Search for Dirac Magnetic Monopoles using the ATLAS detector

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In 1931, Dirac introduced the idea of a magnetic monopole in order to explain the quantization of the electric charge,

eg = nhc/2

where n is an integer, n=1,2,3…

He showed that if they exist, they must carry a "magnetic charge", called the Dirac unit charge

$$\mathbf{g_D=68.5e}$$

in cgs units .

The existence of such a magnetically charged particle would also symmetrize Maxwell's Equations of Electrodynamics.

Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\epsilon_0}$	$\nabla \cdot \mathbf{E} = \frac{\rho_e}{\epsilon_0}$
Gauss' law for magnetism:	$\nabla \cdot \mathbf{B} = 0$	$\nabla \cdot \mathbf{B} = \mu_0 c \rho_m$
Faraday's law of induction:	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} - \mu_0 c \mathbf{J}_m$
Ampère's law (with Maxwell's extension):	$\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}_e$	$\nabla \times \mathbf{B} = \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}_e$

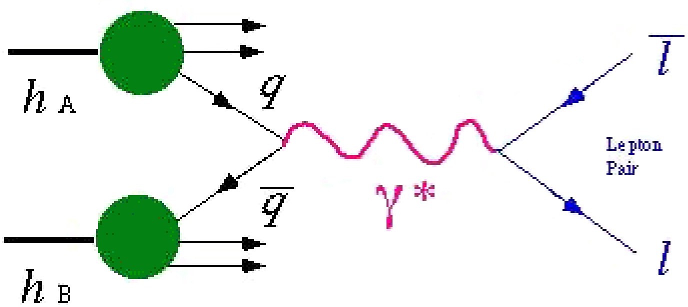
with ρ_m the "magnetic charge density" and J_m the "magnetic current".

There is no theoretical prediction on the mass of a magnetic monopole but the current experimental limit sets it above 350 GeV (CDF, 2004).

The magnetic monopole can have spin of 0, 1/2 or 1.

1.Generation

We assume that the magnetic monopoles can be produced from the interaction of a quark/antiquark pair which annihilate into a virtual Z_0 /gamma which decays into a monopole antimonopole pair.



In our study we choose to use Pythia as a generator to produce lepton (muon) pairs with various masses (200 GeV, 400 GeV, 600 GeV, 800 GeV).

The total cross section is calculated by replacing the electromagnetic coupling with the corresponding coupling for magnetic monopoles

$$\alpha_m = g^2/4\pi \sim 34$$

Fig.1: Energy and Pt distributions for a magnetic monopole with 600GeV mass

The generated particles would still carry an electric charge because the magnetic charge is not defined in any generator. We will compensate for that by changing the trajectory equation in the simulation.

Regarding the PDG identification code for magnetic monopoles, it was set up as 50 and has been implemented in the Athena release 11.0.5.

2.Behavior in Magnetic Field

The ATLAS detector has a central solenoid that provides a 2T, homogeneous, magnetic field inside the inner Tracker detector. The field is parallel to the beam axis.

By solving the equation of motion of a magnetically charged particle in an uniform magnetic field (in the absence of any electric fields) we were able to describe the trajectory of such a particle.

Fig.2: Trajectory of a magnetic monopole with 600GeV mass

This illustrates the unique features of the monopole track:

1 a linear trajectory in the transversal plane (which is not shown)

2 a parabola shape in the eta-z plane (as shown in fig.1)

This unusual trajectory is an important part of the magnetic monopole signature.

We implemented this property using the Atlfast simulation by adjusting the trajectory equation to simulate the passage of a magnetic monopole through the detector.

The code has been included in Athena release 11.0.3

3. **Energy loss**

We considered the energy loss of a monopole due to three electromagnetic processes:

- ionization (including density dependent suppression effect arising from charge polarization of the medium),
- pair production,
- bremsstrahlung.

Mass(GeV)	**Energy(GeV)**	**γ**
200	200-2500	1-12.5
400	400-2800	1-7
600	600-3200	1-5.3
800	800-3000	1-3.8

Our study concludes that, in the gamma range of interest (fig.3), the energy loss by ionization is the dominant process (Fig.4).

To get an idea of how big the monopole ionization is, we compared it to the muon ionization in the $\beta\gamma$ interval 1-1000

We can conclude that, in our range of interest ($\beta\gamma$ around 5):

(dE/dx)monopoles/(dE/dx)mu ~500

So another important property of the magnetic monopole signature is the high ionization in the interaction with matter.

3.1 How far will the monopole travel inside the ATLAS detector

Once we were able to identify the process by which the monopole loses energy we want to be able to predict how far it will travel inside the ATLAS detector.

A)First attempt

Using the formula for radiation length (the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung) in g/cm^2:

$$1/X_0=4\alpha N_A Z(Z+1)r_e^2\log(183\ Z^{-1/3})/A$$

And knowing the average X_0 for different regions of the detector we can calculate the average Z for that region.

Replacing Z in the formula for the energy loss by ionization for magnetic monopoles:

$$dE_{col}/dx= -(4\ Z\quad {}_M N_A/Am_e)\{\ \ln[m_e \beta^2 \gamma^2/I] - \ /2\}$$

We can evaluate dE_{col}/dx.

In the above formulas:

α = fine structure constant (~1/137)
α_M = coupling constant for magnetic monopoles (~34)
NA = Avogadro's number (6.022 x 10^{23}/mole)
Z = atomic number of traversed material
A = atomic weight of traversed material
r_e = electron radius (2.818 x 10^{-13} cm)
m_e = electron mass (0.5 MeV)

To find an estimate for X_0 in the Inner Detector we used the graph in the TDR.

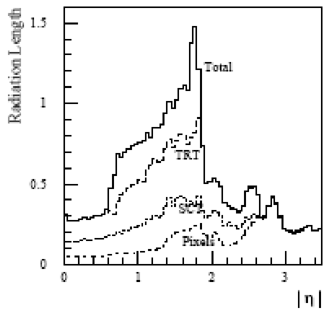


Figure 3-5 Material distribution of the ID vs |η| for the 98_2 layout, used in this report. The various bands include all services and supports within the corresponding fiducial volumes. The pixel band also includes the beam pipe. The total includes the ID services outside the TRT.

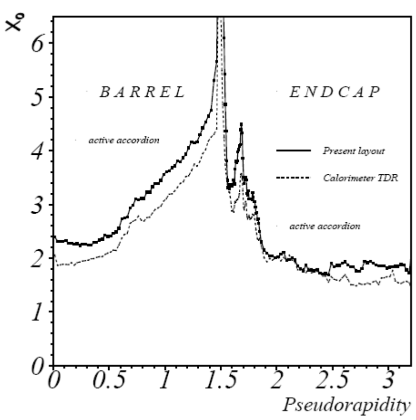
There are 3 regions:

X_0 = 0.3 for 0<η<0.8

X_0 =0.7 for 0.8<η<2 **dE/dx <3.5 Gev/cm^{-2} g**

X_0= 0.3 for 2<η<2.5

Applying the same procedure for the Calorimeter:



There are 3 regions:

X_0 =2.3 for 0<η<0.5

X_0 = 4 for 0.5<η<2 **dE/dx <2.5 GeV/cm^{-2} g**

X_0= 1.7 for 2<η<3

In order to estimate the total energy loss in Inner Detector and Calorimeter, we need the average densities.

B. Second attempt

Use the muon energy loss and energy deposition in the Inner Detector and Calorimeter and scale it using the $(dE/dx)_{monopoles}/(dE/dx)_{mu}$ ratio calculated previously.
We are currently working on this!