Magnetic monopole searches with the MoEDAL experiment at the LHC

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Magnetic monopoles

• Dirac argument (1931): existence of magnetic charge would explain electric charge quantisation
  - Basic unit of magnetic charge: \( g_D = 68.5e \)
  - Monopoles should carry a multiple of \( g_D \): \( g = Ng_D \)
  - \( 2Ng_D \) according to Schwinger's argument (1966)
  - \( 3Ng_D \) if basic electric charge is \( e/3 \) (quark charge)

• Coupling to the photon \( \gg 1 \)
  - Non-perturbative dynamics
  - Very large ionisation energy loss

• Magnetic charge conservation ensures that monopoles would be stable and produced in pairs
Monopole searches

- **In cosmic rays** (e.g. MACRO detector array)
- **In matter** (e.g. polar volcanic rocks, see previous talk)
- **At colliders** (each time a new energy regime is reached)
Monopole searches at the LHC

- **ATLAS** set the first limits on monopole production at the LHC
  - 2 fb\(^{-1}\) of 7 TeV \(pp\) collision data
  - Cross section limits for \(g = g_D\) and 
    \[200 < \text{mass} < 1500 \text{ GeV}\]
    (PRL 109, 261803 (2012), arXiv:1207.6411)
- **8 TeV collision data collected in 2012:**
  - ATLAS and CMS \(\rightarrow g \leq 2g_D\)
  - MoEDAL test arrays \(\rightarrow g \leq 6g_D\)
  - Monopoles trapped in ATLAS and CMS beam pipes \(\rightarrow g \geq 4g_D\)
  - Complementary techniques!
The MoEDAL experiment

- **International collaboration of 42 members from 19 institutes**
- **Dedicated to highly-ionising particle detection**
  - Magnetic monopoles and other long-lived massive charged particles
  - Sensitivity surpasses other LHC experiments in many cases + complementary
- **Design consists of 4 detector subsystems**
  - The TDR Nuclear Track detector (NTD) array \((Z \geq 5)\)
  - The Very High Charge Catcher (VHCC) NTD array \((Z \geq 50)\)
  - The Magnetic Monopole Trapper (MMT) absorbing array
  - The TimePix chip (TMPX) online radiation monitoring system

http://moedal.web.cern.ch/
MoEDAL detection principles

Passive detector arrays exposed to collision products around LHC interaction point-8

Nuclear track detectors (NTDs):
- Thin plastic foils
- Track-etch technique for signature of high ionisation

Magnetic monopole trapper (MMT):
- Aluminium absorber
- Induction technique for signature of magnetic pole
MoEDAL arrays

Test arrays deployed in 2012 (8 TeV)
→ NTD and MMT exposure, first MMT data shown today
Final arrays to be deployed in 2015-2016 (14 TeV)
MMT 2012 – geometrical acceptance

Array placed 1.8 m away from the interaction point, covers 1.3 % of the total solid angle
MMT 2012 – kinematic acceptance

Relatively low material budget in front of the MMT ($\sim 14 \text{ g} \cdot \text{cm}^{-2}$)

→ probe yet unexplored kinematic ranges:

• Low energies
• Forward region

Important to cover wide energy and angular ranges due to large model uncertainties
MMT 2012 – probed parameter space

Charge $> 1g_{D}$ and mass $> 1500$ GeV still unconstrained in LHC energy regime...

This is now being remedied!

Calculations methods described in EPJC 72, 1985 (2012), arXiv:1112.2999
Magnetometer measurements

Laboratory of Natural Magnetism, ETH Zurich

Magnetically shielded room

DC-SQUID magnetometer

For details about the method and calibration, see previous talk by D. Milstead

(see also EPJC 72, 2212 (2012), arXiv:1206.6793)
Box 11 measurements

Rods cut into 66 samples of length ranging from 10 to 30 cm
Results of Box 11 measurements

- Left plot shows **persistent current** after first passage for all samples
- **Excellent charge resolution** ($< 0.1 \, g_D$) except for two outliers at $-0.3 \, g_D$
- Both candidates are large (30 cm) samples. **Repeated measurements** (right) reveal small occasional offset jumps. This is a known effect, observed for large samples (see also EPJC 72, 2212 (2012), arXiv:1206.6793)
- No monopole with charge $> 0.5 \, g_D$ in MMT box 11
Summary (1)

- Magnetic monopoles are fundamental well-motivated objects
  - Should carry a *multiple* of the Dirac charge
- The LHC collided protons at 8 TeV (will increase to 14 TeV)
  - Provides a unique opportunity to constrain monopole production in an hitherto *unexplored* mass range
- The MoEDAL experiment uses complementary approaches:
  - In-flight detection – track-etch technique
  - Trapping – induction technique
Summary (2)

• The MoEDAL Magnetic Monopole Trapper (MMT) test array was exposed to 0.75 fb$^{-1}$ of 8 TeV $pp$ collisions in 2012
  – First measurements were presented today (9% of the array)
  – Scanning of full MMT array will continue this Summer
  – Probes monopole charges and masses in a range inaccessible to general-purpose experiments, and can provide faster results
Extra slides
Monopole binding in matter

- **To atoms**
  - Binding energies of the order of a few eV
- **To nuclei with non-zero magnetic moments**
  - Binding energies of the order of 200 keV
    
- **At the surface of a ferromagnetic**
  - Image force of the order of 10 eV/Å
  - Robust prediction (classical)
Monopole ionisation energy loss

\[ -\frac{dE}{dx} = K \frac{Z}{A} \frac{z^2}{\beta^2} \left[ \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 \right] \]

**Electric**

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

**Magnetic**

No Bragg peak!

**Dirac monopole:** \(|g_D| = 68.5 \rightarrow \text{several thousand times greater} \)

\(dE/dx\) than a minimum-ionising \(|z|=1\) particle
Monopole production

EM coupling constant for Dirac charge = 34.25
→ non-perturbative dynamics, no reliable cross sections and kinematics!

“Natural” benchmark models:

- Photon fusion
- Drell-Yan
8 TeV monopole production kinematics
Range of monopoles in ATLAS and CMS

EPJC 72, 1985 (2012), arXiv:1112.2999
Monopoles in 14 TeV collisions: comparison of different LHC experiments

Cross section needed for 10 events within detector acceptance

EPJC 72, 1985 (2012), arXiv:1112.2999
ATLAS monopole search

- Electron trigger requires energy in second calorimeter layer (EM2) → sensitive to high energy or low charge ($N = 1$)
- Dedicated tracking and simulation
- Signature: high ionisation hits and narrow energy deposition
- Results: cross section limits 2-30 fb for masses up to 1500 GeV

PRL 109, 261803 (2012), arXiv:1207.6411
Visible energy in Liquid-Argon

- Birks' law models electron-ion recombination effects
  - over-suppresses signal at high dE/dx
- For high charges, need HIP correction obtained from heavy ion data

![Graph showing the ratio of MC to Exp vs. dE/dx for various charges. The charges z=1, z=2, z=10, z=26, z=57, and z=79 are highlighted. The graph compares the ratio before and after HIP correction.](image-url)
ATLAS monopole search – efficiency

PRL 109, 261803 (2012), arXiv:1207.6411
ATLAS monopole search – results

- Valid for Dirac ($N=1$) monopoles
- Blue curve is model-independent (factoring out acceptance)

PRL 109, 261803 (2012), arXiv:1207.6411
Collider cross section limits for a Dirac monopole

Each limit is valid in a given mass range, generally assuming Drell-Yan like pair production mechanism

Trapping array experiment at Fermilab

- Steel beam dump exposed to 300 GeV protons
  - Scanned with a monopole extraction device
  - Assumptions different than for the induction technique (arguably less reliable)

Phys. Rev. D 8, 3717 (1973)
MODAL experiment at LEP1

- Nuclear-track detectors surrounding I5 interaction point
- 91 GeV electron-positron collisions
- 0.3 pb limit in dashed regions

Monopole trapping in H1 beam pipe

- HERA collider, 300 GeV electron-proton collisions
- Monopoles and dyons with very high magnetic charges would stop in the aluminium beam pipe
  - Scanned with SQUID magnetometer (induction technique)
- 0.1 – 1 pb limit (up to 140 GeV monopole with $g \geq g_D$)

EPJC 41, 133 (2005), arXiv:hep-ex/0501039
Recent magnetometer tests for trapped monopoles searches
Proof-of-principle using accelerator material near CMS
Calibration cross-check with long, thin solenoids

EPJC 72, 2212 (2012), arXiv:1206.6793
MMT design

- **Material: Aluminium**
  - Large nuclear dipole moment (spin 5/2) → likely to bind monopoles
  - No activation
  - Low magnetisation
  - Cheap

- **Boxes:**
  - 18 rods 60 cm long and 2.5 cm diameter
  - Nicely fits magnetometer sample holder

- **2012 array:** 11 boxes in front of VELO vacuum chamber

- **2015 arrays:** In front, on the side, and below the VELO chamber
MMT tests with magnetometer

- Aluminium modules identical to those used in the MMT setup
- Monopoles with charge down to $0.5g_D$ can be identified without ambiguity
Array covers 1.3 % of the total solid angle
MMT 2012 – integrated luminosity

Array exposed to 0.75 fb\(^{-1}\) of 8 TeV pp collisions