Measurement of Dark Matter Content at the LHC

Bhaskar Dutta
Collaborators: R. Arnowitt, A. Gurrola, T. Kamon, A. Krislock, D. Toback
Texas A&M University

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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
Anatomy of $\sigma_{\text{ann}}$

$$\Omega \tilde{\chi}_1^0 h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} \nu \rangle} \, dx$$

$$< \sigma_{\text{ann}} \nu > \sim \frac{\alpha^2}{M^2} \sim 1 \text{ pb}$$

$$\left( \Omega_{\text{CDM}} \right)^{-1} \propto 0.23$$

A near degeneracy occurs naturally for light stau in mSUGRA.

**Co-annihilation (CA) Process**

Griest, Seckel '91

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

$$e^{-\Delta M / 20}$$

Precision Cosmology at the LHC
Coannihilation, GUT Scale

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:

\[
m_{\tilde{E}^c}^2 = m_0^2 + 0.15 m_{1/2}^2 + (37 \text{ GeV})^2 \quad m_0^2 = 0.16 m_{1/2}^2
\]

Thus for \(m_0 = 0\), \(\tilde{E}^c\) becomes degenerate with \(\tilde{\chi}_1^0\) at \(m_{1/2} = 370\) 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 in mSUGRA

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?

Measurement of Dark Matter Content at the LHC
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.
Excess in $E_T^{\text{miss}} + \text{Jets}$

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


- $E_T^{j1} > 100 \text{ GeV}$, $E_T^{j2,3,4} > 50 \text{ GeV}$
- $M_{\text{eff}} > 400 \text{ GeV}$ ($M_{\text{eff}} \equiv E_T^{j1} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}}$)
- $E_T^{\text{miss}} > \text{max}[100, 0.2 M_{\text{eff}}]$

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

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

$M(\text{gluino}) = 1886$; $M(\text{squark}) = 1721$

Measurement of Dark Matter Content at the LHC
Goal

✓ Establish the “CA region” signal

✓ Measure SUSY masses

✓ Determine mSUGRA parameters

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

\[ \Delta M = M_{\tilde{\chi}^0_1} - M_{\tilde{\chi}^0_1} = 5 \sim 15 \text{ GeV} \]
**$p_T^{\text{soft}}$ 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

\[
\begin{align*}
\tilde{g} &= 831 \text{ GeV} \\
\tilde{\chi}_2^0 &= 264 \text{ GeV} \\
\tilde{\chi}_1^0 &= 137.4 \text{ GeV} \\
\tilde{\tau}_1 &= 143.1 \text{ GeV} \\
\text{End point} &= 62.0 \text{ GeV}
\end{align*}
\]
**$E_T^{\text{miss}} + 2j + 2\tau$ Analysis Path**

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

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

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

**OS $\tau\tau$**
- $M_{\tau\tau} \text{ histogram}$

**LS $\tau\tau$**
- $M_{\tau\tau} \text{ histogram}$

**OS mass**

**OS–LS mass**

**LS mass**

We use ISAJET + PGS4

**PLB 639 (2006) 46**

Measurement of Dark Matter Content at the LHC
$M_{\tau\tau}$ Distribution

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

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

- $\Delta M = 10.6$ GeV
- $M_{\tilde{\chi}_1^0} = 140.7$ GeV
- $M_\phi = 831.0$ GeV
- $M_{\tilde{\chi}_2^0} = 748.0$ GeV
- $M_{\tilde{\tau}} = 260.3$ GeV

- $\Delta M = 10.6$ GeV
- $M_{\tilde{\chi}_1^0} = 140.7$ GeV
- $M_\phi = 831.0$ GeV
- $M_{\tilde{\chi}_2^0} = 748.0$ GeV
- $M_{\tilde{\tau}} = 321.5$ GeV

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

Measuring Relic Density at the LHC
4 j+$E_T^{\text{miss}}$: $M_{\text{eff}}$ Distribution

- $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV [No e’s, µ’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; $\varepsilon_b \sim 50\%$])
- $E_T^{\text{miss}} > \text{max}[100, 0.2 M_{\text{eff}}]$

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)
$3 j + 1 b + E_T^{\text{miss}} : M_{\text{eff}}^{(b)}$ Distribution

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

At Reference Point

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

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

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

($m_{1/2} = 335$ GeV)

($m_{1/2} = 365$ GeV)

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


Measurement of Dark Matter Content at the LHC
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

$$N_{\tau^+\tau^-} - N_{\tau^+\tau^+}$$

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
- $M_{\text{eff}}(b)$: 4 jets +missing energy

All these variables depend on masses $=>$ model parameters

Since we are using 6 variables, we can measure the model parameters and the grand unified scale symmetry (a major ingredient of this model)
Determining SUSY Masses (10 fb$^{-1}$)

7 Eqs (as functions of SUSY parameters)

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

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

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

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

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

\[ M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{\chi}_1^0) \]

\[ M_{\text{eff}}(b) = f_7(\tilde{g}, \tilde{q}_L, t, b) \]

Invert the equations to determine the masses

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

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

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

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

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

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

Measurement of Dark Matter Content at the LHC
$M_{\tau\tau}^{\text{peak}}, M_{\text{eff}}^{(b)\text{peak}} \ldots$ Sensitive to $A_0$, $\tan\beta$, $m_0$ and $m_{1/2}$

$M_{j\tau\tau}^{\text{peak}}, M_{\text{eff}}^{\text{peak}} \ldots$ Sensitive to $m_0$, $m_{1/2}$

Measurement of Dark Matter Content at the LHC
Determining mSUGRA Parameters

✓ Solved by inverting the following functions:

\[ M_{j\tau\tau} = f_1(m_{1/2}, m_0) \]
\[ M_{\tau\tau} = f_2(m_{1/2}, m_0, \tan \beta, A_0) \]
\[ M_{\text{eff}} = f_3(m_{1/2}, m_0) \]
\[ M_{\text{eff}}^{(b)} = f_4(m_{1/2}, m_0, \tan \beta, A_0) \]

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

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

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


Measurement of Dark Matter Content at the LHC
✓ $m_0$ is large, $m_{1/2}$ can be small,
   e.g., $m_0 = 3550$ GeV, $m_{1/2} = 314$ GeV, $\tan \beta = 10$, $A_0 = 0$

$M(\text{gluino}) = 889$ GeV,
$\Delta M(\chi_3^0 - \chi_1^0) = 81$ GeV,
$\Delta M(\chi_2^0 - \chi_1^0) = 59$ GeV,
$\Delta M(\chi_3^0 - \chi_2^0) = 22$ GeV

$\text{Br}(\tilde{g} \rightarrow \chi_2^0 \bar{t}t) = 10.2\%$
$\text{Br}(g \rightarrow \chi_2^0 \bar{u}u) = 0.8\%$
$\text{Br}(\tilde{g} \rightarrow \chi_3^0 \bar{t}t) = 11.1\%$
$\text{Br}(\tilde{g} \rightarrow \chi_3^0 \bar{u}u) = 0.009\%$
Dilepton Mass at FP

\[ M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0) = 59 \text{ GeV} \]

\[ M(\tilde{\chi}_3^0) - M(\tilde{\chi}_1^0) = 81 \text{ GeV} \]

OSSF $-\$OSDF (e^+ e^- + \mu^+ \mu^- - e^\pm \mu^\mp)$

Baer, Barger, Salughnessy, Summy, Wang, PRD, 75, 095010 (2007),
Crockett, Dutta, Flanagan, Kamon, Kolev, 08;

Measurement of Dark Matter Content at the LHC
Determination of masses: FP

Relic density calculation depends on $\mu$, $\tan\beta$ and $m_{1/2}$

All other masses are heavy

$m_{1/2}$, $\mu$, and $\tan\beta$ can be solved from $M(\text{gluino})$, $\Delta M (\chi_3^0 - \chi_1^0)$ and $\Delta M (\chi_2^0 - \chi_1^0)$

$M(\text{gluino})$, $\Delta M (\chi_3^0 - \chi_1^0)$ and $\Delta M (\chi_2^0 - \chi_1^0)$ can be measured with an accuracy of $\sim 10\%$
### Summary

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

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

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

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

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

\[
\rho_{\tilde{\chi}_1^0} h^2 = 0.1
\]

\[
\frac{\delta \Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} \approx 6\% \text{ (30 fb}^{-1}\text{)}
\]
[4] For large $m_0$, when staus are not present, the mSUGRA parameters can still be extracted, but with less accuracy.

[5] This analysis can be applied to any SUSY model.

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

work in progress...