Measurement of Dark Matter Relic Density using Taus at CMS

Teruki Kamon
Texas A&M University

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Probing the SUSY Dark Matter

Dark Matter (DM) Particle in SUSY & Cosmological Connection

SUSY Signal in Co-annihilation (CA) Region
DM Density ($\Omega h^2$) at the LHC

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback
For earlier studies, see Arnowitt et al., PLB 649 (2007) 73; Arnowitt et al., PLB 639 (2006) 46
DM Particle in SUSY

Astrophysics

WMAP 5: 23.3% (± 1.3%)

CDM = Neutralino ($\widetilde{\chi}_1^0$)

\[
\Omega_{\chi_1^0} h^2 \approx \int_0^{x_f} \frac{1}{\langle \sigma_{ann} v \rangle} dx
\]

\[
\langle \sigma_{ann} v \rangle = \frac{\pi \alpha^2}{8 M^2}
\]

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Choosing Benchmark Model ...

An accidental near degeneracy occurs naturally for light stau in many models. The mSUGRA model is one of them and chosen as our 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 $M_{GUT}$
- $m_0$ : Common scalar mass at $M_{GUT}$
- $A_0$ : Trilinear coupling at $M_{GUT}$
- $\text{sign}(\mu)$ : Sign of $\mu$ in $W^{(2)} = \mu H_u H_d$

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

Key experimental constraints

- $2.2 \times 10^{-4} < B(b \rightarrow s\gamma) < 4.5 \times 10^{-4}$
- $(g-2)_\mu : \sim 3\sigma$ deviation from SM
- $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$ (WMAP3)
**DM Allowed Regions**


### Diagram

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

### Excluded by

1. **Rare B decay** \( b \rightarrow s \gamma \)
2. **No CDM candidate**
3. **Magnetic moment of muon**

### Reference Point

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

**ΔM = 5-15 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}^0 )</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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</tbody>
</table>

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Proving $\Omega_{\text{SUSY DM}}$ in Inclusive Jets+$E_T^{\text{miss}}$

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

$X = \text{Dilepton mass endpoint from } \chi^0_2 \text{ decay to reconstruct the SUSY masses}$

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

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

LM1 (Low Mass Case 1)

$\sigma = 55 \text{ pb}$

$M_{\tilde{g}} = 611$

$M_{\tilde{q}} = 559$

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

$B(\chi^0_2 \rightarrow \tilde{\ell}_R) = 11.2\%$

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

Arnowitt et al., to appear in PRL (2008)

Dilepton mass “edge” in the $\chi^0_2 \rightarrow ee/\mu\mu \chi^0_1$ decays for reconstruction of SUSY Masses $\Rightarrow \Omega$
Dilepton Endpoint in CA Region

In the CA region, the $ee$ and $\mu\mu$ channels are almost absent.

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

$\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow \tilde{\chi}_2^0 q\bar{q}$
$B(\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R \ell) \approx 0\%$
$B(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau) \approx 100\%$
$B(\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_L \ell) \approx 0\%$

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

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

$E_T^{\text{vis(true)}} > 20, 20\, \text{GeV}$
$E_T^{\text{vis(true)}} > 40, 20\, \text{GeV}$
$E_T^{\text{vis(true)}} > 40, 40\, \text{GeV}$

$p_T^{\tau} > 20\, \text{GeV}$ is essential!
SUSY Anatomy in the CA Region

$\tilde{g}$ $\tilde{u}$ $\tilde{u}_L$

$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ (CDM)

$M_{j\tau\tau}$ & $M_{j\ell}$

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

Cuts to reduce the SM backgrounds ($W^\pm$ 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$\tau$
  - $M_{\tau\tau}$ histogram
- LS $\tau\tau$
  - $M_{\tau\tau}$ histogram

[Key Assumption]

$\varepsilon_\tau = 50\%$, fake rate 1% for $p_T^{\text{vis}} > 20$ GeV
OS–LS $M_{\tau\tau}$ Distribution

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

$\tilde{g}$

$\tilde{u}_L$  $\tilde{t}_2$  $\tilde{b}_2$  $\tilde{e}_L$  $\tilde{\tau}_2$  $\tilde{\chi}_2^0$
$\tilde{u}_R$  $\tilde{t}_1$  $\tilde{b}_1$  $\tilde{e}_R$  $\tilde{\tau}_1$  $\tilde{\chi}_1^0$

831
748 728 705 319 329

725 561 645 251 151.3 140.7

Clean peak even for low $\Delta M$

$M_{\tilde{\chi}_2^0} = 260.3$ GeV

$M_{\tilde{\chi}_2^0} = 321.5$ GeV

$Larger \tilde{\chi}_2^0 \text{ Mass} \rightarrow Larger M_{\tau\tau}$

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

$M_{\tilde{\tau}_1} \propto M_{\tau\tau}^{\text{max}}$

Independent of the gluino masses!

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OS–LS Slope($p_T^{\text{soft}}$)

$\Delta M = 16.9$ GeV
$\Delta M = 10.6$ GeV
$\Delta M = 5.1$ GeV

Independent of the gluino masses!

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

$M_{\tilde{g}}$ (GeV)

$M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0})$, slope$= f_2(\Delta M, M_{\tilde{\chi}_1^0})$

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**$M_{j\tau\tau}$ Distribution**

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

\[
M_{j\tau\tau}^{\text{peak}} \propto M_{j\tau\tau}^{\text{end}}
\]

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

2) Choose the 2\textsuperscript{nd} large value $\Rightarrow$ Peak value $\sim$ True Value

---

**Counts / 50 GeV**

$M_{j\tau\tau}^{(2)}$ (GeV)

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

**$M_{j\tau1}^{(2)\text{peak}} = f_4(M_{\tilde{q}_L}, \Delta M, M_{\tilde{\chi}^0_2}, M_{\tilde{\chi}^0_1})$**

**$M_{j\tau2}^{(2)\text{peak}} = f_5(M_{\tilde{q}_L}, \Delta M, M_{\tilde{\chi}^0_2}, M_{\tilde{\chi}^0_1})$**

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**$M_{\text{eff}}$ Distribution**

- **Excess in $E_T^{\text{miss}} + \text{Jets}**
  - $M_{\text{eff}} \equiv E_T^{j1} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}}$

  - 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; $E_T^{\text{miss}} > \max [100, 0.2 M_{\text{eff}}]$

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

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

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

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Determining SUSY Masses (10 fb⁻¹)

6 equations for 5 SUSY masses

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

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

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

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

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

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

Invert the equations to determine the masses

\[ \begin{align*}
M_{\tilde{\chi}_1^0} & = 141 \pm 19 \text{ GeV} \\
M_{\tilde{\chi}_2^0} & = 260 \pm 15 \\
M_{\tilde{\chi}_1^0} & = 141 \pm 19 \\
\Delta M & = 10.6 \pm 2.0 \\
M_{\tilde{g}} / M_{\tilde{\chi}_2^0} & = 3.1 \pm 0.2 \ (\text{theory } = 3.19) \\
M_{\tilde{g}} / M_{\tilde{\chi}_1^0} & = 5.9 \pm 0.8 \ (\text{theory } = 5.91)
\end{align*} \]

We test a gaugino univesality at 15% level.
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 (\( p_T^{\text{vis}} > 20 \) GeV)

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

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

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 \( A_0 \)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[2] Determined SUSY masses using:

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

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

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...
Plan for $\text{Jets}+E_{T}^{\text{miss}}+\tau's$

- We are: Jonathan Asaadi,(*) Alredo Gurrola,(*) Teruki Kamon, Chi-Nhan Nguyen, Alexei Safonov, and David Toback (Texas A&M);
  Seema Sharma(*) (Tata Institute/LPC), Sunanda Banerjee (Fermilab)
  Manoranjan Guchait (Tata Institute, India);
  Anwar Bhatti (Rockefeller) and Shuichi Kunori (Maryland);
  Ulrich Goerlach (Louis Pasteur)

- Short-term tasks:
  - development of the analysis strategy for $\tau's$ in the $\text{Jet}+E_{T}^{\text{miss}}$ final state;
  - development of the current SUSY PAT (w/ a focus on taus).

- Very long-term tasks - develop the analysis strategy for 3 inclusive $\text{Jet}+E_{T}^{\text{miss}}$ samples to probe $\Omega_{\chi} h^2$:
  - Taus + Jets + MET
  - 4jets + MET
  - 1b + 3jets + MET