Decoding the origin of dark matter

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SUSY09, June 6th, 2009

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Outline

The origin of dark matter
- Hyperbolic Branch (HB)
- Stau Coannihilation (Stau-Co)

LHC signatures
- Missing transverse momentum
- Jet signals
- Tagged b-jet signals
- Leptonic signals

Dark matter direct detection experiments
- Probing HB and Stau-Co regions by dark matter direct detection
- Dual probe by the LHC and by dark matter direct detection experiments
**Hyperbolic Branch (HB) & Stau Coannihilation (Stau-Co)**

### mSUGRA
- Gravity mediated SUSY breaking
- Universal soft breaking
- Parameter space spanned by $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, and $\text{sign}(\mu)$.

### WMAP constraints
- Hyperbolic Branch/Focus Point (HB/FP)
- Coannihilation
  - Stau Coannihilation, $\tilde{\chi}_1 \tilde{\tau}_1 \rightarrow X$
  - Stop Coannihilation, $\tilde{\chi}_1 \tilde{t}_1 \rightarrow X'$
  - Gluino Coannihilation, $\tilde{\chi}_1 \tilde{g} \rightarrow X''$
  - Other Coannihilations
- Pole Region
  $$\tilde{\chi}_1 \tilde{\chi}_1 \rightarrow A/H \rightarrow X \quad M_{A,H} \sim 2M_{\tilde{\chi}_1}$$
Monte Carlo Simulation with $2 \times 10^6$ model points in the mSUGRA parameter space $m_0 < 4$ TeV, $m_{1/2} < 2$ TeV, $|A_0/m_0| < 10$, $\tan \beta < 60$, and with $\mu > 0$ reveals that the most common SUSY models originating from the HB and Stau-Co regions. (D. Feldman, Z. Liu and P. Nath, JHEP 0804, 054, 2008)
Nature of soft breaking


1785 mSUGRA models out of 2 million point scan with Monte Carlo simulation

- $m_0$ (TeV) < 4
- $m_{1/2}$ (TeV) < 2
- $|A_0/m_0|$ < 10
- $1 < \tan \beta < 60$
- $\mu > 0$
- $m_t$ (GeV) = 170.9

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Decoding the origin of dark matter
Using LHC signatures to probe the origin of dark matter generation

### LHC Simulation Procedure

- micrOMEGAs + SuSpect
- SUSY Les Houches Accord (SLHA)
- PYTHIA 6.4.11 + PGS4 (MSEL=39)
- Level 1 (L1) triggers (CMS)
- SM (QCD, $b\bar{b}$, $t\bar{t}$, DY, $Z/W+$ jets, $ZZ$, $WZ$, $WW$)
- Post Trigger Cuts
- SMART (＝ SUSY Matrix Routine)
- $N_{\text{SUSY}} > \text{Max} \{5\sqrt{N_{\text{SM}}}, 10\}$

### LHC signatures

- Missing transverse momentum
- Leptonic signals
- Jet signals
- Tagged b-jet signals
In an event, we only select photons, electrons, and muons that have transverse momentum $P^p_T > 10$ GeV and $|\eta^p| < 2.4$, $p = (\gamma, e, \mu)$.

- Taus which satisfy $P^{\tau}_T > 10$ GeV and $|\eta^{\tau}| < 2.0$ are selected.

- For hadronic jets, only those satisfying $P^{j}_T > 60$ GeV and $|\eta^{j}| < 3$ are selected.

- We require a large amount of missing transverse momentum, $P^{\text{miss}}_T > 200$ GeV.

- There are at least two jets that satisfy the $P_T$ and $\eta$ cuts.
Figure: $N_{\text{SUSY}}$ vs. $P_T^{\text{miss}}$ for two models in the Stau-Co and HB regions along with the SM background under the post-trigger level cuts. The Stau-Co and HB model points are ($m_0, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$) as (71.5, 348, 334, 10, +) and (1694, 216, −740, 50, +)
HB model point

- LHC sparticle production is gaugino dominant (gauginos are lighter)
  \[ pp \rightarrow (\tilde{g}\tilde{g}/\tilde{\chi}_2^0\tilde{\chi}_1^\pm/\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp) \]
- Gauginos have longer decay chains (3 body decay)
  \[ \tilde{g} \rightarrow \tilde{\chi}_i^0 + q + \tilde{q} \]
  \[ \tilde{\chi}_j^\pm \rightarrow \tilde{\chi}_j^0 + q + \tilde{q}' \]
  \[ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + f + \tilde{f} \]
  \[ \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + f + \tilde{f}' \]
- Longer decay chains result in reduced \( P_T^{\text{miss}} \)

Stau-Co model point

- LHC sparticle production is squark dominant (sfermions are lighter)
  \[ pp \rightarrow (\tilde{g}\tilde{q}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g}) \]
- Squarks have shorter decay chains (2 body decay)
  \[ \tilde{q}_R \rightarrow \tilde{\chi}_1^0 + q \]
  \[ \tilde{q}_L \rightarrow (\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) + (q, q') \]
- Shorter decay chains produce more \( P_T^{\text{miss}} \)
What can we learn from missing energy regarding the origin of dark matter?

Figure: \( N_{\text{SUSY}} \) vs. \( \langle P^\text{miss}_T \rangle \) for each parameter point in the Stau-Co and HB. \( \langle P^\text{miss}_T \rangle \) acts as an indicator of Stau-Co and HB regions.
Jet signature

$$N_{SUSY} = N_{SUSY}(n_{jet} \geq n_{jet}^*)$$

Figure: Total SUSY events with $n_{jet}^*$ taken as a variable of the two mechanisms (Stau-Co & HB) with assumed LHC luminosity of 10 fb$^{-1}$. Curves (connecting $N_{SUSY}/\sqrt{SM}$ for discrete $n_{jet}^*$) correspond to various models with $M_{LSP} < 275$ GeV for the Stau-Co and $M_{LSP} < 230$ GeV for the HB.
Tagged b-jet signatures

Stau-Co vs HB ($n_{jet} \geq n_{jet}^* = 2$)

Figure: $N(nb)/\sqrt{\text{SM}(nb)}$ vs $nb$ for the Stau-Co and HB regions where $N(nb)$ ($\text{SM}(nb)$) is the number of SUSY (SM) events that contain $n$ b-tagged jets. A sharp discrimination between the Stau-Co and the HB by b-tagging is observed.
Tagged b-jet signatures

HB, \[ \tilde{g} \rightarrow \tilde{\chi}_j^0 + b + \bar{b} \]
\[ \tilde{g} \rightarrow \tilde{\chi}_j^\pm + b(\bar{b}) + \bar{t}(t) \]
Figure: $N(2\tau)$ (the number of events with two hadronically decaying $\tau$-jets) vs $N(4b)$ (the number of events with 4 tagged-$b$ jets). The $\sqrt{\text{SM}}$ values in each channel are indicated by 'X' on the plots.
Figure: $N(0b)$ (the number of events without any tagged b-jets) vs $N(4b)$ (the number of events with 4 tagged-b jets). The $\sqrt{SM}$ values in each channel are indicated by 'X' on the plots.
Direct Detection of Dark Matter

Effective interaction

In direct detection experiments one measures the cross section of the WIMP scattering off the heavy nuclei such as germanium. The \( \chi-p \) scattering is described by the effective four-fermi interaction

\[
L_{\text{eff}} = \bar{\chi} \gamma_\mu \gamma_5 \chi \bar{q} \gamma^\mu (A P_L + B P_R) q + C \bar{\chi} \chi m_q \bar{q} q + D \bar{\chi} \gamma_5 \chi m_q \bar{q} \gamma_5 q \\
+ E \bar{\chi} i \gamma_5 \chi m_q \bar{q} q + F \bar{\chi} \chi m_q \bar{q} i \gamma_5 q.
\]

Dark matter experiments

- DAMA
- ZEPLIN
- EDELWEISS
- XENON
- CDMS & SuperCDMS
- ...
Figure: A comparison of $\sigma(\chi p)$ for the models from HB region (also known as Chargino Pattern mSP1) vs the patterns that Stop is the NLSP, mSP11-mSP13. The analysis shows a Wall consisting of a clustering of points in the Chargino Patterns mSP1 with a $\sigma(\chi p)$ in the range $10^{-44} \pm 0.5 \text{ cm}^2$ enhancing the prospects for the observation of dark matter by SuperCDMS, ZEPLIN-MAX, or LUX.
Figure: A comparison of $\sigma(\chi p)$ for models originating from Stau-Co region (mSP5) and models in which Higgses become lighter than all other sparticles except the LSP.
Dual probe of the LHC signatures and the dark matter experiments


Figure: Right panel: An exhibition of the trileptonic signal vs $\sigma_{SI}^{\chi p}$. Points in the vertical region to the right constitute the Chargino Wall. Left panel: an exhibition of $\left\langle P_{T}^{\text{miss}} \right\rangle$ vs $\sigma_{SI}^{\chi p}$. The cluster of points at the end to the right constitute the Chargino Ball. The CDMS/Xe10 constraints and constraints expected from SuperCDMS are also shown. A clear discrimination of Stau-Co and HB can be seen in these plots.
The most common models under the framework of mSUGRA originate from HB and Stau-Co mechanisms by which the dark matter is generated in the early universe.

By analyzing the various LHC signatures, including multi leptons, hadronic jets, b-tagging, and missing transverse momentum, one can discriminate between the Stau-Co region and the HB region for the mSUGRA model.

There are a copious number of models originating from the HB region which have a large neutralino-proton scalar cross section within the reach of the next generation of dark matter experiments.

The direct detection of dark matter along with the LHC signatures provide a dual probe of SUSY. In some cases, dark matter detection can probe the parameter space which may not be easily accessible to the LHC, and vice versa.