Measurement of Relic Density at the LHC

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SUSY in Early Stage at the LHC

The signal to look for: 4 jet + missing $E_T$

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**Example Analysis**

**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 \times M_{\text{eff}}]\]


**FIG. 1.** LHC point 1 signal and standard model backgrounds. Open circles: SUSY signal. Solid circles: $tt$. Triangles: $W \rightarrow l \nu, \tau \nu$. Downward triangles: $Z \rightarrow \nu \bar{\nu}, \tau \bar{\tau}$. Squares: QCD jets. Histogram: sum of all backgrounds.

**FIG. 6.** Scatterplot of $M_{\text{SUSY}} = \min(M_{3/2}M_F)$ vs $M_{\text{eff}}$ for randomly chosen SUGRA models having the same light Higgs boson mass within ±3 GeV as for LHC point 5.
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 with an accuracy of around 6% at WMAP.

**Question:**

To what accuracy can we calculate the relic density based on the measurements at the LHC?
✓ We establish the dark matter allowed regions from the detailed features of the signals.

✓ We accurately measure the masses and model parameters (all four mSUGRA parameters).

✓ We calculate the relic density and compare that with WMAP observation.
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 \quad $M_{\text{chargino}} > 104$ 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. $(g-2)_{\mu}$: 3 $\sigma$ descripency

Measurement of Relic Density at the LHC
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
Relic Density Calculation

\[
\left( \Omega_{\text{CDM}} \right)^{-1} \propto \begin{vmatrix}
\tilde{\chi}_1^0 \\
\tilde{\chi}_1^0 \\
h, H, A, Z \\
\end{vmatrix}^2
\]

In the stau-neutralino coannihilation region

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

Griest, Seckel '91
Our Reference Point

\[ m_{1/2} = 351, \ m_0 = 210, \ \tan \beta = 40, \ \mu > 0, \ A_0 = 0 \]

[ISAJET version 7.69]

TABLE I: Masses (in GeV) of SUSY particles for our reference point \( m_{1/2} = 351 \) GeV, \( m_0 = 210 \) GeV, \( \tan \beta = 40 \), \( \mu > 0 \), and \( A_0 = 0 \). We use ISAJET v7.69 The \( \tilde{q}_L \) and \( \tilde{q}_R \) masses are represented by the \( \tilde{u}_L \) and \( \tilde{u}_R \) masses. \( \Delta M = 10.6 \) GeV.

<table>
<thead>
<tr>
<th>( \tilde{g} )</th>
<th>( \tilde{q}_L )</th>
<th>( \tilde{t}_2 )</th>
<th>( \tilde{b}_2 )</th>
<th>( \tilde{e}_L )</th>
<th>( \tilde{\tau}_2 )</th>
<th>( \tilde{\chi}_2^0 )</th>
<th>( \tilde{\chi}_1^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>831</td>
<td>748</td>
<td>728</td>
<td>705</td>
<td>319</td>
<td>329</td>
<td>260.3</td>
<td>140.7</td>
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<tr>
<td>725</td>
<td>561</td>
<td>645</td>
<td>251</td>
<td>151.3</td>
<td></td>
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</tbody>
</table>

Measurement of Relic Density at the LHC
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$E_T^{\text{miss}} + \text{jets} + \geq 2\tau$
$p_T^{\text{soft}}$ Slope and $M_{\tau\tau}$

$p_T$ and $M_{\tau\tau}$ distributions in true di-$\tau$ pairs from neutralino decay with $|\eta| < 2.5$

Slope of $p_T$ distribution of “soft $\tau$” contains $\Delta M$ information

Low energy $\tau$'s are an enormous challenge for the detectors

\[
\begin{align*}
\tilde{g} &= 831 \text{ GeV} \\
\tilde{\chi}_2^0 &= 264 \text{ GeV} \\
\tilde{\chi}_1^0 &= 137.4 \text{ GeV} \\
\tilde{\tau}_1 &= 143.1 \text{ GeV}
\end{align*}
\]

End point = 62.0 GeV
\[ E_T^{\text{miss}} + 2j + 2\tau \] Analysis Path

Cuts to reduce the SM backgrounds \((W+\text{jets, ...})\)

\[
E_T^{\text{miss}} > 180 \text{ GeV}, \quad N(\text{jet}) \geq 2 \text{ with } E_T > 100 \text{ GeV}
\]

\[
E_T^{\text{miss}} + E_T^{j1} + E_T^{j2} > 600 \text{ GeV}; \quad N(\tau) \geq 2 \text{ with } P_T > 40, 20 \text{ GeV}
\]

CATEGORIZE opposite sign (OS) and like sign (LS) ditau events

OS \(\tau\tau\)
- Low \(p_T\) histogram
- High \(p_T\) histogram

LS \(\tau\tau\)
- Low \(p_T\) histogram
- High \(p_T\) histogram

\{ Low OS \rightarrow Low OS–LS \rightarrow Low LS \}
\{ High OS \rightarrow High OS–LS \rightarrow High LS \}

Measurement of Relic Density at the LHC
**$M_{\tau\tau}$ Distribution**

\[
M_{\tau\tau}^{\text{max}} = M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\tau}_1^0}^2}{M_{\tilde{\chi}_2^0}^2}}
\]

*Clean peak even for low $\Delta M$  Larger $\tilde{\chi}_2^0$ Mass $\to$ Larger $M_{\tau\tau}$*

---

**We choose the peak position as an observable.**

*Measurement of Relic Density at the LHC*
$M_{\tau\tau}$ Distribution

$M_{\tau\tau}$ depends on $m_0$, $m_{1/2}$, $A_0$ and $\tan\beta$

Measurement of Relic Density at the LHC
$M_{j\tau\tau}$ Distribution

\[ M_{j\tau\tau}^{\text{end}} = M \tilde{q} \sqrt{1 - \frac{M_{\tilde{\chi}_2^0}}{M_{\tilde{q}}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{q}}^2}} \]

\[ M_{j\tau\tau}^{\text{peak}} \propto M_{j\tau\tau}^{\text{end}} \]

$M_{\tau\tau} < M_{\tau\tau}^{\text{endpoint}}$

Jets with $E_T > 100$ GeV

$J\tau\tau$ masses for each jet

Choose the 2$^{\text{nd}}$ large value

Squark Mass = 660 GeV

Squark Mass = 840 GeV

\[ \Delta M = 10.6 \text{ GeV} \]
\[ M_{\tilde{\chi}_4^0} = 140.7 \text{ GeV} \]
\[ M_{\tilde{\chi}_2^0} = 260.3 \text{ GeV} \]

Peak value depends on squark mass

We choose the peak position as an observable.

Measurement of Relic Density at the LHC
*Measurement of Relic Density at the LHC*

\[ M_{j\tau\tau} \text{ Distribution} \]

\[ M_{j\tau\tau}^{\text{peak}} \text{ depends on } m_0, m_{1/2} \]
\( M_{\text{eff}} \) Distribution

- \( E_{T}^{j1} > 100 \, \text{GeV}, \quad E_{T}^{j2,3,4} > 50 \, \text{GeV} \) [No e’s, μ’s with \( p_{T} > 20 \, \text{GeV} \)]
- \( M_{\text{eff}} > 400 \, \text{GeV} \) (\( M_{\text{eff}} \equiv E_{T}^{j1} + E_{T}^{j2} + E_{T}^{j3} + E_{T}^{j4} + E_{T}^{\text{miss}} \)) [No b jets; \( \varepsilon_{b} \sim 50\% \)]
- \( E_{T}^{\text{miss}} > \max [100, 0.2 \, M_{\text{eff}}] \)

At Reference Point
\( M_{\text{eff}}^{\text{peak}} = 1274 \, \text{GeV} \)

\( M_{\text{eff}}^{\text{peak}} = 1220 \, \text{GeV} \quad (m_{1/2} = 335 \, \text{GeV}) \)
\( M_{\text{eff}}^{\text{peak}} = 1331 \, \text{GeV} \quad (m_{1/2} = 365 \, \text{GeV}) \)
$M_{\text{eff}}^\text{peak}$ vs. $m_0$, $m_{1/2}$

$M_{\text{eff}}^\text{peak}$ .... insensitive to $A_0$ and $\tan \beta$. 

Measurement of Relic Density at the LHC
$M_{\text{eff}}^{(b)}$ Distribution

- $E_T^{j1} > 100 \text{ GeV}, \quad E_T^{j2,3,4} > 50 \text{ GeV} \ [\text{No e’s, μ’s with } p_T > 20 \text{ GeV}]
- M_{\text{eff}}^{(b)} > 400 \text{ GeV} \ (M_{\text{eff}}^{(b)} \equiv E_T^{j1=b}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{\text{miss}} \ [j1 = b \text{ jet}])
- E_T^{\text{miss}} > \max [100, 0.2 \ M_{\text{eff}}]

At Reference Point

$M_{\text{eff}}^{(b)\text{peak}} = 1026 \text{ GeV}$

$M_{\text{eff}}^{(b)\text{peak}} = 933 \text{ GeV} \quad M_{\text{eff}}^{(b)\text{peak}} = 1122 \text{ GeV}$

$(m_{1/2} = 335 \text{ GeV}) \quad (m_{1/2} = 365 \text{ GeV})$

$M_{\text{eff}}^{(b)}$ can be used to determine $A_0$ and $\tan\beta$ even without measuring stop and sbottom masses

Measurement of Relic Density at the LHC
$M_{\text{eff}}^{(b)\text{peak}}$ vs. $X$

$A_0$

$M_{\text{eff}}^{(b)\text{peak}}$ .... sensitive to $A_0$ and $\tan \beta$.

Measurement of Relic Density at the LHC
Determining Model Parameters

The Model parameters are solved by inverting the following functions:

\[ M_{j\tau\tau} = f_1(m_{1/2}, m_0), \quad M_{\tau\tau} = f_2(m_{1/2}, m_0, \tan\beta, A_0) \]

\[ M_{\text{eff}} = f_3(m_{1/2}, m_0), \quad M_{\text{eff}}^{(b)} = f_4(m_{1/2}, m_0, \tan\beta, A_0) \]

\[ m_0 = 205 \pm 4; \quad m_{1/2} = 350 \pm 4.2; \quad A_0 = 0 \pm 16; \quad \tan\beta = 40 \pm 0.8 \ (10 \ fb^{-1}) \]

We can also determine the sparticle masses using these observables and a few additional ones, e.g., \( M^{(\text{peak})}_{j\tau} \), etc

\[ M_{\tilde{q}} = 748 \pm 25; \quad M_{\tilde{g}} = 831 \pm 21; \quad \Delta M = 10.6 \pm 2; \]
\[ M_{\tilde{\chi}_1^0} = 141 \pm 19; \quad M_{\tilde{\chi}_2^0} = 260 \pm 15; \]

Gaugino Universality can be checked!
How does the uncertainty in the Dark Matter relic density change with Luminosity?

$\delta \Omega h^2 / \Omega h^2 \sim 6\% \quad (30 \text{ fb}^{-1})$

Measurement of Relic Density at the LHC
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

The mSUGRA parameters are determined using:
1) $M_{\text{eff}}^\text{peak}$
2) $M_{\tau\tau}^\text{peak}$
3) $M_{\tau\tau}^\text{peak}$
4) $M_{\text{eff}}^\text{peak}(b)$

$m_0=205 \pm 4$; $m_{1/2}=350 \pm 4.2$; $A_0=0 \pm 16$; $\tan\beta=40 \pm 0.8$ (10 fb$^{-1}$)

$\delta \Omega h^2/\Omega h^2 \sim 6\%$ (30 fb$^{-1}$)

- Squark, Gluino, stau, neutralino(1,2) can be determined without using mSUGRA assumptions
- Gaugino universality can be checked at 15% level