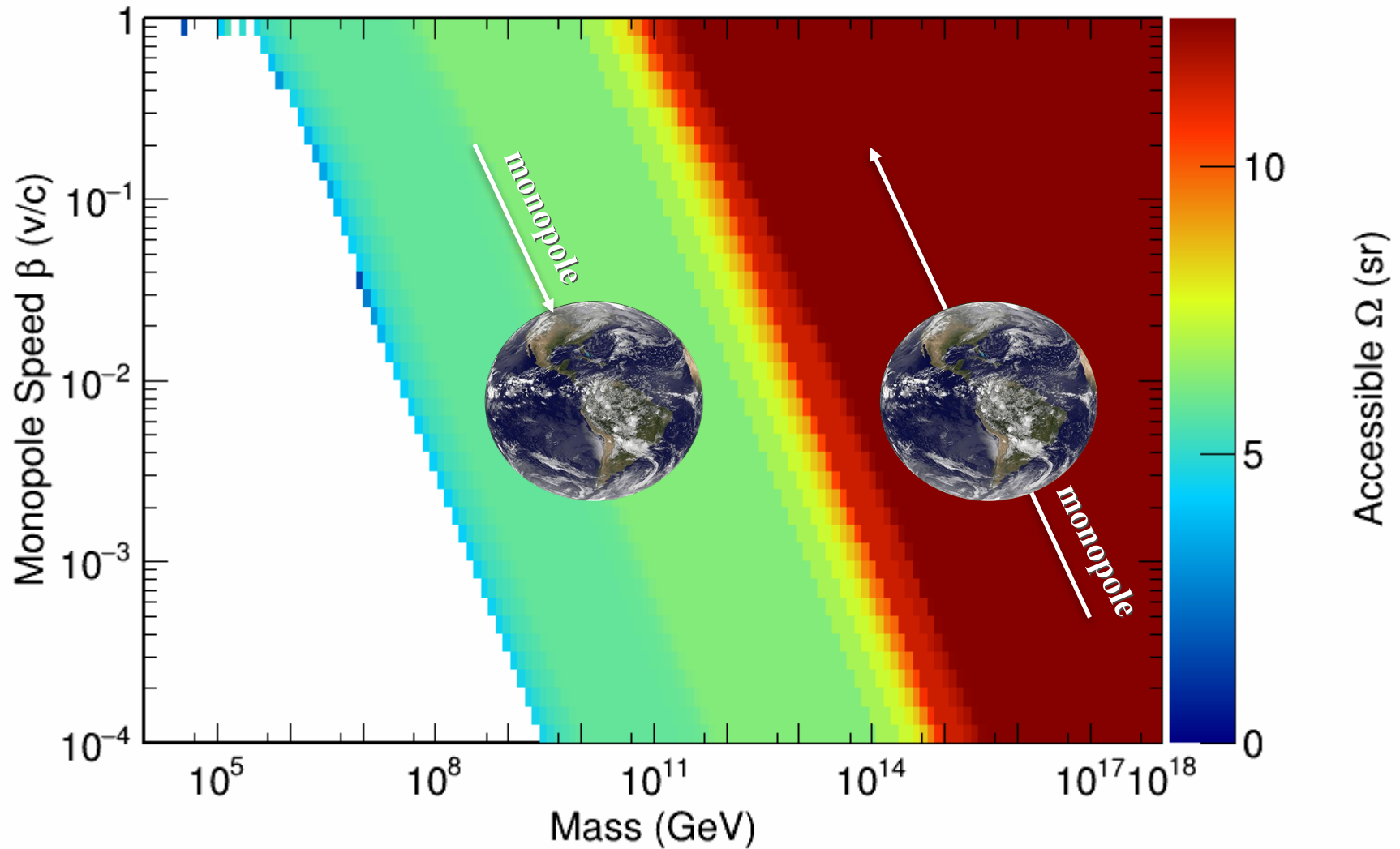
- ◆ February 2016 – October 2024
- ◆ 2,985 days (2,743 days marked as good)



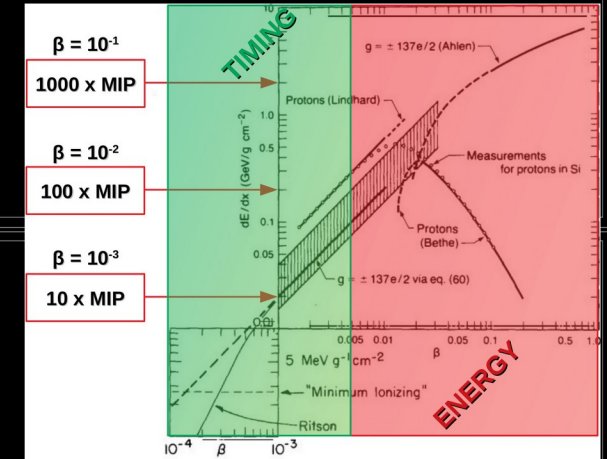
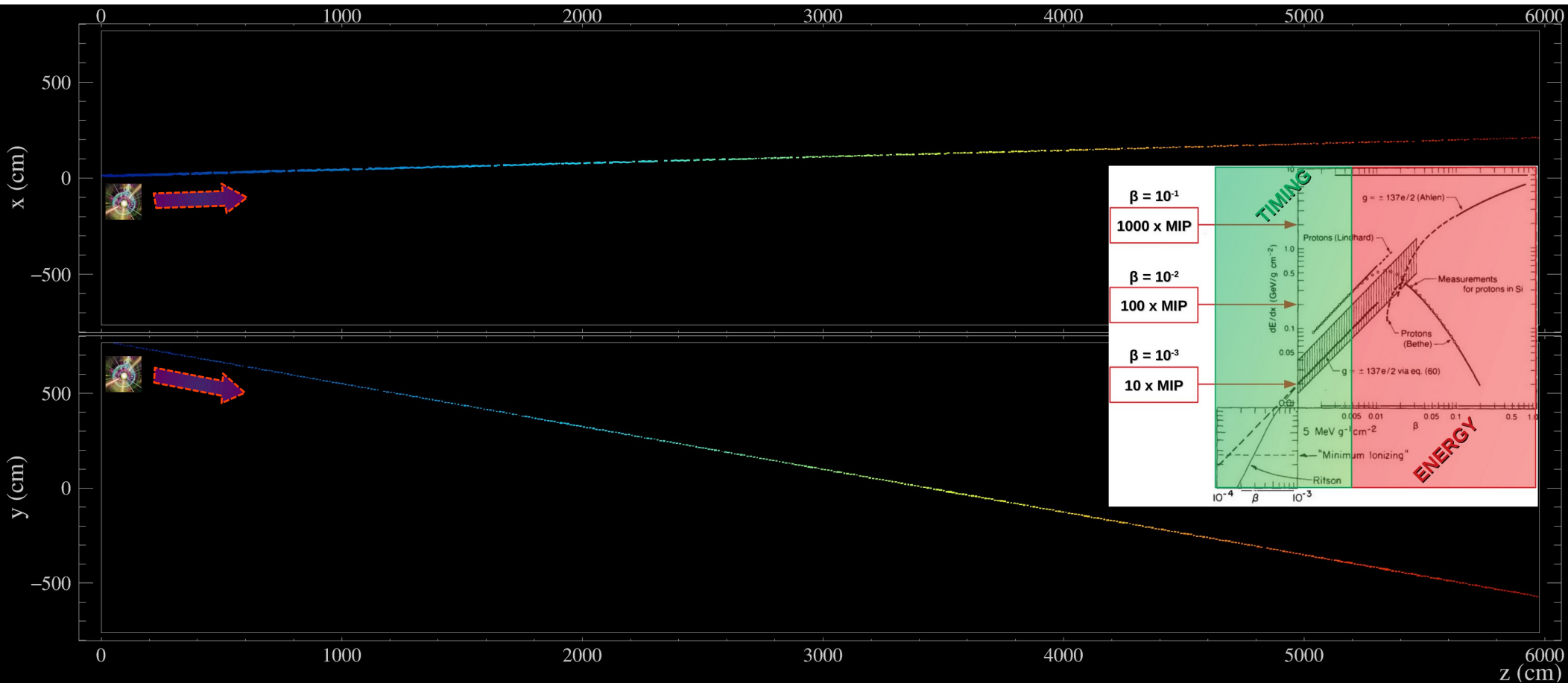
Simulation and Overlay

- **Isotropic** monopoles were generated distributed **uniformly** over all FD surfaces.
- Monopole **mass** = 10^{16} **Gev/c²**, **$g_D = 1$** , **$e = 0$** .
- For timing-based search monopoles with **β** in the range [**10^{-4}** , **10^{-2}**] were investigated.
- MC samples were **overlaid** with 5 ms FD activity samples.

Acceptance Region



Simulated Slow Monopole EVD



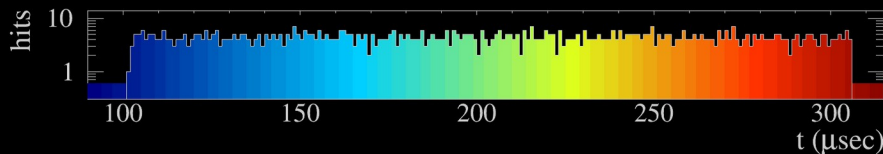
NOvA - FNAL E929

Run: 1 / 1

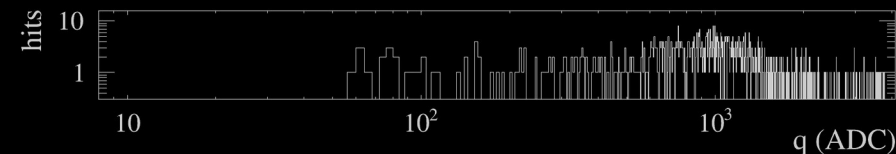
Event: 1 / NuMI

UTC Thu Jan 1, 1970

00:00:0.000000000

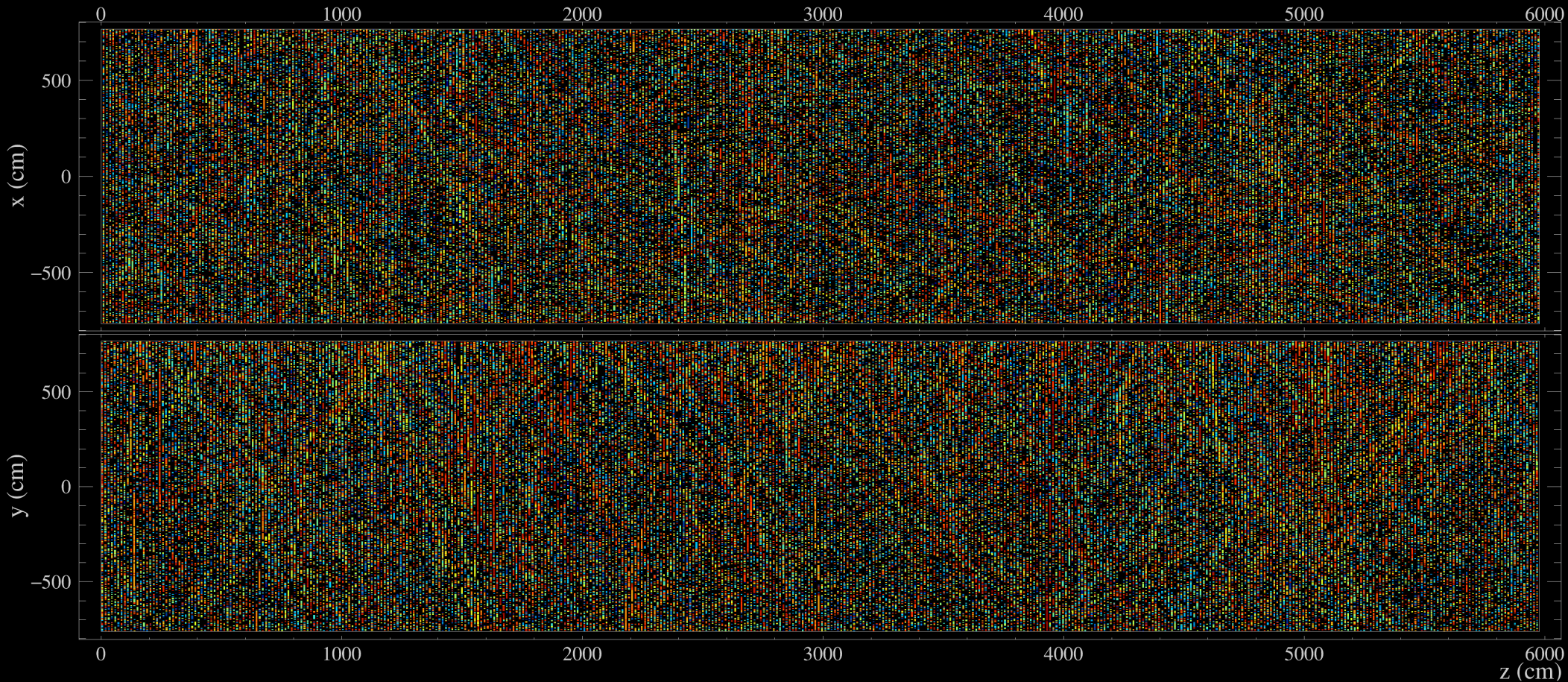


Travel time through the detector



Energy deposition

Simulated monopole + FD 5 ms activity Event



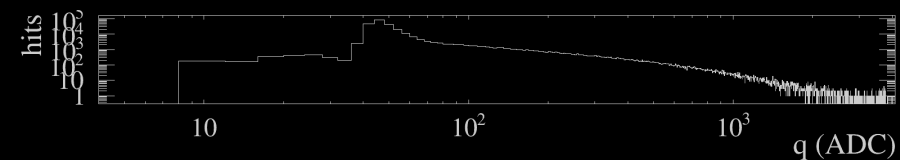
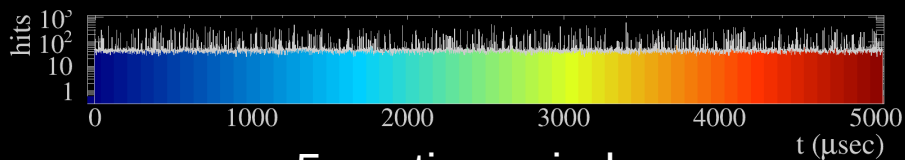
NOVA - FNAL E929

Run: 24000 / 1

Event: 1 / NuMI

UTC Thu Jan 1, 1970

00:00:0.000000000



Offline reconstruction algorithm

- identify cosmic tracks with Cosmic Tracker (on all hits)
- remove hits with less than 100 ADC
- remove hits associated with cosmic tracks
- remove isolated hits

Monopole Cluster

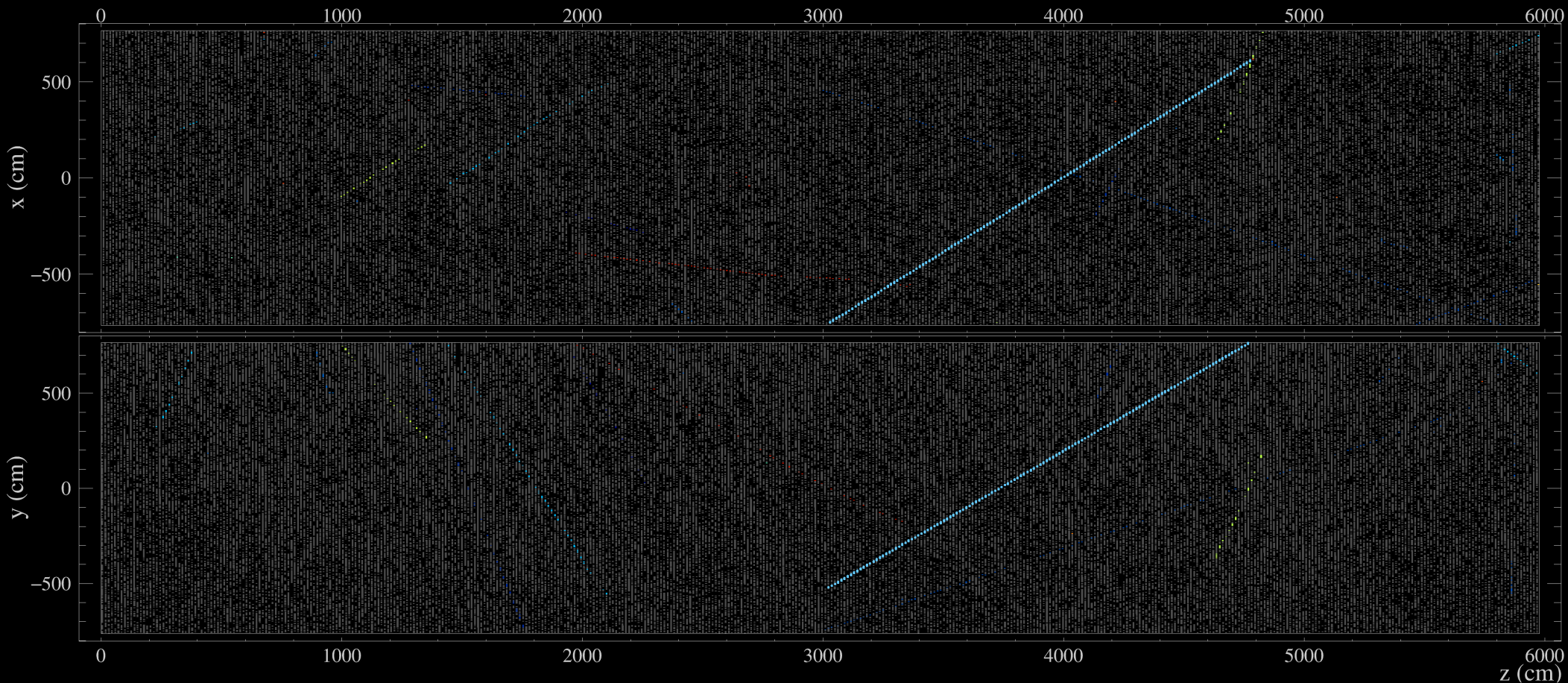
- run slicer to remove uncorrelated hits
 - using Window Slicer
 - with increased time window of 10 μ s

Monopole Slice

- remove slices with $\Sigma E > 2 \times 10^6$ ADC
- identify straight line objects
 - using standard Hough Tracker
- merge 2D tracks into 3D tracks
 - only keep tracks with at least 100 hits
 - sort tracks from slowest to fastest (i.e. first track = slowest track)

Monopole Track

Monopole Track



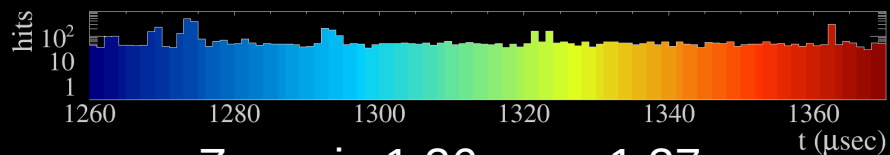
NOvA - FNAL E929

Run: 24000 / 1

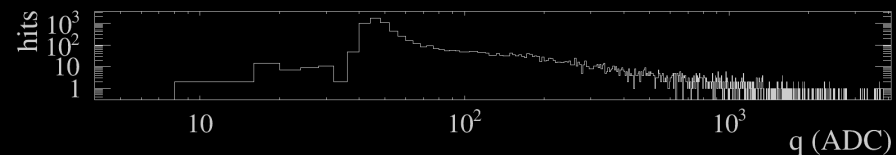
Event: 1 / NuMI

UTC Thu Jan 1, 1970

00:00:0.000000000



Zoom in 1.26 ms – 1.37 ms



Pre-selection filter

- Events that **timed out** removal

- ...

Monopole Cluster

- ...

Monopole Slice

- ...

Monopole Track

- Pre-selection **filter** module

- ♦ To be filtered and stored primary event should have at least **1** reconstructed track inside.

- Filter helped to reduce the total dataset size for more than 20 times.

Analysis Strategy – Offline

- We want to identify straight line tracks.

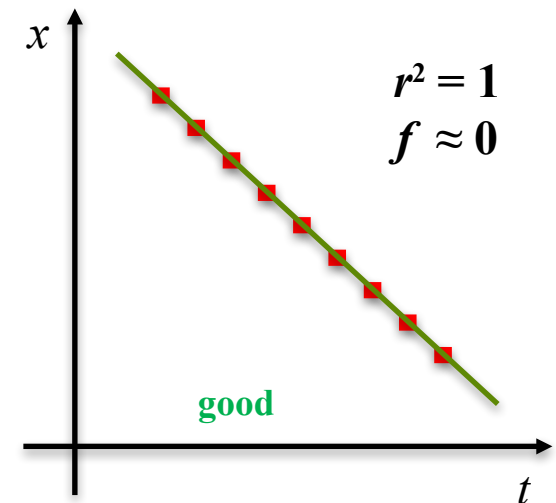
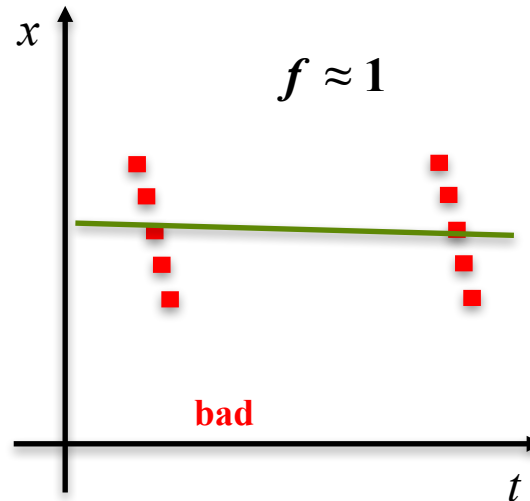
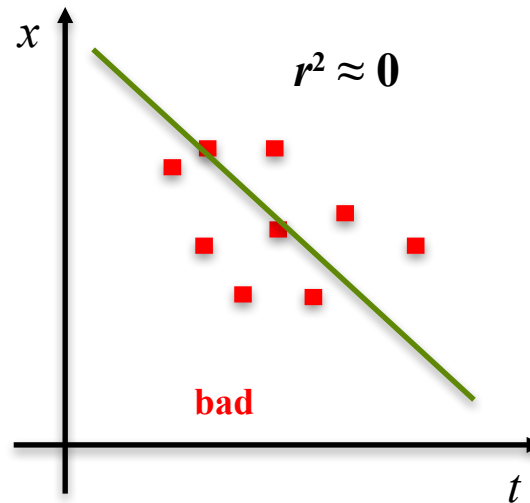
- Two powerful discriminators:

- ◆ Correlation coefficient: r^2

$$r = \frac{\sum_j^n (t_j - \bar{t})(x_j - \bar{x})}{\sqrt{\sum_j^n (t_j - \bar{t})^2 \sum_j^n (x_j - \bar{x})^2}}$$

- ◆ Time gap fraction:

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



Selection: Track Variables

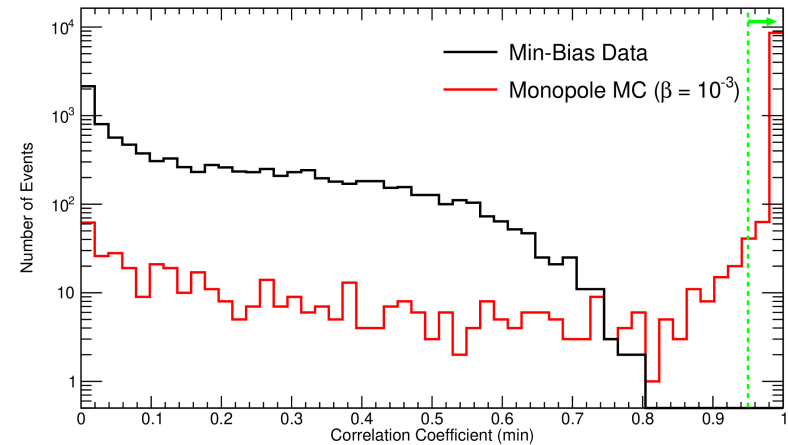
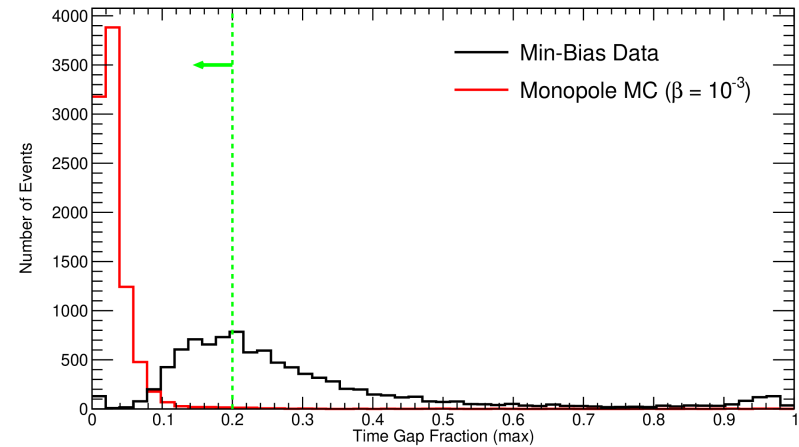
Selection Cuts

$$\beta < 10^{-2}$$

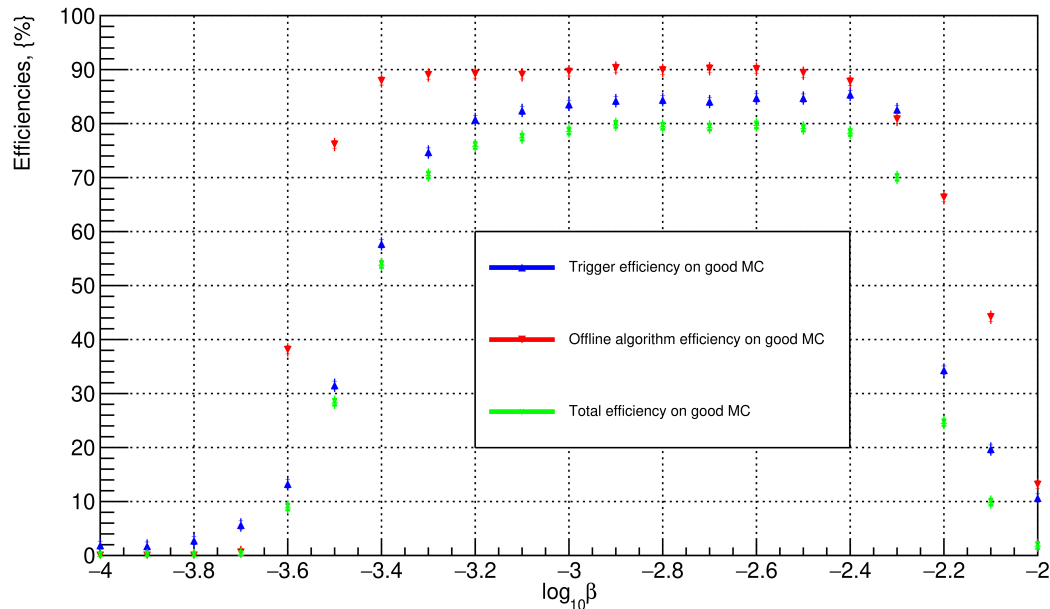
$$L_{\text{track}} > 10 \text{ m}$$

$$f < 0.2$$

$$r^2 > 0.95$$



Efficiencies



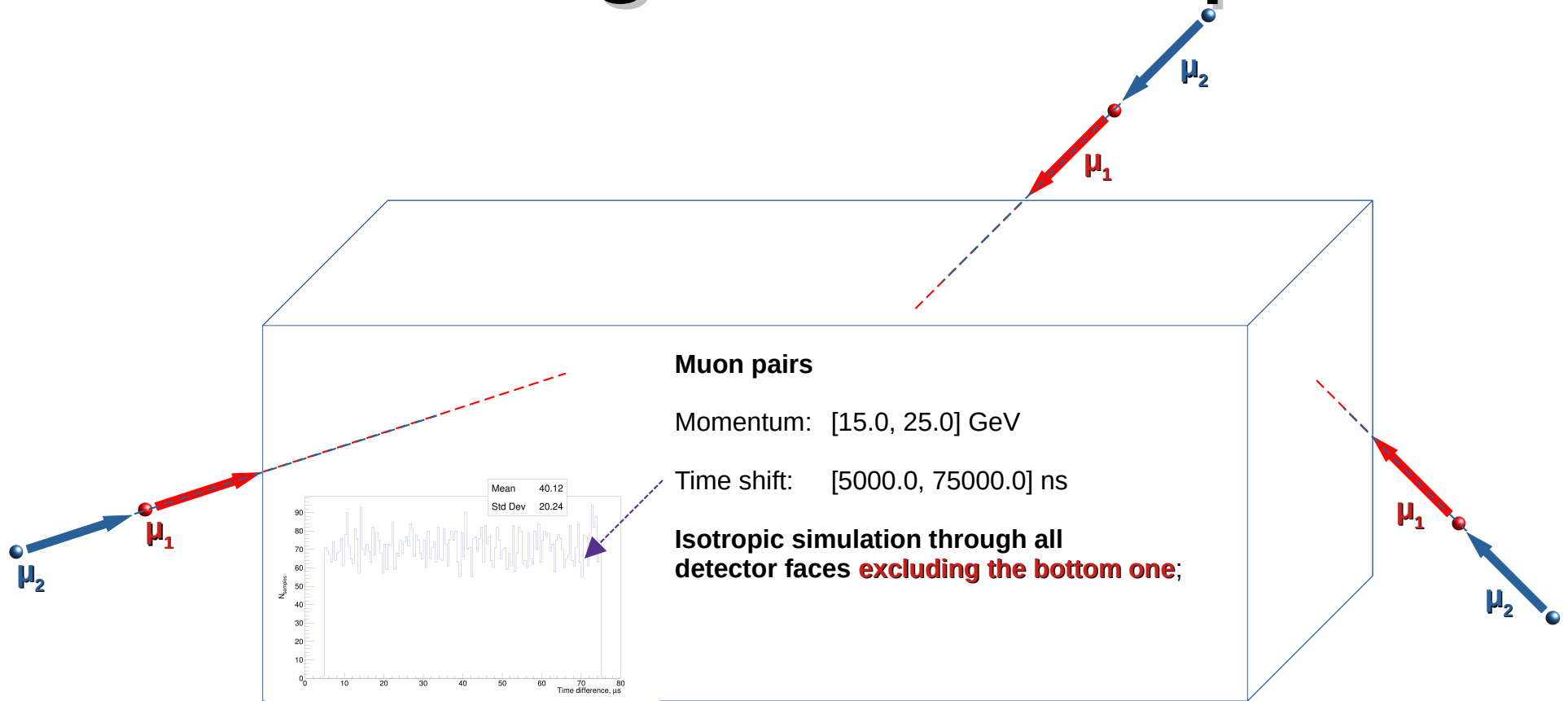
DDT and offline algorithm efficiencies for “good” MC monopoles: $|\theta_{yz}|$ and $|\theta_{xz}| < 85^\circ$, **Length** > 1000 cm.

Overall Efficiency: Number of monopoles selected by **trigger** and **offline** algorithm divided by number of **all** monopoles generated at each beta.



$\log_{10}(\beta_{MC})$	Overall Efficiency
-3.7	0.1%
-3.6	4.5%
-3.5	14.7%
-3.4	28.9%
-3.3	39.1%
-3.2	42.8%
-3.1	44.7%
-3.0	45.2%
-2.9	45.7%
-2.8	46.0%
-2.7	46.1%
-2.6	46.7%
-2.5	46.0%
-2.4	45.8%
-2.3	40.2%
-2.2	13.8%
-2.1	5.3%
-2.0	1.0%

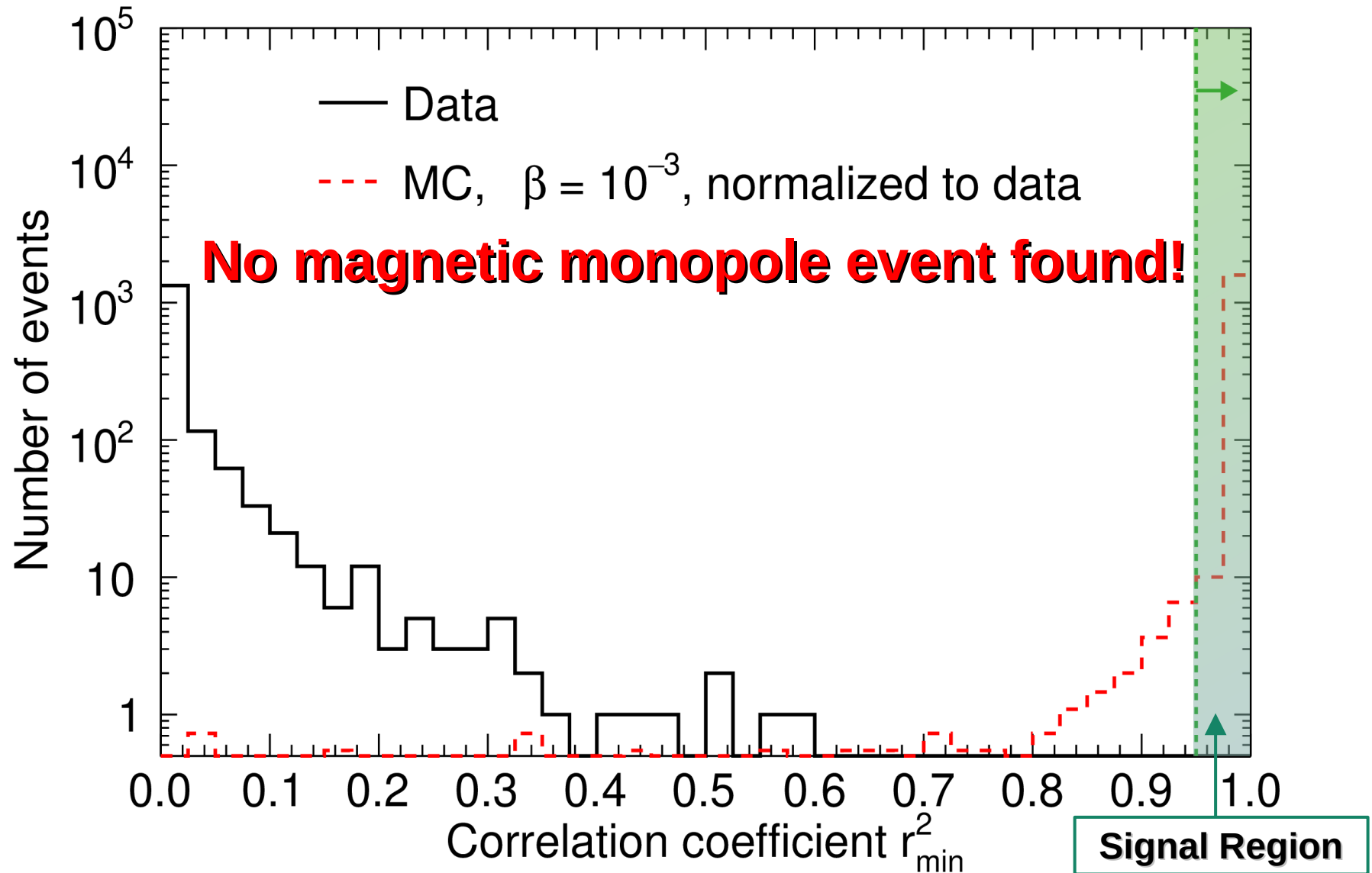
False-signal: Muon pairs



Offline algorithm rejected all events and could not even reconstruct a single track candidate.

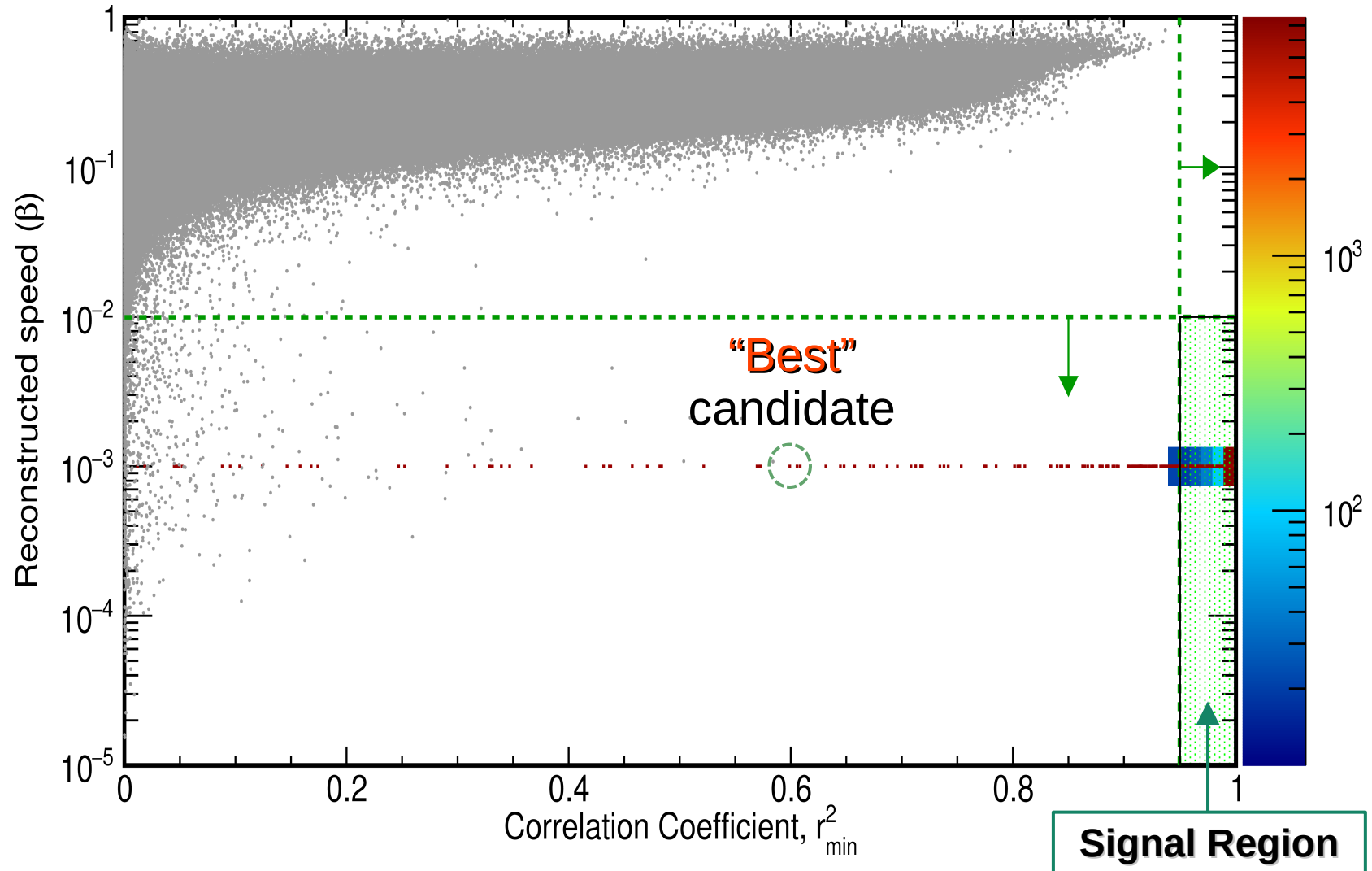
Results

$r_{\min}^2$ variable [N-1] Data vs MC

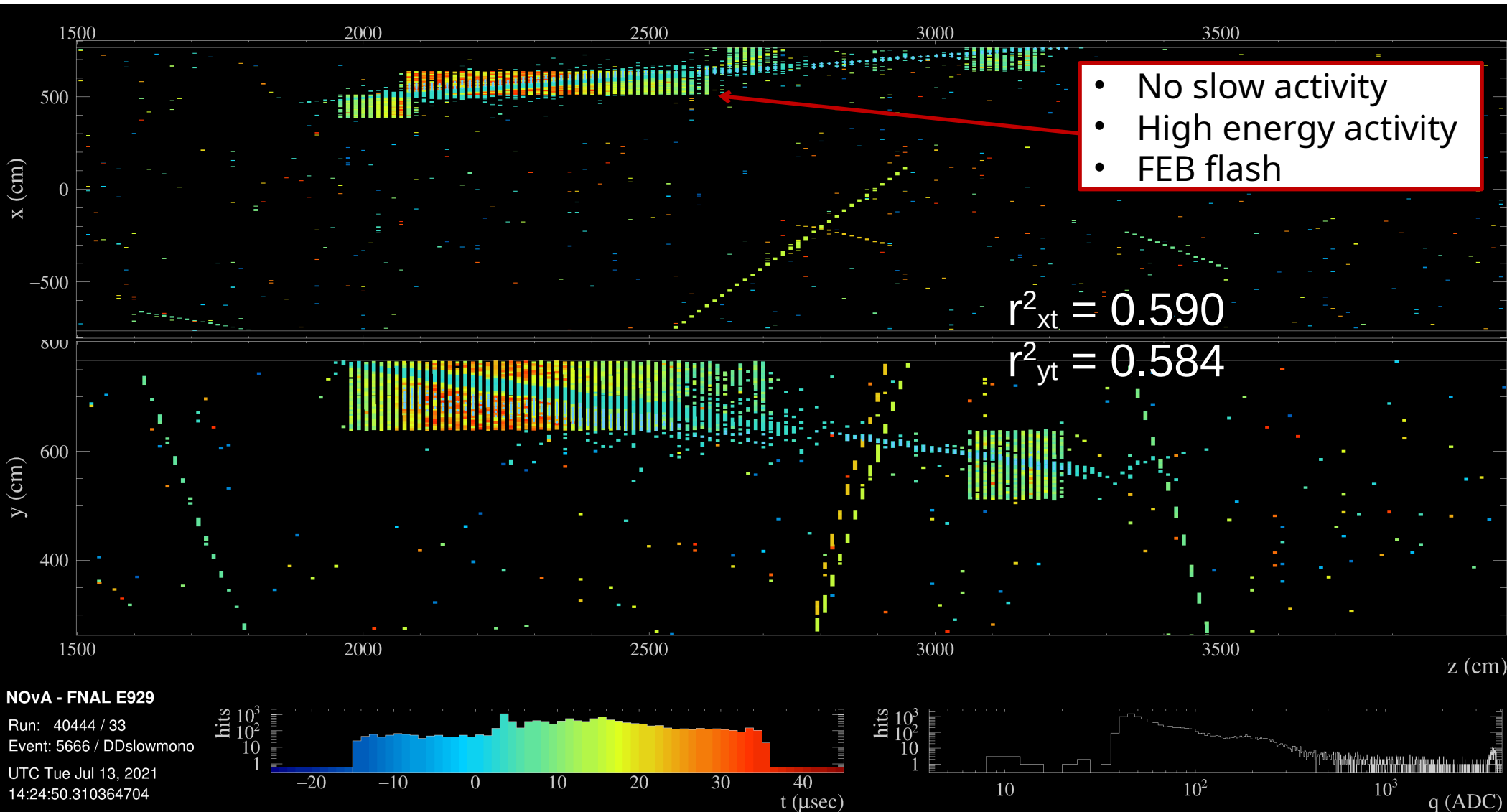


$r^2_{\min}$ variable [N-1] vs β

No magnetic monopole event found!



40444:33:5666 Reconstructed track



Sensitivity

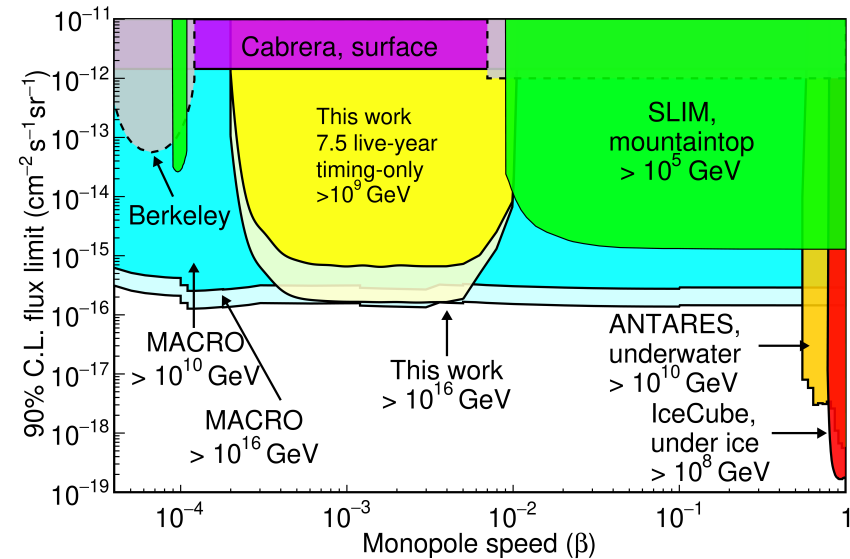
➤ Flux Limit Calculation:

- Projected surface area A_{proj}
- Solid angle coverage Ω
- Integrated livetime t
- Overall efficiency ε

➤ **$\Phi_{90\%} = 2.3 / A\varepsilon\Omega t$**

➤ Due to its surface location with little overburden and large surface area, monopoles with mass $> 10^9$ GeV can reach the Far Detector.

➤ NOvA sets the only limits around $\beta = 10^{-3}$ for magnetic monopoles lighter than 10^{10} GeV.



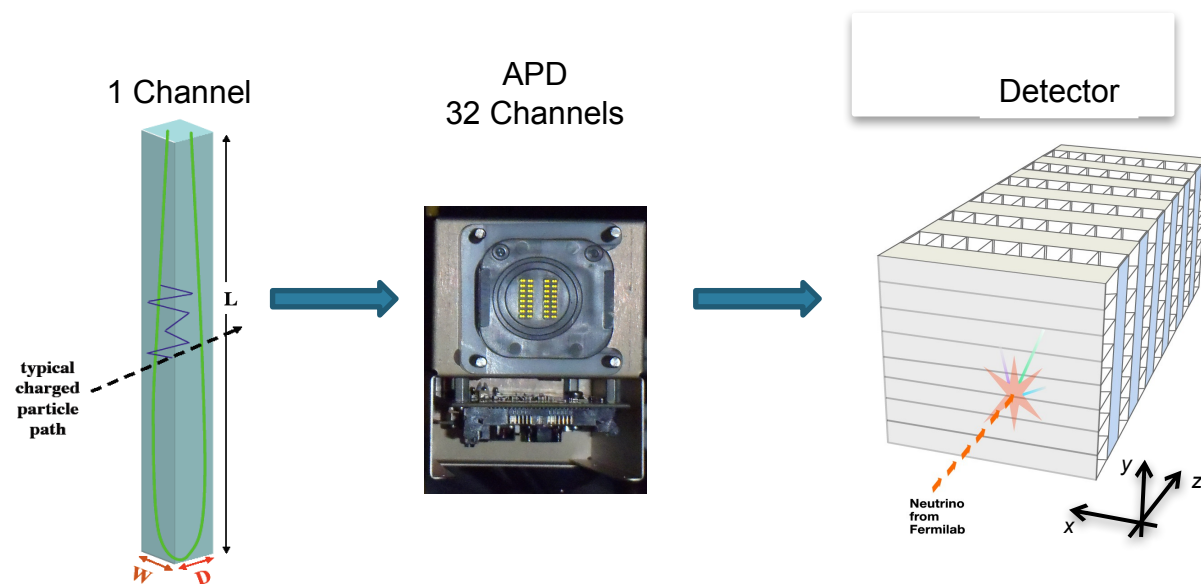
Summary

- NOvA has the **unique ability** to search for **subluminal** (slower than $c/100$) exotic particles that would usually be absorbed by large shielding or overburdens of other experiments.
- We searched for magnetic monopoles:
 - ◆ In the absence of any signal, we set **limits** as low as $8 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. **[arxiv link]**

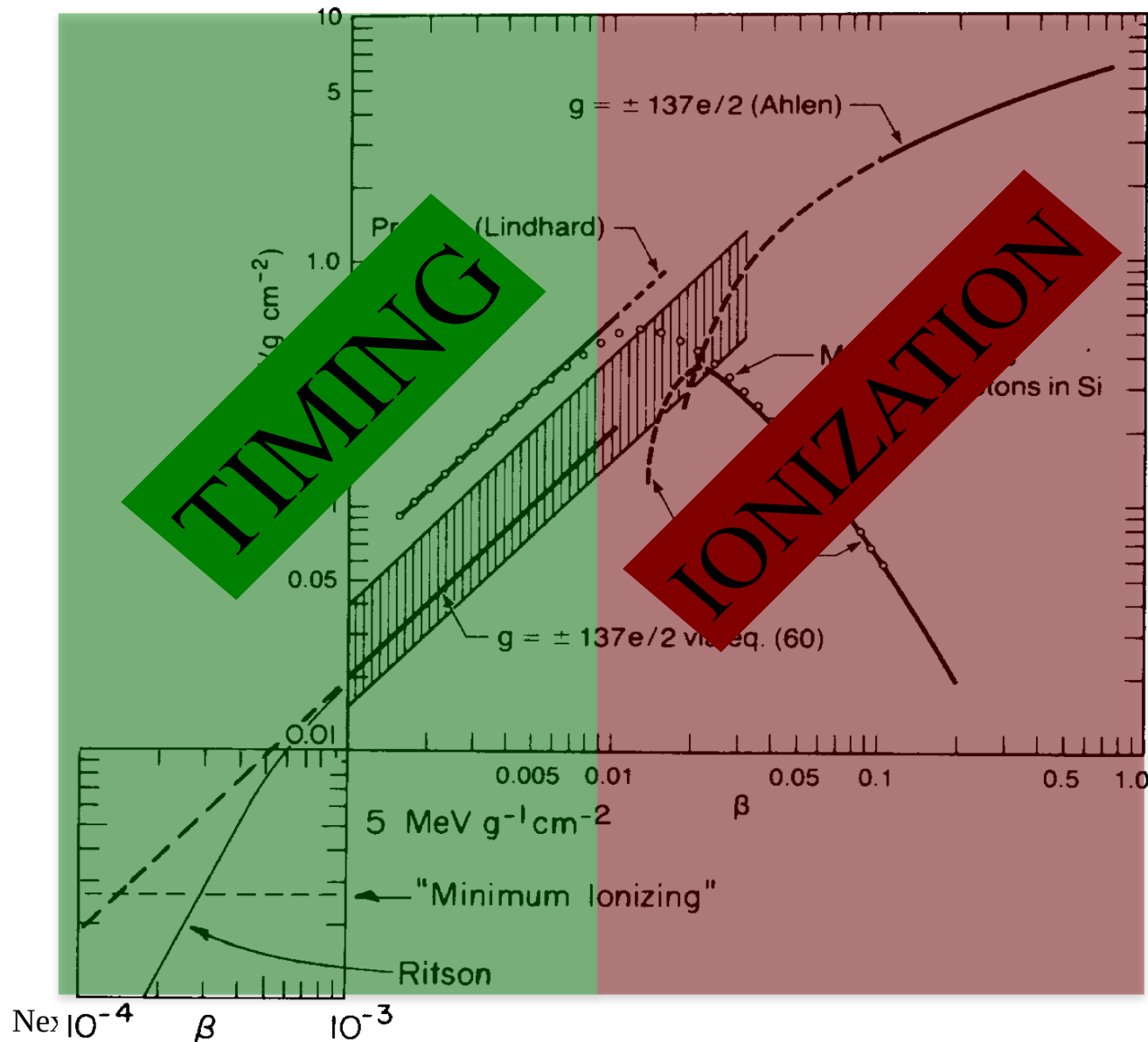
Thank you for your attention!

Backup

- 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)



Analysis Strategy



➤ We divide the magnetic monopole searches into two broad categories based on:

- A. Ionization
- B. Timing

High Gain periods based on trigger changes

From
10/13/15
to
12/15/15
SF = 10



From
12/15/15
to
10/11/17
SF → 4
Extra_info set up
for time-out bit

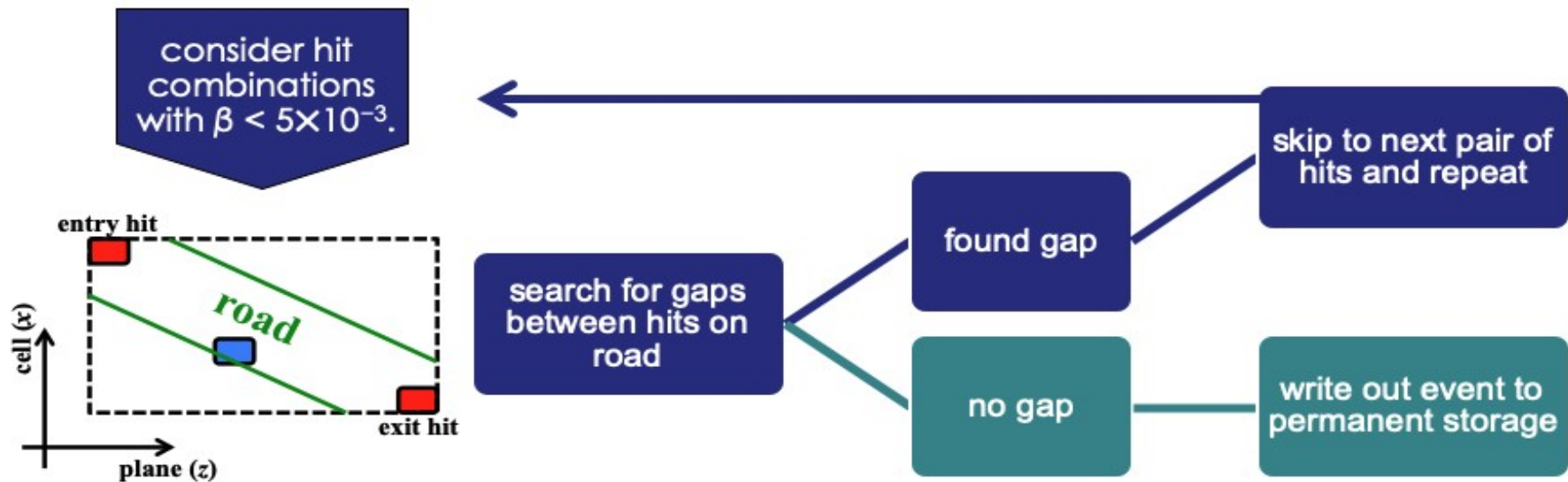
From
10/11/17
to
09/15/21
Only small time
period used for
timed-out files



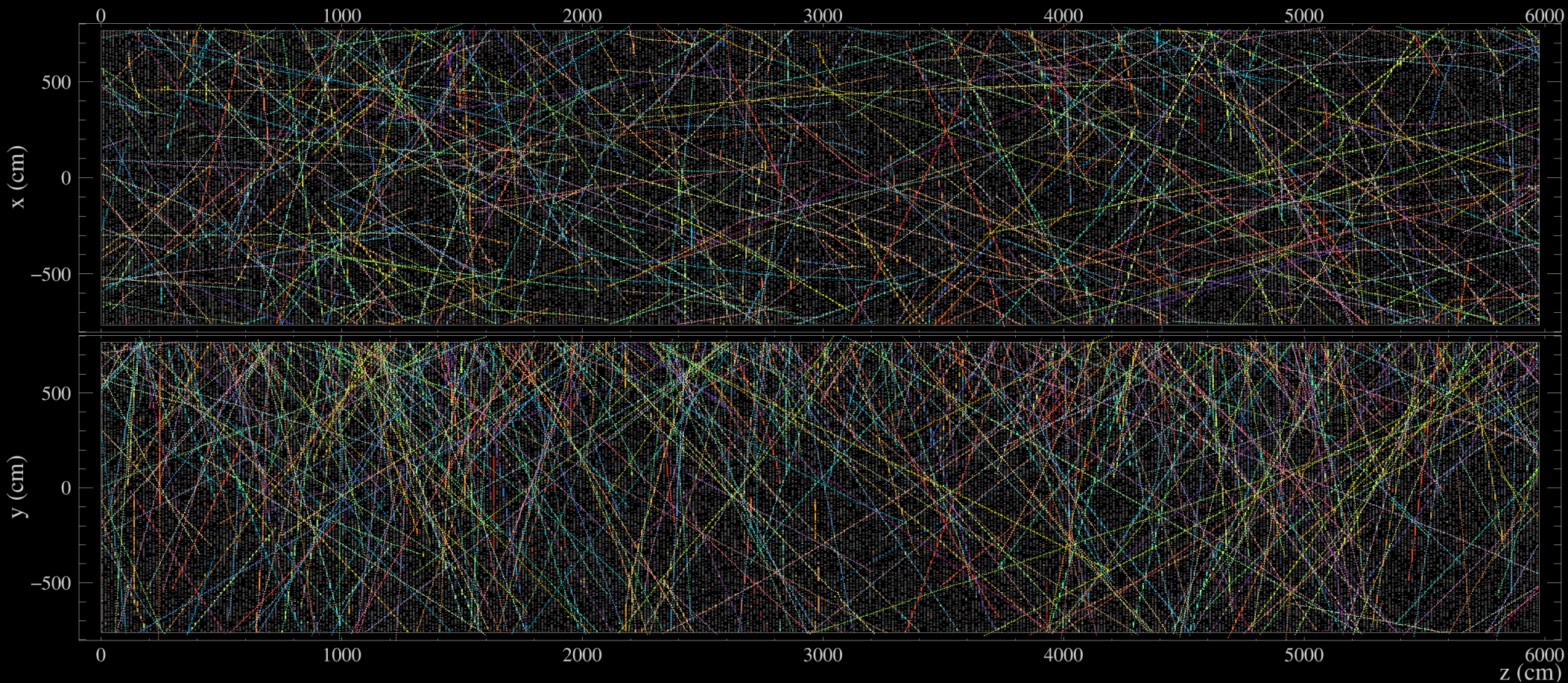
From
09/15/21
to
Present
SF → 1
Change input
path

Online Trigger algorithm

- 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).



Cosmic tracks



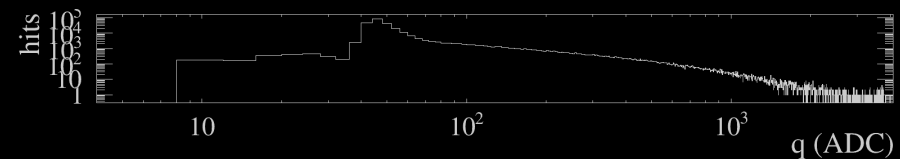
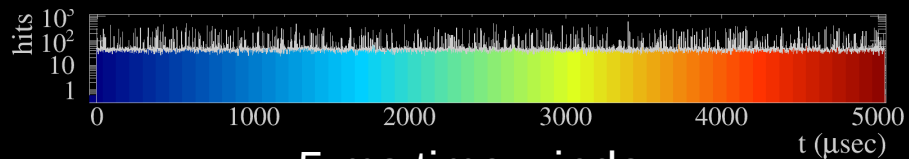
NOvA - FNAL E929

Run: 24000 / 1

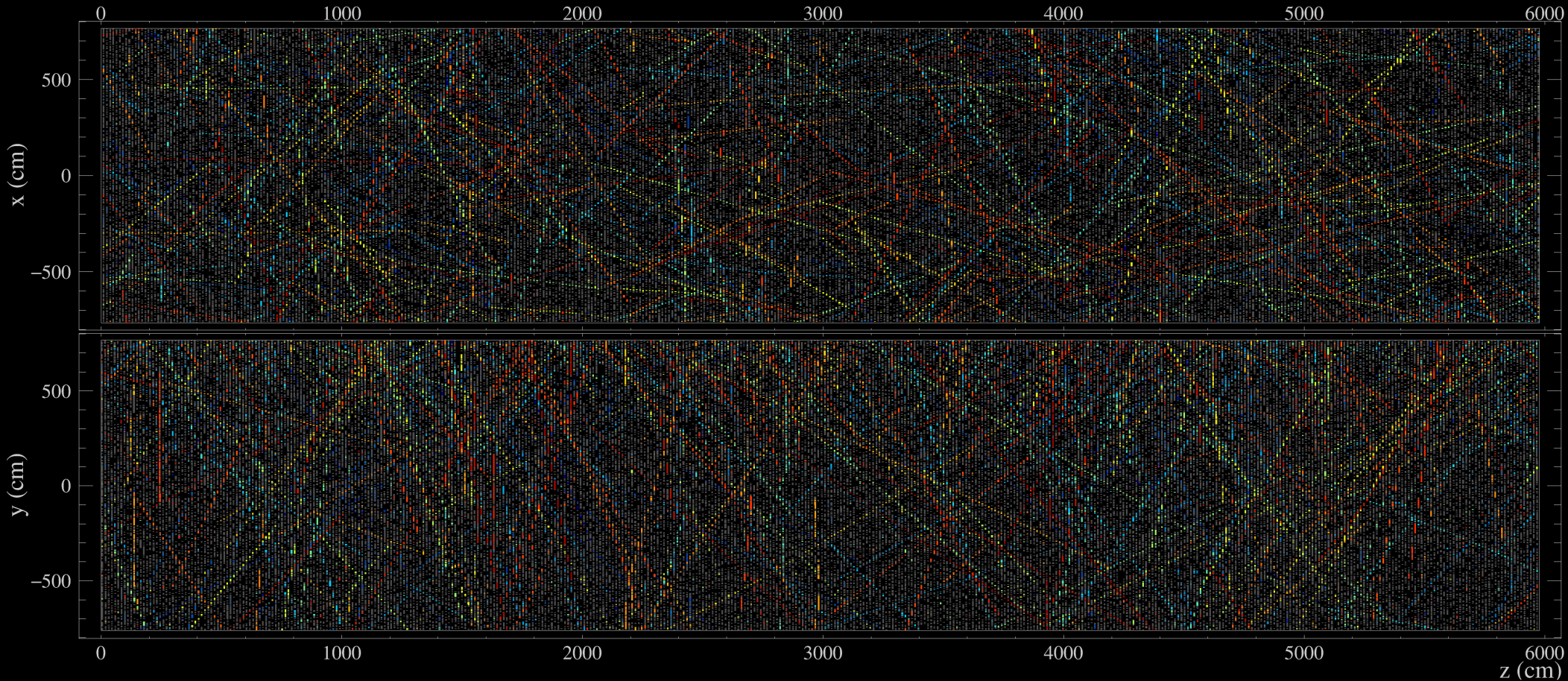
Event: 1 / NuMI

UTC Thu Jan 1, 1970

00:00:0.000000000



Without low energy hits



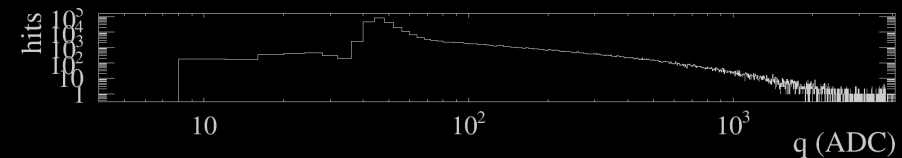
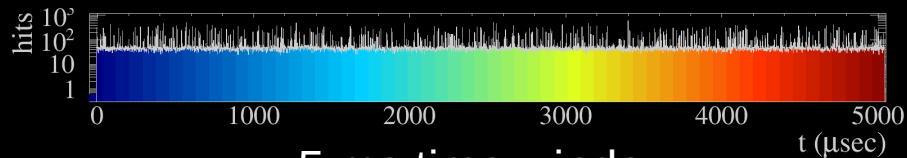
NOvA - FNAL E929

Run: 24000 / 1

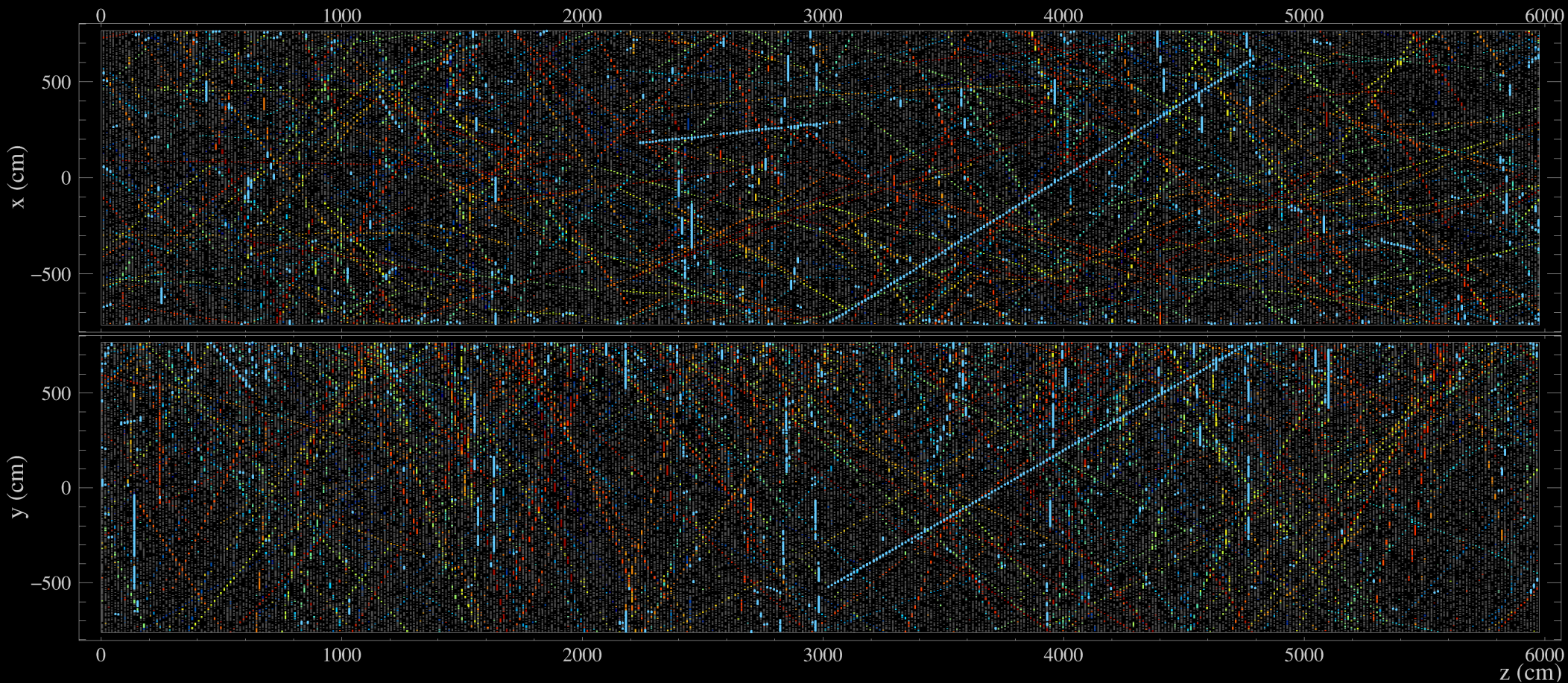
Event: 1 / NuMI

UTC Thu Jan 1, 1970

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Monopole Cluster



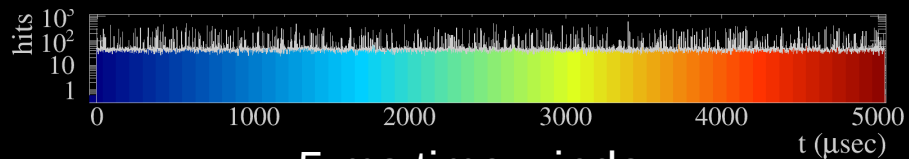
NOvA - FNAL E929

Run: 24000 / 1

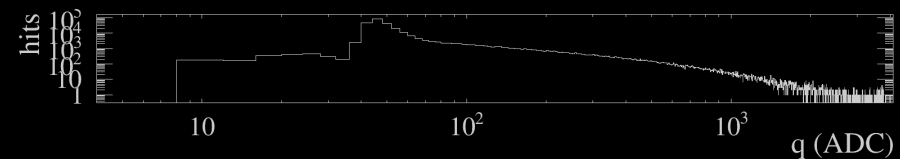
Event: 1 / NuMI

UTC Thu Jan 1, 1970

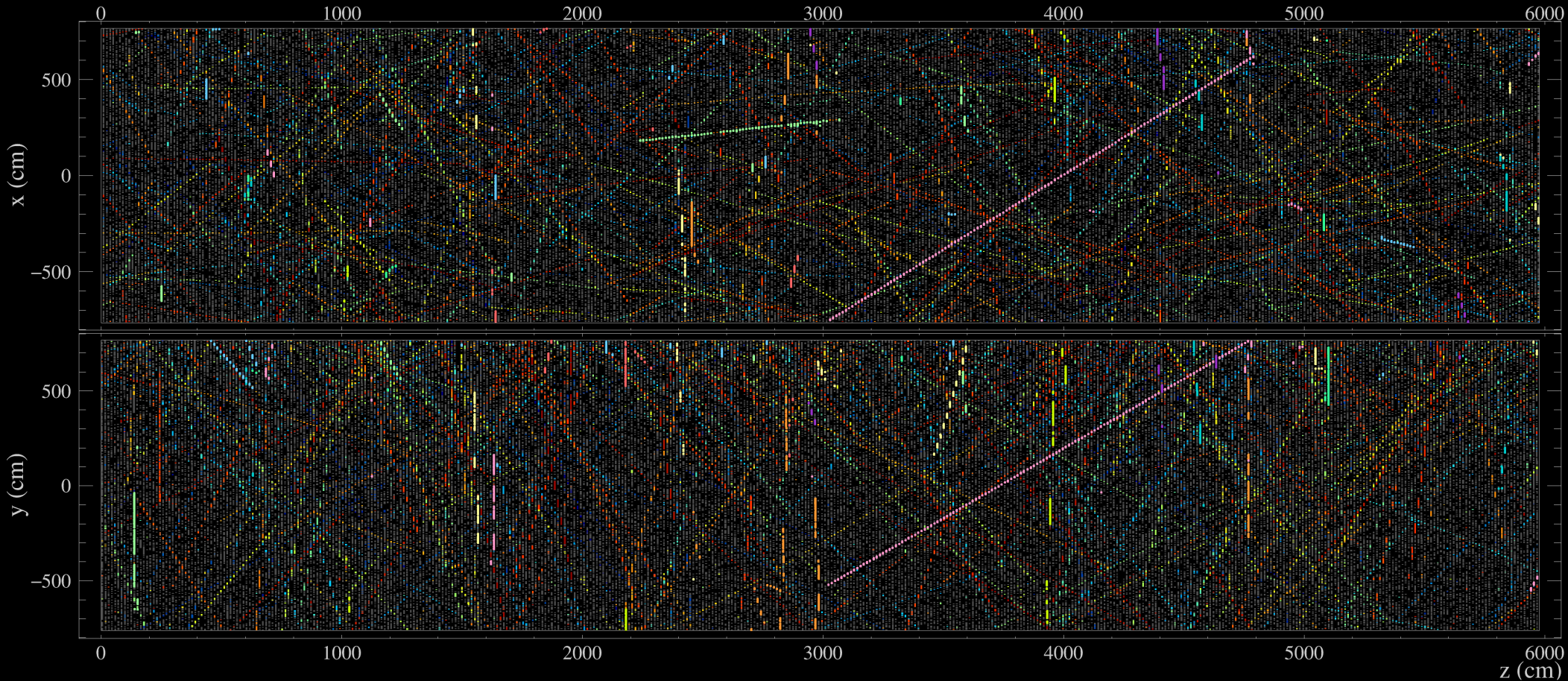
00:00:0.000000000



5 ms time window



Monopole Slices



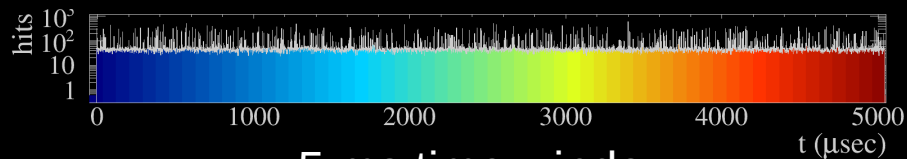
NOvA - FNAL E929

Run: 24000 / 1

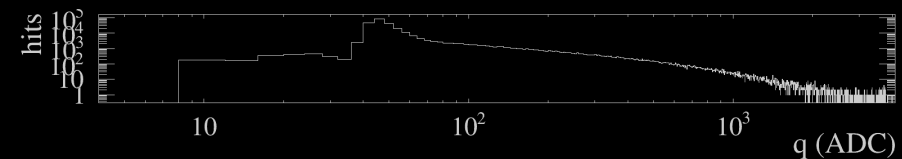
Event: 1 / NuMI

UTC Thu Jan 1, 1970

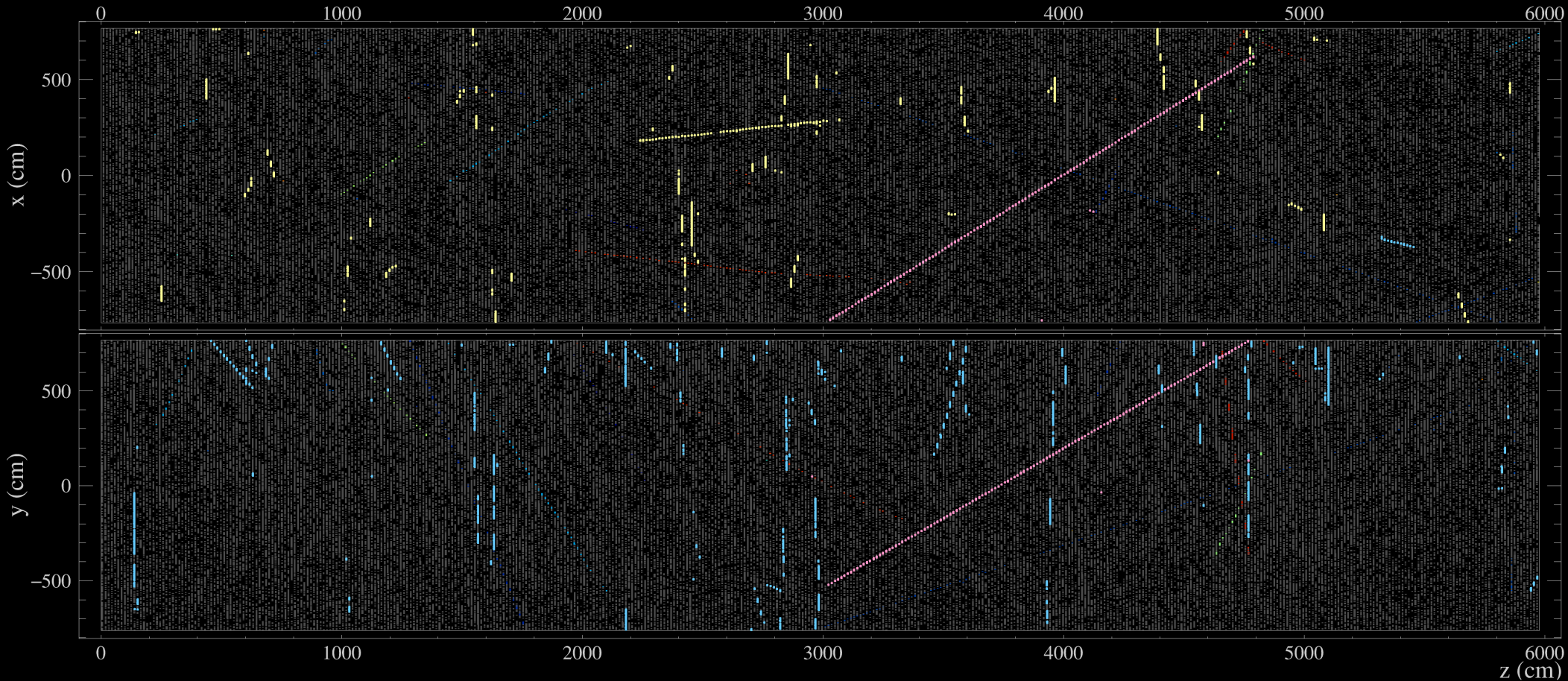
00:00:0.000000000



5 ms time window



Time Zoom around True Monopole Slice



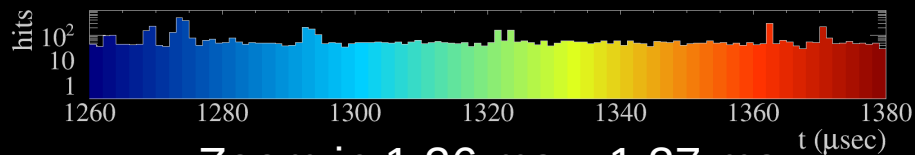
NOvA - FNAL E929

Run: 24000 / 1

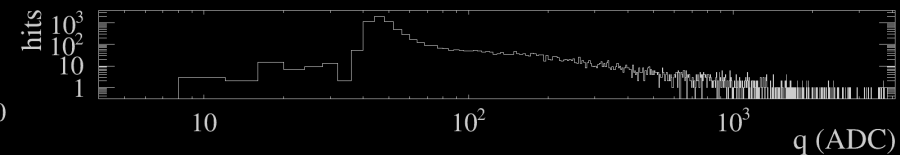
Event: 1 / NuMI

UTC Thu Jan 1, 1970

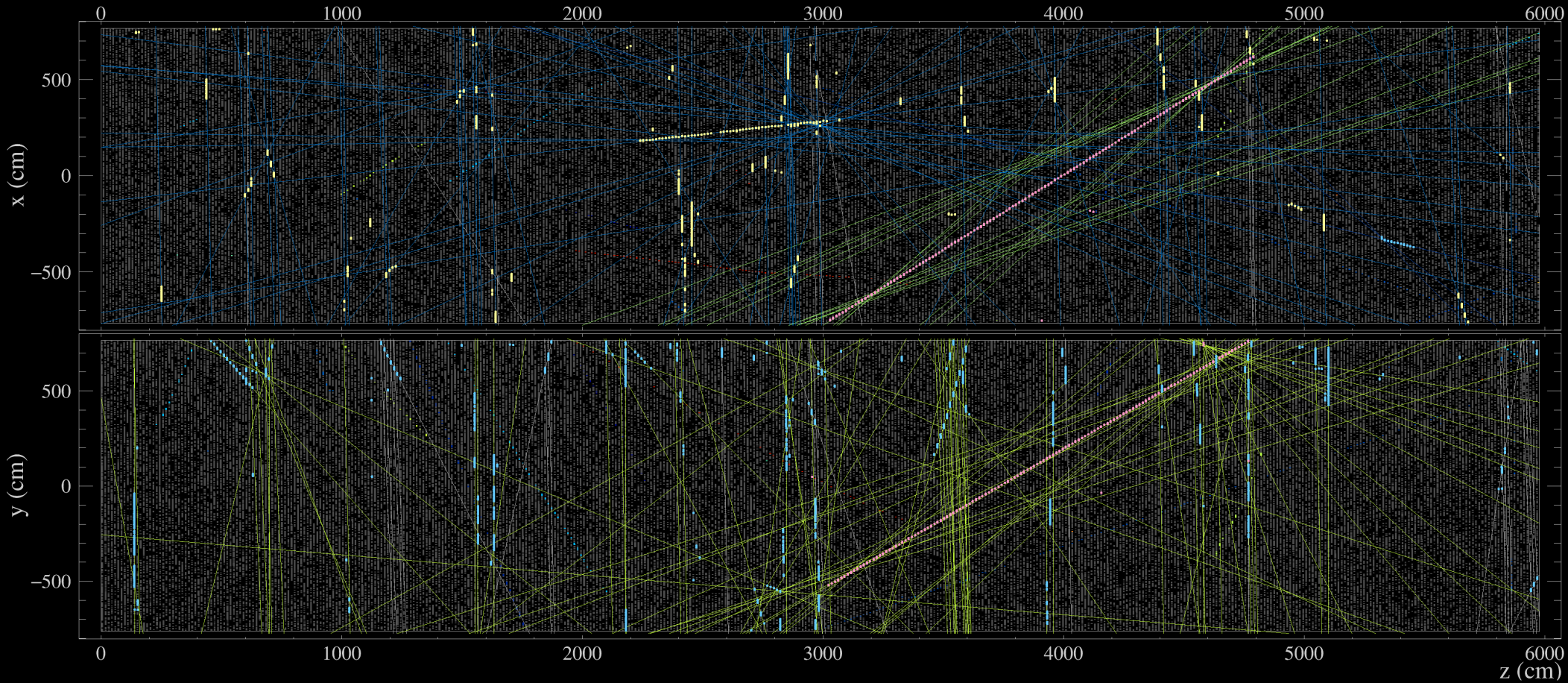
00:00:0.000000000



Zoom in 1.26 ms – 1.37 ms



Hough Tracking



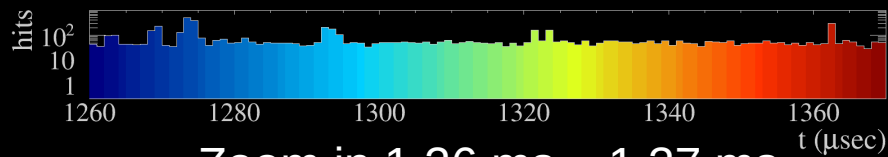
NOvA - FNAL E929

Run: 24000 / 1

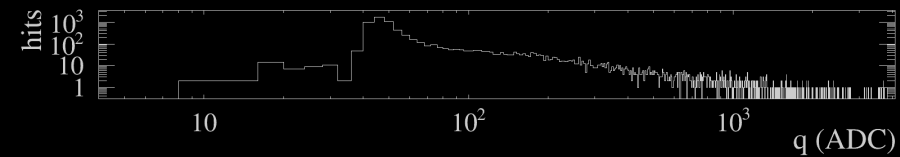
Event: 1 / NuMI

UTC Thu Jan 1, 1970

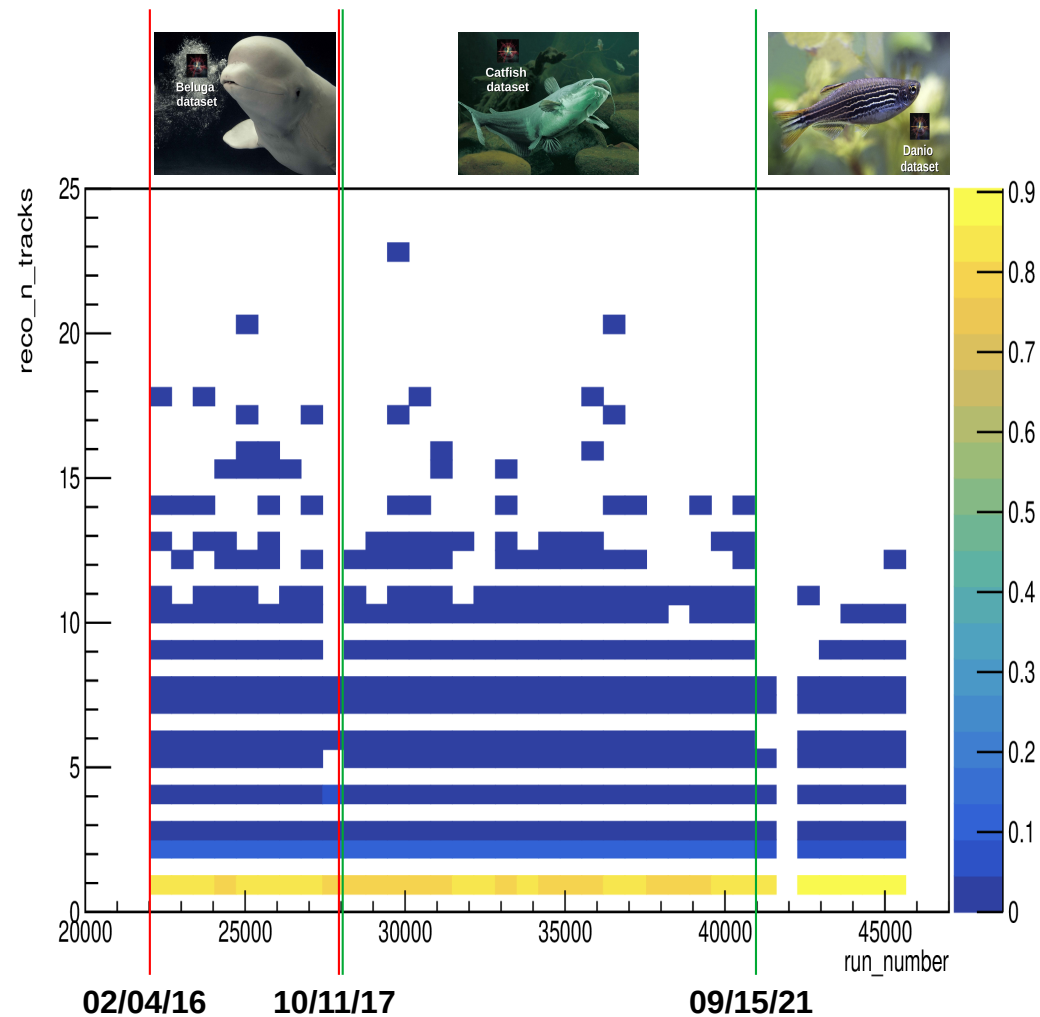
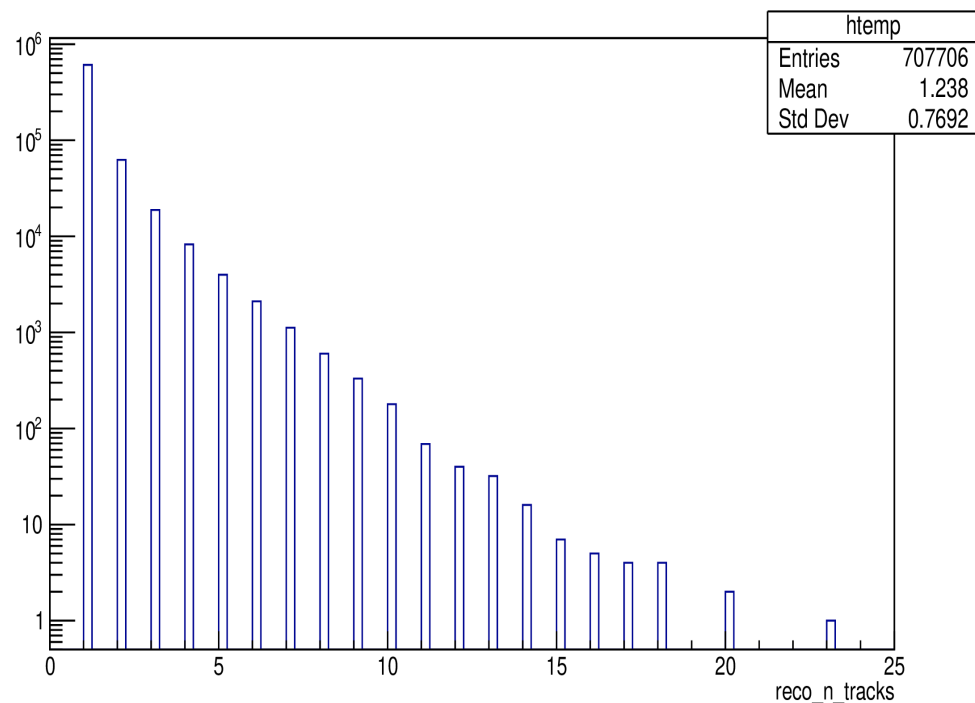
00:00:0.000000000



Zoom in 1.26 ms – 1.37 ms

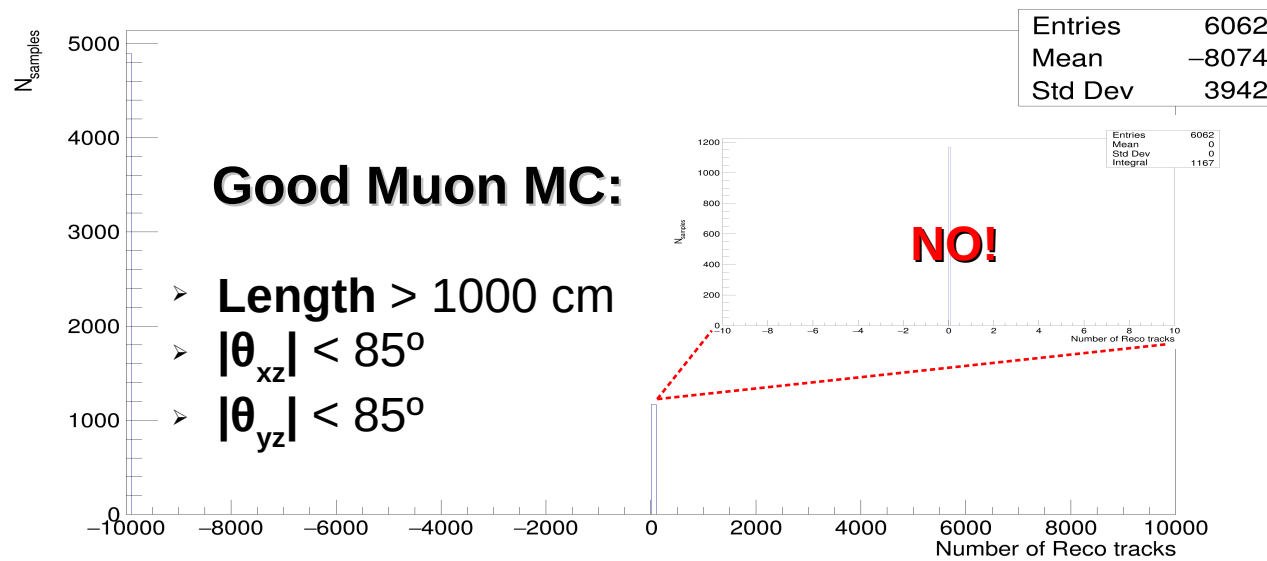


Reco_n_tracks vs Run number (*Monitoring*)



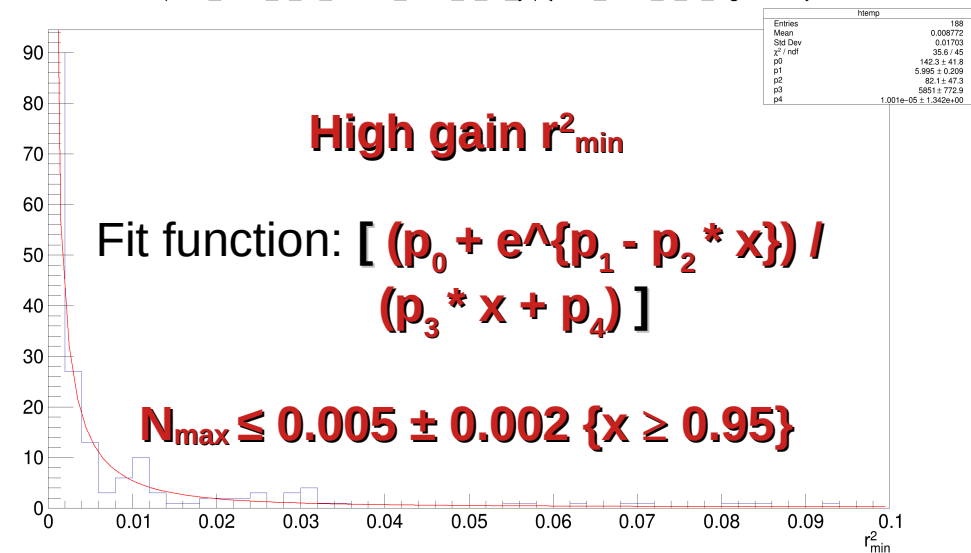
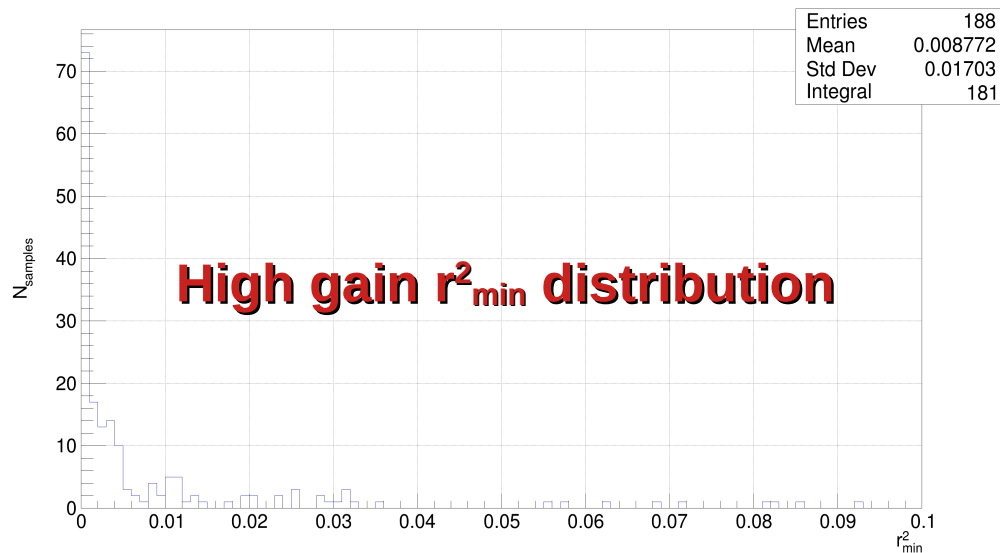
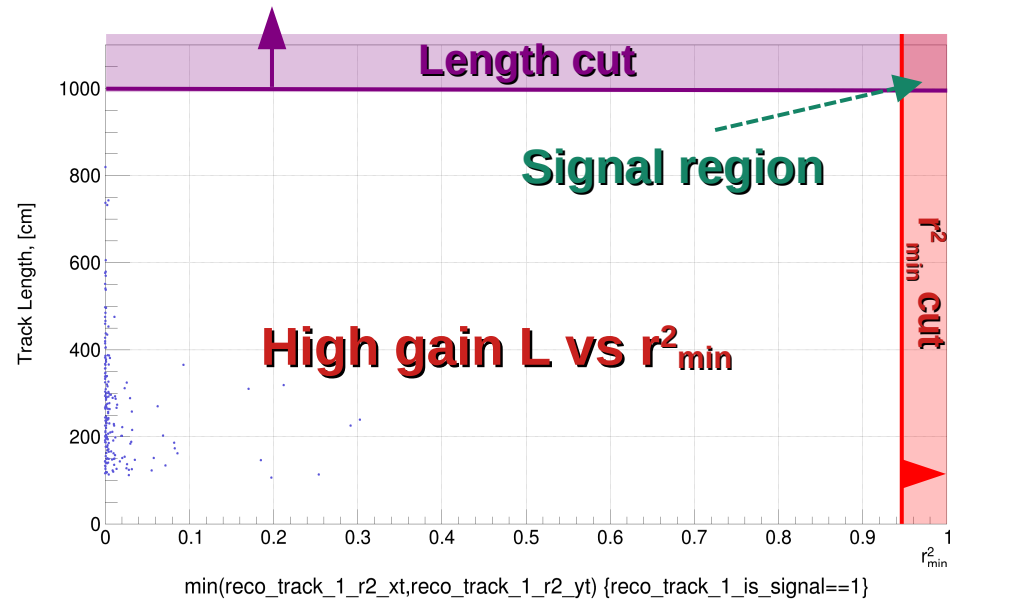
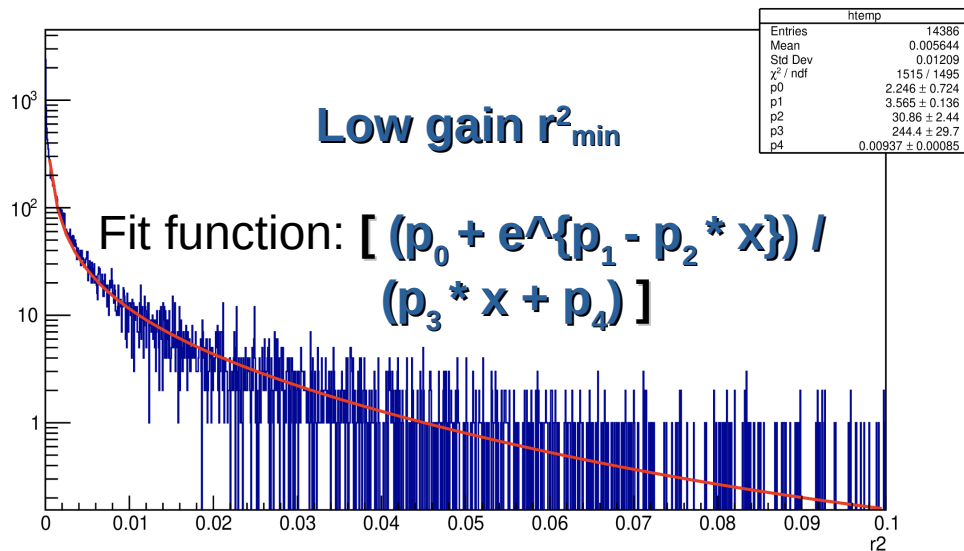
False-signal: Muon pairs

- **Offline analysis didn't find any signal-like event:**
 - **~80%** events were blocked by **monocluster**.
 - The remaining **~20%** passed through the analysis chain but **didn't form even 1** reconstructed track.



Sideband Studies

- Good “starting” point is to investigate the resulting Monopole Tree from the **Low gain** dataset.
 - Experimentally was decided to apply all the cuts except the $r^2_{\min}$ (the tightest one) and use its distribution to “extrapolate” our sideband expectations to the signal region.
 - Find the fit function and its parameters to evaluate the function behavior on the signal edge.
- Analyze the **High gain** dataset and apply the knowledge from the **Low gain** investigations.
- **High gain** forced analysis **modifications** (to collect some statistics):
 - Minimum number of hits for the track candidate was reduced from **100** to **15**.
 - Number of stored reconstructed tracks was increased from **3** to **50** (from the slowest to the fastest).
 - **Track length** and $r^2_{\min}$ cuts were **relaxed**.
- **2072 High gain** SNEWS files with **471191** events inside were analyzed to investigate the data sideband (~ 2356 s).



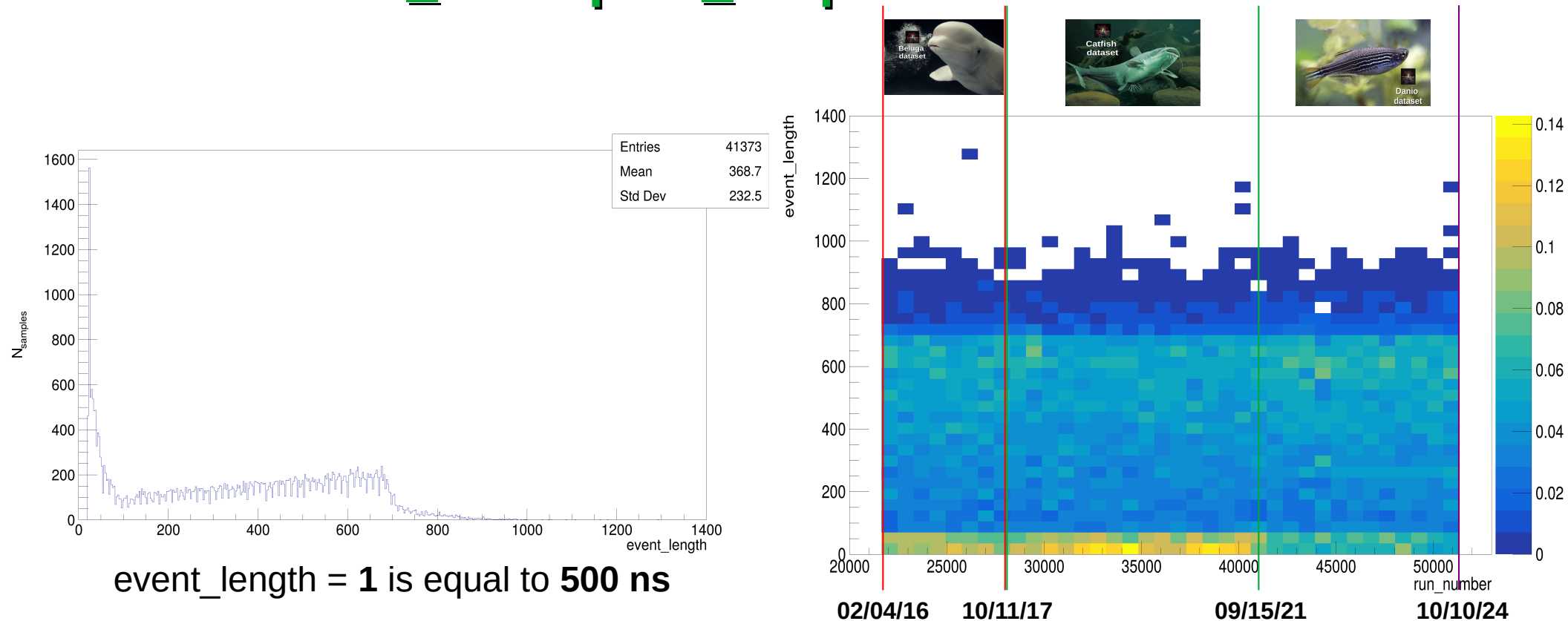
Estimated background is **extremely conservative** due to **forced modifications**.
Background is expected to be **considerably lower** than this small number.

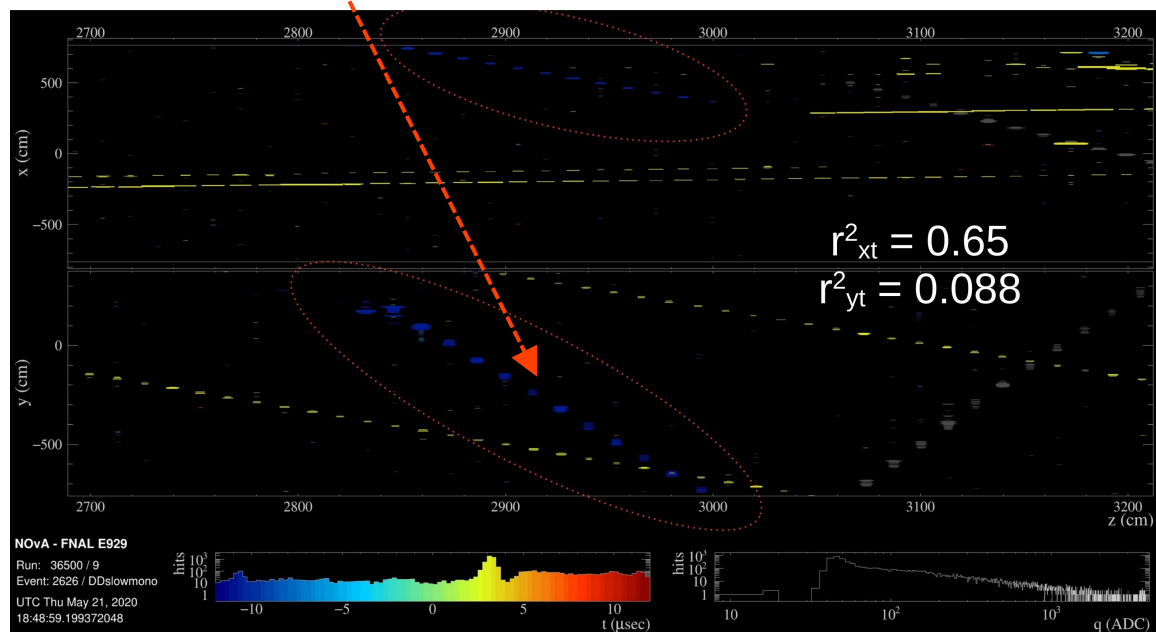
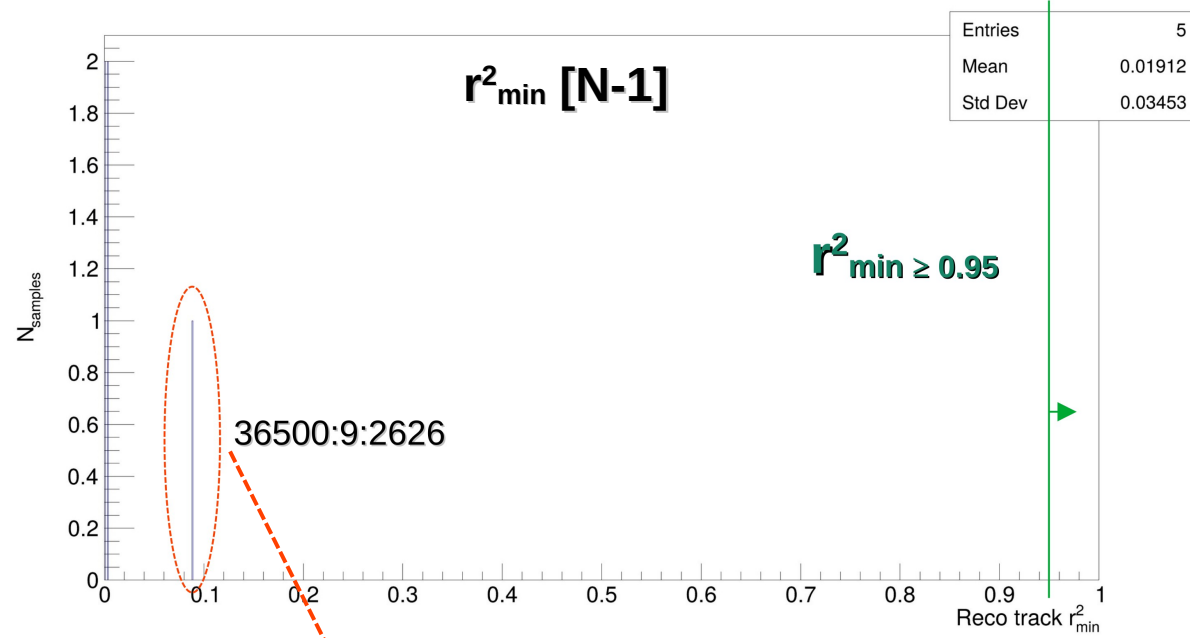
Burner sample

First run: 22157, subrun: 09

Every 250th run was checked ~ 1 run / month (0.4%)

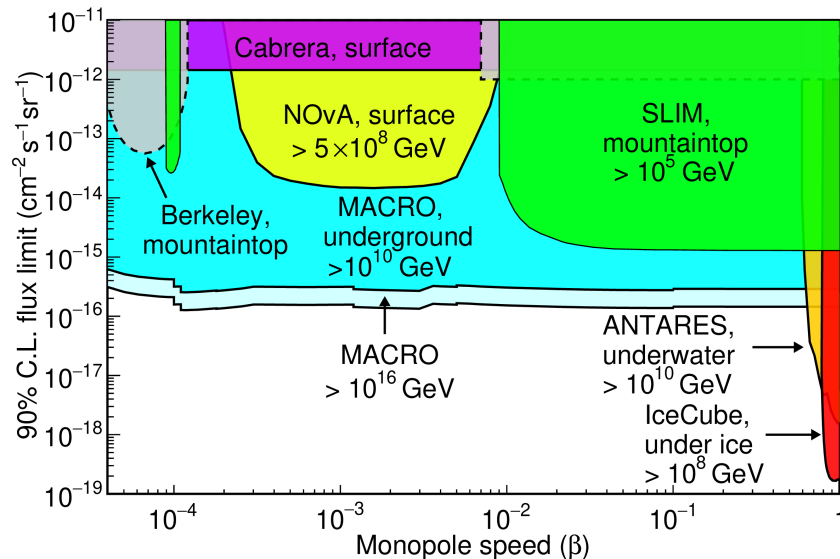
slow_monopole_ntuples were checked





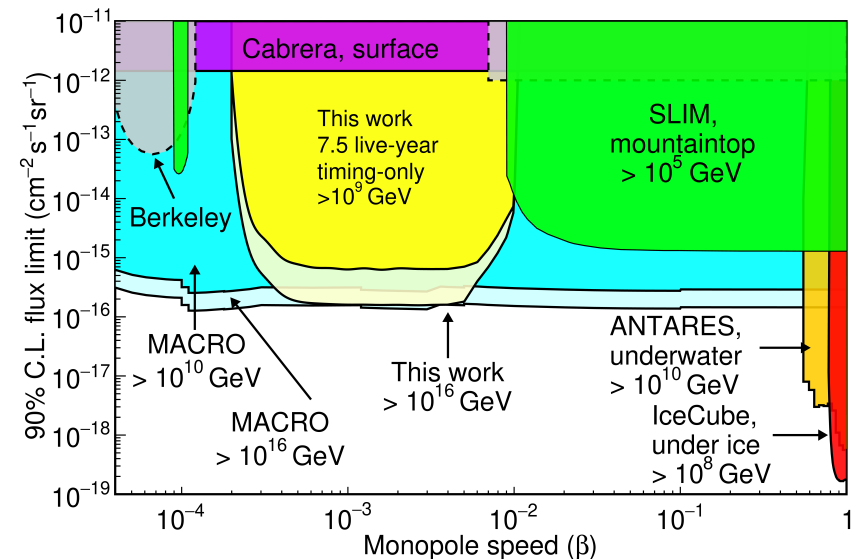
Sensitivity

Low gain



- APD gain is **100**
- **95-day** exposure
- Set mass limits in flux / speed space

High gain



- APD gain is **140**
- Around **3000 days** of exposure
- Majority of the data were pre-selected
- Reconstruction cuts are the same