Long Lived Charged Particles

Shufang Su • U. of Arizona

PPC07
Outline

- Long lived charged particle
  - Collide search limit
  - Cosmological constraints

- Connection to Dark Matter
  - Light gravitino dark matter (GMSB)
  - SuperWIMP dark matter
  - Cosmological implications
  - Collider implications
Long Lived Charged Particle in SM

proton (stable): accidental global B and L symmetry

electron (stable): gauge U(1)_{EM}

Stable particle appears when there is an unbroken symmetry

LSP in SUSY, LKP in UED, ...

muon (τ=2×10^{-6} sec): \( \Gamma \propto \frac{m_{\mu}^5}{m_W^4} \)

small coupling, small available phase space
Lots of candidates for long lived charged particle in BSM physics ...
<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>$\tilde{\chi}^0_1$</td>
<td>MSSM</td>
<td>$\tilde{\tau}<em>1$ mass (determined by $m^2</em>{\tilde{\tau}<em>{L,R}}$, $\mu$, tan $\beta$, and $A</em>\tau$) close to $\tilde{\chi}^0_1$ mass.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>Large $N$, small $M$, and/or large tan $\beta$.</td>
</tr>
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<td>$\tilde{g}$</td>
<td>$\tilde{\chi}^0_1$</td>
<td>MSSM</td>
<td>Small $m_{\tilde{\tau}<em>{L,R}}$ and/or large tan $\beta$ and/or very large $A</em>\tau$.</td>
</tr>
<tr>
<td>AMSB</td>
<td></td>
<td>Small $m_0$, large tan $\beta$.</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\ell}_1$</td>
<td>$\tilde{G}$</td>
<td>GMSB</td>
<td>$\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small tan $\beta$ and $\mu$.</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>$\tilde{g}$</td>
<td>MSB</td>
<td>$\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_1$</td>
<td>$\tilde{\chi}^0_1$</td>
<td>MSSM</td>
<td>$m_{\tilde{\chi}^+<em>1} - m</em>{\tilde{\chi}^0_1} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg</td>
</tr>
<tr>
<td>AMSB</td>
<td></td>
<td>$M_1 &gt; M_2$ natural. $m_0$ not too small. See MSSM above.</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{\chi}^0_1$</td>
<td>MSSM</td>
<td>Very large $m^2_{\tilde{g}} \gg M_3$, e.g. split SUSY.</td>
</tr>
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<td>SUSY GUT extensions [25–27].</td>
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<td>$\tilde{\chi}^0_1$</td>
<td>MSSM</td>
<td>Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.</td>
</tr>
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<td>GMSB</td>
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<td>$\tilde{\ell}_1$</td>
<td>$\tilde{\chi}^0_1$</td>
<td>MSSM</td>
<td>Non-universal squark and gaugino masses. Small $m^2_{\tilde{g}}$ and $M_3$, small tan $\beta$, large $A_t$.</td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
<td></td>
<td>Small $m^2_{\tilde{g}}$ and $M_3$, large tan $\beta$ and/or large $A_b \gg A_t$.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1
### Non-SUSY models

<table>
<thead>
<tr>
<th>$Q_{em}$</th>
<th>$C_{QCD}$</th>
<th>$S$</th>
<th>Model(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8</td>
<td>1</td>
<td>Universal Extra Dimensions (KK gluon)</td>
</tr>
</tbody>
</table>
| $\pm 1$ | 1         | $\frac{1}{2}$ | Universal Extra Dimensions (KK lepton)  
|         |           |     | Fat Higgs with a fat top ($\psi$ fermions)  
|         |           |     | 4th generation (chiral) fermions  
|         |           |     | Mirror and/or vector-like fermions  
|         |           | 0   | Fat Higgs with a fat top ($\psi$ scalars)  
| $\pm \frac{4}{3}$ | 3 | $\frac{1}{2}$ | Warped Extra Dimensions with GUT parity (XY gaugino)  
| $\pm \frac{2}{3}$ | 3 | $\frac{1}{2}$ | Universal Extra Dimensions (KK down, KK up)  
| $\epsilon < 1$ | 1 | $\frac{1}{2}$ | GUT with $U(1) - U(1)'$ mixing  
|         |           |     | Extra singlets with hypercharge $Y = 2\epsilon$  
|         |           |     | Millicharged neutrinos  
| ?       | ?         | $0/\frac{1}{2}/1$ | “Technibaryons”  

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“Long Lived” and “Charged”

How long is long lived?

- $< \text{age of Universe (}10^{17}\text{ sec)}$: Heavy isotope search
- $> 10^{-8} \sim 10^{-7}\text{ sec}$: stable collider-wise

What charge?

- electric charge
- magnetic charge: magnetic monopole
- color charge: long lived gluinos (in split SUSY)
“Long Lived” and “Charged”

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**Collider Searches**

**Signature:**

slow, highly-ionizing, charged track

- large dE/dx
- time of flight
- Ring Imaging Cherenkov detection

![Graph](image-url)
### Collider Searches

**charge = ± 1**

<table>
<thead>
<tr>
<th>Ecm (GeV)</th>
<th>Collision</th>
<th>Exp</th>
<th>Mass (GeV)</th>
<th>σ(pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>pp</td>
<td>CDF</td>
<td>100-270</td>
<td>0.3-2</td>
</tr>
<tr>
<td>300</td>
<td>ep</td>
<td>H1</td>
<td>&lt;100</td>
<td>190</td>
</tr>
<tr>
<td>130-209</td>
<td>e+e-</td>
<td>OPAL</td>
<td>45-102</td>
<td>0.005-0.03</td>
</tr>
<tr>
<td>189</td>
<td>e+e-</td>
<td>DELPHI</td>
<td>68-93</td>
<td>0.02-0.04</td>
</tr>
<tr>
<td>130-183</td>
<td>e+e-</td>
<td>DELPHI</td>
<td>2-91</td>
<td>0.05-0.3</td>
</tr>
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<td>130-172</td>
<td>e+e-</td>
<td>ALEPH</td>
<td>45-86</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>91.2</td>
<td>e+e-</td>
<td>ALEPH</td>
<td>10-72</td>
<td>1.6-140</td>
</tr>
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<td>91.2</td>
<td>e+e-</td>
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<td>3-45</td>
<td>0.15-3.0</td>
</tr>
</tbody>
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- **Current Bound (LEP)** $m_{sl} > 98$ GeV
- **Tevatron reach:** $m_{sl} > 180$ GeV (10 fb$^{-1}$), now?
- **LHC reach:** $m_{sl} > 700$ GeV for 100 fb$^{-1}$
CMB photon energy distribution

\[ f_\gamma(E) = \frac{1}{e^{E/(kT)+\mu} - 1} \]

- early decay: \( \mu = 0 \)
  thermalized through \( \gamma e \rightarrow \gamma e, \ eX \rightarrow eX\gamma, \ \gamma e \rightarrow \gamma\gamma e \)

- late decay: \( \mu \neq 0 \)
  statistical but not thermodynamical equilibrium

\[ |\mu| < 9 \times 10^{-5} \]

Fixsen et. al., astro-ph/9605054
Hagiwara et. al., PDG
BBN Constraints

Big bang nucleosynthesis

Fields, Sarkar, PDG (2002)

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Big bang nucleosynthesis

\( \eta/10^{-10} = 6.1 \pm 0.4 \)

Fields, Sarkar, PDG (2002)
### Big bang nucleosynthesis

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<th>Time</th>
<th>(sec)</th>
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<th>10</th>
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<th>$10^4$</th>
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<td>Hadronic Energy</td>
<td></td>
<td>Thermalizes through EM interactions</td>
<td>Interacts with background hadrons</td>
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<td></td>
<td></td>
<td></td>
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</tr>
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<td></td>
<td>$p + e \leftrightarrow n + \nu$</td>
<td>No constraints</td>
<td>$n + p \rightarrow D \rightarrow ^4\text{He}$</td>
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<td>$n + ^4\text{He} \rightarrow D$</td>
<td>D overproduction</td>
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<td>Constraints weak</td>
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$$\gamma \gamma_{BG} \rightarrow e^+ e^-, \quad \gamma e_{BG} \rightarrow \gamma e$$

$$E_{\text{max}} = \frac{m_e^2}{22T} = 12 \text{ MeV} \left[ \frac{t}{10^6 \text{sec}} \right]^{1/2}$$
BBN constraints

- Decay lifetime $\tau_{\text{NLSP}}$
- EM/had energy release

$$\xi_{\text{EM,had}} = \varepsilon_{\text{EM,had}} \cdot \text{Br}_{\text{EM,had}} \cdot Y_{\text{NLSP}}$$
BBN constraints

• Decay lifetime $\tau_{\text{NLSP}}$
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\[ \xi_{\text{EM, had}} = \varepsilon_{\text{EM, had}} \cdot \text{Br}_{\text{EM, had}} \cdot Y_{\text{NLSP}} \]

\[ Y_{\text{NLSP}} = \frac{n_{\text{NLSP}}}{n_\gamma} \approx 3.0 \times 10^{-12} \left[ \frac{\text{TeV}}{m_{\text{SWIMP}}} \right] \left[ \frac{\Omega_{\text{SWIMP}}}{0.23} \right] \]
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Kawasaki, Kohri and Moroi, astro-ph/0402490
**BBN constraints**

- **charged particles catalyze BBN**
  - constrain stau lifetime < $10^4$ sec

\[ ^4\text{He} X^- + d \rightarrow ^6\text{Li} + X^- \]

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Kaplinghat, Tajaraman (2006);
Kohri, Takayama (2006);
Cyburt, Ellis, Fields, Olive, Spanos (2006);
Hamaguchi, Hatssuda, Kamimura, Kino, Yanagida (2007);
Bird, Koopmans, Pospelov (2007);
Takayama (2007)
Connection to Dark Matter

- **does not address dark matter**

- **WIMP dark matter**
  - MSSM with stau NLSP and neutralino LSP coannihilation
decay inside the detector

- **non-WIMP dark matter**
  - does not relate to WIMP-miracle
e.g., GMSB stau NLSP with light gravitino LSP
  - relate to WIMP-miracle
    - superWIMP scenario
e.g., SUGRA stau NLSP with heavy gravitino LSP
    - UED \( \tau_{KK} \) NLKP with graviton LKP
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    **superWIMP scenario**
    e.g., SUGRA stau NLSP with heavy gravitino LSP
    UED $\tau_{KK}$ NLKP with graviton LKP
Gravitino

- Gravitino: superpartner of graviton
- Obtain mass when SUSY is spontaneously broken $m_{\tilde{G}} \sim F/m_{pl}$
- Stable when it is LSP - candidate of Dark Matter
**GMSB with Light Gravitino**

**slepton NLSP decay**

\[ c\tau_{\text{NLSP}} = 0.1 \left( \frac{100 \text{ GeV}}{m_{\text{NLSP}}} \right)^3 \left( \frac{m_{\tilde{G}}}{2.4 \text{ eV}} \right) \text{ mm} \]

\[ m_{\tilde{G}} = 2.4 c_{\text{grav}} \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^2 \text{ eV} \]

**stau could either decay or being stable inside the detector**

**gravitino relic density**

\[ \Omega h^2 \sim (m_{\tilde{G}}/\text{keV}) (100/\text{g.}) \]

Moroi, Murayama and Yamaguchi, PLB303, 289 (1993)

- \( m_{\tilde{G}} \sim \text{keV} \): warm Dark Matter
- \( m_{\tilde{G}} > \text{keV} \): problematic! gravitino dilution necessary
  \[ \Rightarrow \text{stringent bounds on reheating temp.} \]

- **no direct connection between stau and gravitino relic density**
WIMP

**Boltzmann equation**

\[
\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)
\]

- expansion
- \(\chi\chi \rightarrow ff\)
- \(ff \rightarrow \chi\chi\)

![Graph showing the evolution of the comoving number density with increasing \(<\sigma_A v>\). The graph includes a dashed line indicating the equilibrium density \(N_{EQ}\) and the x-axis labeled as \(x = m/T\) (time →).]
Boltzmann equation

\[ \frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2) \]

Thermal equilibrium

\[ \chi \rightarrow ff \]

\[ ff \rightarrow \chi \chi \]
WIMP

Boltzmann equation

\[ \frac{d\bar{n}}{dt} + 3H\bar{n} = -\langle\sigma v\rangle(n^2 - n_{eq}^2) \]

- expansion
- \( \chi\chi \rightarrow ff \)
- \( ff \rightarrow \chi\chi \)

Universe cools:

\( n = n_{eq} \sim e^{-m/T} \)

Comoving Number Density

Increasing \( \langle\sigma_A v\rangle \)

\( N_{eq} \)

\( x = m/T \) (time \( \rightarrow \))
WIMP

Boltzmann equation

\[
\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)
\]

\(\chi \chi \rightarrow ff\)

\(ff \rightarrow \chi \chi\)

Freeze out, n/s \~ const

Comoving Number Density

\(N_{eq}\)

\(x = m/T\ (time \rightarrow)\)
WIMP

Boltzmann equation

\[ \frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2) \]

expansion \( \chi \chi \rightarrow ff \)

ff \( \rightarrow \chi \chi \)

Increasing \( <\sigma_A v> \)

Comoving Number Density

\( N_{EQ} \)

\( x = m/T \) (time \( \rightarrow \))
WIMP - Miracle

WIMP: Weak Interacting Massive Particle

- \( m_{\text{WIMP}} \sim m_{\text{weak}} \)
- \( \sigma_{\text{an}} \sim \alpha_{\text{weak}}^2 m_{\text{weak}}^{-2} \)

\[
\Omega h^2 \sim \frac{2.6 \times 10^{-10} \text{GeV}^{-2}}{\langle \sigma_A v \rangle} \\
\langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_{\text{weak}}^2} 0.1 \sim 10^{-9} \text{GeV}^{-2}
\]

\[\Rightarrow \Omega h^2 \sim 0.3\]
**WIMP - Miracle**

**WIMP: Weak Interacting Massive Particle**

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\end{align*}
\]

\[\Rightarrow \Omega h^2 \sim 0.3\]

• **appear in particle physics models motivated independently by attempts to solve Electroweak Symmetry Breaking**

• **relic density are determined by $m_{\text{pl}}$ and $m_{\text{weak}}$**
  - naturally around the observed value
  - no need to introduce and adjust new energy scale
superWIMP

WIMP $\rightarrow$ superWIMP + SM particles

Feng, Rajaraman and Takayama (2003)

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmüller, Hamaguchi, Ratz, Yanagida (2004); Roszkowski, Ruiz de Austri, Choi (2004); Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); ...

$N_{\text{EQ}}$

$x = m/T$ (time $\rightarrow$)

Increasing $<\sigma_A v>$
WIMP → superWIMP + SM particles

Feng, Rajaraman and Takayama (2003)
WIMP $\rightarrow$ superWIMP + SM particles

$10^4 \, s < t < 10^8 \, s$

Feng, Rajaraman and Takayama (2003)
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$10^4 \text{ s} < t < 10^8 \text{ s}$

$\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}$

Feng, Rajaraman and Takayama (2003)
WIMP → superWIMP + SM particles

Feng, Rajaraman and Takayama (2003)

$10^4 \text{s} < t < 10^8 \text{s}$

$$\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}$$

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WIMP $\rightarrow$ superWIMP + SM particles

Feng, Rajaraman and Takayama (2003)

$10^4 \text{ s} < t < 10^8 \text{ s}$

$$\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}$$

**superWIMP**

e.g. Gravitino LSP
LKK graviton

**WIMP**

• neutral
• charged
**superWIMP in SUSY**

**SUSY case**

WIMP $\rightarrow$ superWIMP + SM particles
**SUSY case**

WIMP $\rightarrow$ superWIMP + SM particles

- **Charged slepton**
- Superpartner of lepton
superWIMP in SUSY

**SUSY case**

- **WIMP → superWIMP + SM particles**
  - **Charged slepton**
    - Superpartner of lepton
  - **Gravitino**
    - Superpartner of graviton
superWIMP in SUSY

**SUSY case**

WIMP $\rightarrow$ superWIMP + SM particles

**Charged slepton**
Superpartner of lepton

**Gravitino**
Superpartner of graviton

EM, had. cascade

$\Rightarrow$ change CMB spectrum

$\Rightarrow$ change light element abundance predicted by BBN

Strong constraints!
**superWIMP in SUSY**

**SUSY case**

WIMP $\rightarrow$ superWIMP + SM particles

- **Charged slepton**
  - Superpartner of lepton

- **Gravitino**
  - Superpartner of graviton

**EM, had. cascade**

$\Rightarrow$ change CMB spectrum

$\Rightarrow$ change light element abundance predicted by BBN

Strong constraints!

**Decay lifetime**

$\propto m_{pl}^2 / m_{G}^3$
Neutralino LSP vs. Gravitino LSP

WIMP

SuperWIMP

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$Y_{\text{NLSP}} = \frac{n_{\text{NLSP}}}{n_\gamma} \approx 3.0 \times 10^{-12} \left[ \frac{\text{TeV}}{m_\tilde{G}} \right] \left[ \frac{\Omega_{\tilde{G}}}{0.23} \right]$ 

$200 \text{ GeV} \leq \delta m \leq 400 \sim 1500 \text{ GeV}$

$m_\tilde{G} \leq 200 \text{ GeV}$

Feng, SS and Takayama (2004)

**fix $\Omega_{\tilde{G}} = 0.23$**
\[ Y_{\text{NLSP}} = \frac{n_{\text{NLSP}}}{n_\gamma} \sim 3.0 \times 10^{-12} \left[ \frac{\text{TeV}}{m_\tilde{G}} \right] \left[ \frac{\Omega_\tilde{G}}{0.23} \right] \]

\[ 200 \text{ GeV} \leq \delta m \leq 400 \sim 1500 \text{ GeV} \]
\[ m_\tilde{G} \leq 200 \text{ GeV} \]

\[ \text{solve } ^7\text{Li anomaly} \]

Feng, SS and Takayama (2004)

\[ \text{fix } \Omega_\tilde{G} = 0.23 \]
mSUGRA

Ellis et. al., hep-ph/0312262

Usual WIMP allowed region

superWIMP allowed region

BBN EM constraints only

$m_{3/2} = 0.2 \ m_0, \ \tan \beta = 10, \ \mu > 0$

$r < 1$

Stau NLSP

$\tau_{NSP} < 10^4 \ s$
Small Scale Structure

• **SuperWIMPs are produced in late decays with large velocity (0.1 c - c)**

• suppress small scale structure

• constant density cores in small mass halo

• reduce concentration in large mass halos

• warm DM with cold DM pedigree

Dalcanton, Hogan (2000);
Lin, Huang, Zhang, Brandenberger (2001);
Sigurdson, Kamionkowski (2003);
Profumo, Sigurdson, Ullio, Kamionkowski (2004);
Kaplinghat (2005);
Cembranos, Feng, Rajaraman, takayama (2005);
Strigari, Kaplinghat, Bullock (2006);
Bringmann, Borzumati, Ullio (2006)
Collider Production

\[ \Omega_{\text{WIMP}}, \Omega_{\text{SWIMP}} \leq \Omega_{\text{DM}} \]

WIMP annihilate efficiently in early universe

WIMP be produced efficiently at colliders

Upper bound on \( \Omega \)

Lower bound on rates

Birkedal, Matchev and Perelstein (2004)
Feng, SS and Takayama (2005)
Feng, SS and Takayama (2005)

σ (fb)

200 400 600 800 1000 1200 1400 1600 1800 2000
m_L (GeV)

Tevatron

LHC

S-wave
P-wave
Drell–Yan

superWIMP @ collider
• Decay life time
• SM particle energy/angular distribution ...

⇒ $m_{\tilde{G}}$

⇒ $m_{pl}$ ...
- Decay life time
- SM particle energy/angular distribution ...

\[ \Rightarrow m_{\tilde{G}} \]

\[ \Rightarrow m_{pl} \ldots \]

- Probes gravity in a particle physics experiments!
- BBN, CMB in the lab
- Precise test of supergravity: gravitino is a graviton partner
• Decay life time
• SM particle energy/angular distribution ...
  ⇒ \( m_\tilde{G} \)
  ⇒ \( m_{pl} \) ...

• Probes gravity in a particle physics experiments!
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How to trap slepton?
How to trap slepton?

- Decay life time
- SM particle energy/angular distribution ...
  \[ \Rightarrow m_\tilde{\chi} \]
  \[ \Rightarrow m_{\text{pl}} \]

- Probes gravity in a particle physics experiments!
- BBN, CMB in the lab
- Precise test of supergravity: gravitino is a graviton partner

Feng and Smith, (2004)
De Roeck et. al., (2005)
Slepton could live for a year, so can be trapped then moved to a quiet environment to observe decays.

- LHC: $10^6$ slepton/yr possible, but most are fast. Catch 100/yr in 1 kton water.
Slepton could live for a year, so can be trapped then moved to a quiet environment to observe decays.

- LHC: $10^6$ slepton/yr possible, but most are fast. Catch 100/yr in 1 kton water.
- LC: tune beam energy to produce slow sleptons, can catch 1000/yr in 1 kton water.
Conclusions

Long lived charge particles appears in many BSM models

Slow moving, highly ionization track at colliders

Cosmological constraints from BBN, CMB, ...

Link to dark matter: superWIMP scenario

- naturally obtain $\Omega$
- solve BBN $^7$Li anomaly
- small scale structure
- could be tested at colliders