Dark matter: direct detection, indirect detection, colliders and joint analysis

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http://home.slac.stanford.edu/pressreleases/2006/20060821.htm
Collider studies of Dark Matter already under way ... 

... although on a somewhat larger scale than we're used to.
DM at (Terrestrial) Colliders

- Collider recreates conditions which existed soon after Big Bang
- If DM light
  - collider acts as DM factory
  - permanently increases DM budget of universe.
  - ‘non-thermal’ production mechanism...

- Colliders study DM production, astroparticle searches study DM interaction ➔ complementarity
Collider DM Signatures

- Canonical DM model: supersymmetry (SUSY)
- Generic SUSY signature: Missing (Transverse) Energy
- Generated by escape of DM particles \( \rightarrow \) generic signature for DM
- Observation of ME signal necessary but not sufficient to prove DM signal (DM particle could decay outside detector)

Proof of both existence and identity of DM only by combining collider and astroparticle data
Complementarity

- Collider measurements complementary to direct and indirect astroparticle searches / measurements
  - Uncorrelated systematics
  - Measure different parameters

- Aim to test compatibility of e.g. collider SUSY signal with DM hypothesis
  - Fit model to collider measurements
  - Use to calculate astroparticle DM observables $\Omega_\chi h^2$, $m_\chi$, $\sigma_{\chi p}^{{\text{si}}}$ etc.

Strongest possible test of particle physics dark matter model
LHC Dark Matter studies will proceed in four stages:

1) Discovery phase
   - MET signature
   - lifetime studies

2) Inclusive Studies
   - measurement of mass scale,
   - comparison of significance in inclusive channels.

3) Exclusive studies + interpretation within specific model framework
   - e.g. Constrained MSSM / mSUGRA SUSY models
   - Specific model needed to calculate e.g. relic density \( \rightarrow \) general SUSY studies will be less model dependent.

4) Less model-dependent interpretation
   - Relax model-dependent assumptions

Use canonical SUSY example for subsequent discussion.
Inclusive Searches

- Heavy strongly-interacting SUSY states (squarks, gluinos) pair-produced copiously in p-p collisions.
- Cascade decays through lighter states to invisible LSP (DM).
- Signature: MET (DM) + jets + leptons
- Big challenge to understand SM backgrounds in new kinematic regime

- First indication of SUSY / DM parameters from relative significance / cross-section in different channels
Inclusive Studies

- Following any discovery next task will be to test broad features of potential Dark Matter candidate.
- **Question 0**: Is it SUSY?
  - Hard to answer ➔ measure spin (later)
- **Question 1**: Is R-Parity Conserved?
  - If YES possible DM candidate
  - LHC experiments sensitive only to LSP lifetimes < 1 ms (<< \( t_u \sim 13.7 \text{ Gyr} \))

- **Question 2**: Is the LSP the lightest neutralino?
  - Natural in many MSSM models
  - If YES then test for consistency with astrophysics
  - If NO then what is it?
  - e.g. Light Gravitino DM from GMSB models (not considered here)
Exclusive Measurements

- Two neutral LSPs escape from each event
  - Impossible to measure mass of each sparticle using one channel alone
- Use kinematic end-points to measure combinations of masses
- Classic example: OSSF di-lepton production at end of decay chain
  - Background subtraction with OSOF sample

Sequential two-body decays \((m(l)<m(\chi^0_2))\)

Three-body decays \((m(l)>m(\chi^0_2))\)
‘Model-Independent’ Masses

- Additional constraints from end-points in invariant masses with quarks (jets)

\[ (\chi_0^0)^2 = (\xi - \eta)(\eta - \xi) \]

- Solve end-point constraints to obtain individual masses, assuming particular (model-dependent) hierarchy:

### Table 1: Additional Constraints on Invariant Masses

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Preliminary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m_{\chi_1^0} )</td>
<td>88 ± 60 ± 2</td>
<td>118</td>
</tr>
<tr>
<td>( m_{\chi_2^0} )</td>
<td>189 ± 60 ± 2</td>
<td>219</td>
</tr>
<tr>
<td>( m_{\tilde{q}} )</td>
<td>614 ± 91 ± 11</td>
<td>634</td>
</tr>
<tr>
<td>( m_{\tilde{\ell}} )</td>
<td>122 ± 61 ± 2</td>
<td>155</td>
</tr>
<tr>
<td>Observable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m_{\chi_1^0} - m_{\chi_2^0} )</td>
<td>100.6 ± 1.9 ± 0.0</td>
<td>100.7</td>
</tr>
<tr>
<td>( m_{\tilde{q}} - m_{\chi_1^0} )</td>
<td>526 ± 34 ± 13</td>
<td>516.0</td>
</tr>
<tr>
<td>( m_{\tilde{\ell}} - m_{\chi_1^0} )</td>
<td>34.2 ± 3.8 ± 0.1</td>
<td>37.6</td>
</tr>
</tbody>
</table>

ATLAS, mSUGRA bulk region, 1 fb⁻¹
Model-Dependent Constraints

• Initially insufficient weak-scale SUSY parameters measured to calculate DM observables from e.g. generic MSSM.
• Instead assume simplified model (e.g. mSUGRA) and perform global fit of parameters to LHC observables
  – Public codes available e.g. SFITTER, FITTINO;
  – c.f. global EW fits at LEP, ZFITTER, TOPAZ0 etc.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SU3 value</th>
<th>fitted value</th>
<th>exp. unc.</th>
<th>theo. + exp. unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>tanβ</td>
<td>6</td>
<td>7.4</td>
<td>4.6</td>
<td>–</td>
</tr>
<tr>
<td>$M_0$</td>
<td>100 GeV</td>
<td>98.5 GeV</td>
<td>±9.3 GeV</td>
<td>±9.5 GeV</td>
</tr>
<tr>
<td>$M_{1/2}$</td>
<td>300 GeV</td>
<td>317.7 GeV</td>
<td>±6.9 GeV</td>
<td>±7.8 GeV</td>
</tr>
<tr>
<td>$A_0$</td>
<td>−300 GeV</td>
<td>445 GeV</td>
<td>±408 GeV</td>
<td>–</td>
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</table>

• mSUGRA bulk region (SU3 model) 1 fb$^{-1}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected % precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0$</td>
<td>± 2%</td>
</tr>
<tr>
<td>$m_{1/2}$</td>
<td>± 0.6%</td>
</tr>
<tr>
<td>tan(β)</td>
<td>± 9%</td>
</tr>
<tr>
<td>$A_0$</td>
<td>± 16%</td>
</tr>
</tbody>
</table>

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<th>fitted value</th>
<th>exp. unc.</th>
<th>theo. + exp. unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>tanβ</td>
<td>13.9</td>
<td>±2.8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$M_0$</td>
<td>104 GeV</td>
<td>±18 GeV</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$M_{1/2}$</td>
<td>309.6 GeV</td>
<td>±5.9 GeV</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$A_0$</td>
<td>489 GeV</td>
<td>±189 GeV</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

• mSUGRA bulk region (SPS1a model) 300 fb$^{-1}$

ATLAS Preliminary
• Use fitted model parameters to calculate DM observables (e.g. for 300 fb\(^{-1}\), SPS1a model)
  – \(\Omega_{\chi} h^2 = 0.1921 \pm 0.0053\)
  – \(\log_{10}(\sigma_{\chi p}/\text{pb}) = -8.17 \pm 0.04\)

SPS1a: >5\(\sigma\) error (300 fb\(^{-1}\))

Micromegas 1.1 (Belanger et al.) + ISASUGRA 7.69

DarkSUSY 3.14.02 (Gondolo et al.) + ISASUGRA 7.69

\(\Omega_{\chi} h^2\)

300 fb\(^{-1}\)

ATLAS

\(\sigma_{\chi p}\)

300 fb\(^{-1}\)

ATLAS

Polesello et al JHEP 0405 (2004) 071
Target Models

- SUSY (e.g. mSUGRA) parameter space strongly constrained by cosmology (e.g. WMAP satellite) data.

mSUGRA $A_0=0$, $\tan(\beta) = 10$, $\mu>0$

'Selectron Co-annihilation region: LSP ~ pure Bino. Small slepton-LSP mass difference makes measurements difficult.'

'Focus point' region: significant $\tilde{h}$ component to LSP enhances annihilation to gauge bosons

'Bulk' region: t-channel slepton exchange - LSP mostly Bino. 'Bread and Butter' region for LHC Expts.

Also 'rapid annihilation funnel' at Higgs pole at high $\tan(\beta)$, stop co-annihilation region at large $A_0$
Coannihilation Signatures

- Small slepton-neutralino mass difference gives soft leptons
  - Low electron/muon/tau energy thresholds crucial.
- Decays of $\tilde{\chi}_2^0$ to both $\tilde{l}_L$ and $\tilde{l}_R$ kinematically allowed.
  - Double dilepton invariant mass edge structure;
  - Edges expected at 56 / 98 GeV for this model
- Stau channels enhanced (large tan$\beta$)
  - Soft tau signatures;
  - Edge expected at 79 GeV for this model;
  - Less clear due to poor tau visible energy resolution.

- $m_0=70$ GeV
- $m_{1/2}=350$ GeV
- $A_0=0$; tan$\beta=10$; $\beta>0$
Focus Point Signatures

- Large $m_0 \rightarrow$ sfermions are heavy
- Most useful signatures from heavy neutralino decay
- Direct three-body decays $\tilde{\chi}^0_n - \tilde{\chi}^0_1 \rightarrow \tilde{\chi}^0_1$ II
- Edges give $m(\tilde{\chi}^0_n)-m(\tilde{\chi}^0_1)$ : flavour subtraction applied
- Caveat: cross-sections can be small (need lots of lumi), number of observables limited

$$\frac{d\Gamma}{dM_{\text{inv}}} = C_{\text{Norm}} M_{\text{inv}} \sqrt{M_{\text{inv}}^4 - M_{\text{inv}}^2 (\mu^2 + M^2) + (\mu M)^2} \cdot \left[ -2M_{\text{inv}}^4 + M_{\text{inv}}^2 (2M^2 + \mu^2) + (\mu M)^2 \right].$$

$$M = m_A + m_B \quad \mu = m_A - m_B$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without cuts</th>
<th>Exp. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$</td>
<td>68±92</td>
<td>103.35</td>
</tr>
<tr>
<td>$M_2-M_1$</td>
<td>57.7±1.0</td>
<td>57.03</td>
</tr>
<tr>
<td>$M_3-M_1$</td>
<td>77.6±1.0</td>
<td>76.41</td>
</tr>
</tbody>
</table>

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Dark Matter in the MSSM

- Can relax mSUGRA constraints to obtain more ‘model-independent’ relic density estimate.
- Much harder – needs more measurements
- Not sufficient to measure relevant (co-)annihilation channels – must exclude all irrelevant ones also …
- Stau, higgs, stop masses/mixings important as well as gaugino/higgsino parameters

Nojiri et al., JHEP 0603 (2006) 063

\[ \Omega_{\chi} h^2 \]

\[ m_{\tau\tau} = 5 \text{ GeV} \]

\[ 300 \text{ fb}^{-1} \]

SPA point

\[ \Omega_{\chi} h^2 \text{ vs } m_{\tau\tau} \]

\[ \Omega_{\chi} h^2 \text{ vs } m_{\tau\tau} \]

\[ 0.5 \text{ GeV} \]

\[ 300 \text{ fb}^{-1} \]

\[ \text{Fractional error on } \Omega h^2 \]

\[ \text{Uncertainty on } \Omega h^2 \text{ (GeV)} \]
ILC Measurements

- Precision ‘less model-dependent’ (e.g. MSSM) predictions for DM observables probably require ILC
  - Requires relevant states (not just DM) to be accessible
- Improvement over LHC depends strongly on
  - Channels accessible
  - States contributing to (co-)annihilation processes
ILC Measurements

- If accessible many more tools available at ILC
  - Precision spectroscopy
  - Polarization
  - Threshold studies (spin measurement)
  - Precision cross-sections

Baltz, Battaglia, Peskin and Wizansky, PRD74 (2006) 103521
It works both ways!

- So far discussed impact of collider measurements on DM observables
- Works both ways $\rightarrow$ astroparticle observables constrain underlying PP model
  - e.g. relic density / direct detection measurements fix LSP content in FP region
- Alternatively collider + AP measurements constrain astrophysical uncertainties (halo profile (indirect), flux(direct))

Baltz, Battaglia, Peskin and Wizansky, PRD74 (2006) 103521

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Summary

- Following a New Physics discovery LHC will aim to test the Dark Matter hypothesis.
- Conclusive result only possible in conjunction with astroparticle experiments (constraints on LSP life-time).
- Estimation of relic density and direct / indirect DM detection cross-sections in model-dependent scenario will be first goal.
- Less model-dependent measurements will follow ➔ detailed studies probably require ILC
- Ultimate goal: observation of neutralinos at LHC confirmed by observation of e.g. signal in (in)direct detection Dark Matter experiment at predicted mass and cross-section.

This would be major triumph for both Particle Physics and Cosmology!
Particle physics / cosmology interface of great interest to public …
BACK-UP SLIDES
Heavy Gaugino Measurements

- Potentially possible to identify dilepton edges from decays of heavy gauginos.
- Requires high stats.
- Crucial input to reconstruction of MSSM neutralino mass matrix (independent of SUSY breaking scenario).

ATLAS 100 fb$^{-1}$

SPS1a
Measurements With Squarks

- Dilepton edge starting point for reconstruction of decay chain.
- Make invariant mass combinations of leptons and jets.
- Gives multiple constraints on combinations of four masses.
- Sensitivity to individual sparticle masses.
**SUSY Spin Measurement**

- **Q:** How do we know that a SUSY signal is really due to SUSY?
  - Other models (e.g. UED) can mimic SUSY mass spectrum

- **A:** Measure spin of new particles.
- One possibility – use ‘standard’ two-body slepton decay chain
  - charge asymmetry of lq pairs measures spin of $\tilde{\chi}_2^0$
  - relies on valence quark contribution to pdf of proton (C asymmetry)
  - shape of dilepton invariant mass spectrum measures slepton spin

![Diagram of SUSY particles and decay chains](image)

- Spin-0, mostly wino
- Spin-0, mostly bino
- Measure Angle
- Polarise
- $\tilde{\chi}_2^0$
- $\tilde{\chi}_1^0$

**Graphs:**
- $A^{+-} = \frac{l^+ - l^-}{l^+ + l^-}$
- $m_{lq}$
- $m_{ll}$
- $150$ fb$^{-1}$
- ATLAS

**Notes:**
- Spin-0 = flat
- Point 5
- Straight line dist (phase-space)