MoEDAL - a New Light on the High Energy Frontier

James L. Pinfold
For the MoEDAL Collaboration
University of Alberta
MoEDAL’s PHYSICS APPROACH

DIRECTLY SEARCH FOR ANOMALOUSLY IONIZING AND VERY LONG-LIVED AVATARS OF NEW PHYSICS

MINIMALY IONIZING PARTICLES

HIGHLY IONIZING PARTICLES

MULTI- MESSENGERs OF NEW PHYSICS

MoEDAL PROBES NEW PHYSICS

MoEDAL COMPLEMENTS ATLAS & CMS
The general purpose experiments have as their prime physics purpose the discovery & elucidation of the Higgs boson....

The corresponding “baseline” physics propose for MoEDAL is the search for the Magnetic Charge

BUT ATLAS, CMS & MOEDAL CAN DO MUCH MORE
The Magnetic Monopole's Importance

They restore symmetry to Maxwell's Equations

They explain electric charge quantization

GUT & EW monopoles are excitations of the Higgs field

They are required by GUTs string theory & M-theory
Magnetic Monopole Properties

**Magnetic charge**

\[ ng = \frac{n}{68.5} e \]

(if \( e \rightarrow \frac{1}{3} e \); \( g \rightarrow 3g \))

HIGHLY IONIZING

**Coupling constant**

\[ \frac{g}{\Theta c} \sim 34. \text{ Spin } \frac{1}{2}? \]

**Energy acquired in a magnetic field**

\[ 2.06 \text{ MeV/gauss.m} = 2 \text{ TeV in a 10 m, 10T solenoidal field} \]

**The monopole mass is not predicted within the Dirac’s theory, \sim 4-7 \text{ TeV EW monopole}**
Monopole Production at Colliders

\[ e^+ e^- \rightarrow M \bar{M}, \ \text{pp} \rightarrow M \bar{M}, \ e^+ p \rightarrow e^+ p \bar{M} M, \ \text{etc.} \]

Drell-Yan Production

\[
\begin{align*}
q & \quad \alpha_{EM} \\
\bar{q} & \quad \gamma \\
\bar{m} & \quad \alpha_{M/Mbar} \\
m & \quad m
\end{align*}
\]

Two-photon production

\[
\begin{align*}
e^+ & \quad \gamma \\
e^+ & \quad \gamma \\
p & \quad \gamma \\
\bar{p} & \quad \gamma \\
\bar{q} & \quad \gamma
\end{align*}
\]

Indirect search using virtual monopole box diagrams allow – observable two high energy gammas.
Anomalous Ionization Signature

\[-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right]\]

**ELECTRIC CHARGE (z)**

**VERY HIGH IONIZATION**

\[Z \uparrow \beta (\approx v/c) \downarrow\]

\[g = n \frac{137e}{2} = n \times 68.5e\]

**IONIZATION**

\[(dE/dX)_g \approx n^2 4700 \ (dE/dX)_{\text{proton}}\]

**MAGNETIC CHARGE (g)**

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

The velocity dependence of the Lorentz force cancels 1/\beta^2 term
They fought on the high energy frontier

MoEDAL is installed and started to take data in p-p and p-A running at ~13 TeV in 2015
MoEDAL – Physics Scenarios (34+)

- Quirks
- Q-balls
- 4th Gen fermions
- Electroweak monopoles
- D-particles
- Light TP monopoles
- Monopolium
- Doubly charged Higgs
- Doubly charged higgsinos

MASSIVE CS PARTICLES
6 scenarios

MAGNETIC
CHARGE
6 scenarios

DOUBLY
CHARGE PARTICLES
8 scenarios

SUSY
9 scenarios

EXTRA
DIMENSIONS
5 scenarios


MBH remnants
Stable MBHs
KK-particles
Heavy Sleptons
Metastable charginos
Long lived gluinos
R-hadrons
Fat Higgs scenarios
Doubly charged fermions
The LHC Detectors with Results - MoEDAL

MoEDAL is largely passive and made up of three detector systems

NUCLEAR TRACK DETECTOR
Plastic array (~200 sqm) – Like a Giant Camera

TRAPPING DETECTOR ARRAY
A tonne of Al to trap Highly Ionizing Particles for analysis

TIMEPIX Array - a digital Camera for real time radiation monitoring
• Acceptance for at least one monopole from monopole pair production to hit NTDs ~70% (over 150 m² of plastic)
• **Largest NTD array** (*150 m² tot*) **ever deployed at an accelerator**
  – NTD tacks consist of CR39 (Thr. 5 mip) & Makrofol (Thr. 50 mip)
  – Damage revealed by controlled etching - etch pits are formed
  – Charge resolution is \( \sim |0.1|e \), where \(|e|\) is the electron charge
  – Precision of each track measurement \( \pm 20-20 \) microns

• **NTDs are calibrated at heavy-ion beams at NSRL & NA61**

• **ATLAS and CMS cannot calibrate for highly ionizing plastic**
Signal in the MMT & SQUID Detectors

Monopole trapped by aluminium nuclei

The MoEDAL trapping detectors at IP8

THE Zurich DC-SQUID magnetometer

The Signal

SQUID coil current is a constant amount after the passage of a monopole
MoEDAL Monopole Search Results at \( \sqrt{s} = 13 \) TeV - PRL 118 061811 (2017)

- **First monopole constraints in 13 TeV pp collisions**
  - Probe TeV masses for up to 5\( g_D \) for the 1st time at the LHC
  - Exclude monopole with \( |g| = 4g_D \) for the 1st time at the LHC

<table>
<thead>
<tr>
<th>mass limits [GeV]</th>
<th>1( g_D )</th>
<th>2( g_D )</th>
<th>3( g_D )</th>
<th>4( g_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoEDAL 13 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(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>
</tr>
<tr>
<td></td>
<td>460</td>
<td>760</td>
<td>800</td>
<td>650</td>
</tr>
<tr>
<td>DY spin-0</td>
<td>700</td>
<td>920</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td></td>
<td>420</td>
<td>600</td>
<td>560</td>
<td></td>
</tr>
<tr>
<td>MoEDAL 8 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DY spin-1/2</td>
<td>1340</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1050</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS 8 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DY spin-1/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DY spin-0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MoEDAL Apparatus for Penetrating Particles (MAPP)

MAPP will be able to take data in p-p, p-A,A-A and also fixed target interactions using SMOG (an internal gas target in LHCb)

MAPP has three motivations

- To search for particles with charges $<< 1e$ (ATLAS & CMS limited to searches with particles of charge $e \geq 1/3$)
- To search for new pseudo-stable neutrals with long lifetime and anomalously penetrating particles
MoEDAL Addresses Fundamental Questions:

- Are there extra dimensions?
- What happened just after the big bang?
- What is the nature of Dark matter?
- Does magnetic charge exist?
- Are there new symmetries of nature?
MoEDAL Addresses Fundamental Questions:

- Are there extra dimensions?
- What happened just after the big bang?
- What is the nature of Dark matter?
- Are there new symmetries of nature?

STAYED TUNED - The LHC could be poised on the threshold of new physics.
ADDITIONAL SLIDES
MoEDAL- Beampipe Consortium have submitted a proposal to CMS to utilize their replaced surplus-to-requirement IP region beam pipe in order to scan them for the presence of very highly ionizing monopoles trapped in the beam pipe walls.
Cross-section limits for magnetic (LEFT) and electric charge (RIGHT) (from arXiv:1112.2999V2 [hep-ph])

MoEDAL COMPLEMENTS the physics reach of the existing LHC experiments
The MoEDAL Trapping Detector System

- Only 1/3 of the trapping array used for $\sqrt{s}=13$ TeV search
  - The full sensitivity includes results from all of the trapping and NTD detectors – so much improved results in the future
- Total mass of trapping detectors $\sim 800$ kg of Al ($\sim 2400$ bars)
  - Read out by a SQUID magnetometer calibrated with special solenoids
  - First time a purpose built trapping detector has ever been deployed
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015

The luminosity delivered to MoEDAL in 2015 was 366 pb⁻¹

Despite “Sparky” the Beech Marten – LHC is now on track
The MoEDAL Monopole Search at $s = 8$ TeV - JHEP 1608 (2016) 067

| DY Lower Mass Limits [GeV] | $|g| = g_D$ | $|g| = 2g_D$ | $|g| = 3g_D$ |
|---------------------------|-----------|-----------|-----------|
| spin-1/2                  | 700       | 920       | 840       |
| spin-0                    | 420       | 600       | 560       |

MoEDAL

ATLAS

World best limits for $|g| > g_D$
(previously $\sim 400$ GeV at the Tevatron)
"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value." - Spanish Royal Commission, rejecting Christopher Columbus' proposal to sail west.

In 2015 the LHC experiments – now including MoEDAL - set sail out on a voyage of discovery at the new LHC high energy frontier of 13TeV - stay tuned for the report of new worlds