Relic Density at the LHC

B. Dutta

Texas A&M University

In Collaboration With:

R. Arnowitt, A. Gurrola, T. Kamon, A. Krislock, D. Toback

The signal to look for: 4 jet + missing $E_T$
Kinematical Cuts and Event Selection

- $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV
- $M_{\text{eff}} > 400$ GeV ($M_{\text{eff}} \equiv E_T^{j1} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}}$)
- $E_T^{\text{miss}} > \text{Max} \ [100, 0.2 \ M_{\text{eff}}]$
SUSY scale is measured with an accuracy of 10-20%.

- This measurement does not tell us whether the model can generate the right amount of dark matter.

- The dark matter content is measured to be 23% with an accuracy of around 5% at WMAP.

Question:

To what accuracy can we calculate the relic density based on the measurements at the LHC?
Strategy

✓ We establish the dark matter allowed regions from the detailed features of the signals.

✓ We accurately measure the masses.

✓ We calculate the relic density and compare with WMAP.
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. $M_{\text{Higgs}} > 114 \text{ GeV}$ $M_{\text{chargino}} > 104 \text{ GeV}$
ii. $2.2\times10^{-4} < Br (b \rightarrow s \gamma) < 4.5\times10^{-4}$
iii. $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$
iv. $(g-2)_\mu$
Dark Matter Allowed Regions

We choose mSUGRA model. However, the results can be generalized.

Focus point region – the lightest neutralino has a larger higgsino component

A-annihilation funnel region – This appears for large values of $m_{1/2}$

Neutralino-stau coannihilation region
In the stau neutralino coannihilation region

\[
(\Omega_{\text{CDM}})^{-1} \propto \begin{bmatrix}
\tilde{\chi}^0_1 & h, H, A, Z \\
\tilde{\chi}^0_1 & f
\end{bmatrix}^2 + \begin{bmatrix}
\tilde{\chi}^0_1 & \tilde{f} \\
\tilde{\chi}^0_1 & f
\end{bmatrix}^2 + \ldots
\]

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

Griest, Seckel '91
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:

\[
m^2_{E^c} = m^2_0 + 0.15 m^2_{1/2} + (37 \text{ GeV})^2
\]

\[
m^2_{\tilde{\chi}_1^0} = 0.16 m^2_{1/2}
\]

Thus for \(m_0 = 0\), \(\tilde{E}^c\) becomes degenerate with \(\tilde{\chi}_1^0\) at \(m_{1/2} = 370\) GeV, i.e. the coannihilation region begins at \(m_{1/2} = (370-400)\) 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.
Coannihilation Region

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

Can we measure \( \Delta M \) at colliders?
SUSY Signals at the LHC

In Coannihilation Region of SUSY Parameter Space:

Final state: $\frac{3}{4}$ τs+jets + missing energy

Use hadronically decaying τ

Trigger on the jets and missing $E_T$

$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15$ GeV
Three Observables

1. Sort τ’s by $E_T$ ($E_T^1 > E_T^2 > …$) and use OS-LS method to extract τ pairs from the decays

2. Use counting method ($N_{OS-LS}$) & ditau invariant mass ($M_{\tau\tau}$) to measure mass difference $\Delta M$ (between the lightest stau and the neutralino) and gluino mass

3. Measure the $P_T$ of the low energy τ to estimate the mass difference $\Delta M$
Since we are using 3 variables, we can measure $\Delta M$, $M_{\text{gluino}}$ and the universality relation of the gaugino masses

\[ \text{i.e.} \quad M_{\tilde{g}} \sim 2.8m_{1/2}, \quad M_{\tilde{\chi}^0_2} \sim 0.8m_{1/2}, \quad M_{\tilde{\chi}^0_1} \sim 0.4m_{1/2} \]

$M_{\text{gluino}}$ measured from the $M_{\text{eff}}$ method may not be accurate for this parameter space since the tau jets may pass as jets in the $M_{\text{eff}}$ observable.

The accuracy of measuring these parameters are important for calculating relic density.
High Energy Proton-Proton collisions produce lots of Squarks and Gluinos which eventually decay. Identify a special decay chain that can reveal $\Delta M$ information.

A Smoking Gun at the LHC?
$M_{\tau\tau}^{\text{vis}}$ in ISAJET

Version 7.69 ($m_{1/2} = 347.88$, $m_0 = 201.1$) $\rightarrow$ $M_{\text{gluino}} = 831$

Chose di-$\tau$ pairs from neutralino decays with
(a) $|\eta| < 2.5$
(b) $\tau =$ hadronically-decaying tau

$\tilde{\chi}_2^0 \rightarrow \tau \tilde{\chi}_1^0 \rightarrow \tau \tau \tilde{\chi}_1^0$
($\Delta M = 5.7$ GeV)

$\tilde{\chi}_2^0 = 264.1$
$\tilde{\chi}_1^0 = 137.4$
$\tilde{\tau}_1 = 143.1$
End pont = 62.0

$E_T^{\tau} > 20$ GeV is essential!
EVENTS WITH CORRECT FINAL STATE: $2\tau + 2j + E_T^{\text{miss}}$

APPLY CUTS TO REDUCE SM BACKGROUND ($W+jets, \ldots$)

- $E_T^{\text{miss}} > 180$ GeV
- $E_T^{j1} > 100$ GeV
- $E_T^{j2} > 100$ GeV
- $E_T^{\text{miss}} + E_T^{j1} + E_T^{j2} > 600$ GeV

ORDER TAUS BY $P_T$ & APPLY CUTS ON TAUS: WE EXPECT A SOFT $\tau$ AND A HARD $\tau$

- $P_T^{\text{all}} > 20$ GeV
- $P_T^{\tau1} > 40$ GeV

LOOK AT $\tau$ PAIRS AND CATEGORIZE THEM AS OPPOSITE SIGN (OS) OR LIKE SIGN (LS)

**OS:**
- FILL LOW OS $P_T$ HISTOGRAM WITH $P_T$ OF SOFTER $\tau$
- FILL HIGH OS $P_T$ HISTOGRAM WITH $P_T$ OF HARDER $\tau$

**LS:**
- FILL LOW LS $P_T$ HISTOGRAM WITH $P_T$ OF SOFTER $\tau$
- FILL HIGH LS $P_T$ HISTOGRAM WITH $P_T$ OF HARDER $\tau$
**$E_T^{\text{miss}} + 2j + 2\tau$ Analysis**

[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 $\varepsilon_\tau = 50\%$, 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
$W+\text{jets} : 44$ events
SUSY : 590 events

---

**Graphs**

- Top
  
  - $E_T^{\text{jet1}} + E_T^{\text{jet2}}$ vs. $E_T^{\text{jet1}} + E_T^{\text{jet2}}$
  
  - $M_{\text{gluino}} = 830$ GeV
  
  - $\Delta M = 10.6$ GeV

- SUSY
  
  - $E_T^{\text{jet1}} + E_T^{\text{jet2}}$ vs. $E_T^{\text{jet1}} + E_T^{\text{jet2}}$
  
  - $M_{\text{gluino}} = 830$ GeV
  
  - $\Delta M = 10.6$ GeV
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.
Also, get more events for large $\Delta M$.

Slope of $P_T$ distribution contains $\Delta M$ Information.

Slope of $P_T$ distribution is largely unaffected by Gluino Mass.

Low energy $\tau$’s are an enormous challenge for the detectors.
More Observables

- Look at the mass of the $\tau^+\tau^-$ in the events
- Can use the same sample to subtract off the non-$\chi_2$ backgrounds $\rightarrow$ Clean peak!

Larger $\Delta M$:
- More events
- Larger mass peak

Clean peak
Even for low $\Delta M$
• The slope of the $P_T$ distribution of the $t$'s only depends on the $\Delta M$
• The event rate depends on both the Gluino mass and $\Delta M$
• Can make a simultaneous measurement

An important measurement without Universality assumptions!

Results for ~300 events (10 fb$^{-1}$ depending on the Analysis)
As the neutralino masses rise the $M_{\tau\tau}$ peak rises.
Universal scenario?

Use all 3 observables to make simultaneous measurements

Compare measured $M_{\tilde{\chi}_2^0}$ to $M_{\tilde{\chi}_2^0}^{\text{Unversality}}$ from $\Delta M, M_{\tilde{g}}$

Only Assume $M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$

$\sim 15 \text{ GeV or } \sim 3\%$
Assuming Universality

Use Events, $M_{\tau\tau}$ and Slope to measure

$\Delta M$, $M_{\tilde{g}}$ and $M_{\tilde{\chi}^0_2}$ simultaneously

(Results for $M_{\tilde{G}} = 830$ GeV, $\Delta M = 10.6$ GeV)

Results for ~300 events (10 fb$^{-1}$ depending on the Analysis)

~15 GeV or ~2%

~0.5 GeV or ~5%

Analysis only assumes $M_{\tilde{\chi}^0_1} \sim 0.17 M_{\tilde{g}}$

Analysis assumes $M_{\tilde{\chi}^0_2} \sim 0.32 M_{\tilde{g}}$ and $M_{\tilde{\chi}^0_1} \sim 0.17 M_{\tilde{g}}$
We determine \( \delta m_0/m_0 \approx 1.2\% \) and \( \delta m_{1/2}/m_{1/2} \approx 2\% \) (for \( A_0 = 0, \tan\beta = 40 \)) (at 10 fb\(^{-1}\))
$\Delta M$ and $M_{\text{gluino}} \rightarrow \Omega \tilde{\chi}_1^0 h^2$

(for fixed $A_0$ and $\tan \beta$)

\[ \delta \Omega h^2 / \Omega h^2 \sim 7\% \text{ (10 fb}^{-1}) \]

(for $A_0=0$, $\tan \beta=40$)
Conclusion

- $M_{\text{eff}}$ will establish the existence of SUSY
- Different observables are needed to establish the dark matter allowed regions in SUSY model at the LHC

Analysis with visible $E_T^{\tau} > 20$ GeV establishes stau-neutralino coannihilation region

2$\tau$ analysis: Discovery with 10 fb$^{-1}$
- $\delta \Delta M / \Delta M \sim 5\%$, $\delta m_g / m_g \sim 2\%$ using $M_{\text{peak}}$, $N_{\text{OS-LS}}$ and $p_T$

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

- $\delta \Omega h^2 / \Omega h^2 \sim 7\%$ for $A_0=0$, $\tan \beta=40$ (10 fb$^{-1}$)