Cosmology and Colliders

R. Arnowitt, ¹ A. Aurisano, ¹* B. Dutta, ¹ T. Kamon, ¹
V. Khotilovich, ¹* N. Kolev, ² P. Simeon, ¹**
D. Toback, ¹ P. Wagner ¹*

1) Department of Physics, Texas A&M University
2) Department of Physics, Regina University, Canada
* Graduate Student  ** Undergraduate Student

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Cosmology, SUSY, WIMP

Stau neutralino coannihilation in minimal supergravity (mSUGRA) model

Prospects of detection of SUSY in coannihilation region at the ILC

Prospects of detection at the LHC

Conclusion

Can the mSUGRA naturally provide small $\Delta M$?

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

Griest, Seckel'91
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

i. $M_{\text{Higgs}} > 114$ GeV   $M_{\text{chargino}} > 104$ GeV

ii. $2.2 \times 10^{-4} < Br (b \rightarrow s \gamma) < 4.5 \times 10^{-4}$

iii. $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$

iv. $(g-2)_\mu$
Stau Neutralino Coannihilation and GUT Scale

In mSUGRA model the lightest stau seems to be naturally close to the lightest neutralino mass especially for large \( \tan \beta \).

For example, the lightest selectron mass is related to the lightest neutralino mass in terms of GUT scale parameters:

\[
\tilde{m}^2_{\tilde{e}_c} = m^2_0 + 0.15 m^2_{1/2} + (37 \text{ GeV})^2 \\
\tilde{m}^2_{\tilde{\chi}_1^0} = 0.16 m^2_{1/2}
\]

Thus for \( m_0 = 0 \), the mass of \( \tilde{E}_c^2 \) becomes degenerate with the \( \tilde{\chi}_1^0 \) mass at \( m_{1/2} = 370 \text{ GeV} \), i.e. the coannihilation region begins at

\[ m_{1/2} = (370-400) \text{ GeV} \]

For larger \( m_{1/2} \) the 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,
Can we measure $\Delta M$ at colliders?
At the ILC ...

Stau-Pair Production

$\Delta M$ Measurement

$\delta \Delta M / \Delta M \sim 10\% \ (500 \ fb^{-1})$

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

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

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

What will be $\delta \Delta M / \Delta M$?
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 $E_T \rightarrow E_T^{\text{miss}} + \text{jets} + \tau's$
$E_T^{\text{miss}} + 2j + 2\tau$ Analysis (I)

[1] ISAJET + ATLFAST sample of $E_T^{\text{miss}}$, 2 jets, and at least 2 taus with $p_T^{\text{vis}} > 40$, 20 GeV and $\mathcal{E}_{\tau} = 50\%$, 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
$E_T^{\text{miss}} + 2j + 2\tau$ Analysis (II)

10 fb$^{-1}$

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

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

$M_{\text{max}} = 10$ fb$^{-1}$

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 $\Delta M$

$p_T^{\tau} > 20$ GeV is essential!
2τ Analysis: Discovery Luminosity

[Assumption] The gluino mass is measured with \( \delta M/M_{\text{gluino}} = \pm 5\% \) in a separate analysis.

A small \( \Delta M \) can be detected in first few years of LHC.
$E_T^{\text{miss}} + 1j + 3\tau$ Analysis

Much smaller SM background, but a lower acceptance

[1] ISAJET + PGS sample of $E_T^{\text{miss}}$, 1 jet and at least 3 taus with $p_T^{\text{vis}} > 40, 40, 20$ GeV and $\varepsilon_\tau = 50\%$, 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$^{-1}$
3τ Analysis: Combined Results

- Use $N_{OS-LS}$ 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$^{-1}$)
Next: combine $N_{\text{OS-LS}}$ and $M_{\ell\ell}$ values to measure $\Delta M$ and $M_{\text{gluino}}$ simultaneously.

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

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

$\delta \Delta M / \Delta M \sim 15\%$ and $\delta M_{\text{gluino}} / M_{\text{gluino}} \sim 6\%$
Signals in the stau-neutralino coannihilation region are studied using mSUGRA model as a benchmark scenario ($\Delta M \sim 10 \text{ GeV}$)

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

- **2$\tau$ analysis**: Discovery with $10 \text{ fb}^{-1}$
  - $\delta \Delta M / \Delta M \sim 18\%$ 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 $30 \text{ fb}^{-1}$ 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
    (It may be hard to measure the gluino mass otherwise due to the low energy taus in the signal.)

- The analyses can be done for the other models that don’t suppress $\chi^0_2$ production.

✓ **Comparison**: $\delta \Delta M / \Delta M \sim 10\%$ ($500 \text{ fb}^{-1}$) at the ILC if we implement a very forward calorimeter to reduce two-$\gamma$ background.
Backups
SUSY is an interesting class of models to provide a massive neutral particle ($m \sim 100$ GeV) and weakly interacting (WIMP).
### Reference Points

**$m_{1/2} = 360$ GeV**

**$M_{\text{gluino}} = 830$ GeV**

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

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$M_{\tau\tau}^{\text{max}}$

|       | 60.0 | 68.3 | 78.7 | 84.1 | 91.2 |
Reach in $m_{1/2}$?

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

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

$m_{1/2} = 360$ GeV

Sliding cut on $E_T^{\text{jet1}} + E_T^{\text{jet2}} + E_T^{\text{miss}}$
2τ Analysis: Accuracy in $\Delta M$

$\Delta M = 10 \pm 1.2^{+1.4}_{-1.2}$ GeV (10 fb$^{-1}$)

$\Rightarrow$ We extract $\Delta M$ from $M_{\text{peak}}$.

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

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

Negligible $f_{j \rightarrow \tau}$ dependence
3τ Analysis: Accuracy in $\Delta M$ & $M_{\text{gluino}}$

$\Delta M = 9 \text{ GeV}$

$M_{\tilde{g}} = 850 \text{ GeV}$

Combined Measurement

$\rightarrow 22\% - 15\%$

(10 - 30 fb$^{-1}$)

$\rightarrow 9\% - 6\%$

(10 - 30 fb$^{-1}$)
Remark: 3 $\tau$ events with Jet $\rightarrow$ $\tau$ Fakes

What is accepted by OS–LS?

<table>
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<tr>
<th>Process</th>
<th>“2$\tau$”</th>
<th>“3$\tau$”</th>
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<td>$\tilde{\chi}_2^0 \tilde{\chi}_1^0$</td>
<td>yes, no</td>
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</tbody>
</table>

- $\tilde{\tau}$ pairs will be cancelled in OS–LS, but $\tau\tau$ pairs from $\chi_2^0$ contribute in the $\tau\tilde{\tau}$ case to the $N_{\text{OS–LS}}$ counting. Doesn’t affect $\Delta M$ measurement!

- The uncertainty on the jet $\rightarrow \tau$ fake rate is required to be known, but $\Delta M$ measurement is not significantly effected at a level of 20% systematic uncertainty.
$E_T^{\text{miss}} + 2j + 2\tau$ Analysis (I)

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CDF
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($\Delta M = 10.6$ GeV)