Searches for New Physics with the MoEDAL detector at the LHC

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for the MoEDAL Collaboration

17th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY
Workshop on the Standard Model and Beyond
September 2 – 10, 2017, Corfu, Greece
MoEDAL at LHC

International collaboration
~70 physicists from
~20 participating institutions

UNIVERSITY OF ALABAMA
UNIVERSITY OF ALBERTA
INFN & UNIVERSITY OF BOLOGNA
UNIVERSITY OF BRITISH COLUMBIA
CERN
UNIVERSITY OF CINCINNATI
CONCORDIA UNIVERSITY
GANGNEUNG-WONJU NATIONAL UNIVERSITY
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF HELSINKI
IMPERIAL COLLEGE LONDON
KING’S COLLEGE LONDON
KONKUK UNIVERSITY
UNIVERSITY OF MÜNSTER
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY
NORTHEASTERN UNIVERSITY
TECHNICAL UNIVERSITY IN PRAGUE
QUEEN MARY UNIVERSITY OF LONDON
INSTITUTE FOR SPACE SCIENCES, ROMANIA
STAR INSTITUTE, SIMON LANGTON SCHOOL
TUFT’S UNIVERSITY
IFIC VALENCIA
Key feature: high ionisation

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

charge

velocity: $\beta = \frac{v}{c}$

$= \frac{z}{\beta}$

High ionisation (HI) possible when:

- multiple electric charge ($H^{++}$, Q-balls, etc.) = $n \times e$
- very low velocity & electric charge, i.e. Stable Massive Charged Particles (SMCPs)
- magnetic charge (monopoles, dyons) = $n g_D = n \times 68.5 \times e$
  - a singly charged relativistic monopole has ionisation $\sim 4700$ times MIP!!
- any combination of the above

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

Magnetic charge

Ahlen formula

Particles must be **massive, long-lived & highly ionising** to be detected at **MoEDAL**
MoEDAL sensitivity

Cross-section limits for magnetic and electric charge assuming that:
- ~ one MoEDAL event is required for discovery and ~100 events in the other LHC detectors
- integrated luminosities correspond to about two years of 14 TeV run


MoEDAL offers robustness against timing and well-estimated signal efficiency
MoEDAL physics programme

SUSY R-hadrons sleptons

Doubly charged Higgs

Black-hole remnants

Q-balls

Magnetic monopoles

KK extra dimensions

D-matter

Quirks

Searching for massive, long-lived & highly ionising particles

MoEDAL physics program
The MoEDAL detector components
MoEDAL detector

MoEDAL is unlike any other LHC experiment:
- mostly passive detectors; no trigger; no readout
- the largest deployment of passive Nuclear Track Detectors (NTDs) at an accelerator
- the 1st time trapping detectors are deployed as a detector

DETECTOR SYSTEMS
① Low-threshold NTD (LT-NTD) array
   • \( z/\beta > \sim 5 - 10 \)
② Very High Charge Catcher NTD (HCC-NTD) array
   • \( z/\beta > \sim 50 \)
③ TimePix radiation background monitor
④ Monopole Trapping detector (MMT)
HI particle detection in NTDs

- Passage of a highly ionising particle through the plastic NTD marked by an invisible damage zone ("latent track") along the trajectory.
- The damage zone is revealed as a cone-shaped etch-pit when the plastic sheet is chemically etched.
- Plastic sheets are later scanned to detect etch-pits.

Looking for aligned etch pits in multiple sheets.
1 & 2 NTDs deployment

2012: LT-NTD
NTDs sheets kept in boxes mounted onto LHCb VELO cavern walls

2015-2016: LT-NTD
Top of VELO cover
Closest possible location to IP

2015-2016: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT
# 3 TimePix radiation monitor

- Timepix (MediPix) chips used to measure online the radiation field and monitor spallation product background
- Essentially act as little electronic “bubble-chambers”
- The only active element in MoEDAL

- 256×256 pixel solid state detector
- 14×14 mm active area
- amplifier + comparator + counter + timer

Sample calibrated frame in MoEDAL TPX04

2015 deployment of MediPix chips in MoEDAL
4 MMT: Magnetic Monopole Trapper

- **Binding energy** of monopoles in nuclei with finite magnetic dipole moments of $\mathcal{O}(100 \text{ keV})$
- MMTs analysed with superconducting quantum interference device (SQUID)
- Material: Aluminium
  - large nuclear dipole moment
  - relatively cheap
- **Persistent current**: difference between resulting current after and before
  - first subtract current measurement for empty holder
  - if other than zero → monopole signature

Typical sample & pseudo-monopole curves
**MMTs deployment**

### 2012
11 boxes each containing 18 Al rods of 60 cm length and 2.54 cm diameter (160 kg)

### 2015-2016
- Installed in additional locations: sides A & C, too
- Approximately 800 kg of Al
- Total 2400 aluminum bars
Results on monopole mass & charge from MMTs

- @ 8 TeV  JHEP 1608 (2016) 067 [arXiv:1604.06645]
Magnetic monopoles

- Motivation
  - symmetrisation of Maxwell’s eqs.
  - electric charge quantisation
- Properties
  - magnetic charge = \( ng = n \times 68.5e \)
  - coupling constant = \( g/\hbar c \sim 34 \)
  - spin and mass not predicted

<table>
<thead>
<tr>
<th>Name</th>
<th>Without Magnetic Monopoles</th>
<th>With Magnetic Monopoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss's law:</td>
<td>( \nabla \cdot \vec{E} = 4\pi \rho_e )</td>
<td>( \nabla \cdot \vec{E} = 4\pi \rho_e )</td>
</tr>
<tr>
<td>Gauss' law for magnetism:</td>
<td>( \nabla \cdot \vec{B} = 0 )</td>
<td>( \nabla \cdot \vec{B} = 4\pi \rho_m )</td>
</tr>
<tr>
<td>Faraday's law of induction:</td>
<td>( -\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} )</td>
<td>( -\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi \vec{J}_m )</td>
</tr>
<tr>
<td>Ampère's law (with Maxwell’s extension):</td>
<td>( \nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi \vec{J}_e )</td>
<td>( \nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi \vec{J}_e )</td>
</tr>
</tbody>
</table>

Production mechanisms in colliders

- Drell Yan mechanism
- Photon fusion
- Box diagram

MoEDAL improves reach of monopole searches w.r.t. cross section & charge

HIGHLY IONISING
MMT2015: scanning

- Analysed with SQUID at ETH Zürich
- Excellent charge resolution (< 0.1 g<sub>D</sub>) except for outliers

Persistent current after first passage for all samples

Persistent current for multiple measurements of candidates

No monopole with charge > 0.5 g<sub>D</sub> observed in MMT samples at 99.5% CL

Detector: prototype of 222 kg of aluminium bars
Exposure: 0.371 fb<sup>-1</sup> of 13 TeV pp collisions during 2015

PRL 118 (2017) 061801 [arXiv:1611.06817]
MMT2015: analysis

Geometry

Material description between IP & detector

Kinematics

Event generation of Drell Yan production

coupling $\gg 1 \Rightarrow$ non-perturbative!

Propagation in matter

- Ahlen formula
- Monopole energy loss
- Stopping range

JHEP 1608 (2016) 067

arXiv:1606.01220
MMT2015: results

Detector: prototype of 222 kg of aluminium bars
Exposure: 0.371 fb$^{-1}$ of 13 TeV $pp$ collisions during 2015

- First monopole searches at 13 TeV at LHC
- First limits for magnetic charge of $5 g_D$ and masses > 3.5 TeV

PRL 118 (2017) 061801 [arXiv:1611.06817]
Monopole mass limits

- Mass limits are *highly model-dependent*
  - Drell-Yan production does *not* take into account non-perturbative nature of the large monopole-photon coupling
- Exclude low masses for $|g| = 4g_D$ for the first time at LHC
- World-best collider limits for $|g| \geq 2g_D$

| DY lower mass limits [GeV] | $|g| = g_D$ | $|g| = 2g_D$ | $|g| = 3g_D$ | $|g| = 4g_D$ |
|-----------------------------|-------------|-------------|-------------|-------------|
| **MoEDAL 13 TeV** spin ½   | 890         | 1250        | 1260        | 1100        |
| spin 0                      | 460         | 760         | 800         | 650         |
| **MoEDAL 8 TeV** spin ½    | 700         | 920         | 840         | —           |
| spin 0                      | 420         | 600         | 560         | —           |
| **ATLAS 8 TeV** spin ½     | 1340        | —           | —           | —           |
| spin 0                      | 1050        | —           | —           | —           |

PRL 118 (2017) 061801
[arXiv:1611.06817]
Beyond magnetic monopoles

• What about *electrically*-charged particles?
Why MoEDAL when searching SMCPs?

- ATLAS and CMS triggers have to
  - rely on other “objects”, e.g. $E_T^{\text{miss}}$, that accompany SMCPs, thus limiting the reach of the search
    - final states with associated object present
    - trigger threshold set high for high luminosity
  - develop specialised triggers
    - dedicated studies needed
    - usually efficiency significantly less than 100%

- Timing: signal from (slow-moving) SMCP should arrive within the correct bunch crossing

- MoEDAL mainly constrained by its geometrical acceptance

- When looking for trapped particles
  - monitoring of detector volumes in an underground/basement laboratory has less background than using empty butches in LHC cavern
# Slepton searches comparison

<table>
<thead>
<tr>
<th>ATLAS / CMS</th>
<th>MoEDAL</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Velocity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta &gt; 0.2$</td>
<td>$\beta &lt; 0.2$</td>
<td>Complementarity 😊</td>
</tr>
<tr>
<td>Constrained by LHC bunch pattern</td>
<td>Constrained by NTD $Z/\beta$ threshold</td>
<td></td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not simple, involving several detector components, electronics, triggers, ...</td>
<td>Simple and robust</td>
<td>😊</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon \times A$ order of 20%</td>
<td>$\sim 100%$ (if $\beta \leq 0.2$)</td>
<td>😞</td>
</tr>
<tr>
<td>See limitations in previous slide</td>
<td>• Geometry: $\sim 50%$ for 2015; scalable to higher coverage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• $\beta$-cut yield: $\sim 10%$</td>
<td>highly model dependent</td>
</tr>
<tr>
<td><strong>Acceptance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May be considerable or difficult to estimate</td>
<td>Practically zero</td>
<td>For same signal yield, MoEDAL should have better sensitivity 😊</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Practically zero</td>
<td>LIMITING FACTOR 😞</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>high</td>
<td>factor of 10-50 less</td>
</tr>
</tbody>
</table>
Nuclear Track Detectors coverage

- High acceptance in central region $\eta \sim 0$
  - back-to-back pair production means probability $\sim 70\%$ for at least one SMCP to hit NTD
- For particles over $z/\beta$ threshold, detection efficiency practically $100\%$

Credit: Daniel Felea
SUSY long-lived particles (*relevant for MoEDAL*)

- **Long-lived sleptons (staus mostly)**
  - **Gauge-mediated symmetry-breaking (GMSB):** stau NLSP decays via gravitational interaction to gravitino LSP
  - **Coannihilation region in CMSSM:** long lived stau, when \( m(\tilde{\tau}) - m(\tilde{\chi}_1^0) < m(\tau) \)
    - naturally long lifetime for stau in both cases

- **R-hadrons**
  - **Gluinos in Split Supersymmetry:** \( \tilde{g}q\tilde{q}, \tilde{g}qq\tilde{q}, \tilde{g}\tilde{g} \)
    - long-lived because squarks very heavy
    - gluino hadrons may *flip charge* as they pass through matter
  - **Stops:** \( \tilde{t}\tilde{q}, \tilde{t}qq \)
    - e.g. stop NLSP in gravitino dark matter
    - e.g. as LSP in R-parity violating SUSY, long-lived when RPV coupling(s) small

- **Long-lived charginos**
  - **Anomaly-mediated symmetry-breaking (AMSB):** \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_1^0 \)
    - are mass degenerate \( \Rightarrow \tilde{\chi}_1^\pm \) becomes long-lived
Improving complementarity

- Relaxing constraints imposed in ATLAS/CMS selections
- Example: CMS dE/dx analysis @7-8 TeV [JHEP07 (2013) 122, arXiv: 1305.0491]

<table>
<thead>
<tr>
<th></th>
<th>tracker+TOF</th>
<th>tracker-only</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>$p_T$ (GeV/c)</td>
<td>&gt;45</td>
<td></td>
</tr>
<tr>
<td>$d_z$ and $d_{xy}$ (cm)</td>
<td>&lt;0.5</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{p_T}/p_T$</td>
<td>&lt;0.25</td>
<td></td>
</tr>
<tr>
<td>Track $\chi^2/n_d$</td>
<td>&lt;5</td>
<td></td>
</tr>
<tr>
<td># Pixel hits</td>
<td>&gt;1</td>
<td></td>
</tr>
<tr>
<td># Tracker hits</td>
<td>&gt;7</td>
<td></td>
</tr>
<tr>
<td>Frac. Valid hits</td>
<td>&gt;0.8</td>
<td></td>
</tr>
<tr>
<td>$\Sigma p_T^{trk}(\Delta R &lt; 0.3)$ (GeV/c)</td>
<td>&lt;50</td>
<td></td>
</tr>
<tr>
<td>$dE/dx$ measurements</td>
<td>&gt;5</td>
<td></td>
</tr>
<tr>
<td>$dE/dx$ strip shape test</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>$E_{cal}(\Delta R &lt; 0.3)/p$</td>
<td>&lt;0.3</td>
<td></td>
</tr>
<tr>
<td>$I_h$ (MeV/cm)</td>
<td>&gt;3.0</td>
<td></td>
</tr>
<tr>
<td>$\Delta R$ to another track</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

Relaxing both constraints

In collaboration with Kazuki Sakurai
Results for $\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \tau^+\tau_1^- $

$\tilde{\chi}_1^0$ long-lived despite large mass split between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ decays in tracker

$\tilde{\chi}_1^0$ long-lived despite large mass split between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ decays in tracker

(massive) $\tau^\pm$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks $\Rightarrow$ large impact parameters $d_{xy}$, $d_z$

$\tilde{\tau}_1$ metastable, e.g. gravitino LSP $\rightarrow$ detected by MoEDAL

Run 2 (2018) vs. Run-3 (2023) luminosity

End-of-run-3 (2023) luminosity

CMS affected two-ways:

a) no pixel hit
b) too large impact parameters

• Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event
• Conservative estimate of MoEDAL luminosity

MoEDAL can cover long-lifetime region inaccessible by ATLAS/CMS even with a moderate NTD performance $z/\beta > 10$
Summary & outlook

- MoEDAL is searching for (meta)stable highly ionising particles
  - least tested signals of New Physics
  - predicted in variety of theoretical models
  - design optimised for such searches
  - combining various detector technologies

- Results on monopole searches at 8 TeV & 13 TeV published
  - no magnetic monopole detected
  - bounds set significantly extend previous results at high charges

- Looking forward to many more results from Run-II and beyond
  - for other monopole interpretations
    - production via photon fusion
    - spin 1 monopoles
  - with NTDs
  - for electrically-charged particles
Thank you for your attention!
Spares
Analysis procedure

- **Electrically-charged particle**: \( \frac{dE}{dx} \sim \beta^{-2} \) → slows down appreciably within NTD → opening angle of etch-pit cone becomes smaller

- **Magnetic monopole**: \( \frac{dE}{dx} \sim \ln \beta \)
  - slow MM: slows down within an NTD stack → its ionisation falls → opening angle of the etch pits would become larger
  - relativistic MM: \( \frac{dE}{dx} \) essentially constant → trail of equal diameter etch-pit pairs

- The reduced etch rate is simply related to the *restricted energy loss* \( \text{REL} = (\frac{dE}{dx})_{10\text{nm}} \) from track
Dirac’s Monopole

- Paul Dirac in 1931 hypothesized that the magnetic monopole exists.
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid.
- Dirac’s quantisation condition:

\[ ge = \left[ \frac{\hbar c}{2} \right] n \quad OR \quad g = \frac{n}{2\alpha} e \quad (from \quad \frac{4\pi\epsilon g}{\hbar c} = 2\pi n \quad n = 1, 2, 3, \ldots) \]

- Where \( g \) is the “magnetic charge” and \( \alpha \) is the fine structure constant \( 1/137 \)
- This means that \( g = 68.5e \) (when \( n=1 \))!
- The other way around: IF there is a magnetic monopole then charge is quantised:

\[ e = \left[ \frac{\hbar c}{2g} \right] n \]
Cross section limits versus mass

Limits extend up to masses > \textbf{2500 GeV} for the first time at the LHC

- reminder: shown (tiny) LO DY cross sections are not reliable
  \Rightarrow makes sense to probe and constrain very high masses

Detector: prototype of \textbf{160 kg} of Al rods
Exposure: \textbf{0.75 fb}^{-1}
of \textbf{8 TeV pp} collisions

Cross section limits versus charge

World-best limits for $|g| > 1.5 \, g_D$
- previously $\sim 400$ GeV at Tevatron [e.g. CDF hep-ex/0509015]
- first time at the LHC

Detector: prototype of 160 kg of Al rods
Exposure: 0.75 fb$^{-1}$ of 8 TeV pp collisions

JHEP 1608 (2016) 067
[arXiv:1604.06645]
Complementarity of MoEDAL & other LHC exps

**ATLAS+CMS**
- Optimised for *singly* electrically charged particles ($z/\beta \sim 1$)
- LHC timing/trigger restricts sensitivity to (nearly) relativistic particles ($\beta \approx 1$)
- Typically a largish statistical sample is needed to establish a signal
- ATLAS & CMS cannot be calibrated for highly ionising objects
- Magnetic charge detection via its trajectory in non-bend plane → calibration introduces large systematics

**MoEDAL**
- Designed to detect charged particles, with effective or actual $z/\beta > 5$
- No trigger/electronics → slowly moving ($\beta < \sim 0.5$) particles are no problem
- One candidate event should be enough to establish a signal (no SM bkg)
- MoEDAL NTDs are calibrated using heavy ion beams
- Magnetic-charge sensitivity directly calibrated in a clear way

MoEDAL strengthens & expands the physics reach of LHC
Doubly-charged Higgs

- Extended Higgs sector in BSM models: $SU_L(2) \times SU_R(2) \times U_{B-L}(1)$ P-violating model
- Higgs triplet model with massive left-handed neutrinos but not right-handed ones
- Common feature: **doubly charged Higgs bosons** $H^{\pm\pm}$ as parts of a Higgs triplet
- Lifetime
  - depends on many parameters: Yukawa $h_{ij}$ (long if $< 10^{-8}$), $H^{\pm\pm}$ mass, ...
  - essentially there are no constraints on its lifetime $\Rightarrow$ relevant for MoEDAL

![Plot](image)

Partial decay width of $H^{\pm\pm} \rightarrow W^\pm W^\pm$

Black-hole remnants

- In some **Large Extra Dimension** models the formation of **TeV Black Holes (BH)** by high energy SM particle collisions is predicted
  - BH average charge $4/3$
  - slowly moving ($\beta \lesssim 0.3$)
- Charged Hawking BH evaporate but not completely
  - certain fraction of final BH remnants carry **multiple charges**
  - highly ionising, relevant to MoEDAL

BHR charges @ 14 TeV LHC [CHARYBDIS+PYTHIA]

Hossenfelder, Koch, Bleicher, hep-ph/0507140