LONG-LIVED HEAVY CHARGED PARTICLES AT THE LHC

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Studies of long-lived heavy charged particles (e.g., slepton\(\text{s}\)) (let’s call them CHAMPs here) are

- **Well-motivated** – by gauge hierarchy, dark matter. No more exotic than MET
- **Timely** – real possibilities for the Tevatron and early years of the LHC
- **Easy** – just because it’s easy doesn’t mean it’s wrong
- **Fun** – “If every individual student follows the same current fashion …, then the variety of hypotheses being generated…is limited…But if [the truth] lies in another direction, who will find it? Only someone who has sacrificed himself…But if my own experience is any guide, the sacrifice is really not great because…you always have the psychological excitement of feeling that possibly nobody has yet thought of the crazy possibility you are looking at right now.”

  — Richard Feynman, Nobel Lecture
OUTLINE

• MET Myths

• Theoretical Frameworks
  – GMSB, SUGRA, AMSB, Universal Extra Dimensions, …

• Searches
  – Current Bounds, LHC Prospects

• Studies
  – Masses, Spins, Mixings, Decay
MET MYTHS

Myth #1: Dark matter → MET at colliders

Supersymmetry
- R-parity
  - Neutralino DM
    - Fayet, Farrar (1974)
    - Goldberg (1983); Ellis et al. (1984)

Universal Extra Dimensions
- KK-parity
  - Kaluza-Klein DM
    - Appelquist, Cheng, Dobrescu (2000)
    - Servant, Tait (2002)
      - Cheng, Feng, Matchev (2002)

Branes
- Brane-parity
- Branons DM
  - Cembranos, Dobado, Maroto (2003)
...
COUNTER-ARGUMENTS

• Dark matter might be axions or something else, completely decoupled from weak scale physics

• But what about the WIMP miracle?

• Seems to argue for stable WIMPs and therefore MET
COUNTER-EXAMPLE: SUPERWIMPS

Feng, Rajaraman, Takayama (2003)

Consider supersymmetry (similar story in UED). There is a gravitino, mass \( \sim 100 \text{ GeV} \), couplings \( \sim M_w/M_{Pl} \sim 10^{-16} \)

- \( \tilde{G} \) not LSP

- Assumption of most of literature

- \( \tilde{G} \) LSP

- Completely different cosmology and particle physics
SUPERWIMP RELICS

• Suppose gravitinos $\tilde{G}$ are the LSP

• WIMPs freeze out as usual

• But then all WIMPs decay to gravitinos after $M_{Pl}^2/M_W^3 \sim$ seconds to months

Like WIMPs: a particle (gravitino) naturally gets the right relic density

Unlike WIMPs: If WIMP is charged, signal is CHAMP, not MET
COSMOLOGY OF LATE DECAYS

Late decays impact light element abundances, CMB, ...

Lots of recent work, boundary of excluded region moves, but viability is not in question. In fact, these considerations strengthen the CHAMP motivation: BBN excludes $\chi \rightarrow Z \tilde{G}$, but $\tilde{I} \rightarrow I \tilde{G}$ ok

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MYTH 2: PRECISION EW $\rightarrow$ MET

- Large Electron Positron Collider at CERN, 1989-2000

- LEP and SLC confirmed the standard model, stringently constrained effects of new particles

- Problem: Gauge hierarchy $\rightarrow$ new particles $\sim 100$ GeV
  LEP/SLC $\rightarrow$ new particles $> 3$ TeV
  (even considering only flavor-, CP-, B-, and L-conserving effects)
LEP’S COSMOLOGICAL LEGACY

- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.
  
  Cheng, Low (2003); Wudka (2003)

- This is a powerful argument that the LHC may make DM

- But it does not necessarily imply MET (see superWIMPs)
MYTH 3: OTHER CONSTRAINTS → MET

- E.g., proton decay in SUSY:

  $\begin{align*}
  p \rightarrow d \bar{u} e^+ \\
  u \rightarrow \bar{u} \bar{u} \pi^0
  \end{align*}$

- Forbid this with R-parity conservation: $R_p = (-1)^{3(B-L)+2S}$
  - SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Require $\prod R_p = 1$ at all vertices

- Consequence: the lightest SUSY particle (LSP) is stable
But this also does not require MET

- **R-parity might be broken**
  - B (or L) conservation alone forbids proton decay
  - admittedly an unattractive possibility, as one loses dark matter and R-parity must still be nearly conserved

- **R-parity might be conserved**
  - See superWIMPs: gravitino could be the stable LSP, signal is CHAMPs
BOTTOM LINE

• MET is not necessarily the most motivated signature of new physics at the LHC

• Easy to think of scenarios that
  – Solve the gauge hierarchy problem
  – Have DM with naturally the right relic density
  – Are consistent with EW precision constraints
  – Are consistent with all other constraints
  – Have no MET signal at the LHC

• Let’s consider CHAMPs. How general are they?
THEORETICAL FRAMEWORKS

• Supersymmetry: Motivations
  – The gauge hierarchy problem
  – Force unification
  – Radiative electroweak symmetry breaking
  – Maximal extension of space-time symmetries
  – String theory

• Flavor problem: gravitational contributions to squark and slepton masses, typically \( \sim \) gravitino mass \( m_{\tilde{G}} \), generically violate flavor, CP

• These violate low energy constraints (badly)
  – Flavor: Kaon mixing, \( \mu \rightarrow e \gamma \)
  – Flavor and CP: \( \varepsilon_K \)
  – CP: neutron EDM, electron EDM

• The flavor problem motivates essentially all of SUSY model building

\[ m_{\tilde{q}}^2 = \begin{pmatrix}
\sim m_G^2 \\
\sim m_G^2 \\
\sim m_G^2 \\
\sim m_G^2
\end{pmatrix} \]
GAUGE-MEDIATED SUSY BREAKING

- Introduce a source of universal slepton and squark masses mediated by messenger particles
  - $N_5$ $5 + 5$’s
  - Mass $M$

- To solve flavor problem
  $m_{\tilde{G}} \ll m_0 \rightarrow$ LSP = $\tilde{G}$

- NLSP
  - Which particle: determined by $N_5$
  - Lifetime: determined by $F \leftrightarrow M$

\[ m_{\tilde{q}} = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix} + \begin{pmatrix} \sim m_G^2 & \sim m_G^2 & \sim m_G^2 \\ \sim m_G^2 & \sim m_G^2 & \sim m_G^2 \\ \sim m_G^2 & \sim m_G^2 & \sim m_G^2 \end{pmatrix} \]

\[ M_i(M) = N_5 \Lambda c_i \frac{g_i^2(M)}{16\pi^2} \]

\[ M_i^2(M) = 2N_5\Lambda^2 \sum_{i=1}^{3} C_i^f \left[ \frac{g_i^2(M)}{16\pi^2} \right]^2 \]
GMSB SIGNATURES

- Stau is the NLSP in much of parameter space (if $N_5 > 1$)

- Decay length shown is a lower bound: increased if SUSY breaking in other sectors

- 4 possible signatures:
  - Prompt photon
  - MET
  - Multi-leptons
  - CHAMPs

\[ c_\tau > 100 \text{ m} \]
GRAVITY-MEDIATED SUSY BREAKING

- Solve the flavor problem by fiat

- mSUGRA’s famous 4+1 parameters:
  \[ m_0^2, M_{1/2}, A_0, \tan \beta, \text{sign}(\mu) \]

- Excluded regions
  - LEP limits
  - Stau LSP

- But this is incomplete
  - Missing \( m_{\tilde{G}} \)
  - Assumes \( m_0^2 > 0 \)
Extend the mSUGRA parameters to

\[ m_0^2, M_{1/2}, A_0, \tan \beta, \text{sign}(\mu), \text{and } m_{3/2} \]

- If LSP = gravitino, then no reason to exclude stau (N)LSP region
- Also include small or negative

\[ m_0 \equiv \text{sign}(m_0^2) \sqrt{|m_0^2|} \]
- This includes no-scale/gaugino-mediated models with \( m_0 = 0 \)
- Much of the new parameter space is viable with a slepton NLSP and a gravitino LSP
OTHER SUSY FRAMEWORKS

• Long-lived heavy particles may result from phase space suppression or decay through heavy virtual particles

• 2 common (but imperfect) motivations
  – Winos in AMSB (but $M_1 = 3.3 M_2$, typically gives $c\tau < 10$ cm)
  – Gluinos in split SUSY (unnatural)

\[
\begin{aligned}
\chi^0, \pi^\pm, \pi^+\pi^- 0, e\nu, \mu\nu, \ldots
\end{aligned}
\]
UNIVERSAL EXTRA DIMENSIONS

- Assume 1 extra dimension, where the 5th dimension is a circle with radius $R$

- All Kaluza-Klein level 1 states have mass $R^{-1}$

- This is broken by many effects, but the lightest KK states are still highly degenerate

Appelquist, Cheng, Dobrescu (2000)
UED COMMON LORE

• UED looks like SUSY
  – $n=2$ and higher levels typically out of reach
  – $n=1$ Higgses $\rightarrow A, H^0, H^\pm$
  – Colored particles are heavier than uncolored ones
  – LKP is stable $B^1 \rightarrow$ MET at LHC

• Spectrum is more degenerate, but basically similar to SUSY
  “Bosonic supersymmetry”

Cheng, Matchev, Schmaltz (2002)
BUT THERE’S MORE

- $R$ is the only new parameter, but it is not the only free parameter: the Higgs boson mass is unknown.

- Original collider studies set $m_h = 120$ GeV, but it can be larger (KK towers modify EW precision constraints).

- $H^0$, $A$, $H^\pm$ masses depend on $m_h$.

- Also, there’s another state in the theory: the KK graviton $G^1$. 

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Including the KK graviton and varying over the Higgs mass, we find several possible LKPs (and NLKPs)

- The lightest states are extremely degenerate

- One might expect degeneracies of

  \[ m_W^2 R \approx 10 \text{ GeV} , \]

  but these are tightened by modest accidental cancelations
CHAMPS IN UED

• In minimal UED, after all particle and astrophysical constraints, NLKP → LKP is
  \[ H^{\pm 1} \rightarrow B^1 f f' \]

• Mass splitting \( \Delta m < 7 \text{ GeV} \)

• Decay length \( c\tau > 10 \mu\text{m} \)
SEARCHES

• Current Bounds
  – LEP: slepton mass > 97.5 GeV, chargino > 102.5 GeV
  – CDF Run I: slepton cross section < 1 pb
  – CDF Run II: top squark mass > 249 GeV
- D0 Run II: chargino mass > 200 GeV
- D0 Run II: slepton cross section < 0.1 pb
  - assumes only Drell-Yan pair production (no cascades)
  - require 2 slow, isolated “muons”
  - about a factor of 5 from unexplored mass territory
LHC DISCOVERY POTENTIAL

- Look for Drell-Yan slepton pair production
- Require events with 2 central, isolated “muons” with
  - \( p > 100 \text{ GeV} \)
  - \( p_T > 20 \text{ GeV} \)
- Finally assume TOF detector resolution of 1 ns, require both muons to have TOF delays > 3 ns

<table>
<thead>
<tr>
<th>Model</th>
<th>Total cross-section</th>
<th>After Drell-Yan cuts</th>
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</thead>
<tbody>
<tr>
<td>Model A</td>
<td>18 pb</td>
<td>9 pb</td>
</tr>
<tr>
<td>Model B</td>
<td>43 fb</td>
<td>28 fb</td>
</tr>
<tr>
<td>QCD</td>
<td>( 10^2 \text{mb} )</td>
<td>&lt; 1 pb</td>
</tr>
<tr>
<td>( \gamma^* / Z \rightarrow \mu \mu )</td>
<td>100 nb</td>
<td>3 pb</td>
</tr>
<tr>
<td>W+jet</td>
<td>360 nb</td>
<td>&lt; 40 fb</td>
</tr>
<tr>
<td>Z+jet</td>
<td>150 nb</td>
<td>7 pb</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>800 pb</td>
<td>430 fb</td>
</tr>
<tr>
<td>WW, WZ, ZZ</td>
<td>2.5 nb</td>
<td>150 fb</td>
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</table>

<table>
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<tr>
<th>Time delay of Drell-Yan: background</th>
<th>0ns</th>
<th>1 ns</th>
<th>2ns</th>
<th>3ns</th>
<th>4ns</th>
<th>5ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 pb</td>
<td>1.35 pb</td>
<td>3.3 fb</td>
<td>0.2 ab</td>
<td>&lt; 0.1 ab</td>
<td>&lt; 0.1 ab</td>
<td></td>
</tr>
<tr>
<td>Drell-Yan: Model A</td>
<td>9 pb</td>
<td>5.2 pb</td>
<td>2.9 pb</td>
<td>1.8 pb</td>
<td>1.1 pb</td>
<td>750 fb</td>
</tr>
</tbody>
</table>

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• Require $5\sigma$ signal with $S > 10$ events for discovery

• Model A is “best case scenario”

• Lesson: Very early on, the LHC will probe new territory
CMS/ATLAS ANALYSES

- Ongoing work on CHAMP search and reconstruction
  - ATLAS (Tarem et al.): added ToF calculation to level 2 trigger to improve reconstruction efficiency
  - CMS (Rizzi): studied both dE/dx and ToF (Analysis Note (2006))

![Graph showing entries/bin for different categories]

- Efficiency of 2 μ reconstruction programs as function of β

![Graph showing reconstruction efficiency for Muid and Staco]
PRECISION STUDIES

- CHAMP masses may be measured precisely

\[ m_{\tilde{\tau}_1} = \frac{p_{\text{meas}}}{\beta \gamma_{\text{meas}}} \]

- CHAMP spins determined by reconstructing the angular distribution of Drell-Yan production in the COM frame

**Figure 3:** Scatter plot of measured velocity $\beta \gamma_{\text{meas}}$ versus measured mass (left), with supersymmetric events in black and SM background events in red, and a corresponding plot of the measured stau mass (right) with an additional cut on the velocity of $0.3 < \beta \gamma < 0.6$.

Rajaraman, Smith (2007)
FLAVOR MIXINGS

• In CHAMP scenarios, all particles are observed, ideal for detailed measurements of masses and mixings

• Consider, e.g., hybrid SUSY models: flavor-conserving mGMSB + flavor-violating gravity-mediated masses

\[
M^2_{\nu} = m^2_L 1 + x \tilde{m}^2 X_L \\
M^2_{E_L} = m^2_L 1 + m_E m_E^\dagger + x \tilde{m}^2 X_L \\
M^2_{E_R} = m^2_R 1 + m_E^\dagger m_E + x \tilde{m}^2 X_R , \quad X_L = \begin{pmatrix} c_{10}\lambda_{n10} & c_{11}\lambda_{n11} & c_{12}\lambda_{n12} \\ c_{11}\lambda_{n11} & c_{13}\lambda_{n13} & c_{14}\lambda_{n14} \\ c_{12}\lambda_{n12} & c_{14}\lambda_{n14} & c_{15}\lambda_{n15} \end{pmatrix} \\
X_R = \begin{pmatrix} c_{16}\lambda_{n16} & c_{17}\lambda_{n17} & c_{18}\lambda_{n18} \\ c_{17}\lambda_{n17} & c_{19}\lambda_{n19} & c_{20}\lambda_{n20} \\ c_{18}\lambda_{n18} & c_{20}\lambda_{n20} & c_{21}\lambda_{n21} \end{pmatrix}
\]

• Such models can explain all observed lepton masses and mixings in terms of a few horizontal symmetry charges; can they be tested at the LHC?

Feng, Lester, Nir, Shadmi (2007)
CHAMP TRAPPING

• CHAMPs can be trapped and moved to a quiet environment to study their decays

• Can catch 1000 per year in a 1m thick water tank

• Alternatively, can try to catch uncorrelated-with-beam-crossing decays from CHAMPs in detector, or mine for CHAMPs in detector hall walls

Feng, Smith (2004)

De Roeck et al. (2005)
SLEPTON RANGE

- Ionization energy loss described by Bethe-Bloch equation:

\[
\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \ln \left( \frac{2m_\gamma c^2 \beta^2 \gamma^2}{I \sqrt{1 + \frac{2m_\gamma c^2 \beta^2 \gamma^2}{M}} + \frac{w^2}{M^2}} \right) - \beta^2 - \frac{\delta}{2} \right]
\]

\[
m_\tilde{\tau} = 219 \text{ GeV}
\]
MODEL FRAMEWORK

• Results depend heavily on the entire SUSY spectrum
• Consider mSUGRA with $m_0=A_0=0$, $\tan\beta = 10$, $\mu>0$
  
  $M_{1/2} = 300, 400, \ldots, 900$ GeV
LHC

Of the sleptons produced, $O(1)\%$ are caught in 10 kton trap

10 to $10^4$ trapped sleptons in 10 kton trap (1 m thick)
IMPLICATIONS FROM CHAMP DECAYS

\[ \tau (\tilde{l} \to l\tilde{G}) = \frac{6}{G_N} \frac{m^2_{\tilde{G}}}{m_l^5} \left[ 1 - \frac{m^2_{\tilde{G}}}{m_l^2} \right]^{-4} \]

- Measurement of \( \tau \), \( m_{\tilde{l}} \) and \( E_l \to m_{\tilde{G}} \) and \( G_N \)
  - Probes gravity in a particle physics experiment!
  - Measurement of \( G_N \) on fundamental particle scale
  - Precise test of supergravity: gravitino is graviton partner
  - Determines \( \Omega_{\tilde{G}} \): SuperWIMP contribution to dark matter
  - Determines \( F \): supersymmetry breaking scale, contribution of SUSY breaking to dark energy, cosmological constant

Hamaguchi et al. (2004); Takayama et al. (2004)
CONCLUSIONS

• Long-lived heavy charged particles (CHAMPs) are motivated by gauge hierarchy and dark matter, just like MET

• CHAMPs are far more promising in the early years at the LHC – 100 pb$^{-1}$ is probably sufficient to say many interesting things

• There are several simple frameworks for investigating this possibility

• If found, physics at the LHC may be much easier and interesting than many people think