The Stau-Neutralino Coannihilation Region at the LHC

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Talk Outline

• Supersymmetry and Cosmology.

• Available mSUGRA parameter space:
  We use: (a) Rare decay constraints, (b) Collider bounds, (c) Cosmological constraints.

• $\tilde{\chi}_1^0 - p$ cross-section for Dark Matter Detectors.

• Signal, backgrounds and measurement of the susy masses at the LHC $\sqrt{s}=14$ TeV.

• Conclusion
Supersymmetry and Cosmology

- $\tilde{\chi}^0_1$: the lightest neutralino as a stable dark matter candidate (R-parity invariant SUSY model).

- The relic density of these neutralinos is given by:

$$\Omega_{\tilde{\chi}^0_1} h^2 \sim \int_0^{x_f} dx (\langle \sigma_{ann} v \rangle)^{-1}$$

where $\sigma_{ann}$ is calculated in terms of SUSY model parameters typically using the following annihilation diagrams:
Minimal SUGRA (mSUGRA) Model

- It is found that a large region of mSUGRA parameter space needs the "coannihilation effect" to be allowed (after including other experimental constraints).

- Coannihilation: A second particle becomes nearly degenerate with the $\tilde{\chi}_1^0$.  

\[ \text{[Griest, Seckel:92]} \]

\[
\begin{array}{c}
\tilde{\chi}_1^0 \\
\tau \\
\tau \\
\gamma
\end{array}
\]

- This contribution: $\propto \exp[-\Delta M/20]$ for $m_{\tilde{\chi}_1^0}=400$ GeV, $\Delta M \equiv m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$.  

mSUGRA model depends on 4 parameters and 1 sign:

- $m_0$: Scalar soft breaking mass at $M_G$,

- $m_{1/2}$: Gaugino mass at $M_G$
  \[ m_{\tilde{\chi}_1^0} \approx 0.4 m_{1/2}; m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 0.8 m_{1/2}, \]

- $A_0$: cubic soft breaking mass at $M_G$,

- $\tan \beta$: $<H_2> / <H_1>$ at the electroweak scale,

- $\frac{|\mu|}{\mu}$: sign of Higgs mixing parameter
  \[ W^{(2)} = \mu H_1 H_2. \]
(i) Accelerator bounds:
\[ m_h \geq 114 \text{ GeV}, \quad m_{\tilde{\chi}^\pm} \geq 104 \text{ GeV}. \]

(ii) \( b \rightarrow s\gamma \) bounds:
\[ 2 \times 10^{-4} < BR(b \rightarrow s\gamma) < 4.5 \times 10^{-4} \]

(iii) Relic density bounds:
\[ 0.094 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.129. \]

(iv) \( a_\mu^{\text{SUGRA}} \) bounds of BNL E821 experiment.
Narrow Coannihilation Region

\[ \Delta M \sim 5 \text{ - } 15 \text{ GeV} \]

The (blue) vertical lines: \((\tilde{\chi}_1^0 - \rho \text{ cross-sections}) \text{ (from left):} \]
\[ 0.03 \times 10^{-6} \text{ pb, } 0.002 \times 10^{-6} \text{ pb, } 0.001 \times 10^{-6} \text{ pb} \]
Questions:
(1) What are the signals from the narrow coannihilation corridor?
(2) Can the signal be seen over the background?
(3) Can we discover this corridor in the first few years of the LHC running?
(4) What is the accuracy of the mass measurement (since $\Delta M$ is $\sim$ 10 GeV)?

Comparison:

● At the ILC: The $\Delta M$ can be measured with an accuracy of 10%. [Khotilovich, Arnowitt, Dutta, Kamon, PLB 618 (05) 182].
Signals and Measurements at LHC

- **Squark-gluino** production cross section is very large.

- The **Squark, Gluino** decays, e.g.

  \[
  p + \tilde{q} \rightarrow \chi^0_2 + \chi^0_2 + \text{jets}
  \]

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

- **4 \tau** (2 low energy and 2 high energy) + jets + \( \not{E_T} \).

- We choose: \( m_{1/2} = 360 \text{ GeV} \), \( \tan \beta = 40 \), \( \mu > 0 \), \( A_0 = 0 \) and \( m_0 : 210, 212, 215, 217, 220 \) (GeV).

Where: \( M_{\tilde{\chi}^0_1} : 144.2 \), \( M_{\tilde{g}} : 831 \), \( M_{\tilde{\nu}_{R(L)}} : 740(765) \) (GeV), \( \Delta M(M_{\tilde{\tau}_1} - M_{\tilde{\chi}^0_1}) : 5.7, 7.6, 10.6, 12.5, 15.4 \) (GeV).
Signals and ...

- Two different final states:
  1) Two taus + 2 jets + $E_T$; 2) three taus + 1 jet + $E_T$.

- We use ATLFAST MC and ISAJET event generator.

- Two observables:
  1) the number of OS—LS events ($N_{OS-LS}$);
  2) the peak position of the di-tau invariant mass $M_{\tau\tau}$ in OS—LS events.

- We consider the SM $t\bar{t}$ background and develop cuts to reduce this background.

- **fake effects**: a jet may be misidentified as a tau. The fake rate we use is 1%.
  The fake effect can be large since the SUSY cascade decays produce lots of jets.
Two tau $\vec{E}_T$

Event selection:

- The dominant background: $t\bar{t}$ pair production where each $t$ decays: $t \rightarrow b\tau\nu$ to a final state of $\vec{E}_T + 2b + 2\tau$. The additional $\tau$ may come from: $b \rightarrow c\tau\nu$.

- Choose two jets each with $E_T > 100$ and $\vec{E}_T > 180$ GeV. Define $H_T \equiv E_{T}^{\text{jet1}} + E_{T}^{\text{jet2}} + \vec{E}_T$ to distinguish SUSY events from the top events and choose $H_T > 600$ GeV.

- Require two reconstructed/identified $\tau$’s with $p_T^{\text{vis}} > 20$ GeV with one tau having $p_T^{\text{vis}} > 40$ GeV. Reconstruction/identification efficiency is 50%.
$\slashed{E}_T$ vs $E_T^{\text{jet1}} + E_T^{\text{jet2}}$

- $t\bar{t}$ (left) vs SUSY (right) Background; $\Delta M = 10.6$ GeV.

Require $E_T^{\text{jet1}} > 100$ GeV, $E_T^{\text{jet2}} > 100$ GeV, $\slashed{E}_T > 180$ GeV, and $H_T \equiv E_T^{\text{jet1}} + E_T^{\text{jet2}} + \slashed{E}_T > 600$ GeV.

- Negligible $t\bar{t}$ background.
\[ M_{\tau\tau}^{\text{vis}} \]

- An invariant mass \( M_{\tau\tau} \) for each of possible combina-
tional pairs of two \( \tau \)'s is calculated and categorized as
opposite sign (OS) or like sign (LS) charge combinations.
Example: \( \Delta M = 10.6 \text{ GeV} \) (10 \( fb^{-1} \) luminosity):
\[ p_T^{\text{vis}}(\tau) > 20 \text{ GeV(Left)}; p_T^{\text{vis}}(\tau) > 40 \text{ GeV(Right)}; \]

- The expected end point position: 78.7 (GeV).
- The peak is formed due to \( \tilde{\chi}_2^0 \rightarrow \tau \tilde{\tau}_1 \).
$\Delta M$ Dependence

- The OS—LS counts change as a function of $\Delta M$.
- The peak of the $M_{\tau\tau}^{\text{vis}}$ distributions of OS—LS shifts as a function of $\Delta M$.

- The gluino mass varies by 5%.
- The "fake" effect is negligible.
Counting OS-LS pairs

- The $5\sigma$ significance reach for the coannihilation region as a function of luminosity (the gluino mass is varied by 10%).

- The error for $\Delta M$ measurement is about 20% for 5-15 GeV.
$3 \tau + 1j + \not{E}_T$ Analysis

Event selection:
$E_T(jet) + \not{E}_T > 400 \text{ GeV}$, $E_T(jet) > 100 \text{ GeV}$, $E_T(\tau_1) > 40$, $E_T(\tau_2) > 40$, $E_T(\tau_3) > 20$ GeV.

SUSY events and $t\bar{t}$ background:
Comparison of the reach in $\Delta M$ using 3 tau (left) and 2 tau (right) signals.
Conclusion

- Cosmologically allowed mSUGRA parameter space: The neutralino stau coannihilation effect is dominant for smaller scalar and gaugino masses in the mSUGRA model. This coannihilation effect is also present in nonuniversal models.

- Signals from the coannihilation region at the LHC has been studied:
  \[2\tau + 2j + \slashed{E}_T \text{ or } 3\tau + 1j + \slashed{E}_T\]

- The detection of the signal is difficult due to the presence of low energy tau (arising due to small mass difference between the lightest stau and the lightest neutralino).
Conclusion...

- But $p_T^{\text{vis}}(\tau) > 20$ GeV is the key.

- The key observables are:
  OS-LS counts and the peak of the ditau mass distribution as a function of $\Delta M$.

- The observables are not affected by "fake" effects.

- It is possible to have $5\sigma$ discovery in certain regions of the coannihilation channel even for $5 \, fb^{-1}$ of luminosity.

- The uncertainty in the $\Delta M$ measurement is about 20%.