Search for Magnetic Monopole with NOvA Far Detector

PPC 2024

October 14 - 18, 2024, IIT Hyderabad, India

Lipsarani Panda

(on Behalf of NOvA Collaboration)

National Institute of Science Education and Research, Bhubaneswar

Outline

1. Motivation for the magnetic monopole search
2. NOvA detectors at Fermilab
3. Monopole search strategy at NOvA far detector
4. NOvA and other experiments sensitivity for magnetic monopoles

Motivation

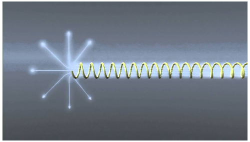
Quantization of electric charge

P. Dirac, in 1931, provided an elegant argument for the quantisation of electric charge in the presence of a magnetic monopole.

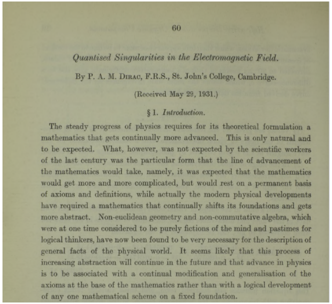
$$eg = [\frac{\hbar c}{2}]n \rightarrow e = [\frac{\hbar c}{2g}]n \text{ , n = 1,2,3 ...}$$

$$\text{For n=1 , } g_D = 68.5e$$

'g' is the magnetic charge, 'e' is the electron charge, and g_D represent the Dirac charge.



Dirac string



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Quantised Singularities in the Electromagnetic Field.

By P. A. M. Dirac, F.R.S., St. John's College, Cambridge.

(Received May 29, 1931.)

§ 1. *Introduction.*

The steady progress of physics requires for its theoretical formulation a mathematics that gets continually more advanced. This is only natural and to be expected. What, however, was not expected by the scientific workers of the last century was the particular form that the line of advancement of the mathematics would take, namely, it was expected that the mathematics would get more and more complicated, but would rest on a permanent basis of axioms and definitions, while actually the modern physical developments have required a mathematics that continually shifts its foundations and gets more abstract. Non-euclidean geometry and non-commutative algebra, which were at one time considered to be purely fictions of the mind and pastimes for logical thinkers, have now been found to be very necessary for the description of general facts of the physical world. It seems likely that this process of increasing abstraction will continue in the future and that advance in physics is to be associated with a continual modification and generalisation of the axioms at the base of the mathematics rather than with a logical development of any one mathematical scheme on a fixed foundation.

Magnetic monopoles are expected to be highly ionizing due to such high charge.

Motivation (continued)

Restore symmetry between electricity and magnetism

- **Maxwell**, in 1873, explained the connection between electricity and magnetism.
- Existence of a magnetic monopole would restore symmetry in Maxwell's equation.

Laws	W/O Monopole	With Monopole
Gauss's law	$\nabla \cdot \overrightarrow{D} = 4\pi\rho_e$	$\nabla \cdot \overrightarrow{D} = 4\pi\rho_e$
Gauss's law	$\nabla \cdot \overrightarrow{B} = 0$	$\nabla \cdot \overrightarrow{B} = 4\pi\rho_m$
Faraday's law	$-\nabla \times \overrightarrow{E} = \frac{1}{c}\frac{\partial B}{\partial t}$	$-\nabla \times \overrightarrow{E} = \frac{1}{c}\frac{\partial B}{\partial t} + \frac{4\pi}{c}J_m$
Ampère's law	$\nabla \times \overrightarrow{H} = \frac{1}{c}\frac{\partial D}{\partial t} + \frac{4\pi}{c}J_e$	$\nabla \times \overrightarrow{H} = \frac{1}{c}\frac{\partial D}{\partial t} + \frac{4\pi}{c}J_e$

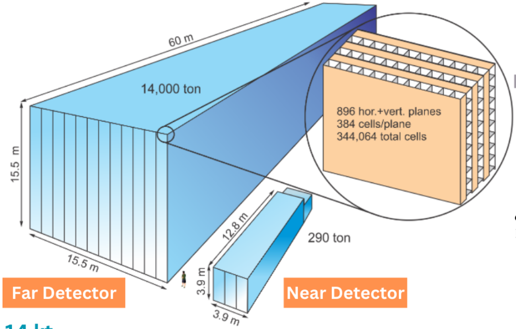
Monopole in Grand Unified Theories

- **'t Hooft and Polyakov**, in 1974, discovered that monopoles are fundamental solutions in GUTs.
- GUT monopoles are superheavy with mass $10^{17} GeV/c^2$, not producable in particle accelerators.

NOvA (NuMI Off-Axis ν_e Appearance) Detectors

NOvA primarily studies neutrino oscillation. **NOvA Far Detector has remarkable capabilities to search for monopoles and other subluminal exotic particles.**

Two scintillator detectors

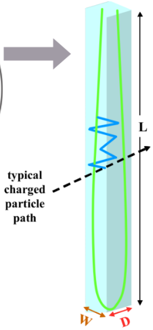


Far Detector

14 kt,
on the surface,
810 km from
Fermilab

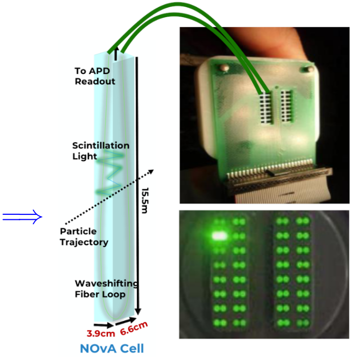
Near Detector

290 t,
105 m underground,
at the Fermilab



NOvA Cell

$\Longrightarrow$



Light detection technique with APD.

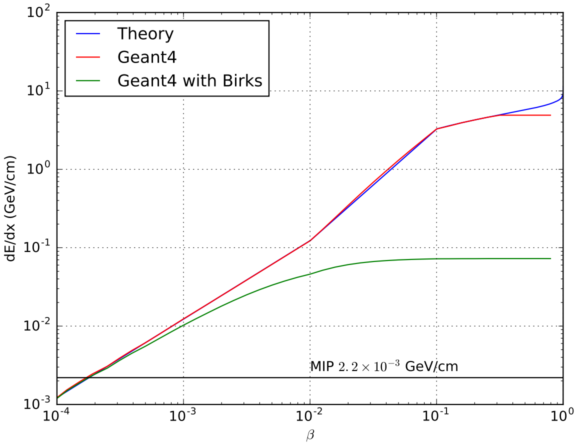
Simulation of Magnetic Monopoles

Bethe-Ahlen formula for energy loss of magnetic monopoles in matter:

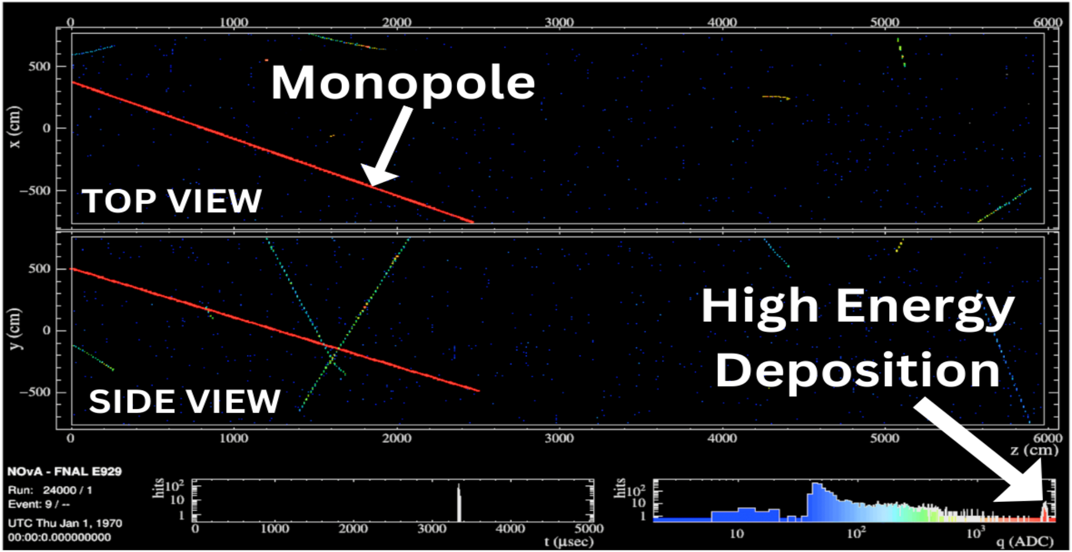
Magnetic charge | QED correction | Bloch correction

$$\frac{-dE}{dx} = C\frac{Z}{A} g^2 \left[\ln\frac{2 m_e c^2 \beta^2 \gamma^2}{I} + \frac{K|g|}{2} - \frac{1}{2} - B(g)\right]$$

- We generate isotropic monopoles of mass $10^{16} GeV/c^2$, one unit of Dirac charge and zero electric charge.
- Monopoles are produced over a beta range $[10^{-4}, 0.8]$.
- **Monopoles are expected to produce very bright signal including Cherenkov light above Cherenkov threshold.**



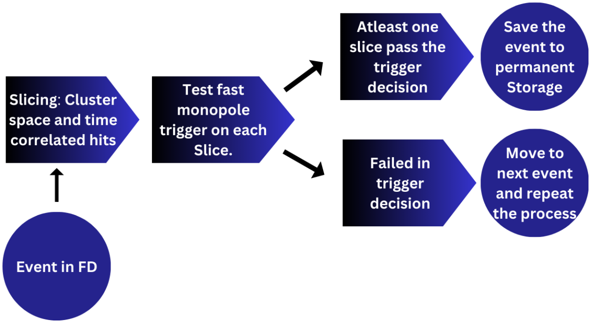
dE/dx vs. true speed of simulated monopole.



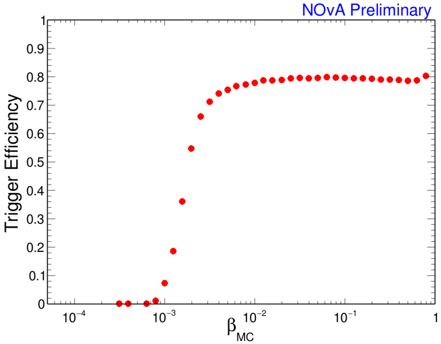
Event display of a simulated monopole overlaid with cosmics.

Fast Monopole Trigger

We have developed a software trigger that continously searches for monopole-like patterns in the data stream composed of mostly 150 kHz of cosmic rays.



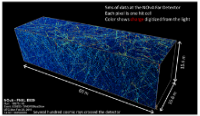
Fast monopole trigger configuration



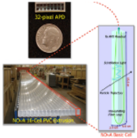
Fast monopole trigger efficiency vs. β_{MC}

We have $\sim$ 80% trigger efficiency for $\beta_{MC} >= 0.005$

Analysis Technique

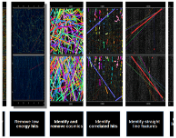


Particle interaction in detector

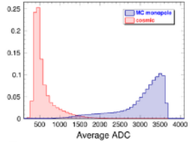


Electronics readout

Data driven trigger



Event reconstruction

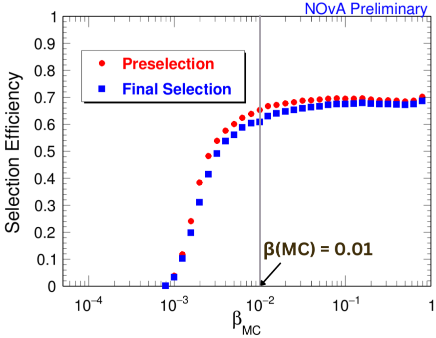


Analysis

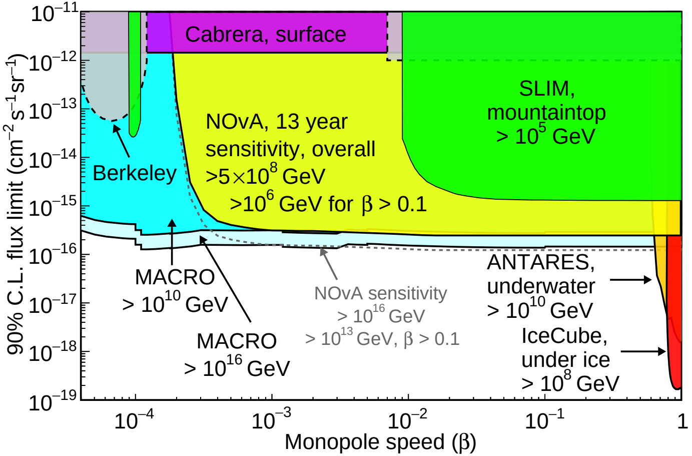
Analysis Strategy:

- Compare reconstructed variables for MC and cosmics and reject obvious background with preselection cuts.
- Optimize signal selection criteria and estimate selection efficiency.

$$\text{Efficiency} = \frac{\#\ \text{Monopoles passing selection criteria}}{\#\text{Monopoles simulated}}$$



NOvA Future Sensitivity



Future sensitivity for magnetic monopoles. The numbers expressed in the unit of GeV denote the mass of the monopoles.

- **Due to its surface location with little overburden and large surface area, monopoles with mass $> 10^8$GeV and mass $> 10^6$ GeV for $\beta > 0.1$ can reach the FD.**

- **NOvA has the unique potential to probe a new region and has the potential to present the best limit for low mass monopoles.**

Summary

- Due to its earth surface proximity and large surafece area, the NOvA far detector is sensitive to an extensive range of magnetic monopole masses and velocities, which are generally ruled out by underground experiments.
- We have a novel trigger algorithm at far detector to identify potential monopole like activities and save it for further analysis.
- We have robust reconstruction algorithm and offline analysis techniques to get rid of cosmics and have a good efficiency of final selection criteria.
- **Stay tuned for the NOvA magnetic monopole result!** .

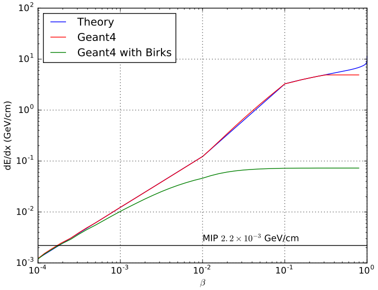
"One would be surprised if Nature had made no use of it." - P. Dirac(1931)

THANK YOU FOR YOUR ATTENTION!

The NOvA Collaboration

BACK-UP

Birk's Suppression



Energy loss of monopoles

Birk's Suppression

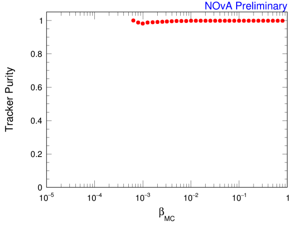
$$\boxed{\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1+K_B \frac{dE}{dx}}}$$

$$K_B = 0.01155 \frac{g}{cm^2 MeV}$$

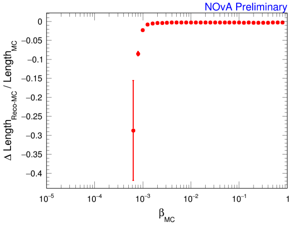
- The Geant4 simulation is consistent with the theoretical energy deposition, except for $\beta > 0.3$.
- It shows that the visible light yield from the simulated monopoles is constrained by Birks effect starting from $\beta = 2 \times 10^{-4}$ and is capped at $\beta = 0.03$.

Reconstruction Performance

- The tracking performance is evaluated by tracker purity.
- Purity is number of monopole hits included in a track divided by total hits included in the track.
- Purity equals unity for successfully reconstructed tracks.
- Validation using truth and reconstruction information of the track.
- The top plot shows purity in the track and for fast monopoles it is very close to 1.
- The bottom plot shows the truth and reconstruction values are very close to each other for fast monopoles.



Average purity of tracks

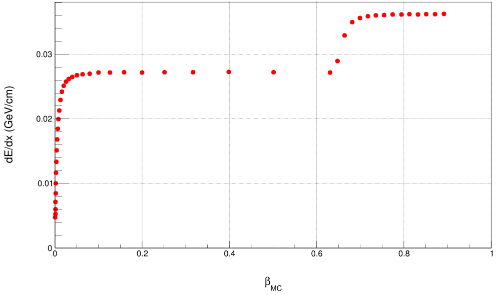


Reco-MC validation

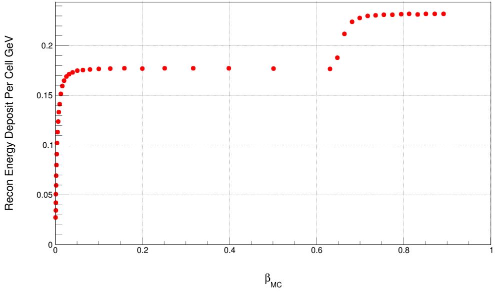
Recent Work: Cherenkov Modelling

Monopoles are expected to produce $(\frac{ng}{e})^2$ times as much Cherenkov light as a particle with electric charge 'e' and and the same speed in a medium with refractive index 'n', given the relative permeability of the medium is unity.

- The scintillator index of refraction is around 1.47.
- Cherenkov threshold around $\beta = 0.68$.
- We expect nearly 10,000 times as much Cherenkov light as a muon.

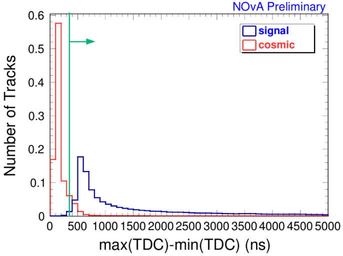


Energy deposition per unit length versus the β_{MC}

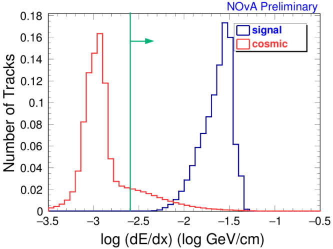


Energy deposition per cell versus the β_{MC}

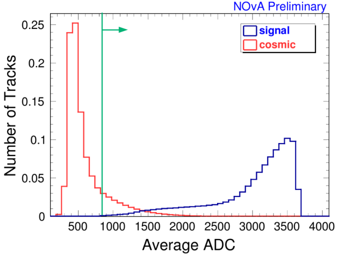
Data - Monopole Comparison



Time gap between the first and the last hits > 350 ns.



log dE/dx > -2.6



mean ADC > 850

Energy loss of Monopoles

For monopoles with β > 0.1: **ionisation is dominated** and the energy loss is given by the Bethe-Bloch formula adapted by Ahlen to magnetic monopoles :

$$\frac{dE}{dx}=\frac{4\pi N_e g^2 e^2}{m_e c^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I}+\frac{K(|g|)}{2}-\frac{1}{2}-\frac{\delta}{2}-B(|g|)\right]\ MeV\,g^{-1}cm^2$$

$$B(|g|)=0.248,\ |g|=\frac{137e}{2},\ K(|g|)=0.406,\ |g|=\frac{137e}{2},\ \gamma=\frac{1}{(1-\beta^2)^{\frac{1}{2}}}$$

$$X=\log_{10}(\beta\gamma)=\log_{10}\left(\frac{p}{Mc}\right)$$

$$\delta=\begin{cases}\ln(\beta^2\gamma^2)-2\ln\left(\frac{I}{\hbar\omega_p}\right)+a(X_1-X)^m & \text{if } X_0<X<X_1\\ \ln(\beta^2\gamma^2)-2\ln\left(\frac{I}{\hbar\omega_p}\right)-1 & \text{if } X>X_1\\ 0 & \text{if } X<X_0 \text{ (non conductors)}\\ \delta_0.10^{2(X-X_0)} & \text{if } X<X_0 \text{ (conductors)}\end{cases}$$

where I is the mean excitation energy , δ is the density correction factor k the QED correction , and B the Bloch correction

For monopoles with 0.01 < β < 0.1: **neither ionisation nor atomic excitation is negligible** and the energy loss is not well defined and so polynomial interpolation is performed between β = 0.01 and β = 0.1

For monopoles with β < 0.01: **atomic excitation is dominated**

$$\frac{dE}{dx}=\frac{2\pi N_e g^2 e^2\beta}{m_e c^2 v_F}\left[\ln\frac{2m_e v_F\Lambda}{\hbar}-0.5\right]$$

$$v_F=\left(\frac{\hbar}{m_e}\right)(3\pi^2 N_e)^{\frac{1}{3}}$$

$$\Lambda=0.53\,\mathring{A}\,(Bohr\ Radius)$$