Dark Matter in SUGRA Models and the LHC


Department of Physics, Texas A&M University

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Experimental Constraints on mSUGRA at Large $\tan \beta$

- Higgs Mass ($M_h$)
- Branching Ratio $b \rightarrow s\gamma$
- Magnetic Moment of Muon
- WMAP Dark Matter Favored region

Magnetic Moment of Muon

If confirmed...

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Co-Annihilation in the Early Universe

- If there is a second SUSY particle with small mass (similar to that of the LSP) it can have a large abundance in the early universe.
- The presence of large amounts of this second particle would allow large amounts of the LSP to annihilate away and reduce the Dark Matter relic density to the value observed today.
  - Co-annihilation effect (Griest, Seckel:92)
  - Common in many models

Particle Physics solution to a Cosmology problem?

The lightest $\tilde{\tau}$ is a good candidate.
Outline of the Talk

- **Co-annihilation Signals at the LHC**
  - A Smoking Gun: Small $\Delta M = M_{\tilde{\tau}} - M_{\tilde{\chi}_1^0}$
- **Experimental Observables and Discovery**
- **Measurements**
  - Masses: $\Delta M, M_{\text{Gluino}}, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0}$
  - mSUGRA Parameters: $M_0$ and $M_{1/2}$
- **Do we live in a mSUGRA world with Universal Couplings?**
- **Cosmological Measurement:** $\Omega_{\tilde{\chi}_1^0} h^2$
- **Conclusions**
What do we want to know?

Measure the SUSY masses/parameters

4 Independent Variables

- $M_0 = 210$ GeV
- $M_{1/2} = 350$ GeV
- $\tan\beta = 40$
- $A_0 = 0$
- $Sgn(\mu) > 0$

Doesn't affect the phenomenology much after $\tan\beta > 15$

- $\tilde{M}_0 = 830$ GeV
- $\tilde{M}_{\tilde{g}} = 260$ GeV
- $\tilde{M}_{\tilde{t}} = 151.2$ GeV
- $\tilde{M}_{\tilde{\chi}_0} = 140.6$ GeV

$mSUGRA$

Universality Constraints:
- $M_{\tilde{\chi}_2^0} \sim 0.32 M_{\tilde{g}}$
- $M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$

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

$\Delta M = 10.6$ GeV

Want to measure these two values and test these two relations
Identifying Events at the LHC

Trigger on the jets and missing $E_T$

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Create a Sample of $\tilde{\chi}_2^0$ Events

- Require at least two $\tau$'s to get our $\tilde{\chi}_2^0$
- Large Missing Transverse energy to get the $\tilde{\chi}_1^0$
- At least one very energetic jet to indicate the presence of a squark or gluino at the top of the chain

The dominant background is typically $t\bar{t}b\bar{t}$, so we require an extra object and large kinematics to reject it

1. Require a third $\tau$ from one of the other gauginos (common) $\Rightarrow 3\tau+$Jet+Met
2. Require a second large jet from the other squark/gluino and large $H_T$ $\Rightarrow 2\tau+2$Jets+Met

More details in

Discovery Luminosity

A small $\Delta M$ can be detected in first few years of LHC
~100 Events

76x210 Discovery Luminosity
10^-20 fb
−1

Variation in gluino mass

5σ significance

10-20 fb⁻¹

5%
−5%

ΔM [GeV]

L [fb⁻¹]

10²

10

5

10

15

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Lots of handles in the cascade decays to provide good Observables

\[
\tilde\tau \rightarrow \tau \tilde\chi^0_1
\]

Slope of \( P_T \) distribution of “soft \( \tau \)” contains \( \Delta M \) Information

Low energy \( \tau \)'s are an enormous challenge for the detectors

Independent variable:
Get more events for large \( \Delta M \)

Slope of \( P_T \) distribution is largely unaffected by Gluino Mass

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More Observables

\[ \tilde{\chi}_2^0 \rightarrow \tau\bar{\tau}\tilde{\chi}_2^0 \] gives a peak in \( M_{\tau\tau} \)

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

Larger \( \tilde{\chi}_2^0 \) Mass \( \rightarrow \) Larger \( M_{\tau\tau} \)

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Another Mass Peak

\[ \tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tau\tilde{\chi}_2^0 \] gives a peak in \( M_{\tau\tau} \)

Peak value depends on squark mass

[Squark Mass = 660 GeV]
[Squark Mass = 840 GeV]
4 Variables and 4 Unknowns

1. Number of events
2. Slope of the $P_T$ distribution of the softest $\tau$
3. The peak of the $M_{\tau\tau}$ distribution
4. The peak of the $M_{j\tau\tau}$ distribution

Make Simultaneous Measurements

$M_{\tilde{g}} = 830$ GeV
$M_{\tilde{\chi}_2^0} = 260$ GeV
$\Delta M = M_{\tilde{\tau}} - M_{\tilde{\chi}_1^0} = 10.6$ GeV
$M_{\tilde{\chi}_1^0} = 140.6$ GeV

$M_0 = 210$ GeV
$M_{1/2} = 350$ GeV
$M_{\tilde{\chi}_2^0} \sim 0.32 M_{\tilde{g}}$
$M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$

Equivalent Measurements

Measure Parameters and Test Universality

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Measure $\Delta M$ and the Gluino Mass

- The slope of the $p_T$ distribution of the $\tau$'s only depends on the $\Delta M$.
- The event rate depends on both the Gluino mass and $\Delta M$.
- Can make a simultaneous measurement.

An important measurement without Universality assumptions!

Assuming the Universality Constraints Improves the Measurement.

Results for $\sim 300$ events (10 fb$^{-1}$ depending on the Analysis).

($\text{Results for } M_\tilde{g} = 830, \Delta M = 10.6$)

$\sim 15 \text{ GeV or } \sim 2\%$

$\sim 0.5 \text{ GeV or } \sim 5\%$
Infer $m_0$ and $m_{1/2}$

Assuming Universality

Results for

- $\tilde{M}_0 = 830 \text{ GeV}$
- $\Delta M = 10.6 \text{ GeV}$

$\sim 3 \text{ GeV}$ or $\sigma \sim 2\%$

$\sim 7 \text{ GeV}$ or $\sigma \sim 3\%$
Do we live in a world with Universal Couplings?

Use all 4 observables to make simultaneous measurements of $M_{\tilde{\chi}_1^0}, M_{\tilde{\chi}_2^0}, \Delta M$ and $M_{\tilde{g}}$ and compare to the mSUGRA Mass Relations

\[ M_{\tilde{\chi}_2^0} \sim 0.32 M_{\tilde{g}} \]
\[ M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}} \]
We can measure $\Omega_{\tilde{\chi}_1^0} h^2$ either way.

No Universality Assumptions
4 Observables and 4 Unknowns

With Universality Assumptions
4 Observables and 2 Unknowns

20% 10%

Compare to WMAP which is 5%

Small $\Delta M$ measurement
→ Confidence we are in the co-annihilation region
→ LSP is the Dark Matter
Conclusions

• If the co-annihilation region is realized in nature it provides a natural Smoking Gun

• The LHC should be able to uncover the striking small-$\Delta M$ signature with $\sim 10$ fb$^{-1}$ of data in multi-$\tau$ final states and make high quality measurements with the first few years of running

• The future is bright for Particle Physics and Cosmology as these precision measurements should allow us to measure $\Delta M$ without Universality assumptions, test Universality and make comparisons to the precision WMAP data
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\[ \Delta M = 10.6 \text{ GeV} \]
\[ M_{\chi_1^0} = 140.7 \text{ GeV} \]
\[ M_{\chi_2^0} = 260.3 \text{ GeV} \]
\[ M_{\tilde{u}_L} = 660.0 \text{ GeV} \]
\[ M_{\tilde{u}_R} = 840.0 \text{ GeV} \]
Cosmology Measurements

With the same assumptions we can use $\Delta M, M_\tilde{g}$ to measure $\Omega_{\tilde{\chi}_1^0} h^2$ to 7% 
(Compare to WMAP which is 5%)

$$|\delta \Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2| = 5\%$$
$$|\delta \Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2| = 10\%$$

$A_n = 0, \tan\beta = 40$
$\text{sign}(\mu) = 1$

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Some caveats
Introduction and Physics Goals

• What problems are we trying to solve?
  - Dark Matter
  - Hierarchy problem in the Standard Model
  - Other Particle Physics problems...

• Is there a single solution to both of these problems?
  - Minimal solution?
Aside...

We note that while the analysis here was done with mSUGRA, a similar analysis is possible for any SUGRA models (most of which possess a co-annihilation region) provided the production of neutralinos is not suppressed.
The Players and their Roles

Cosmologists/ Astronomers  Particle Theorists  Particle Experimentalists

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Structure of the Analysis

1. Use the current constraints/understanding to motivate the co-annihilation region of Supersymmetry in mSUGRA

2. Assume this is a correct description of nature and see how well we could measure things at LHC

3. Convert these results into useful numbers for both particle physics and cosmology
Hypothetical Timeline

• Pre-2005: Strong constraints on Dark Matter density, the Standard Model and Supersymmetry
• 2005: Phenomenologists use these results to constrain a SUSY model → Tell the experimentalists at LHC where to look
• 2008-10: Establish that we live in a Supersymmetric world at the LHC
• 2011: Precision measurements of the particle masses and SUSY parameters → compare Dark Matter relic density predictions to those from WMAP
The Players and Their Roles

Astronomy and Cosmology tell us about Dark Matter

Particle Physics Theory Predicts Supersymmetry → Dark Matter Candidate

Convert the masses into SUSY model parameters and $\Omega h^2$

Do we live in a world with Universal Couplings?

Learn more about the universe with two separate measurements of $\Omega h^2$

Experimentalists at FNAL/LHC do direct searches for SUSY particles

Discover SUSY and measure the masses of the superparticles

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### mSUGRA in 1 Slide

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<th>Parameter</th>
<th>Description</th>
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<td>$m_{1/2}$</td>
<td>Gaugino mass at $M_{\text{GUT}}$</td>
</tr>
<tr>
<td>$m_0$</td>
<td>Scalar soft breaking mass at $M_{\text{GUT}}$</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Cubic soft breaking mass at $M_{\text{GUT}}$</td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>$&lt;H_2&gt;/&lt;H_1&gt;$ at the electroweak scale</td>
</tr>
<tr>
<td>sign($\mu$)</td>
<td>Sign of Higgs mixing parameter ($W^{(2)} = \mu H_1 H_2$)</td>
</tr>
</tbody>
</table>

#### Translation for Experimentalists and Cosmologists:

Each combination of these parameters uniquely determines the masses of all the superparticles and the Relic Density ($\Omega_{\tilde{\chi}_1^0} h^2$)
Outline

• Supersymmetry and the Co-annihilation region
  - The important experimental constraints
  - A Smoking Gun: Small $\Delta M = M_{\text{stau}} - M_{\text{LSP}}$

• Identifying events at the LHC
  - Discovery and Experimental Observables

• Measurements of
  - Particle masses: $\Delta M$, $M_{\text{Gluino}}$ & $M_{\chi^2}$
  - Supersymmetry parameters: $M_0$ and $M_{1/2}$
  - Cosmological implications: $\Omega_{\text{LSP}} h^2$

• Conclusions
Structure of the Analysis

1. Use the current constraints/understanding to motivate the co-annihilation region of Supersymmetry in mSUGRA

2. Assume this is a correct description of nature and see how well we could measure things at LHC

3. Convert these results into useful numbers both particle physics and cosmology
“Vanilla” mSUGRA and Cosmology

mSUGRA parameters uniquely determine the:
- LSP mass
- Interaction Cross Sections
- Sparticle abundances in the early universe
- Relic Density today

Use WMAP Relic Density measurements to further constrain SUSY parameter space.

Typically the following annihilation diagrams are important...

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Problem

- Most of mSUGRA space predicts too much Dark Matter today
- Need another mechanism to reduce the predicted LSP relic density to be consistent with the amount of Dark Matter observed by WMAP
Experimental Constraints

Particle Physicists:
- Non-observation of the Higgs and the Gauginos and their mass limits
- Measurement of branching ratio of the $b$-quark $\rightarrow s\gamma$

Astronomers and Cosmologists:
- WMAP measurement of the Relic Density

- $M_{\text{Higgs}} > 114 \text{ GeV}$
- $M_{\text{chargino}} > 104 \text{ GeV}$
- $2.2 \times 10^{-4} < \text{Br} (b \rightarrow s\gamma) < 4.5 \times 10^{-4}$
- $a_\mu \times 10^{-10} = 27 \pm 10 \ (g - 2)$
- $0.094 < \Omega_{\chi_1^0} h^2 < 0.129 \ (WMAP)$
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Discovery Luminosity

Depends on the number of observable events and the sparticle masses

Above ~5 GeV get more events as more events pass kinematic cuts

Fewer events as the production Cross Section drops

20% Error on Fake Rate

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Some Technical Details

Use event kinematics to separate SUSY from ttbar

SUSY Events
$M_h = 850$ GeV
$\Delta M = 9$ GeV

ttbar Events
Outline

• Supersymmetry and the Co-annihilation region
  - The important experimental constraints
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  - Cosmological implications: $\Omega_{\text{LSP}}h^2$

• Conclusions
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A Smoking Gun at the LHC?

High Energy Proton-Proton collisions produce lots of Squarks and Gluinos which eventually decay

Identify a special decay chain that can reveal $\Delta M$ information

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Many models of Supersymmetry provide a Cold Dark Matter candidate

Work in an Minimal Supergravity (mSUGRA) framework

Build models from $M_{\text{Gut}}$ to Electroweak scale

Models consistent with all known experiments

Universal Couplings

Straight-forward predictions

More on this later

Lightest SUSY Particle

$\tilde{\chi}^0_1$

Cold Dark Matter

SUSY, mSUGRA and Cosmology
Small $\tilde{\tau}$ Mass

In mSUGRA models the mass of the lightest $\tilde{\tau}$ can be close to the $\tilde{\chi}_1^0$ mass because of the Renormalization Group Equations (RGEs) for small $m_0$

For small mass difference we can get the right relic density

$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV}$$
Outline

• Supersymmetry and the Co-annihilation region
  - The important experimental constraints
  - A Smoking Gun: Small $\Delta M = M_{\text{stau}} - M_{\text{LSP}}$

• Identifying events at the LHC
  - Discovery and Experimental Observables

• Measurements of
  - Particle masses: $\Delta M$, $M_{\text{Gluino}}$ & $M_{\chi^2}$
  - Supersymmetry parameters: $M_0$ and $M_{1/2}$
  - Cosmological implications: $\Omega_{LSP} h^2$

• Conclusions
Particle Physics Constrained Region

- Higgs Mass ($M_h$)
- Branching Ratio $b \rightarrow s\gamma$
- Neutralino LSP
- Magnetic Moment of Muon

Mass of Squarks and Sleptons

Excluded

Neutralino LSP

Mass of Gauginos

If confirmed...
What if the Co-Annihilation Region is realized in Nature?

1. Can such a small mass difference be measured at the LHC?

The observation of such a striking small $\Delta M$ would be a smoking gun!

→ Strong indication that the neutralino is the Dark Matter

2. If we can observe such a signal, can we make important measurements?
Aside on our Assumptions...

The WMAP constraints limits the parameter space to 3 regions that should all be studied:

1. The stau-neutralino co-annihilation region

   If $(g-2)_\mu$ holds, mostly only this region is left

Concentrate on this region for the rest of this talk...
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Dark Matter in SUGRA Models
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Dark Matter in SUGRA Models and the LHC
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\[ \Delta M = 10.6 \text{ GeV} \]
\[ M_{\tilde{g}} = 140.7 \text{ GeV} \]
\[ M_{\tilde{p}} = 321.5 \text{ GeV} \]
\[ M_{\tilde{q}} = 831.0 \text{ GeV} \]
Outline of the Talk

• Co-annihilation Signals at the LHC
  - A Smoking Gun: Small $\Delta M = M_{\text{stau}} - M_{\text{LSP}}$
• Experimental Observables and Discovery
• Measurements
  - Particle masses: $\Delta M$, $M_{\text{Gluino}}$, $M_{\chi^2}$, $M_{\chi^1}$
  - Supersymmetry parameters: $M_0$ and $M_{1/2}$
  - Do we live in a mSUGRA world?
• Conclusions

Particle Physics: The lightest $\tilde{\chi}$ is a good candidate
• Combine next two

• Sample of Chi2, not just any tau will do
Not just any \( \tau \) will do!

Our \( \tau \)'s are special!

1. \( \chi_2 \) decays produce a pair of opposite sign \( \tau \)'s
   - Many SM and SUSY backgrounds, jets faking \( \tau \)'s will have equal number like-sign as opposite sign

2. Each \( \chi_2 \) produces one \textit{high energy} \( \tau \) and one \textit{low energy} \( \tau \)

3. The invariant mass of the \( \tau \)-pair reflects the mass of the SUSY particles and their mass differences

\[
M_{\tau\tau} \propto M_{\tilde{\chi}_2^0} \chi_2^0 \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1^0}^2}}
\]

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Measure $\Delta M$ and the Gluino Mass

- The slope of the $p_T$ distribution of the $\tau$'s only depends on the $\Delta M$
- The event rate depends on both the Gluino mass and $\Delta M$
- Can make a simultaneous measurement

An important measurement without Universality assumptions!

Results for $\sim 300$ events (10 fb$^{-1}$ depending on the Analysis)
Add in the Peak of $M_{\tau\tau}$

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

As the neutralino masses rise, the $M_{\tau\tau}$ peak rises.

$M_g = 850$ GeV
$L = 30$ fb$^{-1}$

Average of Fake Rate Variation
Statistical Uncertainty

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Add in the Peak of $M_{j\tau\tau}$

As the squark mass rises the $M_{j\tau\tau}$ peak rises.
What if we Assume the Universality Relations?

Use Events, $M_{\tau\tau}$ and Slope to measure

$\Delta M$, $M_{\tilde{g}}$ and $M_{\tilde{\chi}^0_2}$ simultaneously

(Results for $M_{\tilde{g}} = 830$ GeV, $\Delta M = 10.6$ GeV)

Results for $\sim 300$ events (10 fb$^{-1}$ depending on the Analysis)

$\Delta M$ (GeV)

$M_{\text{mass}}$ (GeV)

$\sim 15$ GeV or $\sim 2\%$

$\sim 0.5$ GeV or $\sim 5\%$

Analysis only assumes $M_{\tilde{\chi}^0_1} \sim 0.17 M_{\tilde{g}}$

Analysis assumes $M_{\tilde{\chi}^0_2} \sim 0.32 M_{\tilde{g}}$

and $M_{\tilde{\chi}^0_1} \sim 0.17 M_{\tilde{g}}$
Measuring the SUSY Masses

For our sample of events we can make four measurements

1. Number of events
2. Slope of the $P_T$ distribution of the softest $\tau$
3. The peak of the $M_{\tau\tau}$ distribution
4. The peak of the $M_{j\tau\tau}$ distribution

Since we are using 4 variables, we can measure 4 things

Since $A$, $\tan\beta$ and sign($\mu$) don’t change the phenomenology much (for large $\tan\beta$) we choose to use our three variables to determine $\Delta M$, $M_{\text{gluino}}$ and the $\chi_2$ and $\chi_1$ Masses
What are we trying to measure?

Our mSUGRA model (described by $m_0$ and $m_{1/2}$) can be written, equivalently, by

$$M_{\tilde{g}} \text{ and } \Delta M = M_{\tilde{\tau}} - M_{\tilde{\chi}_1^0}$$

The Universality relations "determine" the other mass values

$$M_{\tilde{\chi}_2^0} \sim 0.32 M_{\tilde{g}} \text{ and } M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$$

Measure these!

Check these!