Measuring Relic Density at the LHC

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7th July' 08
OUTLINE

- Dark Matter (DM) in Universe
- DM Relic Density ($\Omega h^2$) in SUSY
- mSUGRA Co-annihilation (CA) Region at the LHC
- Prediction of DM Relic Density ($\Omega h^2$)
- Summary

Arnowitt, Dutta, Kamon, Kolev, Toback, PLB 639 (2006) 46
Dark Matter (DM) in Universe
splitting normal matter and dark matter apart

– Another Clear Evidence of Dark Matter –

Ordinary Matter
(NASA’s Chandra X Observatory) (8/21/06)

Approximately the same size as the Milky Way

Dark Matter
(Gravitational Lensing)

Measuring Relic Density at the LHC
SUSY is an interesting class of models to provide a weakly interacting massive neutral particle ($M \sim 100$ GeV).
Anatomy of $\sigma_{\text{ann}}$

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

$$\frac{\Omega_{\tilde{\chi}_1}}{0.23}$$

$$\left(\frac{\Omega_{\text{CDM}}}{\Omega_{\text{CDM}}}\right)^{-1} \propto$$

Co-annihilation (CA) Process

Griest, Seckel ’91

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

A near degeneracy occurs naturally for light stau in mSUGRA.

Measuring Relic Density at the LHC
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:

$$m_{\tilde{E}_c}^2 = m_0^2 + 0.15m_{1/2}^2 + (37 \text{ GeV})^2$$

$$m_{\tilde{\chi}_1^0}^2 = 0.16m_{1/2}^2$$

Thus for $m_0 = 0$, $\tilde{E}_c^2$ becomes degenerate with $\tilde{\chi}_1^0$ at $m_{1/2} = 370 \text{ GeV}$, i.e. the coannihilation region begins at

$$m_{1/2} = (370-400) \text{ GeV}$$

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,
DM Allowed Regions - Illustration

- Higgs Mass ($M_h$)
- Branching Ratio $b \rightarrow s\gamma$
- Magnetic Moment of Muon
- CDM allowed region

Co-annihilation Region

Mass of Squarks and Sleptons

Mass of Gauginos

No CDM Candidate

Excluded (Higgs mass)

Excluded (Magnetic Moment of Muon)

Measuring Relic Density at the LHC
Minimal Supergravity (mSUGRA)

SUSY model in the framework of unification:

4 parameters + 1 sign

- $\tan \beta \quad <H_u>/<H_d>$ at $M_Z$
- $m_{1/2}$ Common gaugino mass at $M_{GUT}$
- $m_0$ Common scalar mass at $M_{GUT}$
- $A_0$ Trilinear coupling at $M_{GUT}$
- $\text{sign}(\mu)$ Sign of $\mu$ in $W^{(2)} = \mu H_u H_d$

Key Experimental Constraints

- $M_{\text{Higgs}} > 114$ GeV
- $M_{\text{chargino}} > 104$ GeV
- $2.2 \times 10^{-4} < \mathcal{B}(b \rightarrow s \gamma) < 4.5 \times 10^{-4}$
- $(g-2)_{\mu} : 3 \sigma$ deviation from SM
- $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$

Arnowitt, Chamesdinne, Nath, PRL 49 (1982) 970;
NPB 227 (1983) 121.

Measuring Relic Density at the LHC
Below is the case of 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 $m_{1/2}$

- **[Stau-Neutralino CA region]**
  - [Bulk region] almost ruled out
Can we measure $\Delta M$ at colliders?

$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15$ GeV
This is one of the key reactions to discover the neutralinos at the LHC.

We will have to extract this reaction out of many trillion pp collisions and measure SUSY masses.
1st analysis: Excess in $E_T^{\text{miss}} + \text{Jets}$

- Excess in $E_T^{\text{miss}} + \text{Jets} \rightarrow \text{R-parity conserving SUSY}$
- $M_{\text{eff}} \rightarrow \text{Measurement of the SUSY scale at 10-20\%}$. \\


- $E_T^{j_1} > 100$ GeV, $E_T^{j_{2,3,4}} > 50$ GeV
- $M_{\text{eff}} > 400$ GeV ($M_{\text{eff}} \equiv E_T^{j_1} + E_T^{j_2} + E_T^{j_3} + E_T^{j_4} + E_T^{\text{miss}}$)
- $E_T^{\text{miss}} > \text{max}[100, 0.2 \times M_{\text{eff}}]$ \\

The heavy SUSY particle mass is measured by combining the final state particles

The CMS experiment measured the mass of the gluino and squark:

$m_{1/2} = 250$, $m_0 = 60$; $\sigma = 45$ fb

$M(\text{gluino}) = 1886$; $M(\text{squark}) = 1721$
Relic Density and $M_{\text{eff}}$

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 4% at WMAP

Question:

To what accuracy can we calculate the relic density based on the measurements at the LHC?
✓ Establish the “CA region” signal

✓ Measure SUSY masses

✓ Determine mSUGRA parameters

✓ Predict $\Omega_\chi h^2$ and compare with $\Omega_{CDM} h^2$
Analysis Strategy

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

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

large $\tan \beta$

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

$X = \tau\tau$

$\Delta M = 5-10 \text{ GeV}$

$\Omega h^2$?
Dilepton Endpoint

- DM content \(\rightarrow\) Measurements of the SUSY masses [e.g., M.M. Nojiri, G. Polesselo, D.R. Tovey, JHEP 0603 (2006) 063]

- Dilepton “edge” in the \(\chi^0_2\) decay in dilepton (ee, \(\mu\mu\), \(\tau\tau\)) channels for reconstruction of decay chain.

**LM1:**
(Low Mass Case 1)

- \(m_{1/2} = 180, m_0 = 850; \sigma = 55\) pb
- [post-WMAP benchmark point B’]
- \(M(\text{gluino}) = 611\)
- \(M(\text{squark}) = 559\)
- gluino \(\rightarrow\) squark+quark
- \(B(\chi^0_2 \rightarrow \text{slep}_R \text{lep}) = 11.2\%\)
- \(B(\chi^0_2 \rightarrow \text{stau}_1 \text{tau}) = 46\%\)
- \(B(\chi^+_1 \rightarrow \text{sneu}_L \text{lep}) = 36\%\)

- SFOS dilepton+jets+\(E_T^{miss}\)
- \(t\bar{t}:WW+j:Z+j:\text{other}\sim 6:1:1:1\)
- flavor subtraction \((e^-\mu^+ + e^+\mu^-)\) to suppress chargino, \(W, \ t\bar{t}, \ WW, \ \text{“other”}\)
- \(L1+\text{HLT trigger path required}\)
- overall systematic on the background 20% (JES dominated)
- \(5\sigma\) discovery with \(\sim 20\) pb\(^{-1}\) (of data understood as expected with 1 fb\(^{-1}\))
Dilepton Endpoint in CA Region

- In the CA region (after the experimental constraints), the $ee$ and $\mu\mu$ channels are almost absent
  \[
  \text{Br}(\chi_2^0 \rightarrow ee \chi_2^0, \mu\mu \chi_1^0) \sim 0\% \\
  \text{Br}(\chi_2^0 \rightarrow \tau\tau \chi_1^0) \sim 100\% \\
  \Delta M = 5-15 \text{ GeV}
  \]

- Questions:
  1. How can we establish the DM allowed regions?
  2. To what accuracy can we calculate the relic density based on the measurements at the LHC?
Our Reference Point

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

[ISAJET version 7.64]

PLB 639 (2006) 46

TABLE I: SUSY masses (in GeV) for our reference point \( m_{1/2} = 350 \) GeV, \( m_0 = 210 \) GeV, \( \tan \beta = 40 \), \( A_0 = 0 \), and \( \mu > 0 \).

<table>
<thead>
<tr>
<th>( \tilde{g} )</th>
<th>( \tilde{u}_L )</th>
<th>( \tilde{u}_R )</th>
<th>( \tilde{t}_2 )</th>
<th>( \tilde{t}_1 )</th>
<th>( \tilde{b}_2 )</th>
<th>( \tilde{b}_1 )</th>
<th>( \tilde{e}_L )</th>
<th>( \tilde{e}_R )</th>
<th>( \tilde{\tau}_2 )</th>
<th>( \tilde{\tau}_1 )</th>
<th>( \tilde{\chi}_2^0 )</th>
<th>( \tilde{\chi}_1^0 )</th>
<th>( \Delta M )</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>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<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>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

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Low energy taus exist in the CA region
However, one needs to measure the model Parameters to predict the Dark matter content in this scenario

\[ \Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV} \]
SUSY Anatomy I

Measuring Relic Density at the LHC
$p_T^{\text{soft}}$ Slope and $M_{\tau\tau}$

$p_T$ and $M_{\tau\tau}$ distributions in true di-$\tau$ pairs from neutralino decay

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

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

\[
\begin{align*}
\tilde{g} & = 831 \text{ GeV} \\
\tilde{\chi}_2^0 & = 264 \text{ GeV} \\
\tilde{\chi}_1^0 & = 137.4 \text{ GeV} \\
\tilde{\tau}_1 & = 143.1 \text{ GeV} \\
\text{End pont} & = 62.0 \text{ GeV}
\end{align*}
\]
I. Hadronic or leptonic?
   - Hadronic

II. How low in $p_T$?
   - CDF: $p_T^{\text{vis}} > 15-20$ GeV

[Assumption]
\[ \varepsilon_\tau = 50\% \text{, fake rate 1\% for } p_T^{\text{vis}} > 20 \text{ GeV} \]
**$E_T^{\text{miss}} + 2j + 2\tau$ 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

**LS $\tau\tau$**

- $M_{\tau\tau}$ histogram

**OS–LS mass**

We use ISAJET + PGS4

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Measuring Relic Density at the LHC
$M_{\tau\tau}$ Distribution

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

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

We choose the peak position as an observable.

Measuring Relic Density at the LHC 24
$E_T^{\text{miss}} + 2j + 2\tau$ Background

[1] 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:
$E_{T}^{\text{jet}1} > 100$ GeV; $E_{T}^{\text{jet}2} > 100$ GeV; $E_{T}^{\text{miss}} > 180$ GeV; $E_{T}^{\text{jet}1} + E_{T}^{\text{jet}2} + E_{T}^{\text{miss}} > 600$ GeV

[2] Number of SUSY and SM events (10 fb$^{-1}$):

- Top : 115 events
- $W$+jets : 44 events
- SUSY : 590 events
Slope($p_T^{\text{soft}}$) vs. $X$

Counts / 10 GeV

$P_T^{\text{vis}}$ (GeV)

$M_{\tilde{\chi}_2^0}$ (GeV)

$P_T^{\text{vis}}$ Slope

$\delta X/X$

$M_{\tilde{\chi}_1}$

$X = \Delta M$

$X = M_{\tilde{\chi}_0}$

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

$M_{\tilde{g}}$ (GeV)
$M_{\tau\tau}$ peak vs. $X$

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

Measuring Relic Density at the LHC
Mjττ vs. X

Measuring Relic Density at the LHC
\[
M_{j\tau\tau}^{\text{end}} = M_{\tilde{q}} \sqrt{1 - \frac{M_{\tilde{\chi}^0_2}^2}{M_{\tilde{q}}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}^0_1}^2}{M_{\tilde{\chi}^0_2}^2}}
\]

- \( M_{\tau\tau} < M_{\tau\tau}^{\text{endpoint}} \)
- Jets with \( E_T > 100 \) GeV
- \( M_{j\tau\tau} \) masses for each jet

Choose the 2\textsuperscript{nd} large value \( \rightarrow M_{j\tau\tau}^{(2)} \)

We choose the \textbf{peak} position as an observable.
$M_{\bar{\chi}_1^0}$ peak vs. $X$

Measuring Relic Density at the LHC
SUSY Anatomy III

Measuring Relic Density at the LHC
$M_{\text{eff}}$ Distribution

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

At Reference Point

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

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

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

Measuring Relic Density at the LHC

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Five Observables

1. Sort $\tau$’s by $E_T$ ($E_T^1 > E_T^2 > ...$)
   - Use OS–LS method to extract $\tau$ pairs from the decays

\[ N_{\tau^+\tau^-} - N_{\tau^0\tau^0} \]

SM+SUSY Background gets reduced

- Ditau invariant mass: $M_{\tau\tau}$
- Jet-$\tau$-$\tau$ invariant mass: $M_{j\tau\tau}$
- Jet-$\tau$ invariant mass: $M_{j\tau}$
- $P_T$ of the low energy $\tau$
- $M_{\text{eff}}$: 4 jets + missing energy

All these variables depend on masses $\Rightarrow$ model parameters

Since we are using 5 variables, we can measure the model parameters and the grand unified scale symmetry (a major ingredient of this model)
Determining SUSY Masses (10 fb$^{-1}$)

6 Eqs (as functions of 5 SUSY masses)

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

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

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

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

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

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

Invert the equations to determine the masses

\[
\begin{align*}
& M_{\tilde{q}_L} = 748 \pm 25; \
& M_{\tilde{g}} = 831 \pm 21; \
& M_{\tilde{\chi}_2^0} = 260 \pm 15; \
& M_{\tilde{\chi}_1^0} = 141 \pm 19; \
& \Delta M = 10.6 \pm 2.0 \\
& \frac{M_{\tilde{g}}}{M_{\tilde{\chi}_2^0}} = 3.1 \pm 0.2 \text{ (theory = 3.19)} \\
& \frac{M_{\tilde{g}}}{M_{\tilde{\chi}_1^0}} = 5.9 \pm 0.8 \text{ (theory = 5.91)}
\end{align*}
\]

We can probe the physics at the Grand unified theory (GUT) scale

The masses $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{g}$ unify at the grand unified scale in SUGRA models

Gaugino universality test at ~15% (10 fb-1)

Another evidence of a symmetry at the grand unifying scale!

Use the masses measured at the LHC and evolve them to the GUT scale using mSUGRA
[1] Established the CA region by detecting low energy $\tau$'s ($p_{T^{\text{vis}}} > 20 \text{ GeV}$)

[2] Determined SUSY masses using:

\[ M_{\tau\tau}, \text{Slope}, M_{j\tau\tau}, M_{j\tau}, M_{\text{eff}} \]

\text{e.g., Peak}(M_{\tau\tau}) = f (M_{\text{gluino}}, M_{\text{stau}}, M_{\tilde{\chi}^0_2}, M_{\tilde{\chi}^0_1})

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

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

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

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

\[\Delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \approx ??? (??? \text{ fb}^{-1})\]
Determination of tanβ

✓ Determination of tanβ is a real problem

✓ One way is to determine stop and sbottom masses and then solve for A₀ and tanβ

E.g., stop mass matrix: 

\[
\begin{pmatrix}
    m_{Q_L}^2 + ... & m_t (A_t + \mu \cot \beta) \\
    m_t (A_t + \mu \cot \beta) & m_{tR}^2 + ...
\end{pmatrix}
\]

Problem: Stop creates a background for sbottom and ...

✓ Instead, we use observables involving third generation sparticles: \( M_{\text{eff}}(b) \) [the leading jet is a b-jet]

✓ We can determine tanβ and A₀ with good accuracy

✓ This procedure can be applied to different SUGRA models
\( M_{\text{eff}}^{(b)} \) Distribution

- \( E_{T}^{j1} > 100 \text{ GeV}, \quad E_{T}^{j2,3,4} > 50 \text{ GeV} \) [No e’s, \( \mu \)'s with \( p_{T} > 20 \text{ GeV} \)]
- \( M_{\text{eff}}^{(b)} > 400 \text{ GeV} \) \( (M_{\text{eff}}^{(b)} \equiv E_{T}^{j1=b}+E_{T}^{j2}+E_{T}^{j3}+E_{T}^{j4}+ E_{T}^{\text{miss}} \) [\( j1 = b \text{ jet} \)]
- \( E_{T}^{\text{miss}} > \max[100, 0.2 \cdot M_{\text{eff}}] \)

At Reference Point

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

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

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

\( M_{\text{eff}}^{(b)} \) can be used to determine A\(_{0}\) and tan\( \beta \) even without measuring stop and sbottom masses


Measuring Relic Density at the LHC
$M_{\text{eff}}^{(b)\text{peak}}$ .... Sensitive to $A_0$ and tan$\beta$

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

✓ Solved by inverting the following functions:

\[
M_{j\tau\tau} = f_1(m_{1/2}, m_0)
\]

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

\[
M_{\text{eff}} = f_3(m_{1/2}, m_0)
\]

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

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

\[
\delta \Omega_{\widetilde{\chi}_1^0} h^2 / \Omega_{\widetilde{\chi}_1^0} h^2 \approx 6\% (30 \text{ fb}^{-1})
\]

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

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

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

\[
\delta \Omega_{\widetilde{\chi}_1^0} h^2 / \Omega_{\widetilde{\chi}_1^0} h^2 \approx 6\% (30 \text{ fb}^{-1})
\]

Measuring Relic Density at the LHC
The accuracy of determining $\tan\beta$ is not so good if we do not have staus in the final states.

Dutta, Kamon, Gurrola, Krislock, Nanopoulos’08

E.g., raise $m_0$

The final states can contain $Z$, Higgs

hep-ph/0612152
Decay Branching Ratios

Identify and classify $\chi_2^0$ decays

Dutta, Kamon, Gurrola, Krislock, Nanopoulos’08
Observables involving Z and Higgs

We can solve for masses by using the end-points.
Observables

Higgs + plus jet + missing energy dominated region:

✓ Effective mass: $M_{\text{eff}}(\text{peak})$: $f_1(m_0,m_{1/2})$

✓ Effective mass with 1 b jet: $M_{\text{eff}}(b)(\text{peak})$: $f_2(m_0,m_{1/2}, A_0, \tan\beta)$

✓ Effective mass with 2 b jets: $M_{\text{eff}}(2b)(\text{peak})$: $f_3(m_0,m_{1/2}, A_0, \tan\beta)$

✓ Higgs plus jet invariant mass: $M_{\text{bbj}}(\text{end-point})$: $f_4(m_0,m_{1/2})$

4 observables=> 4 mSUGRA parameters

However there is no stau in the final states: accuracy for determining $\tan\beta$ will be less

Ref: Dutta, Kamon, Gurrola, Krislock, Nanopoulos’08
Error with 1000 fb-1

Dutta, Kamon, Gurrola, Krislock, Nanopoulos’08
Determining mSUGRA Parameters

✓ Solved by inverting the following functions:

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

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

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

\[
\delta \Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \sim 150\%
\]
2 tau + missing energy dominated regions:

✓ Solved by inverting the following functions:

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

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

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

\[\delta\Omega_{\tilde{\chi}_1^0 h^2} / \Omega_{\tilde{\chi}_1^0 h^2} \sim 19\% \]

For 500 fb\(^{-1}\) of data

Dutta, Kamon, Gurrola, Krislock, Nanopoulos’08
**Summary**

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, $M_{j\tau\tau}$, $M_j$, $M_{\text{eff}}$
   - e.g., $\text{Peak}(M_{\tau\tau}) = f(M_{\text{gluino}}, M_{\text{stau}}, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0})$
   - 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 $M_{\text{eff}}^{(b)}$

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

<table>
<thead>
<tr>
<th>$M_{\tilde{g}}$</th>
<th>831 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\tilde{\chi}_2^0}$</td>
<td>260 GeV</td>
</tr>
<tr>
<td>$M_{\tilde{\tau}}$</td>
<td>151.3 GeV</td>
</tr>
<tr>
<td>$M_{\tilde{\chi}_1^0}$</td>
<td>140.7 GeV</td>
</tr>
</tbody>
</table>

$m_0 = 210 \text{ GeV}$  
$m_{1/2} = 351 \text{ GeV}$  
$\tan\beta = 40$  
$A_0 = 0$  
$\text{sgn}(\mu) > 0$  

\[ \Omega_{\tilde{\chi}_1^0} h^2 = 0.1 \]
Summary...

[4] For large $m_0$, when staus are not present, the mSUGRA parameters can still be extracted, but with less accuracy.

[5] It will be interesting to determine nonuniversal model parameters, e.g., $\mu$ (Higgs sector nonuniversality).

work is in progress