PROCEEDINGS OF SCIENCE

Latest Magnetic Monopole Search Results from NOvA

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The existence of the magnetic monopole has eluded physicists for centuries. The NOvA Far Detector (FD), used for neutrino oscillation searches, also has the ability to identify magnetic monopoles. With a surface area of 4,100 m^2 and a location near the earth's surface, the 14 kt FD provides us with the unique opportunity to be sensitive to potential low-mass monopoles unable to penetrate underground experiments. We have designed a novel data-driven triggering scheme that continuously searches the FD's live data for monopole-like patterns. At the offline level, the largest challenge in reconstructing monopoles is to reduce the 148,000 Hz speed-of-light cosmic ray background. In the absence of any signal events in a 95-day exposure of the FD, we set limits on the monopole flux of 2×10^{-14}cm^{-2}s^{-1}sr^{-1} at 90% C.L. for monopole speed $6 \times 10^{-4} < \beta < 5 \times 10^{-3}$ and mass greater than 5×10^{8} GeV. In this talk, I will review the current monopole results and discuss the sensitivities of future searches using more than 8 years of collected FD data.

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1. Introduction

1.1 NOvA

The NOvA experiment looks for the conversion rate of muon neutrinos into electron neutrinos. The measurement of this and the associated antineutrino rate gives information critical to understanding the mixing parameters θ_{23} and Δm^2, the neutrino mass hierarchy, and even the observed asymmetry of matter over antimatter in the universe. NOvA uses two highly segmented scintillation detectors with an almost fully active detection region, a near detector (ND) at Fermilab and a far detector (FD) in Ash River, MN. A beam of muon neutrinos produced at Fermilab travels through the earth to the FD. NOvA has made significant contributions to the scientific community's understanding of neutrinos since data collection commenced in 2014.

1.2 Search for Magnetic Monopoles

The FD is a rectangular liquid scintillator detector with a mass of over 14 kt and a size of 15 m by 15 m by 60 m, it is constructed of 896 planes that together contain a total of 344,064 channels (cells). Thanks to the data-driven trigger (DDT) system, the FD is able to isolate interesting physics signals hidden among the 148,000 cosmic rays crossing it every second. The DDT system allows placement of the FD near the surface of the earth under only modest shielding. Such a sensitive and large detector has never been placed in such an exposed location before, which opens up a previously inaccessible phase space to search for exotic particles that would usually be absorbed by large shielding or overburdens of other experiments. One such exotic particle is the magnetic monopole. Though posited by widely-credited theoretical work, searches over the past century have yet to find evidence of such a particle's existence.

This analysis is the first to probe uncharted territory for intermediate mass magnetic monopoles, but it is only the first in a series of analyses spanning the entire dataset to be collected by NOvA's full physics run. At the end of NOvA's run, our search sensitivity can be competitive with the leading magnetic monopole searches to date (e.g. MACRO). NOvA's search strategy is twofold, fast magnetic monopoles ($\beta \gtrsim 10^{-2}$) are identified using large energy deposits while slow magnetic monopoles ($\beta \lesssim 10^{-2}$) are identified using low-velocity straight tracks. As usual, β is defined as the ratio between the particle's velocity (v) and the speed of light (c). This document will explain both the fast and slow magnetic monopole searches and present the results from the first slow magnetic monopole search [1].

The slow magnetic monopole search algorithm is designed to search the FD data for slowly moving particles. The event topology is therefore a straight track traversing the FD with a velocity that is a fraction of the speed of light. The signal events were simulated using slow magnetic monopoles. This search has been optimized for $\beta = 10^{-3}$ magnetic monopoles, but has sensitivity to monopoles as slow as $\beta = 3 \times 10^{-4}$ and as fast as 5×10^{-3}.

The fast magnetic monopole search algorithm is designed to search the FD data for particles that deposit a large amount of energy. The event topology is therefore a track with a large total energy deposition. The signal events were simulated using fast magnetic monopoles. This search has sensitivity to monopoles as slow as $\beta = 10^{-3}$ and as fast as the speed of light ($\beta = 1$).

2. Magnetic Monopole Simulation

2.1 Energy Deposition Model

The energy deposition model of magnetic monopoles is well established for slow [2] and fast [3] magnetic monopoles. Figure 1 shows the comparison between the theoretical energy deposition model (blue) and the one implemented in Geant4 (red), which shows good agreement over several orders of magnitude in β. At higher velocities, the magnetic monopole will deposit more energy, not all of which is visible because it is suppressed through the Birks effect. The Geant4 model of this is shown in Figure 1 (green), which shows that the visible energy reaches a plateau at $\beta = 0.03$.

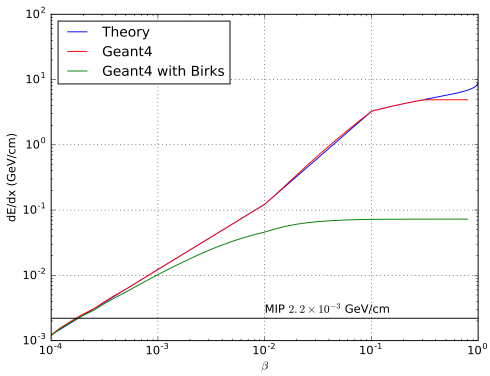

Figure 1: This plot shows a comparison of the Geant4 simulated energy deposition model (red) with the theoretical calculations (blue) [2, 3]. The Birks-suppressed energy deposition model in Geant4 is also shown (green). The minimum-ionizing particle (MIP) energy deposition is shown in black for reference.

2.2 Monte Carlo (MC) Simulation

Geant4 is used to simulate the magnetic monopole. In the absence of information about the distribution of the direction of the monopoles, the probability is assumed to be identical for monopoles coming from any direction, so an isotropic distribution of the monopole directions is used in the simulation. The surface entry point is chosen at random, and the simulated monopole is given direction and speed parameters (β). The speed determines the energy deposition rate (Figure 1). The monopole energy is very large relative to the energy lost in the detector, so it is assumed that the monopole's velocity vector remains constant.

2.3 Signal MC Sample

Monopoles at various velocities are simulated and propagated through the FD, with one monopole per simulated event. Next, each simulated event is combined with a 5 ms long min-bias data produced by a daily trigger. This results in an overlayed event that contains both the true monopole and nominal detector activity over a 5 ms time period. This MC sample is used to measure how well the search algorithm can identify slow monopoles and differentiate them from the overwhelming cosmic ray background present in 5 ms of data.

3. Fast Magnetic Monopole Search

3.1 Trigger

The data is produced by the fast magnetic monopole trigger that operates as part of NOvA's Data-Driven Trigger (DDT) system [4]. In broad strokes, the trigger is designed to select tracks with high-energy hits that cross the entire FD. One way to differentiate signal tracks from other high-energy activity is to require that the weighted energy of the track is near its geometric center. Figure 2 shows that this trigger's efficiency is near 80% for $\beta > 10^{-2}$ and even retains some efficiency all the way down to $\beta = 10^{-3}$.

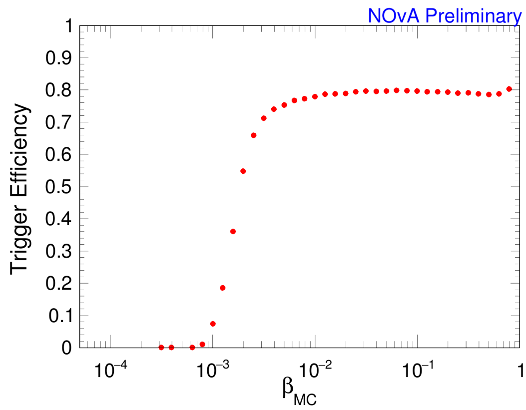

Figure 2: This plot shows the trigger efficiency of the fast magnetic monopole trigger.

3.2 Offline Reconstruction

Unlike the trigger, the offline reconstruction is not limited in time, so it proceeds by identifying tracks from the triggered sample with a much lower requirement on the hit energy. The tracker completeness corresponds to the number of identified MC hits divided by the number of MC hits simulated in an event. A high tracker completeness means that all of the MC hits were identified by the reconstruction. The tracker purity corresponds to the number of identified MC hits divided by the number of total hits in the track. A high tracker purity means that the track only consists of MC hits and few non-MC hits (e.g. background cosmic hits) were clustered into the track. The overall reconstruction quality is high with a track purity of 100% and a track completeness of 90% for $\beta > 10^{-2}$.

4. Slow Magnetic Monopole Search

4.1 Trigger

The slow magnetic monopole trigger is also part of the DDT system and identifies straight lines of hits consistent with a slow track. One event in the DDT world corresponds to a 5 ms readout window. The trigger algorithm starts by considering pairs of hits on the surface of the detector for one such 5-ms-event and identifies hits that lie on a 20-cell wide road between these surface hits.

The algorithm then looks for gaps between the hits on the road and identifies the maximum plane gap (along the z-axis) and the maximum cell gap (along the x- or y-axes). If there is a plane gap larger than 30 planes or a cell gap larger than 20 cells, the algorithm rejects the pair of hits. The procedure is then repeated for all of the pairs of hits on the detector surface. The pairs of surface hits must also have sufficient separation in space and time to originate from a track with a velocity (β) of less than 5×10^{-3}. If the algorithm identifies a pair of surface hits without large gaps, the event is written out to permanent storage. The efficiency of this algorithm is 68% for $\beta = 10^{-3}$.

4.2 Offline Reconstruction

The FD read-out electronics acquire data in two projected views separately, the xz- and yz-views. The y-direction is the vertical dimension while the z-direction points along the neutrino beam originating from Fermilab. The algorithm starts by extracting two-dimensional information from each view and then combines this information into three-dimensional objects known as monopole tracks. First, the algorithm identifies all of the fast moving cosmic ray muons and removes them from the event. The algorithm then removes isolated as well as uncorrelated activity. The remaining energy depositions (hits) are reconstructed using the Hough Tracking Algorithm to identify straight line objects. A line is fitted to the collection of hits associated with the monopole track. Next, the linear correlation coefficient, time gap fraction, and velocity (β) are calculated for this monopole track and used to select monopole signal events. At a minimum, a monopole track must have a reconstructed length of at least 10 m.

Once a line is fitted to the collection of hits associated with the monopole track, standard linear regression techniques can be used to calculate the squared correlation coefficient (r^2) for hits in the xt- and yt-spaces separately. A value of r^2 equal to unity means that the hits lie on a straight line while a value of zero means that the hits are uncorrelated.

For the analysis of the hits to be meaningful, they should also follow a temporal progression. Many of the reconstruction failures occur when two independent speed-of-light cosmic rays are identified as a single monopole track. Such monopole tracks have a cluster of hits occurring early in time, a large time gap, and then another cluster of hits occurring later. To exclude this reconstruction failure mode, the largest time gap fraction is calculated, which is the ratio of the longest time gap between sorted hits and the total time duration of the track. For a high-quality track, the linear correlation coefficient must be close to unity and the time gap fraction must be close to zero.

4.3 Signal Search

The data is produced by the slow monopole trigger that operates as part of NOvA's Data-Driven Trigger (DDT) system [4]. The version of the slow monopole trigger used here was deployed on June 5$^{\text{th}}$, 2015, which defines the beginning of the data sample. On October 12$^{\text{th}}$, 2015, the FD was reconfigured to a higher gain setting, which is used as the end of this data sample. The overall length of the data sample that met all of the data quality requirements is 95 days. This sample was then used to search for magnetic monopole signals.

Training the algorithm on the NOvA data began with the assumption that no monopole existed in small subsamples of the full data set. This was first done with samples approximately 0.3%, 1% and then 10% of the full sample. The signal selection requirements arrived at with the 10% sample are as follows: the time gap fraction must be less than 20% in both views, r^2 must be greater than 0.95 in both views, and the reconstructed velocity (β) must be less than 10^{-2}. The combined trigger and reconstruction efficiency is 53% for $\beta = 10^{-3}$.

The search through the full triggered data sample yielded no signal events, so magnetic monopole flux limits of $2 \times 10^{-14}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ were set at 90% C.L. for monopole speeds $6 \times 10^{-4} < \beta < 5 \times 10^{-3}$ and monopole masses greater than 5×10^8GeV. Figure 3 (left) shows the magnetic monopole flux limits set by this analysis as a function of β together with the leading limits set by other experiments. NOvA sets the only limits around $\beta = 10^{-3}$ for magnetic monopoles lighter than 10^{10} GeV. Figure 3 (right) shows the extrapolated limits for 12 years of NOvA data assuming no efficiency improvements in the search algorithms.

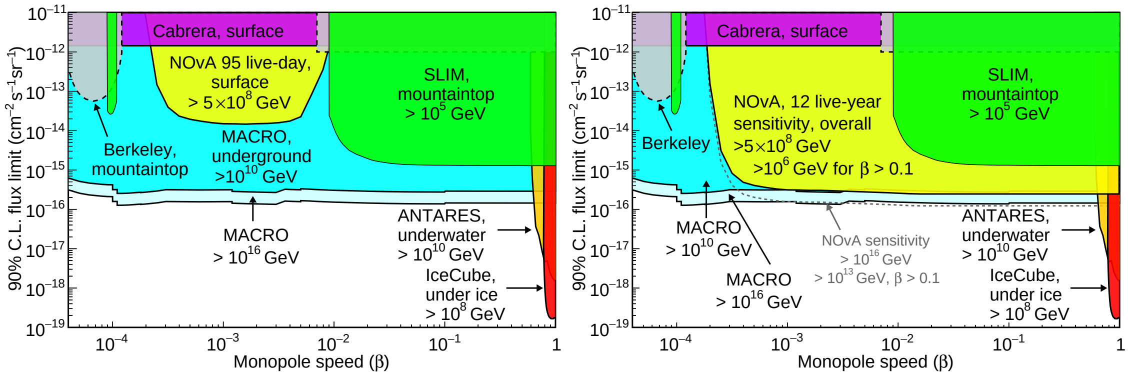

Figure 3: The left plot shows the magnetic monopole flux limit set by the first slow magnetic monopole analysis (yellow) together with existing limits set by other experiments. NOvA sets the only limits around $\beta = 10^{-3}$ for monopoles lighter than 10^{10} GeV. The right plot shows the NOvA limits extrapolated to 12 years for the combined slow and fast magnetic monopole analyses. The limits on top are the ones with lower magnetic monopole mass reach.

Acknowledgments

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