A search for magnetic monopoles and exotic long-lived particles with large electric charge at ATLAS

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Highly ionizing particles (HIPS)

- **Magnetic monopoles**
  - Enforcing symmetries
    \[
    \nabla \cdot \vec{E} = \rho_E, \quad \nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + \vec{j}_E
    \]
  - Understanding charge quantization (Dirac 1931)
    \[
    \frac{q_e q_m}{\hbar c} = \frac{n}{2} \rightarrow g_D = \frac{\hbar c}{2e} \rightarrow \frac{g_D}{e} = \frac{1}{2\alpha_e} \approx 68.5
    \]

- **Highly electrically charged objects (HECOs)**
  - Strangelets
  - Q-balls
  - Micro black hole remnants

- **Production mechanism**
  - Production mechanism at LHC energies is poorly understood. Drell-Yan model gives reasonable kinematics.
  - No preference on spin of HIP.
Energy deposition by HIPs

- Ionization is the dominant mechanism of energy loss for HIPs of mass near TeV scale.
- Large number of energetic $\delta$-electrons produced.
- Energy deposition of magnetically charged particles differs from that of electrically charged particles.

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

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

Monopole $m=1000 \text{ GeV}$, $g=1.0g_D$ in Ar

Realistic LHC scenarios

The ATLAS detector and HIP signatures

Transition Radiation Tracker (TRT)

- Two energy deposition thresholds:
  - Low threshold (LT) for tracking (200 eV)
  - High threshold (HT) for electron ID (6 keV)
- HIP ionization in the TRT exceeds the high level threshold producing HT hits.
- $\delta$-electrons propagate in one or two straws depositing a few keV and producing TRT HT hits.

LAr electromagnetic calorimeter

- Four layers varying in depth and granularity.
- Low lateral dispersion in calorimeter cluster due to absence of electromagnetic cascade.
- HIPs stop early in the calorimeter. Energy deposits in the presampler and EM1 of great importance to this search.
Monte Carlo signal samples

• This search includes HIPs of mass in the range 200 GeV – 2500 GeV and charge:
  - magnetic charge $0.5g_D < |g| < 2.0g_D$
  - electric charge $10 < |z| < 60$

• Fully simulated samples:
  - Single particle HECOs and monopoles.
  - Spin-$\frac{1}{2}$ HECOs and monopoles using Drell-Yan production model.

• Generator level 4-vectors of spin-0 HECOs and monopoles, assuming the Drell-Yan model, have been produced to extrapolate results using single particle selection efficiency maps.
HIP trigger

- ATLAS trigger system is divided in three levels.
- Level 1: requires a region with 18 GeV of energy deposition in calorimeter and less than 1 GeV in hadronic calorimeter.
- Level 2: dedicated trigger uses TRT information only.
- The number and fraction of TRT HT hits in a wedge aligned with the calorimeter region of size $\Delta \phi = \pm 0.015$ are required to be > 20 and > 0.37, respectively.
- Approximately 7 fb$^{-1}$ of $pp$ collisions data collected since late September 2012.

| Spin-$\frac{1}{2}$ | $|z|=20$ | $|z|=40$ | $|g|=1.0 g_D$ | $|g|=2.0 g_D$ |
|-----------------|--------|--------|-------------|-------------|
| $m=500$ GeV     | 24.9   | 22.2   | 15.9        | 0.03        |
| $m=1500$ GeV    | 28.9   | 10.9   | 23.6        | 0.11        |
| $m=2500$ GeV    | 13.7   | 1.12   | 11.3        | 0.03        |

Trigger efficiencies in % for typical spin-$\frac{1}{2}$ Drell-Yan produced HIP samples
HIP reconstruction

- HIPs that passed the dedicated trigger are reconstructed based on a combination of TRT and LAr EM calorimeter information.
  - A HIP candidate comprises a TRT region with a high fraction of TRT HT hits and EM calorimeter cluster.
  - Only EM calorimeter clusters with transverse energy $E_T > 16$ GeV are considered.
  - TRT regions with a large fraction of TRT HT hits in a narrow swath aligned with a selected EM cluster are selected.
  - EM clusters and TRT regions are uniquely paired.
  - Only one candidate per event is selected.
Event selection

- The $w$ variable measures the lateral dispersion of the energy deposition in the calorimeter:
  - Defined as the average of $w_0$, $w_1$ and $w_2$, where
    $$ w_i = \frac{\sum_n^N E_{n,i}}{E_i}, $$
    $E_n$ the nth highest energy cell in layer $i$, and N=2, 4 and 5 for presampler, EM1 and EM2, respectively, with the N optimized to account for the changing granularity.

- The $f_{HT}$ variable offers good discriminating power, specially for higher charge samples.
  - Defined as the ratio of TRT HT hits over all hits in a rectangular road (wedge) of ±4mm ($\Delta \phi = 0.006$) in the barrel (end-cap).
  - Originally designed for monopoles of charge $|g|=1.0g_D$ and HECOs of charge $|z|\geq40$.

Signal region defined as $w > 0.94$ and $f_{HT} > 0.7$
Event selection efficiency

- Efficiency maps have been obtained using single particle HIPs for definition of fiducial regions of high and uniform event selection efficiency.
  - Average efficiency: $\varepsilon_{\text{avg}} > 0.9$
  - Standard deviation: $\sigma(\varepsilon) < 0.125$
- Level 1 trigger acceptance is the main source of inefficiencies.
- The selection criteria is highly efficient for HIP signals that passed the trigger.

### Table 11: Drell-Yan spin-½ Monopole Selection Efficiencies [%]

| Mass [GeV] | $|g| = 0.5\ g_D$ | $|g| = 1.0\ g_D$ | $|g| = 1.5\ g_D$ | $|g| = 2.0\ g_D$ |
|------------|-----------------|-----------------|-----------------|-----------------|
| 200        | 22.32 ± 0.29    | 3.51 ± 0.13     | 0.14 ± 0.03     | 0.001 ± 0.004   |
| 500        | 33.53 ± 0.33    | 14.86 ± 0.25    | 1.16 ± 0.09     | 0.02 ± 0.02     |
| 1000       | 27.83 ± 0.32    | 23.37 ± 0.30    | 3.65 ± 0.13     | 0.055 ± 0.028   |
| 1500       | 23.66 ± 0.30    | 22.15 ± 0.29    | 3.53 ± 0.13     | 0.099 ± 0.033   |
| 2000       | 16.69 ± 0.26    | 16.53 ± 0.26    | 2.79 ± 0.12     | 0.055 ± 0.024   |
| 2500       | 9.796 ± 0.210   | 9.759 ± 0.216   | 1.61 ± 0.09     | 0.02 ± 0.01     |

### Table 12: Drell-Yan spin-½ HECO Selection Efficiencies [%]

| Mass [GeV] | $|z| = 10$ | $|z| = 20$ | $|z| = 40$ | $|z| = 60$ |
|------------|----------|----------|----------|----------|
| 200        | 3.79 ± 0.13 | 9.66 ± 0.21 | 11.89 ± 0.23 | 3.14 ± 0.12 |
| 500        | 6.714 ± 0.177 | 19.03 ± 0.28 | 20.00 ± 0.28 | 6.169 ± 0.170 |
| 1000       | 10.74 ± 0.22 | 24.61 ± 0.30 | 16.85 ± 0.26 | 3.80 ± 0.13 |
| 1500       | 13.83 ± 0.24 | 22.47 ± 0.30 | 9.966 ± 0.212 | 1.43 ± 0.09 |
| 2000       | 15.51 ± 0.26 | 17.47 ± 0.27 | 3.68 ± 0.13 | 0.24 ± 0.03 |
| 2500       | 12.25 ± 0.23 | 10.24 ± 0.21 | 1.05 ± 0.07 | 0.009 ± 0.007 |

**Points excluded from the search due to low acceptance**
Extrapolation to spin-0

- Efficiencies for spin-0 particles are determined based on single particle event selection efficiency maps.
- Only 4-vectors from MC generator are necessary.
- DY spin-0 selection efficiencies higher than DY spin-$\frac{1}{2}$ due to harder spectra.
- Systematic uncertainty associated to this method is determined from comparing extrapolated DY spin-$\frac{1}{2}$ with fully simulated DY spin-$\frac{1}{2}$ samples.

| Mass [GeV] | $|g| = 0.5 \ g_D$ | $|g| = 1.0 \ g_D$ | $|g| = 1.5 \ g_D$ | $|g| = 2.0 \ g_D$ |
|------------|------------------|------------------|------------------|------------------|
| 200        | 42.5 ± 0.3       | 10.0 ± 0.2       | 0.40 ± 0.04      | 0.01 ± 0.01      |
| 500        | 53.8 ± 0.3       | 34.8 ± 0.3       | 4.1 ± 0.1        | 0.11 ± 0.02      |
| 1000       | 44.3 ± 0.3       | 51.1 ± 0.3       | 11.4 ± 0.2       | 0.39 ± 0.04      |
| 1500       | 36.5 ± 0.3       | 49.7 ± 0.3       | 13.8 ± 0.2       | 0.43 ± 0.04      |
| 2000       | 30.9 ± 0.3       | 41.6 ± 0.3       | 10.9 ± 0.2       | 0.32 ± 0.04      |
| 2500       | 22.9 ± 0.3       | 30.8 ± 0.3       | 6.9 ± 0.2        | 0.12 ± 0.02      |

| Mass [GeV] | $|z| = 10$ | $|z| = 20$ | $|z| = 40$ | $|z| = 60$ |
|------------|---------|---------|---------|---------|
| 200        | 5.9 ± 0.2 | 28.0 ± 0.3 | 27.6 ± 0.3 | 8.2 ± 0.2 |
| 500        | 9.8 ± 0.2 | 35.3 ± 0.3 | 42.1 ± 0.3 | 15.1 ± 0.2 |
| 1000       | 15.1 ± 0.2 | 45.7 ± 0.3 | 37.5 ± 0.3 | 11.4 ± 0.2 |
| 1500       | 19.9 ± 0.3 | 47.7 ± 0.3 | 26.7 ± 0.3 | 4.8 ± 0.1 |
| 2000       | 25.5 ± 0.3 | 43.6 ± 0.3 | 13.2 ± 0.2 | 1.15 ± 0.07 |
| 2500       | 26.9 ± 0.3 | 31.7 ± 0.3 | 4.3 ± 0.1 | 0.18 ± 0.03 |

Points excluded from the search due to low acceptance
Systematics uncertainties on selection efficiency

- **Main systematic uncertainties:**
  - **TRT occupancy:** accuracy of pileup description affects the TRT occupancy. (~3%).
  - **HIP correction to Birks’ law for recombination effects:** uncertainties in the experimental heavy ion data limit the precision of the correction. (~10%).
  - **Cross-Talk in LAr EM calorimeter:** cross-talk in $\phi$ is not implemented in ATLAS simulation. It is considered to be 1.8%. (~1%).
  - **$\delta$-ray production model:** the model has a 3% associated uncertainty. Delta ray production is suppressed by this amount. (~5%).
  - **GEANT4 range cut:** low energy $\delta$-rays are not simulated explicitly. The ID range cut is decreased to 25 µm from 50 µm. (~1%).
  - **Detector material density:** ATLAS geometry with increased ID material including Pixel and SCT services is used. (5% – 15%).
  - **Luminosity:** uncertainty due to the luminosity measurement: 2.8%
  - **Spin-0 extrapolation:** uncertainty due to use of efficiency maps instead of full simulation. (~8%).
Background estimate

- Background estimation performed using a data-driven approach.

- ABCD method is used:
  \[ A_{\text{est}} = \frac{B}{D} = 0.41 \pm 0.24\text{(stat.)} \pm 0.16\text{(sys.)} \]

- Signal leakages are taken into account individually for each sample in the limit setting procedure using a likelihood.

\[
\begin{align*}
\mu_A &= \text{eff}_{\text{sig}} \cdot \mu + \mu^U, \\
\mu_B &= \text{eff}_{\text{sig}} \cdot b\mu + \mu^U \tau_B, \\
\mu_C &= \text{eff}_{\text{sig}} \cdot c\mu + \mu^U \tau_C, \\
\mu_D &= \text{eff}_{\text{sig}} \cdot d\mu + \mu^U \tau_B \tau_C
\end{align*}
\]

<table>
<thead>
<tr>
<th>Region</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
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<tbody>
<tr>
<td>Events</td>
<td>blinded</td>
<td>618</td>
<td>3</td>
<td>4539</td>
</tr>
</tbody>
</table>

Number of events in 7 fb\(^{-1}\) of \(\sqrt{s}=8\text{ TeV}\ pp\) data
Model independent expected limits

- Expected limits are set using the CLs method at 95% CL assuming zero observed events.
- An upper limit on the production cross section of \( \sim 0.5 \text{ fb} \) is expected for single HIPs in fiducial regions.
**Drell-Yan production model expected results**

- Pair production of spin-0 and spin-$\frac{1}{2}$ HIPs using the Drell-Yan model.
- Expected upper limits on production cross section are set assuming zero observed events.
- Improvement with respect to 2011 results is expected.
Conclusion

• Improved limits with respect to search on 2011 data on production cross section and mass for monopoles of charge $1.0g_D$ are expected.

• Run 2 search for HIPs:
  - Improved HIP dedicated trigger: integrates TRT ±4mm rectangular road.
  - Accumulated knowledge from searches for HIPs in run 1 data.
  - Possibility of including dyons (electrically and magnetically charged particles).
  - Extrapolation method allows study of any production model.
Backup
Energy deposition by HIPs

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

![Graph showing energy deposition as a function of velocity for different materials.](image)

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

![Graph showing energy deposition for monopoles.](image)
Spin-0 vs. spin-$\frac{1}{2}$

Spin-$\frac{1}{2}$

Spin-0

MadGraph 5

Charge 1.0 $g$

Charge 1.0 $g_D$

Events/(0.1 GeV)

Events/(10 GeV/c)

Events/(0.05 units)

Events/(10 GeV)

Kinetic Energy $E_K$ [GeV]

Pseudorapidity $\eta$
Signatures in ATLAS

The dashed tracks are invisible to the detector.
HIP trigger

![Graphs showing data and MC predictions for different scenarios.](image)

- **Data**
- **MC $W^\pm \rightarrow e^\nu$**
- **DY spin- $1/2$ m=1000 GeV, $|g| = 1.0g_D$**
- **DY spin- $1/2$ m=1000 GeV, $|g| = 1.5g_D$**

$\sqrt{s} = 8$ TeV, 7.0 fb$^{-1}$
Offline selection

- HIP TRT trigger
- CaloCalTopoCluster
- $E_T^{EM} > 16$ GeV
- $E_{\text{pre}} > 5$ GeV OR $E_{EM1} > 5$ GeV
- $E_{\text{Had}} < 1$ GeV
- $|\eta| < 1.375$ OR $1.52 < |\eta| < 2$
- $w > 0.94$
- $f_{HT} > 0.7$
• Limits are set using the CLs method at 95% CL.

• An upper limit on the production cross section of \(~0.5\,\text{fb}\) has been obtained for single HIPs in fiducial regions.
Single monopole
$m=1000$ GeV, $g=1.0g_D$
Systematics uncertainties

- **TRT occupancy**: accuracy of pileup description affects the TRT occupancy. (~3%).

- **Cross-Talk in LAr EM calorimeter**: cross-talk in \( \phi \) is not implemented in ATLAS simulation. It is considered to be 1.8%. (~1%).

- **\( \delta \)-ray production model**: the model has a 3% associated uncertainty. Delta ray production is suppressed by this amount. (~5%).

- **Detector material density**: ATLAS geometry with increased ID material including Pixel and SCT services. (5% – 15%).
• **HIP correction to Birks’ law**: uncertainties in the experimental heavy ion data limit the precision of the correction. (\(\sim 10\%\)).

• **GEANT4 range cut**: low energy \(\delta\)-rays are not simulated explicitly. The ID range cut is decreased to 25 \(\mu\)m from 50 \(\mu\)m. (\(\sim 1\%\)).

• **Luminosity**: uncertainty due to the luminosity measurement: 2.8%

• **Spin-0 extrapolation**: uncertainty due to use of single particle efficiency maps instead of full simulation. (\(\sim 8\%\)).