Detection of SUSY Signals in Stau-Neutralino Coannihilation at Colliders

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Complementarity between Dark Matter Searches and Collider Experiments
UC Irvine, California, USA
Saturday June 10 and Sunday June 11
Cosmology, SUSY, WIMP \( \Rightarrow \) Stau neutralino coannihilation in minimal supergravity (mSUGRA) model

Prospects of detection of SUSY in coannihilation region at the LHC

Conclusion and Future Tasks
THINKING ABOUT THE UNIVERSE

- 14 B yrs
- 500 M yrs
  Galaxy Formation
- 1 s
- $10^{-7}$ s
  SUSY Dark Matter
- $10^{-11}$ s
  Standard Model + SUSY
- $10^{-43}$ s
  Quantum Gravity

- $t = 10^{-35}$ s
  $T = 10^{5}$ GeV
- $t = 10^{-33}$ s
  $T = 10^{4}$ GeV
- $t = 10^{2}$ s
  $T = 1$ GeV
- $t = 10^{-4}$ s
  $T = 1$ MeV
- $t = 3$ minutes
- $t = 400,000$ years
  $T = 3000$ K (1 eV)
- $t = 5$ K (1 meV)

Early Universe

Cosmological Connection?
SUSY is an interesting class of models to provide a massive neutral particle \((m \sim 100 \text{ GeV})\) and weakly interacting (WIMP).

\[
\Omega \tilde{\chi}_1^0 h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} v \rangle} \, dx
\]

\[
\langle \sigma_{\text{ann}} v \rangle = \frac{\pi \alpha^2}{8m^2}
\]

\[
0.2 \leq \Omega \tilde{\chi}_1^0 h^2 \leq 0.9 \text{ pb}
\]
CDM = Neutralino ; NLSP = stau

\[
(\Omega_{\text{CDM}})^{-1} \propto \left[ \begin{array}{c}
\tilde{\chi}_1^0 \\
\tilde{\chi}_1^0 \\
h, H, A, Z
\end{array} \right]
\]

\[
\left[ \begin{array}{c}
\tilde{\chi}_1^0 \\
\tilde{\chi}_1^0 \\
f
\end{array} \right]
\]

\[
\left[ \begin{array}{c}
\tilde{\chi}_1^0 \\
f
\end{array} \right]
\]

\[
\left[ \begin{array}{c}
\tilde{\tau}_1 \\
\gamma
\end{array} \right]
\]

\[
e^{-\Delta M / 20}
\]

\[
\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}
\]

mSUGRA naturally provides a lighter stau.
Minimal Supergravity (mSUGRA)

4 parameters + 1 sign

- $m_{1/2}$: Common gaugino mass at $M_G$
- $m_0$: Common scalar mass at $M_G$
- $A_0$: Trilinear coupling at $M_G$
- $\tan \beta$: $<H_u>/<H_d>$ at the electroweak scale
- $\text{sign}(\mu)$: Sign of Higgs mixing parameter ($W^{(2)} = \mu H_u H_d$)

Experimental Constraints

1. $M_{\text{Higgs}} > 114$ GeV  $M_{\text{chargino}} > 104$ GeV
2. $2.2 \times 10^{-4} < Br (b \rightarrow s \gamma) < 4.5 \times 10^{-4}$
3. $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$
In SUGRA models, the lightest stau seems to be naturally very close to the lightest neutralino mass especially for large $\tan \beta$.

For example, the R- selectron ($\tilde{E}^c$) mass is related to the lightest neutralino ($\tilde{\chi}^0_1$) mass by the following relations at the electroweak scale:

$$m_{\tilde{E}^c}^2 = m_0^2 + (6/5) f_1 m_{1/2}^2 - \sin^2 \theta_W M_W^2 \cos(2\beta)$$

$$m_{\tilde{\chi}^0_1} = (\alpha_1/\alpha_G)m_{1/2}$$

where $f_i = [1-(1+\beta_i t)^{-2}]/\beta_i$, $t = \ln(M_G/M_Z)^2$, $\beta_1$ is the $U(1)_Y$ $\beta$ function coefficient (one loop), $\alpha_1$ is the $U(1)_Y$ gauge coupling constant ($\times 5/3$) at the $M_Z$ scale and $\alpha_G$ is the gauge coupling constant at $M_G$. 
Stau Neutralino Coannihilation and GUT Scale

- Numerically this gives e.g., for $\tan \beta = 5$

$$m_{\tilde{E}^c}^2 = m_0^2 + 0.15m_{1/2}^2 + (37 \text{ GeV})^2$$

$$m_{\tilde{\chi}_1^0}^2 = 0.16m_{1/2}^2$$

- Thus for $m_0 = 0$, the mass of $\tilde{E}^c$ becomes degenerate with the $\tilde{\chi}_1^0$ at $m_{1/2} = 370$ GeV, i.e. co-annihilation effects roughly begin at $m_{1/2} \approx (350 - 400)$ GeV. (The numerical coefficients are determined by solving the renormalization group equations).

- For larger $m_{1/2}$, the near degeneracy is maintained by increasing $m_0$, and we get: a corridor in the $m_0 - m_{1/2}$ plane.

The coannihilation channel occurs in most SUGRA models with non-universal soft breaking,
Cosmologically Allowed Region

- Dark Energy 73%
- Dark Matter 23%
- Cold Atoms 4%

$m_{\chi_0} > m_{\tau}$

$m_{1/2}$ vs $m_0$ plot with labeled regions:
- $A_0 = 0$, $\mu > 0$, $\tan \beta = 40$
- $b \rightarrow s \gamma$
- $a < 11 \times 10^{-10}$

$m_{1/2}$ [GeV] vs $m_0$ [GeV] graph.
Can we measure $\Delta M$ at colliders?

$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15$ GeV
Cosmology, SUSY, WIMP ⇒ Stau neutralino coannihilation in minimal supergravity (mSUGRA) model

Prospects of detection of SUSY in coannihilation region at the LHC


Conclusion and Future Tasks
SUSY Signature at the LHC

Squark-Gluino Production

\[ \tilde{\chi}_2^0 \rightarrow \tau^+ + \tilde{\tau}_1^- \rightarrow \tau^+ + \tau^- \tilde{\chi}_1^0 \]

Triggering the jets and missing \( E_T \) → \( E_T^{\text{miss}} + \) jets + \( \tau^0 \)s
$E_T^{\text{miss}} + 2\text{j} + 2\tau$ Analysis (I)

[1] Sample of $E_T^{\text{miss}}$, 2 jets, and at least 2 taus with $p_T^{\text{vis}} > 40, 20$ GeV and $\epsilon_\tau = 50\%$, fake ($f_{j \rightarrow \tau}$) = 1%. Optimized cuts:

- $E_T^{\text{jet1}} > 100$ GeV; $E_T^{\text{jet2}} > 100$ GeV
- $E_T^{\text{miss}} > 180$ GeV
- $E_T^{\text{jet1}} + E_T^{\text{jet2}} + E_T^{\text{miss}} > 600$ GeV

[2] Number of SUSY and SM events (10 fb$^{-1}$):
- Top : 115 events
- $W$+jets : 44 events
- SUSY : 590 events


OS–LS counts (10 fb$^{-1}$) for $M_{\tau\tau} < 100$ GeV:
- Top : 6 counts
- $W$+jets : 1 count
- SUSY : 125 counts

$M_{\text{gluino}} = 830$ GeV ($\Delta M = 10.6$ GeV)
$E_T^{\text{miss}} + 2j + 2\tau$ Analysis (II)

$\mathbf{p_T^{\text{vis}} > 40, 20 \text{ GeV}}$

10 fb$^{-1}$

$M_{\text{peak}}$

$M_{\text{max}} = 78.7 \text{ GeV}$

How to Establish the Discovery

1. $N_{\text{OS–LS}}$ (Number of OS–LS counts)

2. Clear peak ($M_{\text{peak}}$) and end-point ($M_{\text{max}}$) in di-tau mass distribution for OS–LS pairs

3. $M_{\text{peak}}$ is used to determine $\Delta M$

$\mathbf{p_T^{\tau} > 20 \text{ GeV}}$ is essential!
A small $\Delta M$ can be detected in first few years of LHC.

[Assumption] The gluino mass is measured with $\delta M / M_{\text{gluino}} = \pm 5\%$ in a separate analysis.
$ightarrow$ We extract $\Delta M$ from $M_{\text{peak}}$. 

I. $\delta M_{\text{peak}} = \text{r.m.s}(M_{\text{peak}}) / \sqrt{N_{\text{OS-LS}}}$

II. $\delta M/M_{\text{gluino}} = \pm 5\%$

$\Delta M = 10 \pm 1.2^{+1.4}_{-1.2} \text{ GeV (10 fb}^{-1})$
Reach in $m_{1/2}$?

Reach in $m_{1/2}$?

Sliding cut on $E_{T}^{\text{jet1}} + E_{T}^{\text{jet2}} + E_{T}^{\text{miss}}$

With 100 fb$^{-1}$, the LHC could probe $m_{1/2}$ up to $\sim 700$ GeV

$\tan \beta = 40, \mu > 0 \quad A_0 = 0$

$m_{1/2} = 360$ GeV

$m_{1/2} = 360$ GeV

$m_{1/2}$ - $M_{\tilde{\chi}^0}$ [GeV]

30

20

10

0

200 400 600 800

$m_{1/2}$ [GeV]

1000

100

10

1

300 400 500 600 700 800

Luminosity (fb$^{-1}$)

$m_{1/2}$ (GeV)
**$E_T^{\text{miss}} + 1j + 3\tau$ Analysis**

Much smaller SM background, but a lower acceptance

1. Sample of $E_T^{\text{miss}}$, 1 jet and at least 3 taus with $p_T^{\text{vis}} > 40, 40, 20$ GeV and $\mathcal{E}_\tau = 50\%$, fake ($f_{j\rightarrow\tau}$) = 1\%. Final cuts:
   - $E_{T\text{jet}1} > 100$ GeV, $E_T^{\text{miss}} > 100$ GeV, $E_{T\text{jet}1} + E_T^{\text{miss}} > 400$ GeV

2. Select OS low di-tau mass pairs, subtract off LS pairs

Small dependence on the uncertainty of $f_{j\rightarrow\tau}$

Note: $f_{j\rightarrow\tau} = 0\% \rightarrow 1.6$ counts/fb$^{-1}$
Remark: 3τ events with Jet → τ Fakes

What is accepted by OS–LS?

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<th>Analysis</th>
<th>&quot;2τ&quot;</th>
<th>&quot;3τ&quot;</th>
</tr>
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<tr>
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</tr>
<tr>
<td>τ̄τ̄j</td>
<td>yes</td>
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</tr>
</tbody>
</table>

Can produce ττ and τj pairs

- τj pairs will be cancelled in OS–LS, but ττ pairs from χ2̄0 contribute in the ττj case to the NOS–LS counting. Doesn’t affect ΔM measurement!

- The uncertainty on the jet → τ fake rate is required to be known, but ΔM measurement is not significantly effected even if the fake rate has a 20% systematic uncertainty.
3τ Analysis: Combined Results

- Use $N_{\text{OS-LS}}$ and $M_{\tau\tau}$ to independently measure $\Delta M$
- Both produce high quality measurements
- As in the 2τ analysis, we assume a gluino mass
- Dominant uncertainty
  - 5% uncertainty on $M_{\text{gluino}}$

Combined results: $\Delta M = 10 \pm 1.3$ GeV (30 fb$^{-1}$)
3 $\tau$ Analysis: Measure $\Delta M$ and $M_{\text{gluino}}$

Next: combine $N_{\text{OS-LS}}$ and $M_{\tau\tau}$ values to measure $\Delta M$ and $M_{\text{gluino}}$ simultaneously.

Counts drop with $M_{\text{gluino}}$

Mass rises with $M_{\text{gluino}}$

![Graph showing counts drop and mass rise with gluino mass](image)
$3 \tau$ Analysis: Accuracy in $\Delta M$ & $M_{gluino}$

- $\Delta M = 9$ GeV
- $M_{gluino} = 850$ GeV
- Combined Measurement

$\rightarrow$ 22% - 15%
(10 - 30 fb$^{-1}$)

$\rightarrow$ 9% - 6%
(10 - 30 fb$^{-1}$)
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Conclusion

Signals in the stau-neutralino coannihilation region are studied using mSUGRA model as a benchmark scenario ($\Delta M \sim 10$ GeV)

**LHC**: Two analyses with visible $p_T^{\tau} > 20$ GeV:

- **2$\tau$ analysis**: Discovery with 10 fb$^{-1}$
  - $\delta \Delta M / \Delta M \sim 18\%$ using $M_{\text{peak}}$ with 5\% gluino mass error

- **3$\tau$ analysis**: Combine $N_{\text{OS-LS}}$ and $M_{\text{peak}}$ measurements
  - $\delta \Delta M / \Delta M \sim 13\%$ with 30 fb$^{-1}$ and 5\% gluino mass error
  - $\delta \Delta M / \Delta M \sim 15\%$ and $\delta M_{\text{gluino}} / M_{\text{gluino}} \sim 6\%$ with no gluino mass assumption

- The analyses can be done for the other models that don’t suppress $\chi_2^0$ production.

As a comparison, $\delta \Delta M / \Delta M \sim 10\%$ (500 fb$^{-1}$) at the ILC if we implement a very forward calorimeter to reduce two-photon background.

Future Tasks

How do we know the stau-neutralino co-annihilation is responsible for the relic density?

(1) No large higgsino component of neutralino – otherwise it will lower the relic density further.

(2) No $A$ or $H$ annihilation channel – it will lower the relic density.

(3) No other co-annihilation channels such as stop, sbottom, chargino.

All these criteria will have their unique signatures...

Small $\mu$ → Check chargino ...

$M_{A,H} = 2M_{\tilde{\chi}_1^0}$
Backups
### Reference Points

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<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
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<th>Value 3</th>
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<td>144.2</td>
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<tr>
<td>$\Delta M(\equiv M_{\tilde{\tau}<em>1} - M</em>{\tilde{\chi}^0_1})$</td>
<td>5.7</td>
<td>7.6</td>
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<td>$M_{\tilde{\tau} \tilde{\tau}}$</td>
<td>60.0</td>
<td>68.3</td>
<td>78.7</td>
<td>84.1</td>
<td>91.2</td>
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</table>
At the ILC ...

Stau-Pair Production

\[ \Delta M \] Measurement

\[ \frac{\delta \Delta M}{\Delta M} \approx 10\% \ (500 \ fb^{-1}) \]

if we implement a very forward calorimeter to reduce two-photon background.

Can we discover the signals in the coannihilation region at the LHC?

Final State: \[ \tau^+ \tau^- \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]

What will be \[ \delta \Delta M / \Delta M \]?