Prospects for SUSY using the ATLAS Detector at the Large Hadron Collider

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Introduction

SUSY maximal extension of Lorentz group. Inherent to most string theories: currently appear to be our best hope for incorporating gravity

Weak-scale SUSY well motivated as solution to gauge-hierarchy problem, gauge coupling unification etc.

R-parity conserving SUSY also provides good Cold Dark Matter Candidate (CDM now well established by WMAP results).

SUSY one of primary motivations for construction of LHC

MSSM 105 additional free parameters (masses, mixing angles, phases)

Different models / phenomenologies depending on mediation of SUSY breaking: SUGRA, GMSB, AMSB. Constrained models (few parameters)

mSUGRA \( m_0, m_{1/2}, A_0, \tan\beta, \text{sgn}(\mu) \)

mGMSB \( M_{\text{mes}}, N_{\text{mes}}, \Lambda, \tan\beta, \text{sgn}(\mu) \)

mAMSB \( m_0, m_{\text{aux}}, \tan\beta, \text{sgn}(\mu) \)
SUSY at ATLAS

This talk:

- mSUGRA (though some ‘model independent’ measurements)
- Assume R-Parity conservation $\rightarrow$ missing energy signature
- With appropriate selection criteria ($p_T$ jets, $p_T$ leptons, missing energy)
  SM background for many SUSY analyses are effectively negligible. Largest potential backgrounds then from competing SUSY decays.

Need to generate full SUSY spectrum for each point in parameter space

- Most analyses rely on fast simulation, or parametrisation of detector response. Some results from full simulation now available (5 fb$^{-1}$).
- What can be done early on?
  - Discovery of SUSY (or discovery of non-SM missing energy signal)
  - Determination of SUSY mass scale
  - Determination of SUSY cross-section
  - Initial look at SUSY masses (will likely need much more luminosity)
LHCC SUSY Benchmark Points (1996)

mSUGRA

$m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $\text{sgn}(\mu)$

LHCC Point 5:

$m_0 = 100$ GeV;
$m_{1/2} = 300$ GeV;
$A_0 = -300$ GeV;
$tan\beta = 2.1$; $\mu > 0$

Cosmologically interesting but higgs mass now excluded by LEP

Modified LHCC Point 5:

as above but $\tan\beta = 6$
More Recent Benchmark Points (and slopes)

• Post-LEP Benchmarks for Supersymmetry hep-ph/0106204
• Points d’Aix GDR SUSY Workshop Aix-La-Chappele, 2001

• In each case, points (and slopes in the case of SPS) defined for
  – mSUGRA
  – mGMSB
  – mAMSB

• Account for LEP SUSY, Higgs mass constraints,
• Account for $b \rightarrow s \gamma$, $g_\mu-2$, LSP relic density $\Omega_\chi h^2$
• More recently WMAP results on $\Omega_\chi h^2$ → increased interest in focus point
  and co-annihilation regions.

This talk, mostly mSUGRA
ATLAS Reach for mSUGRA

Jets + n(leptons) + missing energy
- n=0,1
- n=2,3

Reach defined by
- 10 fb⁻¹
- ≥ 10 events
- S/B¹/² > 5
ATLAS mSUGRA Mass Reach

\[ \tan \beta = 2, \mu > 0 \]

- 1 lepton
- 0 leptons
- 2 leptons (SS, OS)
- 3 leptons

Jets + n(leptons) + missing energy:
Reach to \( \sim 2 \) TeV

for \( M_{\tilde{g}}, M_{\tilde{q}} \)
Determination of SUSY mass scale

\[ M_{\text{eff}} = \sum_i |p_T^i| + E_{\text{miss}}^T \]

Peaks at ~ twice SUSY Mass scale

\[ M_{\text{SUSY}} \sim \frac{\sum \sigma_i m_i}{\sum \sigma_i} \]

Pseudo ‘model independent’

Works also for GMSB, AMSB models assuming adequate production \( \sigma \)

Normalization strongly correlated to total SUSY cross-section \( \sigma_{\text{SUSY}} \)

Tovey ATLAS-PHYS-2002-013
Exclusive measurements (sparticle masses)

Measurement of SUSY parameters (masses etc)

- Unknown LSP ($\tilde{\chi}_1^0$) mass means no direct reconstruction
- Use cascade decays to determine combinations of masses from endpoints of visible mass distributions

$$\tilde{g} \rightarrow \tilde{q}q \rightarrow qq\tilde{\chi}_2^0 \rightarrow qq\tilde{l}l \rightarrow qqll\tilde{\chi}_1^0$$
Dilepton Edge Measurements

Sharp OSSF dilepton invariant mass edge sensitive to combinations of sparticle masses

$$M_{ll}^{\text{max}} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(l_R)}{M^2(\tilde{\chi}_2^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(l_R)}} = 108.93 \text{ GeV}$$

Assumes $\tilde{\chi}_2^0 \rightarrow l_R l \rightarrow \tilde{\chi}_1^0$ kinematically accessible (e.g. LHC Point 5, sps1a).

Edge measured with precision $\sim 0.5 \text{ GeV}$

SM & SUSY background subtraction using OF distribution (here for 5fb$^{-1}$, full simulation)
Measurements With Squarks

Dilepton edge point starting point for reconstruction of decay chain

Make invariant mass combination of leptons and jets

Yields multiple constraints on combinations of four masses

Combined constraints give sensitivity to individual sparticle masses
Combine measurements from edges from different jet/lepton combinations to obtain ‘model-independent’ mass measurements. [Allanach et al., hep-ph/0007009]

<table>
<thead>
<tr>
<th>Related edge</th>
<th>Kinematic endpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t^q t^q$ edge</td>
<td>$(m_{t^q}^\text{max})^2 = (\bar{t} - \bar{t})(\bar{t} - \bar{t})/\bar{t}$</td>
</tr>
<tr>
<td>$t^q t^q$ edge</td>
<td>$(m_{t^q}^\text{min})^2 = \max \left[ \frac{(\bar{E} - \bar{E})(\bar{E} - \bar{E})}{\bar{E}}, \frac{(\bar{E} - \bar{E})(\bar{E} - \bar{E})}{\bar{E}} \right]$</td>
</tr>
<tr>
<td>$\chi^0_1 lR$ edge</td>
<td>$(m_{\chi^0_1}^\text{min})^2 = X + (\bar{E} - \bar{E}) \left[ \bar{E} + \bar{E} \sqrt{\bar{E} - \bar{E} \sqrt{\bar{E} - \bar{E}}} \right]$</td>
</tr>
<tr>
<td>$\chi^0_2 qL$ edge</td>
<td>$(m_{\chi^0_2}^\text{min})^2 = \frac{\bar{E}(\bar{E} - \bar{E})(\bar{E} - \bar{E})}{\bar{E}(\bar{E} - \bar{E})}$</td>
</tr>
</tbody>
</table>

$\chi^0_1 lR$ threshold: $(m_{\chi^0_1}^\text{min})^2 = \frac{\bar{E}(\bar{E} - \bar{E})(\bar{E} - \bar{E})}{\bar{E}(\bar{E} - \bar{E})}$

$\chi^0_2 qL$ edge: $(m_{\chi^0_2}^\text{min})^2 = (\bar{E} - \bar{E})((\bar{E} - \bar{E})/\bar{E})$

$\chi^0_1 lR$ high-edge: $(m_{\chi^0_1}^\text{min})^2 = \max \left[ (m_{\chi^0_1}^\text{max})^2, (m_{\chi^0_1}^\text{min})^2 \right]$

$\chi^0_2 qL$ low-edge: $(m_{\chi^0_2}^\text{min})^2 = \min \left[ (m_{\chi^0_2}^\text{max})^2, (\bar{E} - \bar{E})(\bar{E} - \bar{E}) \right]$

$M_{\chi_1 \chi_2 \chi_3} = m_{\chi_1} - m_{\chi_2}$

<table>
<thead>
<tr>
<th>Sparticle</th>
<th>Exp. precision (100 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{q}_L$</td>
<td>$\pm 3%$</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2$</td>
<td>$\pm 6%$</td>
</tr>
<tr>
<td>$\tilde{t}_R$</td>
<td>$\pm 9%$</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>$\pm 12%$</td>
</tr>
</tbody>
</table>
Right-handed Squark Mass

Typically BR ($\tilde{q}_R \rightarrow \tilde{\chi}^0_1 q$) > 99%. (no dilepton chain through $\tilde{\chi}^0_2$)

Search for events with 2 hard jets and lots of $E_T^{miss}$.
Reconstruct mass using ‘stransverse mass’

$$m_{T2}^2 = \min_{q_T^{\chi(1)} + q_T^{\chi(2)} = E_T^{miss}} \left[ \max \{ m_T^2(p_T^{j(1)}, q_T^{\chi(1)}; m_\chi), m_T^2(p_T^{j(2)}, q_T^{\chi(2)}; m_\chi) \} \right]$$

- Needs $\tilde{\chi}^0_1$ mass measurement as input

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$\tilde{q}_R$ squark

ATLAS

30 fb$^{-1}$

Right squark

SPS1a

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statistical precision
~ 4 GeV
Other analysis techniques exist that do not rely on endpoint measurements

\[ \tilde{g} \rightarrow \tilde{b}b \rightarrow \tilde{\chi}_2^0 bb \rightarrow \tilde{l}bbl \rightarrow \tilde{\chi}_1^0 bbll \]


Assume \( \tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{l}_R \) masses known from other measurements (as described)

Six unknowns \( M_{\tilde{g}}, M_{\tilde{b}}, p_{\tilde{\chi}_1^0} \) for five equations:

Combine two events: 10 equations for 10 unknowns (2 masses common)

Does not rely on having events near the endpoint

\[
\begin{align*}
M_{\tilde{\chi}_1^0}^2 &= p_{\tilde{\chi}_1^0}^2 \\
M_{\tilde{b}}^2 &= (p_{\tilde{\chi}_1^0} + p_{\tilde{l}_1})^2 \\
M_{\tilde{\chi}_2^0}^2 &= (p_{\tilde{\chi}_1^0} + p_{\tilde{l}_1} + p_{\tilde{l}_2})^2 \\
M_{\tilde{b}}^2 &= (p_{\tilde{\chi}_1^0} + p_{\tilde{l}_1} + p_{\tilde{l}_2} + p_{\tilde{b}_1})^2 \\
M_{\tilde{g}}^2 &= (p_{\tilde{\chi}_1^0} + p_{\tilde{l}_1} + p_{\tilde{l}_2} + p_{\tilde{b}_1} + p_{\tilde{b}_2})^2
\end{align*}
\]
Measurement of Lightest Chargino Mass

Mass of lightest chargino very difficult to measure as does not participate in standard dilepton SUSY decay chain

Use decay $\tilde{\chi}^+_1 \rightarrow W^+ \tilde{\chi}^0_1$ with dilepton decay chain on other ‘leg’ of the event

Use kinematics to calculate $M(\tilde{\chi}^+_1)$

Use sideband subtraction technique obtain peak at true $M(\tilde{\chi}^+_1)$ [218 GeV] $\sim 3\sigma$ significance for 100 fb$^{-1}$.

Requires known $\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^+_R, \tilde{\chi}^0_L$ masses
ATLAS SUSY Full Simulation 5fb⁻¹

Modified LHCC Point 5:
\[ m_0 = 100 \text{ GeV}; \]
\[ m_{1/2} = 300 \text{ GeV}; \]
\[ A_0 = 300 \text{ GeV}; \]
\[ \tan \beta = 6; \mu > 0 \]

Reconstructed
560 GeV

Expected
590 GeV

Reconstructed
422 ± 9 GeV

Expected
501 GeV

Reconstructed
100.25 ± 1.14 GeV

Expected
100.31 GeV

Reconstructed
619.6 ± 8.2 GeV

Expected
612 GeV
Special Regions (Focus Point, Coannihilation)

WMAP results severely constrain mSUGRA parameter space

$$\Omega_{\text{CDM}} h^2 = 0.1126^{+0.0161}_{-0.0181}$$

Favoured regions \((m_0,m_{1/2})\) are

Coannihilation region
- sleptons almost degenerate with LSP → slow leptons
- Dilepton studies underway

Focus point region
- Low $\tilde{q}, \tilde{g}$ cross-sections
- High squark, slepton masses

Investigation of these points in progress
ATLAS Studies at Focus Point

Difficult due to very heavy squarks, sleptons, low squark/gluino cross-sections

Neutralino/chargino production abundant but without large jets + missing energy signal ($M_{\text{eff}}$)

Dilepton edge analysis for direct $\tilde{\chi}_n^0 \rightarrow \tilde{\chi}_1^0 ll$ decays. Combination with jets for $\tilde{g}$ mass reconstruction under investigation

Light $g$ reconstruction via three body decay

$$\tilde{g} \rightarrow \tilde{\chi}qq^{(l)}$$

$M(\tilde{g}) - M(\chi_1^{\pm}) = 530 \text{ GeV}$
Summary

If TeV scale SUSY exists, it should be discovered at the LHC.

How well we can measure the model parameters depends how lucky we are (and perhaps how clever)

Most studies so far have use mSUGRA, fast simulation

Studies of mGMSB and mASMB models also underway

Lots of work on using taus (not discussed here)

Lots of interesting kinematic reconstruction techniques

Need more work on fully simulated events (including pileup in the case of analyses relying on high-luminosity running). But results from analysis of fully reconstructed data in line with results from fast simulations.

Need more investigation of focus-point and coannihilation regions

and ........ need to wait until sometime in 2008