# Search of Magnetic Monopoles with the NOνA Detector

**NOνA Collaboration**

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University of Virginia

# Out Line

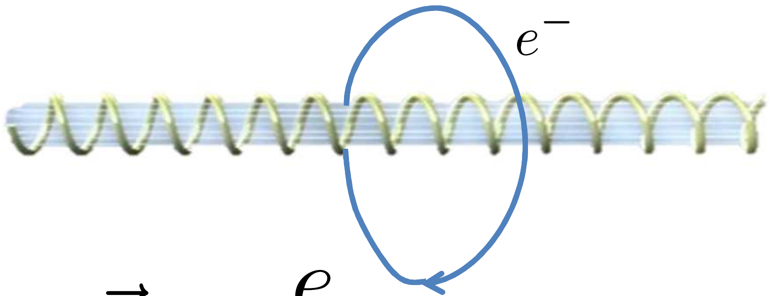
- Introduction to Magnetic Monopoles
- Motivation of Searching Magnetic Monopoles
- NOνA Project and NOνA Far Detector
- Simulation of Magnetic Monopole
- Data Driven Trigger
- NOνA's Potential on monopole
- Outlook

# Introduction: Dirac String

P.A.M Dirac (1902-1984) Video obtained at: http://moedal.web.cern.ch/

# Introduction: Dirac String

Assume an electron is transported along a closed path enclosing the Dirac String, the phase transition of its wave function should be:




$$\Delta\alpha = \frac{e}{\hbar c}\oint \vec{A}\cdot d\vec{l} = \frac{e}{\hbar c}4\pi g = 2\pi n$$

$$\Longrightarrow \quad g = \frac{n\hbar c}{2e} = n\frac{\alpha}{2}e$$

**Dirac Quantization Condition**

$$\Longrightarrow \quad g_D = \frac{\alpha}{2}e$$

Dirac Charge

# Introduction: GUT Monopole

**Standard Model**

$$SU(3)_C \times [SU(2)_L \times U(1)_Y]$$

STRONG ELECTRO-WEAK

$$U(1)_Q$$

Unified Interaction

**Grand Unified Theory**

$$SU(5)$$

# Introduction: GUT Monopole

**Standard Model**

$$SU(3)_C \times [SU(2)_L \times U(1)_Y]$$

STRONG ELECTRO-WEAK

$\alpha_X = 1/40$ **Unified Interaction** $M_x \sim 10^{14} GeV - 10^{15} GeV$

**Grand Unified Theory**

$$SU(5)$$

# Motivation: Symmetry Broken by Symmetry

To accommodate magnetic monopoles in classic electromagnetism,
let's rewrite the Maxwell Equations in a symmetric way:

$$\nabla \cdot \vec{D} = 4\pi \rho_e \qquad \nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t} + \frac{4\pi}{c}\vec{J}_e$$

Scalar

vector

$$\nabla \cdot \vec{B} = 4\pi \rho_m \qquad -\nabla \times \vec{E} = \frac{1}{c}\frac{\partial \vec{B}}{\partial t} + \frac{4\pi}{c}\vec{J}_m$$

pseudoscalar

pseudovector

# Motivation: Symmetry Broken by Symmetry

If you accept the idea of magnetic charge, you may notice the following Duality Transforms are completely trivial:

$$\begin{pmatrix} \rho_e \\ \rho_m \end{pmatrix} = \begin{pmatrix} cos\xi & sin\xi \\ -sin\xi & cos\xi \end{pmatrix} \begin{pmatrix} \rho'_e \\ \rho'_m \end{pmatrix}$$

$$\begin{pmatrix} \vec{j}_e \\ \vec{j}_m \end{pmatrix} = \begin{pmatrix} cos\xi & sin\xi \\ -sin\xi & cos\xi \end{pmatrix} \begin{pmatrix} \vec{j}'_e \\ \vec{j}'_m \end{pmatrix}$$

$$\begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} = \begin{pmatrix} cos\xi & sin\xi \\ -sin\xi & cos\xi \end{pmatrix} \begin{pmatrix} \vec{E}' \\ \vec{H}' \end{pmatrix}$$

It is just our convention to say a particle possessing an electric charge or magnetic charge. What really matters is the fraction…

**CP violation** is a necessary consequence of the existence of a particle carrying both electric charge and magnetic charge.

# Monopole Physics: Interaction

$$\vec{F} = g\left(\vec{B} - \vec{\beta} \times \vec{E}\right)$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_R + \frac{d\sigma}{d\Omega}_\Delta$$

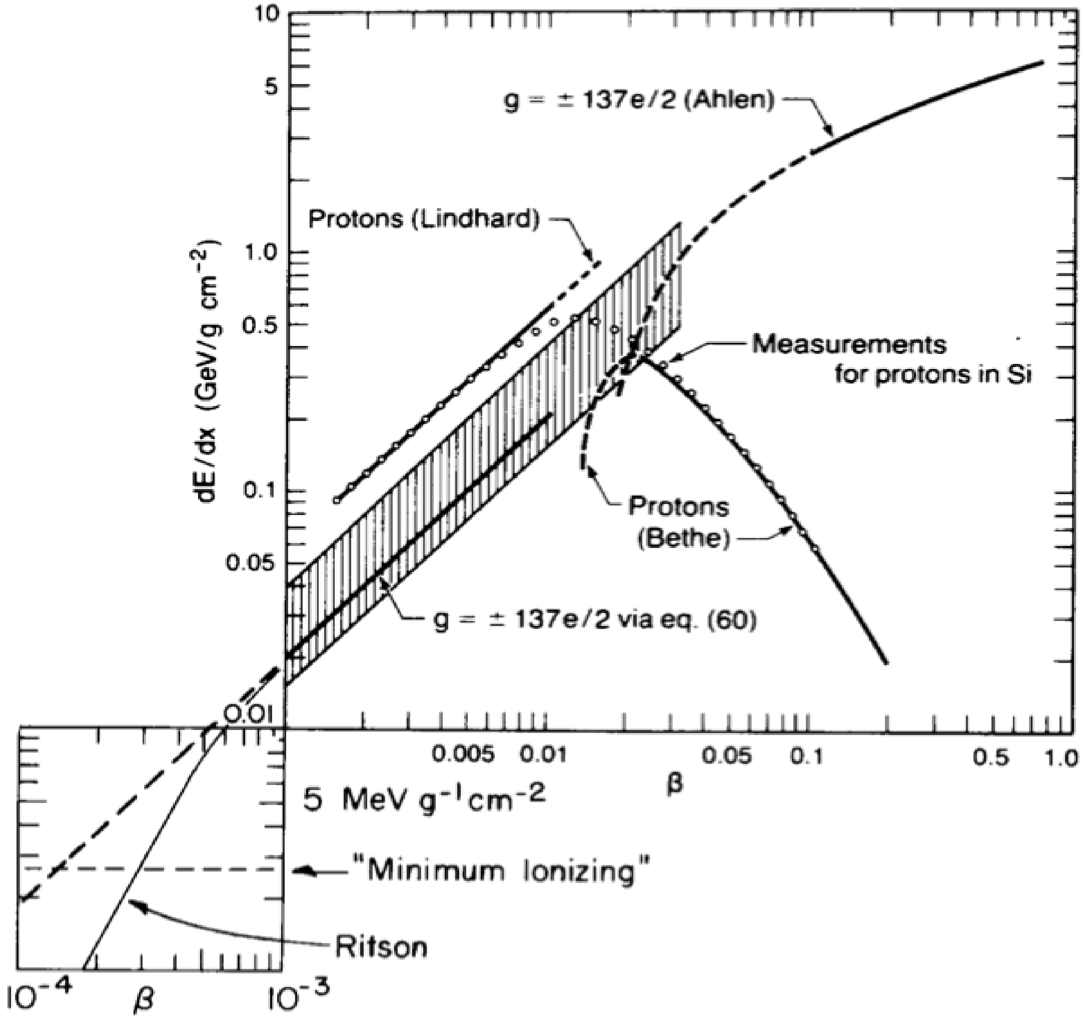
$$\frac{d\sigma}{d\Omega}_R = \frac{g^2 e^2}{4p^2 c^2 sin^4(\psi/2)}$$

Rutherford Scattering

$$\frac{d\sigma}{d\Omega}_\Delta$$

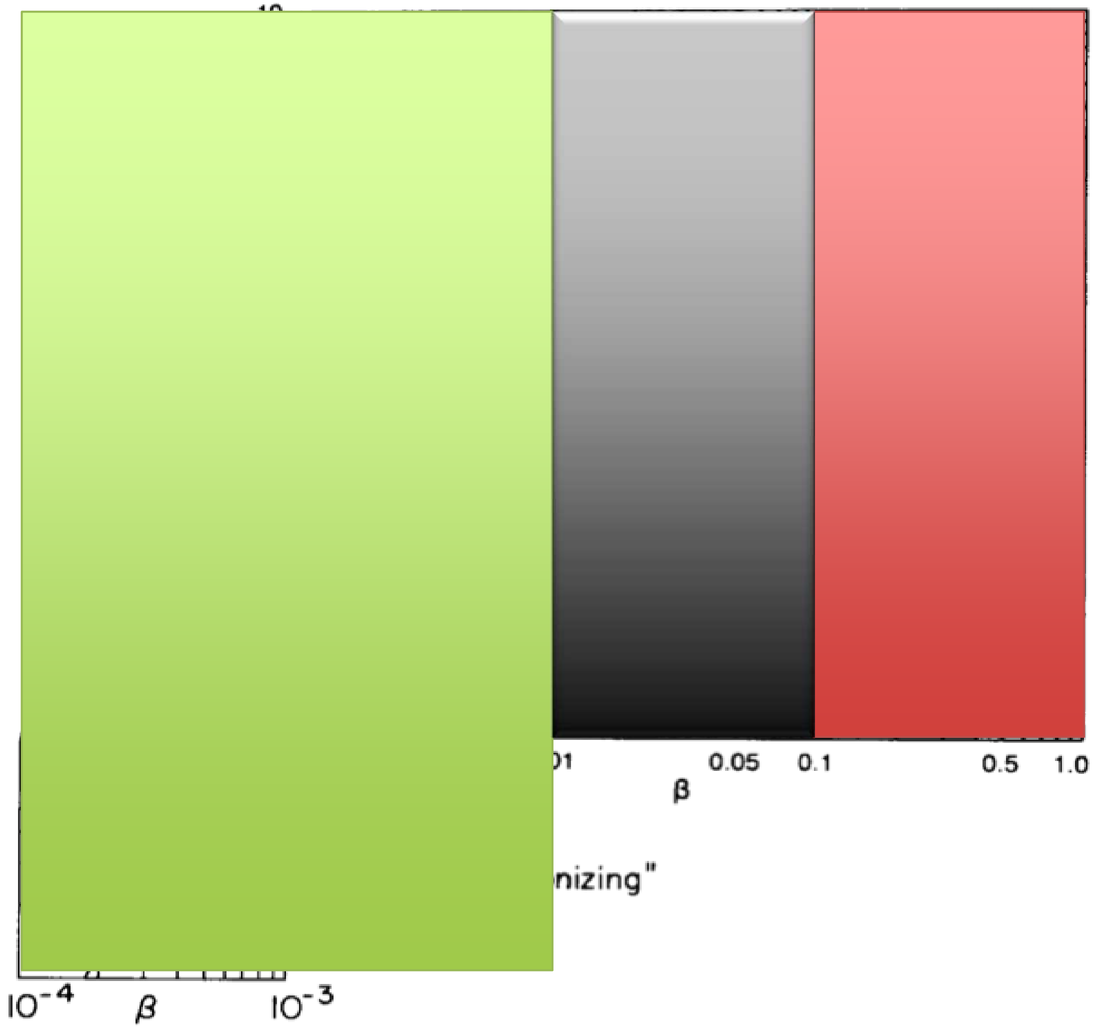
Correction by considering the electron spin (Y. Kazama, C. N. Yang, and A. S. Goldhaber, Phys. Rev. D 15, 2287 (1977) )

# Monopole Physics: Energy Loss in Matter




Energy loss for monopoles of a single Dirac charge in Silicon. experimental data open circle for protons in Silicon are also shown. The solid curves are calculated from the corresponding theoretical work mentioned in parentheses. The solid curve inside the shaded region shows the Ahlen and Kinoshita result for monopoles. The figure is reprinted from D. E. Groom's 1986 review article.

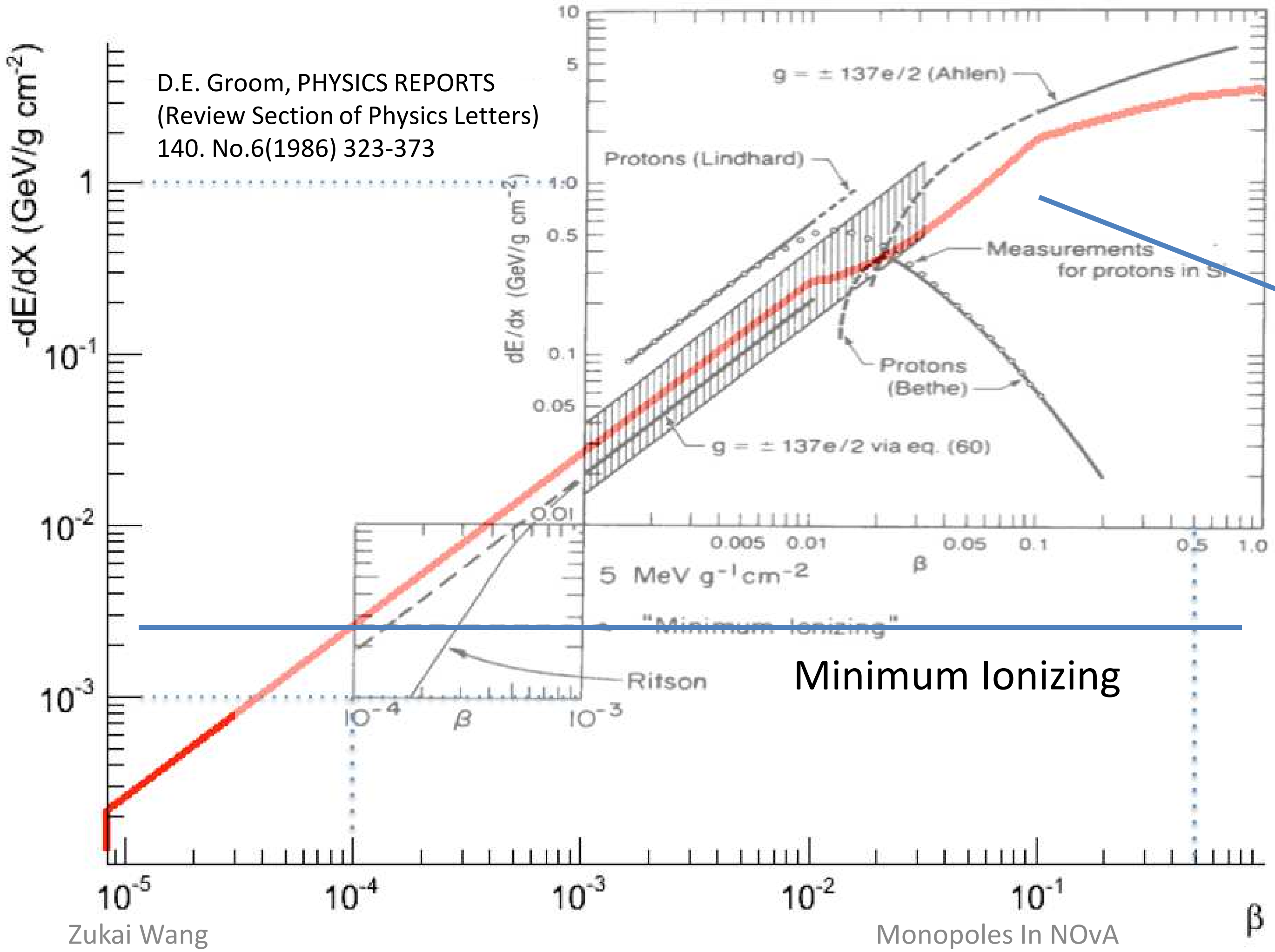
# Monopole Physics: Energy Loss in Matter




Bethe-Bloch Analog (Ahlen Formula)

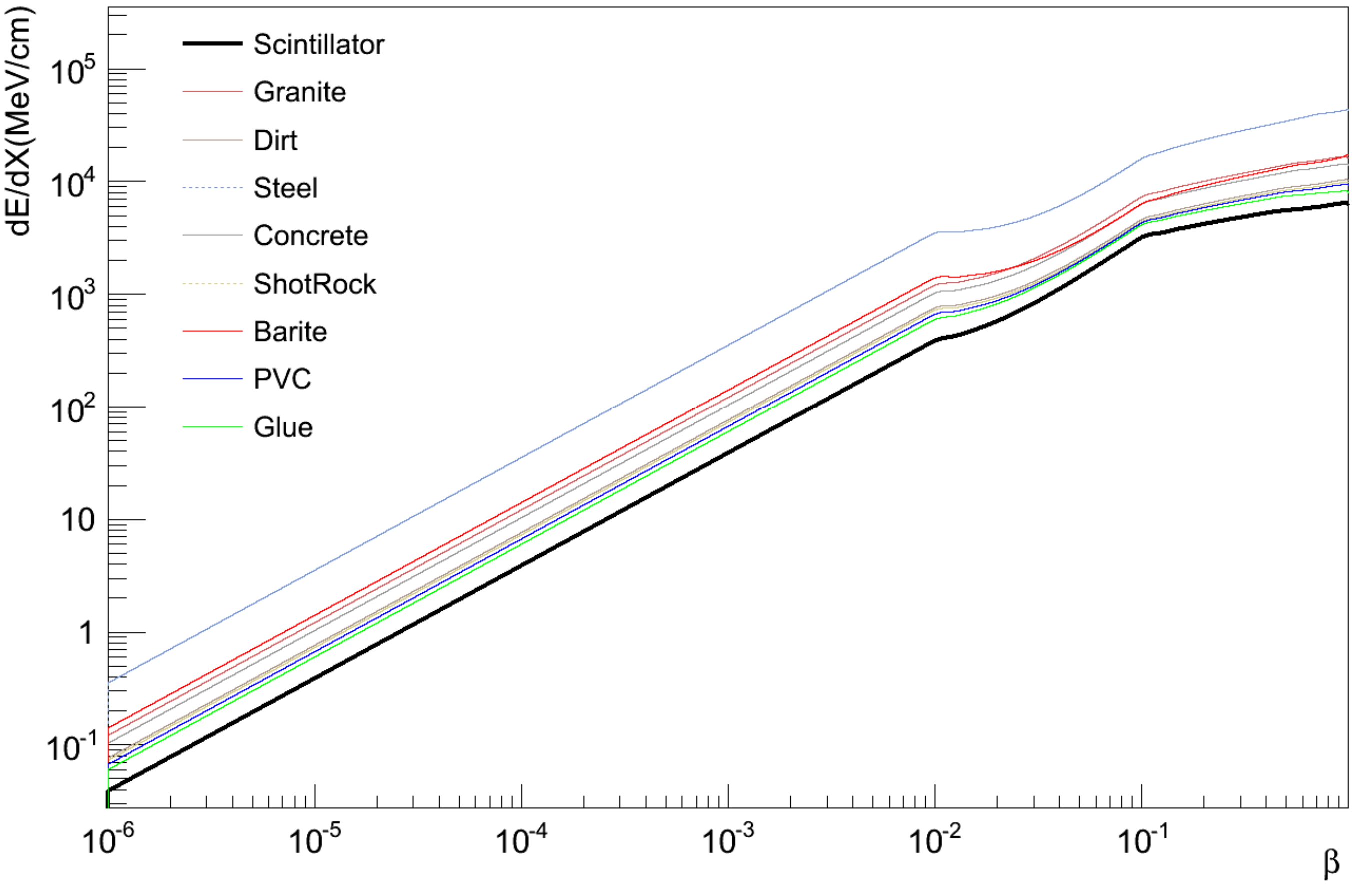
Generalized Lindhard Theory

# Simulation: Monopole Physics: Energy Loss




Geant4 simulation of monopole transportation in Silicon.
And the a linear interpolation was implemented to the unknown region.

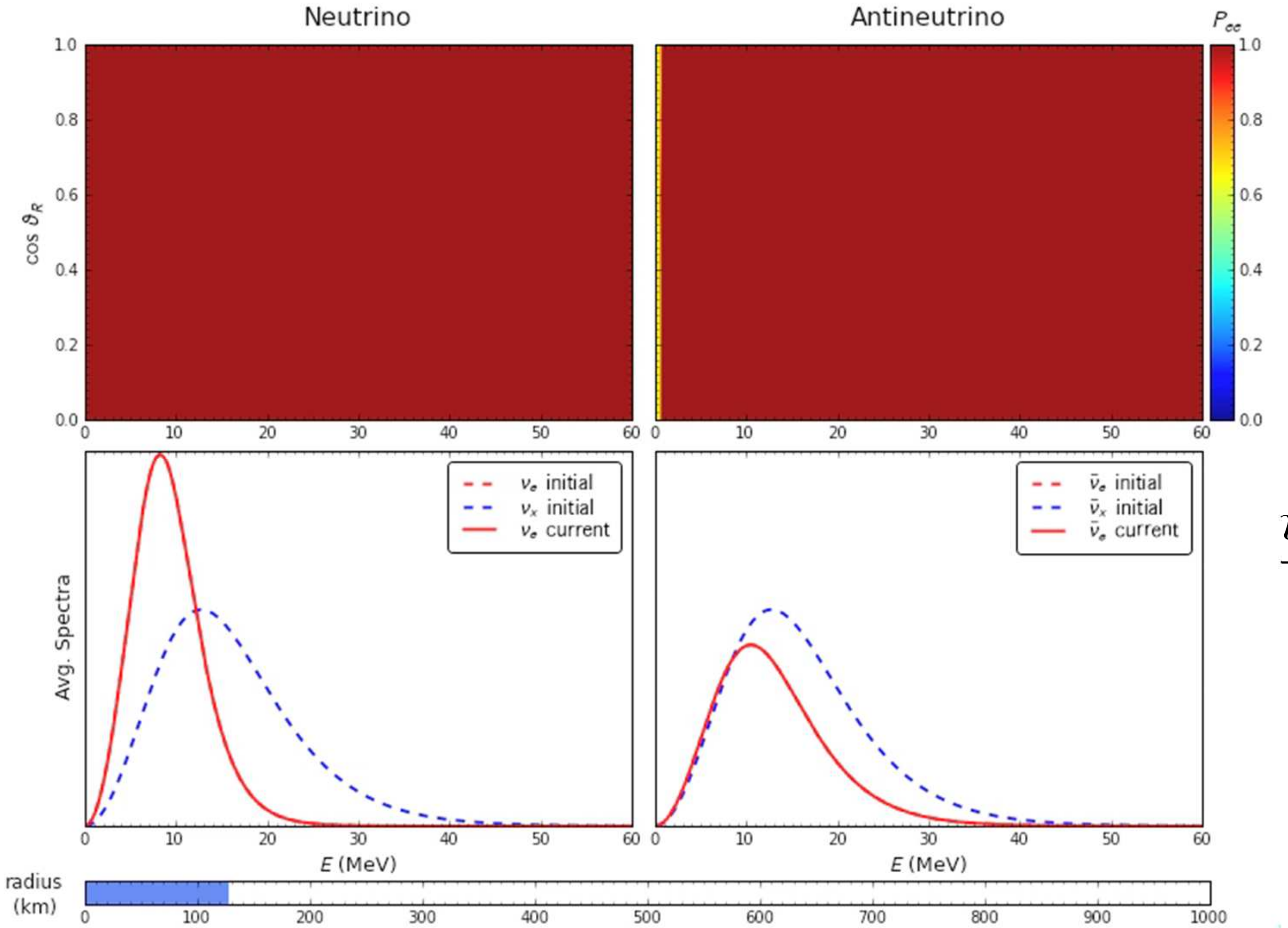
# Simulation: Energy Loss of Monopole: In All Related Material



# Neutrino Oscillation

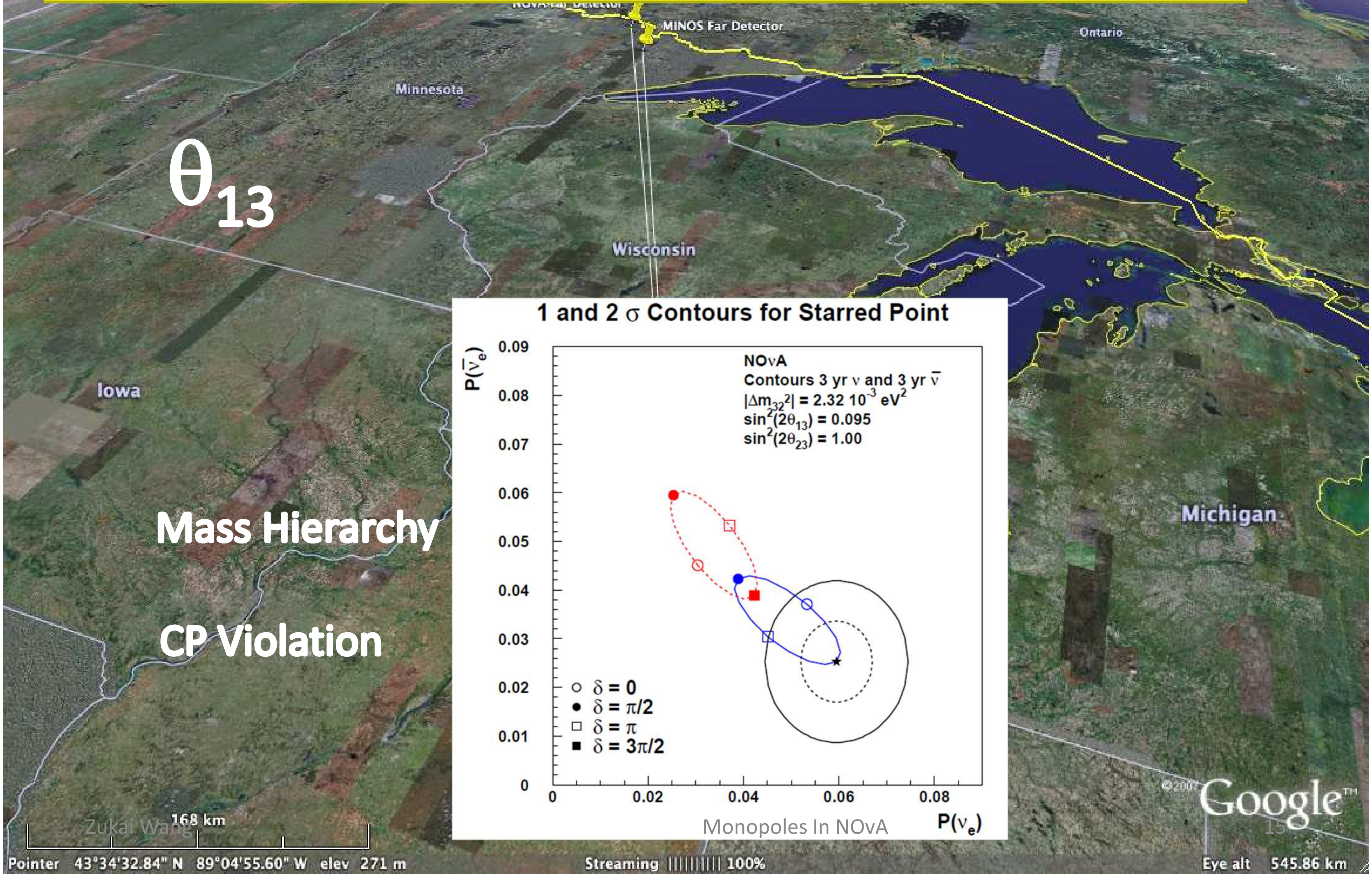
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} \qquad \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$P_{vac}($




http://arxiv.org/abs/1006.2359

# NOνA: NUMI Off-Axis $\nu_e$ Appearance




$\theta_{13}$

Mass Hierarchy

CP Violation

# NOνA Far Detector

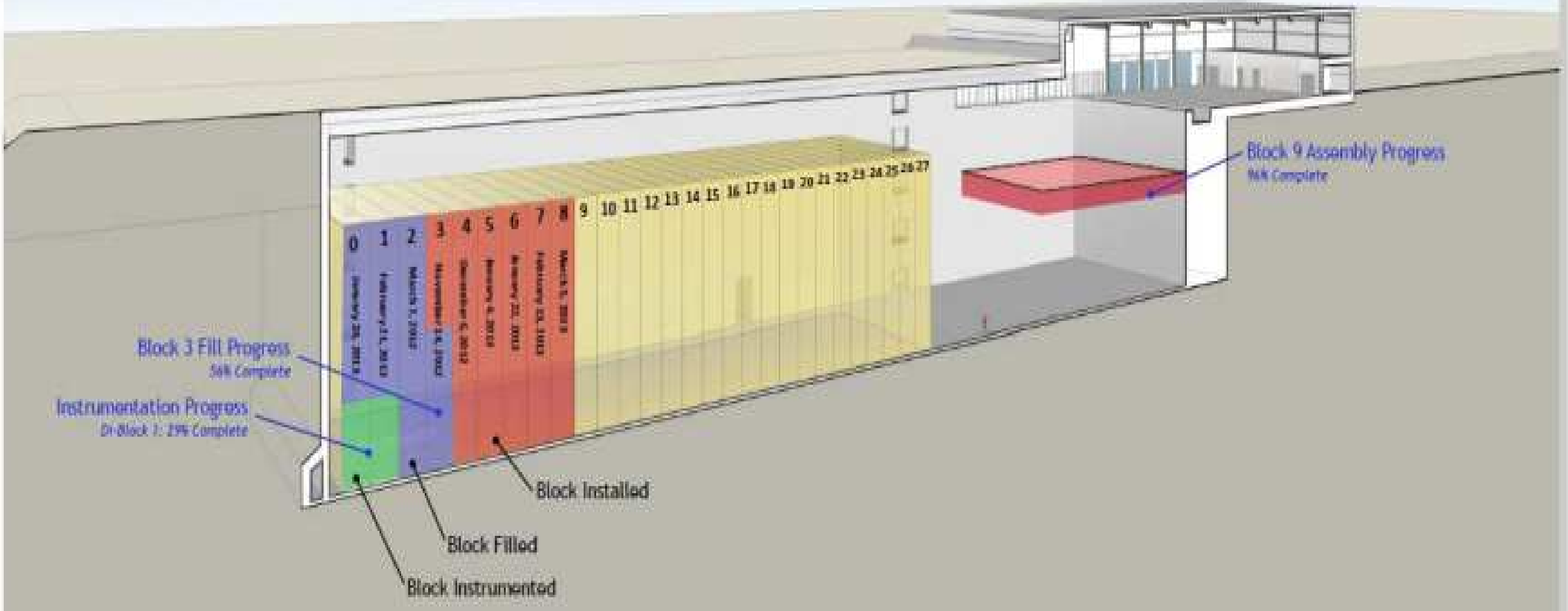
15.6m x 15.6m x 66.9m

344,064 Cells

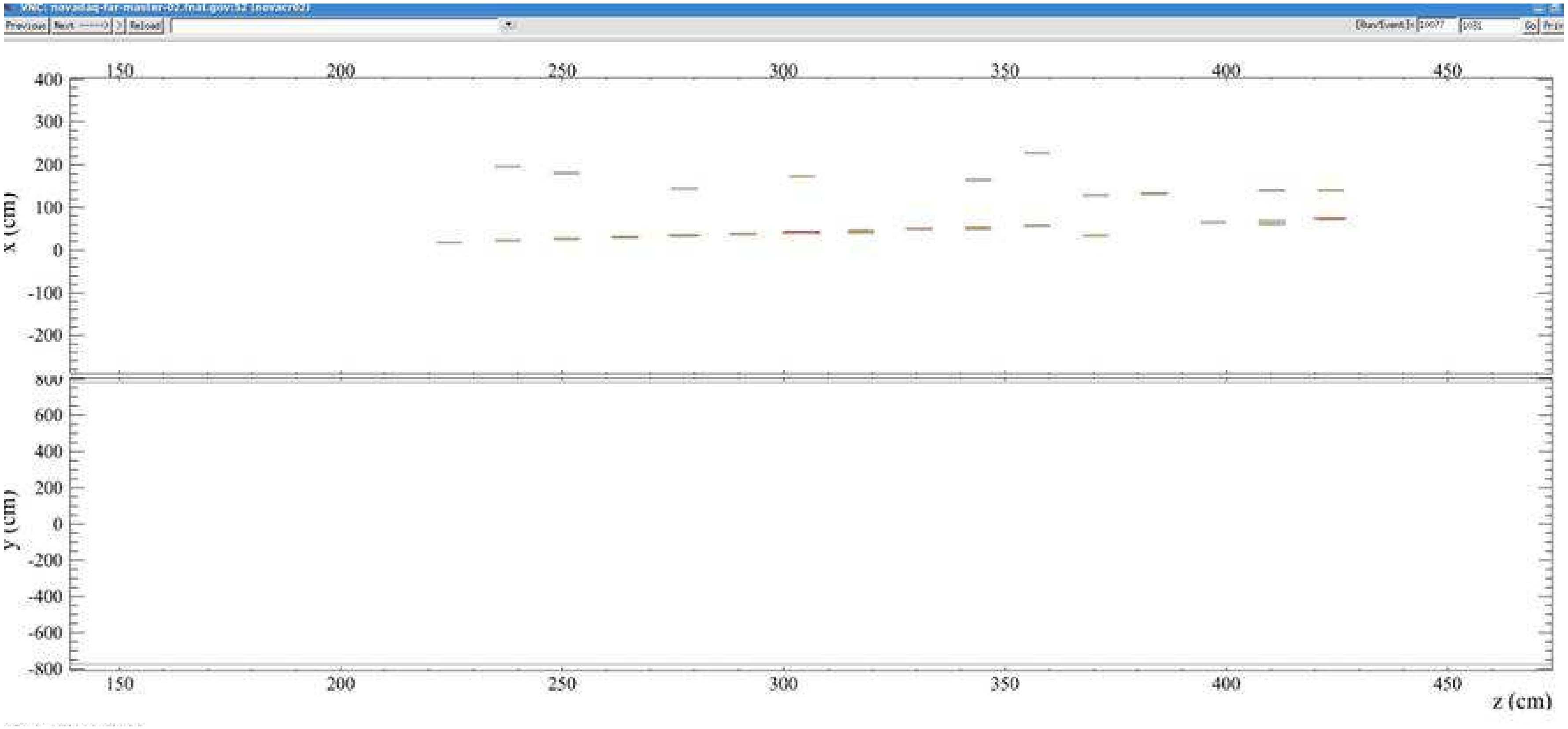
14 kTon

# NOνA Far Detector

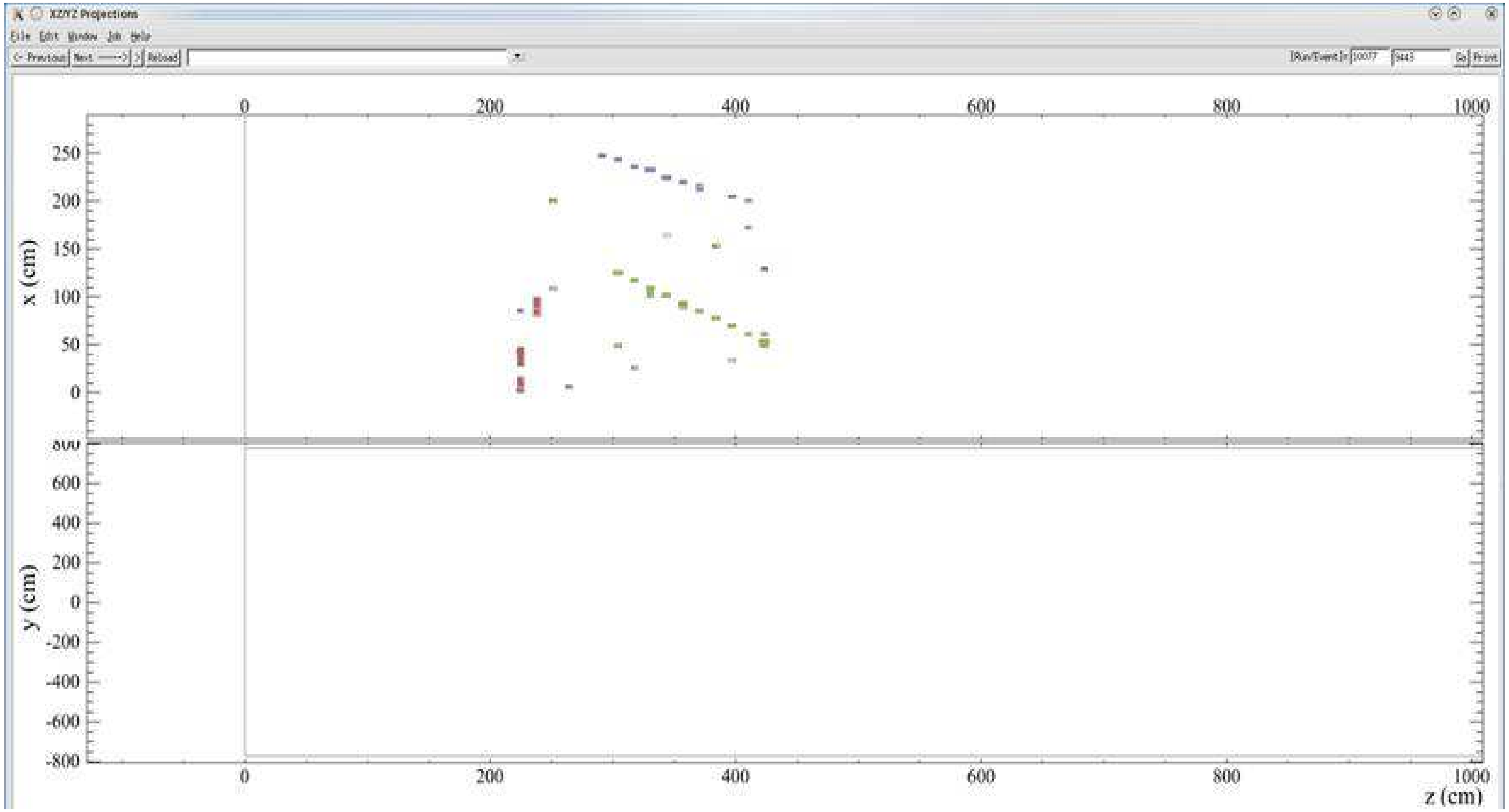
# NOνA Far Detector Construction Status



# NOνA Far Detector



# NOνA Far Detector



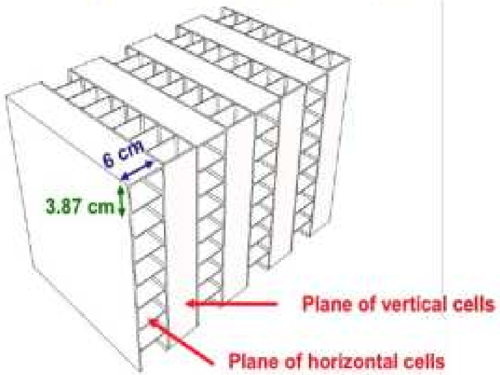
# NOνA Far Detector Technology

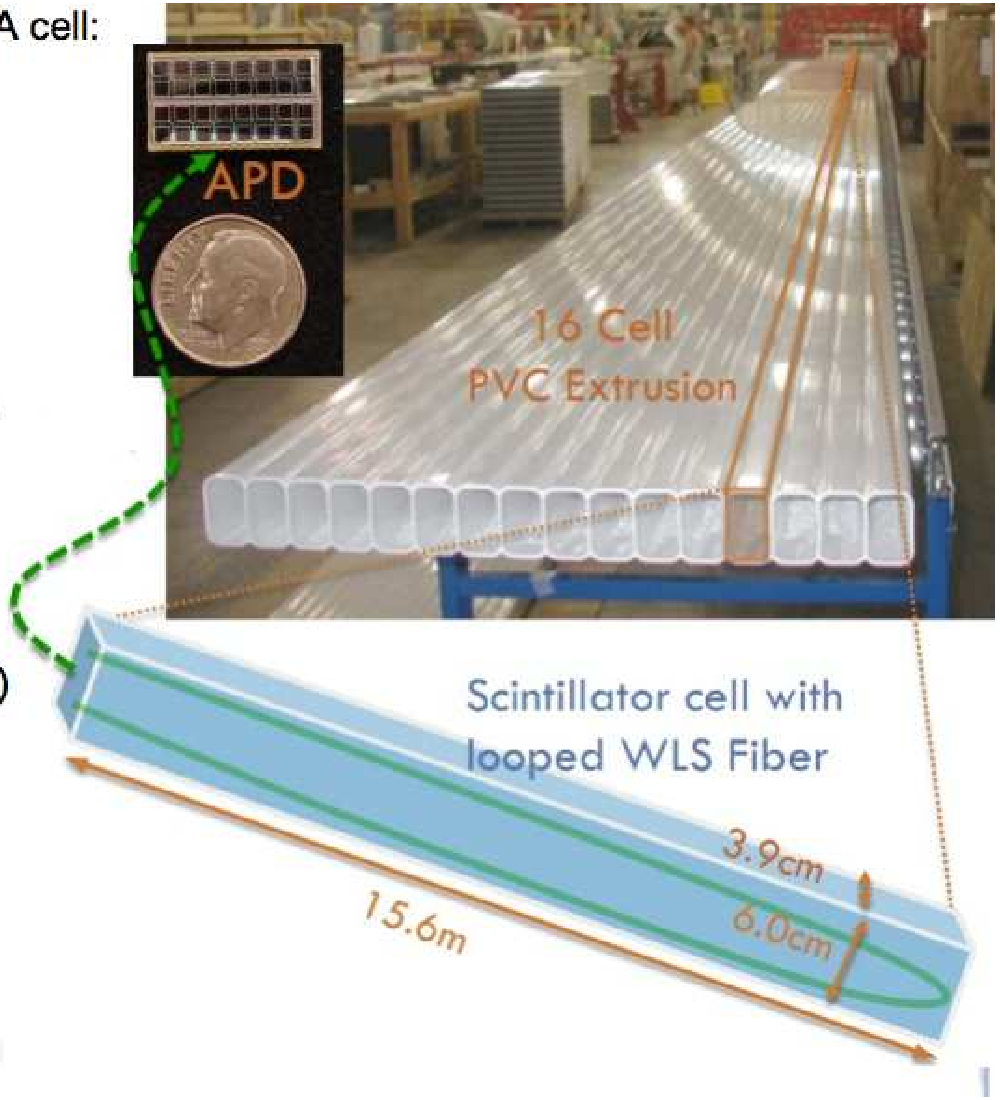
16-cell PVC extrusions (15% $TiO_2$). Each NOvA cell:

3.9 cm x 6.0cm x 15.6 cm

32 in a sealed module. Alternating X/Y planes.

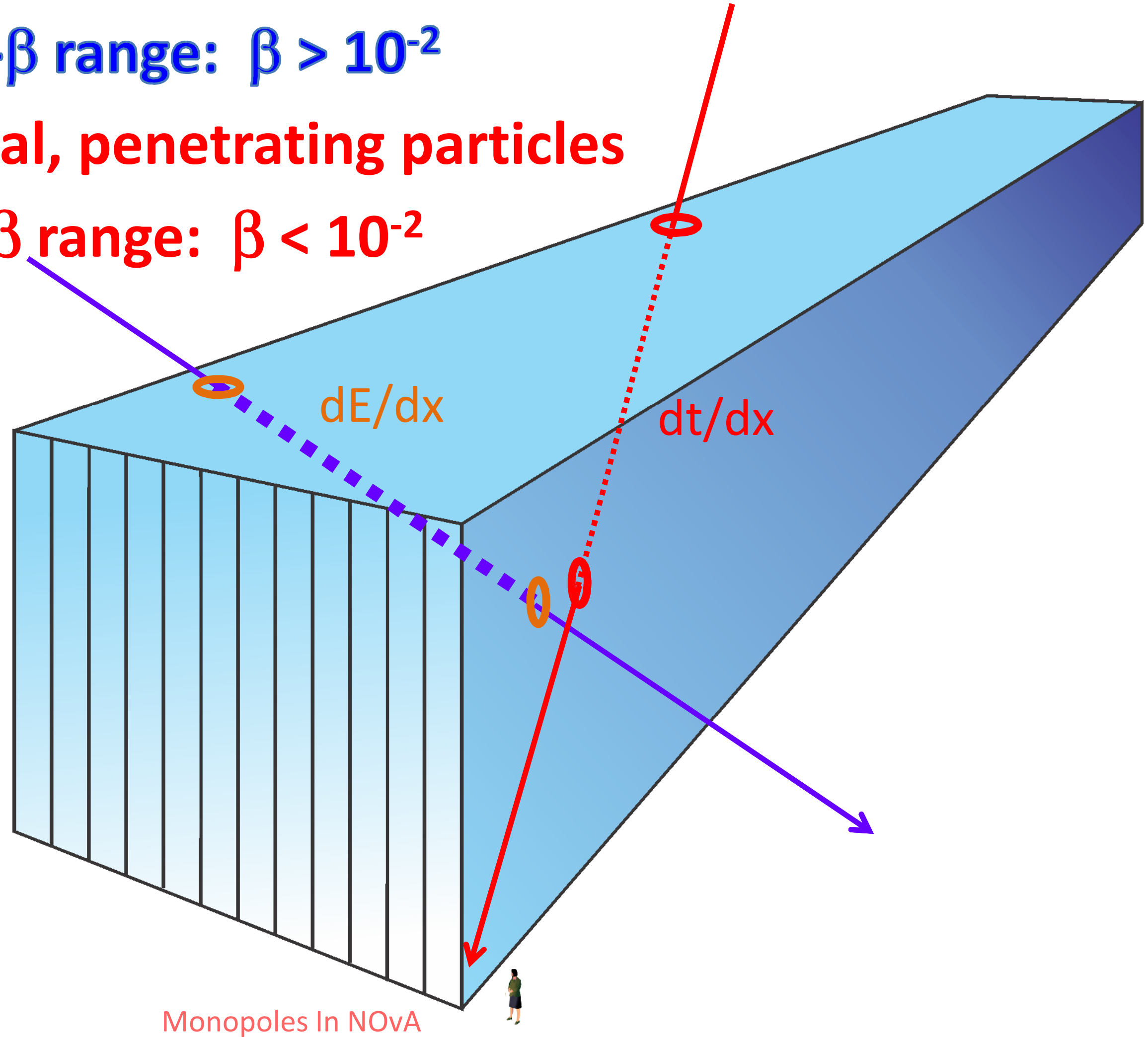
Read out by wavelength-shifting fiber into one pixel of a 32-pixel avalanche photodiode (APD)



# NOνA Monopole Search Strategy

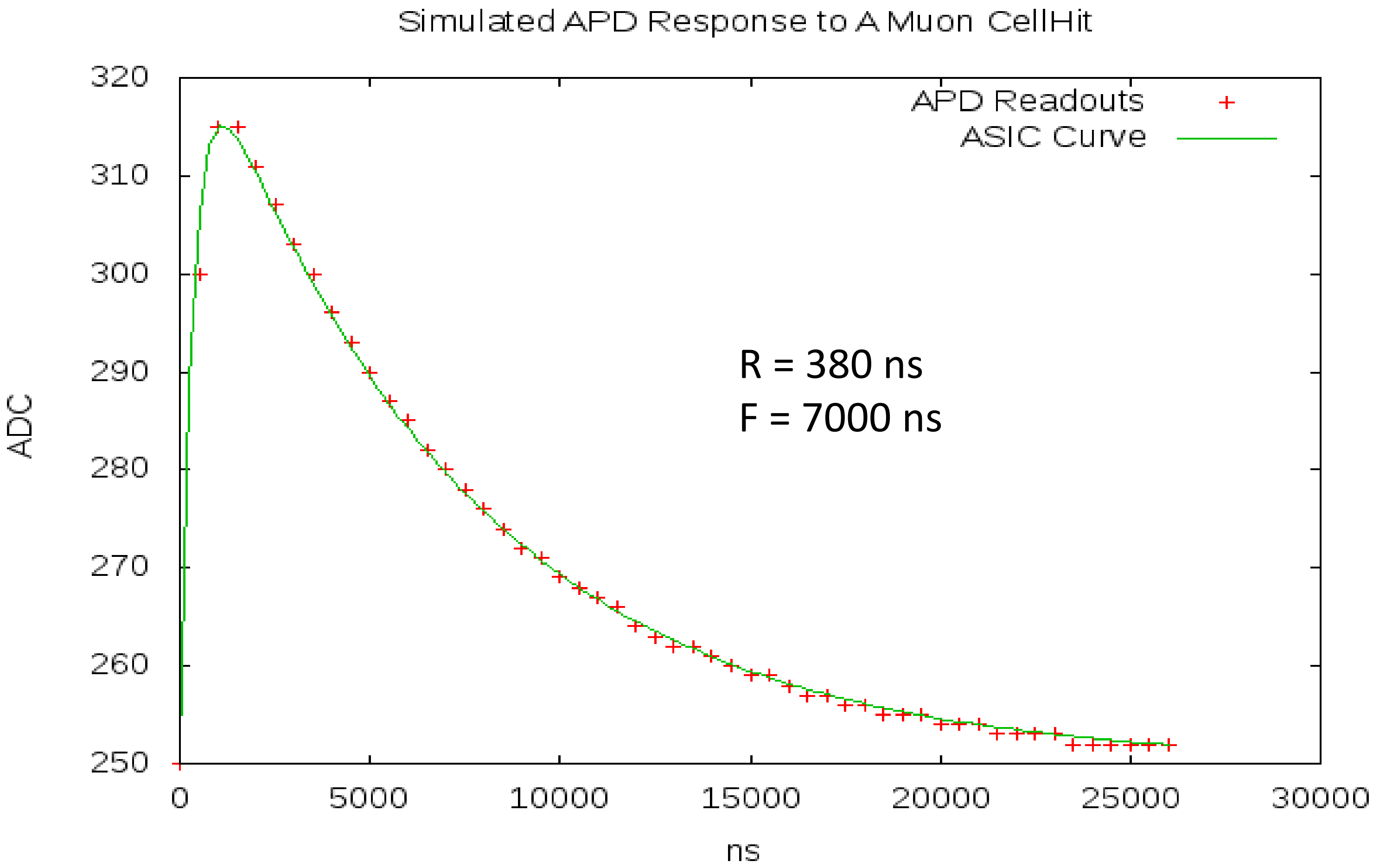
1. **Look for highly-ionizing, penetrating particles**
   - **Covers the high-β range: $\beta > 10^{-2}$**
2. **Look for sub-luminal, penetrating particles**
   - **Covers the low-β range: $\beta < 10^{-2}$**



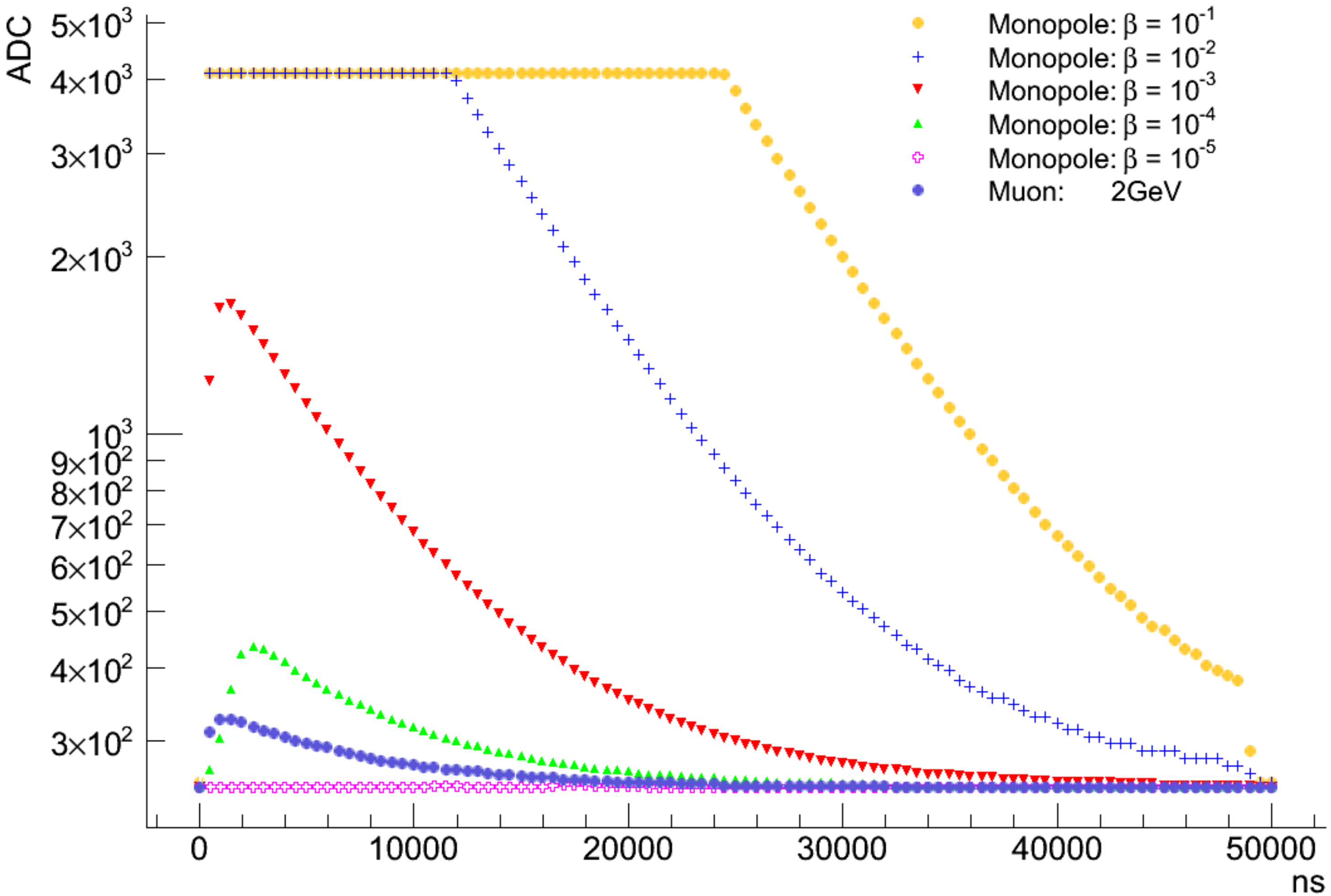
# NOνA Far Detector Technology

ASIC: Application Specific Integrated Circuit

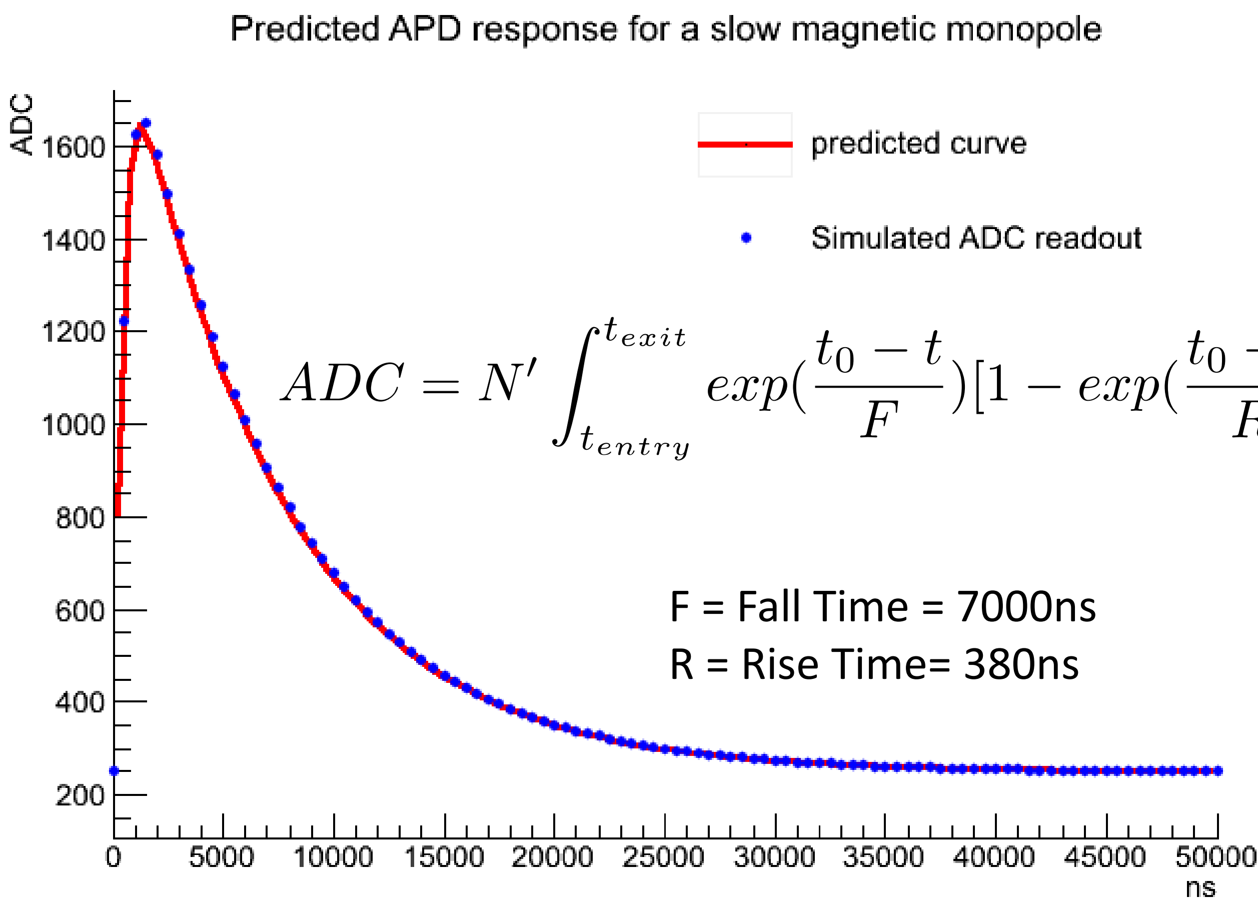
$$ADC = N \times exp[-(t - t_0)/F]\{1 - exp[-(t - t_0)/R]\}$$



# Simulation: Detector Response



# Calibration: Single Cell Hit of a slow Monopole



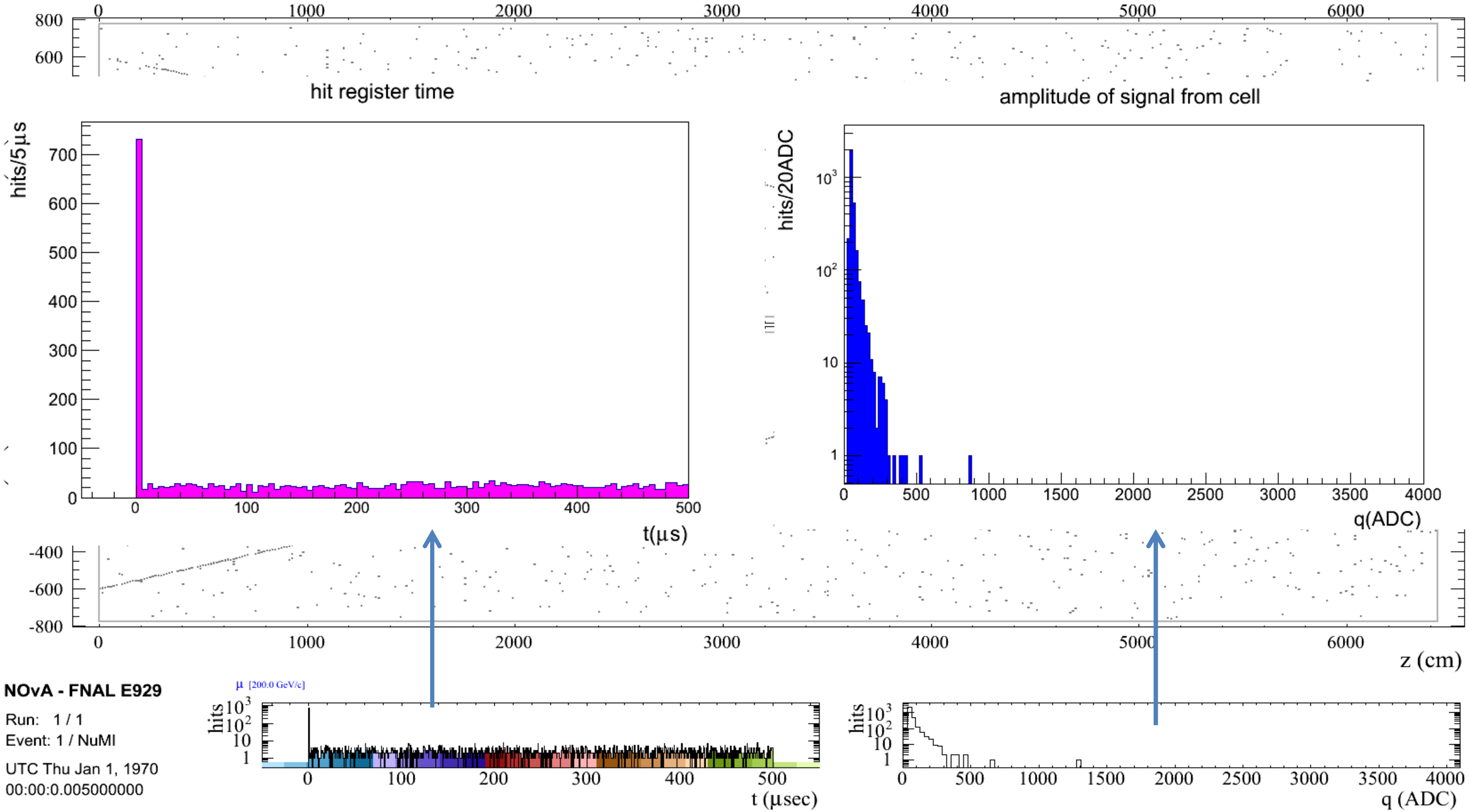

$$ADC = N' \int_{t_{entry}}^{t_{exit}} exp(\frac{t_0 - t}{F})[1 - exp(\frac{t_0 - t}{R})]\theta(t - t_0)dt_0$$

F = Fall Time = 7000ns

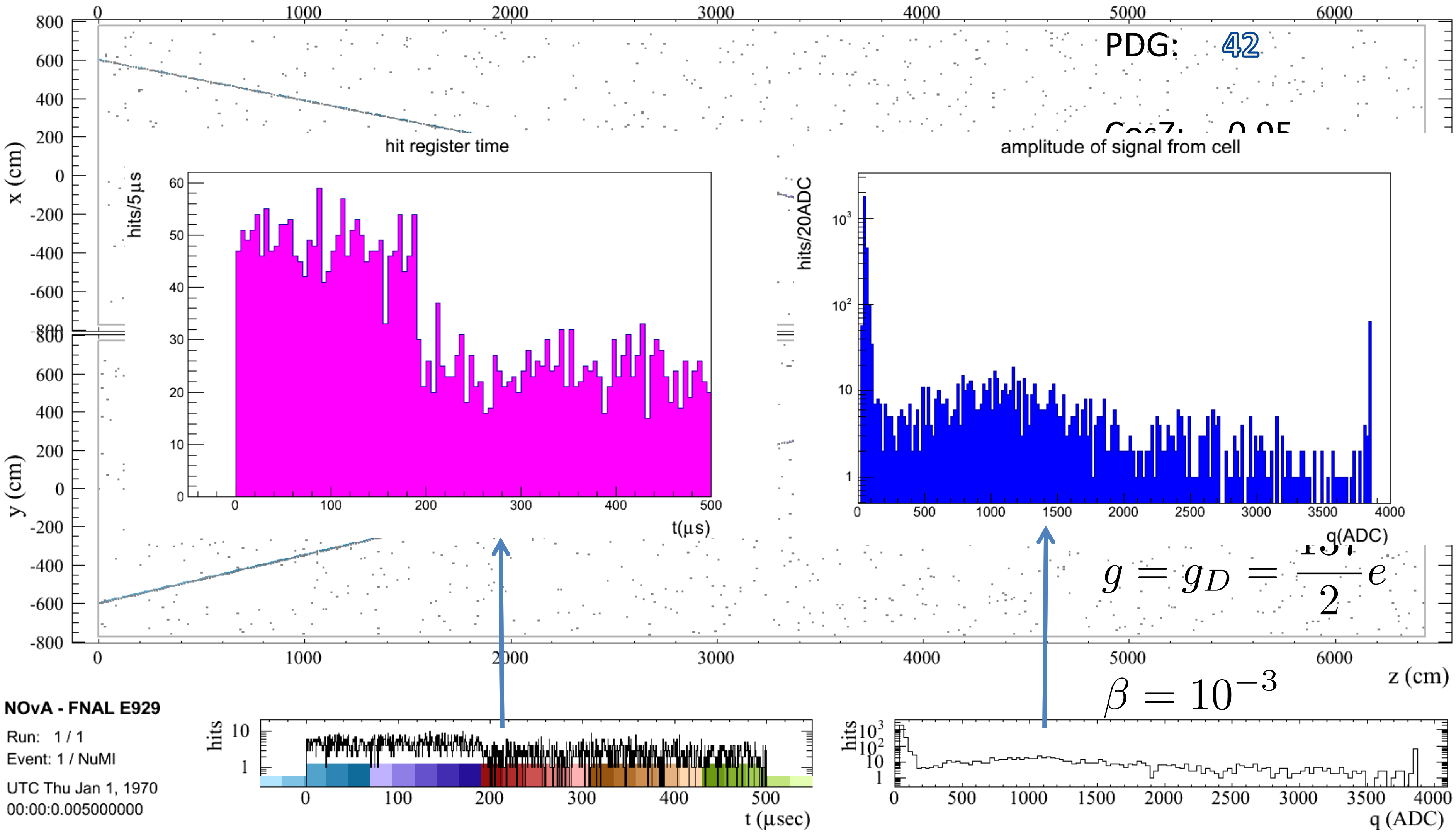
R = Rise Time= 380ns

Illustration of APD response of a monopole with $\beta = 10^{-3}$ passing through a cell horizontally described by an analytical expression.

# Simulation: Event Display of High Energy Muon



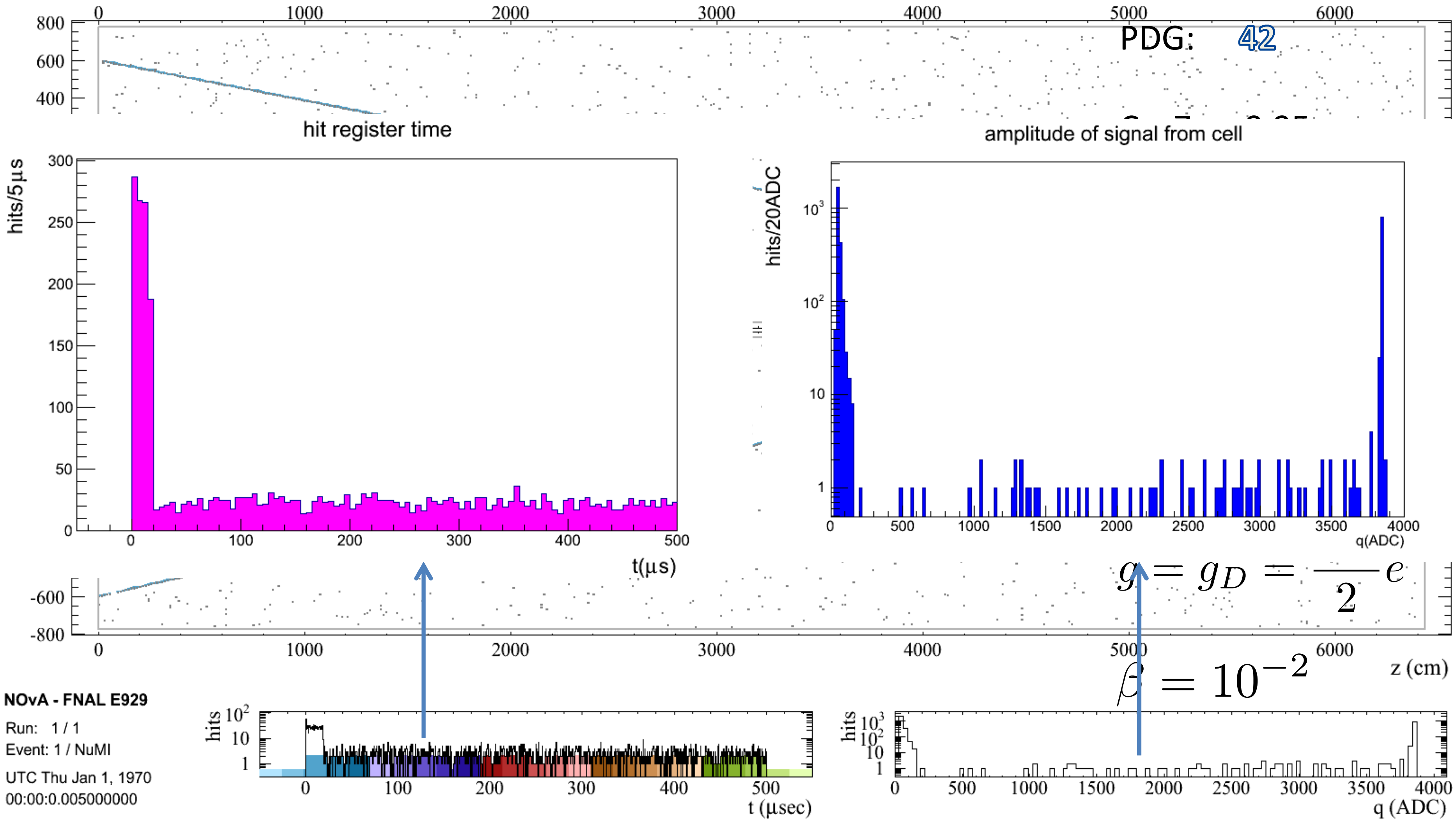
# Simulation: Event Display of Single Monopole




$$g = g_D = \frac{137}{2}e$$

$$\beta = 10^{-3}$$

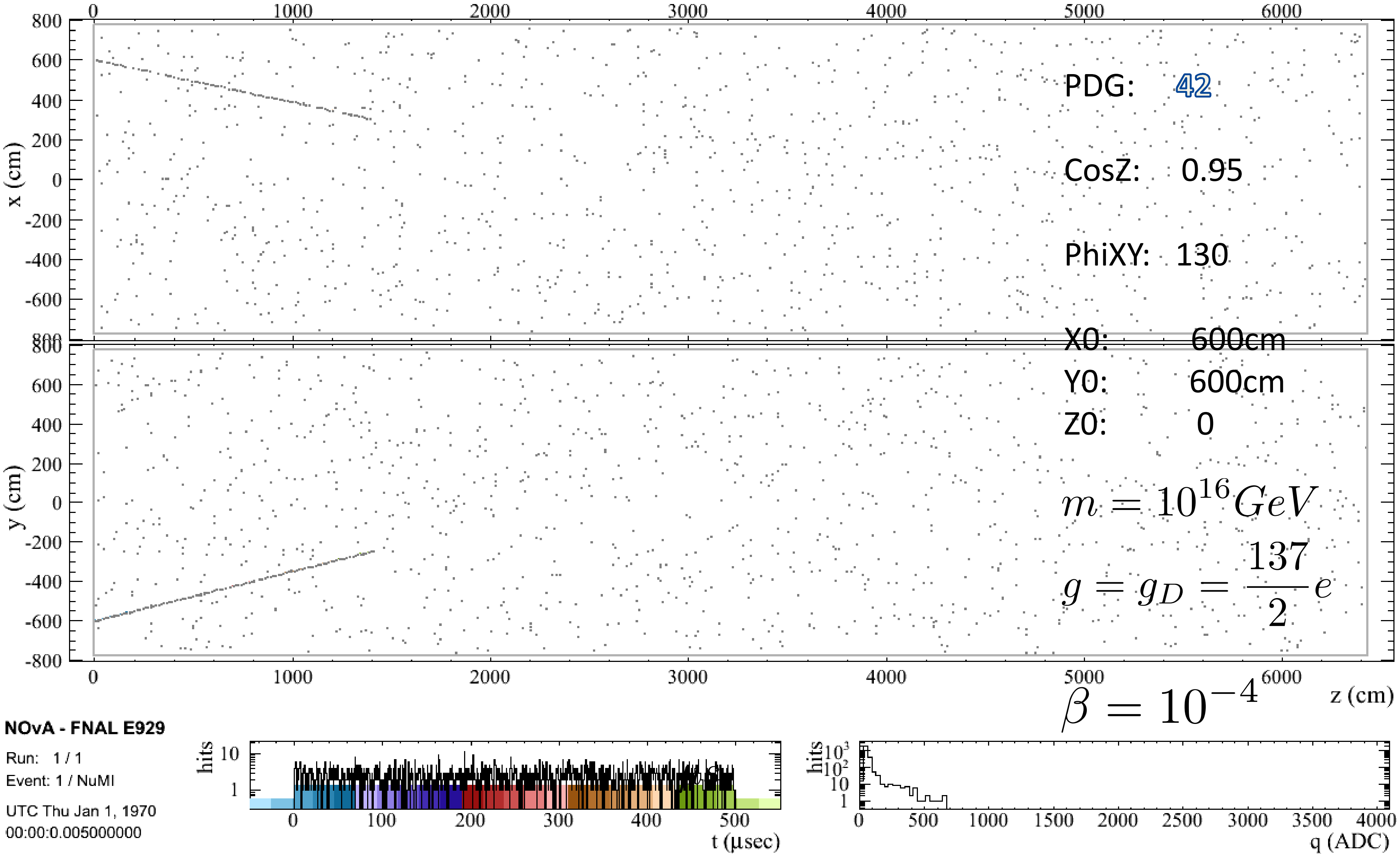
# Simulation: Event Display of Single Monopole



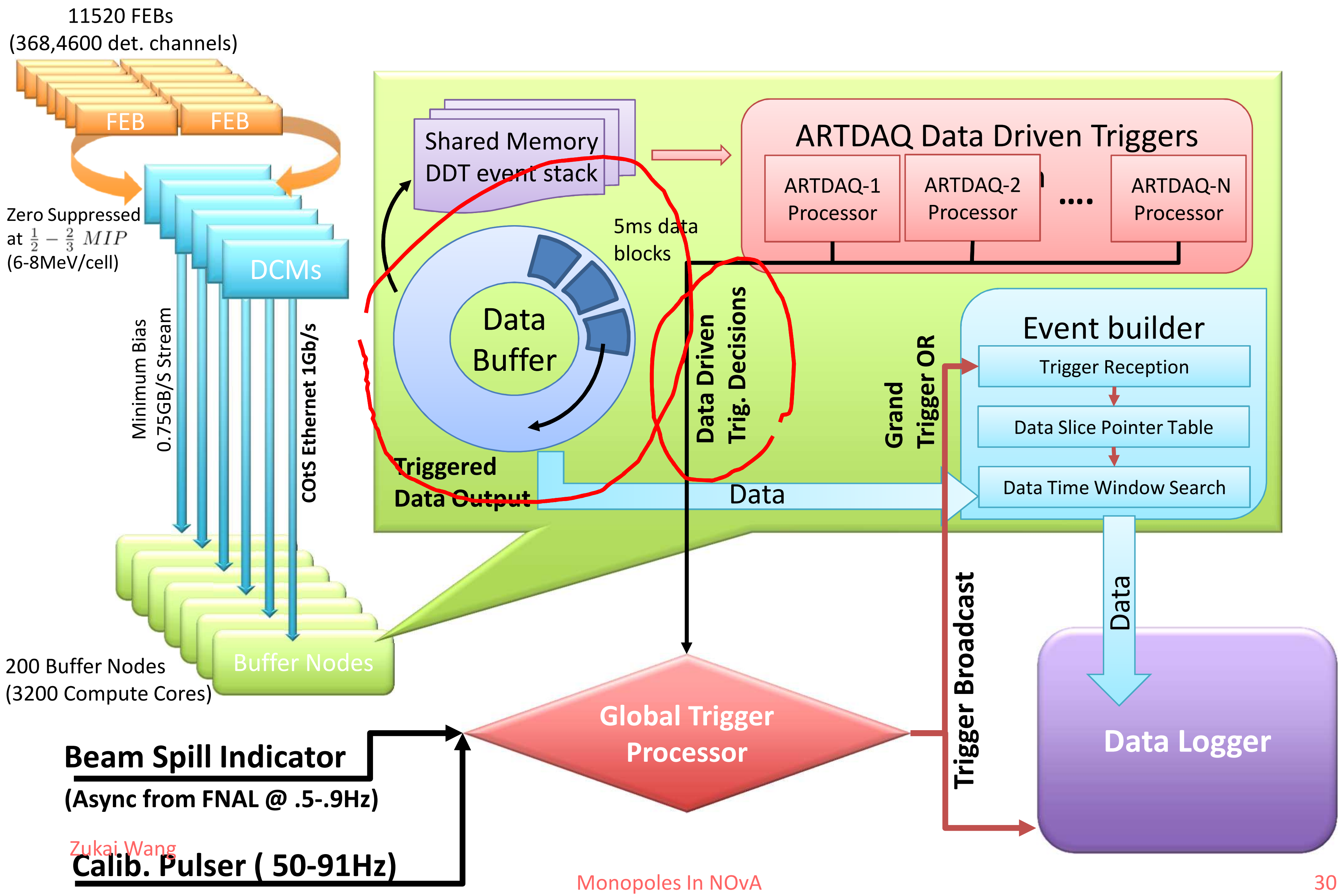

$$g = g_D = \frac{e}{2}$$

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

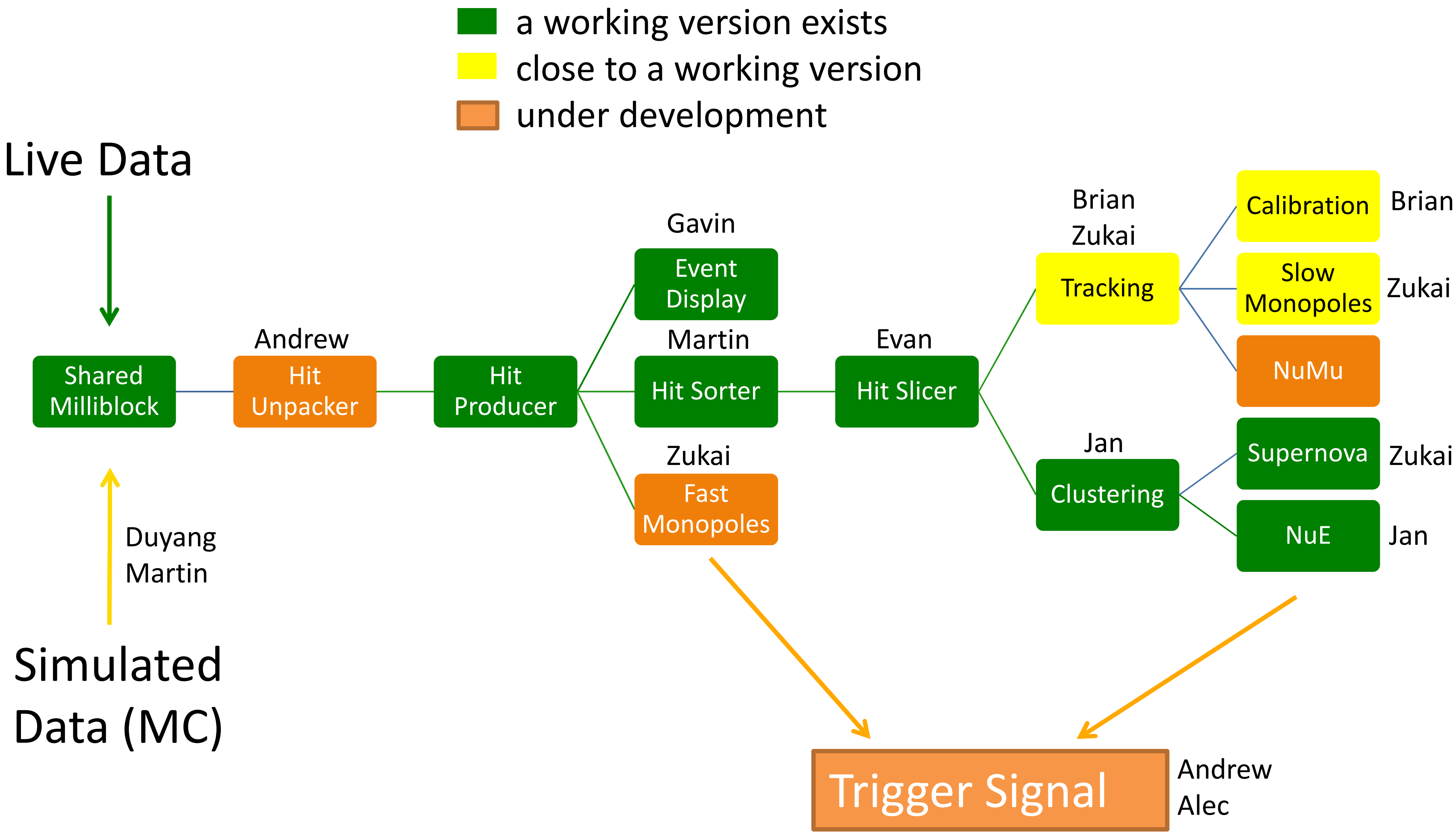
# Simulation: Event Display of Single Monopole



# DAQ & DDT: Architecture



# DDT: Framework

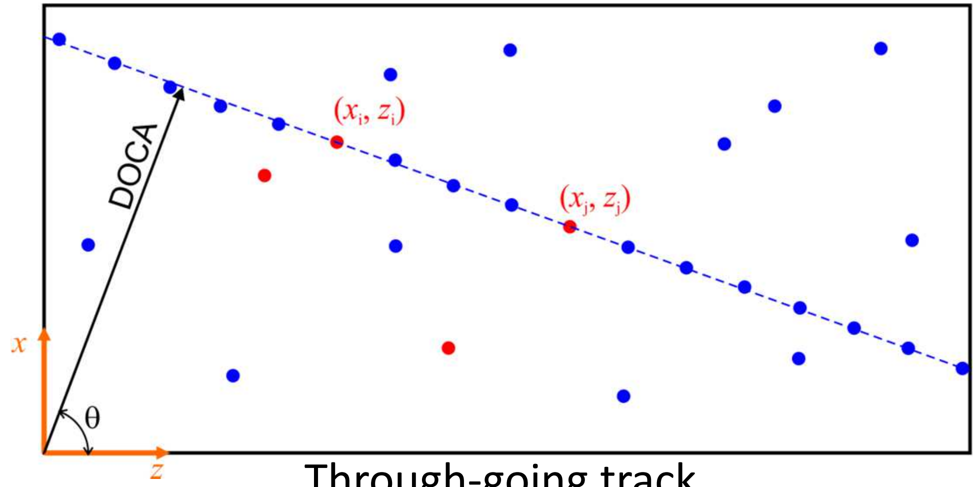




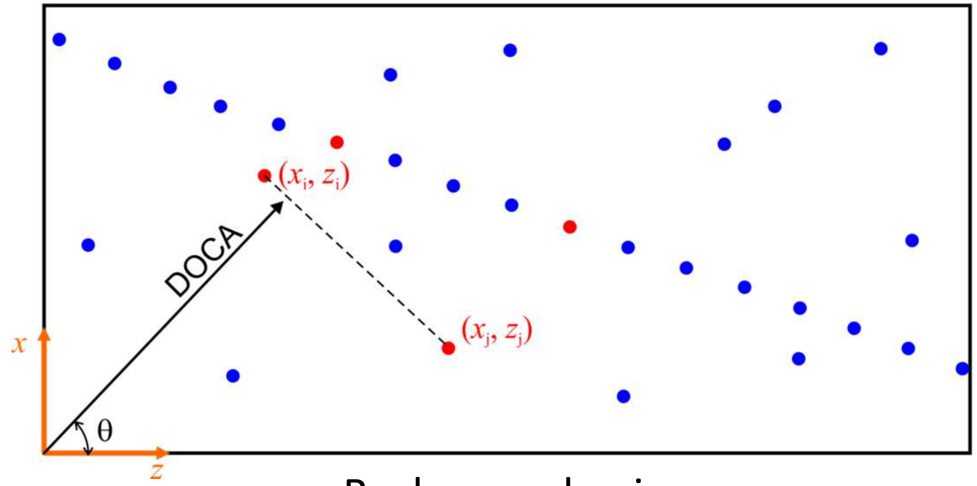

from M. Frank's talk in NOvA Collaboration Mtg Jan 2013

# DDT: PatRec Algorithm

- **"3D" Hough Transform**
- Take all pairs of hits and find three voting parameters for each.
  - DOCA
  - cosθ
  - Ordinary straight track reconstruction algorithm
  - $1/v$
  - This additional parameter implies a timing cut in recognizing a track with certain velocity
- In this 3D Hough space monopoles are identified as clusters of points, "noise" is randomly spread out

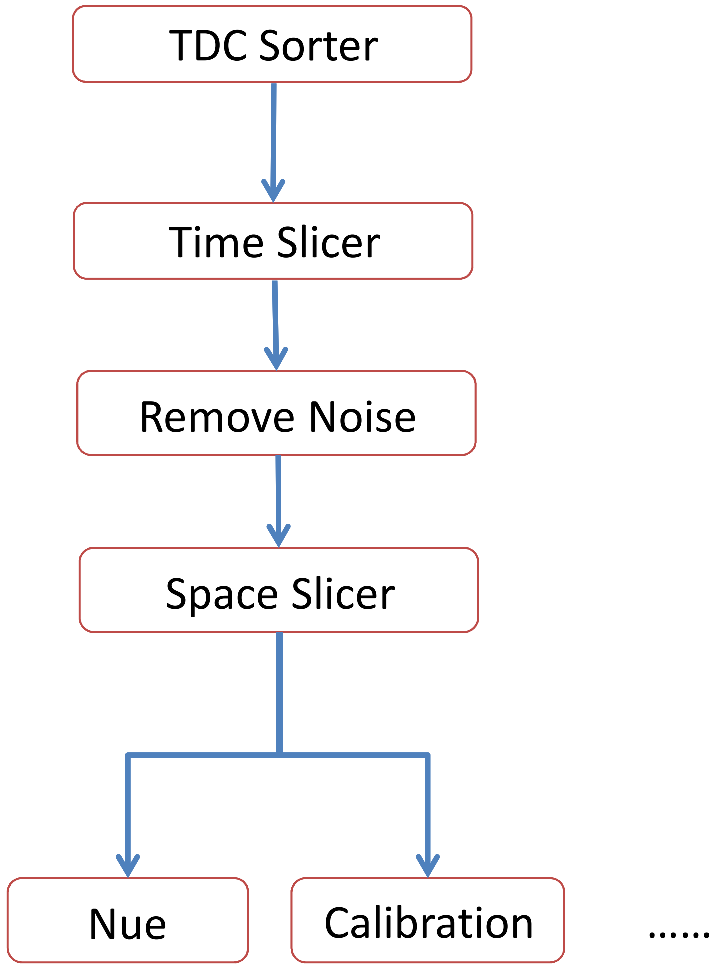



Through-going track.

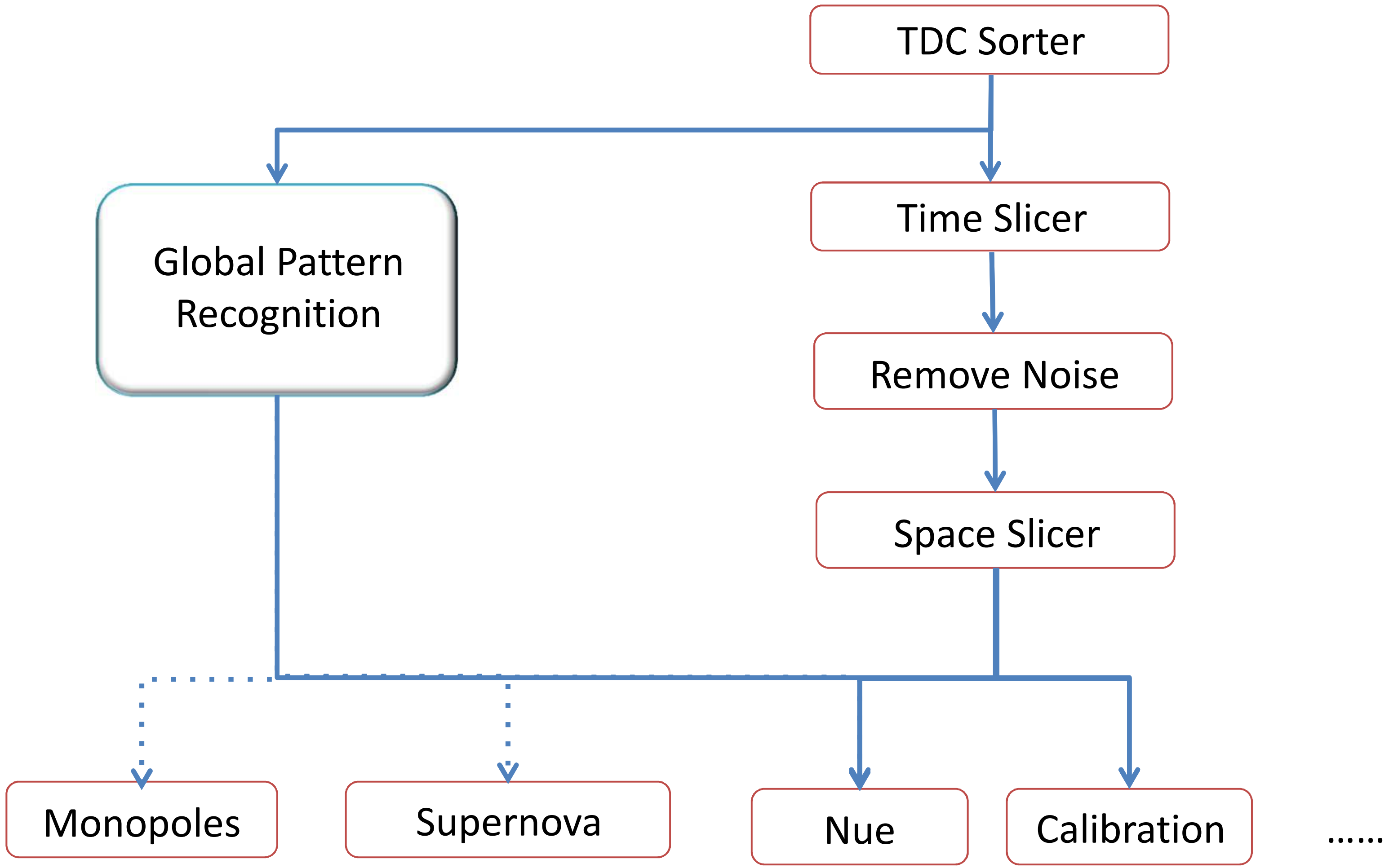



Background pair.

# DDT:Structure of Trigger With PatRec



# DDT: Structure of Trigger With PatRec



# DDT: Algorithm: Logic Flow

**Partitioning**

- Partition by DCM and Time Slice: this step reduces the number of combinations

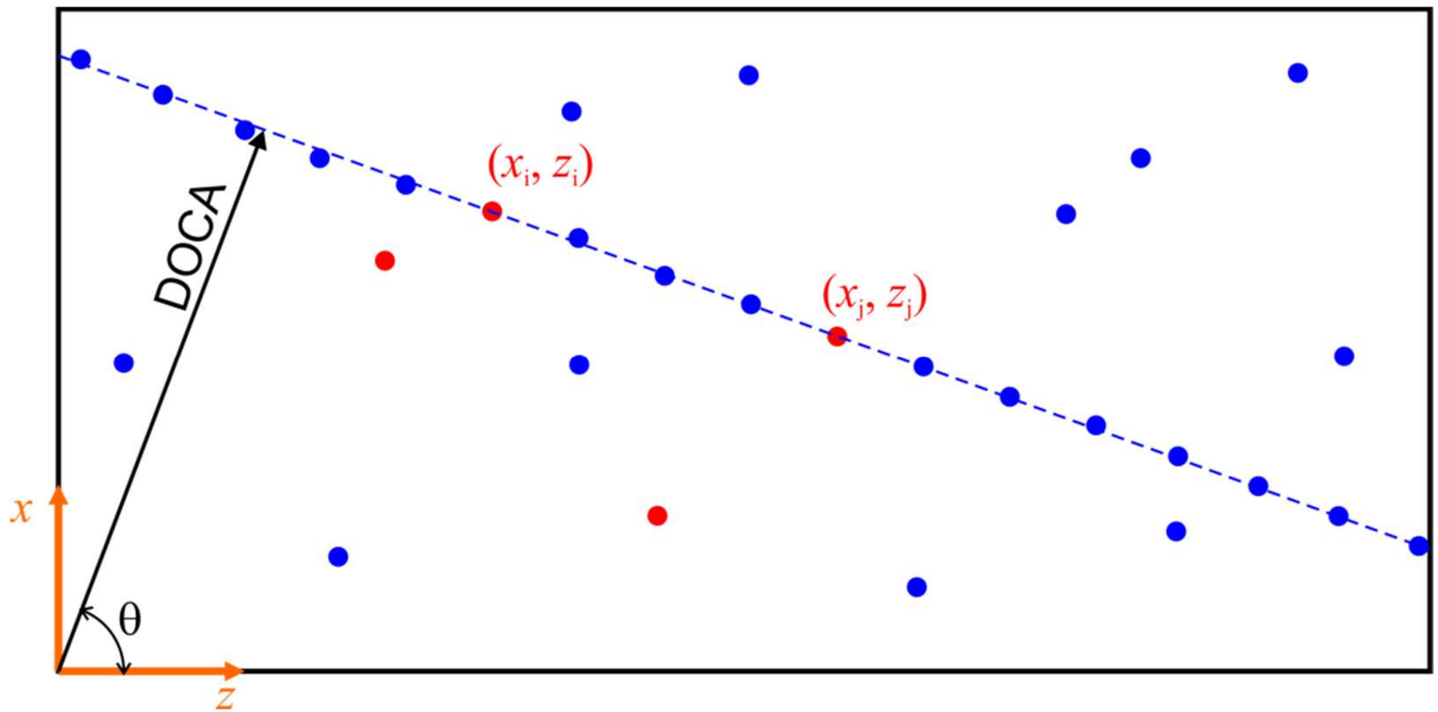
**Making Pairs**

- Looping over all hits combinations
- Calculating the voting parameters for each pair

**Peak Identification**

- Transform results of each pair are put into corresponding containers
- Making selections of each container to register a peak(track)

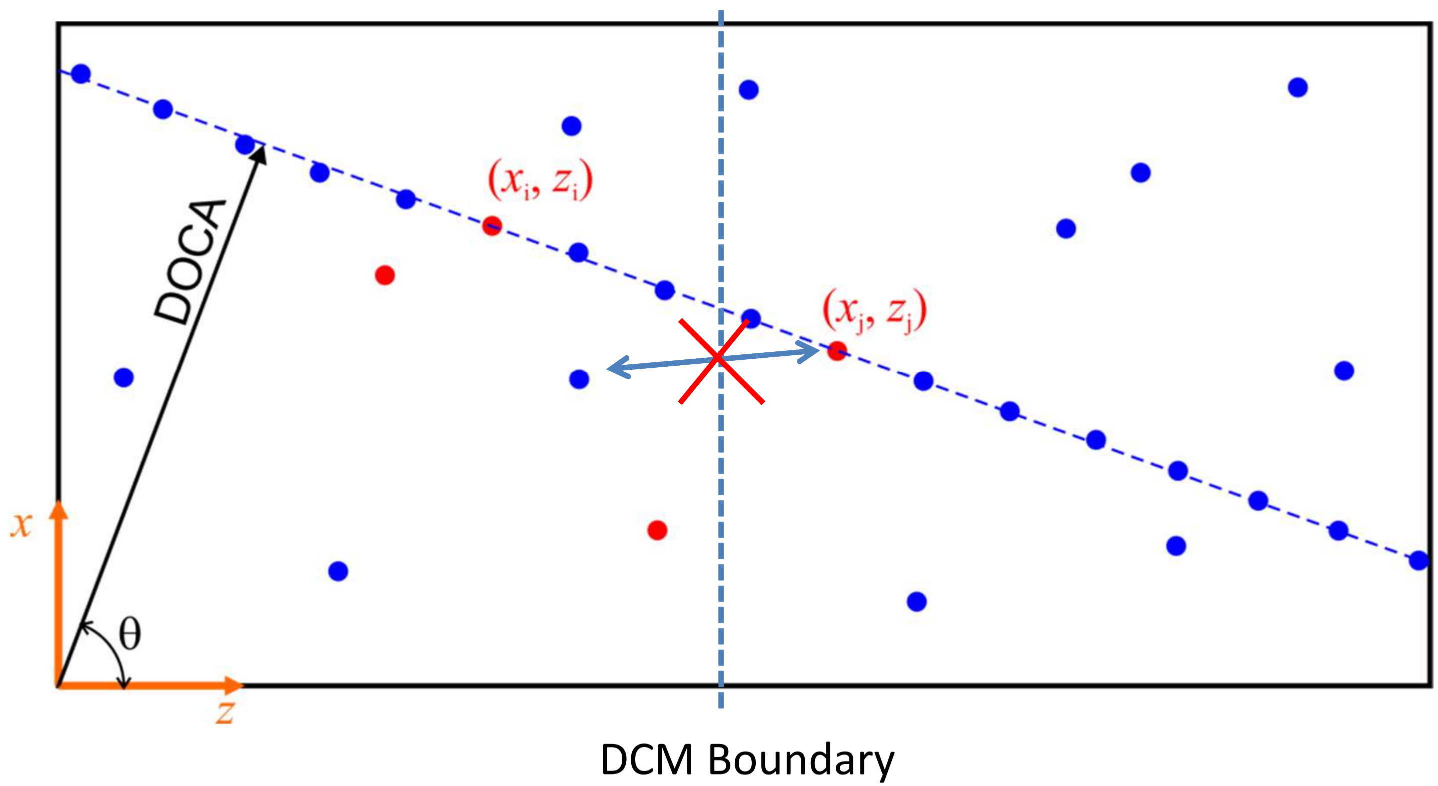
# DDT: Algorithm: Why Partition?




$$C_S(N_s) = N_s(N_s - 1)/2$$

$$C_b(N_s, N_b) = (N_b + N_s)(N_b + N_s - 1)/2 - C_s(N_s) = N_b(N_b + 2N_s - 1)/2$$

# DDT: Algorithm: Why Partition?




$$C_S(N_s) \geq N_s(N_s - 1)/4$$

$$C_b(N_s, N_b) = N_b(N_b + 2N_s - 1)/4$$

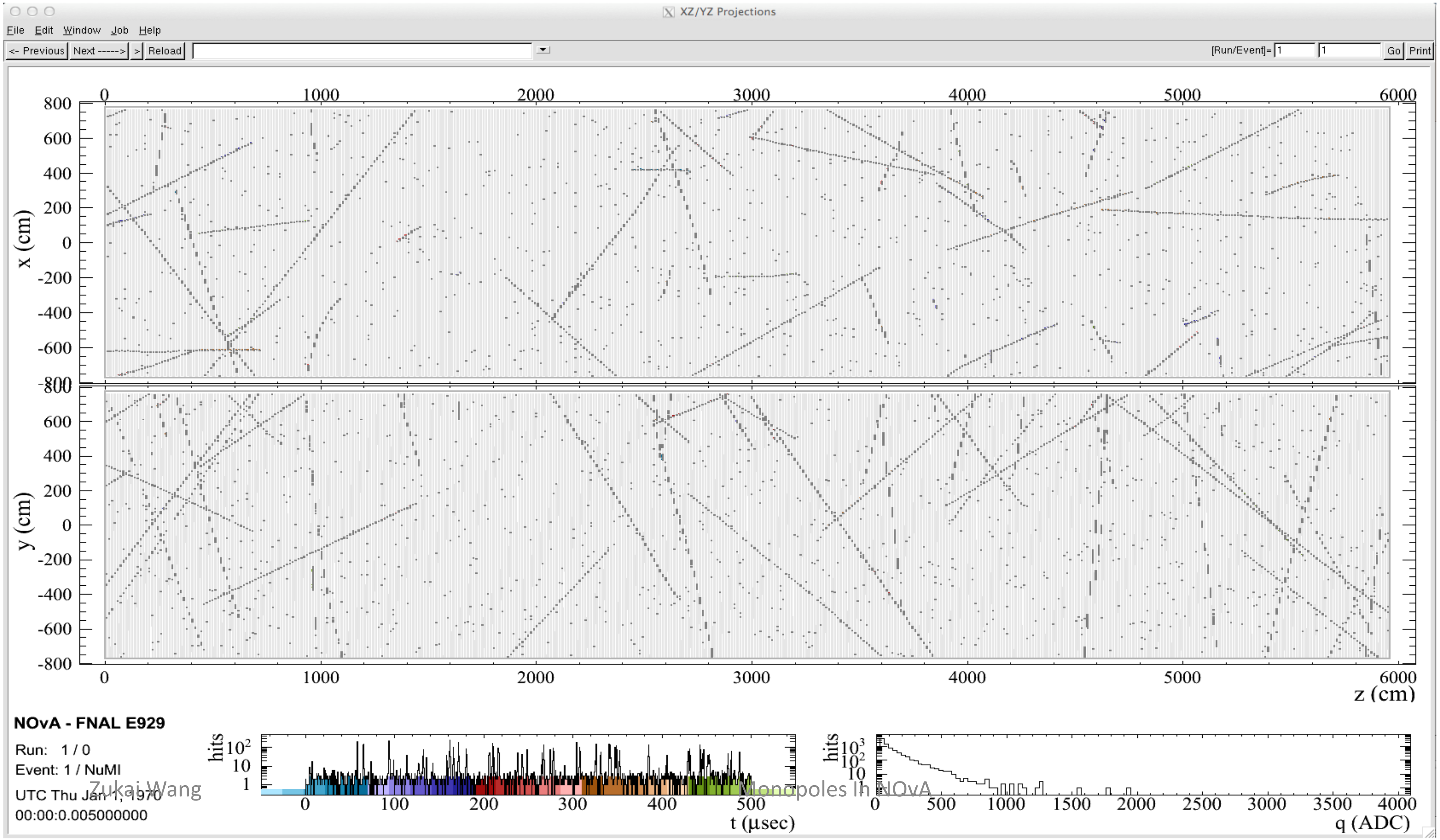
$$\frac{C_S}{C_B}$$

# Algorithm Illustration

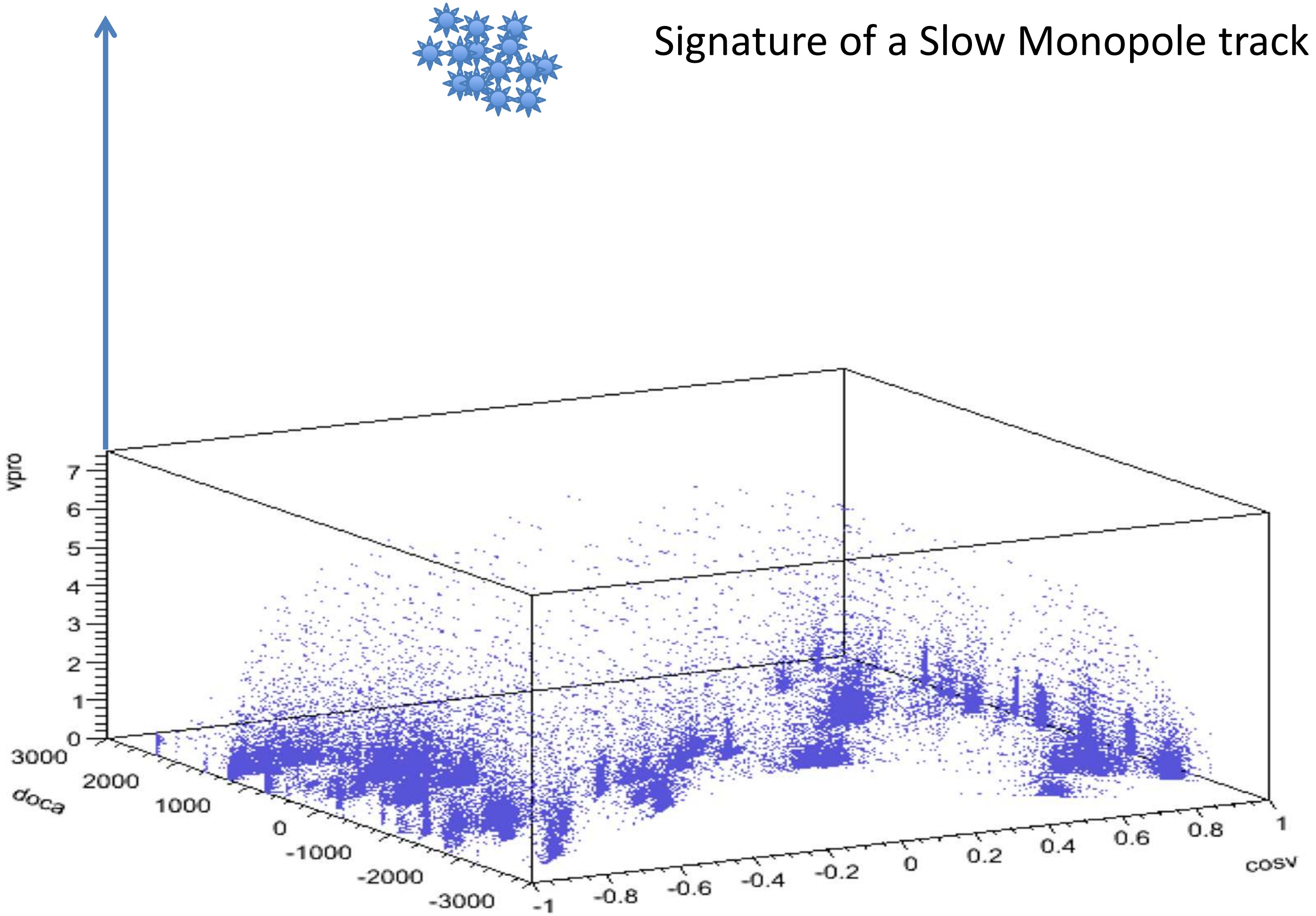
Here is an example of simulated cosmic events in 500 μs, containing ~10,000 hits.

Our goal is to quickly pick out the all the hits belonging to **any** track.

# Illustration: Cosmic Raw Hits

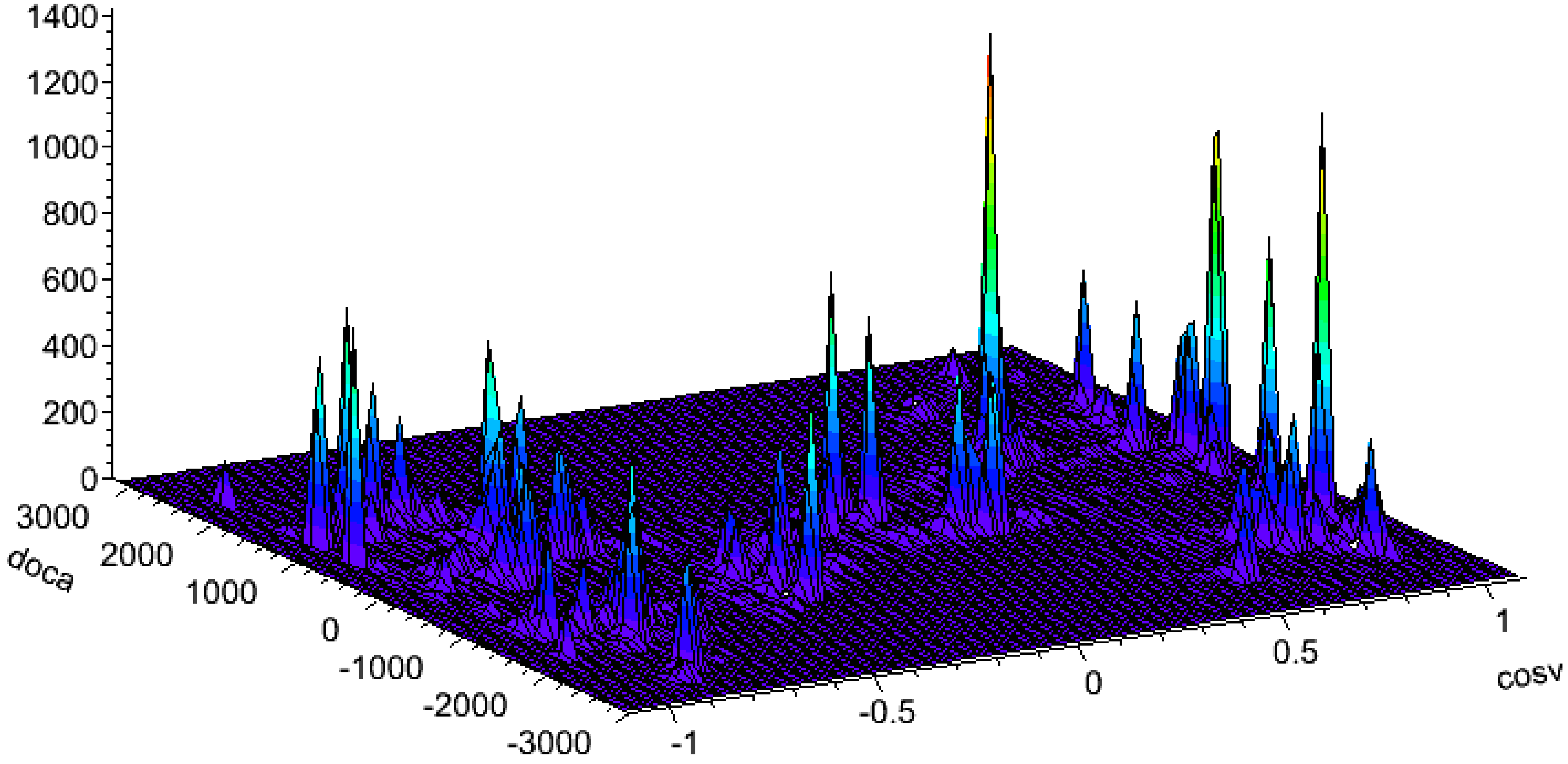


# 3D Hough Space of Cosmic Tracks



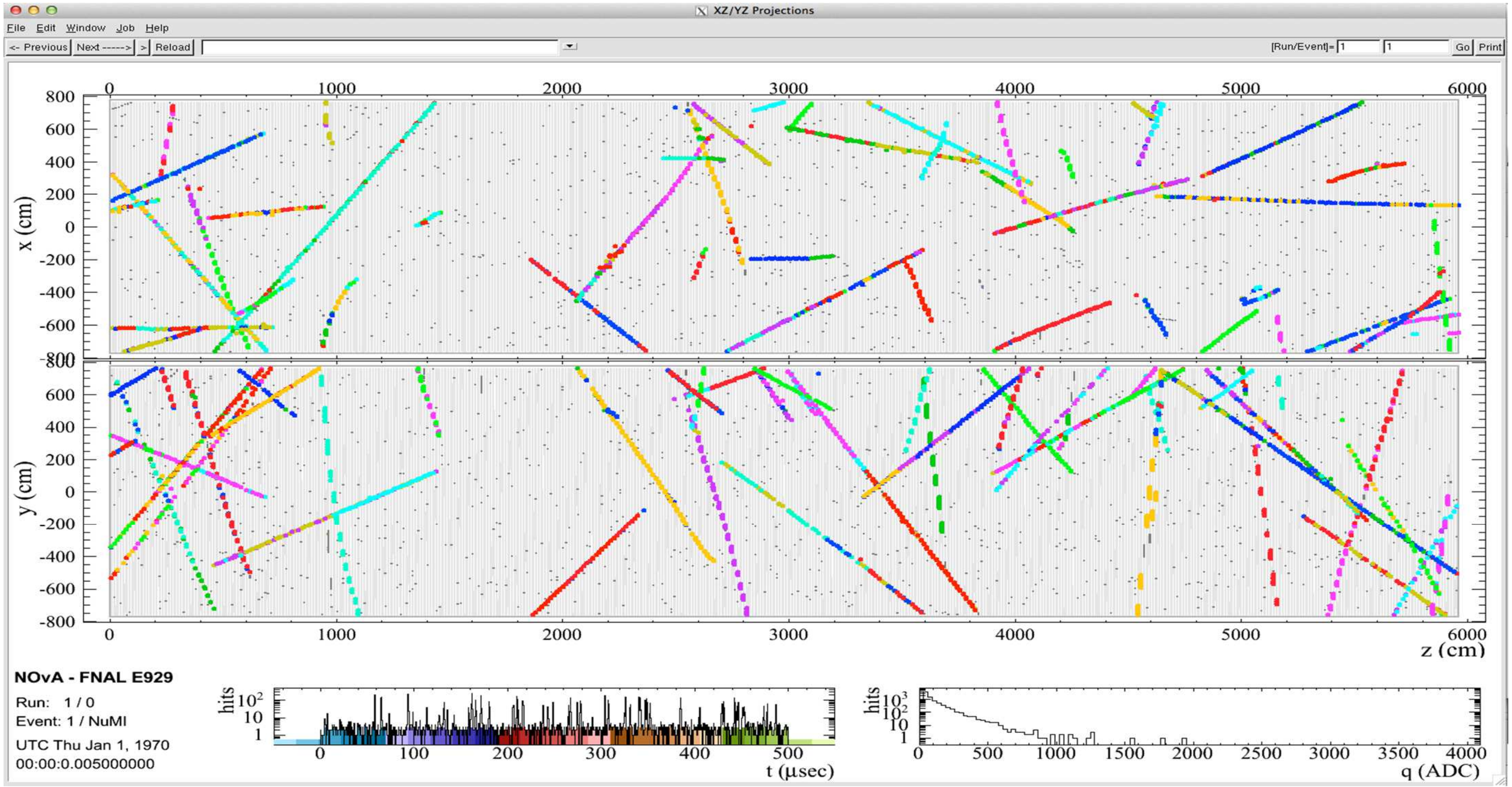

Combinations with Vpro > 7ns/cm have been cut off (supposed to contain all hits of cosmic rays).

# Reconstruction::Algorithm::"Ground Floor" of Hough Space




No Slow Monopoles on this floor

# Illustration: Reconstructed 2D Tracks



# Result

- A test using a cosmic simulation of 50 ms live time has been done: containing ~5,000 cosmic tracks with 1,004,344 hits in FD.
- Timing & Overall Performance:

  Finds all tracks that hit more than 2 planes

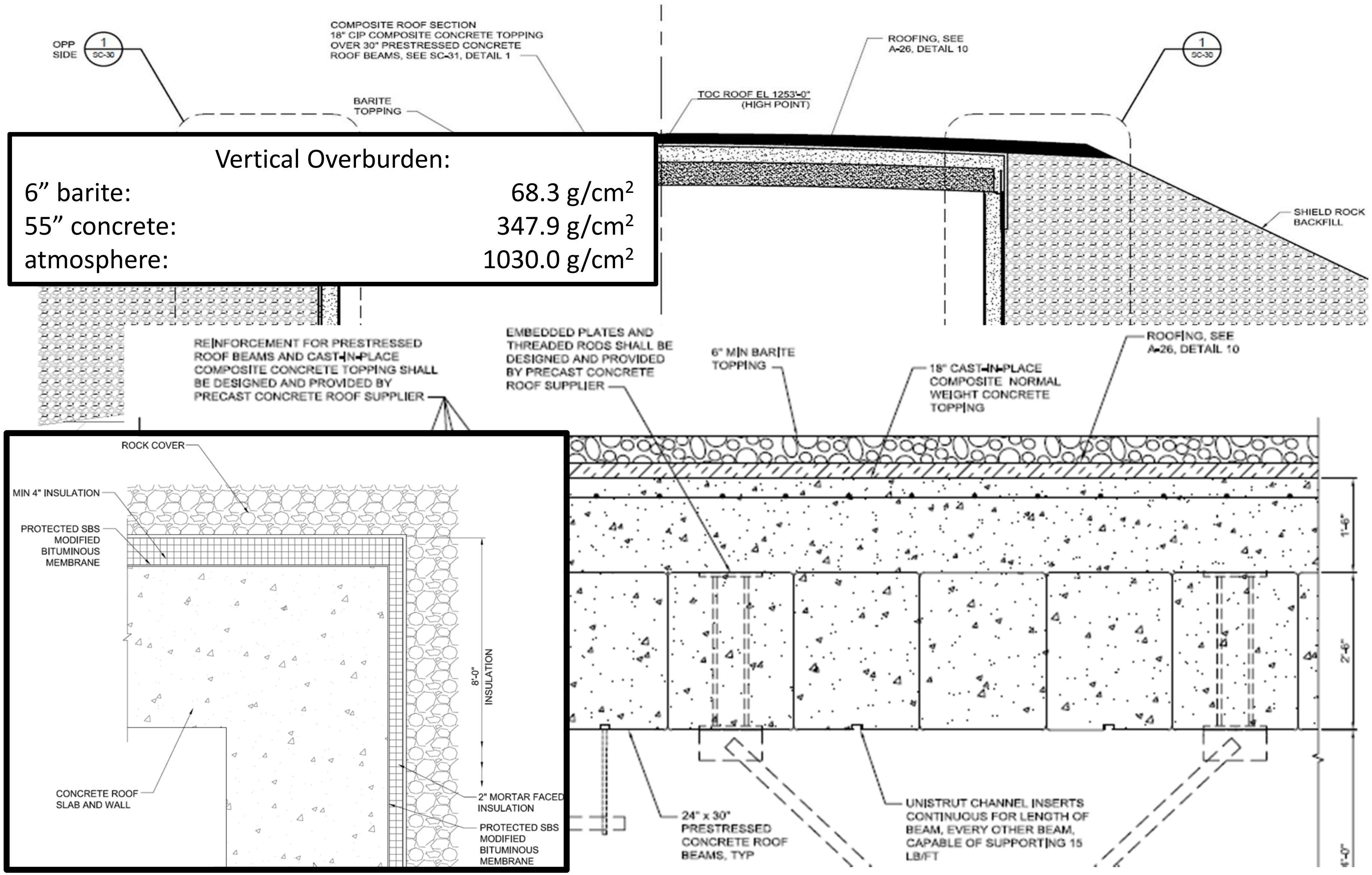
  ~5 times faster than previous reconstruction module

| | # of total tracks | # of tracks longer than 2 planes |
|---|---|---|
| MC Truth | 4840 | 2987 |
| Reco Info | 3272 | 2987(100% reconstructed!) |

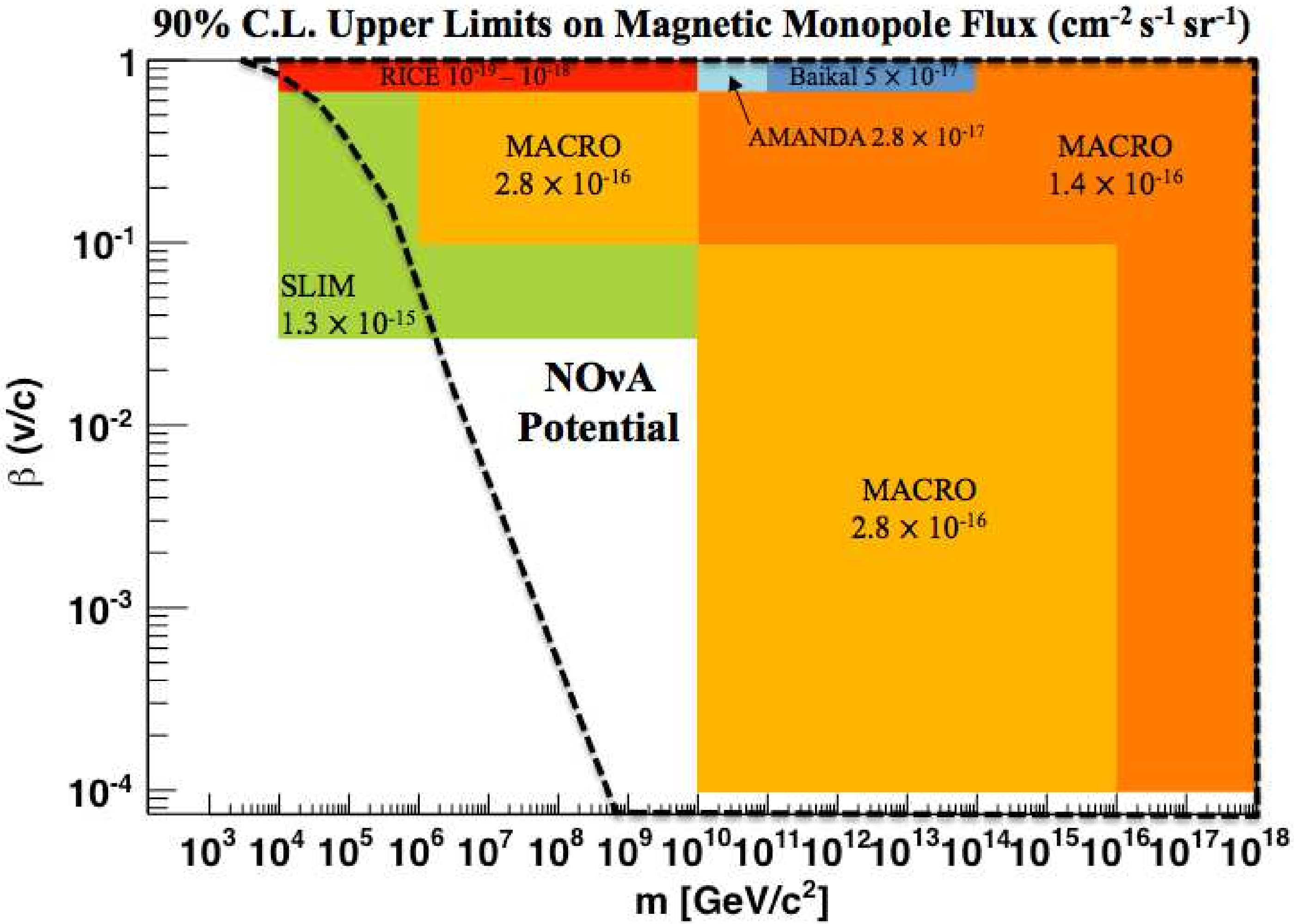
# Limit: NOvA Potential: Overburden

Vertical Overburden:

| | |
|---|---|
| 6” barite: | 68.3 g/cm$^2$ |
| 55” concrete: | 347.9 g/cm$^2$ |
| atmosphere: | 1030.0 g/cm$^2$ |

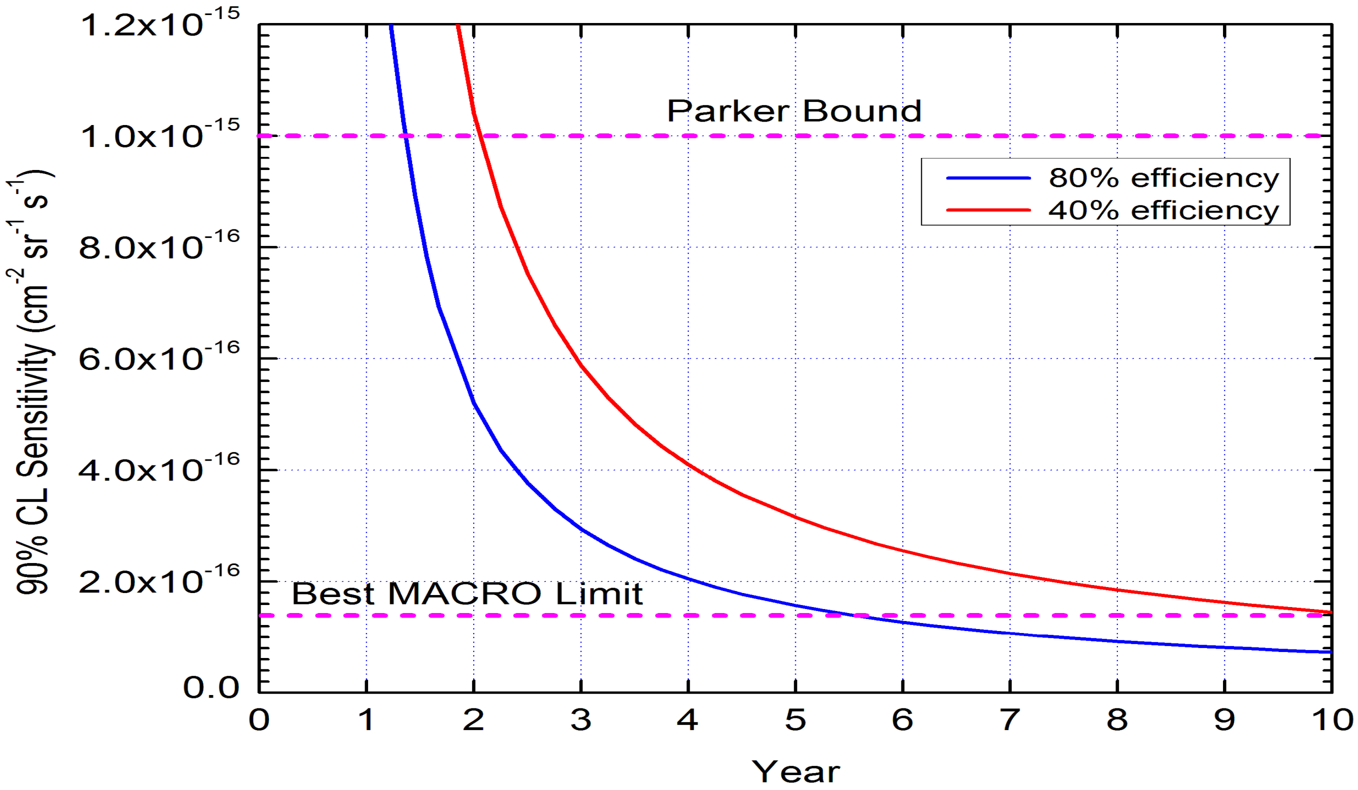


# Limit: NOνA Potential




The NOνA potential curve is generated with a toy MC with a simplified calculation of energy loss of monopoles from outer space.

# Sensitivity: NOvA Potential




- Sensitivity goes as surface area: $\pi FA$, where F is the flux
- Our acceptance is not yet known: we hope we can do better for 80% for high-mass monopoles and perhaps half that for low-mass
- Eventually, if the acceptance is large enough, we can beat MACRO
- Should be able to beat SLIM for intermediate-mass monopoles

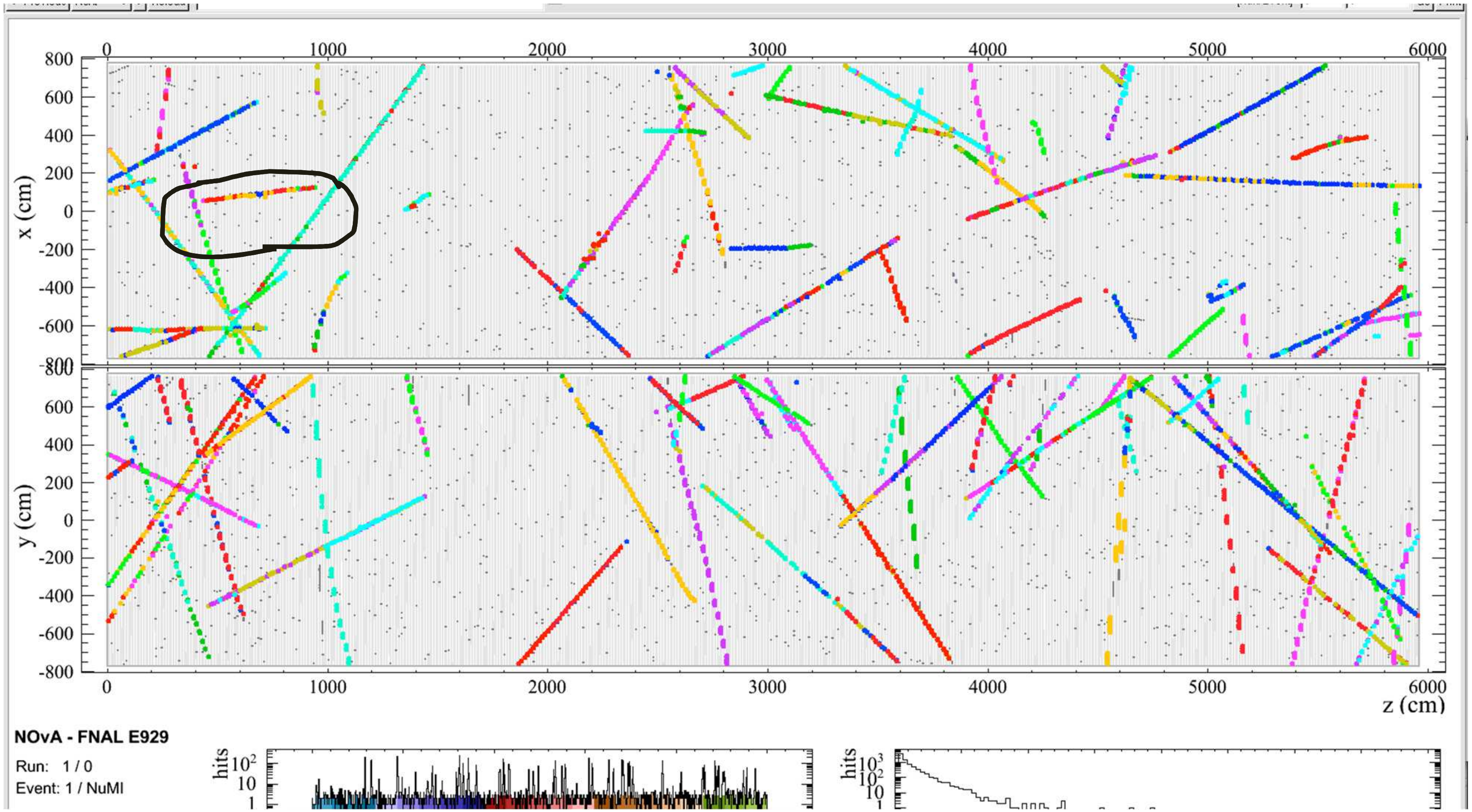
# Outlook: Problems To Be Solved

- Simulation: Overlay Mechanism;
- Reconstruction & Trigger: Current pattern recognition package is still not fast enough;
- Efficiency Estimation

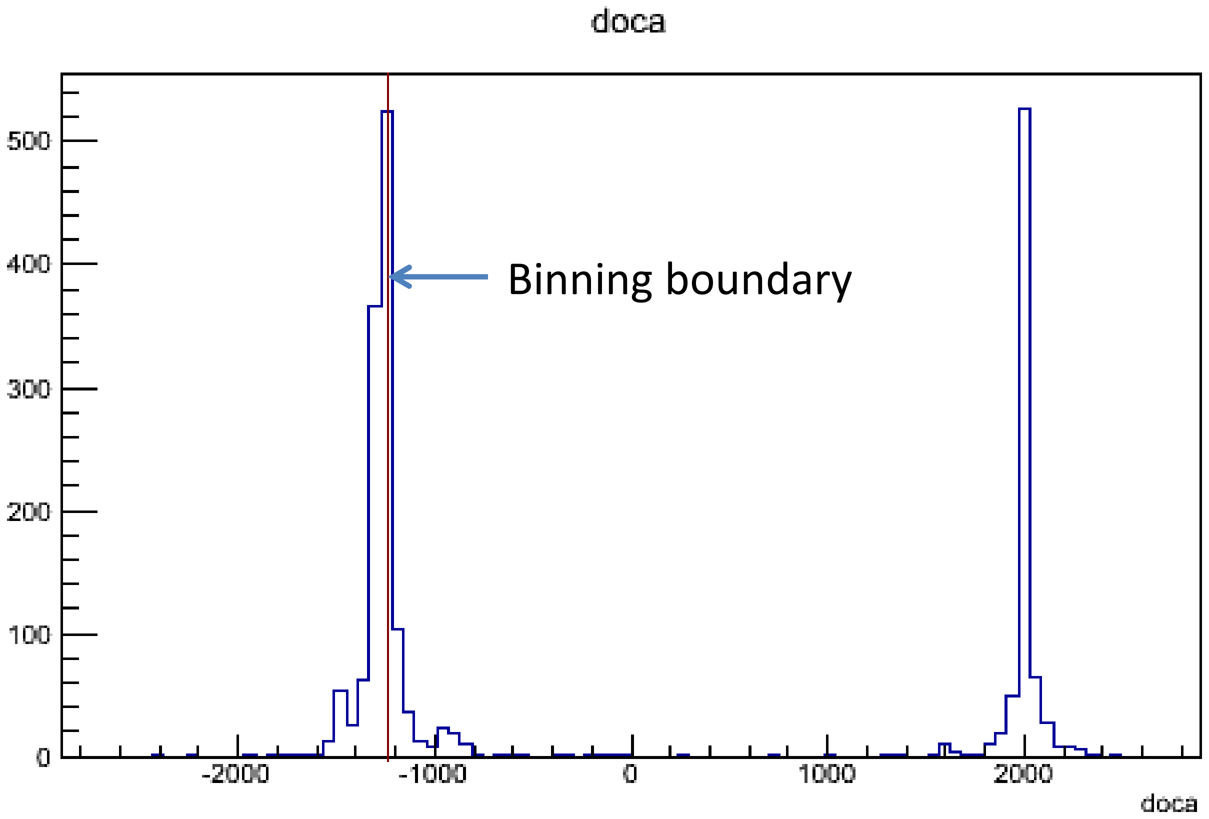
# Acknowledgement


- Vladimir Ivanchenko: advices in using Monopole package of Geant4
- Eric Katsavounidis: his PHD thesis(1995 in Caltech) on MACRO and advices
- Fermilab Artists (Chris Green, Mark F Paterno, etc)
- UVA Folks (Craig Dukes, Craig Group, Ralf Ehrlich, Martin Frank, etc)

# Back Up: Problem 1: Split Tracks

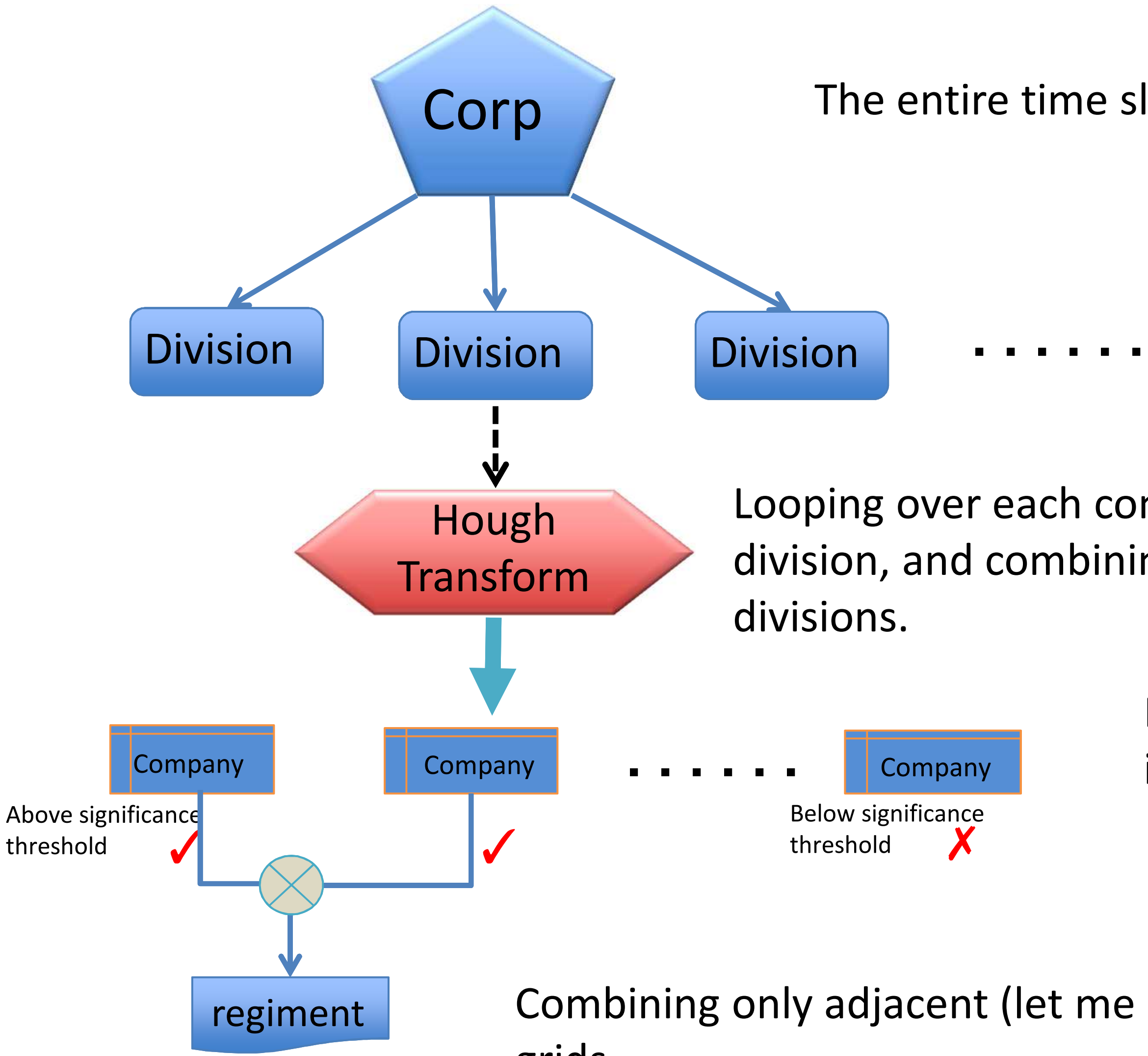


# Back Up: Problem: Split Tracks




No matter how loose the binning is, you always have a chance to split the Hough peak. To prevent looping over all hits again, the binning is pre-determined.

# Potential Solution: Combining Grids




The entire time slice

Partitioned by DCM boundaries

Looping over each combination of cells in the division, and combining all the ballots from all divisions.

Each Hough result is put into the cubic grids:

$$c \times d \times v$$

Combining only adjacent (let me explain this in the next slide) grids

# Defining Adjacent Grids

- Now we have $v \times c \times d$ grids in the cube (v bins in vpro, etc), and each grid can be labeled as:

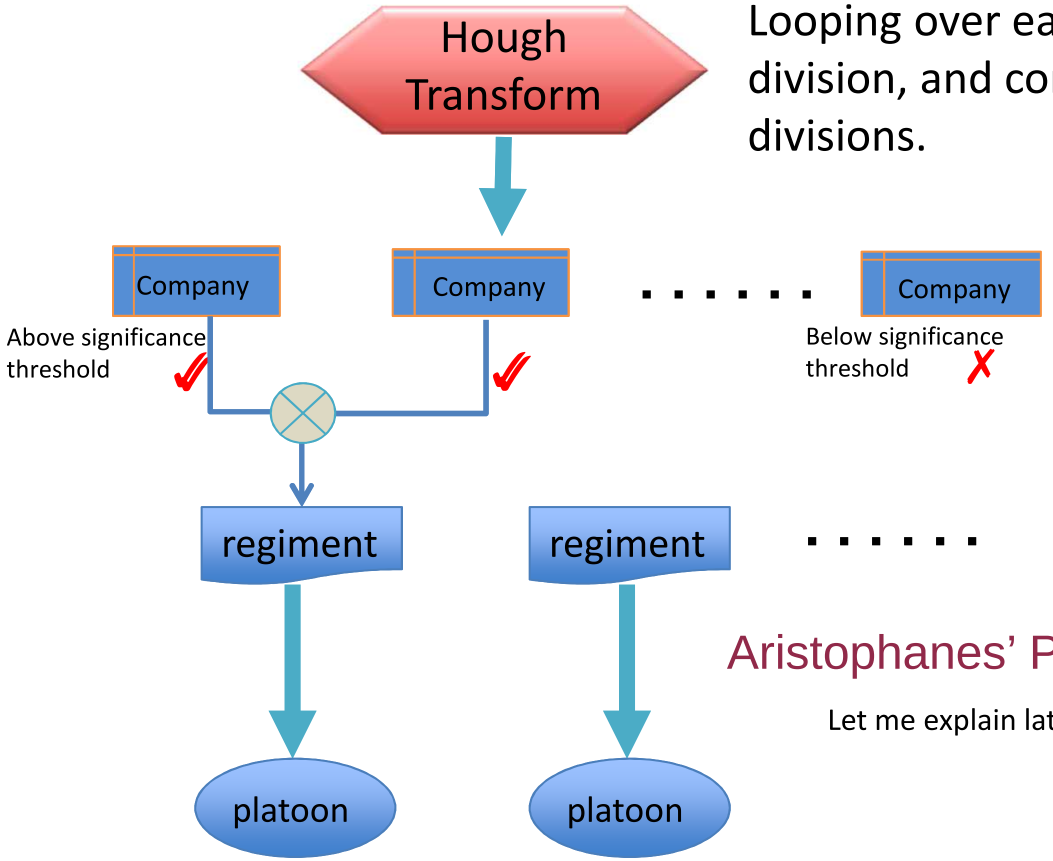
$$(v_i, c_i, d_i)$$

- The distance of the two grids $(v_i, c_i, d_i)$ and $(v_j, c_j, d_j)$ is defined as following:

$$(v_i - v_j)^2 + (c_i - c_j)^2 + (d_i - d_j)^2$$

- Two grids are adjacent to each other if their distance is below 4.

# Algorithm: General Organizing



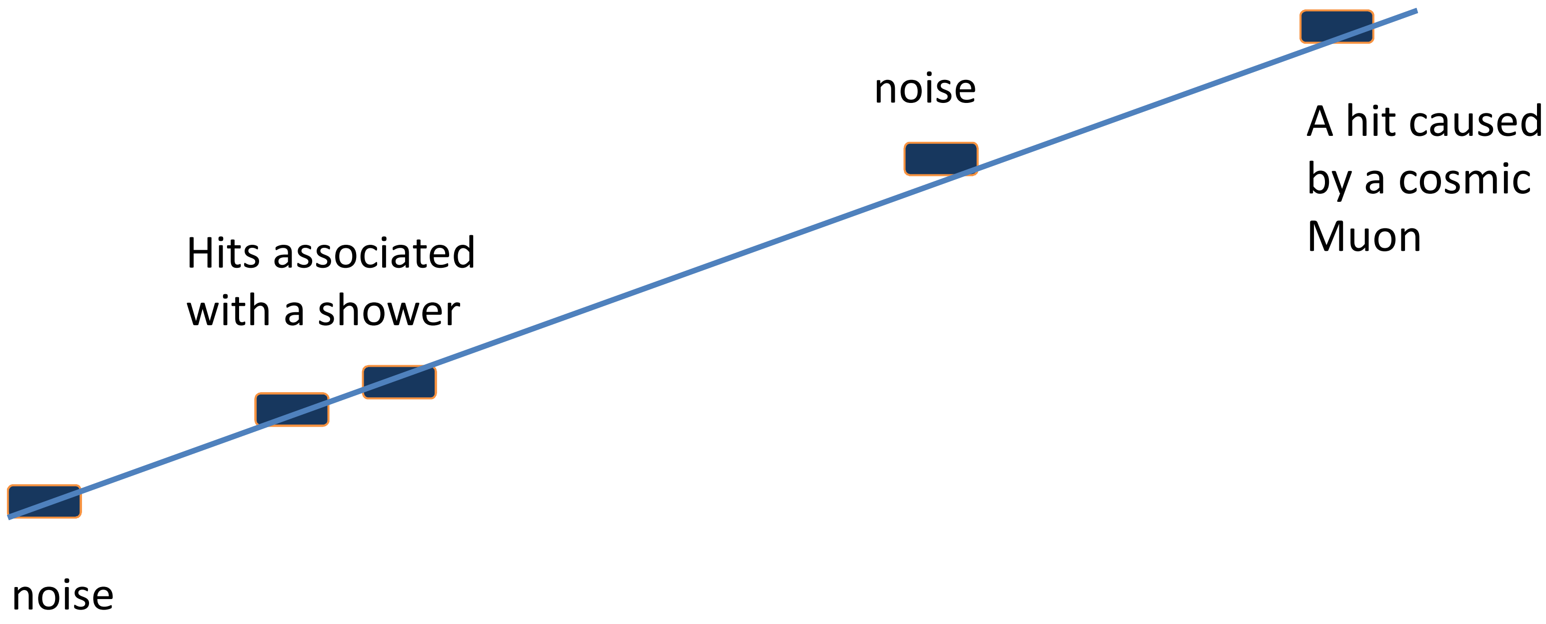

Looping over each combination of cells in the division, and combining all the ballots from all divisions.

Each Hough result is put into the cubic grids:

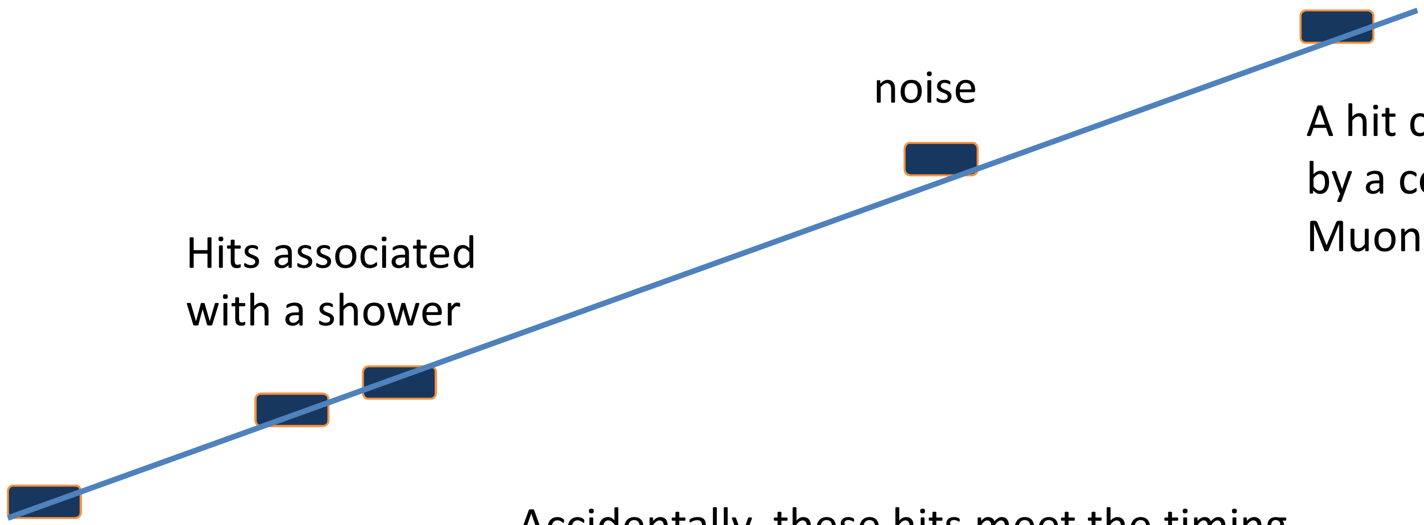
$$c \times d \times v$$

Platoon: hit list, which contains all the hits in a track (if perfectly done).

# Back Up::Problem 2: Fake Tracks

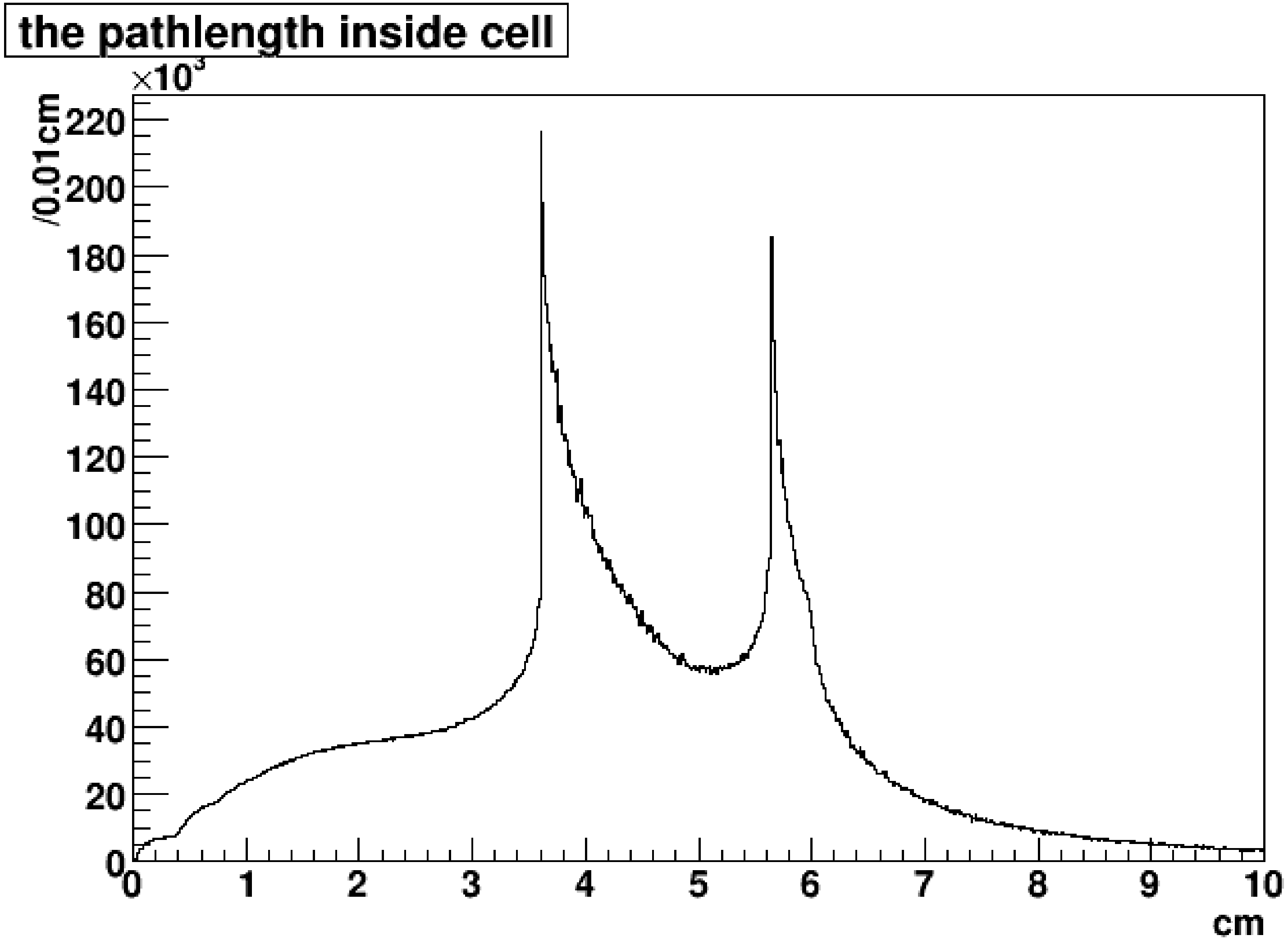


# Back Up: Problem 2: Fake Tracks



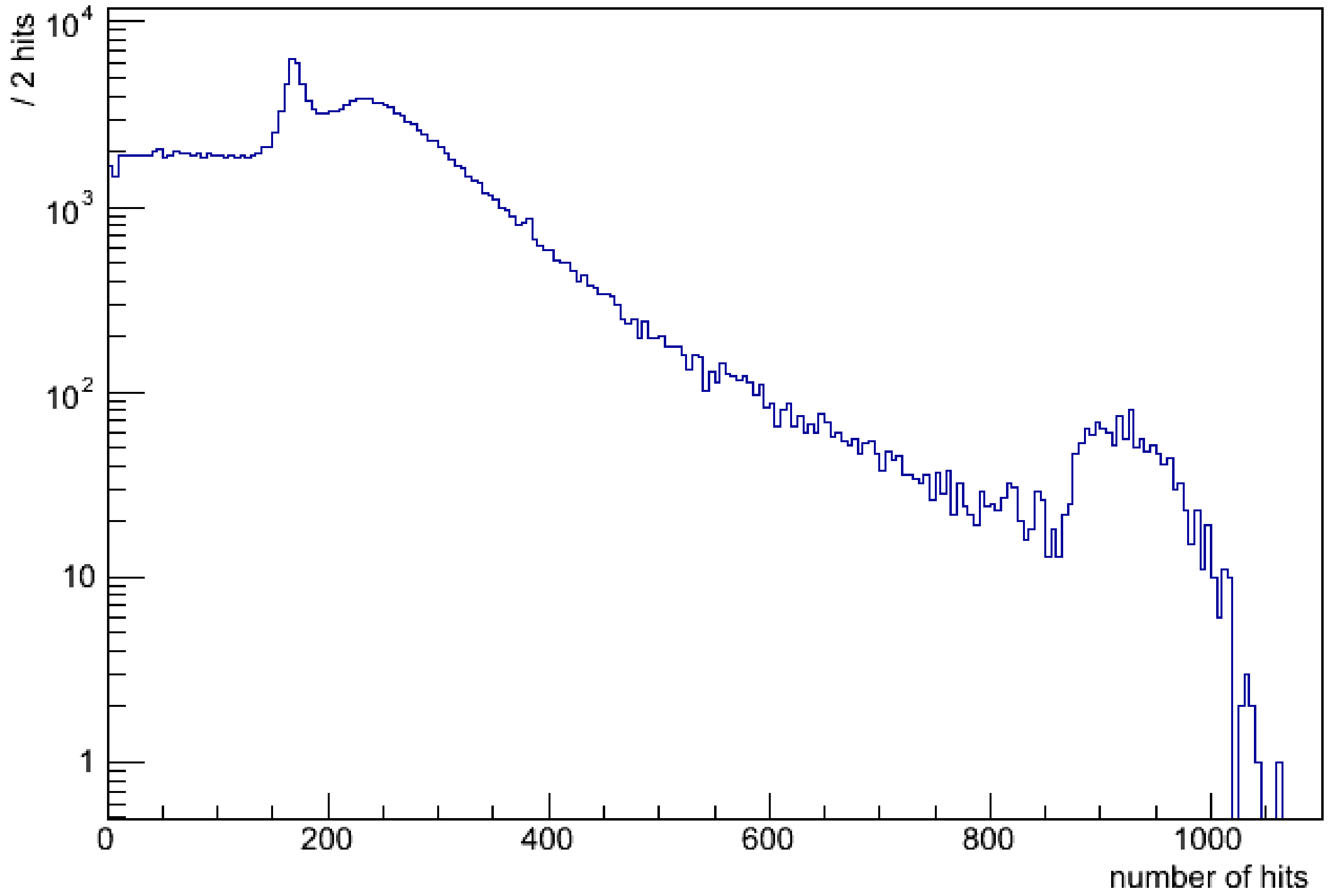

Accidentally, these hits meet the timing requirements to be filled into the same velocity grid.

# Back Up: Path Length Inside Cell



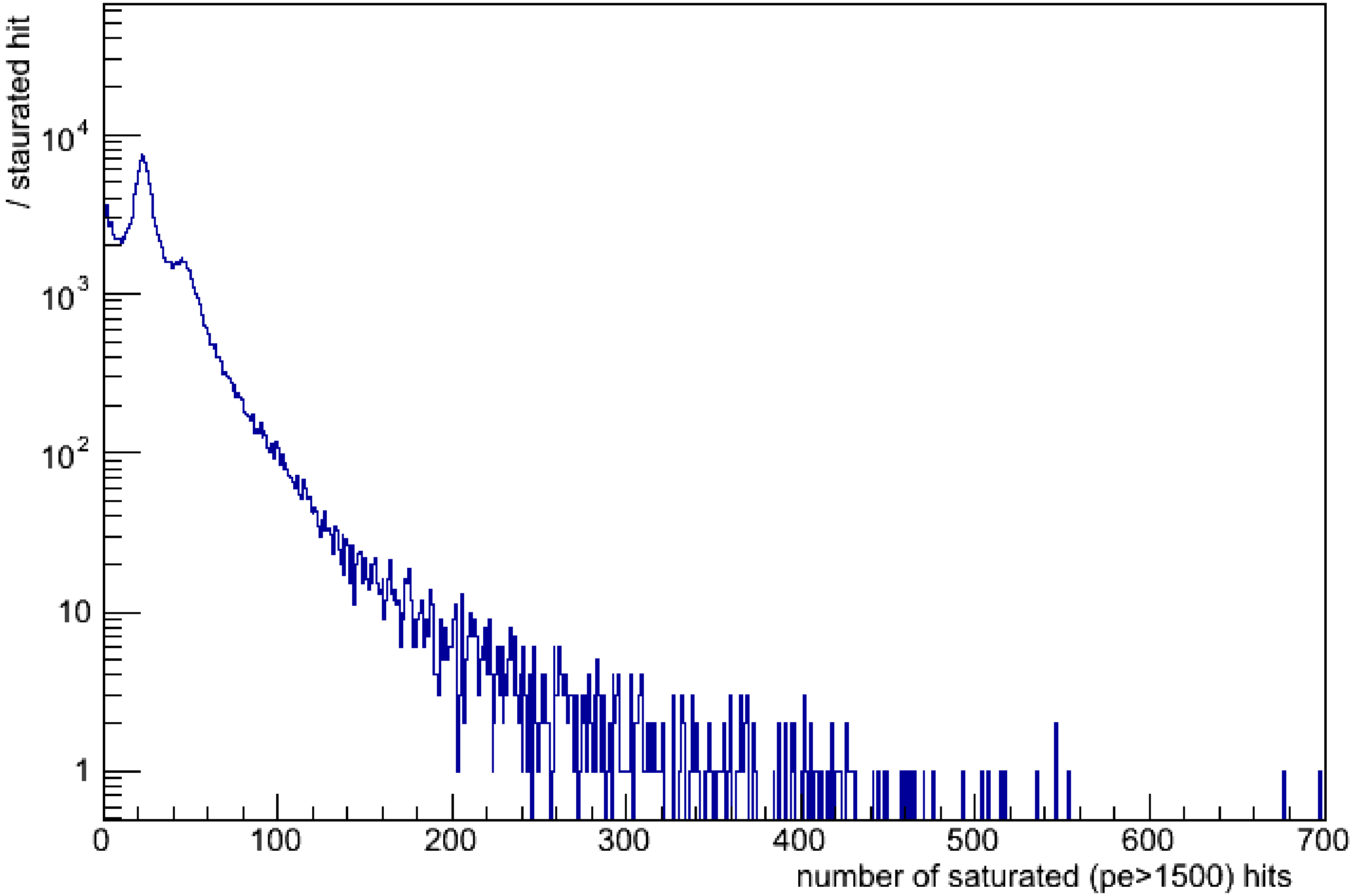

200,000 Isotropic generated monopole's distribution.

# Back Up:Number of Cells Hits per Monopole in FD



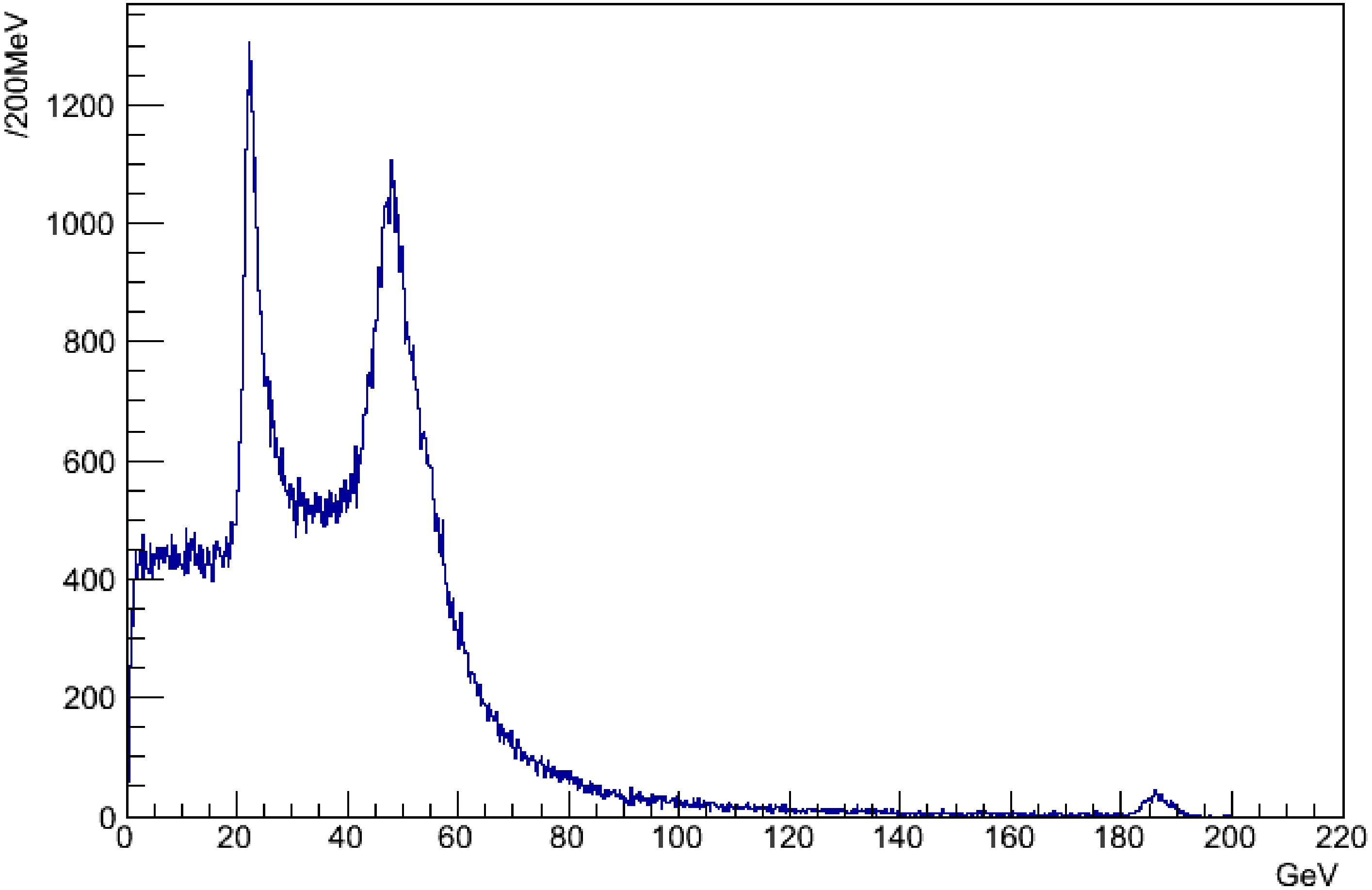

200,000 Isotropic generated monopole's distribution.

# Back Up: Number of Saturated Cells Hits per Monopole in FD



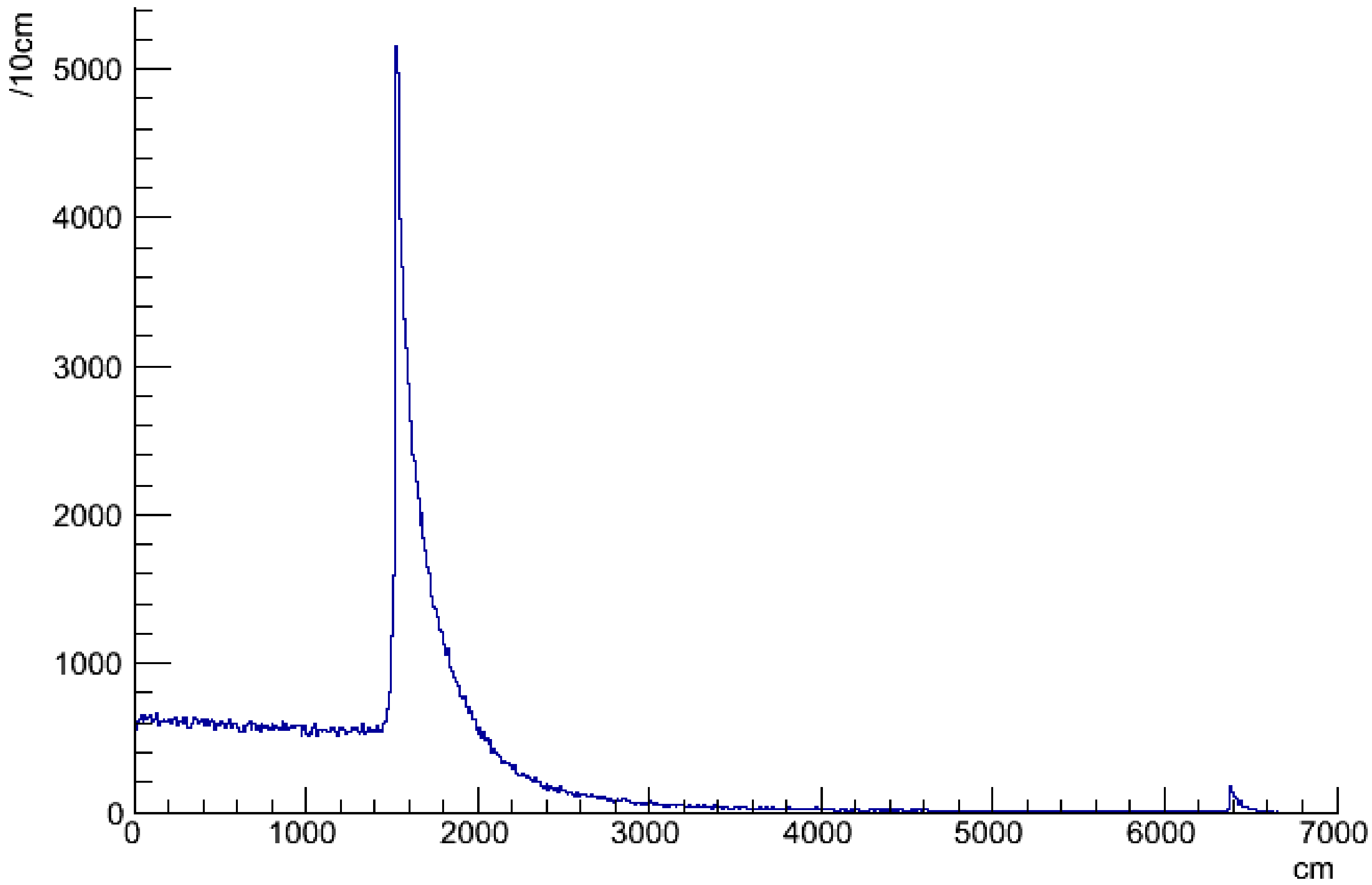

Note: assuming hits with PE > 1500 will be saturated, without considering attenuation.

# Back Up: Energy Deposit per Monopole in FD




200,000 Isotropic generated monopole's distribution.

# Back Up: Path Length Inside FD




200,000 Isotropic generated monopole's distribution.

# Back Up: Monopole Physics: Ahlen Formula

$$\frac{4\pi N_e g^2 e^2}{m_e c^2}[ln\frac{2m_e c^2\beta^2\gamma^2}{I_m} + \frac{K(|g|)}{2} - \frac{1}{2} - \frac{\delta_m}{2} - B(|g|)]$$

Mean Ionization Potential:

$$Im = exp\{\frac{2}{\pi\omega^2}\int_0^\infty \omega\Im[\varepsilon(\omega)]ln\hbar\omega d\omega\}$$

Shifting Parameters:

| $\|g\|/g_D$ | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| B | 0.248 | 0.672 | 1.022 | 1.243 | 1.464 | 1.685 |
| K | 0.406 | 0.346 | 0.346 | 0.346 | 0.346 | 0.346 |

$$g_D = \frac{\alpha}{2}e$$

# Back Up: Monopole Physics:Lindhard Technique

Assuming the monopole passes through a degenerate Fermi gas of non-interacting electrons (this assumption is applicable when the monopole is slow enough: $\beta < 0.01$ ):

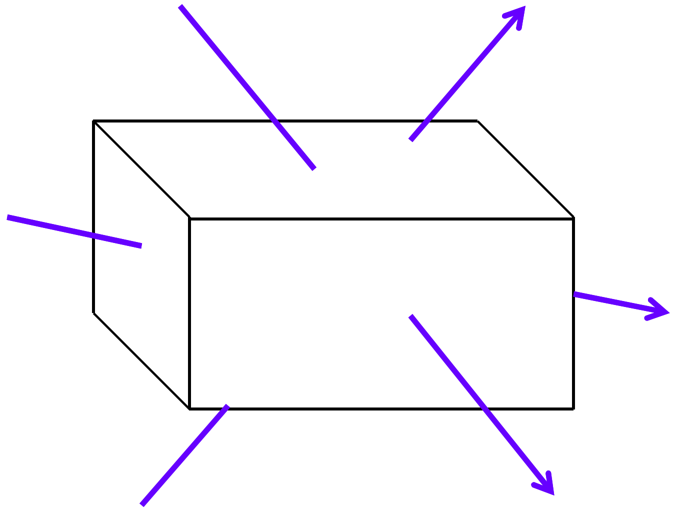
as the monopole's velocity decreases, fewer electrons of the Fermi sea are "available" for ionizing.

$$\frac{dE}{dx} = Cg^2 v$$

$$C = C(\omega_p, v_F)$$

# Monopole Sensitivity

- Sensitivity roughly proportional to detector area
- Very high-mass monopoles come isotropically from all sides, unlike cosmic rays, lower mass monopoles from above
- The observed isotropic rate is: $R = \pi F A \varepsilon$
  - $F$ is the flux of monopoles ($cm^{-2} sr^{-1}$)
  - $A$ is the total detector area ($cm^2$)
  - $\varepsilon$ is the detector efficiency, livetime, etc.
- What we are after is not $R$, but the flux $F = R/\pi A \varepsilon$
- If we see no monopoles assume $R = 2.3$ to get the 90% CL limit:
  - $F(90\%\ CL) = 2.3 / \pi A \varepsilon$



Some areas

| | |
|---|---|
| NOvA: | 4290 $m^2$ |
| MACRO: | 3482 $m^2$ |
| SLIM: | 427 $m^2$ |
| OHYA: | 2000 $m^2$ |

# DDT::Algorithm: General Organizing

- Assume each cell hit is a soldier…

Cell hit ID: 007……700

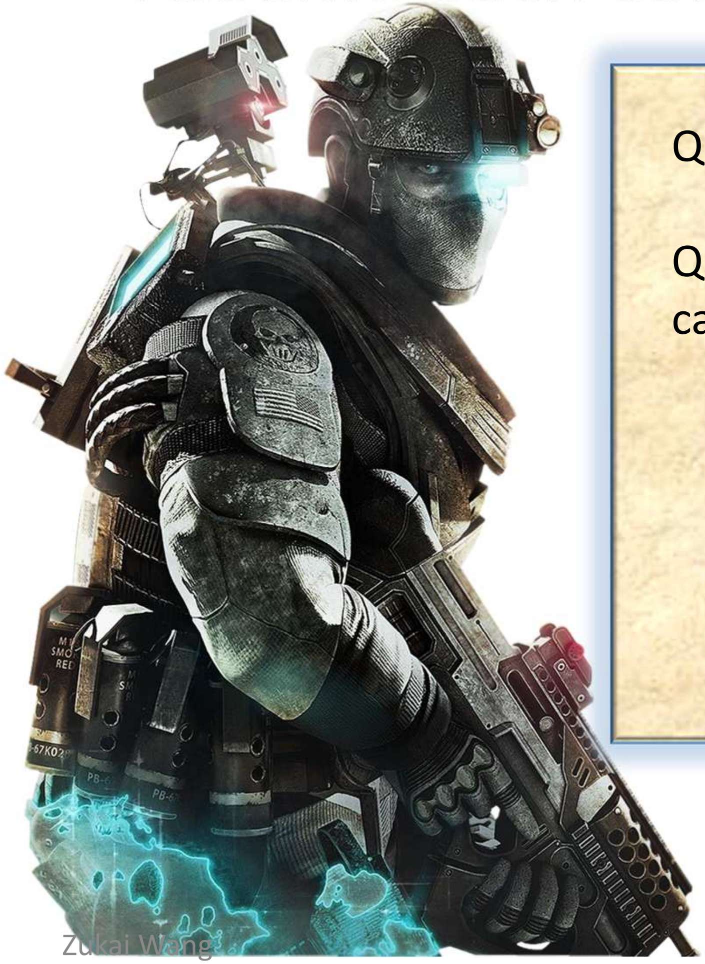
# DDT::Algorithm::Mission

- Assume each cell hit is a soldier…

Quickly identifying all hits from each straight track;

# DDT::Algorithm::Mission

- Assume each cell hit is a soldier…

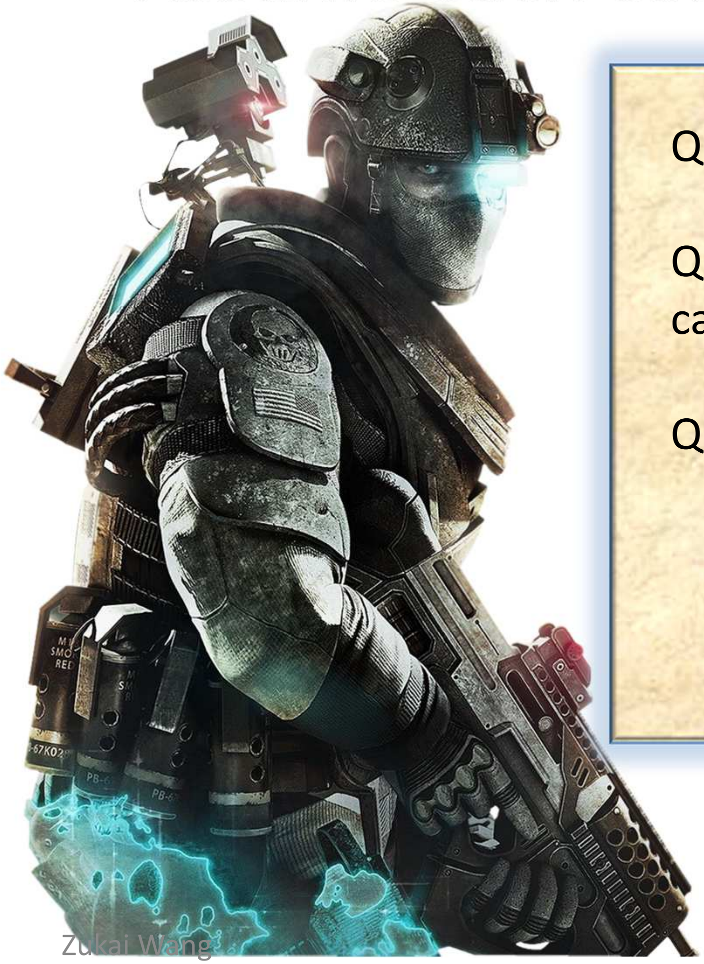


Quickly identifying all hits from each straight track;

Quickly pick out the monopole tracks among them (in case there are some);

# DDT::Algorithm::Mission

- Assume each cell hit is a soldier…

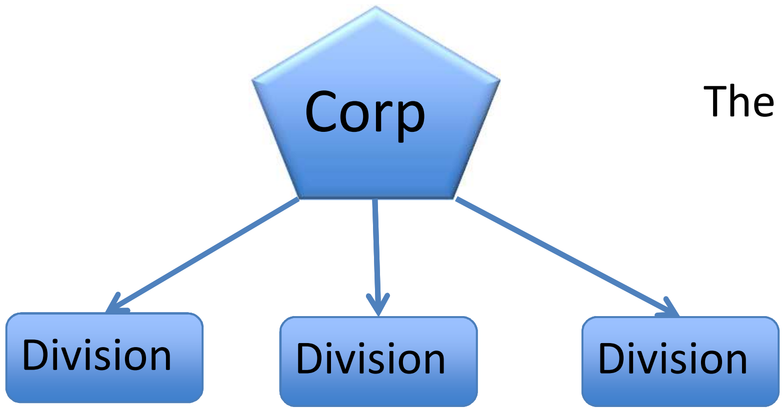


Quickly identifying all hits from each straight track;

Quickly pick out the monopole tracks among them (in case there are some);

Quickly generating a trigger window for each track.

# DDT::Algorithm::Partitioning

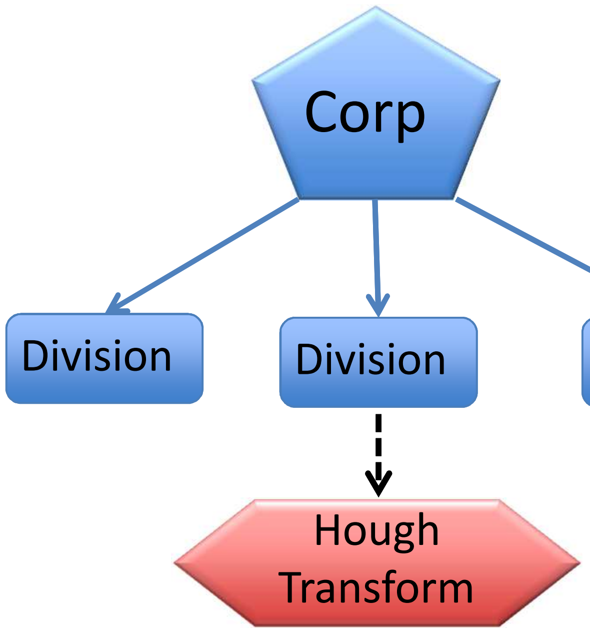



The entire time slice

. . . . . .

Partitioned by DCM boundaries

# DDT::Algorithm::Partitioning

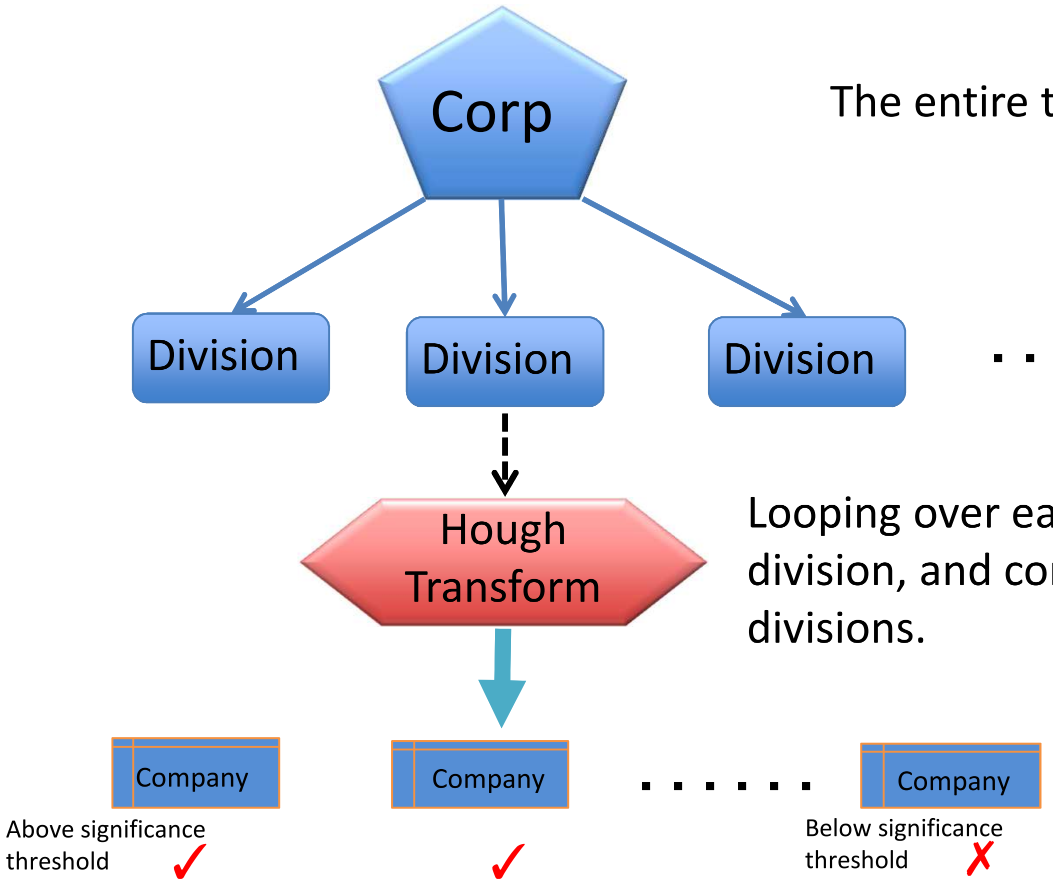



The entire time slice

Partitioned by DCM boundaries

Looping over each combination of cells in the division, and combining all the ballots from all divisions.

# DDT::Algorithm::Mission




The entire time slice

Partitioned by DCM boundaries

Looping over each combination of cells in the division, and combining all the ballots from all divisions.

Each Hough result is put into the cubic grids:

$$c \times d \times v$$

# Algorithm: Aristophanes' Process

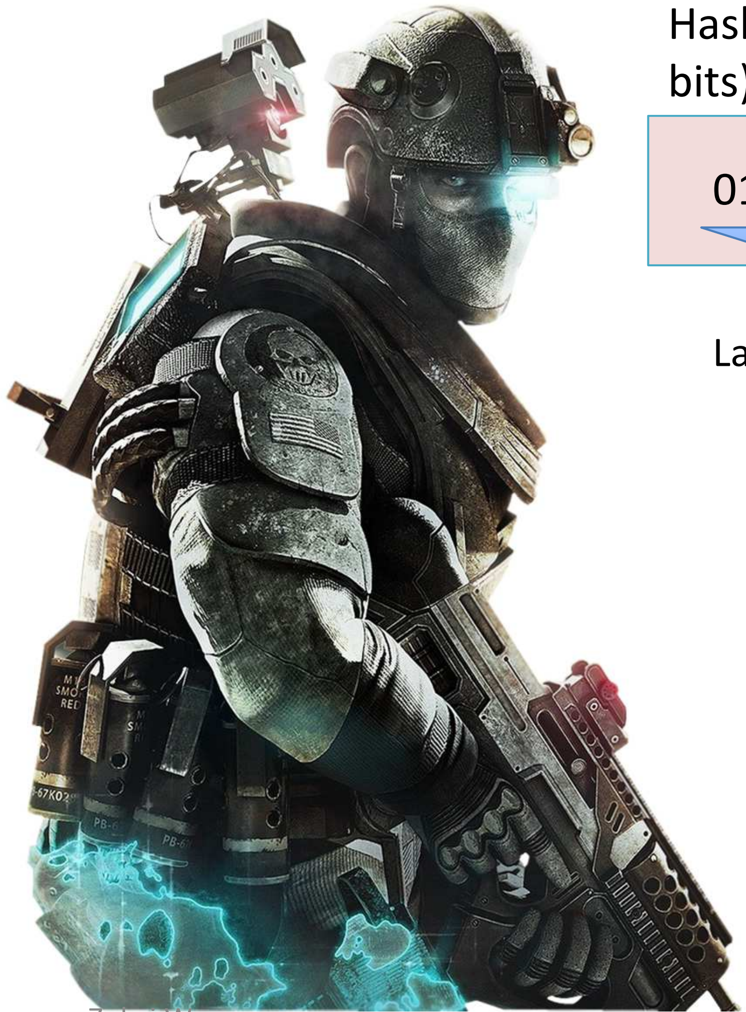
*The statue of Aristophanes and Menander*

Remember, the elements we pushed back into the companies are ***pairs*** of cell hits.

We need to pick out all the individual hits from a regiment to form a platoon.

The challenge is to avoid pushing back a same hit twice. And this is achieved by using "unordered_set".

# Algorithm: Uniqueness



Hash function compares the unique id (64 bits) of every soldier:

0101101…0010001 000101111110 10111001

Last 44 bits of TDC | 12 bits: Plane | 8 bits: Cell

time | space

Almost impossible for an ID collision of 2 hits in a time slice.

Note: this is theoretically possible only when the slice is longer than $2^{18}s$……