Monopoles at future neutrino detectors

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Introduction

It all started with Paul Dirac in 1931

Why is the electron charge quantized and why does it have that value?

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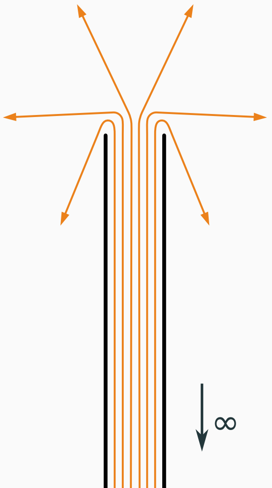
Dirac proposed the existence of magnetic poles (monopoles) as a solution.

Dirac envisioned a semi-infinitely long, infinitesimally thin solenoid as a magnetic monopole



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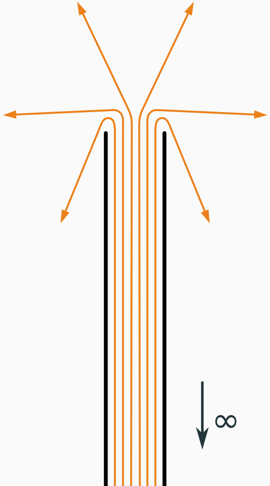
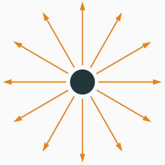


- At the end of the solenoid, the magnetic field resembles that of a single charge:



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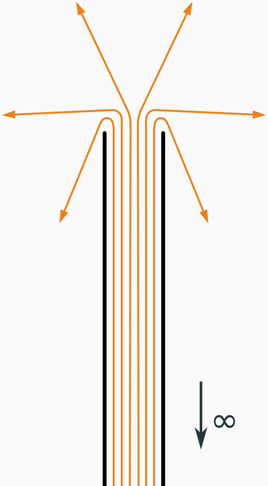

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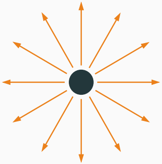
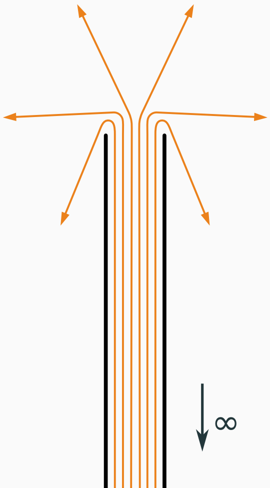


- What do we do with the rest of the solenoid?

If the infinitesimally thin solenoid is not detected, we can identify the object as a monopole



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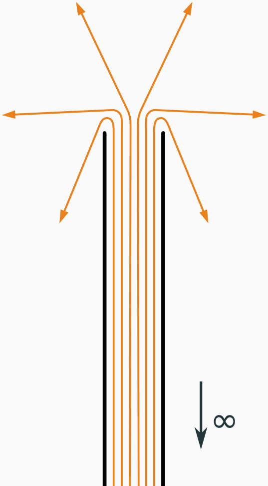

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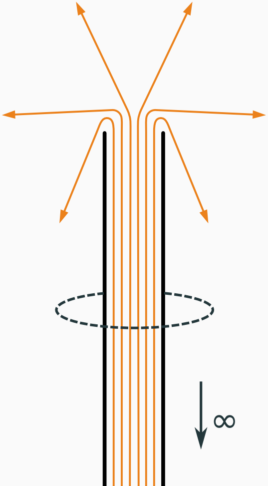

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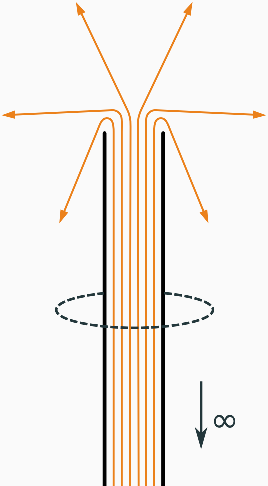

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- The magnetic field of the monopole with magnetic charge g is

$$\mathbf{B} = \boldsymbol{\nabla} \times \mathbf{A} = g \frac{\hat{\mathbf{r}}}{r^2} \,.$$

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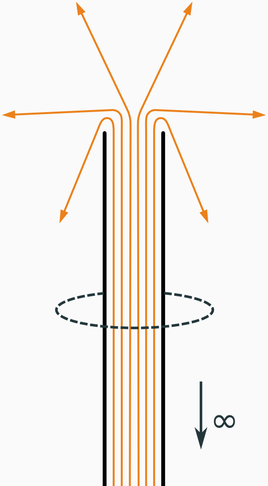

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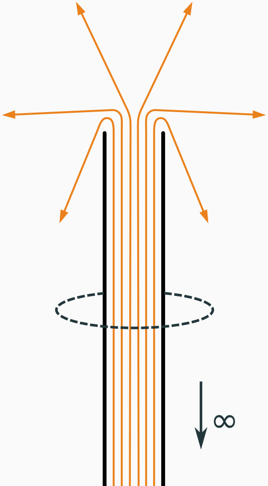

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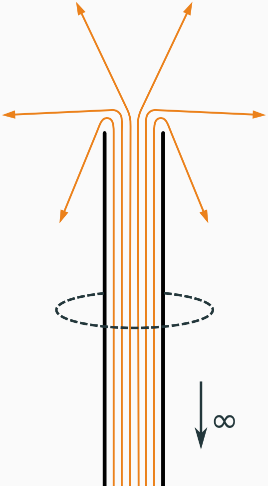

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- The electron fails to see the solenoid if the phase is trivial:

$$e^{i4\pi eg/(\hbar c)} = 1 \quad \Rightarrow \quad g = \frac{n}{2e}\hbar c\,.$$

Check out *arXiv*:1810.13403 for a comprehensive review on Dirac's quantization condition.

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The existence of a magnetic monopole implies quantization of the electric charge.

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P.A.M. Dirac, *Proc. Roy. Soc. Lond. A* **133** (1931) 60.

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i) Dirac showed that the existence of monopoles is consistent with quantum electrodynamics (QED).

ii) Later on, ’t Hooft and Polyakov demonstrated that monopoles arise naturally in grand unified theories (GUT) and have calculable and predictable properties.

References:

P.A.M. Dirac, *Proc. Roy. Soc. Lond. A* **133** (1931) 60.

G.’t Hooft, *Nucl. Phys. B* **79** (1974) 276.

A.M. Polyakov, *JETP Lett.* **20** (1974) 194.

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    - Other searches from NOvA and IceCube were performed.

Monopole interactions with fermions via Callan-Rubakov processes

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Both violate $(B+L)$ in two units.

Let us start with the antiproton synthesis

The differential cross-section in the center-of-mass (CoM) frame of the antiproton synthesis process $M\, e^-_R \to M\, \overline{p}_L$ is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{{q_J}^2}{2} \frac{|\mathbf{p}^{\mathbf{cm}}_{\overline{\mathbf{p}}}|}{|\mathbf{p}^{\mathbf{cm}}_{\mathbf{e}}|^3} \left[\sin\left(\frac{\theta^{\mathrm{cm}}}{2}\right)\right]^{4|q_J|-2} .$$

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where θ^{cm} is the scattering angle in the CoM frame.

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where q_J is $g/2$, half of the monopole magnetic charge, in units of $2\pi\hbar/e$.

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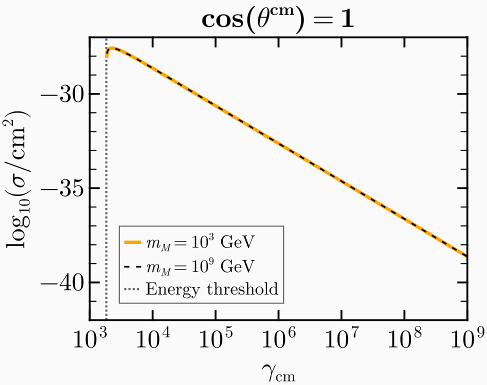
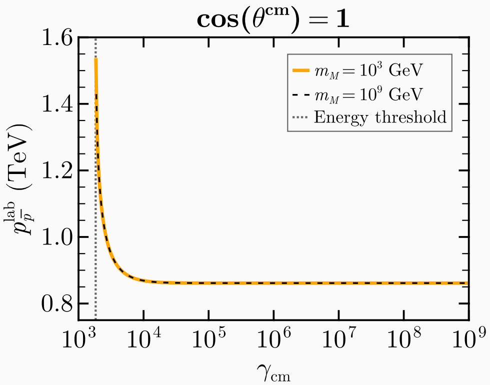
In the lab frame, the monopole must have an energy above a threshold to produce the antiproton:

$$E_{\mathrm{th}} = \frac{2m_p m_M + m_p^2 - m_e^2}{2m_e} \approx 2 \times 10^3 m_M .$$

More relativistic monopoles give a smaller cross-section. However, the final antiproton momentum in the lab frame plateaus, independently of m_M



PMC, Khoze, and Turner, *arXiv*:**2504.14918** [hep-ph]



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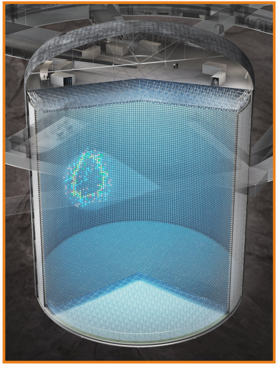
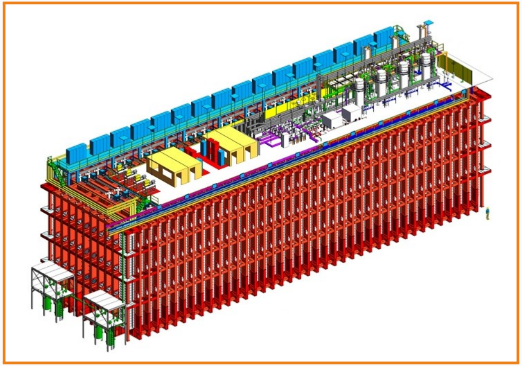
Detection using neutrino detectors

Hyper-K with 187 kilotons of pure water and DUNE far detector with 40 kilotons of liquid argon are used for the analysis



Hyper-K detector
(Hyper-K collaboration)



DUNE far detector
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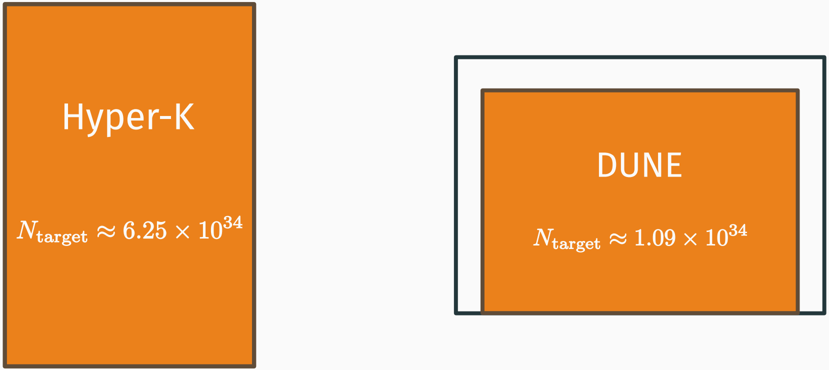
Expanding the detector with the Earth's crust to increase the number of targets



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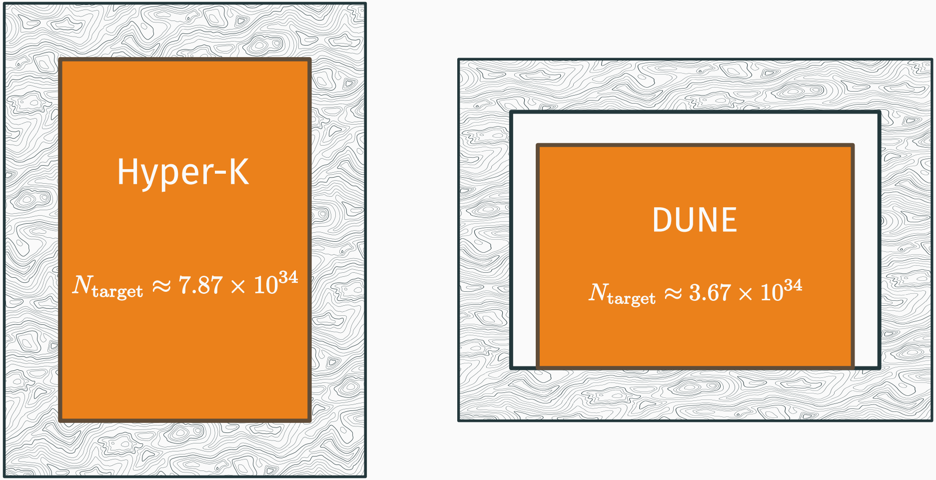
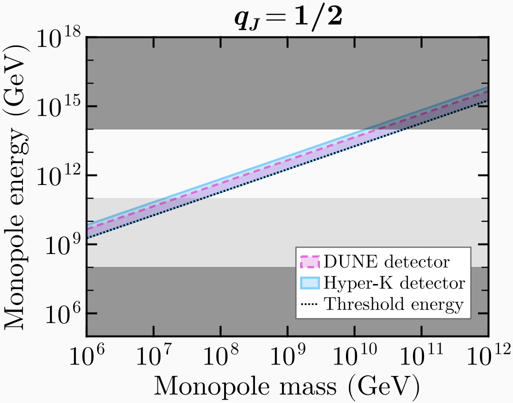


Results

Exclusion regions at 90% C.L. for a monopole flux $\Phi = 4\pi \times 10^{-16}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (one order of magnitude below Parker's bound). Colored bands depict allowed values



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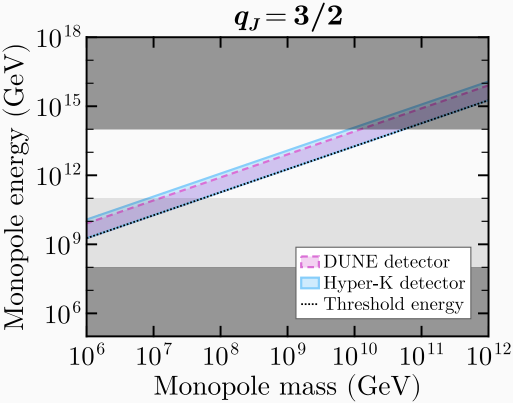

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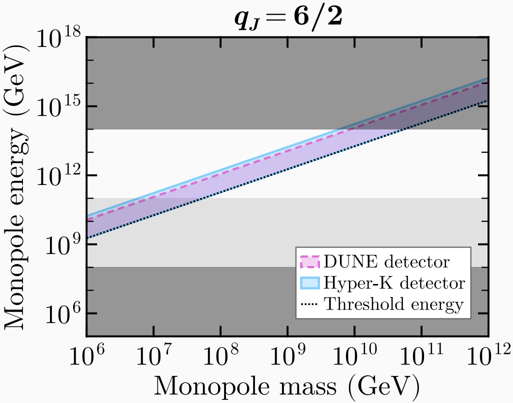

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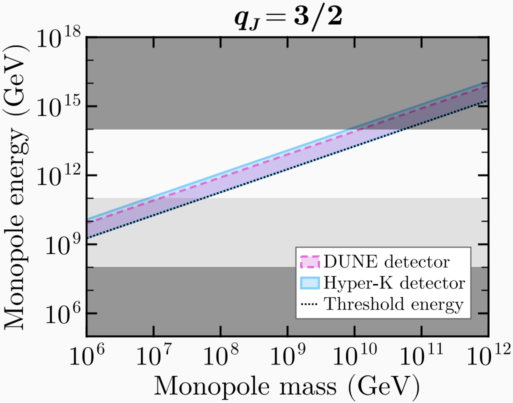

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Thank you!