SUSY (s)lepton flavour studies with ATLAS

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Flavour in the era of the LHC, 7-10 November, CERN
Outline

• mSUGRA
• Sleptons
• Fast simulation studies
• Full simulation studies
• Spin measurement
• Slepton non-universality
mSUGRA

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

R-parity is conserved:
At the end of every SUSY decay chain is LSP, no mass peaks, no direct mass measurement

Techniques for mass measurement:
- kinematic endpoints
- stransverse mass
Sleptons

**Production:**

indirectly: from decays of heavier gauginos

\[ \tilde{\chi}_2^0 \rightarrow \tilde{l}_{R,L} l \]

directly: \( \tilde{l}_L l_L, \tilde{l}_R l_R \) (small cross sections)

**Decays:** to kinematically open gauginos

\[ \tilde{l}_R \rightarrow l \tilde{\chi}_1^0 \]
\[ \tilde{l}_L \rightarrow l \tilde{\chi}_1^0, l \tilde{\chi}_2^0, \nu \tilde{\chi}_1^\pm \]
Mixings, masses

• At the unification scale SUSY scalars are mass degenerate. At the EW scale: $m(\tilde{f}_L) > m(\tilde{f}_R)$

• L/R mixing is proportional to fermion masses, and can be neglected for selectrons, smuons. In the stau case, L/R stau mixing is significant. Mass eigenstates are: $\tilde{\tau}_1$, $\tilde{\tau}_2$. $\tilde{\tau}_1$ is the lightest slepton.
Fast simulation studies
SPS1a (bulk region)
\[ m_0 = 100 \text{ GeV}, \]
\[ m_{1/2} = 250 \text{ GeV}, \]
\[ A_0 = -100 \text{ GeV}, \]
\[ \tan(\beta) = 10, \mu > 0 \]

\[ \tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}_R^- l q \rightarrow llq \tilde{\chi}_1^0 \]

Left squark cascade decay

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

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007
**Fit results**

<table>
<thead>
<tr>
<th>Edge</th>
<th>Nominal Value</th>
<th>Fit Value</th>
<th>Syst. Error Energy Scale</th>
<th>Statistical Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(\ell\ell)_{\text{edge}}$</td>
<td>77.077</td>
<td>77.024</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>$m(q\ell\ell)_{\text{edge}}$</td>
<td>431.1</td>
<td>431.3</td>
<td>4.3</td>
<td>2.4</td>
</tr>
<tr>
<td>$m(q\ell)_{\text{min}}$</td>
<td>302.1</td>
<td>300.8</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>$m(q\ell)_{\text{edge}}$</td>
<td>380.3</td>
<td>379.4</td>
<td>3.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$m(q\ell\ell)_{\text{thres}}$</td>
<td>203.0</td>
<td>204.6</td>
<td>2.0</td>
<td>2.8</td>
</tr>
</tbody>
</table>

5 endpoints measurements, 4 unknown masses

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

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

\[
m(\chi_1^0) = 96 \text{ GeV} \quad \Delta m(\chi_1^0) = 4.8 \text{ GeV} \quad \Delta m(\chi_2^0) = 4.7 \text{ GeV},
\]

\[
m(l_R) = 143 \text{ GeV} \quad \Delta m(l_R) = 4.8 \text{ GeV} \quad \Delta m(q_L) = 8.7 \text{ GeV}.
\]

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007
Direct slepton production

\[ \tilde{l}_R \tilde{l}_R, \tilde{l}_L \tilde{l}_L \rightarrow l^+ l^- + E_T^{miss} \]

Signature: 2 SFOS leptons + missing transverse energy

It is possible to estimate slepton mass by using stransverse mass:

\[ M_{T2} = \min_{E_T^{miss}=E_{T1}^{miss}+E_{T2}^{miss}} \left\{ \max \left\{ m_T^2(p_{T1}^{l1}, E_{T1}^{miss}), m_T^2(p_{T2}^{l2}, E_{T2}^{miss}) \right\} \right\} \]


Endpoint of the stransverse mass is function of the mass difference between slepton and LSP

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007
Example: SPS1a

\[ M(\tilde{\chi}_1^0) = 96 \text{ GeV}, \ M(\tilde{l}_R) = 143 \text{ GeV}, \ M(\tilde{l}_L) = 202 \text{ GeV} \]

**Stransverse mass** \( M_{T2} \)

**Left slepton mass**

Create a data sample from signal and background events

compare shape of result to a set of signal distrib. for different \( l_L \) masses

pick fit with lowest \( \chi^2 \) as the mass

\( \tilde{l}_L \) can be estimated to 3-4 GeV

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007
Full simulation studies
Data Challenges for Rome Physics Workshop

Preliminary results of new full simulated data for set of mSUGRA points chosen according to recent experimental data. Full simulation SM background data are currently produced and studied.

DC1 bulk region point - SU3
\[ m_0 = 100 \text{ GeV}, \ m_{1/2} = 300 \text{ GeV}, \ A_0 = -300 \text{ GeV}, \ \tan\beta = 6, \ \text{sgn}(\mu) = + \]

Coannihilation point – SU1
\[ m_0 = 70 \text{ GeV}, \ m_{1/2} = 350 \text{ GeV}, \ A_0 = 0 \text{ GeV}, \ \tan\beta = 10, \ \text{sgn}(\mu) = + \]

Focus point – SU2
\[ m_0 = 3350 \text{ GeV}, \ m_{1/2} = 300 \text{ GeV}, \ A_0 = 0 \text{ GeV}, \ \tan\beta = 10, \ \text{sgn}(\mu) = + \]
SU3 dileptons

Selected events with two OS leptons.

\[(e^+e^-) + \beta^2(\eta) (\mu+\mu-) - \beta(\eta) (e+\mu-)\]

\[
\begin{array}{|c|c|}
\hline
\chi^2/ndf & 98.98 / 90 \\
p0 & 294.7 \pm 91.7 \\
p1 & 100.3 \pm 0.4 \\
p2 & 1.521 \pm 0.472 \\
\hline
\end{array}
\]

Edge = \(100.3 \pm 0.4\) GeV

Edge after cuts: \(99.8 \pm 1.2\) GeV

Fit with a triangular distribution with gaussian smearing. Edge in good agreement with true value 100.31 GeV

SM Background expected to be negligible after cuts. However, SUSY statistic also reduced. Study of SM background and optimization of cuts generally still under way
**SU3: leptons+jets**

Leptons combined with two jets with highest $P_T$

Flavour subtraction & efficiency correction applied

- **Smaller of $M(llq)$**
  - $M_{llq}^{\text{max}} = 501$ GeV

- **Larger of $M(llq)$**
  - $M_{llq}^{\text{min}} = 271$ GeV

4.20 fb^{-1}

$2j100+2l10$

[Graphs showing distributions of $m_{llq}$]
Each s-lepton is close in mass to one of the neutralinos – **one of the leptons is soft**

- Selection: $e^+e^-$ or $\mu^+\mu^-$ pair

\[ q_L \rightarrow \tilde{\chi}_2^0 \, q \rightarrow l_{L,R} \, l \, q \rightarrow llq \, \tilde{\chi}_1^0 \]

\[ 264 \quad 255, \; 154 \quad 137 \]

\[ \mu \quad -e \quad \mu \mu \quad ee + \]

- **MC Truth, $l_R$**
- **MC Truth, $l_L$**
- **MC Data**

\[ 20.6 \, fb^{-1}, \; full \; sim \]

\[ ee+\mu\mu-e\mu \]

\[ 20.6 \, fb^{-1} \]

\[ \text{MC Truth, } l_R \]

\[ \text{MC Truth, } l_L \]

\[ \text{MC Data} \]

\[ 20.6 \, fb^{-1} \]

\[ \text{MC Truth, } l_R \]

\[ \text{MC Truth, } l_L \]

\[ \text{MC Data} \]

\[ 20.6 \, fb^{-1} \]
**SU2**

\[ \tilde{\chi}^0_3, \tilde{\chi}^0_2 \rightarrow l l \tilde{\chi}^0_1 \]

Focus-Point

Heavy scalars: no scalar lepton in $\chi$ decay

\[ \Delta m = m(\chi_n^0) - m(\chi_1^0) = 57, 76 \text{ GeV} \]

Dilepton mass 6.9 fb\(^{-1}\)

Cuts to reject SM: 2j100+4j50+xE100

With only 6.9 fb\(^{-1}\) of data we begin to see the edge structure emerge. More statistic needed for fit.
Tau signatures

- Taus provide independent information on SUSY model even if lepton signatures are available.
- Tau ID is much harder than electron or muon ID, particularly for soft taus (e.g. co-annihilation point).
- Need to focus on hadronic decays since the LHC vertex detectors cannot cleanly identify $\tau \to l\nu\nu$.
- Looked at ditau invariant mass distributions from decay:
  \[ \tilde{\chi}_2^0 \to \tilde{\tau}_1^\pm \tilde{\tau}^\mp \to \tau^\pm \tau^\mp \tilde{\chi}_1^0 \]
- Triangular ditau mass shape is distorted due to missing energy from neutrinos. Available statistics are much lower due to tau reconstruction efficiency.
Events with 2 OS tau leptons

• Use MC fit and apply it to the background subtracted distribution using the endpoint and normalisation as parameters.

• It gives good description of the endpoint

One of the taus produced in the squark cascade decay chain is very soft
⇒ Limited statistics

• One possible solution is to combine the hard $\tau$ ($E_T > 40$ GeV) with any track having $p_T > 6$ GeV and no other track with $p_T > 1$ GeV in $R < 0.4$. Signal is clear, but need more statistic for fit.
Spin measurement, slepton non-universality
Due to neutralino spin $1/2$, angular distribution of slepton is not spherically symmetric, invariant mass $M(q\tilde{l}^{\text{near}})$ is charge asymmetric.

Example

Parton distributions

\[ M(ql_{\text{near}}) \]

\[ M(ql_{\text{far}}) \]

\[ M(ql) \]

\[ A.J. \ Barr, \ Phys. \ Lett. \ B596 \ (2004) \ 205 \]

\[ l_{\text{near}} \text{ and } l_{\text{far}} \text{ are experimentally indistinguishable. Instead, study of } M(l^{-}q) \text{ and } M(l^{+}q) \text{ distributions. Each distribution contain contribution from both near and far lepton and contribution from both quark and antiquark. Quark and antiquarks have opposite asymmetries and are experimentally indistinguishable. LHC is } pp \text{ collider } \rightarrow \text{ more quarks then antiquarks will be produced.} \]
Asymmetry

\[ A = \frac{s^+ - s^-}{s^+ + s^-} \]

\[ s^\pm = \frac{d\sigma}{d(m_{l\pm q})} \]

Asymmetry is negative for low values of \( M(lq) \) and positive for large values. This is consistent with spin \( \frac{1}{2} \) neutralino and spin 0 slepton.


SPS1a Non-zero \( M(lq) \) asymmetry may be observed with \( 30 \text{fb}^{-1} \) (Goto, Kawagoe, Nojiri, PRD 70, 075016)
Decay of neutralino to both left and right slepton is open. Decays of second neutralino to left and right slepton have opposite sign asymmetries.

\[ \tilde{\chi}_2^0 \rightarrow \tilde{l}_R l, \tilde{l}_L l \]

\( l = e, \mu \)

M(ql)_{\text{near}} \leftrightarrow 209 \text{ GeV}

M(ql)_{\text{near}} \leftrightarrow 620 \text{ GeV}

Asymmetry is negative near smaller M(ql) endpoint. Negative asymmetry may still be seen with L=300 fb\(^{-1}\).

Goto, Kawagoe, Nojiri, PRD 70, 075016 (hep-ph/0406317)
L-R slepton mixing

Left/right slepton mixing affect
- the charge asymmetry
- \( \tilde{\chi}_2^0 \rightarrow \tilde{l}_l \tilde{l}_l \) decay width for \( l=\mu, \tau \)

SELECTRONS: L-R mixing negligible, maximal asymmetry

SMUONS: asymmetry smaller than in selectron case
if L-R mixing is observable.

STAUS: L-R mixing significant,
asymmetry opposite to selectron case

\[ \Gamma(\tilde{\chi}_2^0 \rightarrow \tau\tilde{\tau}_1) > \Gamma(\tilde{\chi}_2^0 \rightarrow \mu\tilde{\mu}_1) > \Gamma(\tilde{\chi}_2^0 \rightarrow e\tilde{e}_1) \]

In order to get small systematic error on endpoints and BR
need to understand: lepton efficiency and acceptance,
lepton energy scale
# Example

Calculated ratio of asymmetries and widths

<table>
<thead>
<tr>
<th></th>
<th>( A(e):A(\mu):A(\tau) )</th>
<th>( \Gamma(e): \Gamma(\mu): \Gamma(\tau) )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPS1a</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tan(\beta)=10 )</td>
<td>1 : 0.93 : -0.84</td>
<td>1 : 1.04 : 13.7</td>
</tr>
<tr>
<td>( \tan(\beta)=15 )</td>
<td>1 : 0.83 : -0.95</td>
<td>1 : 1.09 : 37.6</td>
</tr>
<tr>
<td>( \tan(\beta)=20 )</td>
<td>1 : 0.70 : -0.99</td>
<td>1 : 1.17 : 80.2</td>
</tr>
</tbody>
</table>

With larger \( \tan(\beta) \), stronger L-R mixing.

**Needed tools:** L-R mixing in 1st two generations (available in SPHENO, but not in ISAJET/HERWIG/PYTHIA)

Goto, Kawagoe, Nojiri, PRD 70, 075016 (hep-ph/0406317)
Detectability of selectron/smuon non-universality

- Statistical significance of the non-universal effect between selectron and smuon for large $\tan(\beta)$ is investigated at point SPS1a with modified $\tan(\beta)$.
- With larger $\tan(\beta)$, L-R mixing is larger, but $\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{l}_R^0 l)$ for $l=e, \mu$, is more suppressed.
- Non-universal asymmetry is too small effect.
- Non-universal BRs are more sensitive and with $300\text{fb}^{-1}$ can see an effect of selectron/smuon non-universality.

One may test non-universality by comparing: $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ endpoints which can be measured with $0.1\text{GeV}$ precision.

Goto, Kawagoe, Nojiri, PRD 70, 075016 (hep-ph/0406317)
Conclusions

**Fast simulation** studies shows that by using kinematic endpoint technique and transverse mass SUSY masses can be reconstructed.

**Preliminary full simulation results** shows that large number of mass relations can be measured for leptonic and tau signatures with few fb$^{-1}$ of data in different mSUGRA regions. To be studied more carefully: acceptance, callibration, trigger, SM background, fit to distributions.

Measurement of charge asymmetry in left squark decay are consistent with neutralino spin $\frac{1}{2}$ and slepton spin 0.

Non-universal BR for selectron and smuon can be observed at ATLAS.