Long-lived Particle Searches at Colliders

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• Fundamental physics puzzles
• Split-SUSY and long-lived gluinos
• Magnetic Monopoles
• Past searches – LEP, Tevatron
• ATLAS search plans
History of new particles

• 1950-1974 :
  ➢ hadron jungle, neutrino
  ➢ quark model confirmed

• 1974-1994 :
  ➢ heavy quarks, tau, $W$ and $Z$...
  ➢ 3 generations, EW unification confirmed

• 2010 and onward :
  ➢ We generally expect new particles to be heavy and short-lived (e.g., Higgs boson)
  ➢ Long-lived? (e.g., WIMP)
Today's particle physics puzzles

- Origin of mass, mass hierarchy
- Unification of forces
- Matter-antimatter asymmetry
- Dark matter

Proposed searches

- Higgs boson
- Precision measurements
- Exotic phenomena, e.g., Supersymmetry

New data needed!
Split-SUSY
arXiv:hep-th/0405159

- Accept the unnaturalness of the Higgs mass
- Supersymmetry breaking occurs at $M_s >> 1$ TeV
- Scalars have mass at this scale
Nice features of split-SUSY

• Unification of couplings
• Long proton lifetime
• Long-lived gluino
→ R-Hadrons!

\[ \tilde{g} \rightarrow \tilde{q} \rightarrow q, \tilde{q}, \chi \]
Examples of well-motivated exotic long-lived particles

- Neutral LSP dark matter \((R\text{-parity cons.})\)
- Metastable squark or gluino \((\text{kinematics})\)
- Metastable stau NLSP \((\text{LSP gravitino})\)
- Magnetic Monopole \((\text{charge conservation})\)
- Leptoquark \((\text{weak coupling})\)
Magnetic Monopoles

• Dirac's argument (1931)
  – Angular momentum of field of electron-monopole system:

\[ L = \int r \times E \times B \text{d}r \text{d}\theta \text{d}\phi \]

\[ = \frac{\mu_0 e \gamma}{4\pi} \Rightarrow e = \frac{nh}{g\mu_0} \quad g_D = \frac{h}{e\mu_0} \]

• “explain” charge quantization

• Symmetrize Maxwell Equations

• Ingredient in Grand Unification Theories
Monopoles – kinematics

• Direct pair production processes at colliders:

- Higher-order corrections?
  - Strong $g$ coupling $\rightarrow$ non-perturbative dynamics !!!
  - Must rely on models for the cross section and kinematics calculations!
Monopoles - ionization

• Stopping power for electrically charged particle

\[ \frac{dE}{dx} = \frac{4\pi e^4 Z_1^2}{m_e c^2 \beta^2 n} \left( \frac{1}{2} \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I_e^2} \right) - \beta^2 - \frac{\delta}{2} \right) \]

• Stopping power for monopole (charge \( g \))

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

• \( g \approx 137/2 \ e \): several thousand times greater \( \frac{dE}{dX} \)
Monopole bending in a magnetic field

- Acceleration along beam axis
- Parabolic trajectory in rz plane

Tasso: W. Braunschweig et al., Z. Phys. C38 (1988) 543
SQUID technique

- At HERA and the Tevatron
- Search for trapped Monopoles
- Old beam pipe and detector material in a superconducting coil to sense flux jump
Plastic track-etch detectors

- Pits due to highly-ionizing particles
- Tevatron
- LEP


- **MoEDAL** (LHC)
  - At Point 8
  - Run in 2010
Current cross section limits for Dirac Monopoles

- Limits only valid for given mass ranges
- Unwise to quote mass limits (must assume production model)
Long-lived particles carrying colour charge

- **Colour-triplets**:
  - Spin-0: leptoquark, squark
  - Spin-1/2: KK-quark, 4\textsuperscript{th} gen quark

- **Colour-octets**:
  - Spin-1/2: gluino
  - Spin-1: KK-gluon

- Large production cross sections
- R-Hadrons with integer charges
Heavy Coloured objects at the LHC

- **Strong process**, e.g. gluino pair production
  - mass 300 GeV → more than 100000/fb
    (14 TeV pp collisions)

![Diagram showing gluino pair production](image)

![Graph showing cross-sections vs mass](image)
R-Hadrons

- **Long-lived** > 50 ns (size of ATLAS)
- **Heavy** > 250 GeV (current limit)
- **Coloured**

Pair production
Hadronization
Baryon exchange
Charge exchange
Elastic scattering etc...
High-Pt Muon track

**Generic signature:** slow and high momentum
R-Hadrons: mass spectra

- **Quark-like**: similar to charmed and bottomed hadrons (e.g. \( \Lambda_c^+ \))
- **Gluon-like**: assume a model
  - Lightest state \( \rightarrow \) neutral or charged?
  - Gluino balls?

<table>
<thead>
<tr>
<th>Heavy Parton</th>
<th>States</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squark</td>
<td>( \tilde{q}u, \tilde{q}d )</td>
<td>( m_{\tilde{q}} + 0.3 )</td>
</tr>
<tr>
<td></td>
<td>( \tilde{q}ud )</td>
<td>( m_{\tilde{q}} + 0.7 )</td>
</tr>
<tr>
<td>Gluino</td>
<td>( \tilde{g}q\bar{q}, \tilde{g}ud, \tilde{g}d\bar{u}, \tilde{g}g )</td>
<td>( m_{\tilde{g}} + 0.7 )</td>
</tr>
<tr>
<td></td>
<td>( \tilde{g}uds )</td>
<td>( m_{\tilde{g}} + 0.7 )</td>
</tr>
</tbody>
</table>

arXiv:0908.1868
CDF search using dE/dx in inner detector

CDF search using TOF in muon detector

- 250 GeV mass limit for a long-lived scalar top quark

Published mass limits

- Assume standard couplings
- What are the limits for a color-octet?
Generic signature-based long-lived particle searches in ATLAS

- Displaced vertices / kinks
- Non-pointing photons
- Low EM calorimeter fraction
- Out-of-bunch-crossing
- Slow tracks
- High invariant mass dimuons
- Highly ionizing tracks

decaying

non-decaying
Early data: **Generic & Simple**

- **Systematics**
  - Efficiency
  - Robustness
  - Backgrounds

- **Non-optimum conditions**

- **Look for extreme signatures**

- **Use several independent variables**

![Diagram of particle tracks and labels for ID track and $\mu^+\mu^-$]
Expected signature: low speed

- Measure time-of-flight of high-momentum objects
  - Calorimeter
  - muon RPC
- If correlation
  - Slow massive particle!
Expected signature: reconstructed mass

R-Hadrons

muons
Expected signature: invariant mass of two muons
R-Hadrons: possible selection criteria

1. **Low $\beta$** in muon system and/or calorimeter
   - **Fakes**: muon $\beta$ distributions obtained from $Z \rightarrow \mu\mu$

2. **High-$p_T$** muon track without associated ID track
   - **Fakes**: ID efficiency vs. $p_T$ obtained from $Z \rightarrow \mu\mu$

3. **Additional muon** and high invariant mass
   - **Fakes**: high-$p_T$ tails obtained from $Z \rightarrow \mu\mu$

4. **A combination of the above**
What could happen

• Look for **anomalies** in spectra of muon objects
  
  – All variables behave as expected for ordinary muons → **cross section and mass limits**
  
  – **Excess** → Detector effect? Unexpected backgrounds? New physics?

• **Combine** all variables: **unmistakable events**?
High-Q/Monopoles in ATLAS

- High E in small area
- $E/p \sim 1$ when $\beta \sim 1$
- $E/p \rightarrow 0$ when $\beta < 1$
- $E/p \gg 1$ with 100% TRT HT hits
Summary

• Fundamental physics puzzles
  – We expect new physics at the TeV scale
  – LHC will probe these regions
  – Signatures: electrons, jets, missing energy, long-lived particles!

• Search techniques with general-purpose experiments (experience from LEP and Tevatron)
  – Late arrival / late decays
  – Energy loss
  – Special event topologies
Outlook

• As soon as the LHC machine runs at high energies
  – Look at all possible signatures
  – Can we do something even with non-optimized data?
  – e.g. R-Hadrons, Monopoles in ATLAS
    → striking events
  – Possibly large cross sections
    → high masses accessible early
Extra slides
Free quarks / low-charge objects

SUSY models giving rise to SMPs

<table>
<thead>
<tr>
<th>SMP</th>
<th>LSP</th>
<th>Scenario</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\tau}_1 )</td>
<td>( \tilde{\chi}_1^0 )</td>
<td>MSSM</td>
<td>( \tilde{\tau}<em>1 ) mass (determined by ( m</em>{\tilde{\tau}<em>{2,n}}^2, \mu, \tan \beta ), and ( A</em>\tau )) close to ( \tilde{\chi}_1^0 ) mass.</td>
</tr>
<tr>
<td>( \tilde{\tau}_1 )</td>
<td>GMSB</td>
<td>Large ( N ), small ( M ), and/or large ( \tan \beta ).</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\tau}_1 )</td>
<td>AMSB</td>
<td>Small ( m_{\tilde{\tau}<em>{2,n}} ) and/or large ( \tan \beta ) and/or very large ( A</em>\tau ).</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\ell}_1 )</td>
<td>( \tilde{\chi}_1^0 )</td>
<td>MSSM</td>
<td>( \tilde{\ell}_1 ) NLSP (see above). ( \tilde{\ell}_1 ) and ( \tilde{\mu}_1 ) co-NLSP and also SMP for small ( \tan \beta ) and ( \mu ).</td>
</tr>
<tr>
<td>( \tilde{\ell}_1 )</td>
<td>GMSB</td>
<td>( \tilde{\ell}_1 ) and ( \til\mu_1 ) co-LSP and also SMP when stau mixing small.</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_1^+ )</td>
<td>( \tilde{\chi}_1^0 )</td>
<td>MSSM</td>
<td>Very large ( M_{1,2} \gtrsim 2 ) TeV ( \gg</td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 )</td>
<td>AMSB</td>
<td>( M_1 &gt; M_2 ) natural. ( m_0 ) not too small. See MSSM above.</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 )</td>
<td>GMSB</td>
<td>SUSY GUT extensions [25–27].</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 )</td>
<td>GMSB</td>
<td>Very small ( M_3 \ll M_{1,2} ). O-II models near ( \delta_{GS} = -3 ).</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 )</td>
<td>AMSB</td>
<td>Non-universal squark and gaugino masses. Small ( m_{\tilde{\chi}}^2 ) and ( M_3 ), small ( \tan \beta ), large ( A_\tau ).</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 )</td>
<td>AMSB</td>
<td>Small ( m_{\tilde{u}}^2 ) and ( M_3 ), large ( \tan \beta ) and/or large ( A_b \gg A_t ).</td>
<td></td>
</tr>
</tbody>
</table>

Table 1

Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario.

Gluino lifetime sin split-SUSY

\[ \tau \approx 0.03 \left( \frac{m_s}{10^9 \text{GeV}} \right)^4 \left( \frac{\text{TeV}}{m_{\tilde{g}}} \right)^5 \text{s} \]

- Allowed in most scenarios
- Gluino cτ~1 meter
- Gluino hadronizes
Interactions of R-Hadrons with detector material

- Heavy parton unlikely to interact (cross section suppressed by $1/m^2$)
- Effectively low-energy (~GeV) interactions involving light quarks
  - Regge Theory
- Light quark flavor can change several times during the passage through the detector

Non-pointing photons

- In GMSB, the symmetry is broken by gauge interactions through messenger gauge fields. If decay length of the neutralino is comparable to the size of the ATLAS inner detector, high pT photons could enter the calibrimeter at angles ($\eta_2$) deviating significantly from the nominal pointing angle ($\eta_2$).
  
  i.e. $\eta_2 \neq \eta_2$

![Diagram of Middle Layer and Front Layer with clusters and decay chain]
Displaced vertices

Late decays into muons and taus via RPV:

- Most similar
- We are looking for DV with muons.
- BR very small

Are CDF ghost events due to RPV SUSY: probably not
Are we sensitive to this kind of events: yes
Event selection

Search for stop and gluino R-Hadrons, optimized for 1 fb⁻¹ of integrated luminosity for pp collisions at 14 TeV

• **Trigger**: muon trigger

• **Selection**: jet veto + one of the following criteria
  - Hard \( p_T > 250 \) GeV muon track lacking inner track
  - Two hard back-to-back inner tracks with few high-threshold (HT) hits
  - Two hard back-to-back *like-sign* muon tracks
  - One hard muon track with inner track of *opposite charge*
Simulated data

• **Signal samples**
  – Gluinos 300, 600, 1000, 1300, 1600, 2000 GeV
  – Stops 300, 600, 1000 GeV

• **Background samples**
  – QCD dijets (PYTHIA) with $p_T > 140$ GeV
  – Top pairs (semi-leptonic)
  – $W$ and $Z$ with muons in final state

• **Full ATLAS simulation**

• **Standard ATLAS reconstruction**
Final state observables

- $p_T$ of muon tracks (normalized to 1 fb$^{-1}$)

- High-threshold (HT) hits in inner tracker
Charge-flipping signature

\[ q_{ID}p_{T,ID}/q_{\mu}p_{T,\mu} \]

Gluino masses: (GeV)
- 300
- 600
- 1000
- 2000

Stop masses: (GeV)
- 300
- 600
- 1000

ATLAS
Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass [GeV]</th>
<th>Event Rate / fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{g}$</td>
<td>300</td>
<td>6400</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>11</td>
</tr>
<tr>
<td>$t_1^\tau$</td>
<td>300</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>4</td>
</tr>
<tr>
<td>BG</td>
<td>QCD di-jet</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>$Z\rightarrow\mu\mu$</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Instrumental backgrounds

- Use $Z \rightarrow \mu\mu$ *tag-and-probe*
  - High-$p_T$ tail fractions
  - Charge misidentification probability
  - Standalone track reconstruction efficiency

- *In situ* determination of both ID and muon system performances at high $p_T$
  
  - Mu20 trigger
  - Require another muon track with $p_T > 20$ GeV
  - Use for Z mass tagging
  - Is the muon track consistent?