Slow magnetic monopoles search in NOvA

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AYSS 2017

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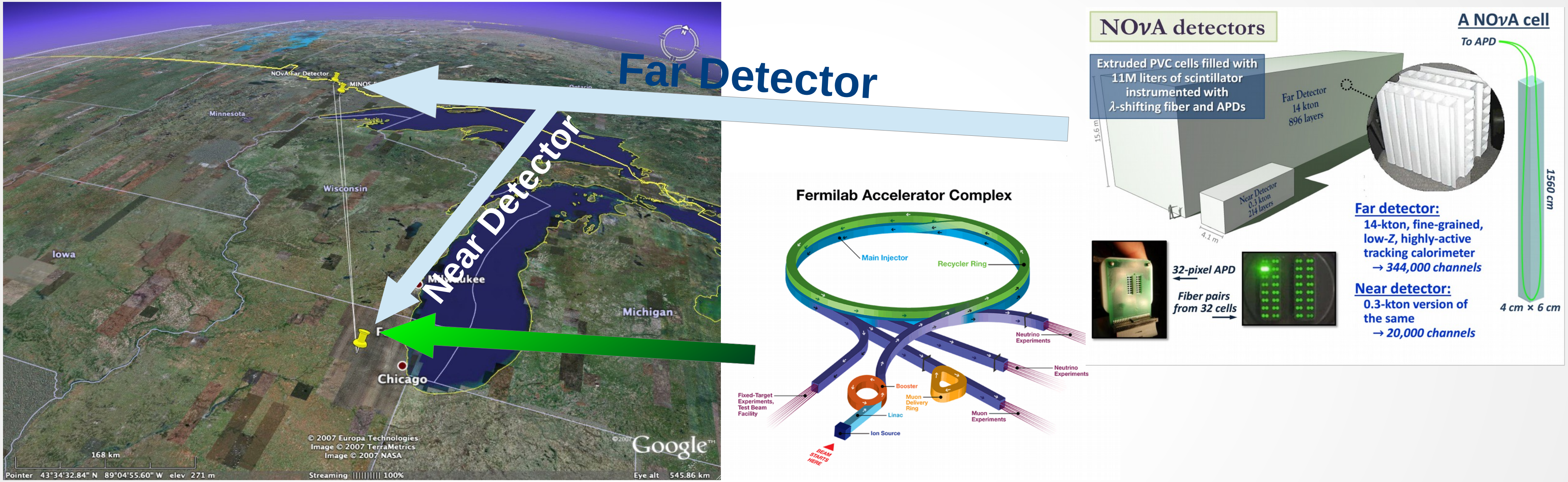
NOvA

NuMI
Off-Axis
ν_e
Appearance

NOvA Collaboration

260 scientists from **7** Countries (**44** Institutions),
are looking for **Neutrino Oscillations**

NOvA experiment. Design



NOvA is a long-baseline accelerator neutrino experiment.
It is a very powerful tool for measurements of different neutrino parameters.

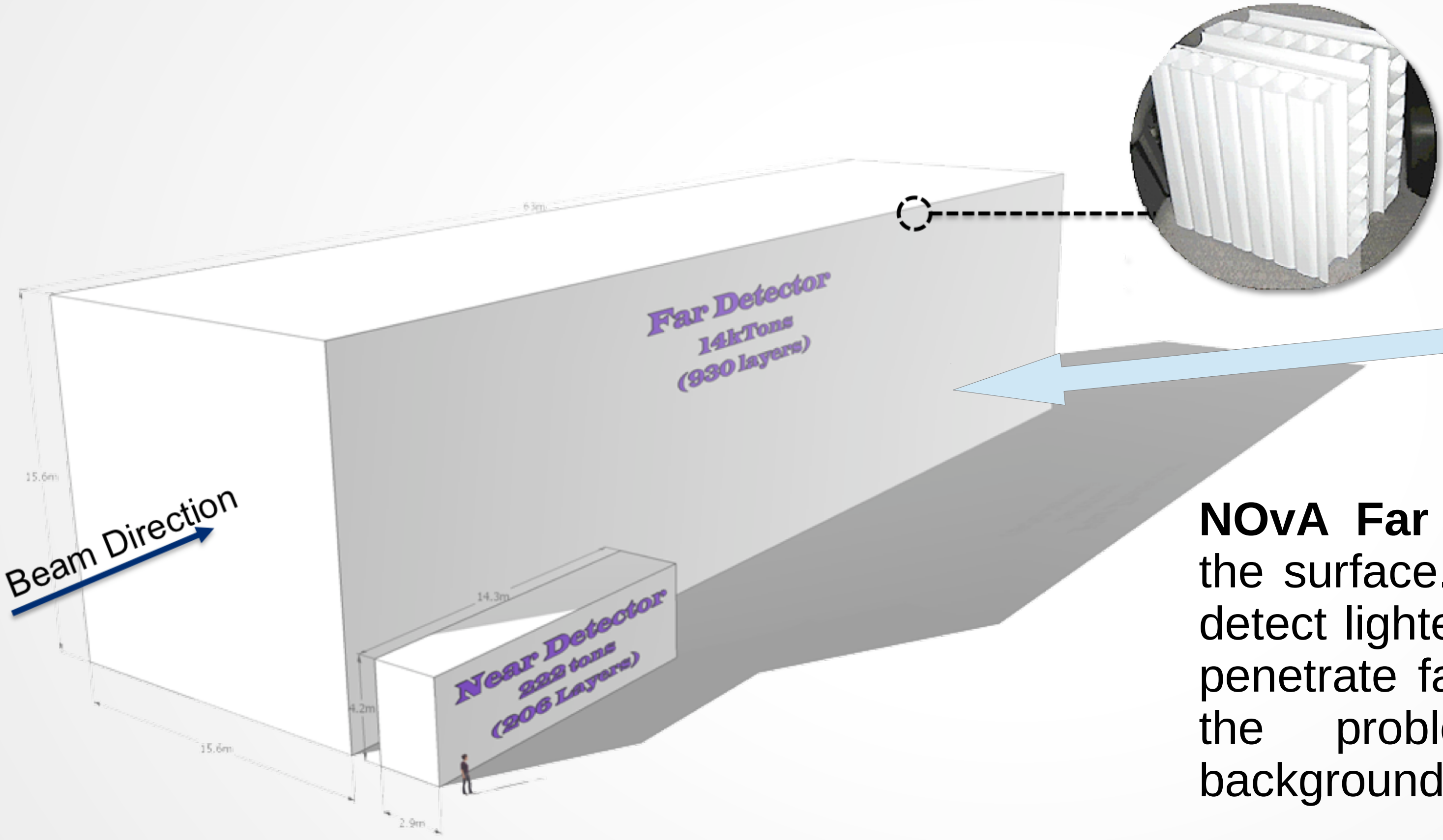
NOvA Goals

- Within ν_e appearance NOvA catchs mass hierarchy and CP-violation phase
- Within ν_μ disappearance NOvA precisely measures θ_{23} octant
- Search beyond the Standard Model
  - Sterile neutrino(s)
  - Dark Matter
  - **Magnetic monopoles**
- Look into the Universe
  - Supernova neutrinos
  - Cosmic rays
  - Gravitational waves coincidence
- Within high intensity neutrino beam NOvA Near Detector measures neutrino cross-sections

NOvA at JINR

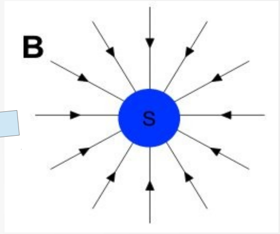
- Remote Operation Center at Dubna (ROC-Dubna)
- NOvA test benches at JINR
- Computing Infrastructure including LIT resources
- MC Simulation and Theory effort from BLTP
- ν_e Analysis optimization
- Neutrino signal from Supernova
- Study of the Cosmic Ray (Muons)
- **Search for Slow Monopole**
- Near Detector Measurements

NOvA Detectors (Monopole)



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.

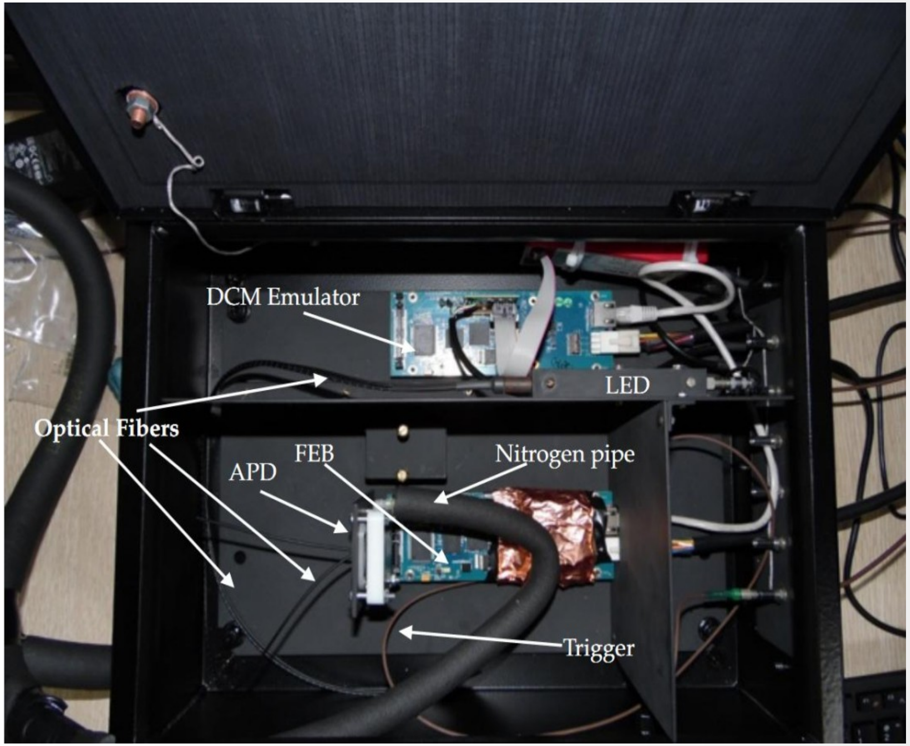
NOvA Test Bench (electronics)

Nikolay Anfimov (staff)

Zinoviy Krumstein (staff)

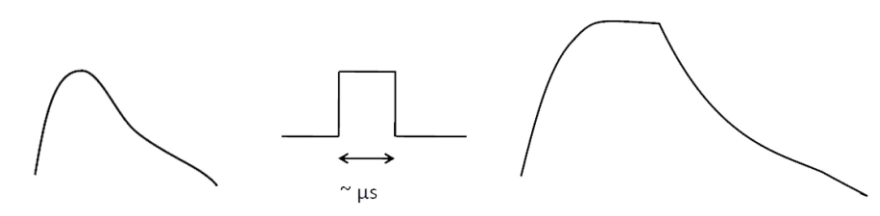
Albert Sotnikov (staff)

Alexander Antoshkin (PhD student)

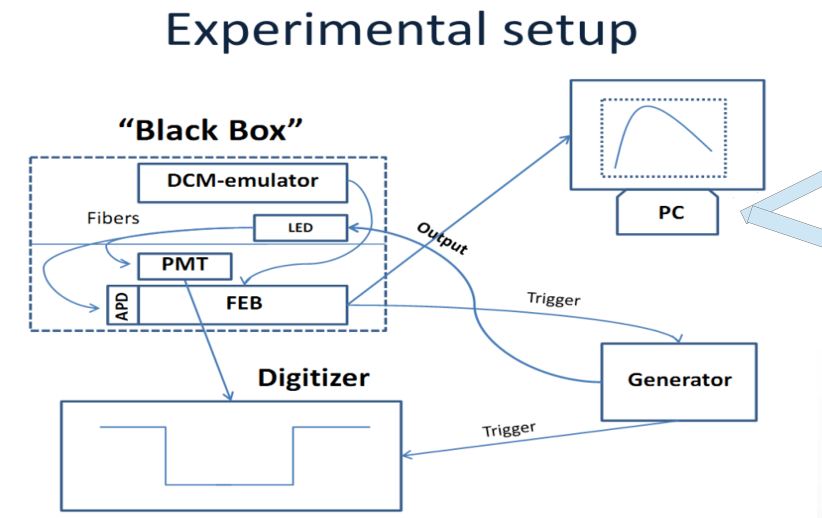


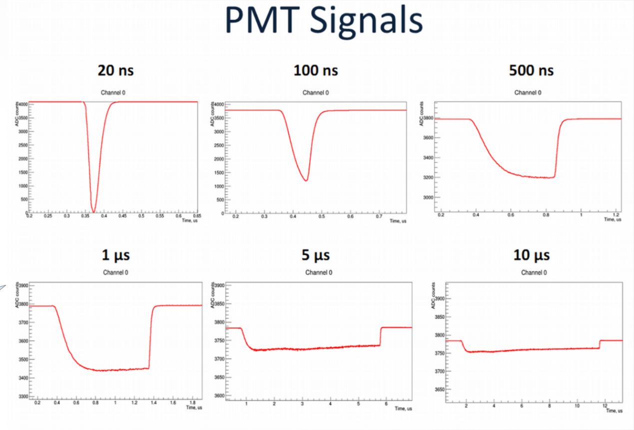
1) Great thank to **Krumstein Z.V.** for general support!
2) Great thank to **Anfimov N.V.** for bench construction!
3) Great thank to **Sotnikov A.P.** for help with software!

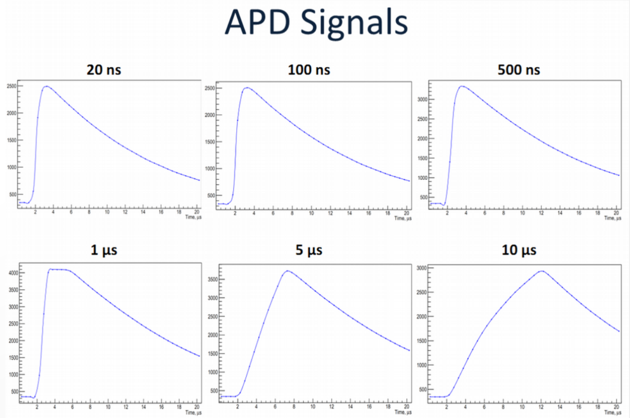
Electronics response to long signals. Monopole measurements within test bench



Standard signal | Theoretically predicted | Signal after convolution







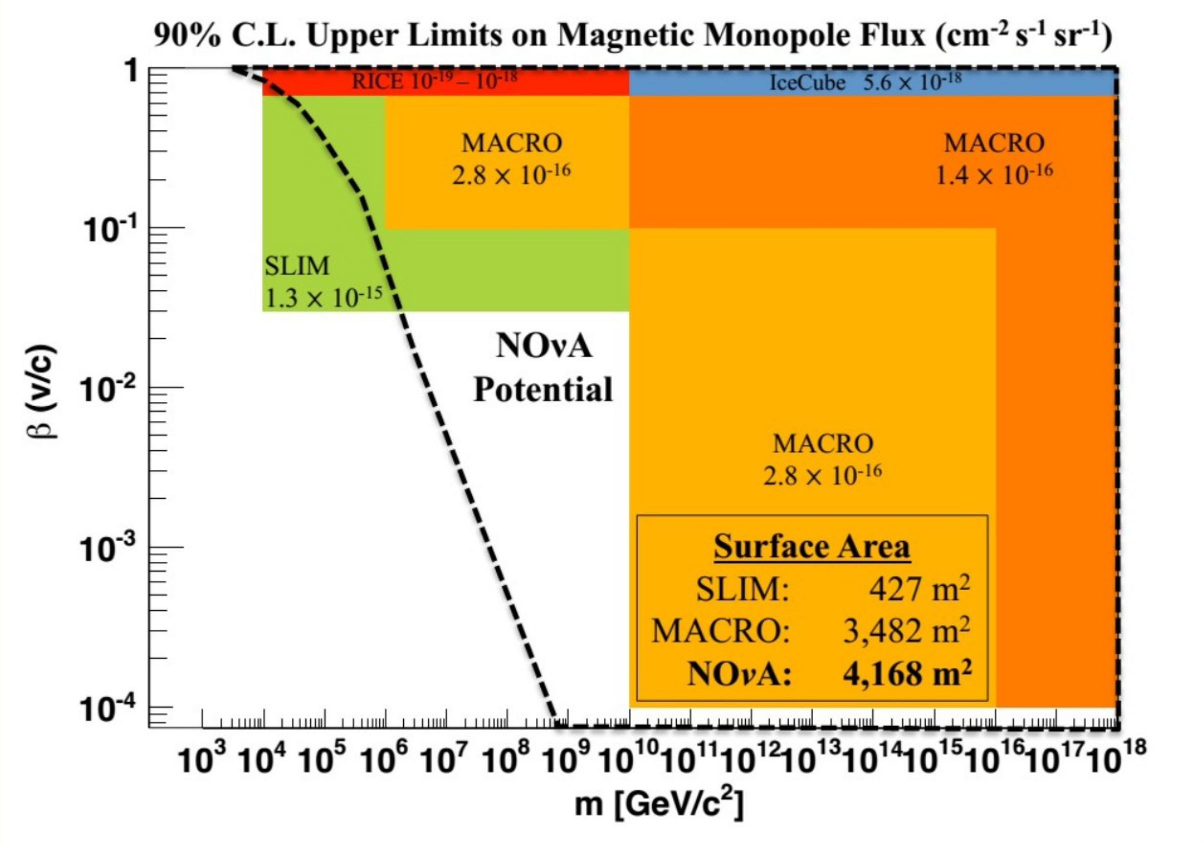
In collaboration with **Martin Frank**

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:

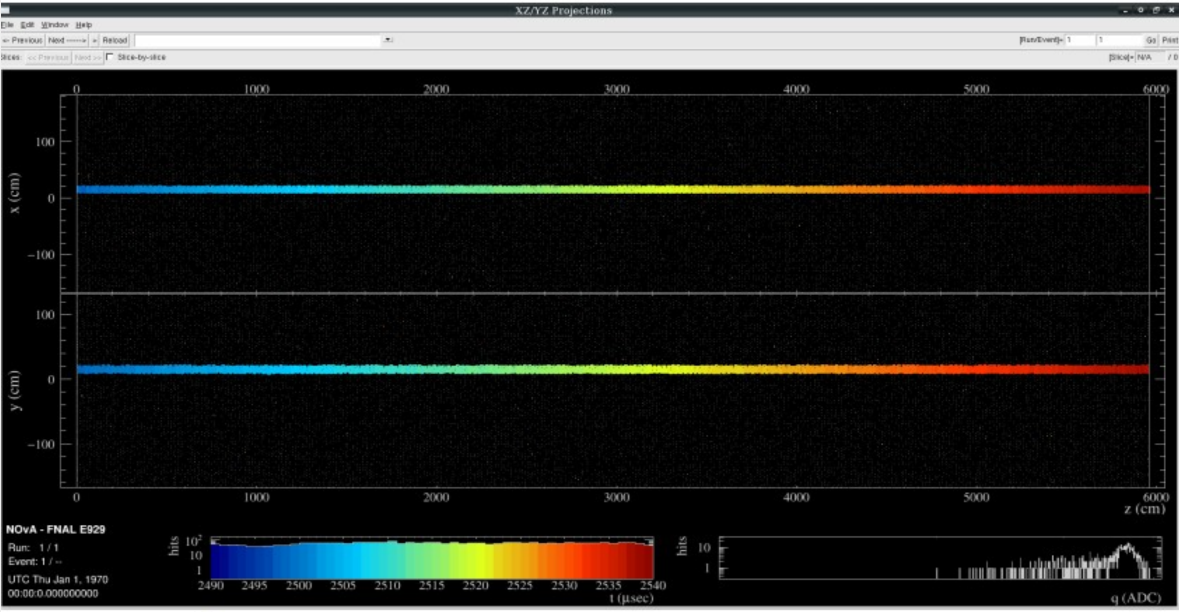
- Their existence would explain the quantization of electric charge.
- It is possible to restore symmetry between electricity and magnetism by means their introduction into the theory of electromagnetism.
- Magnetic monopoles naturally appears in Grand Unification Theories (GUT).

NOvA Potential. Monopole Flux



Monopoles properties

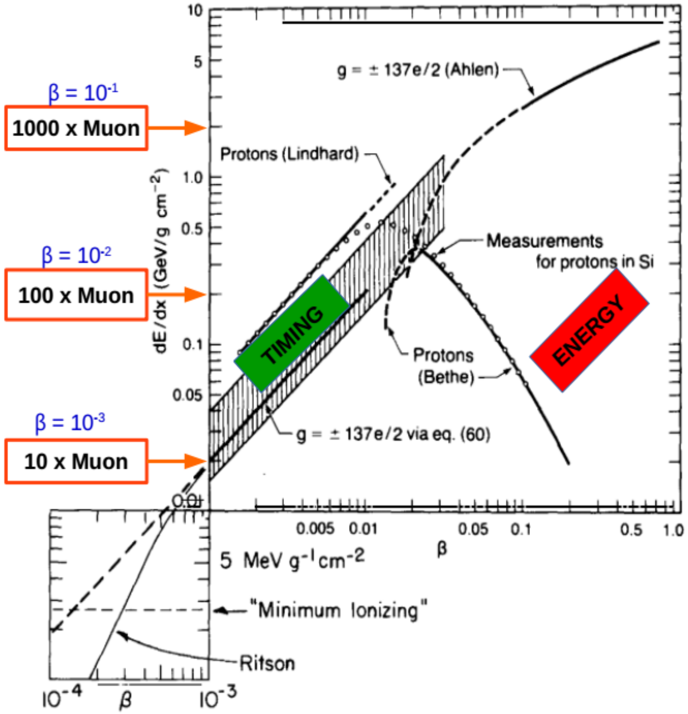
β = υ/c = velocity/speed of light



50 μs → β = 10^{-3}

Highly ionizing particle

Monopole energy loss



Data Samples

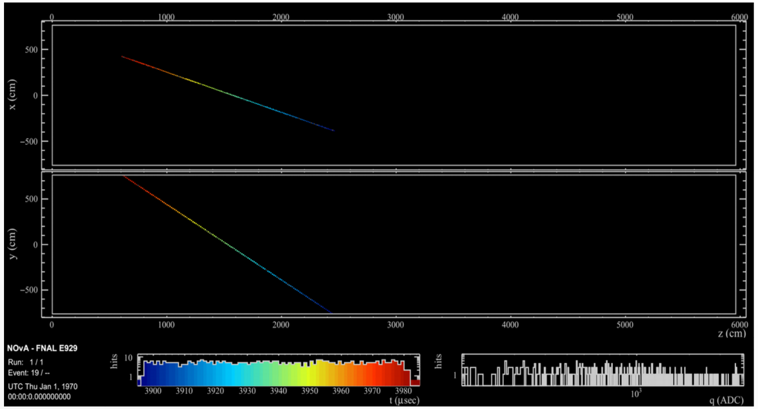
- **Monte Carlo** (Simulated monopoles + 5 ms long non-bias data produced by the daily SNEWS trigger → true monopole and nominal detector activity). Four velocities β_{sim}: 5×10^{-4}, 1×10^{-3}, 5×10^{-3}, 1×10^{-2}.
- **Slow Monopoles Triggered Events** (Slow Monopole Trigger → first run is **19728**,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

Event selector and algorithm.

- **Slow monopole trigger** – primal selector (High ionization)
- **Offline reconstruction** – secondary selection („slow“ tracks)
- **Final check** – *Linear Regression coefficient* and *Time Gap Fraction*.

In a nutshell we try to extract something

like this



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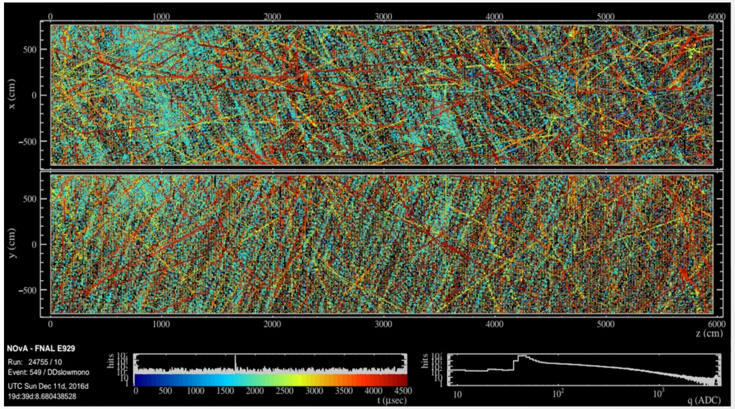


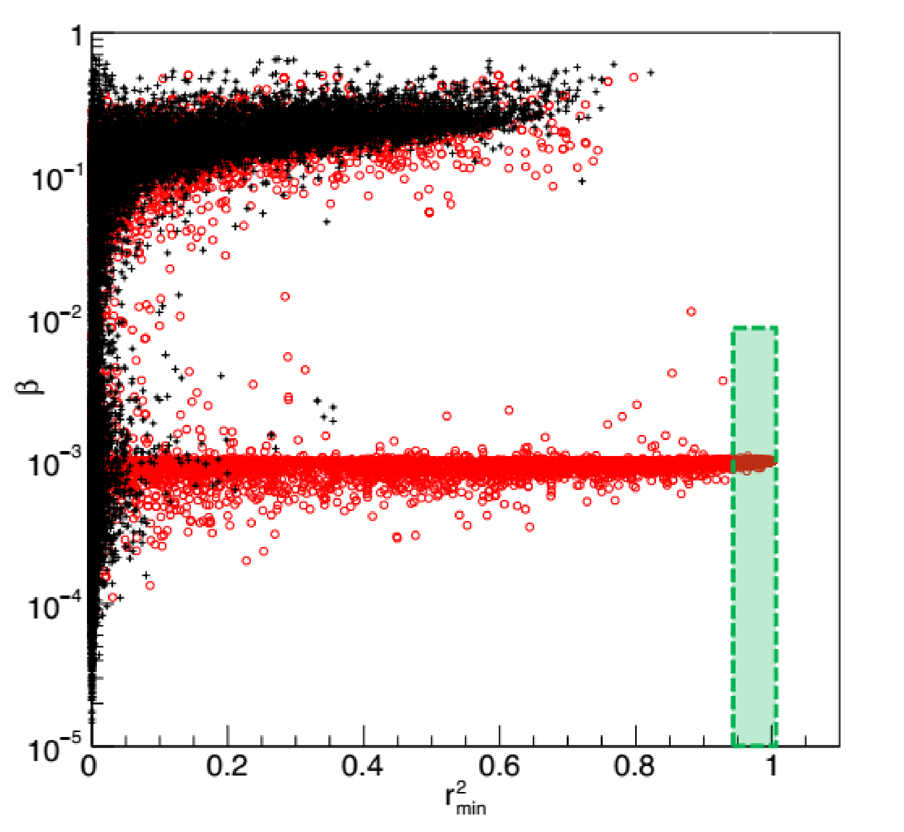
Slow Monopoles – What if you select an event?

- Discovery of monopoles = 
- Claiming to discover monopoles when you haven‘t =
- If there‘s no event in the box, everything is OK!
- If there is, we have a plan:
  - Check the event, is it clearly not a monopole? If so, it‘s OK.
  - Otherwise (event looks like monopole), we have to check:
    - dE/dx and timing distributions
    - Running conditions, other events in the run and various parameters

Not the best analysis!

Velocity vs. Regression coefficient
10% Data. Results

1) Let us see how our cut performs as a function of reconstructed velocity.
2) Data: black
3) MC: red
4) Signal: green

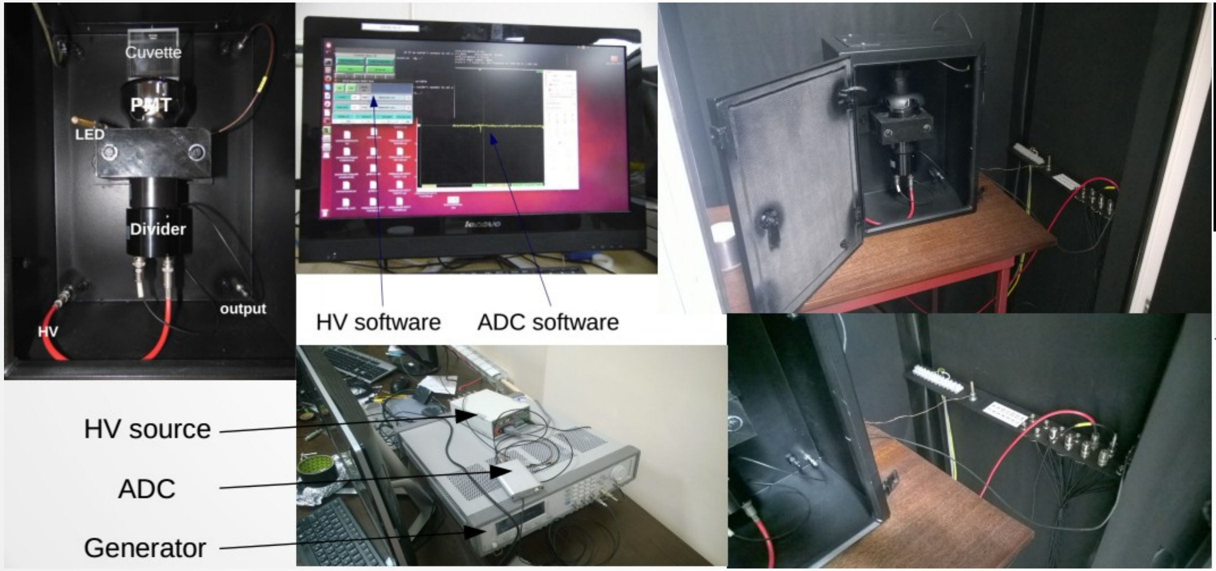


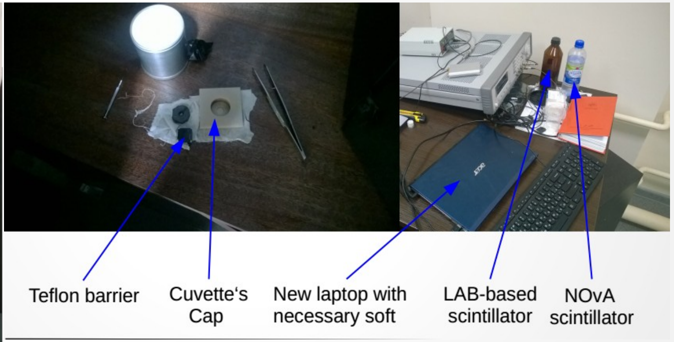
Conslusions and future plans

- 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 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.

Current activities (1/2)

- **NOvA test bench for measurements of the NOvA scintillator properties**



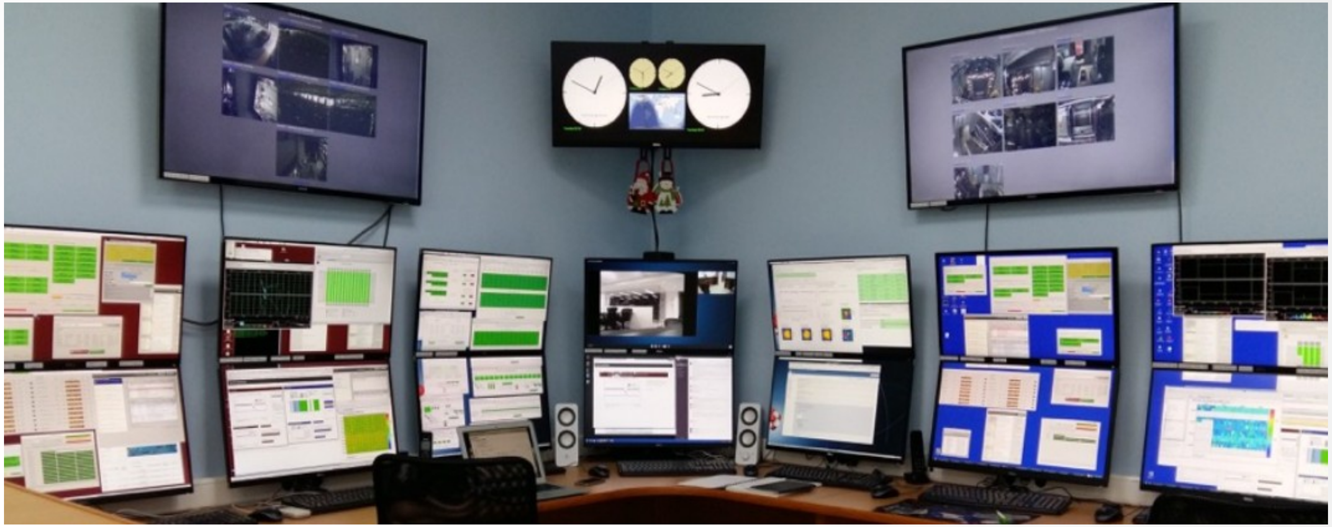


Supervision of two **diplomas**: one **bachelor** and one **magister**

Current activities (2/2)

ROC-Dubna

Operates since 2015



1) Great thank to **Anfimov N.** and **Samoylov O.** for ROC-Dubna construction.
2) Great thank to **Sheshukov A.** for help with backup connection solution.
3) More then 1 year ago I became ROC-Dubna **liaison** – everything inside it is my duty!
4) NOvA JINR team is really large – ROC-Dubna helps us to cover our shift quotas – right now we have more then 50 days of shift time. Even our Moscow colleagues usually take shifts from here.

Publications

- **Measurement of the neutrino mixing angle θ23 in NOvA** [arXiv:1701.05891]. *Published in Phys.Rev.Lett. 118 (2017) no.15, 151802*
- **Constraints on Oscillation Parameters from νe Appearance and νμ Disappearance in NOvA** [arXiv:1703.03328]. *Published in Phys.Rev.Lett. 118 (2017) no.23, 231801*
- **Search for active-sterile neutrino mixing using neutral-current interactions in NOvA** [arXiv:1706.04592]. *Published in Phys.Rev. D96 (2017) no.7, 072006*
- First measurement of the Sivers asymmetry for gluons from SIDIS data [arXiv:1701.02453]. *Published in Phys.Lett. B772 (2017) 854-864*
- First measurement of transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process [arXiv:1704.00488]. *Published in Phys.Rev.Lett. 119 (2017) no.11, 112002*
- Observation of X(3872) muoproduction at COMPASS [arXiv:1707.01796]
- New analysis of ηπ tensor resonances measured at the COMPASS experiment [arXiv:1707.02848]
- Transverse-momentum-dependent Multiplicities of Charged Hadrons in Muon-Deuteron Deep Inelastic Scattering [arXiv:1709.07374]
- Longitudinal double-spin asymmetry Ap1 and spin-dependent structure function gp1 of theproton at small values of x and Q2 [arXiv:1710.01014]

Talks and pedagogical activities

- Slow magnetic monopoles search in NOvA (AYSS-2017)
- Test bench for measurements of the NOvA scintillator properties at JINR (AYSS-2017)
- Test bench for measurements of the NOvA scintillator properties at JINR (Poster, 47th PAC)
- Slow magnetic monopoles search in NOvA (Poster, 46th PAC)
- NOvA test bench at JINR (Poster, The 2016 European School of High-Energy Physics)
- NOvA test bench at JINR (AYSS-2016)
- Remote Operation Center at Dubna for NOvA experiment (AYSS-2016)
- NOvA test bench at JINR (Poster, 45th PAC)
- NOvA test bench at JINR (AYSS-2016 Proceedings)
- A. Petrushin bachelor's diploma supervision – The NOvA experiment: a study of electronics parameters – *finished wirh excellent mark*.
- Laboratory Practice for students based on NOvA test bench
- A. Petrushin magister diploma and D. Velikanova bachelor diploma supervision – *in progress*.

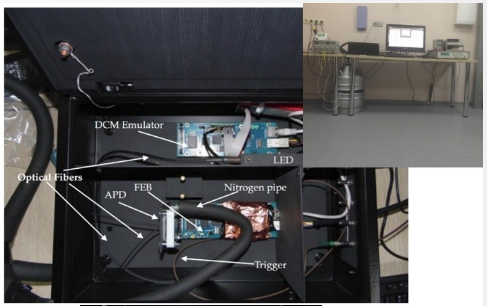
Thank you for your attention!

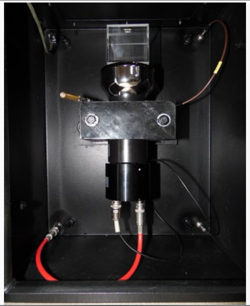
Backup

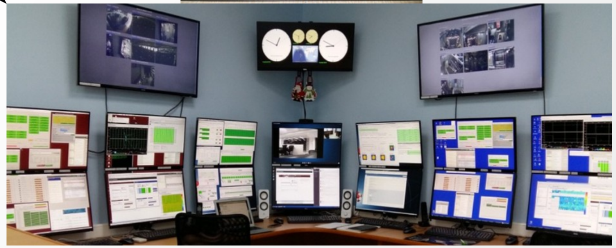
My contribution

- First NOvA test bench at JINR (electronics)
- Second NOvA test bench at JINR (scintillator)
- ROC-Dubna activity – ROC *liaison*
- **Slow magnetic monopole search**

  a) Hardware and b) analysis
- Author since Nov. 2015



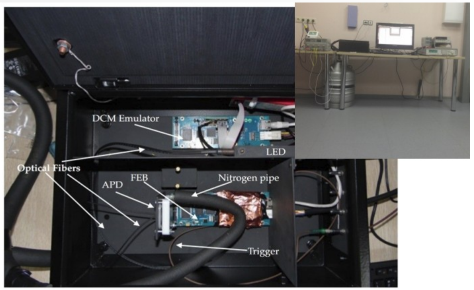


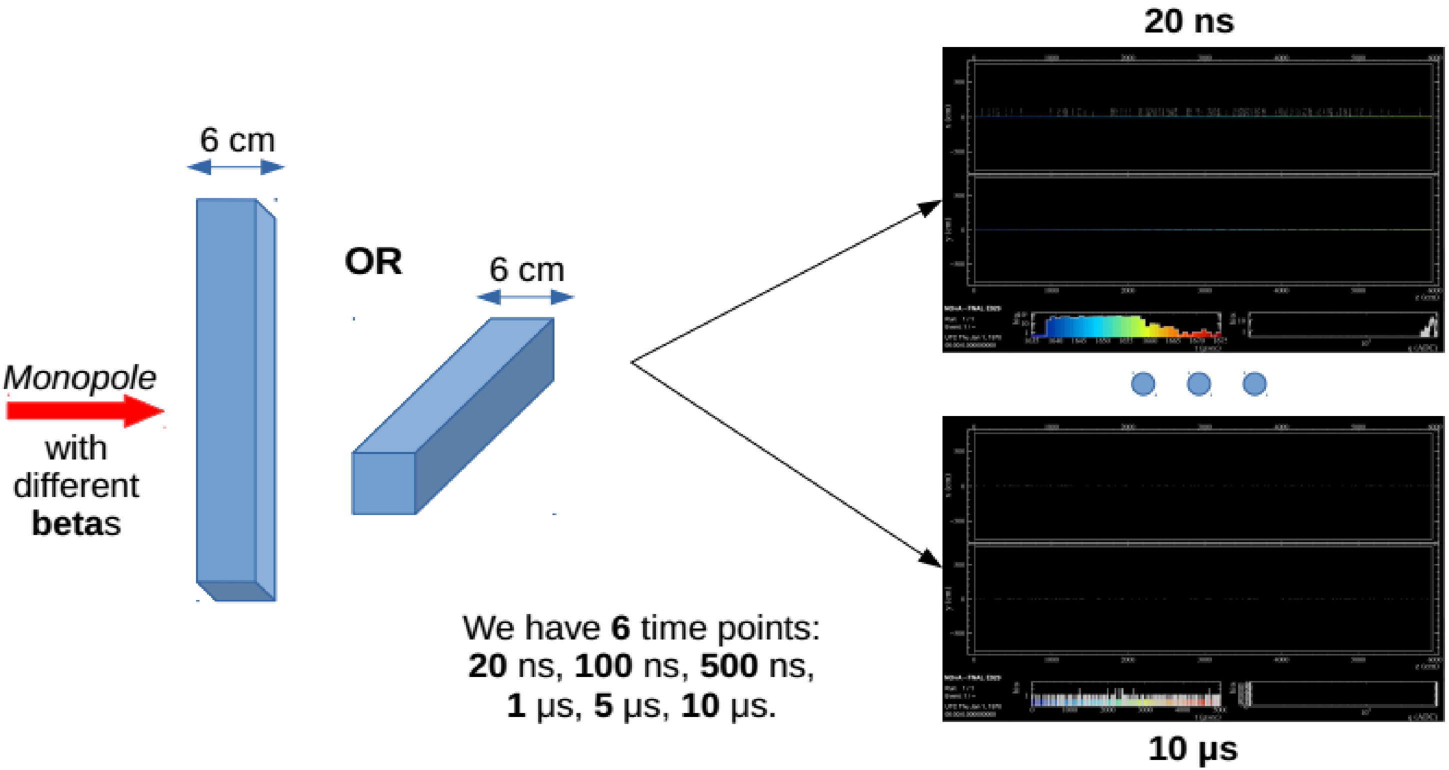


Backup (ReadoutSim vs Bench)
Hardware test №2

ReadoutSim

Bench

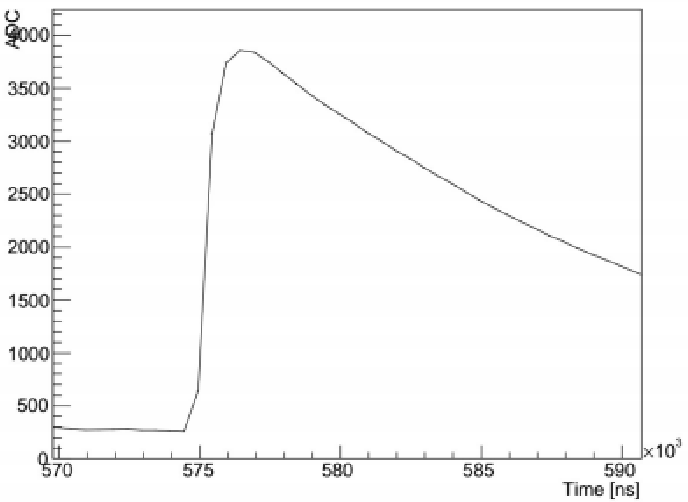




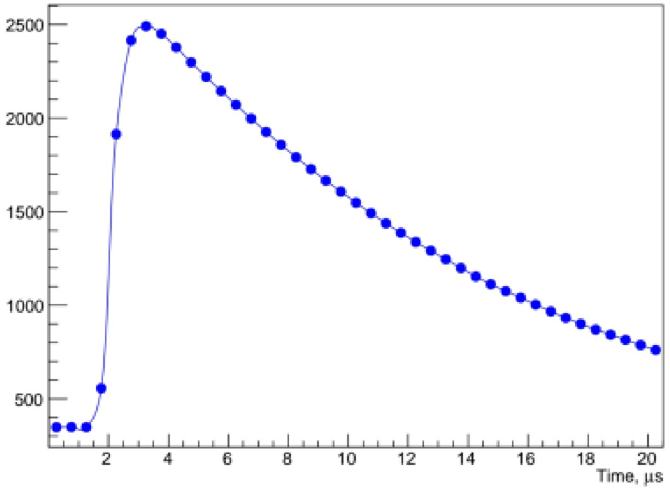
We have **6** time points:
20 ns, **100** ns, **500** ns,
1 μs, **5** μs, **10** μs.

Comparison (one point – 20 ns) Hardware test №2

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**

Results
Hardware test №2

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.

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**.

Analysis part
Slow monopole trigger

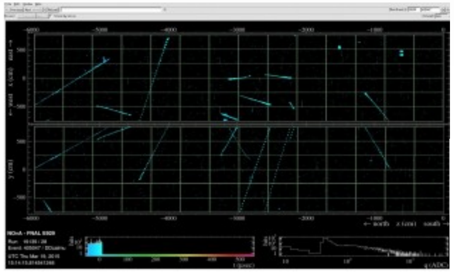
Hits filter
- **Threshold ADC>150 and ADC<4000**

Hits cluster
- **Cluster hits by time and space**

Find surface hits
- **Find entry and exit hits pairs**

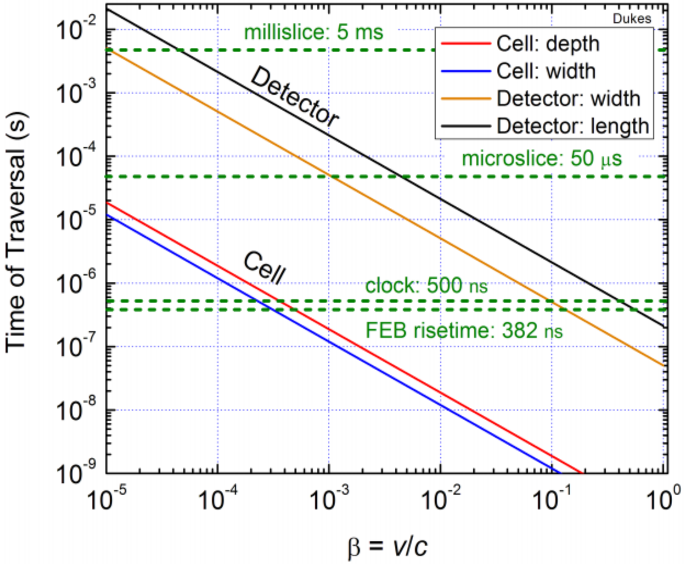
Hits between entry and exit
- **Road width 20 cells**
- **Allowed time deviation 1 μs**

Calculate plane and cell gaps



Event Display

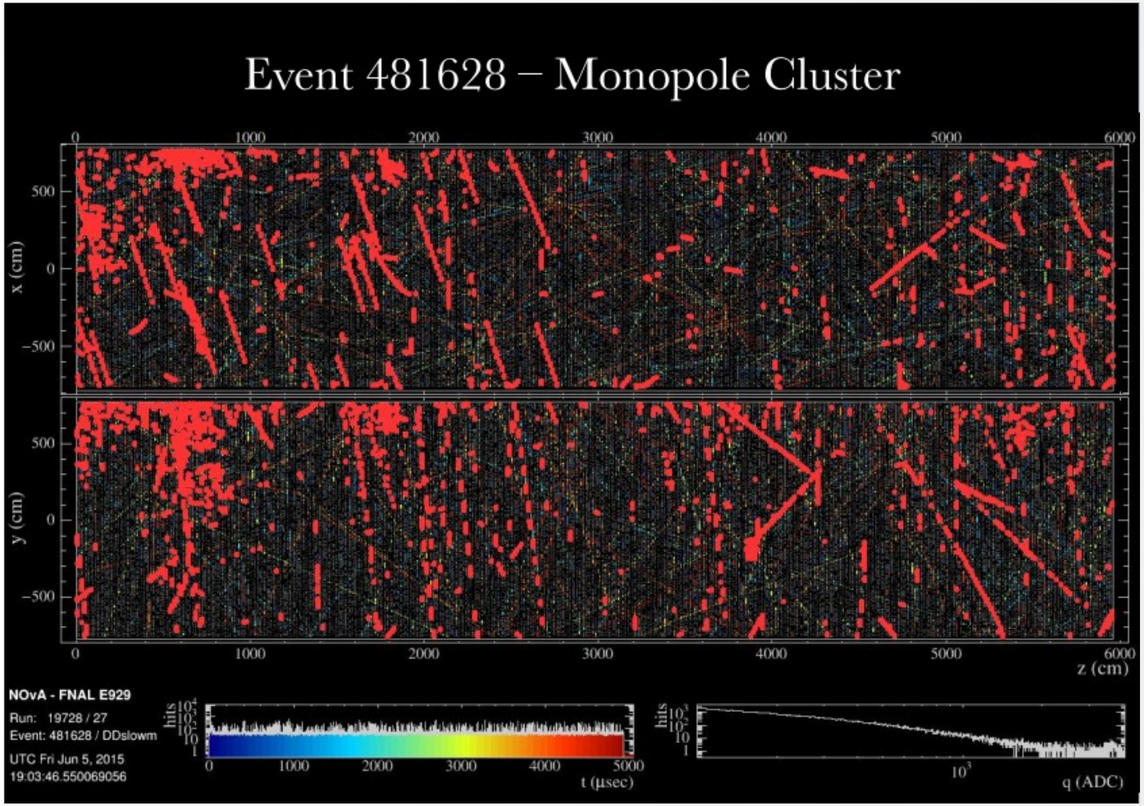
Monopole velocity



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

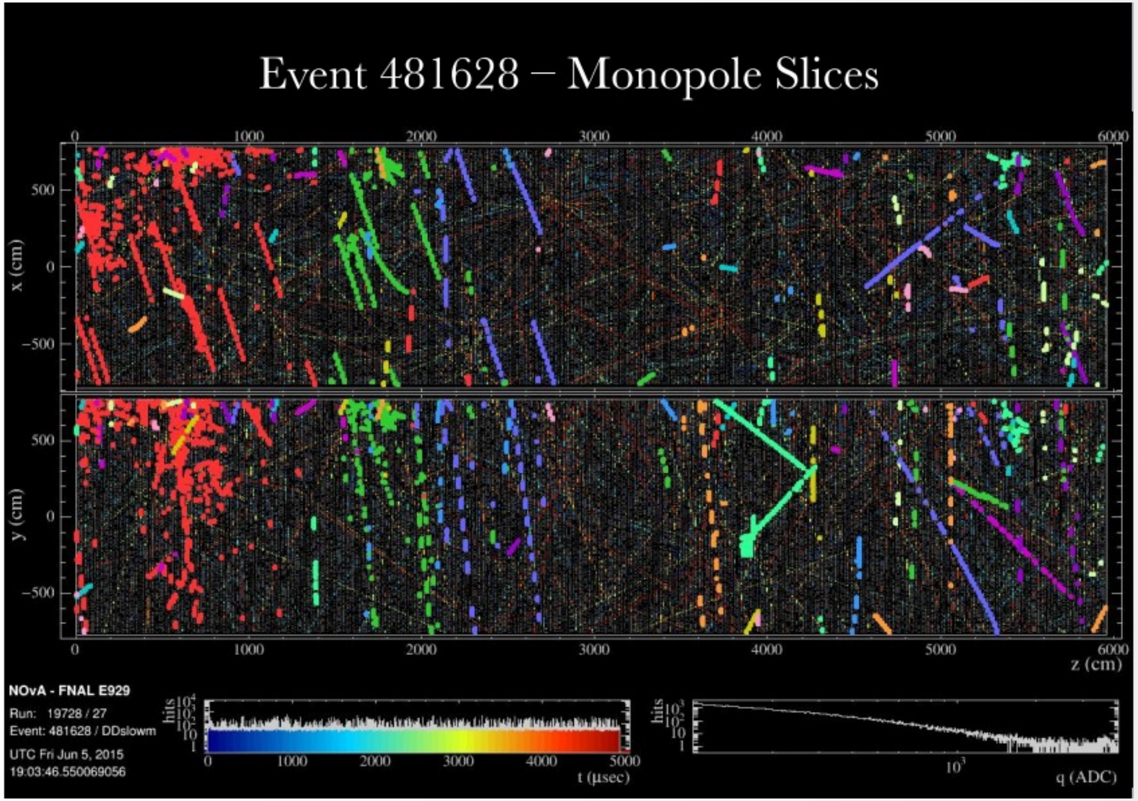
Offline reconstruction algorithm → Monopole cluster

- 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



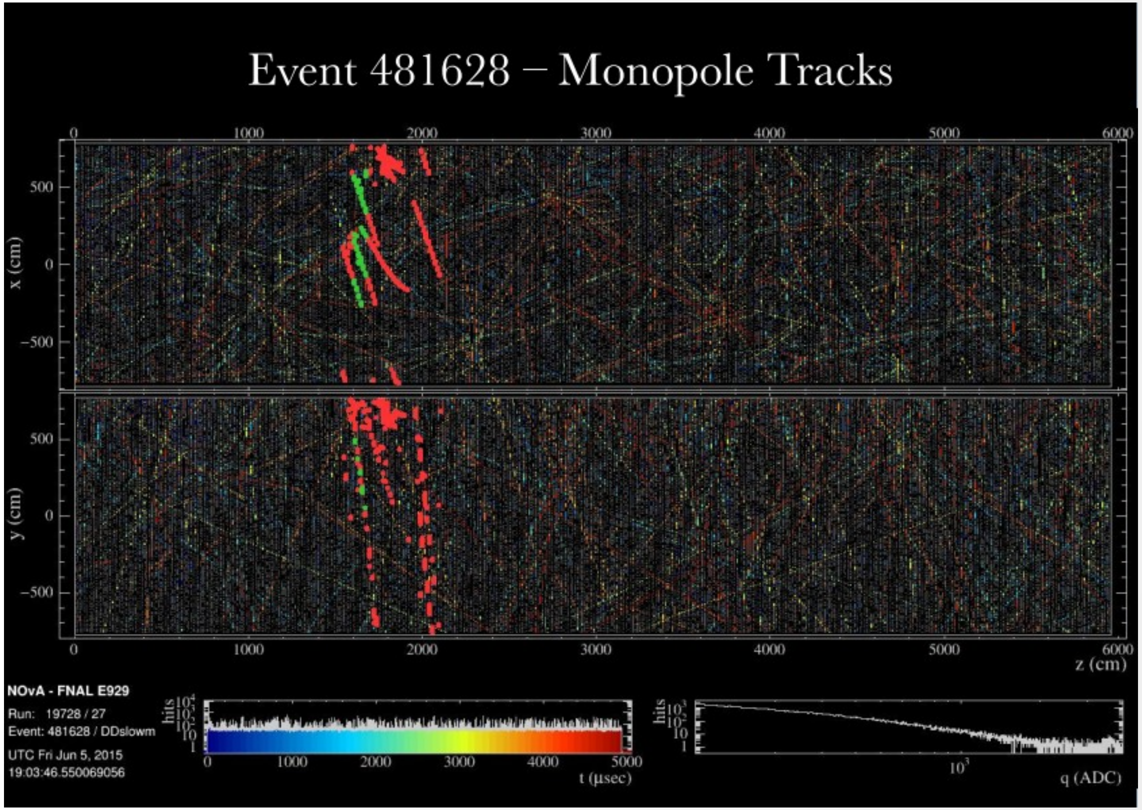
Offline reconstruction algorithm → Monopole slicer

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



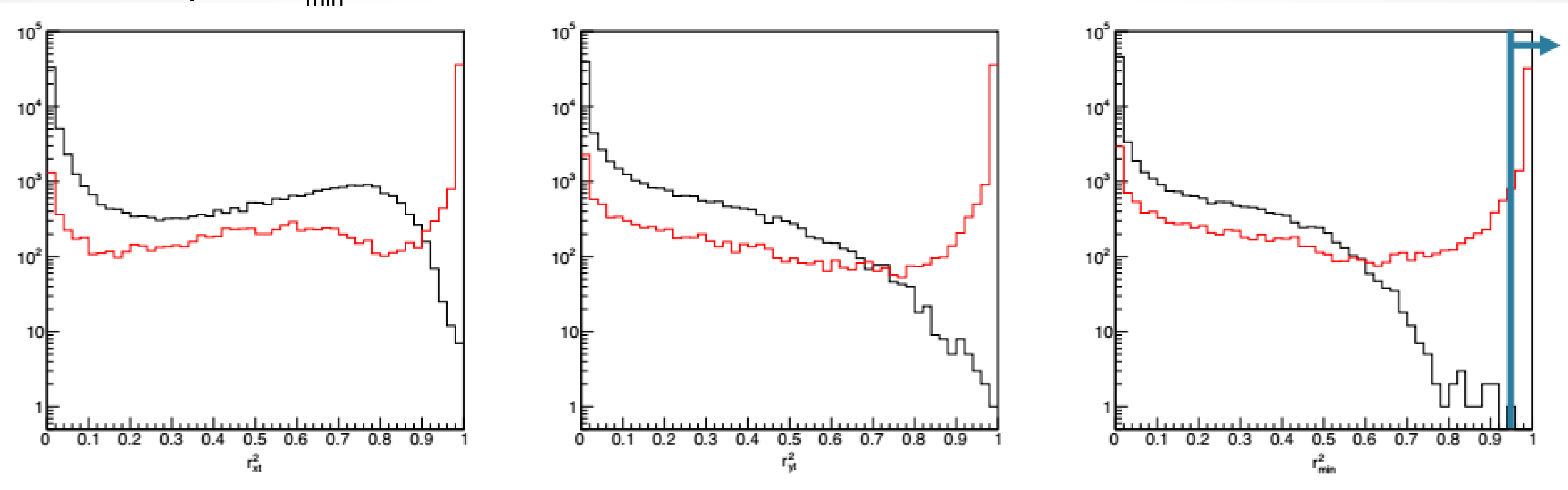
Offline reconstruction algorithm → Monopole track

- 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)



Linear Regression coefficient

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



Time Gap Fraction

- Histograms of linear regression coefficient (black: 10% data, MC: red) for:
- f^2_{xt} : calculated from *xt*-hits (left)
- f^2_{yt} : calculated from *yt*-hits (left)
- f^2_{max}: maximum of the above two for each event (right)
- We require $f^2_{max} > 0.2$