Searching for monopoles – why bother?

• They restore symmetry in Maxwell's equations
• They explain electric charge quantisation (Dirac 1931)
  – Fundamental Dirac magnetic charge $g_D$:
    $$ g = ng_D \text{ with } n = 1, 2, 3... \text{ and } g_D \text{ equivalent to } 68.5e $$
• They appear as topological solutions in models of spontaneous gauge symmetry breaking ('t Hooft and Polyakov 1974)
The search for the magnetic monopole

- In cosmic rays and in matter

- At colliders
  Phys. Today 69, 40 (2016)

Monopole searches are performed at colliders every time a new energy regime is made accessible
The search for the magnetic monopole

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Monopole searches are performed at colliders every time a new energy regime is made accessible.

New long-lived particles give unconventional signatures → complementary approach: dedicated detectors!
The Monopole & Exotics Detector at the LHC

- Dedicated searches for new long-lived highly-ionising particles
- The 7th LHC experiment, located at IP8
- ~70 members, 25 institutes

http://moedal.web.cern.ch/
The Monopole & Exotics Detector at the LHC

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Detector subsystems
- Plastic NTD arrays with low \( (z/\beta > 5) \) and high \( (z/\beta > 50) \) ionisation thresholds
- TimePix radiation background monitor
- Monopole trapping detector
MoEDAL detection principles

Passive arrays exposed to high-energy LHC collisions

1) Nuclear-track detectors (NTDs)
   - Plastic foil – exposure, etching, scanning
   - Signature of high ionisation: etch-pit cones (~50 μm) in successive sheets
MoEDAL detection principles

Passive arrays exposed to high-energy LHC collisions

1) Nuclear-track detectors (NTDs)
2) Monopole trapping detector
   - Absorbing volume made of stacked aluminium bars
   - Expect strong binding with Al nucleus (~100 keV)
   - Signature of magnetic charge: Induced persistent current after passage through superconducting coil
Highly-ionising particle searches at the LHC
(see EPJC 72, 1985 (2012), arXiv:1112.2999)

- ATLAS and CMS
  \[ |g| \leq 2g_D \]
  \[ 0.3 \leq |z|/\beta \leq 100 \]

- MoEDAL NTD detectors
  \[ |g| \leq 9g_D \]
  \[ 5 \leq |z|/\beta \leq 500 \]

- MoEDAL trapping detector
  \[ |g| \leq 4g_D \]

- Trapping in beam pipes
  \[ |g| \geq 4g_D \]

Complementary techniques!
MoEDAL in 2012

NTD stacks
on surrounding walls

1 array trapping detector prototype
Below beam pipe opposite to LHCb

Test arrays exposed to 8 TeV $pp$ collisions
MoEDAL in 2012

NTD stacks on surrounding walls

First LHC constraints on particles with multiple magnetic charge

JHEP 08, 067 (2016)

1 array trapping detector prototype
Below beam pipe opposite to LHCb

Test arrays exposed to 8 TeV $pp$ collisions
MoEDAL in 2015 and 2016

NTD stacks on top of VELO, close to IP + on surrounding walls

Thin “shower curtain” NTD within LHCb acceptance

TimePix for online monitoring

3 arrays trapping detectors

Full arrays exposed to 13 TeV $pp$ collisions
MoEDAL in 2015/2016

NTD stacks on top of VELO, close to IP + on surrounding walls

Thin “shower curtain” NTD within LHCb acceptance

Full arrays exposed to 13 TeV pp collisions

First monopole constraints in 13 TeV collisions

3 arrays trapping detectors

PRL 118, 061801 (2017)
Passive detection with MoEDAL trapping array (1)

Installation
Exposure (IP8)

3 x 222 kg

19 x 2.5 x 2.5 cm³
Passive detection with MoEDAL trapping array (2)

Installation

Exposure (IP8)

Removal

Scanning (ETH Zurich)

Laboratory of Natural Magnetism, ETH Zurich

Magnetically shielded room

DC-SQUID magnetometer

Superconducting Coil

Sample (fixed to belt)

Conveyor Belt

SQUID (sensor and electronics)
Magnetometer scans

- 672 samples for forward trapping array
- Persistent current measured for each sample
- Samples with persistent current exceeding $0.25 \ g_D$ are set aside as candidates
- Multiple measurements rule out the monopole hypothesis
Magnetic charges in samples (13 TeV exposure in 2015)

First-pass measurement

Multiple measurements of candidates

→ Exclude $> 0.5 \, g_D$ in all samples
Passive detection with MoEDAL trapping array (3)

Material description

installation

Exposure (IP8)

Removal

Scanning (ETH Zurich)
Passive detection with MoEDAL trapping array (4)

Material description

Exposure (IP8) → Removal → Scanning (ETH Zurich)

Event Generation (Madgraph)

Coupling $>> 1$ → non-perturbative dynamics!
Passive detection with MoEDAL trapping array (5)

- **Installation**
- **Exposure (IP8)**
- **Removal**
- **Scanning (ETH Zurich)**

**Material description**

**Simulation (Geant4)**

**Event Generation (Madgraph)**

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

Graph showing dE/dx (GeV cm²/g) vs. p (GeV) for different materials:
- Ahlen, |g| = g₀
- Be
- Al
- Fe
- Pb
Passive detection with MoEDAL trapping array (6)
Passive detection with MoEDAL trapping array (7)
Cross-section limits with 2015 exposure

- First monopole constraints in 13 TeV $pp$ collisions
- Probe masses in the TeV regime for up to $5g_D$
Cross-section limits with 2015 exposure

- First monopole constraints in 13 TeV \( pp \) collisions
- Probe masses in the TeV regime for up to \( 5g_D \)

2016 exposure

- Same cavern conditions as 2015 with 5x more luminosity
- Scans finished a few weeks ago, analysis in progress
### Mass limits (DY model)

**Warning**: cross-section calculation is highly model dependent!

<table>
<thead>
<tr>
<th>mass limits [GeV]</th>
<th>$1g_D$</th>
<th>$2g_D$</th>
<th>$3g_D$</th>
<th>$4g_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoEDAL 13 TeV (this result)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DY spin-1/2</td>
<td>890</td>
<td>1250</td>
<td>1260</td>
<td>1100</td>
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<tr>
<td>DY spin-0</td>
<td>460</td>
<td>760</td>
<td>800</td>
<td>650</td>
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<td>MoEDAL 8 TeV</td>
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<tr>
<td>DY spin-1/2</td>
<td>700</td>
<td>920</td>
<td>840</td>
<td>$-$</td>
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<tr>
<td>DY spin-0</td>
<td>420</td>
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<td>560</td>
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<td>ATLAS 8 TeV</td>
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<tr>
<td>DY spin-1/2</td>
<td>1340</td>
<td>$-$</td>
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<td>$-$</td>
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<tr>
<td>DY spin-0</td>
<td>1050</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

- **Best collider limits** for $|g| > g_D$
- **Exclude low masses** for $|g| = 4g_D$ for the first time at the LHC
- **Constrain** $|g| = 5g_D$ for the first time at the LHC
Summary

MoEDAL is a dedicated LHC experiment for searching for new charged long-lived particles

- Passive detector techniques – robust design
- Complementary to general-purpose experiments
- Pioneering MoEDAL trapping detector first results surpass existing constraints for a range of monopole charges and masses

The LHC monopole hunt continues

- ATLAS/CMS@13 TeV
- MoEDAL NTDs
- Full MoEDAL trapping array
- Trapping in beam pipes
Extras
Magnetometer calibration

- Two independent methods: convolution and solenoid
- Very good agreement between the two
- Linearity demonstrated in range $0.3-10^6 \ g_D$
Direct collider monopole searches
current limits (assuming $|g| = g_D$)
Direct collider monopole searches
current limits (assuming $|g| = 2g_D$)
Rough discovery reach estimates

- Assuming 0.2 background events in ATLAS/CMS and
  ~0.00 background events in MoEDAL