SUSY squark flavour studies with ATLAS

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Outline

Introduction
- SUSY mass scale from inclusive searches
- Left-handed squark
- Sbottom and gluino
- Right-handed squark
- Stop

Conclusions
- Most of the ATLAS work since Physics TDR (1999) done on mSUGRA models.
  A particularly extensive study is available for SPS1a point (fast simulation) – it will be used here to illustrate techniques to reconstruct the squark mass spectrum.

  When available for a given signature, recent full simulation results will also be shown (obtained for other mSUGRA points).
In mSUGRA:

- At the Unification scale, all scalars have the same mass.
- At the EW scale:
  - First two generation almost mass degenerate, but $m(\tilde{q}_L) \neq m(\tilde{q}_R)$
  - Large L-R mixing in 3° generation: $\tilde{b}_1, \tilde{b}_2, \tilde{t}_1, \tilde{t}_2$ mass eigenstates
  - Light $\tilde{b}_1$ and $\tilde{t}_1$

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

SPS1a mass spectrum (colored states)

<table>
<thead>
<tr>
<th>$\tilde{g}(611)$</th>
<th>$\tilde{t}_2(583)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{u}_L(559)$</td>
<td>$\tilde{b}_2(539)$</td>
</tr>
<tr>
<td>$\tilde{u}_R(544)$</td>
<td>$\tilde{b}_1(516)$</td>
</tr>
<tr>
<td>$\tilde{t}_1(501)$</td>
<td></td>
</tr>
</tbody>
</table>

SPS1a:
- $m_0 = 100$ GeV,
- $m_{1/2} = 250$ GeV,
- $A_0 = -100$ GeV,
- $\tan(\beta) = 10$, $\mu > 0$
Strongly interacting sparticles (squarks, gluinos) dominate LHC production. Cascade decays to the stable, weakly interacting lightest neutralino follows.

- **Event topology:**
  - high $p_T$ jets (from squark/gluino decay)
    - Large $E_T^{\text{miss}}$ signature (from LSP)
    - High $p_T$ leptons, b-jets, $\tau$-jets (depending on model parameters)

If sbottom or stop quarks in the decay chain: b-jets

Charm tagging impossible?
First hint of the existence of non-SM physics will probably be an excess of events with large missing energy and hard jets.

The peak of the distribution of the effective mass:

$$M_{\text{eff}} = E_{T}^{\text{miss}} + \sum_{\text{jets}} p_{T}^{\text{jet}}$$

if visible above the background, is strongly correlated with the mass of the SUSY particle produced (gluino or squark): first estimate of SUSY mass scale.
Inclusive searches (Full simulation)

- Full simulation data, produced for seven different mSUGRA points, confirms the good correlation between the Effective Mass peak and the SUSY mass scale.

  Stau coannihilation point: \( m_0 = 70 \text{ GeV} \), \( m_{1/2} = 350 \text{ GeV} \), \( A=0 \), \( \tan\beta = 10 \), \( \mu > 0 \)
A detailed study for SPS1a (bulk region of parameter space) was done in fast simulation.

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007

- $\tilde{q}_L$ mass from
  $\tilde{q}_L \rightarrow q \chi^0_2 \rightarrow q l \bar{l} \rightarrow q l l \chi^0_1$

- $\tilde{q}_R$ mass from
  $\tilde{q}_R \rightarrow q \chi^0_1$

- $\tilde{b}, \tilde{g}$ mass from
  $\tilde{g} \rightarrow b\bar{b} \rightarrow b\bar{b} \chi^0_2 \rightarrow b\bar{b} l\bar{l} \rightarrow b\bar{b} l l \chi^0_1$
The decay chain (note the two isolated leptons)
\[ \tilde{q}_L \rightarrow \tilde{\chi}_2 \, q \rightarrow l_R \, l \, q \rightarrow llq \, \tilde{\chi}_1^{0} \]
Allows to measure several **kinematical endpoints**, each providing one mass relation between the SUSY particles.

- 2 SFOS lep., $p_T > 20$, 10 GeV
- $\geq 4$ jets, $p_T > 150, 100, 50, 50$ GeV
- $M_{\text{eff}} > 600$ GeV
- $E_{T\text{miss}} > \max(100, 0.2 \, M_{\text{eff}})$

**SPS1a**

- **100 fb$$^{-1}$$**
- Fast simulation

**Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007**
**Left squark mass fit**

**Fit results (L = 100 fb\(^{-1}\))**

<table>
<thead>
<tr>
<th>Edge</th>
<th>Nominal Value</th>
<th>Fit Value</th>
<th>Syst. Error</th>
<th>Statistical Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m(ll))</td>
<td>77.077</td>
<td>77.024</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>(m(qll))</td>
<td>431.1</td>
<td>431.3</td>
<td>4.3</td>
<td>2.4</td>
</tr>
<tr>
<td>(m(ql))</td>
<td>302.1</td>
<td>300.8</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>(m(qll))</td>
<td>380.3</td>
<td>379.4</td>
<td>3.8</td>
<td>1.8</td>
</tr>
<tr>
<td>(m(qll))</td>
<td>203.0</td>
<td>204.6</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>(m(ll))</td>
<td>183.1</td>
<td>181.1</td>
<td>1.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Precision limited by systematics: error on jet energy scale (1% expected)

**Mass reconstruction**

\[
\chi^2 = \sum \chi_j^2 = \sum_j \left[ \frac{E_j^{\text{theory}}(m) - E_j^{\text{exp}}}{\sigma_j^{\text{exp}}} \right]^2
\]

\[
E_j^i \equiv E_j^{\text{nom}} + a_j^{\text{fit}} + b_j^{E_{\text{scale}}}
\]

\[
\Delta m(\chi_1^0) = 4.8 \text{ GeV, } \quad \Delta m(\chi_2^0) = 4.7 \text{ GeV, } \\
\Delta m(\tilde{l}_R) = 4.8 \text{ GeV, } \quad \Delta m(\tilde{q}_L) = 8.7 \text{ GeV}
\]

Can compare \(qll\) and \(bl\) thresholds, and measure \(m(\tilde{b})-m(\tilde{u}_L)\)

\(m(\chi_1^0) = 96 \text{ GeV} \quad m(\tilde{l}_R) = 143 \text{ GeV} \quad m(\tilde{q}_L) = 540 \text{ GeV} \)
Going up the decay chain

- Once the mass of the $\chi^0_1$ is known, it is possible to get the momentum of the $\chi^0_2$ using the approximate relation

$$ p(\chi^0_2) = \left( 1- \frac{m(\chi^0_1)}{m(ll)} \right) p_{ll} $$

valid for lepton pairs with invariant mass near the edge.

- The $\chi^0_2$ can be combined with b-jets to reconstruct the gluino and sbottom mass peaks:

$$ \tilde{g} \rightarrow b\bar{b} \rightarrow bb\chi^0_2 $$

b-tagging used to separate light and bottom squark decay chains.
Gluino and sbottom reconstruction

Good combinations.
m(\tilde{g}) and m(\tilde{b}) correlated (Dominant error from \tilde{\chi}^0_2 Momentum affects both)

Bad \tilde{\chi}^0_2 b combinations (b-jet is from gluino decay)

Figure 4. Distribution of m(\tilde{\chi}^0_2) versus m(\tilde{\chi}^+_2) for events passing the selections.

For this analysis we assume that both \tilde{\chi}^+_2 and \tilde{\chi}^0_2 would be measured with the technique described in the previous section. As already discussed above, the results in a strong correlation between the measured \tilde{\chi}^0_2 and \tilde{\chi}^+_2 masses which can be parametrized as:

m(%20{\tilde{\chi}}^0_2) = 82.85 \times m(%20{\tilde{\chi}}^+_2)

Therefore, to evaluate the dependence of the measured gluino mass on the assumed \tilde{\chi}^0_2 and \tilde{\chi}^+_2 masses, we varied only the \tilde{\chi}^+_2 mass between 76 and 116 GeV, and the \tilde{\chi}^0_2 mass
Gluino mass reconstruction

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb$^{-1}$

$\langle m(\chi_{bb}) \rangle = (500.0 \pm 6.4) \text{ GeV}$ with 300 fb$^{-1}$

Error is statistical plus (dominant) 1% uncertainty on jet energy scale
Central value 10 GeV lower than nominal because no dedicated calibration for b-jet energy scale used in this (fast sim) study

m(g)-0.99m($\chi^0_1$) = (500.0 ± 6.4) GeV with 300 fb$^{-1}$

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb$^{-1}$

$\langle m(\chi_{bb}) \rangle$ (GeV)

$\langle M(\chi_{bb}) \rangle$ (GeV)

$\langle M(LSP) \rangle$ (GeV)

Figure 5: $\langle m(\chi_{bb}) \rangle$ after all cuts. The residual SUSY background is shown in blue. Superimposed is a gaussian fit. The distribution is shown for an integrated statistics of 300 fb$^{-1}$.

Figure 6: Estimated $\langle m(\chi_{bb}) \rangle$ as a function of the $m(\chi^0_1)$ assumed as input of the fit.
sbottom mass

ATLAS fast simulation
ATL-PHYS-2004-007
300 fb$^{-1}$

\[ m(\chi^{bb}) - m(\chi^{b}) \text{ (GeV)} \]

With 300 fb$^{-1}$ it should be possible to separate the $\tilde{b}_1$ and $\tilde{b}_2$ peaks

\[ m(\tilde{g}) - m(\tilde{b}_1) = (103.3 \pm 1.8) \text{ GeV} \]
\[ m(\tilde{g}) - m(\tilde{b}_2) = (70.6 \pm 2.6) \text{ GeV} \]

With lower statistics only measure the average squark flavour studies with ATLAS
Right-handed squark

\( \tilde{q}_R \) does not couple to Wino
\( \chi^0_1 \) is nearly a Bino
\( \chi^0_2 \) is nearly a Wino

\( \tilde{q}_R \tilde{q}_R \) production: two high p\(_T\) jets and missing energy

The different decay chains allow separation from q\(_L\)
(veto additional jets and b-tagged jets)

Combine the transverse momentum of two leading jets with missing transverse momentum as follows:

\[
M^2_{T2} = \min_{p_T^1 + p_T^2 = \not{p}_T} \left[ \max \left\{ m^2_T(p_T^1, \not{p}_1), m^2_T(p_T^2, \not{p}_2) \right\} \right]
\]

\( m(\tilde{q}_R) - m(\chi^0_1) = (424.2 \pm 10.9)\text{ GeV} \)

ATLAS fast simulation
ATL-PHYS-2004-007
SPS1a 30 fb\(^{-1}\)
The following masses would be measured by ATLAS for SPS1a:

\[ m(\tilde{\chi}_R^0) - m(\chi^0_1) = (424.2 \pm 10.9) \text{ GeV} \quad 30 \text{ fb}^{-1} \]
\[ m(\tilde{\chi}_L^0) = (444.0 \pm 4.9) \text{ GeV} \quad 300 \text{ fb}^{-1} \]
\[ m(\tilde{\chi}^0) - m(\chi^0_1) = (500.0 \pm 6.4) \text{ GeV} \quad 300 \text{ fb}^{-1} \]
\[ m(\tilde{\chi}^0) - m(\tilde{b}_1) = (103.3 \pm 1.8) \text{ GeV} \quad 300 \text{ fb}^{-1} \]
\[ m(\tilde{\chi}^0) - m(\tilde{b}_2) = (70.6 \pm 2.6) \text{ GeV} \quad 300 \text{ fb}^{-1} \]

After a few years at LHC design luminosity, precision would be limited by systematic error on jet energy scale.

The analysis works in a large fraction of parameter space (when relevant decay chains exist) but results depend on specific point.
Stop edges

\[ \tilde{g} \rightarrow t\tilde{t}_1 \rightarrow tb\chi^\pm_1 \text{ or } \tilde{g} \rightarrow b\tilde{b} \rightarrow bt \chi^\pm_1 \]

tb invariant mass has a maximum function of the masses of \( \tilde{g}, \tilde{b}(\text{or} \tilde{t}) \) and \( \chi^\pm_1 \). Two closely spaced edges from the two decays: can measure a weighed average.

**Selections:**
- total jet energy and missing energy
- 2 b-jets
- lepton veto
- 4 to 6 non-b jets

**Reconstruction:**
- \( m(jj) \) close to \( m(W) \)
- \( m(jjb) \) close to \( m(t) \)
- W-sidebands to estimate and subtract combinatorial background

\[
\text{Fit of } m_{tb} \text{ distribution}
\]
- Ideal distribution: \( dT/dm_{tb} \propto m_{tb} \).
- Fit function: a smeared distribution
  \[
  f(m_{tb}) = \frac{h}{M_{fit}^2} \int_{m_{tb} - \Delta m_{tb}}^{m_{tb} + \Delta m_{tb}} \frac{m}{\sqrt{2\pi} \sigma} e^{-\frac{1}{2} \left( \frac{m - m_{tb}}{\sigma} \right)^2} \, dm
  \]
  on a linear background.
- We obtain the end point \( M_{fit}^2 \) and the edge height \( h \) from the fit.

See J. Hisano et al., Phys. Rev. D68, 035007 for details
On a significant fraction of mSUGRA parameter space, the LHC would be able to measure the mass of $q_R, q_L, b_1, b_2$

Many measurements studied also with Full Simulation data for a variety of points – they confirm that fast simulation results are realistic.

A model-independent measurement of the stop mass is more challenging (but kinematical decays related to stop decays would be observed for most parameter values)

Measurement of mixing angles needs more study
CPV, FV, mixing and non-degenerate masses in first two generations also poorly covered
- availability in HERWIG/PYTHIA/ISAJET?
- criteria to choose parameters? flavour benchmarks?