Multi-lepton SUSY searches with the ATLAS detector

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Introduction

Why multi-lepton SUSY searches are complementary to other searches in the mSUGRA context

Two analysis approaches – jet exclusive and jet inclusive

Analysis, results

Trigger efficiencies, systematic uncertainties

Conclusions
Minimal gravity mediated supersymmetry, mSUGRA, as example signature (R-parity conservation)

- 4 parameters: $m_0, m_{1/2}, A_0$, $\tan \beta$ and a sign
  - Common scalar mass ($m_0$) at GUT scale: sets squark and slepton mass
  - Common gaugino mass ($m_{1/2}$) at GUT scale: sets neutralino, chargino and gluino mass

Translates into:

- $m_{\tilde{g}} : m_{\tilde{\chi}^0_2} : m_{\tilde{\chi}^0_1} \approx 6 : 2 : 1$ at Electro Weak scale
- Similar quasi-fixed hierarchy in the scalar sector, e.g. $m_{\tilde{q}} > m_{\tilde{t}}$

With one exception, all ATLAS benchmark points have sparticle masses below 1 TeV
Final states with 3 or more leptons from decay of heavy gauginos

- If squark and gluino are light – they will dominate the SUSY cross section
  - Leptons from long decay chains
    - Hard jets
    - Large $\not{E}_T$

- If squarks, sleptons and possibly also gluinos are heavy – direct gaugino production becomes important
  - Gauginos may decay leptonically through real or virtual $W^\pm, Z^0$ (or sleptons, if these are not too heavy)
    - Low jet activity
    - Relatively low $\not{E}_T$ – the gauginos are produced back to back
Gaugino pair production

- The so-called “Focus point region” of the SUSY parameter space (SU2) is particularly interesting.
- Characterised by very heavy squarks and sleptons.
- The gauginos are light and dominate the production cross-section.
- Trilepton signal mainly from the pair production of $\chi_1^\pm \chi_2^0$.

<table>
<thead>
<tr>
<th>Point</th>
<th>$m_0$ [GeV]</th>
<th>$m_{1/2}$ [GeV]</th>
<th>$A_0$ [GeV]</th>
<th>$\tan \beta$</th>
<th>sign $\mu$</th>
<th>$\sigma_{LO}$ [pb]</th>
<th>Point Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU2</td>
<td>3550</td>
<td>300</td>
<td>0</td>
<td>10</td>
<td>+</td>
<td>4.86</td>
<td>Focus point region</td>
</tr>
<tr>
<td>SU1</td>
<td>70</td>
<td>350</td>
<td>0</td>
<td>10</td>
<td>+</td>
<td>7.43</td>
<td>Coannihilation region</td>
</tr>
<tr>
<td>SU3</td>
<td>100</td>
<td>300</td>
<td>$-300$</td>
<td>6</td>
<td>+</td>
<td>18.56</td>
<td>Bulk region</td>
</tr>
<tr>
<td>SU4</td>
<td>200</td>
<td>160</td>
<td>$-400$</td>
<td>10</td>
<td>+</td>
<td>262.00</td>
<td>Low mass point</td>
</tr>
<tr>
<td>SU8</td>
<td>210</td>
<td>360</td>
<td>0</td>
<td>40</td>
<td>+</td>
<td>6.44</td>
<td>Funnel region</td>
</tr>
</tbody>
</table>

- The Monte Carlo simulations are done for 14 TeV CM energy.
The trilepton requirement gives strong SM background suppression

The main SM backgrounds
- \( t\bar{t} \) – additional lepton from semileptonic b-decay
- \( Zb \) – additional lepton from semileptonic b-decay
- SM counterpart: diboson production, WZ, ZZ, WW,
  \( Z\gamma \) – additional leptons from photon conversion

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma ) [pb]</th>
<th>k-factor</th>
<th>( \int dt , \mathcal{L} ) [fb(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>24.5</td>
<td>1.67</td>
<td>1.22</td>
</tr>
<tr>
<td>WZ</td>
<td>7.8</td>
<td>2.05</td>
<td>2.98</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.1</td>
<td>1.88</td>
<td>12.7</td>
</tr>
<tr>
<td>Z(\gamma)</td>
<td>2.6</td>
<td>1.30</td>
<td>2.98</td>
</tr>
<tr>
<td>Zb</td>
<td>154</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>450</td>
<td>-</td>
<td>0.92</td>
</tr>
</tbody>
</table>
Object selection

- This analysis requires:
  - Efficient selection of high quality leptons
  - Powerful rejection of leptons from jets and leptonic b-quark decays
- Electrons, muons and jets
  - $p_T > 10$ GeV and within the central barrel region $|\eta| < 2.5$
- Lepton isolation:
  - Less than 10 GeV of transverse energy in a $\Delta R = 0.2$ cone around the track
  - Leptons within $\Delta R < 0.4$ of a jet are rejected. ($\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$)

Requiring $N_l \geq 3$

$p_T$ Leading lepton

Second leading lepton

Third lepton
Event selection

1. At least one pair of opposite sign, same flavour leptons (SFOS) ($e^+e^-$ or $\mu^+\mu^-$) with $M_{l^+l^-} > 20$ GeV

2. $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)

3. $p_{T\text{track, max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\text{track, max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\text{track, max}}^{\Delta R=0.2} (\ell)$ is the maximum $p_T$ of any track in a $\Delta R = 0.2$ cone around the lepton.

4. No SFOS dilepton pair with invariant mass in the $Z^0$-mass window $|M_{SFOS} - M_Z| > 10$ GeV

5. $E_T > 30$ GeV – a moderate $E_T$ cut

6. Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto
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4. No SFOS dilepton pair with invariant mass in the $Z^0$-mass window \[ |M_{SFOS} - M_Z| > 10 \text{ GeV} \]

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Event selection

1. At least one pair of opposite sign, same flavour leptons (SFOS) \((e^+ e^- \text{ or } \mu^+ \mu^-)\) with \(M_{l^+l^-} > 20 \text{ GeV}\)

2. \(N_\ell \geq 3 \ (\ell \in \{e, \mu\})\)

3. \(p_{\Delta R=0.2}^{\text{track,max}} < 2 \text{ GeV for electrons, } p_{\Delta R=0.2}^{\text{track,max}} < 1 \text{ GeV for muons, where } p_{\Delta R=0.2}^{\text{track,max}}(\ell)\) is the maximum \(p_T\) of any track in a \(\Delta R = 0.2\) cone around the lepton.

4. No SFOS dilepton pair with invariant mass in the \(Z^0\)-mass window \(|M_{\text{SFOS}} - M_Z| > 10 \text{ GeV}\)

5. \(E_T > 30 \text{ GeV} \) – a moderate \(E_T\) cut

6. Optional – no jet with \(p_T > 20 \text{ GeV} \) – referred to as the Jet Veto

\(M_{\text{SFOS}}\) after cut 3
Event selection

1. At least one pair of opposite sign, same flavour leptons (SFOS) \((e^+e^- \text{ or } \mu^+\mu^-)\) with \(M_{l^+l^-} > 20 \text{ GeV}\)

2. \(N_\ell \geq 3 \ (\ell \in \{e, \mu\})\)

3. \(p_T^{\Delta R=0.2, \text{track, max}} < 2 \text{ GeV for electrons, } p_T^{\Delta R=0.2, \text{track, max}} < 1 \text{ GeV for muons, where } p_T^{\Delta R=0.2, \text{track, max}} \) is the maximum \(p_T\) of any track in a \(\Delta R = 0.2\) cone around the lepton

4. No SFOS dilepton pair with invariant mass in the \(Z^0\)-mass window
\(|M_{SFOS} - M_Z| > 10 \text{ GeV}\)

5. \(\slashed{E}_T > 30 \text{ GeV} – \text{a moderate } \slashed{E}_T \text{ cut}\)

6. Optional – no jet with \(p_T > 20 \text{ GeV} – \text{referred to as the Jet Veto}\)

**\(M_{SFOS}\) after cut 3**

**\(\slashed{E}_T\) after cut 4**
Event selection

1. At least one pair of opposite sign, same flavour leptons (SFOS) ($e^+e^-$ or $\mu^+\mu^-$) with $M_{l^+l^-} > 20$ GeV
2. $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)
3. $p_{T_{\text{track, max}}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T_{\text{track, max}}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T_{\text{track, max}}}^{\Delta R=0.2} (\ell)$ is the maximum $p_T$ of any track in a $\Delta R = 0.2$ cone around the lepton
4. No SFOS dilepton pair with invariant mass in the $Z^0$-mass window $|M_{SFOS} - M_Z| > 10$ GeV
5. $E_T > 30$ GeV – a moderate $E_T$ cut
6. Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto

$M_{SFOS}$ after cut 3

$E_T$ after cut 4

Leading jet $p_T$ after cut 5
The discovery potential

- Signal significance $I = \frac{S}{\sqrt{S+B}}$
  - $S =$ number of signal events and $B =$ number of background events
- It has been studied for two cases:
  - Jet Veto - all event selection cuts, including the jet veto
  - Jet inclusive - all event selection cuts, except the jet veto

**The tri-lepton analysis including the jet veto with 10 fb$^{-1}$:**
- 29 Focus point region signal events (all direct gaugino), 210 SM-background events, dominated by $ZW$
- Significance: $I = 1.9$, which yields a $5\sigma$ discovery after $\sim 71$ fb$^{-1}$

**The tri-lepton jet inclusive analysis with 10 fb$^{-1}$:**
- 177 Focus point region signal events (95 of them direct gaugino), 718 SM-background events, dominated by $t\bar{t}$
- Inclusive SUSY: $I = 5.9$
- Direct gaugino: $I = 3.3$
The jet inclusive tri-lepton analysis yields a $5\sigma$ discovery signal after less than $\sim 10 \text{ fb}^{-1}$ for all except one studied benchmark point.

Including the background uncertainty (20%), only Low Mass point (SU4) has a $5\sigma$ discovery signal after $\sim 1 \text{ fb}^{-1}$.
This **3-leptons + jet** analysis aims at multi-lepton production in association with jets

- **Cut 1:** $N_\ell \geq 3$ isolated leptons (leptons with $M_{l^+l^-} < 20$ GeV are discarded)
- **Cut 2:** At least one jet with $p_T > 200$ GeV

The effect of the single lepton triggers are included (efficiency $\sim 95\%$)

- $Z_n > 5$ for points for the Low Mass and Bulk points (SU4,SU3) even with 100% background uncertainty

### All numbers normalized to 1 fb$^{-1}$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cut 1</th>
<th>Cut 2</th>
<th>$S/B$</th>
<th>$S/\sqrt{B}$</th>
<th>$Z_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus p.</td>
<td>35</td>
<td>13</td>
<td>1.1</td>
<td>3.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Bulk p.</td>
<td>139</td>
<td>94</td>
<td>7.8</td>
<td>27.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Low mass</td>
<td>1284</td>
<td>312</td>
<td>26.0</td>
<td>90.0</td>
<td>24.4</td>
</tr>
<tr>
<td>$tt$</td>
<td>455</td>
<td>11</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>59</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$ZW$</td>
<td>193</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$WW$</td>
<td>3</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$Z + \gamma$</td>
<td>9</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$Zb$</td>
<td>656</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

- $Z_n$ – significance including the background uncertainty of 20%

$$Z_n = \sqrt{2} \text{ erf}^{-1} (1 - 2p)$$ where $p$ is the Poisson probability that the background fluctuates to the observed signal. The approximate uncertainties for 1 fb$^{-1}$ are estimated to be 20%.
Lepton Trigger Studies - trilepton events

- Direct gaugino production, unlike most SUSY searches:
  - Jet or $E_T$ triggers are not efficient
- Suitable triggers during early low luminosity running at $\mathcal{L} = 10^{31-32} \text{ cm}^{-2}\text{s}^{-1}$
  - Single-lepton: L2_e22i and L2_mup20
  - Studies at Level 2 (L2) – high probability to also pass the Event Filter
- Requiring 3 leptons with $p_T > 10$ GeV – high probability that at least one has high $p_T$
- The OR combination shows good and stable performance after the $N_l \geq 3$ cut

<table>
<thead>
<tr>
<th>Selection Stage</th>
<th>SU2$\chi$</th>
<th>SU3$\chi$</th>
<th>SU3 incl.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L2_e22i</td>
<td>L2_mup20</td>
<td>L2_e22i</td>
</tr>
<tr>
<td>SFOS pair</td>
<td>41%</td>
<td>54%</td>
<td>89%</td>
</tr>
<tr>
<td>SFOS+3$^\text{rd}$ℓ</td>
<td>58%</td>
<td>67%</td>
<td>93%</td>
</tr>
<tr>
<td>after all cuts</td>
<td>57%</td>
<td>66%</td>
<td>92%</td>
</tr>
</tbody>
</table>

- ATLAS has three trigger levels:
  - First level (L1) – hardware trigger
  - Second level (L2) – software-based
  - Event filter (EF) – software-based

- Trigger labels
  - e22i – electron, $p_T > 22$ GeV, isolated
  - mu20 – muon, $p_T > 20$ GeV
The sources of systematic uncertainties in multi-lepton search channels are different to other SUSY channels.

For $\int dt \mathcal{L} = 10 \text{ fb}^{-1}$ it is estimated to be less than 10%.

- Background production rates – large contributions from Diboson production
- Lepton Efficiency – based on “tag-and-probe” method
- Trilepton channel is very sensitive to the rate of leptons from b-decays
- Relevant only when using the jet veto
- Using the jet veto – the majority of the missing energy will recoil against the leptons leading to a small missing energy scale uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No jet veto</td>
</tr>
<tr>
<td>1 Background production rates</td>
<td>0.8%</td>
</tr>
<tr>
<td>2 Lepton Efficiency</td>
<td>2.3%</td>
</tr>
<tr>
<td>3 Fakes ($R_{b\rightarrow\ell}$)</td>
<td>4.0%</td>
</tr>
<tr>
<td>4 Hadronic energy scale</td>
<td>–</td>
</tr>
<tr>
<td>5 Missing energy scale</td>
<td>1.5%</td>
</tr>
<tr>
<td><strong>Total systematic</strong></td>
<td><strong>4.9%</strong></td>
</tr>
<tr>
<td><strong>Statistical</strong></td>
<td><strong>3.7%</strong></td>
</tr>
<tr>
<td><strong>Statistical + Systematic</strong></td>
<td><strong>6.2%</strong></td>
</tr>
</tbody>
</table>

Eventually – all estimates will be done based on real data.
Conclusions

- If squarks and gluinos are heavy – dominant process: direct gaugino production
  - Including the jet veto – $5\sigma$ discovery after $71 \text{ fb}^{-1}$

- Jet inclusive searches:
  - Sensitive to multi-lepton signal from a broad range of scenarios
  - Without the jet veto $5\sigma$ discovery after $\sim 10 \text{ fb}^{-1}$ for most benchmark points
  - For the “Low mass point” SU4 $5\sigma$ discovery after $\sim 1 \text{ fb}^{-1}$
  - 3-leptons + jet – strong background suppression, promising discovery potential, even with $1 \text{ fb}^{-1}$

- High trigger efficiency – OR combination of lepton triggers
- Multi-lepton searches are part of the ATLAS early physics strategies