Particle Physics and Cosmology in the Co-Annihilation Region


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Introduction

• 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?
The Players and their Roles

Cosmologists/Astronomers  Particle Theorists  Particle Experimentalists

PPC 2007  Particle Physics and Cosmology in the Co-annihilation Region
5/17/2007  Dave Toback et. al., Texas A&M University
The Players and Their Roles

Astronomy and Cosmology tell us about Dark Matter

Particle Physics Theory Predicts Supersymmetry → Dark Matter Candidate

Experimentalists at FNAL/LHC do direct searches for SUSY particles

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

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

Do we live in a world with Universal Couplings?

Discover SUSY and measure the masses of the superparticles
Outline of the Talk

• 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
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
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
**mSUGRA in 1 Slide**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<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>$\langle H_2 \rangle / \langle H_1 \rangle$ at the electroweak scale</td>
</tr>
<tr>
<td>$\text{sign} (\mu)$</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 ($\Omega_{\tilde{\chi}_1^0} h^2$).*
Example Translation

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

\[ M_{\tilde{g}} = 830 \text{ GeV} \]
\[ M_{\tilde{\chi}_2^0} = 260 \text{ GeV} \]
\[ M_{\tilde{\tau}} = 151.2 \text{ GeV} \]
\[ M_{\tilde{\chi}_1^0} = 140.6 \text{ GeV} \]

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

In general for mSUGRA models with University Constraints

\[ M_{\tilde{g}} \sim 2.8 m_{1/2}, \quad M_{\tilde{\chi}_2^0} \sim 0.8 m_{1/2}, \quad M_{\tilde{\chi}_1^0} \sim 0.4 m_{1/2} \]
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
  • $M_{Higgs} > 114$ GeV
  • $M_{\text{chargino}} > 104$ GeV
  • $2.2 \times 10^{-4} < Br (b \rightarrow s\gamma) < 4.5 \times 10^{-4}$
  • $a_\mu \times 10^{-10} = 27 \pm 10$ (g - 2)
  • $0.094 < \Omega_{\chi_1^0} h^2 < 0.129$ (WMAP)
Particle Physics Constrained Region

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

If confirmed...
“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...
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
Co-Annihilation?

- 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 relic density observed today.
  - Co-annihilation effect (Griest, Seckel:92)
  - Common in many models

The lightest \( \tilde{\tau} \) is a good candidate.
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

\[
\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV}
\]
Add Dark Matter Constraints

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

If confirmed...

- WMAP Favored region
- Excluded
- Mass of Squarks and Sleptons
- Neutralino LSP
- Mass of Gauginos
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...
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?
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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 both particle physics and cosmology.
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

$\tilde{q} \rightarrow \tilde{g}$

$\tilde{g} \rightarrow \tau^+ \tau^-$

$\tau^+ \rightarrow \tau^+ \tilde{\chi}^0_1$

$\tau^- \rightarrow \tau^- \tilde{\chi}^0_1$

$\tilde{\chi}^0_2 \rightarrow \tau^+ \tau^-$

$\tilde{\chi}^0_1 \rightarrow \tau^- \tilde{\chi}^0_1$

$\tilde{\chi}^0_1 \rightarrow \tau^- \tilde{\chi}^0_1$

$\tilde{\chi}^0_2 \rightarrow \tau^+ \tau^-$

$\tilde{\chi}^0_1 \rightarrow \tau^- \tilde{\chi}^0_1$
Trigger on the jets and missing $E_T$

Particle Physics and Cosmology in the Co-annihilation Region

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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 **high energy** $\tau$ and one **low energy** $\tau$

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

\[ M_{\tau\tau} \propto M_{\chi_2}^0 \sqrt{1 - \frac{M_{\chi_1}^2}{M_{\chi_2}^2}} \sqrt{1 - \frac{M_{\tilde{\tau}_1}^2}{M_{\chi_1}^2}} \]
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 ttbar, 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$\tau$+2Jets+Met

More details in

Some Technical Details

Use event kinematics to separate SUSY from $t\bar{t}$

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

$t\bar{t}$ Events
Look at the $P_T$ distribution of our softest $\tau$

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

Also, get more events for large $\Delta M$

Slope of $P_T$ distribution contains $\Delta M$ Information

Slope of $P_T$ distribution is largely unaffected by Gluino Mass
More Observables...

- Look at the mass of the $\tau^+\tau^-$ in the events.
- Can use the same sample to subtract off the non-$\chi_2$ backgrounds $\Rightarrow$ Clean peak!

Larger $\Delta M$:
- More events
- Larger mass peak

Clean peak
Even for low $\Delta M$
Discovery Luminosity

 Depends on the number of observable events and the sparticle masses

![Graph 1](image1.png)  
\( \Delta M = 850 \text{ GeV} \)

- Above \( \sim 5 \) GeV get more events as more events pass kinematic cuts

![Graph 2](image2.png)  
\( \Delta M = 9 \text{ GeV} \)

- Fewer events as the production Cross Section drops

\( N_{\text{OS-LS}} / \text{fb}^{-1} \)

- 20% Error on Fake Rate
A small $\Delta M$ can be detected in first few years of LHC

$\sim$100 Events
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What are we trying to measure?

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

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

The Universality relations "determine" the other mass values

$$M_{\tilde{\chi}^0_2} \sim 0.32 M_{\tilde{g}}$$ and $$M_{\tilde{\chi}^0_1} \sim 0.17 M_{\tilde{g}}$$
Measuring the SUSY Masses

For our sample of events we can make three 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

Since we are using 3 variables, we can measure three things

Since $A$, $\tan\beta$ and $\text{sign}(\mu)$ 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 $\chi_2$ Mass
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 $M_{\tau\tau}$

$$M_{\tau\tau} \propto M_{\tilde{\chi}_2^0} \left(1 - \frac{M_{\tau_1}^2}{M_{\tilde{\chi}_2^0}^2}\right) \left(1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tau_1}^2}\right)$$

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

Average of Fake Rate Variation

Statistical Uncertainty

$M_0 = 850 \text{ GeV}$
$L = 30 \text{ fb}^{-1}$
Are we in a Universality World?

Use all 3 observables to make simultaneous measurements.

Compare measured $M_{\tilde{\chi}^0_2}$ to $M_{\text{Universality}}$ from $\Delta M, M_{\tilde{g}}$

Only Assume $M_{\tilde{\chi}^0_0} \sim 0.17 M_{\tilde{g}}$

$\sim 15$ GeV or $\sim 3\%$

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What if we Assume the Universality Relations?

Use Events, $M_{\tau\tau}$ and Slope to measure $\Delta M$, $M_{\tilde{g}}$ and $M_{\tilde{\chi}_2^0}$ 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)

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

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

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

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

and $M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$
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• Conclusions
Infer $m_0$ and $m_{1/2}$

Use $\Delta M$ and $M_{\text{gluino}}$ to measure $m_0$ and $m_{1/2}$

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

Assume Universality

$\Delta M \approx 5$ GeV or $\sigma \approx 2\%$

$\approx 10$ GeV or $\sigma \approx 3\%$

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Cosmology Measurements

With the same assumptions we can use \( \Delta M, \tilde{M}_\chi \) to measure \( \Omega_{\chi_1} h^2 \) to 7\% 
(Compare to WMAP which is 5\%)

\[
|\frac{\delta \Omega_{\chi_1} h^2}{\Omega_{\chi_1} h^2}| = 5\% \\
|\frac{\delta \Omega_{\chi_1} h^2}{\Omega_{\chi_1} h^2}| = 10\% \\
A_0 = 0, \tan\beta = 40 \\
sign(\mu) = 1
\]
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 the $\Delta M$ without Universality assumptions and make comparisons to the precision WMAP data with only minor assumptions
Some caveats
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.