Slow magnetic monopoles search in NOvA

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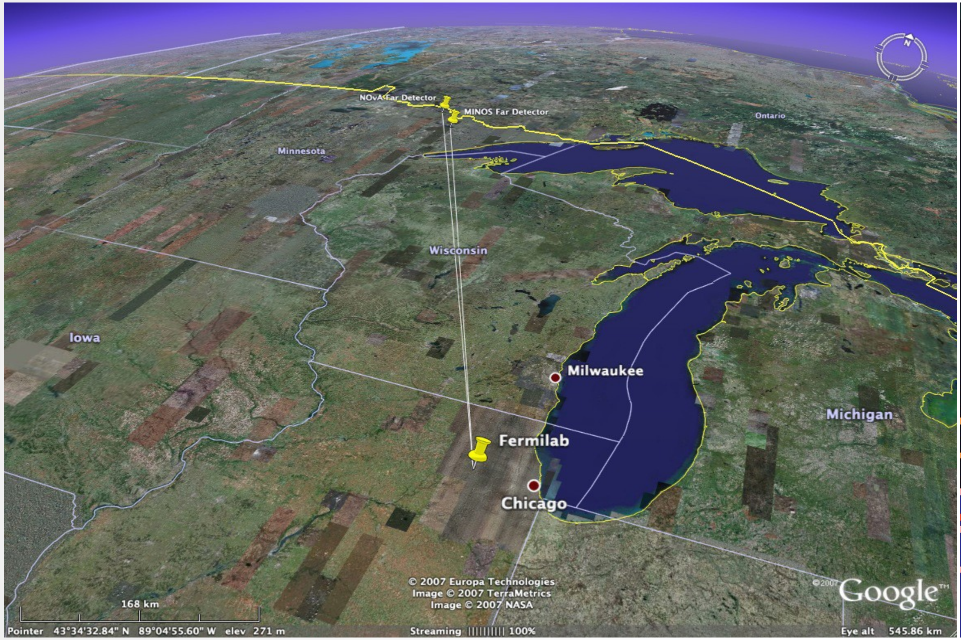
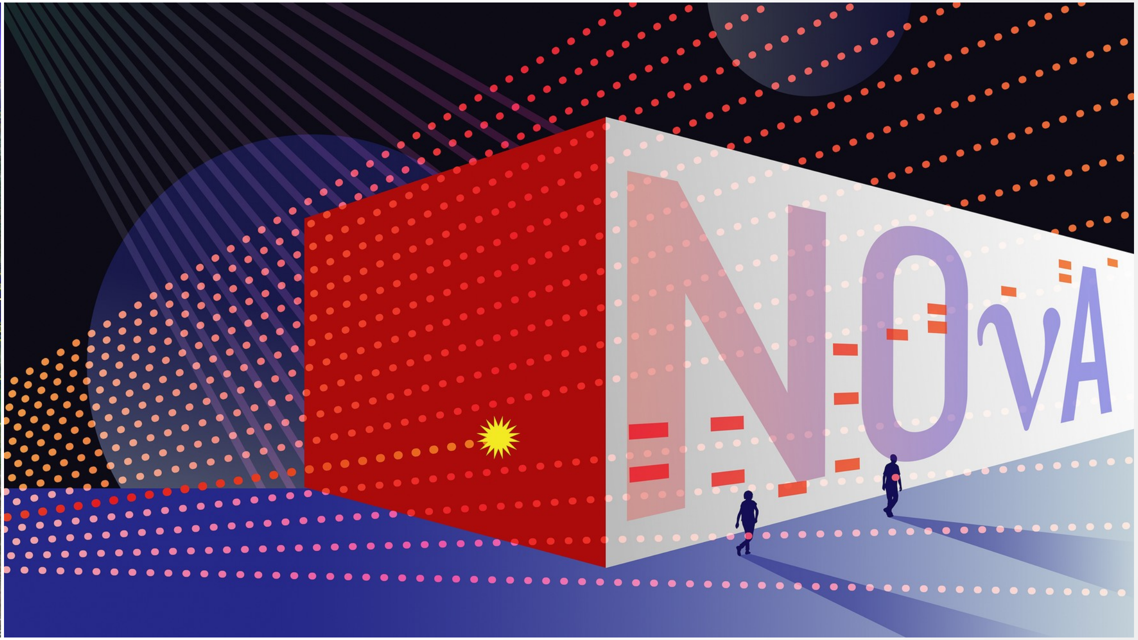
NOvA experiment

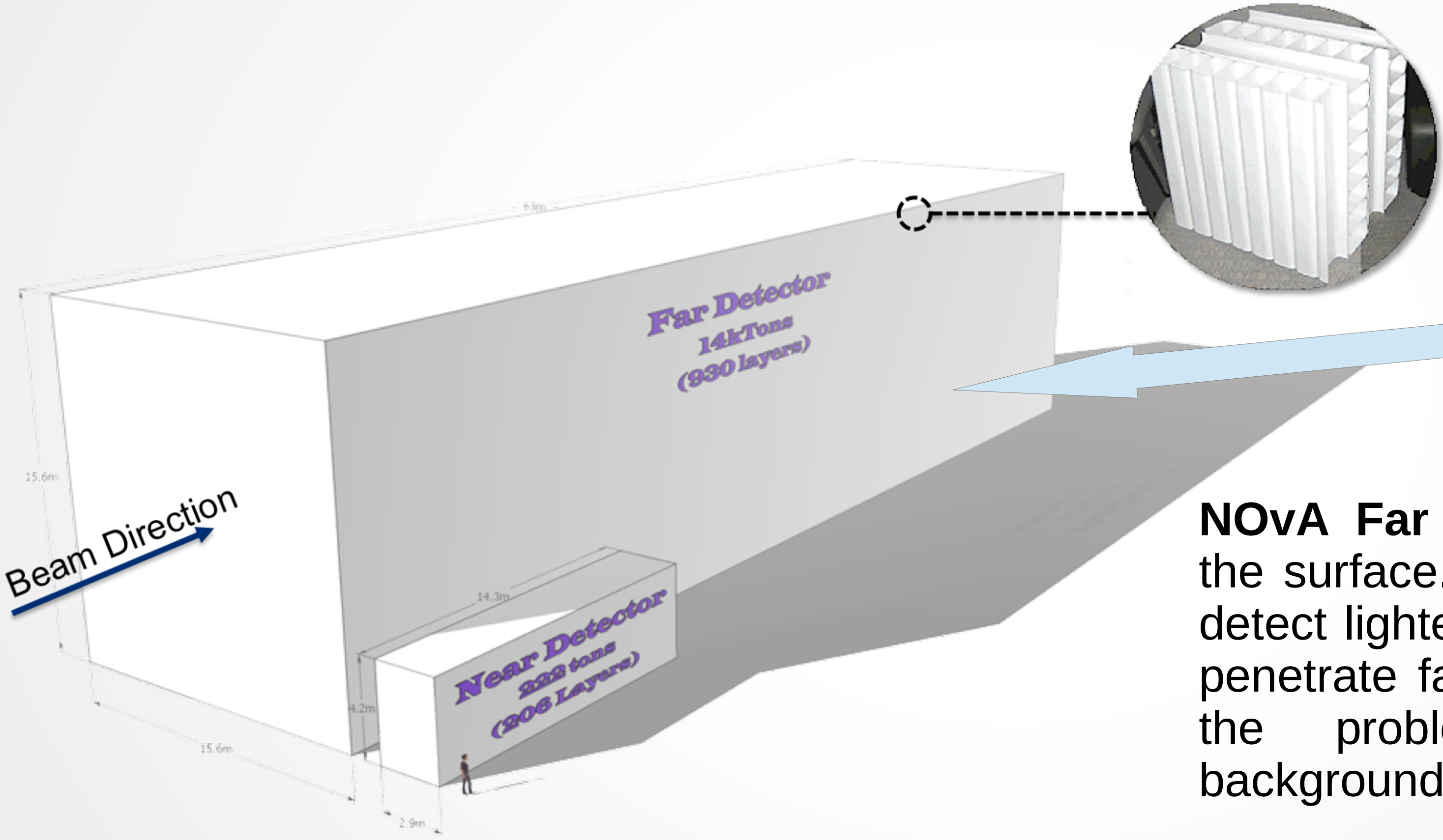




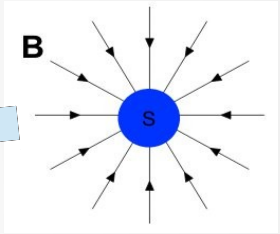
NOvA is a long-baseline accelerator neutrino experiment.

It is a very powerful tool for measurements of different neutrino parameters.

NOvA Detectors



g = 68.5 en
$M_m \sim 10^{17}$ GeV/c^2



NOvA Far Detector is located near the surface. It's a good opportunity to detect lighter monopoles which do not penetrate far into the earth even with the problem of huge cosmic background.

Why are we interested in monopoles?

Quantum mechanical formulation of the **magnetic monopoles** was made by Paul Dirac in 1931. Searches for these particles are very important for several reasons:

- Their existence would explain the quantization of electric charge.
- It is possible to restore symmetry between electricity and magnetism by means their introduction into the theory of electromagnetism.
- Magnetic monopoles naturally appears in Grand Unification Theories (GUT).

Monopoles properties

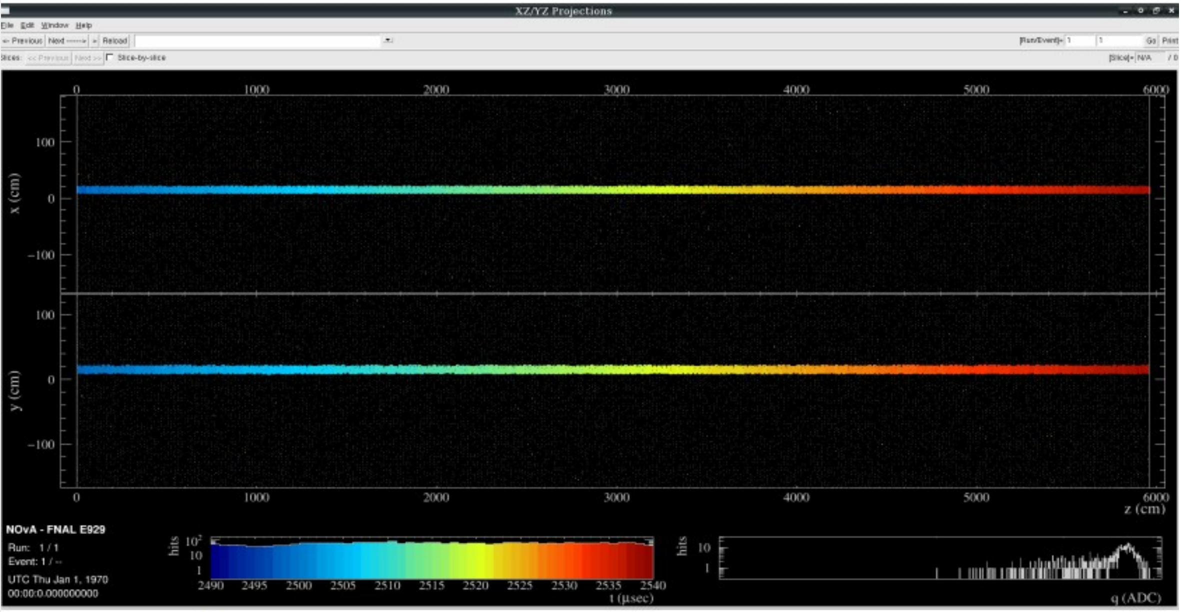
The Dirac's electric charge quantization relation says:

$$e * g = n * \hbar c/2 ,$$

where **e** is a basic electric charge and **n** is an integer. It means that magnetic monopoles could have a magnetic charge (**g**) 68.5 times greater than the charge of the electron. As the result they are expected to be very highly ionizing. "Slow" monopoles with $\beta < 10^{-2}$ can be identified due to their linear tracks with long transit times through the detector. Monopoles with this **β** take **5 μs** to cross the whole detector in comparison with cosmic muon which takes only **50 ns**.

Monopoles properties

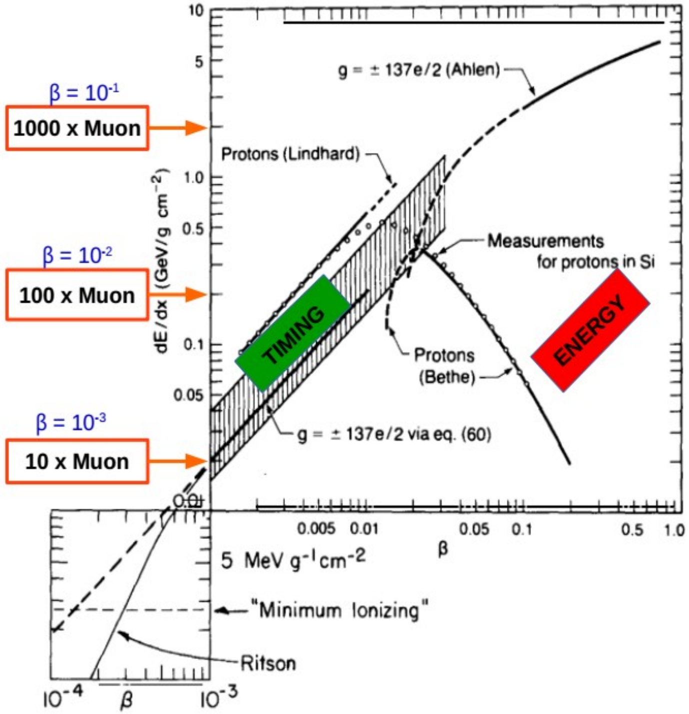
$\beta = \upsilon/c$ = velocity/speed of light



50 μs → $\beta = 10^{-3}$

Highly ionizing particle

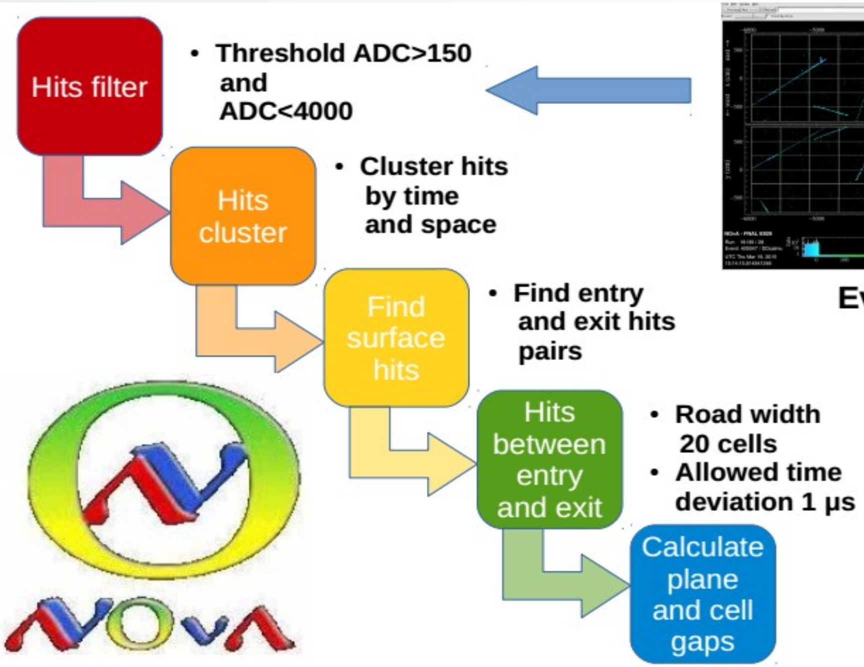
Monopole energy loss

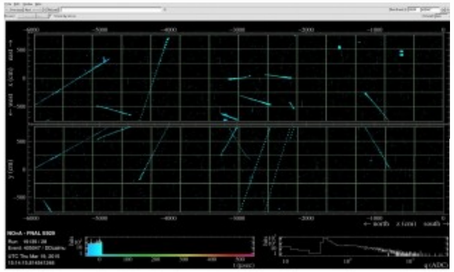


Slow monopole trigger

The slow monopole trigger was implemented in June 2015. It allows to identify slow ($\beta < 10^{-2}$ monopole) tracks by checking the number of plane gaps between the entry and exit hits. We look at all of the hit planes in the contained area and look for gaps.

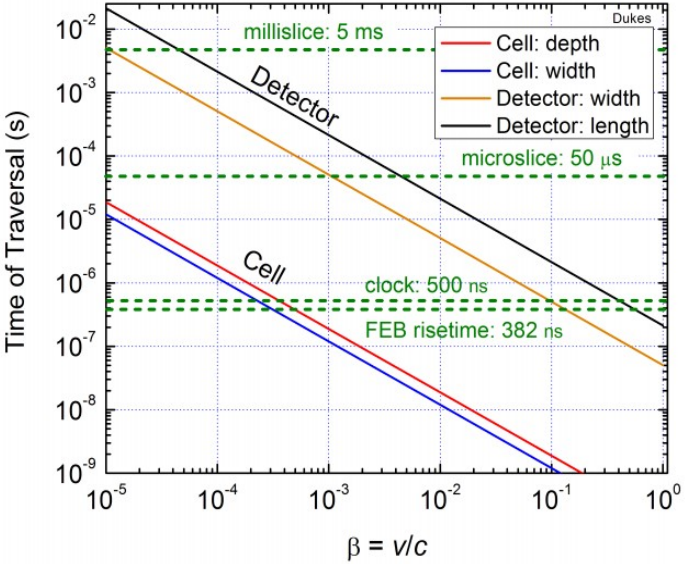
Slow monopole trigger





Event Display

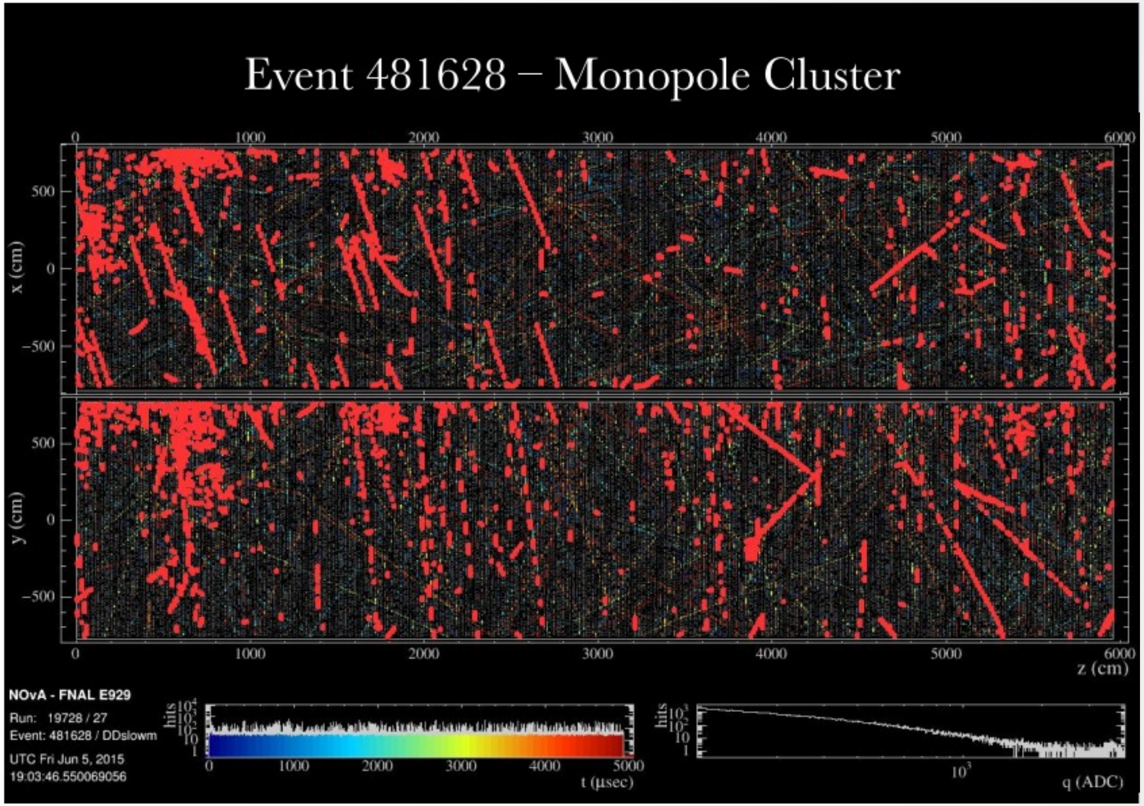
Monopole velocity



I would like to thank **Enhao Song (University of Virginia)** for providing me with the information about this trigger.

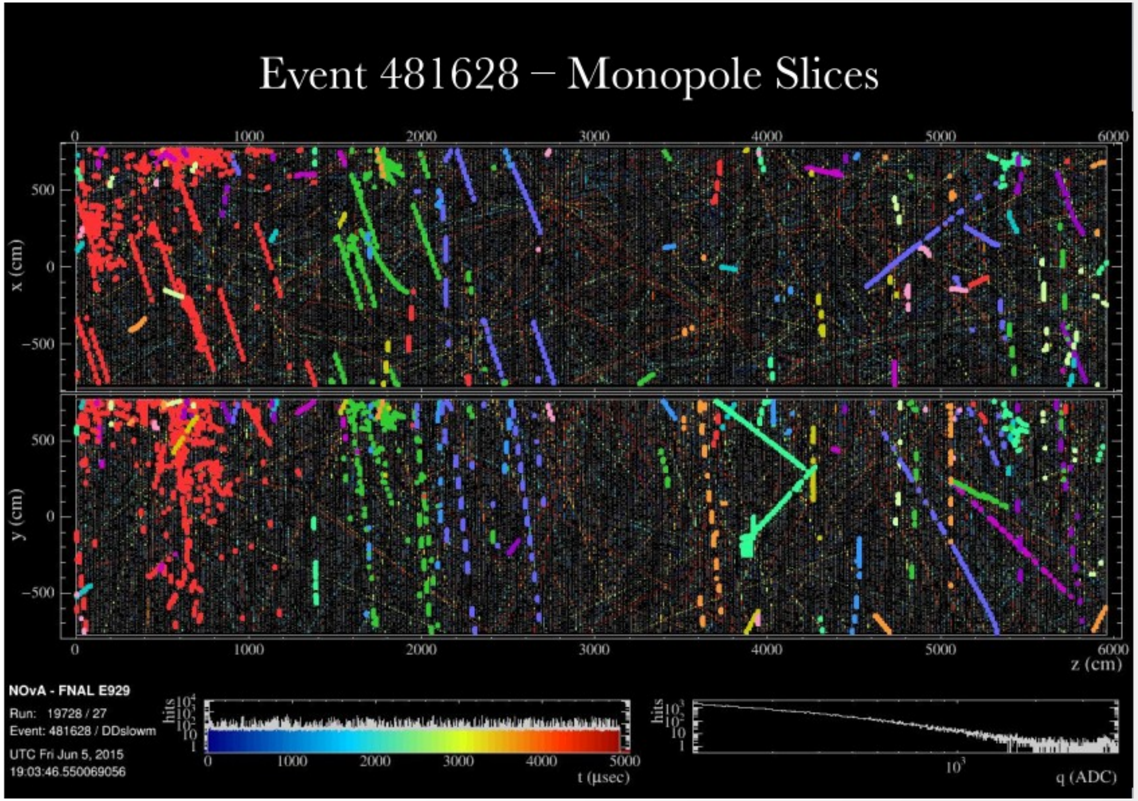
Offline reconstruction algorithm → Monopole cluster

- 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



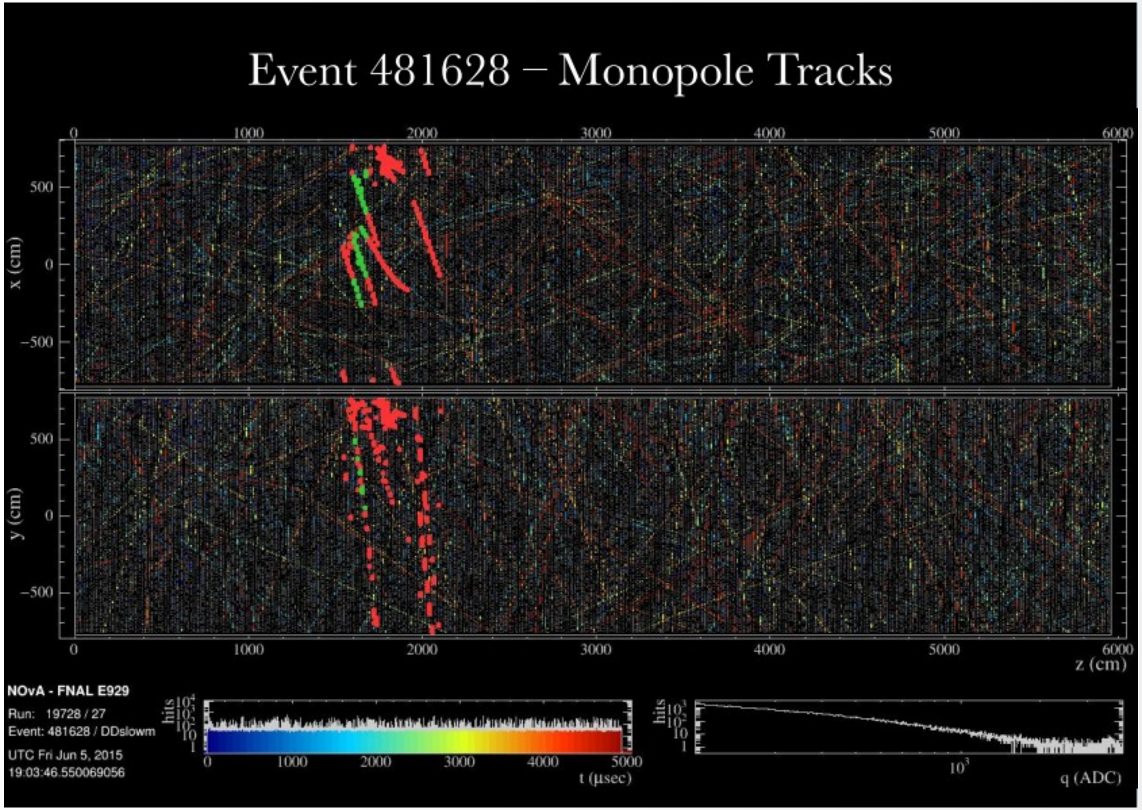
Offline reconstruction algorithm → Monopole slicer

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



Offline reconstruction algorithm → Monopole track

- remove slices with $\Sigma E > 2\times10^6$ ADC
- identify straight line objects
  - Using standard NOvA tool
- 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)



Data Samples

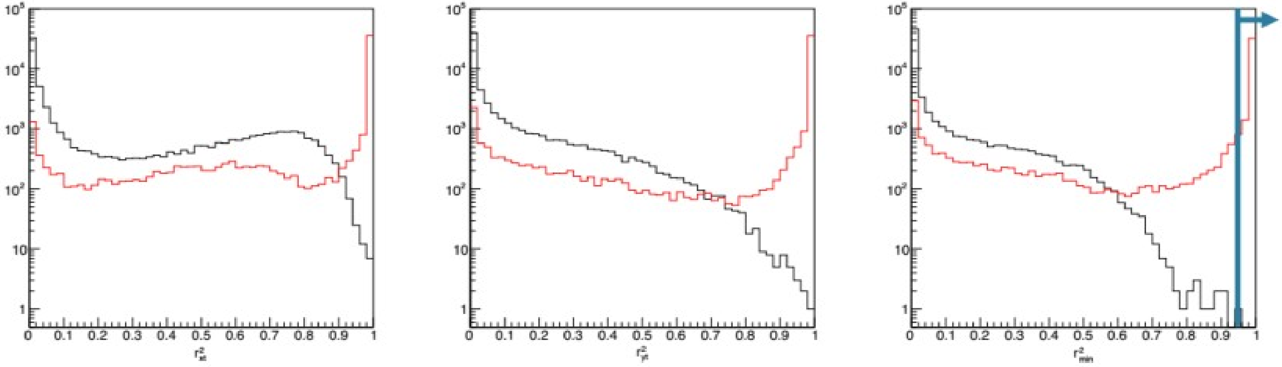
- **Monte Carlo** (Simulated monopoles + 5 ms long non-bias data produced by the daily SNEWS trigger → true monopole and nominal detector activity). Four velocities β_{sim}: 5×10^{-4}, 1×10^{-3}, 5×10^{-3}, 1×10^{-2}.
- **Slow Monopoles Triggered Events** (Slow Monopole Trigger → first run is **19728**, last one is **20752** for Low Gain (*100*) and **20753** like the first one for the new Data Set with High Gain (*150*).)

Event Selection

- True/Reco Number of xz hits ≥ 20
- True/Reco Number of yz hits ≥ 20
- True/Reco ΔPlane xz ≥ 10
- True/Reco ΔPlane yz ≥ 10
- True/Reco Length ≥ 10 m
- The **slowest** track → **primary** monopole track

Linear Regression coefficient

- Histograms of the linear regression coefficient (black: 10% data, MC: red) for:
  - r^2_{xt}: calculated from *xt*-hits (left)
  - r^2_{yt} : calculated from *yt*-hits (center)
  - r^2_{min}: minimum of the above two for each event (right)
- We require $r^2_{min} > 0.95$.



Time Gap Fraction

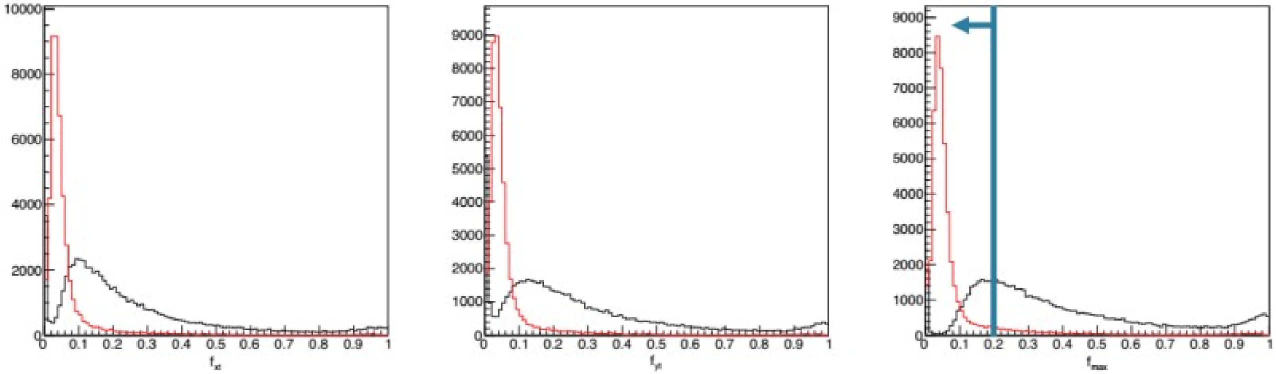
- A common reconstruction failure is when two cosmic rays get clustered together.
- In order to eliminate this, we look for gaps in the timing distribution of the hits.
- First, we sort all of the hits by time (each view separately) and then look for the largest gap (Δt_{max}). The time gap fraction (f) is then defined by:

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

  where Δt_{track} is the full track duration.
- $f = 0$: Good track with no gaps in timing.
- $f = 1$: Uncorrelated activity occurring early and late in time.

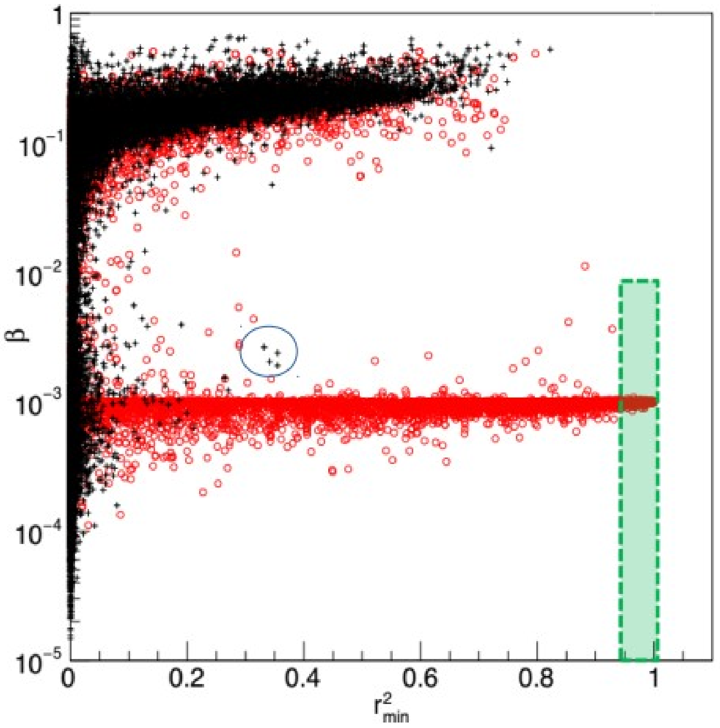
Time Gap Fraction

- Histograms of the time gap fraction (black: 10% data, MC: red) for:
  - f_{xt}: calculated from xt-hits (left)
  - f_{yt}: calculated from yt-hits (center)
  - f_{max}: maximum of the above two for each event (right)
- We require $f_{max} < 0.2$.



Velocity vs. Regression coefficient
10% Data

- Let us see how our cut performs as a function of reconstructed velocity.
- Data: black
- MC: red
- Signal: green



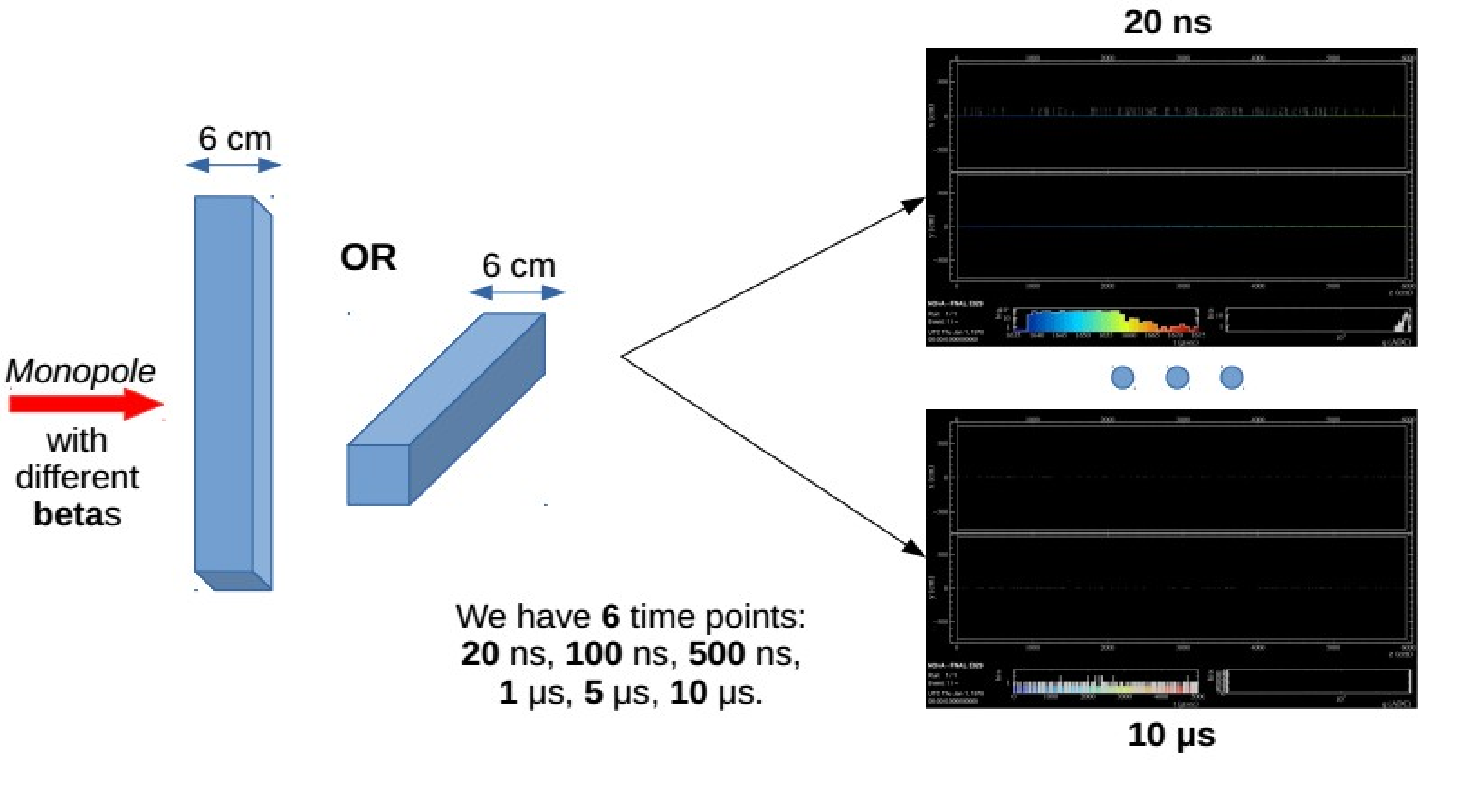
Conslusion

- NOvA far detector is pretty sensitive to lighter monopoles and has the unique potential to "touch" a new region of phase space due to it's location on the surface and our large surface area. These factors give us very high chance to "catch" the magnetic monopoles.
- Slow Monopole Trigger works pretty good.
- Special „cutter“ and „selector“ were developed. We tested only **10%** of **Low Gain** data. Remaining data are waiting for us! Technote is almost ready.
- Right now we asked to allow us apply the „cutter“ for remaining data. Collaboration gave us useful comments. We solved the majority of issues and shortcomings.
- I started to observe **High Gain** data.
- We still **don‘t see** any good candidates in **real data** but our „cutter“ and „selector“ perfectly work on **Monte Carlo** events.

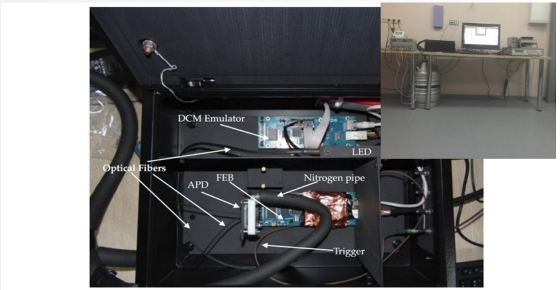
Thank you for your attention!

Backup (ReadoutSim vs Bench)

ReadoutSim

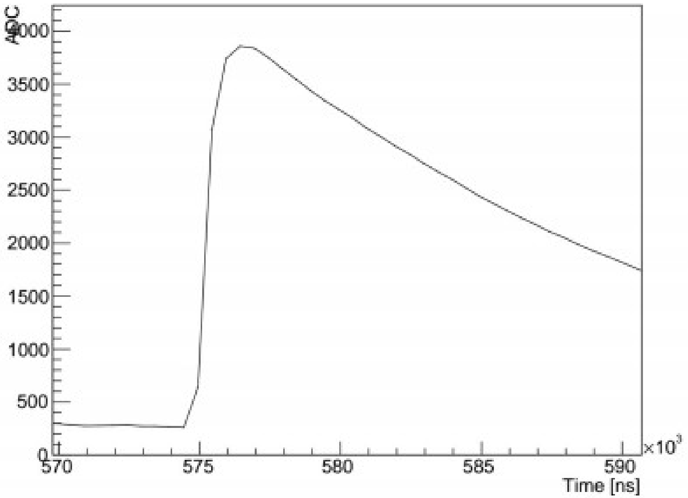


Bench

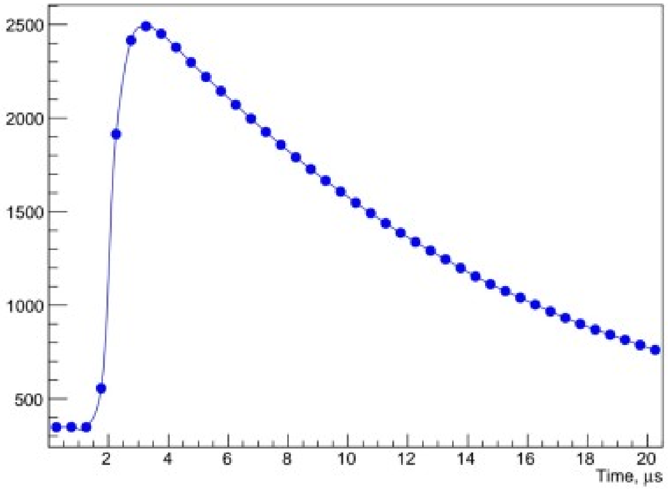


Comparison (one point – 20 ns)

20 ns



T_R = 0.892 μs, T_F = 15.555 μs



T_R = 0.76 μs, T_F = 11.24 μs

* T_R is the time of Amplitude changing from **0** to **(1-1/e)*Amp$_{Max}$**
* T_F is the time of Amplitude changing from **Amp$_{Max}$** to **Amp$_{Max}$/e**

→ **0** is equal to **Pedestal**

Summary

All units in **μs**

	20 ns	100 ns	500 ns	1 μs	5 μs	10 μs
Bench →	T_R = 0.76 T_F = 11.24	T_R = 0.76 T_F = 11.17	T_R = 0.846 T_F = 12.25	T_R = 1.303 T_F = 10.74	T_R = 3.4 T_F = 13.01	T_R = 5.24 T_F ≈ 11
ReadoutSim →	T_R = 0.89 T_F = 15.56	T_R = 0.46 T_F = 13.18	T_R = 0.75 T_F = 9.72	T_R = 1.17 T_F = 9.91	T_R = 2.66 T_F = 13.4	T_R = 4.75 T_F = 13.7

Main results are:

- Points **20 ns, 100 ns, 500 ns, 1 μs** have normal linear behavior for both cases but with different slopes: Bench has T_F = **8.376 + 0.00146*Amp**, ReadoutSim has T_F = **8.89 + 0.00186*Amp**.
- Points **5 μs and 10 μs** have «strange» T_F dependence on the Amplitude.
- T_R depends on the outer pulse width and it's almost the same for Bench and ReadoutSim.