Cosmology at the LHC

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References

LHC:
3taus + jet + $E_T^{miss}$
hep/ph 0608193

LHC:
2 taus + jets + $E_T^{miss}$
(hep-ph/0603128)

ILC:
2 taus + $E_T^{miss}$
(hep-ph/0503165)
SUSY and COSMOLOGY

- \( \text{SUSY} \rightarrow \text{SUGRA} \rightarrow \text{SUGRA Guts} \)
- Build models from MGut to EW scale incorporating all the successes of SM
- \( \text{R-parity} \rightarrow \text{Neutralino as cold dark matter candidate} \)
- Models consistent with WMAP results
- Models going back in time to \( 10^{-7} \) seconds after the Big Bang
Can we verify if dark matter particle in the Galaxy is the neutralino at the LHC

In principle, compare DM detector cross sections, mass, distributions with those measured at the LHC

More immediately, look for a signal at the LHC that is a consequence of the assumption that neutralino is the DM

To investigate this, chose SUSY model: mSUGRA
4 parameters + 1 sign

- $m_{1/2}$: Gaugino mass at $M_G$
- $m_0$: Scalar soft breaking mass at $M_G$
- $A_0$: Cubic soft breaking mass at $M_G$
- $\tan\beta$: $\langle H_2 \rangle/\langle H_1 \rangle$ at the electroweak scale
- sign($\mu$): Sign of Higgs mixing parameter ($W^{(2)} = \mu H_1 H_2$)

Experimental Constraints

i. $M_{\text{Higgs}} > 114 \text{ GeV}$  $M_{\text{chargino}} > 104 \text{ GeV}$
ii. $2.2 \times 10^{-4} < Br (b \to s \gamma) < 4.5 \times 10^{-4}$
iii. $0.094 < \Omega \tilde{\chi}_1^0 h^2 < 0.129$
iv. $(g-2)_\mu$
WMAP Constraints

The WMAP constraints limits the parameter space to 3 regions:

(1) The stau-neutralino coannihilation region

(2) Neutralino having large Higgsino component (focus point)

(3) Annihilation through heavy Higgs (funnel region)

[In addition there is a small bulk region]
Annihilation in the Early Universe

CDM = Neutralino ; NLSP = stau

\[ (\Omega_{\text{CDM}})^{-1} \propto \begin{pmatrix} \tilde{\chi}_1^0 \rightarrow h, H, A, Z \backslash f \end{pmatrix}^2 \]

\[ + \begin{pmatrix} \tilde{\chi}_1^0 \rightarrow \tau, \gamma \end{pmatrix}^2 \]

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

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

Griest, Seckel’91

Can the mSUGRA naturally provide small $\Delta M$?
The accelerator constraints further restrict the parameter space, and if the muon g-2 anomaly maintains, in mSUGRA there remains mainly the coannihilation region.

[Coannihilation is common in many other SUGRA models as it doesn’t depend on universal gaugino masses.]
Coannihilation

Cosmologically Allowed Region

\[ \tan \beta = 40, \mu > 0, A_0 = 0 \]

Can we measure \( \Delta M \) at colliders?

\[ \Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV} \]
(1) Can such a small stau-neutralino mass difference (5-15 GeV) arise in mSUGRA?

(2) Can such a small mass difference be measured at the LHC?

If so, the observation of such a small mass difference would be a strong indication that the neutralino is the DM particle (since both cosmological and accelerator constraints enter in the mass difference).
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:

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

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

Thus for $m_0 = 0$, the mass of $\tilde{E}_c^2$ becomes degenerate with the $\tilde{\chi}_1^0$ mass at $m_{1/2} = 370$ 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,
SUSY Signature at the LHC

Squark-Gluino Production

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\tilde{q} \rightarrow \tau^+ + \tilde{\chi}_1^- \rightarrow \tau^+ + \tau^- \tilde{\chi}_2^0
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Triggering the jets and missing $E_T$ → $E_T^{\text{miss}} + \text{jets} + \tau^0$'s
Coannihilation Signal

1. We expect 2 pairs of taus, one soft and one hard in each pair from neutralino decay.

2. Each pair should be of opposite sign (while SM and SUSY backgrounds, jets faking taus will have equal number like sign as opposite sign).

3. Thus suppress backgrounds statistically by considering number of opposite sign events minus like sign events.
Consider data set with 3 taus of which 2 are hard and 1 is soft:

Let: $E_1^T > E_2^T > E_3^T$, and form the 13 and 23 pairs

Two measurables:

$M =$ mass of tau pairs

$N =$ number of events
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 $\mathcal{E}_\tau = 50\%$, fake ($f_{j\rightarrow \tau}$) = 1%. Final cuts: $E_T^{\text{jet1}} > 100$ GeV, $E_T^{\text{miss}} > 100$ GeV, $E_T^{\text{jet1}} + E_T^{\text{miss}} > 400$ GeV

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

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

Note: $f_{j\rightarrow \tau} = 0\% \rightarrow 1.6 \text{ counts/fb}^{-1}$
Opposite Sign Minus Like Sign Subtraction

\[ \Delta M = 9 \text{ GeV} \]
\[ M_g = 850 \text{ GeV} \]

\[ \Delta M = 20 \text{ GeV} \]
\[ M_g = 850 \text{ GeV} \]
The number of events increases with neutralino-stau mass difference (higher tau acceptance) and decreases with gluino mass (production cross section decreases).

The ditau mass peak increases with neutralino-stau mass difference and with gluino mass.
Event Number vs Gluino and Mass Difference

$M_g = 850$ GeV

1% Fake Rate

20% Error on Fake Rate

$\Delta M = 9$ GeV

1% Fake Rate

20% Error on Fake Rate
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 $M_{\text{gluino}}$

$\frac{\delta \Delta M}{\Delta M} \sim 15\%$ ; $\frac{\delta M_{\text{gluino}}}{M_{\text{gluino}}} \sim 6\%$
Conclusions

If the neutralino-stau mass difference is determined at the LHC to lie in the coannihilation region, it is strong indication that the neutralino is the dark matter particle (otherwise the mass difference would not naturally be so small).

We discussed how it is possible to measure this mass difference and the gluino mass simultaneously at the LHC for the mSUGRA model using the 3 tau signal.

One can also measure the mass difference using a 2 tau signal which has higher acceptance but also larger backgrounds.
Conclusions (cont.)

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 $M_{\text{peak}}$ assuming 5\% gluino mass error

- $3\tau$ analysis
  Using 30 fb$^{-1}$:
  Combine $N_{\text{OS-LS}}$ and $M_{\text{peak}}$ measurements
  $\delta \Delta M / \Delta M \sim 13\%$ and 5\% gluino mass error
Conclusions (cont.)

Reach in $m_{1/2}$?

$$m_{1/2} = 360 \text{ GeV}$$

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

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.

If an independent direct measurement of the gluino mass can be made, and it agrees with the 3 tau result, it would be strong evidence of gaugino unification at the GUT scale.

However, it may not be possible to measure the gluino mass directly in the coannihilation region for large \( \text{tan } \beta \) due to the large number of low energy taus, and the ILC would require a very high energy option to see the gluino.
Finally, the analysis here was done with mSUGRA, but a similar analysis is possible for other SUGRA models (most of which possess coannihilation) provided the production of neutralinos is not suppressed.