MAGNETIC MONOPOLES AND HIGH ELECTRIC CHARGE OBJECTS AT ATLAS

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(VERY) HIGHLY IONIZING PARTICLES (HIPs)

• Magnetic monopole
  • Particle with unit magnetic charge \( g \)

• Elegantly restores symmetry in Maxwell’s Equations

• Explains why charge is quantized (Dirac 1931)
  \[
  \frac{ge}{\hbar c} = \frac{n}{2} \iff \frac{g}{e} = \frac{n}{2\alpha} \approx 68.5n
  \]

• High (equivalent) charge \( \rightarrow \) highly ionizing

• Dirac argument has no spin preference

• High Electric Charge Objects (HECOs)
  • Strangelets, Q-balls and micro black hole remnants
PRODUCTION MECHANISM AT THE LHC

Conservation of magnetic charge mandates pair production

- Electromagnetic interaction $\rightarrow$ HIPs couple to photon
- Two mechanisms: Drell-Yan (DY) and photon fusion (PF)

- Monopole-photon coupling constant
  \[ \alpha_m = \frac{g_B^2}{\hbar c} = \frac{1}{4\alpha_e} \approx 34 \gg 1 \]
  $\Rightarrow$ no perturbative expansion!

- Model with MadGraph5_aMC@NLO
  - Consider DY spin-0, spin-$\frac{1}{2}$, and spin-1 so far
• Red: spin 0
• Green: spin $\frac{1}{2}$
• Blue: spin 1
PAST HIP SEARCHES AT ATLAS

• 2010 7 TeV HECO search, $6 \leq |z| \leq 17$, DY spin $\frac{1}{2}$
  http://dx.doi.org/10.1016/j.physletb.2011.03.033

• 2011 7 TeV Monopole search, $|g| = 1$, DY spin $\frac{1}{2}$
  http://dx.doi.org/10.1103/PhysRevLett.109.261803

• 2012 8 TeV HIP search, $0.5 \leq |g| \leq 2$, $10 \leq |z| \leq 60$, DY, spin 0, $\frac{1}{2}$,
  http://dx.doi.org/10.1103/PhysRevD.93.052009

• 2016 13 TeV HIP search in progress
MONOPOLE INTERACTION WITH DETECTOR

- Energy loss by ionization at high velocities proportional to $g^2$

\[-\frac{dE}{dx} = \frac{4\pi e^2 g^2}{m_e c^2} N_e \left[ \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) + \frac{K(|n|)}{2} - \frac{1}{2} - \frac{\delta}{2} - B(|n|) \right]\]


\[\frac{g_D}{e} = \frac{\hbar c}{2e^2} = \frac{1}{2\alpha} \approx 68.5\]

⇒ 4700 times more than a proton!
⇒ Lots of $\delta$-rays emitted
- Independent of HIP spin
- Monopole trajectory bends in r-z plane
- Need full GEANT4 simulation for HIPs
VALIDATION OF MONOPOLE SIMULATION

- Monopole trajectory bends in the r-z plane:

\[
\frac{dp}{dt} = g \vec{B}
\]

G. Palacino, CERN-THESIS-2015-260
https://cds.cern.ch/record/2119479
VALIDATION OF MONOPOLE SIMULATION

- Implementation of charge parameter and $\beta$ dependence of $dE/dx$

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VALIDATION OF MONOPOLE SIMULATION

- Implementation of acceleration of magnetic charge in solenoidal magnetic field

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VALIDATION OF MONOPOLE SIMULATION

• Time delay of calorimeter cluster

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https://cds.cern.ch/record/2119479
VALIDATION OF MONOPOLE SIMULATION

- HIP correction to Birks’ Law in LAr
  - Compare monopole ionization in LAr calorimeter to published data for gold ions (Z=79) in LAr [E. Shibamura et al., Nucl. Instrum. Meth. A260, 437 (1987)]
  - Accounts for suppression of visible energy due to e-Ar ion recombination
  - Correctly takes care of energy deposition of δ-electrons

HIP SIGNATURE

- HIPs stop early in EM cal → no muon-like signature
- Large energy deposit in EM calorimeter
- High ionization and many $\delta$-rays
  → Lots of high ionization hits in the Transition Radiation Tracker (TRT)
- No bremsstrahlung or pair production
  → Narrow energy deposit in EMCal
- Monopole trajectory bends in r-z plane
  → Incompatible with standard tracking

1200 GeV Magnetic Monopole

Monopole $dE/dx$ in LAr

- Ionization
- Bremsstrahlung
- Pair-production

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TRIGGERING ON HIPS

• At Level 1, have to use what is available: 22 GeV or higher cluster in EM calorimeter, with variable-threshold hadronic veto

• HIPs fail isolation criteria (and track reconstruction) in Level 2 electron triggers due to δ-electrons (and bending for monopoles)

• Level 2 single photon trigger energy threshold too severe

• Custom L2 HIP trigger uses calorimeter and TRT information
  • High efficiency (~50%) and low bandwidth (<1 Hz)
LIQUID ARGON CALORIMETER

- Ionizing particles in liquid argon (LAr) create electron-ion pairs
- An electric field is applied to collect ionization electrons
  - Scale charge appropriately to determine energy deposited
- 4 layers: presampler, EM1, EM2, EM3
**CLUSTER DISPERSION W VARIABLE**

- Defined as the average of $w_0$, $w_1$ and $w_2$, defined for the presampler, EM1 and EM2, respectively.

- $w_i$’s are defined as the fraction of the EM cluster energy contained in the two, four and five highest energy cells in the presampler, EM1 and EM2, respectively.

![ATLAS plot](image)
ATLAS TRANSITION RADIATION TRACKER (TRT)

- ~35 layers of drift-tube straws filled with Xe (Ar) gas
- Two energy thresholds for readout
  1. Low threshold (LT)
  2. High threshold (HT)
Count number of TRT hits in road around calorimeter energy deposit

Select events where the number of high threshold (HT) hits and the fraction $f_{HT}$ of HT hits are above some threshold
ANALYSIS STRATEGY

- Get efficiency maps in $E_{T}^{\text{kin}}$ vs $\eta$ from fully simulated single-particle MC
- Truth-level pair production (DY) MC specifies model- and spin-dependent kinematics
  - Extrapolate efficiency by sampling efficiency maps for $(E_{T}^{\text{kin}}, \eta)$ of each truth particle
- Derive data-driven background estimate using ABCD method
RESULTS

- No HIP observed in 7 fb\(^{-1}\) of 8 TeV data (2012)

- Drell-Yan spin \(\frac{1}{2}\)
RESULTS

- No HIP observed in 7 fb\(^{-1}\) of 8 TeV data (2012)

- Drell Yan spin 0

- Coming soon: result from 34.5 fb\(^{-1}\) of 13 TeV data (2015, 2016)
OPTIONS FOR FUTURE HIP SEARCHES AT ATLAS

• Full Run 2 dataset
• Model interpretations
  • Extend search to include photon fusion production
  • Consider dyons with magnetic charge and electric charge $\sim 1.0e$
• Introduce ATLAS IBL (Inner Barrel Layer pixel detector) into event selection
• Other unmentionable crazy ideas we’ve thought about
• Your suggestion here
BACKUP SLIDES
PAST HIP SEARCHES AT THE LHC

- **ATLAS 2010 7 TeV HECO search**, $6 \leq |z| \leq 17$, [http://dx.doi.org/10.1016/j.physletb.2011.03.033](http://dx.doi.org/10.1016/j.physletb.2011.03.033)
- **ATLAS 2011 7 TeV Monopole search**, $|g|=1$, [http://dx.doi.org/10.1103/PhysRevLett.109.261803](http://dx.doi.org/10.1103/PhysRevLett.109.261803)
- **ATLAS 2012 8 TeV HIP search**, $0.5 \leq |g| \leq 2$, $10 \leq |z| \leq 60$, spin $0$, $\frac{1}{2}$, [http://dx.doi.org/10.1103/PhysRevD.93.052009](http://dx.doi.org/10.1103/PhysRevD.93.052009)
- **ATLAS 2016 13 TeV HIP search in progress**
- **MoEDAL 8 TeV monopole search**, $1 \leq |g| \leq 4$, spin $0$, $\frac{1}{2}$, [http://dx.doi.org/10.1007/JHEP08(2016)067](http://dx.doi.org/10.1007/JHEP08(2016)067)
- **MoEDAL 13 TeV monopole search**, $1 \leq |g| \leq 5$, spin $0$, $\frac{1}{2}$, [http://dx.doi.org/10.1103/PhysRevLett.118.061801](http://dx.doi.org/10.1103/PhysRevLett.118.061801)

- **ATLAS 2011 7 TeV Multicharge search**, $2 \leq |z| \leq 6$, [http://dx.doi.org/10.1016/j.physletb.2013.04.036](http://dx.doi.org/10.1016/j.physletb.2013.04.036)
- **ATLAS 2012 8 TeV Multicharge search**, $2 \leq |z| \leq 6$, [http://dx.doi.org/10.1140/epjc/s10052-015-3534-2](http://dx.doi.org/10.1140/epjc/s10052-015-3534-2)
- **CMS 7,8 TeV Multicharge search**, $1/3 \leq |z| \leq 8$, [http://dx.doi.org/10.1007/JHEP07(2013)122](http://dx.doi.org/10.1007/JHEP07(2013)122)
HIP ENERGY LOSS

- HECO ionization at high velocities proportional to $z^2/\beta^2$

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

- Independent of HECO spin

- $\beta$ dependence is different from that of monopole $dE/dx$:

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