Probing Supersymmetric Cosmology at the LHC

Teruki Kamon and Bhaskar Dutta

(full list of collaborators in the next page)

on

(1) Coannihilation, (2) Over-dense Dark Matter, (3) Focus Point,
(4) Non-universality, (5) String Model

International Workshop on “The LHC and Dark Matter”
Univ. of Michigan, MI, Jan. 6 ~10, 2009
**(Non-)**Standard Cosmology**

*Graduate student, #REU student*

\[
\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2)
\]

**Case 1** “Coannihilation (CA)” Region
For earlier studies, see Arnowitt et al., PLB 649 (2007) 73; Arnowitt et al., PLB 639 (2006) 46

**Case 2** “Over-dense Dark Matter” Region
Dutta, Gurrola,*) Kamon, Krislock,*)

**Case 3** “Focus Point” Region
Arnowitt, Dutta, Flanagan,)#) Gurrola,*) Kamon, Kolev, Krislock*)

**Case 4** “Non-universality”
Arnowitt, Dutta, Kamon, Krislock*)

**Case 5** “String Model”
Dutta, Kamon, Leggett*)

\[ W \neq -1 \]

*Constant in time?*

e.g., Quintessence
– Scalar field dark energy

[Case 4] “Non-universality”
Arnowitt, Dutta, Kamon, Krislock*)

[Case 5] “String Model”
Dutta, Kamon, Leggett*)
Measure SUSY masses

Determine the benchmark model parameters

Identify smoking-gun signal(s) and kinematical variables in a minimal benchmark model.

Prepare kinematical templates by changing one mass at a time.

Ω = 0.23

DM

Work on non-minimal case(s)

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mSUGRA as Benchmark Scenario

4 parameters + 1 sign

\[
\begin{align*}
\tan \beta : & \langle H_u \rangle / \langle H_d \rangle \text{ at } M_Z \\
m_{1/2} : & \text{Common gaugino mass at } M_{\text{GUT}} \\
m_0 : & \text{Common scalar mass at } M_{\text{GUT}} \\
A_0 : & \text{Trilinear coupling at } M_{\text{GUT}} \\
\text{sign}(\mu) : & \text{Sign of } \mu \text{ in } W^{(2)} = \mu H_u H_d
\end{align*}
\]

Key experimental constraints

\[
\begin{align*}
M_{\text{Higgs}} & > 114 \text{ GeV} ; \ M_{\tilde{\chi}_1^\pm} > 104 \text{ GeV} \\
2.2 \times 10^{-4} & < B(b \rightarrow s \gamma) < 4.5 \times 10^{-4} \\
(g - 2)_{\mu} & : \sim 3\sigma \text{ deviation from SM} \\
0.094 & < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129 \ (\text{WMAP3})
\end{align*}
\]
Dark Matter Allowed Regions

Focus Point Region

\[ \Omega_{\tilde{\chi}_0^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} \rangle} dx \]

\[ \Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} \rangle f(x)} dx \]

Note: g–2 data may still be controversial.

Over-dense DM Region

Coannihilation Region

Excluded by
- Rare B decay $b \rightarrow s \gamma$
- No CDM candidate
- Muon magnetic moment

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$\tilde{\chi}_2^0 \rightarrow \tau^+ \tau^- \rightarrow \tau^+ \tau^- \tilde{\chi}_1^0$

hep-ph/0603128

$10 \text{ fb}^{-1}$

$M(\tau\tau)$ [GeV]

$\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0 \rightarrow b\bar{b} \tilde{\chi}_1^0$

hep-ph/0808.1372

$M(bb)$ [GeV]

$g \rightarrow t\bar{t}\tilde{\chi}_2^0 \rightarrow (jjb)(jjb)(ll\tilde{\chi}_1^0)$

In progress

$M(jjb)$ [GeV]
Case 1: CA Region

Excesses in 3 Final States:

a) $E_T^{\text{miss}} + 4j$

b) $E_T^{\text{miss}} + 2j + 2\tau$

c) $E_T^{\text{miss}} + b + 3j$

Example of Analysis Chart:

$E_T^{\text{miss}} + 2j + 2\tau$ Analysis Path

Cuts to reduce the SM backgrounds ($W+$jets, ...)

- $E_T^{\text{miss}} > 180$ GeV, $N(\text{jet}) \geq 2$ with $E_T > 100$ GeV
- $E_T^{\text{miss}} + E_T^{\text{j}1} + E_T^{\text{j}2} > 600$ GeV; $N(\tau) \geq 2$ with $P_T > 40, 20$ GeV

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

$M_{\tau\tau}$ & $p_T(\tau)$

$M_{\tau\tau}$ histogram

OS mass

OS–LS mass

LS mass

Example of Analysis Chart:

$E_T^{\text{miss}} + 2j + 2\tau$ Analysis Path

Cuts to reduce the SM backgrounds ($W+$jets, ...)

- $E_T^{\text{miss}} > 180$ GeV, $N(\text{jet}) \geq 2$ with $E_T > 100$ GeV
- $E_T^{\text{miss}} + E_T^{\text{j}1} + E_T^{\text{j}2} > 600$ GeV; $N(\tau) \geq 2$ with $P_T > 40, 20$ GeV

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

$M_{\tau\tau}$ & $p_T(\tau)$

$M_{\tau\tau}$ histogram

OS mass

OS–LS mass

LS mass

$\varepsilon_\tau = 50\%, f_{\text{fake}} = 1\%$ for $p_T^{\text{vis}} > 20$ GeV

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Constructing Kinematical Variables

➢ 6 equations for 5 SUSY masses

\[ M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]
\[ \text{Slope} = f_2(\Delta M, \tilde{\chi}_1^0) \]
\[ M_{j\tau}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]
\[ M_{j\tau 1}^{(2)\text{peak}} = f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]
\[ M_{j\tau 2}^{(2)\text{peak}} = f_5(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \]
\[ M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{q}_L) \quad \text{(see page 10)} \]

➢ Invert the equations to determine the masses

[1] 2 taus with 40 and 20 GeV; \( M_{\tau\tau} \) & \( p_{T\tau 2} \) in OS–LS technique
[2] \( M_{\tau\tau} < M_{\tau\tau}^{\text{endpoint}} \); Jets with \( E_T > 100 \) GeV; \( M_{j\tau\tau} \) masses for each jet; Choose the 2\(^{\text{nd}}\) large value \( \rightarrow \) Peak value \( \sim \) True Value

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Example: Templates in $E_T^{\text{miss}}+2j+2\tau$

Varying only one mass

<table>
<thead>
<tr>
<th>~g</th>
<th>$\tilde{u}_L$</th>
<th>$\tilde{t}_2$</th>
<th>$\tilde{b}_2$</th>
<th>$\tilde{e}_L$</th>
<th>$\tilde{t}_1$</th>
<th>$\tilde{b}_1$</th>
<th>$\tilde{e}_R$</th>
<th>$\tilde{\tau}_2$</th>
<th>$\tilde{\chi}_2^0$</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></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>725</td>
<td>561</td>
<td>645</td>
<td>251</td>
<td>151.3</td>
<td>140.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clean peak even for low $\Delta M$

Independent of the gluino masses!

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

$M_{\tilde{\chi}_2^0}$

$M_{\tilde{\tau}\tau}^{\text{peak}} = f_1(\Delta M, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0})$
Example: Templates in $E_T^{\text{miss}}+4j$

$M_{\text{eff}} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+ E_T^{\text{miss}}$  \[\text{[No b jets; } \varepsilon_b \sim 50\%] \]

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

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

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

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

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SUSY Masses in $E_T^{\text{miss}}+4j$ and $E_T^{\text{miss}}+2j+2\tau$

- 6 equations for 5 SUSY masses

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

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

$M_{j\tau\tau}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$

$M_{j\tau 1}^{(2)\text{peak}} = f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$

$M_{j\tau 2}^{(2)\text{peak}} = f_5(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$

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

- Inverting Eqs. 10 fb$^{-1}$

$M_{\tilde{q}_L} = 748 \pm 25; \ M_{\tilde{g}} = 831 \pm 21$

$M_{\tilde{\chi}_2^0} = 260 \pm 15; \ M_{\tilde{\chi}_1^0} = 141 \pm 19$

$\Delta M = 10.6 \pm 2.0$

$M_{\tilde{g}} / M_{\tilde{\chi}_2^0} = 3.1 \pm 0.2 \ (\text{theory} = 3.19)$

$M_{\tilde{g}} / M_{\tilde{\chi}_1^0} = 5.9 \pm 0.8 \ (\text{theory} = 5.91)$

Testing gaugino universality at 15% level.
DM Relic Density in mSUGRA

\[
\begin{align*}
M_{\tilde{g}} &= 831 \text{ GeV} \\
M_{\tilde{\chi}_2^0} &= 260 \text{ GeV} \\
M_{\tilde{\tau}} &= 151.3 \text{ GeV} \\
M_{\tilde{\chi}_1^0} &= 140.7 \text{ GeV}
\end{align*}
\]

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

[2] Measured 5 SUSY masses and tested gaugino Universality at \( \sim 15\% \) (10 fb\(^{-1}\))

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

\[
\begin{align*}
m_0 &= \\
m_{1/2} &= \\
\tan \beta &= \\
A_0 &= \\
\text{sgn}(\mu) &> 0
\end{align*}
\]

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

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

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Example: Templates in $E_T^{\text{miss}}+b+3j$

\[
M_{\text{eff}}^{(b)} \equiv E_T^{j_1=b} + E_T^{j_2} + E_T^{j_3} + E_T^{j_4} + E_T^{\text{miss}} \quad [j_1 = b \text{ jet}]
\]

$E_T^{j_1} > 100 \text{ GeV}, \quad E_T^{j_2,3,4} > 50 \text{ GeV} \text{ [No e’s, } \mu \text{'s with } p_T > 20 \text{ GeV]}$

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

$tan\beta = 48 \quad M_{\text{eff}}^{(b)\text{peak}} = 933 \text{ GeV}$

$tan\beta = 40 \quad M_{\text{eff}}^{(b)\text{peak}} = 1026 \text{ GeV}$

$tan\beta = 32 \quad M_{\text{eff}}^{(b)\text{peak}} = 1122 \text{ GeV}$

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

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Determining mSUGRA Parameters

\( M_{\text{peak}}^{\text{eff}}(b) = X_4(m_{1/2}, m_0, \tan \beta, A_0) \)

Solved by inverting the following functions:

\[
M_{\text{peak}}^{\text{eff}}(\tau \tau) = X_1(m_{1/2}, m_0)
\]

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

\[
M_{\text{peak}}^{\text{eff}}(\text{peak}) = X_3(m_{1/2}, m_0)
\]

\[
\tan \beta = 210 \pm 5
\]

\[
m_0 = 350 \pm 4
\]

\[
A_0 = 0 \pm 16
\]

\[
\tan \beta = 40 \pm 1
\]

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

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

\[
= 4.1\% \quad (70 \text{ fb}^{-1})
\]
Case 1 Summary

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

[1] The CA region was established by detecting low energy $\tau$'s ($p_T > 20 \text{ GeV}$)

[2] Kinematical templates for $M_{\tau\tau}$, Slope, $M_{j\tau\tau}$, $M_j$, and $M_{\text{eff}}$ were prepared in a quasi model-independent way, measuring 5 SUSY masses and testing gaugino universality at $\sim 15\%$ (10 fb$^{-1}$)

$\Omega_{\tilde{\chi}_1^0} h^2 = 0.1$

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

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

[4] Working on non-minimal case (Case 4)
Case 2: Over-dense DM Region

$A_0 = 0, \tan \beta = 40$

SSC off-equilibrium and time-dependent-dilaton effects
→ A smoothly evolving dark energy for the last 10 billion years

$f(x) = \text{The supersymmetric dark matter density (neutralinos) dilute by a factor } O(10)$

We need to anticipate searches and discoveries to discriminate between conventional cosmology and SSC.

Smoking gun signals in the region?
## 2 Reference Points

### $m_{1/2} = 440$ GeV; $m_0 = 471$ GeV

<table>
<thead>
<tr>
<th>$\tilde{g}$</th>
<th>$\tilde{u}_L$</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>$\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h^0 + \tilde{\chi}_1^0)$ (%)</th>
<th>$\mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z^0 + \tilde{\chi}_1^0)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1041</td>
<td>1044</td>
<td>954</td>
<td>958</td>
<td>557</td>
<td>532</td>
<td>341</td>
<td>86.8%</td>
<td></td>
</tr>
<tr>
<td>1017</td>
<td>768</td>
<td>899</td>
<td>500</td>
<td>393</td>
<td>181</td>
<td></td>
<td>13.0</td>
<td></td>
</tr>
</tbody>
</table>

### $m_{1/2} = 600$ GeV; $m_0 = 440$ GeV

<table>
<thead>
<tr>
<th>$\tilde{g}$</th>
<th>$\tilde{u}_L$</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>$\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h^0 + \tilde{\chi}_1^0)$ (%)</th>
<th>$\mathcal{B}(\tilde{\chi}_2^0 \rightarrow \tau + \tilde{\tau}_1)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1366</td>
<td>1252</td>
<td>1153</td>
<td>1153</td>
<td>594</td>
<td>574</td>
<td>462</td>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td>1211</td>
<td>957</td>
<td>1094</td>
<td>494</td>
<td>376</td>
<td>249</td>
<td></td>
<td>77.0%</td>
<td></td>
</tr>
</tbody>
</table>
Case 2(a) : Higgs

\( m_{1/2} = 440, \ m_0 = 471, \ \tan \beta = 40, \ m_{\text{top}} = 175 \)

\[ \begin{align*}
    \tilde{g} & \quad 1041 \\
    \tilde{u}_L & \quad 1044 \\
    \tilde{u} & \quad 1044 \\
    \tilde{\chi}_2^0 & \quad 341 \\
    \tilde{\chi}_1^0 & \quad 181 \\
    \tilde{\tau}_1 & \quad 393 \\
    \tilde{\chi}_1^\pm & \quad 462 \\
    h & \quad 114 \\
    Z & \quad 91
\end{align*} \]

\[ E_T^{\text{miss}} > 180 \text{ GeV}; \]
\[ \text{N(jet)} \geq 2 \text{ with } E_T > 200 \text{ GeV}; \]
\[ E_T^{\text{miss}} + E_T^{j1} + E_T^{j2} > 600 \text{ GeV} \]

\[ \text{N}(b) \geq 2 \text{ with } P_T > 100 \text{ GeV; } 0.4 < \Delta R_{bb} < 1 \]

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4 Kinematical Variables

Side-band BG subtraction

\[
M_{bb}^{\text{end point}}_{jbb} = X_1(m_{1/2}, m_0)
\]
\[
M_{\text{peak eff}}^{\text{peak eff}} = X_2(m_{1/2}, m_0)
\]
\[
M_{\text{peak eff}}^{(b)\text{peak eff}} = X_3(m_{1/2}, m_0, \tan \beta, A_0)
\]
\[
M_{\text{peak eff}}^{(bb)\text{peak eff}} = X_4(m_{1/2}, m_0, \tan \beta, A_0)
\]

where:

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

[No b jets; \( \varepsilon_b \sim 50\% \)]

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

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

500 fb^{-1} (m_0 = 471)

500 fb^{-1} (m_0 = 471)

w/ side-band BG subtraction

\( m_{1/2} = 480 \)
Kinematical Templates

Band = Uncertainties with 1000 fb$^{-1}$
Determining mSUGRA Parameters

✓ Solved by inverting the following functions:

\[ M_{\text{end point}}^{jbb} = X_1(m_{1/2}, m_0) \]
\[ M_{\text{peak}}^{\text{eff}} = X_2(m_{1/2}, m_0) \]
\[ M_{\text{peak}}^{(b) \text{eff}} = X_3(m_{1/2}, m_0, \tan \beta, A_0) \]
\[ M_{\text{peak}}^{(bb) \text{eff}} = X_4(m_{1/2}, m_0, \tan \beta, A_0) \]
Determining $\Omega h^2$

✓ Solved by inverting the following functions:

- $M_{jbb\text{ end point}}^{\text{end point}} = X_1(m_{1/2}, m_0)$
- $M_{\text{peak eff}}^{\text{peak eff}} = X_2(m_{1/2}, m_0)$
- $M_{\text{bb peak eff}}^{(b)\text{ peak eff}} = X_3(m_{1/2}, m_0, \tan \beta, A_0)$
- $M_{\text{bb peak eff}}^{(bb)\text{ peak eff}} = X_4(m_{1/2}, m_0, \tan \beta, A_0)$

\[ \begin{align*}
  m_0 &= 472 \pm 50 \\
  m_{1/2} &= 440 \pm 15 \\
  A_0 &= 0 \pm 95 \\
  \tan \beta &= 39 \pm 18
\end{align*} \]

1000 fb$^{-1}$

Note: These regions have large $\Omega h^2$ if one just calculate based on standard cosmology. We put a factor of 0.1 for this non-standard cosmology.

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

$\partial \Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \sim 150\%$
Case 2(b) : Stau and Higgs

$\tilde{m}_{1/2} = 600$, $m_0 = 440$, $\tan \beta = 40$, $m_{\text{top}} = 175$

Follow Case 2(a) and Case 1

\[
\begin{align*}
M_{jbb}^{\text{end point}} &= X_1(m_{1/2}, m_0) \\
M_{\text{eff}}^{\text{peak}} &= X_2(m_{1/2}, m_0) \\
M_{\text{eff}}^{(b)\text{peak}} &= X_3(m_{1/2}, m_0, \tan \beta, A_0) \\
M_{\text{eff}}^{(bb)\text{peak}} &= X_4(m_{1/2}, m_0, \tan \beta, A_0)
\end{align*}
\]
Determining $\Omega h^2$

✓ Solved by inverting the following functions:

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

\[
\begin{align*}
m_0 &= 440 \pm 23 \\
m_{1/2} &= 600 \pm 6 \\
A_0 &= 0 \pm 45 \\
\tan\beta &= 40 \pm 3
\end{align*}
\]

$500 \text{ fb}^{-1}$

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

$b/c \text{ stau} \text{ helps to determine } \tan\beta \text{ accurately.}$
Case 2 Summary

Over-dense Dark Matter Region:

✓ $\sigma_{OD-CDM} \sim \sigma_{CDM}/10$

Implication at the LHC:

✓ Region where $\chi_2^0$ decays to Higgs
  $\delta\Omega_{CDM}/\Omega_{CDM} \sim 150\%$ (1000 fb$^{-1}$)

✓ Region where $\chi_2^0$ decays to stau and Higgs
  $\delta\Omega_{CDM}/\Omega_{CDM} \sim 20\%$ (500 fb$^{-1}$)

Future Work:

○ More over-dense and under-dense cases?
Case 3: Focus Point Region

Prospects at the LHC:
A few mass measurements are available: 2\textsuperscript{nd} and 3\textsuperscript{rd} neutralinos, and gluino

Can we make a cosmological measurement?

Goals:
1) New technique on $\Omega h^2$
2) Improvement on SUSY mass measurements
### Part 1: New to Probe $\Omega h^2$

Given the mass matrix for the neutralino $\tilde{\chi}_0$:

$$
\begin{pmatrix}
M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\
0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\
-M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\
M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0
\end{pmatrix}
$$

where

- $s_W = \sin(\theta_W)$
- $c_W = \cos(\theta_W)$
- $s_\beta = \sin(\beta)$
- $c_\beta = \cos(\beta)$

The mass matrix $M_{\tilde{\chi}_0}$ is then given by:

$$
M_{\tilde{\chi}_0} = A_{4\times4}(m_{1/2}, \mu, \tan\beta)
$$

where

- $M_{\tilde{g}}$
- $D_{21} = M_{\tilde{\chi}_0} - 1$ 
- $D_{31} = M_{\tilde{\chi}_0} - 1$

Finally, the expression for $\Omega_{\tilde{\chi}_0} h^2$ is:

$$
\Omega_{\tilde{\chi}_0} h^2 = Z(m_{1/2}, \mu, \tan\beta)
$$
\[ \delta D_{21} \text{ and } \delta D_{32} \leftrightarrow \delta \mu \text{ and } \delta \tan \beta \]

Example \((\mu = 195, \tan \beta = 10)\): assuming \(\delta M_{\tilde{g}} / M_{\tilde{g}} = 0\)

\[ \frac{\delta D_{21}}{D_{21}} = 1.7\% \quad (1) \quad \frac{\delta D_{31}}{D_{31}} = 1.1\% \quad (1) \quad \frac{\delta M_{\tilde{g}}}{M_{\tilde{g}}} = 4.5\% \quad (2) \quad \frac{\delta M_{h}}{M_{h}} = 1\% \]

(1) D. Tovey, “Dark Matter Searches of ATLAS,” PPC 2007
(2) H. Baer et al., “Precision Gluino Mass at the LHC in SUSY Models with Decoupled Scalars,” Phys. Rev. D75, 095010 (2007), reporting 8% with 100 fb\(^{-1}\)

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$\Omega h^2$ Determination

- $\delta \mu / \mu = 0.7\%$
- $\delta \tan \beta / \tan \beta \sim 31\%$
- $\delta m_{1/2} = 5.6\%$

LHC Goal: $D_{21}$ and $D_{32}$ at 1-2% and gluino mass at 5%

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Part 2: Can we improve the measurements?

\[ \sigma_{\text{total}} = 3.1 \text{ pb} \]

ISAJET 7.75

\[ m_{1/2}=314, \quad m_0=3550, \quad \tan\beta=10, \quad m_{\text{top}}=175 \]

(Focus Point 3)

\[ \tilde{\chi}_2^0 \rightarrow \ell^\pm \ell^\mp \tilde{\chi}_1^0 \]

\[ \tilde{\chi}_2^\pm \rightarrow Z \tilde{\chi}_1^\pm \]

OSSF

OSDF

Number of Events / 1.5 GeV

\[ M(\ell\ell) \text{ (GeV)} \]

Number of Events

\[ N(\ell) \geq 2 \quad (p_T > 10 \text{ GeV}) \]

\[ E_T^{\text{miss}} > 150 \text{ GeV} \]

\[ N(j) (E_T > 50 \text{ GeV}) \]

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Simultaneous Detection of Neutralinos and Top(s)

\[ \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_2^0 \rightarrow (W^+ b)(W^- b)(\ell^+ \ell^- \tilde{\chi}_1^0) \]

<table>
<thead>
<tr>
<th>( E_T^{\text{miss}} + \text{Dilepton + Jets} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] ( N(\ell) \geq 2 )</td>
</tr>
<tr>
<td>( p_T &gt; 10 \text{ GeV};</td>
</tr>
<tr>
<td>[2] ( E_T^{\text{miss}} &gt; 150 \text{ GeV} )</td>
</tr>
<tr>
<td>[3] Selection of ( W \rightarrow jj )</td>
</tr>
<tr>
<td>( p_T(j) &gt; 30 \text{ GeV}; )</td>
</tr>
<tr>
<td>( 0.4 &lt; \Delta R(j,j) &lt; 1.5 )</td>
</tr>
<tr>
<td>( M(jj) &lt; 78 \pm 15 \text{ GeV} )</td>
</tr>
<tr>
<td>[4] Selection of ( t \rightarrow Wb )</td>
</tr>
<tr>
<td>( p_T(b) &gt; 30 \text{ GeV} )</td>
</tr>
<tr>
<td>( 0.4 &lt; \Delta R(jj, b) &lt; 2 )</td>
</tr>
</tbody>
</table>

Working on the gluino mass estimate ...
Collider Scene Investigation

Goal:
Testing a minimal scenario and extracting $\Omega h^2$ (standard and non-standard cosmology cases) at the LHC where a limited number of SUSY mass measurements are available.

So far 3 cases were studied:
✓ Case 1: Coannihilation region
✓ Case 2: Over-dense DM region where $\sigma_{\text{ODCDM}} \sim \sigma_{\text{CDM}}/10$
✓ Case 3: Focus point region ... finalizing
  • new method to calculate $\Omega h^2$
  • importance of catching top(s)

Future:
▪ Further improvements
▪ Case 4 & 5 ... in progress
Luminosity Scenario

- New injectors + IR upgrade Phase 2
- Early operation
- Linac4 + IR upgrade Phase 1
- Collimation Phase 2

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Probing Supersymmetric Cosmology at the LHC

Appendix