Dark Matter, Supersymmetry, and the Early Discovery Potential at the LHC

SUSY2010, Bonn, Germany
August 23-29, 2010

[PN]
Northeastern University, Boston, MA, USA
Outline

- Tensions in SUSY vs dark matter experiments
  WMAP, PAMELA, EGRET, FERMI–LAT, CDMSII, XENON100, COGENT, DAMA-LIBRA, · · ·
- Resolution needs extensions of the standard dark matter as $\tilde{\chi}$. To resolve tensions consider two proposals
  - $U(1)^n$ hidden sector extension of SUGRA models
  - Multicomponent visible sector + hidden sector dark matter in SUGRA models
- Dark matter - LHC connection
- Early SUSY discovery at the LHC at $\sqrt{s} = 7$ TeV with $1fb^{-1}$ of data.
Dark matter experiments

1. WMAP CDM relic density: $\Omega_{CDM} h^2 \sim .1$.
2. Positron flux (PAMELA)
3. Anti-proton flux (PAMELA, CAPRICE, BESS)
4. Photon flux (EGRET, FERMI-LAT)
5. CDMS II and XENON100 limits
6. COGENT: Excess in the DAMA-LIBRA sensitive region

There are significant tensions among these results if one wants to understand them within a single theoretical scheme.
**Pamela Positron Excess**

Difficult to explain Pamela results in the conventional SUSY models. However, there are many possibilities to explain Pamela.

- **Astrophysical origin:** The signal could be of astrophysical origin such as from pulsars.
- **Particle physics models:** It is interesting to investigate particle physics models which could explain this phenomenon.
  - **Pamela excess a signal from the hidden sector.** Dark matter resides in the hidden sector but it can annihilate into the SM particles.
  - **SUSY model** with neutralino as dark matter but with an extended hidden sector.
  - **Multicomponent SUSY dark matter** consisting of Majorana and Dirac particles as dark matter.
  - **Others** ···
Positron Excess vs WMAP

The basic issue: one needs

\[ < \sigma v > \sim 10^{-24} \text{ cm}^3/\text{s} \quad \text{positron excess} \]
\[ < \sigma v > \sim 10^{-26} \text{ cm}^3/\text{s} \quad \text{relic density} \]

Various possibilities for resolution

- **Breit-Wigner** pole enhancement of \( < \sigma v > \) in the galaxy
  

- The boost from coannihilation \( B_{Co} \) of the neutralino in the visible sector with gauginos and higgsinos in the hidden sector to enhance the relic density.
  

- **Sommerfeld** enhancement

- **Non-thermal** processes to enhance relic density.

- Others ···
Enhancement of annihilation cross section in the galaxy

Feldman, Liu, PN, PRD 79, 063509 (2009)
Explaining PAMELA excess in SUSY

Positron Flux from neutralino annihilation
Turner and Wilczek (1990)

\[ \chi^0 + \chi^0 \rightarrow W^+W^-, \quad W^+ \rightarrow e^+\nu \]

Need \( <\sigma v> \sim 10^{-24} \text{cm}^3/\text{s} \) for positron excess but this underproduces the relic density by a factor of about 50-100 below the desired value since

\[ \Omega h^2 \propto 1/ \int <\sigma v> x^{-2} dx, \quad x = m_{\chi^0}/T. \]

Need \( <\sigma v> \sim 10^{-26} \text{cm}^3/\text{s} \) for relic density consistent with WMAP.
Visible Sector
$SU(3)_C \times SU(2)_L \times U(1)_Y$

Hidden Sector
$SU(3)_C \times SU(2)_L \times U(1)_Y$

Hidden Sector Probes
Connector sector is an axion

Stueckelberg mechanism: Kors, PN
Stueckelberg from couplings to 2-form tensor

\[ L_0 = -\frac{1}{12} H^{\mu\nu\rho} H_{\mu\nu\rho} - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{m}{4} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} B_{\rho\sigma} \]

\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad H_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \partial_\nu B_{\rho\mu} + \partial_\rho B_{\mu\nu}. \]

We can write \( L \) in an alternative form

\[ L_1 = -\frac{1}{12} H^{\mu\nu\rho} H_{\mu\nu\rho} - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{m}{6} \epsilon^{\mu\nu\rho\sigma} (H_{\mu\nu\rho} A_\sigma + \sigma \partial_\mu H_{\nu\rho\sigma}) \]

We can recover \( L \) by integrating over \( \sigma \) which gives

\[ d^* H = 0 \]

and inserting it back in \( L_1 \) gives \( L \). Instead suppose we solve for \( H \)

\[ H^{\mu\nu\rho} = -m \epsilon^{\mu\nu\rho\sigma} (A_\sigma + \partial_\sigma \sigma) \]

Insertion back in \( L_1 \) gives

\[ L_2 = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{m^2}{2} (A_\sigma + \partial_\sigma \sigma)^2 \]
**Hidden sector:** $U(1)$ Stueckelberg extension of the SM which communicates with the SM via a connector sector which is an axion which transforms dually under $U(1)_Y$ and $U(1)_X$. B. Kors, PN, PLB 586, 2004, Feldman, Liu, PN (2006)

$$L_{st} = -\frac{1}{2} (\partial_\mu + M_1 C_\mu + M_2 B_\mu)^2$$

Invariant under

$$\delta_Y B_\mu = \partial_\mu \lambda_Y, \quad \delta_Y \sigma = -M_2 \lambda_Y$$

$$\delta_Y C_\mu = \partial_\mu \lambda_X, \quad \delta_X \sigma = -M_1 \lambda_X$$

**Vector boson mass matrix**

$$
\begin{pmatrix}
M_1^2 & M_1 M_2 & 0 \\
M_1 M_2 & M_2^2 + \frac{1}{4} g_Y^2 v^2 & \frac{-1}{4} g_Y g_2 v^2 \\
0 & -\frac{1}{4} g_Y g_2 v^2 & \frac{1}{4} g_2^2 v^2
\end{pmatrix}, \quad \epsilon = M_2/M_1
$$
Constraints on Stueckelberg $Z'$ boson from D0
1008.2023 [hep-ex], August 11, 2010
A Stueckelberg $Z'$ if seen would most likely be an indicator of an underlying string physics

Feldman, Liu, PN
Stueckelberg $Z$ prime

Narrow Stueckelberg $Z$ Prime Resonance

$\varepsilon = 0.03$
$\Gamma_{Z}^{St} = 30 \text{ MeV}$
$M_{Z}^{St} = 500 \text{ GeV}$

PN, Yamada, Yamaguchi
Antoniadis, Binakli, Quiros

Fig. 2. Differential cross section $d\sigma/dm_{\ell}$ as a function of the invariant mass $m_{\ell}$ of the charged lepton pair for three different values of the compactified dimension $M_{P}$. For comparison the analysis for the SM case is also shown.
The $U(1)^n$ extended SUGRA model

Kors, PN, JHEP 0412:005,2004

\[ \mathcal{L} = \mathcal{L}_{\text{MSSM}} + \mathcal{L}_{U(1)^n} + \Delta \mathcal{L} \]

\[ \Delta \mathcal{L} = \int d^2 \theta d^2 \bar{\theta} \sum_{m=1}^{N_S} \left[ \sum_{l=1}^{N_V} M_{l,m} V_l + (\Phi_m + \bar{\Phi}_m) \right]^2, \]

where \( V = \{ B, X, X', X'' \ldots \} \) are vector supermultiplets which include the hypercharge gauge multiplet \( B \), and \( \Phi_m \) are a collection of chiral supermultiplets and \( (N_S, N_V > N_S) \) are the number of (axions,vectors). The neutralino sector is \( (4 + 2n) \) dimensional.

\[ \mathcal{M}[x] = \begin{pmatrix} [M_1]_{2n \times 2n} & [M_2]_{2n \times 4} \\ [M_2]^T_{4 \times 2n} & [M_{\text{MSSM}}]_{4 \times 4} \end{pmatrix} \]

The off diagonal terms are typically of size \( \epsilon \equiv M_2/M_1 \ll 1. \)

Boost via Neutralino Coannihilations ($B_{Co}$) with a $U(1)^n$ hidden gauge sector in extended SUGRA

Feldman, Liu, PN, Nelson, PRD 80, 075001 (2009)

Neutralino coannihilations with the hidden sector produce an effective enhancement of the relic density by a factor $B_{Co}$

$$B_{Co} = \frac{(\Omega_{\chi h^2})_{\text{observed}}}{(\Omega_{\chi h^2})_{MSSM}} \simeq (1 + \frac{d_h}{d_v})^2$$

$d_h$ ($d_v$) are the number of degrees of freedom degenerate with the neutralino in the hidden (visible) sectors.

- Pure Wino Model (PWM): $m_{\chi}^\pm \sim m_{\chi^0}$, $d_v = 6$, $d_h = 2n \times 2$

  $$B_{Co} = (1 + \frac{2}{3}n)^2 = 9 \quad [\text{for } U(1)^3]$$

- Higgsino - Wino Model (PWM): $m_{\chi}^\pm$ and $m_{\chi^0}$ are split, $d_v = 2$, $d_h = 2n \times 2$

  $$B_{Co} = (1 + 2n)^2 = 49 \quad [\text{for } U(1)^3]$$
**Monochromatic Sources**

![Diagram](image)

**Figure:** Neutralino annihilation into $2\gamma$ and similar diagrams for $\gamma Z$. Bern et al; Bergstrom et al.

PWM produces stronger monochromatic sources than HWM and provides a distinguishing feature between the PWM and HWM.

**Monochromatic sources from PWM**

\[
\text{PWM : } \langle \sigma v \rangle_{\gamma\gamma}^{\text{loop}} = 2.0 \times 10^{-27} \text{ cm}^3/\text{s}.
\]
\[
\text{PWM : } \langle \sigma v \rangle_{\gamma Z}^{\text{loop}} = 1.3 \times 10^{-26} \text{ cm}^3/\text{s}.
\]

**Monochromatic sources from HWM**

\[
\text{HWM : } \langle \sigma v \rangle_{\gamma\gamma}^{\text{loop}} = 1.6 \times 10^{-28} \text{ cm}^3/\text{s},
\]
\[
\text{HWM : } \langle \sigma v \rangle_{\gamma Z}^{\text{loop}} = 1.0 \times 10^{-27} \text{ cm}^3/\text{s},
\]
### FERMI-LAT results on $\gamma\gamma$ and $\gamma Z$

<table>
<thead>
<tr>
<th>$E_\gamma$ (GeV)</th>
<th>95% CLUL ($10^{-9}$ cm$^{-2}$s$^{-1}$)</th>
<th>$\langle\sigma v\rangle_{\gamma\gamma}$ [$\gamma Z$] ($10^{-27}$ cm$^3$s$^{-1}$)</th>
<th>$\tau_{\gamma\gamma}$ [$\gamma Z$] (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NFW</td>
<td>Einasto</td>
<td>Isothermal</td>
</tr>
<tr>
<td>30</td>
<td>3.5</td>
<td>0.3 [2.6]</td>
<td>0.2 [1.9]</td>
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<tr>
<td>40</td>
<td>4.5</td>
<td>0.7 [4.2]</td>
<td>0.5 [3.0]</td>
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<td>50</td>
<td>2.4</td>
<td>0.6 [2.7]</td>
<td>0.4 [1.9]</td>
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<td>1.1 [4.2]</td>
<td>0.8 [3.0]</td>
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<td>70</td>
<td>1.2</td>
<td>0.6 [2.0]</td>
<td>0.4 [1.4]</td>
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<tr>
<td>80</td>
<td>0.9</td>
<td>0.5 [1.7]</td>
<td>0.4 [1.2]</td>
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<td>90</td>
<td>2.6</td>
<td>2.0 [6.0]</td>
<td>1.5 [4.3]</td>
</tr>
<tr>
<td>100</td>
<td>1.4</td>
<td>1.4 [3.8]</td>
<td>1.0 [2.8]</td>
</tr>
<tr>
<td>110</td>
<td>0.9</td>
<td>1.0 [2.7]</td>
<td>0.7 [1.9]</td>
</tr>
<tr>
<td>120</td>
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<td>1.6 [4.0]</td>
<td>1.1 [2.9]</td>
</tr>
<tr>
<td>130</td>
<td>1.8</td>
<td>3.0 [7.3]</td>
<td>2.1 [5.3]</td>
</tr>
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<td>140</td>
<td>1.9</td>
<td>3.5 [8.4]</td>
<td>2.5 [6.0]</td>
</tr>
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<td>150</td>
<td>1.6</td>
<td>3.5 [8.2]</td>
<td>2.5 [5.9]</td>
</tr>
<tr>
<td>170</td>
<td>0.6</td>
<td>1.7 [4.0]</td>
<td>1.3 [2.9]</td>
</tr>
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<td>180</td>
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<td>2.7 [6.1]</td>
<td>1.9 [4.4]</td>
</tr>
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<td>190</td>
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<td>3.2 [7.1]</td>
<td>2.3 [5.1]</td>
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<tr>
<td>200</td>
<td>0.9</td>
<td>3.3 [7.3]</td>
<td>2.4 [5.2]</td>
</tr>
</tbody>
</table>

Flux, annihilation cross-section upper limits, and decay lifetime lower limits:


HWM: (.16, 1.0) safe

PWM: (2, 13) near the edge.
Dark Matter - LHC Connection
Gaugino -Higgsino Content of the Neutralino and LHC Signatures

The signatures at the LHC will be dependent on the gaugino vs higgsino content of the neutralino. Thus the neutralino wave function can be expanded as

\[ \chi = \alpha \tilde{\lambda}_B + \beta \tilde{\lambda}_W + \gamma \tilde{h}_1 + \delta \tilde{h}_2 \]

For illustration we consider two models.

- **Model 1:** As the first example we consider the mixed Higgino-Wino model (HWM) which has a substantial higgsino component.

- **Model 2:** As the second example we consider the pure Wino model (PWM) where the neutralino is almost 100% wino. Models of this type arise in anomaly mediated breaking. One characteristic of such models is that the lighter chargino and the neutralino are essentially degenerate \( m_{\chi_1^\pm} \simeq m_{\chi_0} \).

These models lead to distinguishable signatures at the LHC.
Effective mass distribution

Feldman, Liu, PN, Nelson, PRD D 80, 075001 (2009)

\(M_{\text{eff}}\) is defined as the scalar sum of the transverse momenta of four hardest jets \(P_T \geq (200, 150, 50, 50)\) GeV in the event plus missing energy \((E_T^{\text{miss}} \geq 200)\) GeV. The plot is of events for the Higgsino-Wino model (for 5fb\(^{-1}\) yellow) and for Pure Wino model (100 fb\(^{-1}\) blue).
Hints for SUSY

- LEP data on gauge couplings: unification with low lying sparticles can be achieved.
- A significant deviation of \((a_\mu^{exp} - a_\mu^{SM})\) for the muon anomalous magnetic moment.

Recent analyses hint at a deviation between \((3 - 4)\sigma\) away from the standard model prediction and the largest discrepancy claimed is

\[
a_\mu^{exp} - a_\mu^{SM} = +31.6(7.9) \times 10^{-10}
\]


A significant correction points to low lying sparticles in SUSY

- A hint of deviation from the SM value of \(BR(b \to s\gamma)\).
The Hint from \( b \rightarrow s\gamma \)


- The experimental value of \( b \rightarrow s\gamma \) given by the Heavy Flavor Averaging Group (HFAG) along with BABAR, Belle, and CLEO experiments give

\[
BR(b \rightarrow s\gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}
\]

- The SM value including NNLO corrections is

\[
B(b \rightarrow s\gamma) = (3.15 \pm 0.23) \times 10^{-4}
\]

The SM value lies lower than the HFAG value. The result implies a low lying charged Higgs which gives a positive contribution (JoAnn Hewett (1993)).

- If there is a significant cancellation between the charged Higgs and the chargino loops, then the chargino and stop must also be relatively light and thus a good chance of seeing one or more of the sparticles in the early runs at the LHC.
Early SUSY Discovery

Baer, Barger, Lessa, Tata, JHEP 1006, 102 (2010)

\[ A_0 = 0, \tan \beta = 45, \mu > 0, m_t = 172.6 \text{ GeV} \]

\[ m_{\tilde{\nu}} \] 0.1 fb
\[ m_{\tilde{\nu}} \] 0.33 fb
\[ m_{\tilde{\nu}} \] 1 fb
\[ m_{\tilde{\nu}} \] 2 fb

C. W. Bauer, Z. Ligeti, M. Schmaltz, J. Thaler and D. G. E. Walker,
H K. Dreiner, M Kramer, J M. Lindert, B O’Leary,
H. Baer, V. Barger, A. Lessa and X. Tata,
N. Bhattacharyya, A. Datta and S. Poddar,
D. S. M. Alves, E. Izaguirre and J. G. Wacker,
mSUGRA LHC Reach @ 7 TeV

- $\tan \beta = 45$
- $A_0 = 0$
- $\mu > 0$

- $\tilde{\tau}$ LSP
- $0.1 \text{ fb}^{-1}$
- $1 \text{ fb}^{-1}$
- $2 \text{ fb}^{-1}$

LEP excluded

Altunkaynak, Holmes, PN, Nelson, Peim
arXiv: 1008.3423 [hep-ph]
A Display of Signatures/Cuts Used in Early Discovery Analysis at the LHC at $\sqrt{s} = 7$ TeV

<table>
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<th>Signature Name</th>
<th>Description of Cut</th>
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<tr>
<td>$p_T(4) \geq 20$ GeV, $p_T(j_1) \geq 100$ GeV, $p_T(j_2) \geq 40$ GeV</td>
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</table>

TABLE II: List of signatures and cuts used in the early discovery analysis. Our notation is as follows: $\ell = e, \mu$, $n(x)$ is the number of object $x$ in the event, and $p_T(x_n)$ is the transverse momentum of the $n^{th}$ hardest object $x$. We required $E_T^{miss} \geq 200$ GeV and a minimum transverse sphericity of 0.2. The symbol $|$ should be read as the logic “or,” i.e. the cut $n(\tau^+ | \tau^-) = 2$ would be read “the number of $\tau^+$ equals 2 or the number of $\tau^-$ equals 2.”

$$H_T = \sum_{j=1}^{4} p_{Tj} + E_T^{miss}$$
Benchmarks for Early Discovery at $\sqrt{s} = 7$ TeV with 2 fb$^{-1}$

<table>
<thead>
<tr>
<th>Label</th>
<th>NLSP</th>
<th>$m_0$</th>
<th>$m_{\tilde{1}}$</th>
<th>$A_0$</th>
<th>$\tan \beta$</th>
<th>$\delta_2$</th>
<th>$\delta_3$</th>
<th>$\sigma_{\text{SUSY}}$ (pb)</th>
<th>$\sigma_{\text{SI}}$ ($10^{-44}$cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$\chi_1^{\pm}$</td>
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<td>309</td>
<td>1508</td>
<td>32.9</td>
<td>0.553</td>
<td>-0.687</td>
<td>24.3</td>
<td>7.0</td>
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<td>361</td>
<td>1327</td>
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<td>445</td>
<td>1775</td>
<td>24.7</td>
<td>0.718</td>
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</tr>
<tr>
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<td>$\chi_1^{\pm}$</td>
<td>240</td>
<td>313</td>
<td>-522</td>
<td>5.48</td>
<td>-0.376</td>
<td>-0.106</td>
<td>3.5</td>
<td>0.68</td>
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<td>$\tilde{g}$</td>
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<td>755</td>
<td>-2128</td>
<td>45.7</td>
<td>0.745</td>
<td>-0.803</td>
<td>2.2</td>
<td>4.9</td>
</tr>
<tr>
<td>G2</td>
<td>$\tilde{g}$</td>
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<td>639</td>
<td>2710</td>
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<td>-0.850</td>
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<td>3.0</td>
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</tr>
<tr>
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<td>683</td>
<td>2924</td>
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<td>674</td>
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<tr>
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<tr>
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<td>-0.267</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>S7</td>
<td>$\tilde{\tau}_1$</td>
<td>114</td>
<td>518</td>
<td>87</td>
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<td>T1</td>
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<td>548</td>
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<td>21.2</td>
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<td>755</td>
<td>3477</td>
<td>23.4</td>
<td>0.805</td>
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<td>$9.4 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

TABLE III: Benchmarks for models discoverable at the LHC at $\sqrt{s} = 7$ TeV with 2 fb$^{-1}$ of integrated luminosity. The model inputs are given at $M_{\text{GUT}} = 2 \times 10^{16}$ GeV, $\text{sign}(\mu) = +1$, and $\delta_1 = 0$. The displayed masses are in GeV. All models satisfy REWSB and the experimental constraints as discussed in Sec. (II). The spin independent direct detection cross section, $\sigma_{\text{SI}}$, is exhibited as well as the cross section $\sigma_{\text{SUSY}}$ for the production of supersymmetric particles at $\sqrt{s} = 7$ TeV. Our analysis shows that all the models listed in this table are discoverable at the 5\sigma level above the background in several channels as exhibited in Fig. (5).
Altunkaynak, Holmes, PN, Nelson, Peim
arXiv: 1008.3423 [hep-ph]

Green: $0.1\text{fb}^{-1}$  Blue: $1\text{fb}^{-1}$  Red: $2\text{fb}^{-1}$
Altunkaynak, Holmes, PN, Nelson, Peim
arXiv: 1008.3423 [hep-ph]
Altunkaynak, Holmes, PN, Nelson, Peim
arXiv: 1008.3423 [hep-ph]
Altunkaynak, Holmes, PN, Nelson, Peim
arXiv: 1008.3423 [hep-ph]
Multicomponent dark matter


Dark matter may be constituted of more than one component

\[ \Omega_{CDM} = \sum_i \Omega_{CDM_i}. \]

We consider a \( U(1)_X \times U(1)_C \) extension of SUGRA model where \( U(1)_X \) is the hidden sector and \( U(1)_C \) is the anomaly free combination \( \mathcal{L}_e - \mathcal{L}_\mu \)

\[ \mathcal{L} = \mathcal{L}_{\text{MSSM}} + \mathcal{L}_{U(1)^2} + \Delta \mathcal{L} \]

\( \mathcal{L}_{U(1)^2} \) is the kinetic energy for the \( X \) and \( C \) multiplets and for \( \mathcal{L}_{St} \) we assume the following form

\[ \Delta \mathcal{L} = \int d^2 \theta d^2 \bar{\theta} [(M_1 C + M'_2 X + S + \bar{S})^2 + (M'_1 C + M_2 X + S' + \bar{S}')^2]. \]

A Dirac fermion is placed in hidden sector [K. Cheung, T.C. Yuan; Feldman, Liu, PN]. The new particles in this model consist of

- spin 0 : \( \rho, \rho', \phi, \phi' \)
- spin \( \frac{1}{2} \) : \( \psi, \chi^0_5, \chi^0_6, \chi^0_7, \chi^0_8 \)
- spin 1 : \( Z', Z'' \).
Total relic density.

The total relic density is the sum of the Dirac and the Majorana components

\[
(\Omega h^2)_{\text{WMAP}} = (\Omega_{\psi} h^2) + (\Omega_{\chi} h^2) \sim \frac{C_{\psi}}{J_{\psi}} + \frac{C_{\chi}}{J_{\chi}}
\]

\[
C_{\psi} \sim 2 \times \frac{1.07 \times 10^9 \text{GeV}^{-1}}{\sqrt{g^*(\psi)} M_{\text{Pl}}} \quad C_{\chi} \sim \frac{1.07 \times 10^9 \text{GeV}^{-1}}{\sqrt{g^*(\chi)} M_{\text{Pl}}}
\]

\[
J_{\psi} = \int_{x_f^\psi}^{\infty} <\sigma v>_{\psi\bar{\psi}} \, dx, \quad J_{\chi} = \int_{x_f^\chi}^{\infty} <\sigma v>_{\chi\bar{\chi}} \, dx
\]

We assume the local density of dark matter proportional to the relic densities

\[
\rho_{\psi}/\rho_{\chi} \sim (\Omega_{\psi} h^2)/(\Omega_{\chi} h^2)
\]

To get the relic density one needs to solve coupled Boltzmann equations for the two component model

\[
\frac{dn_{\psi}}{dt} = -3Hn_{\psi} - \frac{1}{2} <\sigma v>_{\psi\bar{\psi}} (n_{\psi}^2 - n_{\psi,eq}^2)
\]

\[
\frac{dn_{\chi}}{dt} = -3Hn_{\chi} - \frac{1}{2} <\sigma v>_{\chi\bar{\chi}} (n_{\chi}^2 - n_{\chi,eq}^2) + \frac{1}{2} <\sigma v>_{\psi\bar{\psi}} (n_{\psi}^2 - n_{\psi,eq}^2)
\]
Two-component Dark Matter Model


Positron flux

\[ \frac{\bar{N}}{N + \bar{N}} \]

\[ E \] GeV

\[ \Omega x h^2 = \frac{50}{\Omega h^2} \]

\( \phi_{\bar{p}} \) flux

\[ \phi_{\bar{p}}(\text{TOA}) \]

\[ \frac{1}{m^2 \text{ s sr GeV}} \]

\[ \text{Kinetic Energy} T \] GeV

LeptoSMSSM with Dirac Extension
SMSSM with Dirac Extension

\( \bar{p} \) flux
Two-component Dark Matter Model


Photon flux
Two-component Dark Matter Model

\( \sigma_{SI} \)
Difficult to get $10^{-40}$ cm$^2$ at $m_\chi = 10$ GeV with REWSB and experimental constraints.

LHC data could decode the origin of dark matter in the early universe

Typically the relic density constraints are satisfied in four broad regions of the SUGRA parameter space

- Bulk region
- Pole region
- Coannihilation regions with coannihilations of neutralino with Wino, stau, stop, gluino · · ·
- Region with heavy scalars: Hyperbolic Branch/Focus Point region

Chan, Chattopadhyay, PN; Feng, Matchev, Moroi; Baer, Tata, et.al. · · ·

These regions can lead to distinguishable features at the LHC. As an illustration we contrast the signatures arising from the HB region vs the stau coannihilation region.
Hyperbolic Branch and stau coannihilation regions

- **On HB** the squarks are generally heavy and thus the gluinos are produced more profusely in this region than squarks. The gluinos have longer decay chains and thus missing $P_T$ associated with this region is smaller

  \[ \tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_i^0, \quad q \tilde{q}' \tilde{\chi}_j^\pm \]

  Also a larger multiplicity of quarks, specifically $b$ quarks, produced in the HB region.

- **In the Stau Co-annihilation** region some of the squarks are relatively light and they are more profusely produced than gluinos. The squarks have shorter decay chains and thus missing $P_T$ associated with this region is larger

  \[ \tilde{q} \rightarrow q \tilde{\chi}_i^0, \quad q' \tilde{\chi}_j^\pm \]
OSSF Di-lepton


Hyperbolic Branch

Post Trigger Level Cuts Imposed

Stau Coannihilation

LHC @ 10 fb^{-1}
Conclusions

- An explanation of the various dark matter experiments in terms of particle physics phenomena suggests that the current pictures such as that of the standard SUSY models needs extension.

- We have discussed three possibilities all involving an extra hidden sector appended to the standard sugra picture. LHC data will be able to discriminate among these possibilities.

- Thus if the dark matter experimental results from PAMELA etc are real and further if one seeks particle physics explanation (as opposed to the astrophysical ones) then the hidden sector models are possible directions for further study.

- Low mass regions in the range of few hundred GeV can be explored with $1fb^{-1}$ of data at $\sqrt{s} = 7$ TeV and an early discovery of SUSY at the LHC is a distinct possibility.
Extra Slides
A display of the Processes Analyzed and their standard model Backgrounds at $\sqrt{s} = 7$ TeV

<table>
<thead>
<tr>
<th>SM Process</th>
<th>Cross Section (fb)</th>
<th>Number of Events</th>
<th>Luminosity (fb$^{-1}$)</th>
</tr>
</thead>
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<td>QCD 2,3,4 jets (Cuts1)</td>
<td>$2.0 \times 10^{10}$</td>
<td>74M</td>
<td>$3.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>QCD 2,3,4 jets (Cuts2)</td>
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<td>QCD 2,3,4 jets (Cuts3)</td>
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</tr>
<tr>
<td>QCD 2,3,4 jets (Cuts4)</td>
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<td>1.7M</td>
<td>4.4</td>
</tr>
<tr>
<td>$t\bar{t} + 0,1,2$ jets</td>
<td>$1.6 \times 10^{5}$</td>
<td>4.8M</td>
<td>30</td>
</tr>
<tr>
<td>$b\bar{b} + 0,1,2$ jets</td>
<td>$9.5 \times 10^{7}$</td>
<td>95M</td>
<td>1.0</td>
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<td>$Z/\gamma \to \ell\ell, \nu\bar{\nu} + 0,1,2,3$ jets</td>
<td>$6.2 \times 10^{6}$</td>
<td>6.2M</td>
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<td>$W^\pm \to \ell\nu + 0,1,2$ jets</td>
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<td>1.1</td>
</tr>
<tr>
<td>$Z/\gamma \to \ell\ell, \nu\bar{\nu} + t\bar{t} + 0,1,2$ jets</td>
<td>56</td>
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<td>$1.7 \times 10^{4}$</td>
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<tr>
<td>$Z/\gamma \to \ell\ell, \nu\bar{\nu} + b\bar{b} + 0,1,2$ jets</td>
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<td>0.6M</td>
<td>$1.8 \times 10^{2}$</td>
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<td>$W^\pm \to \ell\nu + t\bar{t} + 0,1,2$ jets</td>
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<tr>
<td>$W^\pm \to \ell\nu + b\bar{b} (t\bar{b}) + 0,1,2$ jets</td>
<td>$2.4 \times 10^{2}$</td>
<td>2.1M</td>
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</tr>
<tr>
<td>$t\bar{t}t\bar{t}$</td>
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<td>0.09M</td>
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<tr>
<td>$t\bar{t}bb$</td>
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<tr>
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<td>1.3M</td>
<td>$1.1 \times 10^{3}$</td>
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<td>$Z \to all + Z \to all$</td>
<td>$7.3 \times 10^{2}$</td>
<td>2.6M</td>
<td>$3.6 \times 10^{3}$</td>
</tr>
<tr>
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<td>$1.5 \times 10^{7}$</td>
<td>16M</td>
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</table>

TABLE I: An exhibition of the standard model backgrounds computed in this work at $\sqrt{s} = 7$ TeV. All processes were generated using MadGraph 4 [10]. Our notation here is that $\ell = e, \mu, \tau$ and $all = \ell, \nu, jets$. Cuts1-Cuts4 indicated in the table are defined in Eq. (1). In the background analysis we eliminate double counting between the process $W^\pm + t\bar{b} (t\bar{b})$ and $t\bar{t}$ by subtracting out double resonant diagrams of $t\bar{t}$ when calculating $W^\pm + t\bar{b} (t\bar{b})$.

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