DARK MATTER and Sparticle Reconstruction at the LHC
OUTLINE

- **Dark Matter : Cosmology and Supersymmetry**
  - A primer

- **Sparticle Reconstruction at the LHC :**
  - A favourable example

- **Sparticle Reconstruction at the LHC :**
  - More difficult cases

- **Conclusions and Outlook**
Dark Matter: Cosmology

Baryon density: \( \Omega_b = 0.044 \pm 0.004 \)
Dark Matter: \( \Omega_m = 0.23 \pm 0.04 \)
Dark Energy: \( \Omega_\Lambda = 0.73 \pm 0.04 \)

Density of cold DM in units of \( \rho_c = 1.86 \times 10^{-29} \text{ g/cm}^3 \):

\( 0.0094 < \Omega_m h^2 < 0.129 \) (2\( \sigma \) range)

After WMAP
Dark Matter: Supersymmetry

Most popular dark-matter candidate:

The Lightest Supersymmetric Particle (LSP)

Generic assumptions in the following:

- R-Parity is conserved
- The LSP is the lightest neutralino, $\chi_1^0$
- Constrained MSSM (m-Chou-Gras-inspired SUSY)
  - $m_0$: universal scalar mass
  - $m_{1/2}$: universal gaugino mass
  - $A_0$: trilinear SUSY parameter (= 0 here)
  - $\tan\beta$: ratio of the two Higgs doublet vev's
  - $\text{sign}(\mu)$: the sign of the Higgs mixing parameter
Dark Matter: Cosmology & Supersymmetry (1)

\[ 0.0094 < \Omega_m h^2 = n_{\text{LSP}} \times m_{\text{LSP}} < 0.129 \]

\[ \rho_{\text{LSP}} = \text{Relic LSP Density} \times \text{LSP mass} \]

The Relic LSP Density decreases when the LSP annihilation cross section in the early universe increases:

\[ \sigma(\chi\chi \rightarrow ff) \propto \frac{m_\chi^2}{(m_\chi^2 + m_f^2)^2} \]

\[ \rho_{\text{LSP}} \propto \frac{(m_\chi^2 + m_f^2)^2}{m_\chi} \approx \frac{m_\chi^3}{m_\chi} \]

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Moriond EW 2004
\[ 0.0094 < \rho_{\text{LSP}} < 0.129 \]

\[ m_\chi = 0.4 m_{1/2} \]

\[ m_{\ell_R}^2 = m_0^2 + 0.15 m_{1/2}^2 + \cdots \]

\[ m_{\ell_L, \nu}^2 = m_0^2 + 0.5 m_{1/2}^2 + \cdots \]

\[ m_{q_{R,L}}^2 = m_0^2 + 6 m_{1/2}^2 + \cdots \]

Upper and lower limits on \( m_0, m_{1/2} \) and \( m_\chi \)

100 - 300 GeV

LIGHT!
**Co-annihilation tail**: The LSP and the NLSP are almost degenerate, e.g., $m_\tilde{\tau} - m_{\chi} < m_\tau$ (no direct decay to $\tau \chi_1^0$).

**Dominant processes:**

1. $\tilde{\tau} \rightarrow \tau \chi_1^0$: The stau disappears slowly.
2. $\tilde{\tau} \rightarrow \tau \chi_1^0$: The LSP co-annihilates for longer.
3. $\tilde{\tau} \rightarrow \gamma$: Smaller relic density! Larger $m_\chi$ possible...

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*Ellis et al., hep-ph/0303043*
**Rapid annihilation**: At large $\tan \beta$, and for $m_0 \approx m_{1/2}$, the LSP mass is about half the heavy Higgs boson mass ($A$ and $H$).

**Dominant process:**

$(\chi_1^0, f) \rightarrow (H, A) \rightarrow (H, A)$

(The annihilation is too rapid if the LSP mass is exactly half the Higgs boson mass, hence the two allowed lines on the plot)

Ellis et al., hep-ph/0303043

$\tan \beta = 35$, $\mu < 0$

$m_h = 114$ GeV

$m_0$ (GeV)

$m_{1/2}$ (GeV)
**Focus Points**: For any (large) value of $m_0$ and $m_{1/2}$, one can always find a value of $\tan \beta$ for which $\mu$ is small. In this configuration, the Higgsino component of the LSP is large (100%), hence a large coupling to $h, H, A$. 

**Dominant processes**:

\[ \chi_1^0 \]

\[ h, H, A \quad \text{(off-shell)} \]

\[ \chi_1^0 \]

\[ \chi_1^0 \]

\[ m_t = 171 \text{ GeV}, \, \tan \beta = 10, \, \mu > 0 \]

\[ m_h = 113 \text{ GeV} \]

Ellis et al., hep-ph/0106204
1) Series of **Benchmarks**

(e.g., à la Ellis et al.)

2) Reach at LHC from $g$ and $q$ production ($\text{Jets} + E_T$)

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**Cosmology & Supersymmetry at LHC**

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Dark Matter and Sparticle Reconstruction at the LHC
A favourable example: Point B

- Visible in the Jet+$\not{E}_T$ trigger rate!

- Gauginos, squarks, sleptons are light (from 100 to 800 GeV/c$^2$)

- Long cascade decay chains possible
  
  e.g.,

- Large $e^+e^-$ & $\mu^+\mu^-$ branching ratios

  Spectacular and constrained final states with b-jets, missing energy and leptons, easy to separate from SM backgrounds.
Point B: End Point Reconstruction (1)

Largest dilepton invariant mass fixed by sparticle masses:

\[ M_{\ell \ell}^{\text{max}} = \frac{\sqrt{\left( m_{\chi_2^0}^2 - m_\ell^2 \right) \left( m_\ell^2 - m_{\chi_1^0}^2 \right)}}{m_\ell} \]

\[ \chi \]

Background Subtracted (Opposite Flavour leptons)

CMS

m(\tilde{q}, \tilde{g}) \sim 600 \text{ GeV}

2 b jets

10 fb^{-1}

1 month at 10^{33}

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Dark Matter and Sparticle Reconstruction at the LHC
Point B : End Point Reconstruction (2)

Largest dilepton-jet and lepton-jet invariant masses:

\[ M_{\ell\ell q}^{\text{max}} = \sqrt{\left(m_{\chi_2^0}^2 - m_{\chi_1^0}^2\right)\left(m_{\chi_2^0}^2 - m_q^2\right)} \]

\[ M_{\ell\ell q}^{\text{max}} = m_\chi^0 - m_q^0 \text{ if } m_q^2 > m_\chi^0 m_q^0 \]

\[ M_{\ell_1 q}^{\text{max}} = \sqrt{\left(m_{\chi_2^0}^2 - m_{\chi_1^0}^2\right)\left(m_{\chi_2^0}^2 - m_{\chi_2^0}^2\right)} \]

\[ M_{\ell_2 q}^{\text{max}} = \sqrt{\left(m_{\chi_1^0}^2 - m_{\chi_1^0}^2\right)\left(m_{\chi_2^0}^2 - m_{\chi_2^0}^2\right)} \]
Point B: End Point Reconstruction (3)

ATLAS/2004-007

$M_{qll}$

$M_{ql}(\text{min})$

$M_{ql}(\text{max})$

$M_{qll}(\text{thresh})$

100 fb$^{-1}$
Point B: Sparticle Mass Evaluation

<table>
<thead>
<tr>
<th>Edge</th>
<th>Nominal Value</th>
<th>Fit Value</th>
<th>Syst. Error</th>
<th>Statistical Error</th>
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<tbody>
<tr>
<td>$m(ll)^{\text{edge}}$</td>
<td>77.077</td>
<td>77.024</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>$m(qll)^{\text{edge}}$</td>
<td>431.1</td>
<td>431.3</td>
<td>4.3</td>
<td>2.4</td>
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<tr>
<td>$m(qll)^{\text{min}}$</td>
<td>302.1</td>
<td>300.8</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>$m(qll)^{\text{max}}$</td>
<td>380.3</td>
<td>379.4</td>
<td>3.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$m(qll)^{\text{thres}}$</td>
<td>203.0</td>
<td>204.6</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>$m(bll)^{\text{thres}}$</td>
<td>183.1</td>
<td>181.1</td>
<td>1.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>

- End-points depend on mass differences \(\Rightarrow\) strong correlations between masses
- Absolute mass values need at least one additional input (e.g., \(m_\chi\) from LC)
- A fit of mSUGRA predictions to the set of measured end-points can also be done (à la LEP vs Standard Model)
Point B: Dark Matter Evaluation

- Generate *gedanken* experiments with the 14 measurements and their expected uncertainties (here for 100 fb$^{-1}$)

- Fit the best mSUGRA point by minimizing the overall $\chi^2$

- Deduce the LSP mass and relic density at the point

- Determine $\Omega_{\chi}h^2$

- Repeat for many such experiments

(The tail disappears only with 300 fb$^{-1}$)

ATLAS/2004-008

100 fb$^{-1}$

$0.192 \pm 0.005$
**Point B: Possible improvements** (ATL 2003-039)

- **Decay chain:**
  
  \[ g \rightarrow \tilde{b} \quad \tilde{b} \rightarrow \chi_2^0 bb \rightarrow \ell \quad bb \quad \ell \rightarrow \chi_1^0 bb \quad \ell \ell \]

- **Five equations for each event (not only end-point events):**

  1. \( m_{\chi_1^0}^2 = p_{\chi_1^0}^2 \)
  2. \( m_{\ell}^2 = (p_{\ell_1} + p_{\ell_2})^2 \)
  3. \( m_{\chi_2^0}^2 = (p_{\chi_1^0} + p_{\ell_1} + p_{\ell_2})^2 \)
  4. \( m_b^2 = (p_{\chi_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1})^2 \)
  5. \( m_g^2 = (p_{\chi_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1} + p_{b_2})^2 \)

- **Nine unknowns: five masses and the LSP four-momentum**
  
  The \( b \) jet and the lepton energies and momenta are all measured.

- **Get one relation between the five masses for each event.** Determine all masses with five events only. **Use all events.** Possibly gain a large factor in statistics (>3?)
More difficult cases for LHC (1)

- **Next-in-line:** Point G, more difficult to find (!)
  
  BR($\chi_2 \to \chi_1 l^+l^-$) about ten times smaller than at Point B
  
  Needs ten times more statistics for a similar accuracy (i.e., 1000 fb$^{-1}$ + the full mass reconstruction method to say something relevant about Dark Matter).

- **Next-to-next:** Point I, BR($\chi_2 \to \chi_1 \tau^+\tau^-$) $\approx$ 100%
  
  Full mass reconstruction method in trouble
  
  Some end points measurable with $\tau \to a_1 \nu_\tau$ ?
  
  Small mass difference does not help ...
  
  Study $\chi_2 \to \chi_1 h \to \chi_1 bb$ ?

- **Some points in the co-annihilation tail** (D, J, L) have also BR($\chi_2 \to \chi_1 \tau^+\tau^-$) $\approx$ 100%.
  
  Other (A, C, H) similar to B, but need 10-100×lumi

NEEDS WORK!
More difficult cases for LHC (2)

- **Focus points (e.g., F):** Gluinos and squarks are within the LHC reach only if $m_{\text{top}}$ is small enough (171 GeV/$c^2$)
  
  For values of $m_{\text{top}}$ closer 180 GeV/$c^2$ as recently measured by D0, only the lighter scalar Higgs boson will be seen at LHC.

- **In the rapid annihilation funnels (K & M), sparticles are too heavy to be detected with less than 300 fb$^{-1}$.
  
  Only the lighter scalar Higgs boson will be seen at LHC if Nature has chosen to sit in these funnels.

- **A linear $e^+e^-$ collider would help in all cases**
  
  LSP mass in the co-annihilation tail with 0.5 - 1 TeV
  More discoveries in F, K, M with 5 TeV or more.
Co-annihilation Bulk:
Full reconstruction and confrontation with space measurements is possible in favourable case(s).
Needs 100 fb$^{-1}$ or more with end-points for a sound comparison.

Co-annihilation Tail:
More work is needed for $\chi_2$ decays in taus or in Higgs boson, and with the full mass reconstruction to exploit the 300 fb$^{-1}$
This work will also benefit to the more favourable cases.

Focus Points, Rapid Annihilation Funnels:
Essentially hopeless, no long decay chains available, sleptons, squarks and gluinos out of reach.
Conclusions and Outlook (2)

- Remember: Study based on mSUGRA predictions, with R parity conservation, and fast detector simulations.

- Non-constrained MSSM?
  Might become really intricate.

- Other SUSY breaking mechanism?
  GMSB just started, need more

- Other/Additional Dark Matter origin?
  Will make the picture completely different

- Full detector simulations?
  (b-tagging performance, missing $E_T$ resolution might change)
STAY TUNED: The Big Show Starts Soon