Neutralino spin measurement with ATLAS

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on behalf of the ATLAS Collaboration

Flavour in the era of the LHC, 4th meeting – CERN, 9 Oct 2006
Contents

- Spin measurement
- SU1 and SU3 points: kinematics
- Event selection
- Study of background
- Charge asymmetries
- Diluting effects on asymmetry
- Summary and conclusions
Spin measurement

- **Left squark cascade decay**
  \[
  \tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow q \tilde{l}_{L,R}^\mp l^\pm \rightarrow q l^\pm l^\mp \tilde{\chi}_1^0
  \]
  Only electrons and muons considered, from \( \tilde{l} = \tilde{e}, \tilde{\mu} \)

If neutralino spin is \( \frac{1}{2} \), angular distribution of slepton is not spherically symmetric, therefore invariant mass \( m(ql^\pm) \) is charge asymmetric:

\[
A_{ql} = \frac{s^+ - s^-}{s^+ + s^-} \quad s^\pm = \frac{d\sigma}{d(m_{ql^\pm})}
\]

- Studies for LHCC5 point by A. J. Barr
Event topology

- In mSUGRA events, strongly interacting sparticles ($\tilde{q}, \tilde{g}$) dominate LHC production.
- Cascade decays to the stable, weakly interacting lightest neutralino (Lightest Supersymmetric Particle) follow, e.g., left squark cascade decay.

- **Typical final state signature:**
  - Large $E_T^{\text{miss}}$ (from LSP)
  - High $p_T$ jets (from squark/gluino decay)
  - Two same-flavour opposite-sign (SFOS) leptons

- Charge asymmetry $A_{ql}$ is suppressed by $q/\bar{q}$ cancelation (anyway at the LHC much more squarks than antisquarks are expected).
- Asymmetry can be also diluted by the experimental impossibility to distinguish near from far lepton.
mSUGRA points considered

- **Point SU1** – stau coannihilation point
  \[ m_0 = 70 \text{ GeV}, \ m_{1/2} = 350 \text{ GeV}, \ A_0 = 0 \text{ GeV} \]
  \[ \tan(\beta) = 10, \ \text{sign}(\mu) = + \]
  \[ \sigma_{LO} = 7.8 \text{ pb} \] (100 fb\(^{-1}\) analysed sample)

- **Point SU3** – bulk region point
  \[ m_0 = 100 \text{ GeV}, \ m_{1/2} = 300 \text{ GeV}, \ A_0 = -300 \text{ GeV} \]
  \[ \tan(\beta) = 6, \ \text{sign}(\mu) = + \]
  \[ \sigma_{LO} = 19.5 \text{ pb} \] (30 fb\(^{-1}\) analysed sample)

ATLAS official Fast Simulation samples + dedicated production in Napoli ATLAS-Tier2
SU1 point kinematics

- Both $\tilde{\chi}_2^0 \rightarrow \tilde{l}_L^\pm l^\mp$ and $\tilde{\chi}_2^0 \rightarrow \tilde{l}_R^\pm l^\mp$ decays are allowed in SU1 (masses are: $m_{\tilde{\chi}_2^0} = 264 \text{ GeV}$, $m_{\tilde{l}_L} = 255 \text{ GeV}$, $m_{\tilde{l}_R} = 154 \text{ GeV}$)

$$\tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow q \tilde{l}_L^0 \rightarrow ql^\pm l^\mp + \tilde{\chi}_1^0$$

$$\tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow q \tilde{l}_R^0 \rightarrow ql^\pm l^\mp + \tilde{\chi}_1^0$$

- Two edges in the dilepton mass (for Left/Right slepton chains)

$$m(ll)_{\text{max}} = \left[ \frac{(m_{\tilde{l}_L}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_L}^2 - m_{\tilde{\chi}_1}^2)}{m_{\tilde{l}_L}^2} \right]^{1/2}$$

- After Left/Right slepton decay chain identification, near and far leptons are distinguishable with high probability from their momenta.
SU3 point kinematics

- Only the right slepton decay $\tilde{\chi}_2^0 \rightarrow \tilde{l}_R^\pm l^\mp$ is allowed in SU3 (masses are: $m_{\tilde{\chi}_2^0} = 219$ GeV, $m_{\tilde{l}_L} = 230$ GeV, $m_{\tilde{l}_R} = 155$ GeV)

$$\tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow q \tilde{l}_R (l^\pm) \rightarrow ql^\pm l^\mp + \tilde{\chi}_1^0$$

- One edge in the dilepton mass (for Right slepton chain).

- Here near and far leptons are undistinguishable.

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In SU1, the **Left Near** scenario looks to be the most promising:
- Charge asymmetry is the most enhanced.
- No significant contamination from $Z$, asking $m(\ell\ell) < m(\ell\ell)^L_{\text{max}}$

Only this case has been considered from now on.
Even if near and far leptons are not distinguishable, in SU3 point charge asymmetry is more pronounced than in SU1, owing to the larger cross section and to the higher branching ratios of decays involved in the left squark cascade decay.

\[ m(\ell l^\pm) \text{ asymmetry for MC truth signal} \]

SU3

\[ L = 30 \text{ fb}^{-1} \]

generated sample

\[ \tilde{l}_R, \ell_{\text{near}} + \ell_{\text{far}} \]

\[ m(\ell l)_{\text{max}} = \sim 400 \text{ GeV} \]
Event selection

- $E_T^{\text{miss}} > 100$ GeV
- At least 4 jets
  - $p_T(j_1) > 100$ GeV,
  - $p_T(j_i) > 50$ GeV, $i=2,3,4$
- Two SFOS leptons
  - $p_T(l) > 6$ GeV (for SU1), 10 GeV (for SU3)
  - $|\eta| < 2.5$, $E_T^{\text{isol}} < 10$ GeV in $\Delta R < 0.2$
- $m(ll) < 100$ GeV
- $m(jll) < 615$ GeV (for SU1) < 500 GeV (for SU3)

In SU1, the decay chain with Left/Right slepton is selected according to dilepton mass:
Near/Far leptons are discriminated by their $p_T$

Preselection cuts
- Mostly against Standard Model

Lepton selection
- Cuts on single isolated leptons

Analysis cuts
- Based on model kinematics, to be applied after observing invariant mass endpoints

Left : $m(ll) < 57$ GeV
Right : 57 GeV < $m(ll)$ < 100 GeV
Reconstructed invariant masses

- Simulated (fast) SM processes:
  - $t\bar{t} + \text{jets}$
  - $W + \text{jets}$
  - $Z + \text{jets}$

- The first two energetic jets in the event are used to form $m(jll)$: no significant effect on $A_{q\ell}$ due to wrong jet.

- Events with two opposite-flavour opposite-sign (OFOS) leptons are kept and statistically subtracted to SFOS events to cancel background from uncorrelated lepton pairs: $\mu^+ \mu^- + e^+ e^- - \mu^\pm e^\mp$
### Efficiencies and contaminations

**Before OFOS subtraction**

<table>
<thead>
<tr>
<th></th>
<th>Efficiency (SU1)</th>
<th>S/B</th>
<th>Efficiency (SU3)</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>(17.0 ± 0.3)%</td>
<td>/</td>
<td>(20.0 ± 0.3)%</td>
<td>/</td>
</tr>
<tr>
<td>SUSY Background</td>
<td>(0.94 ± 0.01)%</td>
<td>0.33</td>
<td>(0.75 ± 0.01)%</td>
<td>1</td>
</tr>
<tr>
<td>$tt + 0$ jets ($lvqq$)</td>
<td>$(1.3 ± 0.3) \times 10^{-6}$</td>
<td>$\sim 80$</td>
<td>$(4 ± 1) \times 10^{-7}$</td>
<td>$\sim 1500$</td>
</tr>
<tr>
<td>$tt + 1$ jets ($lvqq$)</td>
<td>$(2.9 ± 0.2) \times 10^{-5}$</td>
<td>6.3</td>
<td>$(1.2 ± 0.1) \times 10^{-5}$</td>
<td>90</td>
</tr>
<tr>
<td>$tt + 2$ jets ($lvqq$)</td>
<td>$(1.3 ± 0.1) \times 10^{-4}$</td>
<td>3.5</td>
<td>$(5.9 ± 0.4) \times 10^{-5}$</td>
<td>45</td>
</tr>
<tr>
<td>$tt + \geq 3$ jets ($lvqq$)</td>
<td>$(5.3 ± 0.2) \times 10^{-4}$</td>
<td>2.6</td>
<td>$(2.3 ± 0.1) \times 10^{-4}$</td>
<td>37</td>
</tr>
<tr>
<td>$tt + 0$ jets ($l\ell\nu$)</td>
<td>$(1.9 ± 0.4) \times 10^{-6}$</td>
<td>$\sim 200$</td>
<td>$(3.0 ± 0.5) \times 10^{-6}$</td>
<td>$\sim 1000$</td>
</tr>
<tr>
<td>$tt + 1$ jets ($l\ell\nu$)</td>
<td>$(1.5 ± 0.1) \times 10^{-4}$</td>
<td>4.8</td>
<td>$(2.2 ± 0.1) \times 10^{-4}$</td>
<td>20</td>
</tr>
<tr>
<td>$tt + 2$ jets ($l\ell\nu$)</td>
<td>$(2.93 ± 0.04) \times 10^{-3}$</td>
<td>0.64</td>
<td>$(3.89 ± 0.05) \times 10^{-3}$</td>
<td>2.9</td>
</tr>
<tr>
<td>$tt + \geq 3$ jets ($l\ell\nu$)</td>
<td>$(1.65 ± 0.02)%$</td>
<td>0.34</td>
<td>$(2.10 ± 0.02)%$</td>
<td>1.6</td>
</tr>
<tr>
<td>$W + 4$ jets ($l\ell\nu$)</td>
<td>$(1 ± 1) \times 10^{-5}$</td>
<td>24</td>
<td>$(2 ± 2) \times 10^{-6}$</td>
<td>$\sim 1000$</td>
</tr>
<tr>
<td>$W + \geq 5$ jets ($l\ell\nu$)</td>
<td>$(2 ± 2) \times 10^{-5}$</td>
<td>50</td>
<td>$(1 ± 1) \times 10^{-5}$</td>
<td>$\sim 500$</td>
</tr>
<tr>
<td>$Z + 3$ jets</td>
<td>$(3.1 ± 0.4) \times 10^{-5}$</td>
<td>$\sim 500$</td>
<td>$(3.1 ± 0.4) \times 10^{-5}$</td>
<td>$\sim 2000$</td>
</tr>
<tr>
<td>$Z + 4$ jets</td>
<td>$(2.0 ± 0.1) \times 10^{-3}$</td>
<td>27</td>
<td>$(1.7 ± 0.1) \times 10^{-3}$</td>
<td>$\sim 200$</td>
</tr>
<tr>
<td>$Z + \geq 5$ jets</td>
<td>$(7.0 ± 0.2) \times 10^{-3}$</td>
<td>24</td>
<td>$(5.6 ± 0.2) \times 10^{-3}$</td>
<td>$\sim 200$</td>
</tr>
</tbody>
</table>

**After OFOS subtraction**:

- Most of irreducible background comes from **SUSY** (e.g.: correlated leptons from direct/indirect $\chi^0_2$ production), with S/B $> 1$ (for SU1)
- **SM** background from ttbar/W+jets becomes compatible with 0. Small Z+jets fraction survives.
After event selection and OFOS subtraction, reconstructed $m(jl^\pm)$ and
$m(jl^-)$ are taken bin-by-bin to get asymmetry: \[ A_{ql,i} = \frac{m_i(jl^+) - m_i(jl^-)}{m_i(jl^+) + m_i(jl^-)} \]

Suitable binning to get a compromise between:
- good granularity in $m(jl)$,
- proper statistical treatment of asymmetry and errors.

$m(jl)$ ranges fixed according to endpoints and expected resolutions:
\[ [0,220] \text{ GeV (for SU1)} \] and \[ [0,420] \text{ GeV (for SU3)} \]
Evaluation of $m(jl^\pm)$ asymmetry

- Two statistical methods are used to detect a non-zero charge asymmetry:
  - a non-parametric $\chi^2$ test to a zero constant (= hypothesis of symmetry),
  - the Run Test method, based on the number of observed (vs. expected) fluctuations of bin contents with respect to zero.

- The two methods provide independent confidence levels: $CL_{\chi^2}$ and $CL_{RT}$, which can be combined to get $CL_{comb}$.

- Low confidence level $\Rightarrow$ good evidence of a non-zero asymmetry.

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Diluting effects on $m(jl^\pm)$ asymmetry

a) **SUSY** SFOS background contribution
b) **SUSY** OFOS contribution
c) **SM** SFOS and OFOS contributions
d) Selection of **wrong jet** in $m(jl^\pm)$

Although not definitively suppressed in the final selection, all of these **background** contributions to $A_{q_1}$ are proved to have a **flat** behaviour vs. $m(jl^\pm)$ and not to spoil **significantly** the contribution given by **signal** events.
SUSY background asymmetry

No relevant impact on the final $A_{q1}$ asymmetry can be observed.
**SM background asymmetry**

- Both **SFOS** and **OFOS** SM selected lepton pairs show reasonably flat charge asymmetries with high CL$_{\text{comb}}$ compared to SUSY (signal+background) events.

- This is tested on both m(jl) ranges used for SU1 and SU3.

- Similar results varying bin-width and range values.
In both SU1 and SU3 points, SFOS events with a wrongly selected jet (wrt the signal quark) provide no significant \(m(jl^\pm)\) asymmetry.

Selecting the two highest \(p_T\) jets in the event systematically brings to retain (at least) one wrong jet: this is an acceptable compromise for keeping the largest possible signal yield without spoiling asymmetry.
Confidence level vs. luminosity

- Results have been obtained for different integrated luminosities.
  - In SU1 point at least 100 fb$^{-1}$ are needed to observe some non-zero charge asymmetry (e.g. with CL$_{\text{comb}} < 1\%$).
  - For the case of SU3 point, 5÷10 fb$^{-1}$ could be already enough.
Summary and conclusions

- If SUSY will be discovered at LHC, measuring properties of new particles (e.g. spin) is needed for demonstrating that they are indeed the predicted super-partners.
- The method used here on two selected mSUGRA points shows that $m(ql^\pm)$ charge asymmetry is detectable with few fb$^{-1}$ (in SU3) or at least 100 fb$^{-1}$ (in SU1).
- The study must be also performed with more realistic (full) ATLAS simulation and for other SUSY points.
- New techniques to detect charge asymmetry and reduce diluting effects (background, systematics, etc.) are under investigation.
Backup slides
Branching ratios & mass endpoints

**Point SU1**

\[ \sigma(\bar{q}_R \bar{g}) = 1.757 \text{ pb}, \quad \sigma(\bar{q}_L \bar{g}) = 1.620 \text{ pb}, \]
\[ \sigma(\bar{q}_L \bar{q}_R) = 0.885 \text{ pb}, \quad \sigma(\bar{q}_L \bar{q}_L) = 0.665 \text{ pb}, \]
\[ \sigma(\bar{g} \bar{g}) = 0.554 \text{ pb}, \quad \sigma(\bar{q}_L \tilde{\chi}^0) = 0.154 \text{ pb}. \]

- \[ BR(\bar{q}_L \rightarrow q\tilde{\chi}^0_2) = 31.5 \%, \quad BR(\tilde{\chi}^0_2 \rightarrow \tilde{l}_L l) = 6 \%, \]
- \[ BR(\tilde{\chi}^0_2 \rightarrow \tilde{l}_R l) = 3 \%, \quad BR(\tilde{l}_L \rightarrow \tilde{\chi}^0_1 l) = 100 \%. \]

**Point SU3**

\[ \sigma(\bar{q}_R \bar{g}) = 4.469 \text{ pb}, \quad \sigma(\bar{q}_L \bar{g}) = 4.426 \text{ pb}, \]
\[ \sigma(\bar{q}_L \bar{q}_R) = 2.085 \text{ pb}, \quad \sigma(\bar{q}_L \bar{q}_L) = 1.716 \text{ pb}, \]
\[ \sigma(\bar{g} \bar{g}) = 1.544 \text{ pb}, \quad \sigma(\bar{q}_L \tilde{\chi}^0_2) = 0.203 \text{ pb}. \]

- \[ BR(\bar{q}_L \rightarrow q\tilde{\chi}^0_2) = 32 \%, \quad BR(\tilde{\chi}^0_2 \rightarrow \tilde{l}_R l) = 17.6 \%, \]
- \[ BR(\tilde{\chi}^0_2 \rightarrow \tilde{l}_L \rightarrow \tilde{\chi}^0_1 l) = 100 \%. \]

\[ m(l\bar{l})_{\text{max}} = \left[ \frac{(M_{\tilde{\chi}^0_2}^2 - M_{\tilde{l}_R}^2)(M_{\tilde{l}_L}^2 - M_{\tilde{\chi}^0_1}^2)}{M_{\tilde{l}_L}^2} \right]^{1/2} = 56.05 \text{ GeV (left)}, \quad 97.93 \text{ GeV (right)}, \]

\[ m(q\bar{l})_{\text{max}} = \left[ \frac{(M_{\tilde{\chi}^0_2}^2 - M_{\tilde{l}_L}^2)(M_{\tilde{\chi}^0_1}^2 - M_{\tilde{l}_R}^2)}{M_{\tilde{\chi}^0_1}^2} \right]^{1/2} = 611.64 \text{ GeV (left, right)}, \]

\[ m(q\bar{l})_{\text{near}} = \left[ \frac{(M_{\tilde{\chi}^0_2}^2 - M_{\tilde{l}_L}^2)(M_{\tilde{\chi}^0_1}^2 - M_{\tilde{l}_R}^2)}{M_{\tilde{\chi}^0_1}^2} \right]^{1/2} = 580.09 \text{ GeV (right)}, \quad 180.14 \text{ GeV (left)}. \]

\[ m(q\bar{l})_{\text{far}} = \left[ \frac{(M_{\tilde{\chi}^0_2}^2 - M_{\tilde{l}_R}^2)(M_{\tilde{l}_L}^2 - M_{\tilde{\chi}^0_1}^2)}{M_{\tilde{l}_L}^2} \right]^{1/2} = 327.21 \text{ GeV (right)}, \quad 603.08 \text{ GeV (left)}. \]
Distinguishability of leptons in SU1

- After **Left/Right** slepton decay chain identification, *near* and *far* leptons are easily distinguishable from their momenta.

![Graphs showing the distinguishability of leptons in SU1](image-url)
SU3 mass distributions for truth signal

- Lepton-lepton-quark invariant mass distribution
- Lepton-quark invariant mass distribution
SUSY vs. Universal Extra Dimensions


Figure 12: Detector-level charge asymmetries with respect to the jet + lepton rescaled invariant mass, for the (a) UED and (b) SUSY mass spectra given above. Dashed: SUSY. Solid/red: UED.