Probing Supersymmetric Cosmology at the LHC

Teruki Kamon and Bhaskar Dutta

with

Other Collaborators (see the next page)

on

(1) Coannihilation, (2) Overdense 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

January 7, 2009
(Non-)Standard Cosmology

*) Graduate student, #) REU student

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

\[ \frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left( n^2 - n_{eq}^2 \right) + S(\dot{\phi}) \]

[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] “Overdense Dark Matter” Region
Dutta, Gurrola,*) Kamon, Krislock,*) Lahanas, Mavromatos, Nanopoulos

[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 ≠ − 1
Constant in time?
e.g., Quintessence
– Scalar field dark energy

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1) Find smoking gun signal(s)

2) Determine as many SUSY masses as possible

3) Test with a minimal SUSY scenario → see if we can extract the model parameters.

4) Calculate the dark matter relic density

5) Work on non-minimal case

Example

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

\[
\begin{aligned}
m_0 &= 210 \text{ GeV} \\
m_{1/2} &= 351 \text{ GeV} \\
\tan \beta &= 40 \\
A_0 &= 0 \\
\text{sgn}(\mu) > 0 \\
\Omega_{\tilde{\chi}_1^0 h^2} &= 0.1
\end{aligned}
\]
**mSUGRA as Benchmark Scenario**

4 parameters + 1 sign

- \(\tan \beta\) : \(\langle H_u \rangle / \langle H_d \rangle\) 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 \(M_{\text{GUT}}\)
- \(\text{sign}(\mu)\) : Sign of \(\mu\) in \(W^{(2)} = \mu H_u H_d\)

**Key experimental constraints**

\[M_{\text{Higgs}} > 114 \text{ GeV}; M_{\tilde{\chi}^\pm_1} > 104 \text{ GeV}\]

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

\[(g - 2)_\mu : \sim 3\sigma \text{ deviation from SM}\]

\[0.094 < \Omega_{\tilde{\chi}^0_1} h^2 < 0.129 \text{ (WMAP3)}\]
Dark Matter Allowed Regions

**Focus Point Region**

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

Note: \( g-2 \) data may still be controversial.

**Overdense DM Region**

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

**Coannihilation Region**

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

Excluded by
- Rare B decay \( b \to s\gamma \)
- No CDM candidate
- Muon magnetic moment

\( \tan \beta = 40 \)
\( A_0 = 0, \mu > 0 \)

\( m_0 (\text{GeV}) \) vs. \( m_{1/2} (\text{GeV}) \)

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SUSY Phenomenology/Prospects

1. \( \tilde{\chi}_2^0 \rightarrow \tau^\pm \tilde{\tau}^\mp \rightarrow \tau^\pm \tau^\mp \tilde{\chi}_1^0 \)

hep-ph/0603128

2. \( \tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0 \rightarrow b\bar{b} \tilde{\chi}_1^0 \)

hep-ph/0808.1372

3. \( \tilde{g} \rightarrow t\bar{t} \tilde{\chi}_2^0 \)

\( \rightarrow (jjb) (jjb) (ll\tilde{\chi}_1^0) \)

In progress

D0 collaboration (Tevatron)


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

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

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

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Probing Supersymmetric Cosmology at the LHC
Case 1: CA Region

Excesses in 3 final states:

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

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

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

Kinematical variables

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

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

OS $\tau\tau$

$M_{\tau\tau}$ histogram

OS mass

OS–LS mass

LS $\tau\tau$

$M_{\tau\tau}$ histogram

LS mass

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

6 equations for 5 SUSY masses

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

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 2nd large value → Peak value ~ True Value

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Varying only one mass

\[
\begin{array}{cccccc}
\tilde{g} & \tilde{u}_L & \tilde{t}_2 & \tilde{b}_2 & \tilde{e}_L & \tilde{\tau}_2 \\
\tilde{u}_R & \tilde{t}_1 & \tilde{b}_1 & \tilde{e}_R & \tilde{\tau}_1 & \tilde{\chi}_2^0 \\
\tilde{t}_1 & \tilde{b}_1 & \tilde{e}_R & \tilde{\tau}_1 & \tilde{\chi}_1^0 \\
\end{array}
\]

\[
\begin{array}{cccccc}
831 & 748 & 728 & 705 & 319 & 329 & \boxed{260.3} \\
725 & 561 & 645 & 251 & 151.3 & 140.7 \\
\end{array}
\]

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

\[
M^{\text{peak}}_{\tau\tau} \propto M^{\text{max}}_{\tau\tau}
\]

\(M_{\tilde{\chi}_2^0} = 260.3 \text{ GeV}\)

\(M_{\tilde{\chi}_1^0} = 321.5 \text{ GeV}\)

Larger \(\tilde{\chi}_2^0\) Mass \(\rightarrow\) Larger \(M_{\tau\tau}\)
Kinematical Templates in $E_T^{\text{miss}} + 4j$

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

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

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

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

Events / (10 fb$^{-1}$ × 50 GeV)

$M_{\text{eff}}$ peak = 1220 GeV

$m_{1/2} = 335$ GeV

$m_{1/2} = 351$ GeV

$m_{1/2} = 365$ GeV

$M_{\text{eff}}$ peak = 1274 GeV

$M_{\text{eff}}$ peak = 1331 GeV

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

6 equations for 5 SUSY masses

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

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

$M_{j\tau 1}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$

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

$M_{\text{eff}}^{\text{peak}} = f_5(\tilde{g}, \tilde{T}, \tilde{\chi}_1^0)$

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

$\begin{align*}
M_{\tilde{q}_L} &= 748 \pm 25; \quad M_{\tilde{g}} = 831 \pm 21; \\
M_{\tilde{\chi}_2^0} &= 260 \pm 15; \quad M_{\tilde{\chi}_1^0} = 141 \pm 19; \\
\Delta M &= 10.6 \pm 2.0
\end{align*}$

$\begin{align*}
M_{\tilde{g}} / M_{\tilde{\chi}_2^0} &= 3.1 \pm 0.2 (\text{theory} = 3.19) \\
M_{\tilde{g}} / M_{\tilde{\chi}_1^0} &= 5.9 \pm 0.8 (\text{theory} = 5.91)
\end{align*}$

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

[1] Established the CA region by detecting low energy $\tau$'s ($p_T^{\text{vis}} > 20$ 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 $A_0$

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

\[
\begin{aligned}
m_0 &= 0 \\
m_{1/2} &= 0 \\
\tan \beta &= 0 \\
A_0 &= 0 \\
\text{sgn}(\mu) &= 0 \\
\Omega_{\tilde{\chi}_1^0} h^2 &= Z(m_0, m_{1/2}, \tan \beta, A_0)
\end{aligned}
\]

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

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

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

$E_{T}^{j_1} > 100 \text{ GeV}, \ E_{T}^{j_2,3,4} > 50 \text{ GeV} \ [\text{No e's, } \mu'\text{'s with } p_T > 20 \text{ GeV}]$

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

$tan\beta = 48$

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

$tan\beta = 40$

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

$tan\beta = 32$

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

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

✔ Solved by inverting the following functions:

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

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

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

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

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

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

[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 $M_{\text{eff}}^{(b)}$

$$\Delta \Omega \tilde{\chi}_1^0 h^2 / \Omega \tilde{\chi}_1^0 h^2 \approx 6\% (30 \text{ fb}^{-1})$$

[4] Working on non-minimal case (Case 4)
Case 2: Overdense 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></td>
<td>13.0</td>
</tr>
</tbody>
</table>

### 2 Reference Points

**$m_{1/2} = 600$ 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></td>
<td>77.0%</td>
</tr>
</tbody>
</table>
Case 2(a) : Higgs

- $m_{1/2} = 440$, $m_0 = 471$, $\tan \beta = 40$, $m_{top} = 175$

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

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

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4 Kinematical Variables

Side-band BG subtraction

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

where:

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

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

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

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

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Kinematical Templates

Band = Error with 1000 fb$^{-1}$

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Determining mSUGRA Parameters

✓ Solved by inverting the following functions:

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

✓ Solved by inverting the following functions:

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

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

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.
Case 2(b) : Higgs and Stau

Follow Case 2(a) and Case 1

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

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

---

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**Determining $\Omega h^2$**

✓ Solved by inverting the following functions:

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

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

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

\(
\delta\frac{\Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} / \Omega_{\tilde{\chi}_1^0} h^2 \sim 19\%
\)

\[L = 500 \text{ fb}^{-1}\]

$b/c$ *stau* helps to determine $\tan\beta$ accurately.
Over-dense Dark Matter case: $\sigma_{\text{OD-CDM}} \sim \sigma_{\text{CDM}} / 10$

*e.g.*, Supercritical-String-Cosmology (SSC) where scalar field DE is smoothly evolving for 10 B years

Implication at the LHC:

Region where $\chi_2^0$ decays to Higgs

$$\delta \Omega_{\text{CDM}} / \Omega_{\text{CDM}} \sim 150\% \ (1000 \text{ fb}^{-1})$$

Region where $\chi_2^0$ decays to Higgs and stau

$$\delta \Omega_{\text{CDM}} / \Omega_{\text{CDM}} \sim 20\% \ (500 \text{ fb}^{-1})$$
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 $\Omega h^2$

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{\chi}^0} = A_{4 \times 4} \left( m_{1/2}, \mu, \tan \beta \right)$$

$$\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_{1/2}, \mu, \tan \beta)$$
\( \delta D_{21} \) and \( \delta D_{32} \leftrightarrow \delta \mu \) and \( \delta \tan \beta \)

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

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

(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\(^{-1}\)
Ωh² Determination

LHC Goal: D₂₁ and D₃₂ at 1-2% and gluino mass at 5%
Part 2: Can we improve the measurements?

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

**ISAJET 7.75**

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

(Focus Point 3)

\[ \tilde{g} \rightarrow t \ (889) \]
\[ \tilde{\chi}_4^0 \rightarrow \tilde{\chi}_2^0 \ (307) \]
\[ \tilde{\chi}_1^0 \rightarrow Z \ (116) \]
\[ \tilde{\chi}_3^0 \rightarrow \ell^+ \ell^- \ (197) \]
\[ \tilde{\chi}_2^0 \rightarrow W \ (175) \]
\[ \tilde{\chi}_1^+ \rightarrow Z \tilde{\chi}_1^- \ (299) \]

\[ \tilde{\chi}_{2,3}^0 \rightarrow \ell^\pm \ell^\mp \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_2^\pm \rightarrow Z \tilde{\chi}_1^\pm \]

**Legend:**
- Opposite Signs and Same Flavor
- Opposite Signs and Different Flavor

**Graphs:**
- Number of Events / 1.5 GeV
- \( M(\ell\ell) \) (GeV)
- \( N(j) \geq 2 \)
- \( E_T^{\text{miss}} > 150 \text{ GeV} \)
- \( N(j) (E_T > 50 \text{ GeV}) \)

**Inequality:**
\[ N(\ell) \geq 2 \ (p_T > 10 \text{ GeV}) \]
Simultaneous Detection of Neutralinos and Top(s)

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

**E_{T}^{\text{miss}} + Dilepton + Jets**

- [1] \(N(\ell) \geq 2\)
- \(p_T > 10 \text{ GeV}; |\eta| < 2.5\)
- [2] \(E_{T}^{\text{miss}} > 150 \text{ GeV}\)
- [3] Selection of \(W \rightarrow jj\)
  - \(p_T(j) > 30 \text{ GeV}; 0.4 < \Delta R(j,j) < 1.5\)
  - \(M(jj) < 78 \pm 15 \text{ GeV}\)
- [4] Selection of \(t \rightarrow Wb\)
  - \(p_T(b) > 30 \text{ GeV}\)
  - \(0.4 < \Delta R(jj, b) < 2\)

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**Working on the gluino mass estimate ...**
Summary

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 $\sigma_{ODCDM} \sim \sigma_{CDM}/10$
- 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