Measuring Dark Matter Relic Density at the LHC
- mSUGRA Co-annihilation Case -

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PPC2008, New Mexico University
May 19, 2008
Probing the SUSY Dark Matter

Dark Matter (DM) Particle in SUSY & Cosmological Connection

Ω_{SUSY DM} = Ω_{CDM}

SUSY Signal in Co-annihilation (CA) Region
DM Density (Ωh^2) at the LHC

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback
Arnowitt, Dutta, Kamon, Kolev, Toback, PLB 639 (2006) 46
SUSY is an interesting class of models to provide a weakly interacting massive neutral particle ($M \sim 100$ GeV).
Anatomy of $\sigma_{\text{ann}}$

$$\frac{\Omega_{\tilde{\chi}_1} h^2}{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} v \rangle} dx$$

$$(\Omega_{CDM})^{-1} \propto$$

Co-annihilation (CA) Process

Griest, Seckel '91

An accidental near degeneracy occurs naturally for light stau in many models.

Our Benchmark = Model mSUGRA

4/5/08 Measuring Dark Matter Relic Density at the LHC
Minimal Supergravity (mSUGRA)

SUSY model in the framework of unification:

$\langle H_u \rangle = 246$ GeV

4 parameters + 1 sign

$\tan \beta : \frac{\langle H_u \rangle}{\langle H_d \rangle}$ at $M_Z$

$m_{1/2}$ : Common gaugino mass at $M_{\text{GUT}}$

$m_0$ : Common scalar mass at $M_{\text{GUT}}$

$A_0$ : Trilinear coupling at $M_{\text{GUT}}$

sign($\mu$) : Sign of $\mu$ in $W^{(2)} = \mu H_u H_d$

Key Experimental Constraints

$M_{\text{Higgs}} > 114$ GeV; $M_{\tilde{\chi}_1^\pm} > 104$ GeV

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

$(g - 2)_\mu : \sim 3\sigma$ deviation from SM

$0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$
DM Allowed Regions


4 Smoking Gun of CA Region?

Smoking Gun of CA Region?

4 Excluded by


Smoking Gun of CA Region?

4 Smoking Gun of CA Region?

Smoking Gun of CA Region?

4 Smoking Gun of CA Region?

Excluded by

1 Rare B decay \( b \rightarrow s \gamma \)

2 No CDM candidate

3 Magnetic moment of muon

\[
\tan \beta = 40
\]

\[
A_0 = 0, \mu > 0
\]

\[
m_{\chi} > m_{\tilde{\chi}}
\]

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

\[
m_{1/2} = 350, m_0 = 210, \tan \beta = 40, A_0 = 0, \mu > 0
\]

[ISAJET version 7.64]

<table>
<thead>
<tr>
<th>( \tilde{g} )</th>
<th>( \tilde{u}_L )</th>
<th>( \tilde{\chi}_2 )</th>
<th>( \tilde{b}_2 )</th>
<th>( \tilde{e}_L )</th>
<th>( \tilde{\tau}_2 )</th>
<th>( \tilde{\chi}^0_2 )</th>
<th>( \Delta M )</th>
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<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>10.6</td>
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<td>725</td>
<td>561</td>
<td>645</td>
<td>251</td>
<td>151.3</td>
<td>140.7</td>
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5/19/08    Measuring Dark Matter Relic Density at the LHC
Proving $\Omega_{SUSY\ DM}$ in Inclusive Jets+$E_T^{miss}$

Excess in $E_T^{miss}$ + Jets + $X$

$X = $ Dilepton mass endpoint from $\chi_2^0$ decay to reconstruct the SUSY masses

large $\tan\beta$

$X = ee, \mu\mu, \tau\tau$

$X = \tau\tau$

$\Delta M = 5$-$10$ GeV

Nojiri, Polesselo, Tovey, JHEP 0603 (2006) 063

$\Omega_{SUSY\ DM} = \Omega_{CDM}$

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback, arXiv:0802.2968

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Dilepton Endpoint

- DM content → Measurements of the SUSY masses
  [e.g., M.M. Nojiri, G. Polesselo, D.R. Tovey, JHEP 0603 (2006) 063]
- Key: Dilepton “edge” in the $\chi^0_2$ decay in dilepton ($ee, \mu\mu, \tau\tau$) channels for reconstruction of decay chain.

\[ p \rightarrow \tilde{g} + \tilde{q} \rightarrow \tilde{\chi}_2^0 q\bar{q} \]
\[ \tilde{\chi}_2^0 \rightarrow \ell_R \ell^\pm \]

LM1 (Low Mass Case 1):

[post-WMAP benchmark point B']
\[ \sigma = 55 \text{ pb} \]
\[ m_{1/2} = 180, m_0 = 850 \]

\[ M_{\tilde{g}} = 611, M_{\tilde{q}} = 559 \]
\[ B(\tilde{\chi}_2^0 \rightarrow \ell_R \ell^\pm) = 11.2\% \]
\[ B(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau) = 46\% \]
\[ B(\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_L \ell^\pm) = 36\% \]
In the CA region, the $ee$ and $\mu\mu$ channels are almost absent. We are in a different game.

Program:

1. Establish the “CA region” signal
2. Determine SUSY masses/mSUGRA parameters
3. Measure $\Omega_\chi h^2$ and compare with $\Omega_{CDM} h^2$

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

$M_{\tilde{g}} = 831, M_{\tilde{q}} = 748$

$\tilde{g} \rightarrow \tilde{q}\tilde{q} \rightarrow \tilde{\chi}^0_2 q\bar{q}$

$B(\tilde{\chi}^0_2 \rightarrow \ell_R \ell) \approx 0\%$

$B(\tilde{\chi}^0_2 \rightarrow \tilde{\chi}_1 \tau) \approx 100\%$

$B(\tilde{\chi}^+_1 \rightarrow \tilde{\nu}_L \ell) \approx 0\%$
SUSY Anatomy in the CA Region

\[ E_{T}\text{miss} + 2j + 2\tau \text{Analysis Path} \]

Cuts to reduce the SM backgrounds (W+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\(\tau\tau\)
\[ M_{\tau\tau} \text{ histogram} \]

LS\(\tau\tau\)
\[ M_{\tau\tau} \text{ histogram} \]

\[ \{ \text{OS mass} \rightarrow \text{OS–LS mass} \rightarrow \text{LS mass} \} \]

[Key Assumption]
\[ \varepsilon_{\tau} = 50\% , \text{ fake rate } 1\% \]

for \[ p_{T}^{\text{vis}} > 20 \text{ GeV} \]
\( M_{\tau\tau}^{\text{max}} = M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_1^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}} \)

\( M_{\text{peak}} \propto M_{\tau\tau}^{\text{max}} \)

**Clean peak even for low \( \Delta M \)**

\[
\begin{array}{cccccc}
\tilde{g} & \tilde{u}_L & \tilde{d}_L & \tilde{b}_2 & \tilde{e}_L & \tilde{\tau}_2 & \tilde{\chi}_2^0 \\
\tilde{u}_R & \tilde{d}_R & \tilde{b}_1 & \tilde{e}_R & \tilde{\tau}_1 & \tilde{\chi}_1^0 \\
\hline
748 & 728 & 705 & 319 & 329 & \\
725 & 561 & 645 & 251 & 151.3 & 140.7 \\
\end{array}
\]

\( \Delta M = 10.6 \, \text{GeV} \)

Counts / (10 fb\(^{-1}\) x 10 GeV)

- \( \chi_2 \) = 260.3 GeV
- \( \chi_2 \) = 321.5 GeV

\( M_{\text{vis}}^{\tau\tau} \) (GeV)

Larger \( \tilde{\chi}_2^0 \) Mass → Larger \( M_{\tau\tau} \)
$M_{\tau\tau}^{\text{peak}}$ vs. $X$

$X = M \tilde{\chi}_1^0$ with $\Delta M = 10.6$ GeV
$M_{\chi_2} = 260.3$ GeV
$M_{\tilde{g}} = 831.0$ GeV

$X = M \tilde{\chi}_2^0$ with $\Delta M = 10.6$ GeV
$M_{\chi_1} = 140.7$ GeV
$M_{\tilde{g}} = 831.0$ GeV

$X = \Delta M$ with $\Delta M = 140.7$ GeV
$M_{\chi_2} = 260.3$ GeV
$M_{\tilde{g}} = 831.0$ GeV

$X = M_{\tilde{g}}$ with $\Delta M = 10.6$ GeV
$M_{\chi_1} = 140.7$ GeV
$M_{\chi_2} = 260.3$ GeV

Uncertainty Bands with 10 fb$^{-1}$

$M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0})$
**OS–LS Slope**\( (p_T^{\text{soft}}) \)

Independent of the gluino masses!

**Uncertainty Bands with 10 fb\(^{-1}\)**

\[ \text{Counts / 10 GeV} \]

\[ \begin{align*}
\Delta M &= 16.9 \text{ GeV} \\
\Delta M &= 10.6 \text{ GeV} \\
\Delta M &= 5.1 \text{ GeV}
\end{align*} \]

\[ \Delta M = 10.6 \text{ GeV} \]
\[ M_{\tilde{g}} = 140.7 \text{ GeV} \]
\[ M_{\tilde{g}} = 260.3 \text{ GeV} \]

\[ \text{Slope} = f_2(\Delta M, M_{\tilde{\chi}_1}^0) \]

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

\[ M_{\tau\tau} < M_{j\tau\tau}^{\text{endpoint}} \]

Jets with \( E_T > 100 \text{ GeV} \)

\( M_{j\tau\tau} \) masses for each jet

Choose the 2\textsuperscript{nd} large value

\[ \rightarrow M_{j\tau\tau}^{(2)} \]

Peak value ~ True Value

We choose the peak position as an observable.
\[ M_{j\tau\tau}^{(2)\text{peak}} = f_3(M_{\tilde{q}_L}, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0}) \]

\[ M_{j\tau 1}^{(2)\text{peak}} = f_4(M_{\tilde{q}_L}, \Delta M, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0}), \quad M_{j\tau 2}^{(2)\text{peak}} = f_5(M_{\tilde{q}_L}, \Delta M, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0}) \]
Excess in $E_T^{\text{miss}} + \text{Jets}$

Hinchliffe and Paige,

\[ M_{\text{eff}} \equiv E_T^{j1} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}} \]

[No $b$ jets; $\varepsilon_b \sim 50\%$]

- $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV
- [No $e$’s, $\mu$’s with $p_T > 20$ GeV]
- $M_{\text{eff}} > 400$ GeV;
- $E_T^{\text{miss}} > \text{max} [100, 0.2 M_{\text{eff}}]$

$\rightarrow$ SUSY scale measurement at $10$-$20\%$.

CMS
HM1 Scenario

$m_{1/2} = 250$, $m_0 = 60$

$\sigma = 45$ fb

$M_{\tilde{g}} = 1886$

$M_{\tilde{q}} = 1721$
\[ M_{\text{eff}} \text{ Distribution} \]

\[ m_{1/2} = 335 \text{ GeV} \]
\[ M_{\text{eff}}^{\text{peak}} = 1220 \text{ GeV} \]

\[ m_{1/2} = 351 \text{ GeV} \]
\[ M_{\text{eff}}^{\text{peak}} = 1274 \text{ GeV} \]

\[ m_{1/2} = 365 \text{ GeV} \]
\[ M_{\text{eff}}^{\text{peak}} = 1331 \text{ GeV} \]

\[ M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{q}_L) \]

5/19/08  Measuring Dark Matter Relic Density at the LHC
Determining SUSY Masses (10 fb$^{-1}$)

6 equations for 5 SUSY masses

\[ M^{\text{peak}}_{\tau\tau} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

Slope = \[ f_2(\Delta M, \tilde{\chi}_1^0) \]

\[ M^{(2)\text{peak}}_{j\tau\tau} = f_3(\bar{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

\[ M^{(2)\text{peak}}_{j\tau\tau} = f_4(\bar{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

\[ M^{(2)\text{peak}}_{j\tau\tau} = f_5(\bar{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]

\[ M^{\text{peak}}_{\text{eff}} = f_6(\bar{g}, \bar{q}_L) \]

Invert the equations to determine the masses

\[ M_{\tilde{\chi}_1^0} = 141\pm19 \text{ GeV} \]

\[ 1\sigma \text{ ellipse} \]

\[ M_{\tilde{q}_L} = 748\pm25; \quad M_{\tilde{g}} = 831\pm21; \]

\[ M_{\tilde{\chi}_2^0} = 260\pm15; \quad M_{\tilde{\chi}_1^0} = 141\pm19; \]

\[ \Delta M = 10.6\pm2.0 \]

\[ M_{\tilde{g}} / M_{\tilde{\chi}_2^0} = 3.1\pm0.2 \text{ (theory = 3.19)} \]

\[ M_{\tilde{g}} / M_{\tilde{\chi}_1^0} = 5.9\pm0.8 \text{ (theory = 5.91)} \]

We test a gaugino univesality at 15% level.

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DM Relic Density in mSUGRA

$M_{\tilde{g}} = 831 \text{ GeV}$
$M_{\tilde{\chi}_2^0} = 260 \text{ GeV}$
$M_{\tilde{\tau}} = 151.3 \text{ GeV}$
$M_{\tilde{\chi}_1^0} = 140.7 \text{ GeV}$

[1] Established the CA region by detecting low energy $\tau$'s ($p_T^{\text{vis}} > 20 \text{ GeV}$)

[2] Determined SUSY masses using:

$M_{\tau\tau}$, Slope, $M_{j\tau\tau}$, $M_{j\tau}$, $M_{\text{eff}}$

$e.g., M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0})$

Gaugino universality test at $\sim 15\%$ (10 fb$^{-1}$)

[3] Measure the dark matter relic density by determining $m_0$, $m_{1/2}$, $\tan \beta$, and $A_0$

$\Omega_{\tilde{\chi}_1^0} h^2 = $
Determining mSUGRA Parameters

\[
M_{j\tau\tau}^{\text{peak}} = X_1(m_{1/2}, m_0)
\]
\[
M_{\tau\tau}^{\text{peak}} = X_2(m_{1/2}, m_0, \tan \beta, A_0)
\]
\[
M_{\text{eff}}^{\text{peak}} = X_3(m_{1/2}, m_0)
\]
\[
? = X_4(m_{1/2}, m_0, \tan \beta, A_0)
\]

\[
\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2}, \tan \beta, A_0)
\]

\[
\frac{\delta \Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} \approx ??? (??? fb^{-1})
\]

\[
m_0 = ?
\]
\[
m_{1/2} = ?
\]
\[
A_0 = ?
\]
\[
\tan \beta = ?
\]
Introducing $M_{\text{eff}}^{(b)}$

$$M_{\text{eff}}^{(b)} \equiv E_T^{j1=b} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}} \quad [j1 = b \text{ jet}]$$

$E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV [No $e$'s, $\mu$'s with $p_T > 20$ GeV]

$M_{\text{eff}}^{(b)} > 400$ GeV ; $E_T^{\text{miss}} > \text{max} \ [100, 0.2 M_{\text{eff}}]$ 

$m_{1/2} = 335$ GeV  
$M_{\text{eff}}^{(b)\text{peak}} = 933$ GeV

$m_{1/2} = 351$ GeV  
$M_{\text{eff}}^{(b)\text{peak}} = 1026$ GeV

$m_{1/2} = 365$ GeV  
$M_{\text{eff}}^{(b)\text{peak}} = 1122$ GeV

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

✓ Solved by inverting the following functions:

\[
\begin{align*}
M_{j\tau\tau}^{\text{peak}} &= X_1(m_{1/2}, m_0) \\
M_{\tau\tau}^{\text{peak}} &= X_2(m_{1/2}, m_0, \tan \beta, A_0) \\
M_{\text{eff}}^{\text{peak}} &= X_3(m_{1/2}, m_0) \\
M_{(b)\text{eff}}^{\text{peak}} &= X_4(m_{1/2}, m_0, \tan \beta, A_0)
\end{align*}
\]

\[
\begin{align*}
m_0 &= 210 \pm 5 \\
m_{1/2} &= 350 \pm 4 \\
A_0 &= 0 \pm 16 \\
\tan \beta &= 40 \pm 1
\end{align*}
\]

\[
\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2}, \tan \beta, A_0)
\]

\[
\frac{\delta \Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} = 6.2\% \text{ (30 fb}^{-1}) = 4.1\% \text{ (70 fb}^{-1})
\]

\[
L = 10 \text{ fb}^{-1}
\]

\[
50 \text{ fb}^{-1}
\]
[1] Established the CA region by detecting low energy $\tau$’s ($p_T^{\text{vis}} > 20$ GeV)

[2] Determined SUSY masses using:
$M_{\tau\tau}$, Slope, $M_{j\tau\tau}$, $M_{j\tau}$, $M_{\text{eff}}$

e.g., $M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0})$

Gaugino universality test at $\sim 15\%$ (10 fb$^{-1}$)

[3] Measured the dark matter relic density by determining $m_0$, $m_{1/2}$, $\tan\beta$, and $A_0$
using $M_{j\tau\tau}$, $M_{\text{eff}}$, $M_{\tau\tau}$, and $M_{\text{eff}}^{(b)}$

$$\frac{\delta \Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} \approx 6\% \ (30 \ \text{fb}^{-1})$$

[4] Working on non-minimal case...