Searches for electroweak production of neutralinos, charginos and sleptons with the ATLAS detector

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on behalf of the ATLAS collaboration

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Why Weakly Produced SUSY?

- SUSY production at the LHC should be dominated by strong production unless the gluinos and squarks become too heavy.
- Naturalness arguments favor searches for light super-partners.

Limits on gluinos (and squarks) continue to grow, further motivating searches for charginos, neutralinos, and sleptons.
Search Strategy

- Analyses probe for charginos, neutralinos, and slepton production in the multi-lepton channels.
- Example Processes:

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEW! 2 Lepton (e/mu)</td>
<td>ATLAS-CONF-2013-049</td>
</tr>
<tr>
<td>2 Lepton (tau)</td>
<td>ATLAS-CONF-2013-028</td>
</tr>
<tr>
<td>3 Lepton (e/mu)</td>
<td>ATLAS-CONF-2013-035</td>
</tr>
<tr>
<td>4 Lepton (e/mu/tau)</td>
<td>ATLAS-CONF-2013-036</td>
</tr>
</tbody>
</table>

RESULTS:
Full 2012 statistics used!
(20 fb⁻¹ @ 8TeV)
Standard Model Backgrounds

- In order to tackle the most challenging regions where SUSY could be hiding, need well understood SM backgrounds.

- **Reducible**
  - Processes containing at least one ‘fake’ lepton
    - semi-leptonic decay $b$ or $c$ quark
    - mis-identified light quark or gluon jet
    - photon conversion
  - Estimated from Data

- **Irreducible**
  - Processes producing prompt leptons
    - $V$+jets
    - Diboson and Triboson
    - Processes containing top quarks
  - Estimated from MC and corrected using dedicated control regions.

Example: 2-lepton top validation region shows excellent agreement.
2 Lepton Search (e/µ)

- Two signal regions targeting specific diagrams

<table>
<thead>
<tr>
<th>lepton flavour</th>
<th>SR-(m_{T2,90})</th>
<th>SR-(m_{T2,110})</th>
<th>SR-WWa</th>
<th>SR-WWb</th>
<th>SR-WWc</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_T^{f_1})</td>
<td>(e^+e^-,\mu^+\mu^-,e^+\mu^-)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(p_T^{f_2})</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(m_{\ell\ell})</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(p_{T,\ell\ell})</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(\Delta\phi_{\ell\ell})</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(E_{T}^{miss,rel})</td>
<td>(&gt;40\text{ GeV})</td>
<td>(&gt;90\text{ GeV})</td>
<td>(&gt;110\text{ GeV})</td>
<td>(&gt;70\text{ GeV})</td>
<td>(&gt;70\text{ GeV})</td>
</tr>
<tr>
<td>(m_{T2})</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

\(E_T^{miss,rel}\) from SR-\(m_{T2}(90)\) in em channel.

\(E_T^{miss,rel}\) from SR-WWa in em channel.
2 Lepton Results (e/mu)

Overall Good Agreement between prediction and observed!

<table>
<thead>
<tr>
<th>SR-$m_{T2}$</th>
<th>$e^+e^-$</th>
<th>$e^\pm\mu^\mp$</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-$m_{T2,90}$</td>
<td>Observed</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>Background total</td>
<td>$16.6 \pm 2.3$</td>
<td>$20.7 \pm 3.2$</td>
<td>$22.4 \pm 3.3$</td>
</tr>
<tr>
<td>SR-$m_{T2,110}$</td>
<td>Observed</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Background total</td>
<td>$6.1 \pm 2.2$</td>
<td>$4.4 \pm 2.0$</td>
<td>$6.3 \pm 2.4$</td>
</tr>
<tr>
<td>SR-$m_{T2,90}$</td>
<td>Observed</td>
<td>123</td>
<td>16</td>
</tr>
<tr>
<td>Background total</td>
<td>$117.9 \pm 14.6$</td>
<td>$13.6 \pm 2.3$</td>
<td>$7.4 \pm 1.5$</td>
</tr>
</tbody>
</table>

First WW+MET LHC Result!
Exclusion limit from SR-WW for massless neutralinos.

Exclusion limit from SR-$m_{T2}$ for slepton-neutralino mass plane.
2 Lepton Search (tau)

- Search for chargino, neutralino, and slepton production in events with exactly two hadronically decaying taus targeting:
  - Chargino-neutralino production, $\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow \tau_L \nu(\bar{\nu}) \tau_L \tau \rightarrow \tau \nu \tilde{\chi}_1^0 \tau \tilde{\chi}_1^0$;
  - Chargino-chargino production: $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow 2 \times \tilde{\tau}(\tilde{\nu} \tau) \rightarrow 2 \times \tau \nu \tilde{\chi}_1^0$;
  - Direct tau slepton production: $\tilde{\tau}^\pm \tilde{\tau}^\mp \rightarrow 2 \times \tau \tilde{\chi}_1^0$.

- Dominant background sources are mis-identified taus from multi-jet and W boson production with jets (Data-driven: ABCD).

- Integration of $L \, dt \approx 20.7 \, fb^{-1}$

### Signal region requirements

<table>
<thead>
<tr>
<th>$OS , m_{T2}$</th>
<th>requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>at least 1 OS tau pair</td>
<td>jet veto</td>
</tr>
<tr>
<td>$Z$-veto</td>
<td>$E_T^{miss} &gt; 40$ GeV</td>
</tr>
<tr>
<td>$m_{T2} &gt; 90$ GeV</td>
<td>$m_{T2} &gt; 100$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal region requirement</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$OS , m_{T2}$-no b-jet</td>
<td>at least 1 OS tau pair</td>
</tr>
<tr>
<td>$b$-jet veto</td>
<td>$E_T^{miss} &gt; 40$ GeV</td>
</tr>
<tr>
<td>$Z$-veto</td>
<td>$m_{T2} &gt; 90$ GeV</td>
</tr>
</tbody>
</table>

### ATLAS Preliminary

<table>
<thead>
<tr>
<th>Events / 10 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$OS , m_{T2}$</td>
</tr>
</tbody>
</table>

- Data 2012 $(\sqrt{s} = 8 \, TeV)$
- SM Total
- Multi-jet, W+jets
- Diboson
- Z+jets
- $t\bar{t}$
- Single top
- SUSY Ref. Point 1
- SUSY Ref. Point 2

### OS $m_{T2}$-no b-jet

- Data 2012 $(\sqrt{s} = 8 \, TeV)$
- SM Total
- Multi-jet, W+jets
- Diboson
- $t\bar{t}$
- Single top
- SUSY Ref. Point 1
- SUSY Ref. Point 2
2 Lepton Results (tau)

- No excess above SM backgrounds is observed.
- Exclusion limits are set using the simplified-models.

**Good Agreement observed in Signal Regions**

<table>
<thead>
<tr>
<th>SM process</th>
<th>SR OS $m_{T2}$</th>
<th>SR OS $m_{T2}$ -nojet</th>
</tr>
</thead>
<tbody>
<tr>
<td>top</td>
<td>0.2 ± 0.5 ± 0.1</td>
<td>1.6 ± 0.8 ± 1.2</td>
</tr>
<tr>
<td>Z+jets</td>
<td>0.28 ± 0.26 ± 0.23</td>
<td>0.4 ± 0.3 ± 0.3</td>
</tr>
<tr>
<td>diboson</td>
<td>2.2 ± 0.5 ± 0.5</td>
<td>2.5 ± 0.5 ± 0.9</td>
</tr>
<tr>
<td>multi-jet &amp; $W_+$jets</td>
<td>8.4 ± 2.6 ± 1.4</td>
<td>12 ± 3 ± 3</td>
</tr>
<tr>
<td>SM total</td>
<td>11.0 ± 2.7 ± 1.5</td>
<td>17 ± 4 ± 3</td>
</tr>
<tr>
<td>data</td>
<td>6</td>
<td>14</td>
</tr>
</tbody>
</table>

First chargino pair production limit in light stau scenarios at LHC!
3 Lepton Search (e/\mu)

- There are six signal regions grouped into two sets based on the inclusion or exclusion of a candidate Z boson in the event.

**Excluding Z**

<table>
<thead>
<tr>
<th>Selection</th>
<th>SRnoZa</th>
<th>SRnoZb</th>
<th>SRnoZc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{SFOO}$ [GeV]</td>
<td>&lt;60</td>
<td>60–81.2</td>
<td>&lt;81.2 or &gt;101.2</td>
</tr>
<tr>
<td>$E^\text{miss}_T$ [GeV]</td>
<td>&gt;50</td>
<td>&gt;75</td>
<td>&gt;75</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>–</td>
<td>–</td>
<td>&gt;110</td>
</tr>
<tr>
<td>$p_T$ 3rd $\ell$ [GeV]</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>&gt;30</td>
</tr>
<tr>
<td>SR veto</td>
<td>SRnoZc</td>
<td>SRnoZc</td>
<td>–</td>
</tr>
</tbody>
</table>

- Purpose: Near diagonal, No-slep off-shell Z, Slepton

**Including Z**

<table>
<thead>
<tr>
<th>Selection</th>
<th>SRZA</th>
<th>SRZb</th>
<th>SRZc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{SFOO}$ [GeV]</td>
<td>81.2–101.2</td>
<td>81.2–101.2</td>
<td>81.2–101.2</td>
</tr>
<tr>
<td>$E^\text{miss}_T$ [GeV]</td>
<td>75–120</td>
<td>75–120</td>
<td>&gt;120</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>&lt;110</td>
<td>&gt;110</td>
<td>&gt;110</td>
</tr>
<tr>
<td>$p_T$ 3rd $\ell$ [GeV]</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>SR veto</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

- Purpose: WZ-like, No-slep on-shell Z, No slepton

**Purpose:**
- Regions excluding Z target decays via sleptons or off-shell bosons.
- Regions including Z target decays via on-shell bosons.
- Background sources:
  - Reducible – events containing non-prompt leptons (data-driven).
  - Irreducible – Diboson, triboson, and ttbar+V yield prompt leptons (MC).
3 Lepton Results (e/mu)

No Excess observed over SM background

<table>
<thead>
<tr>
<th>Selection</th>
<th>SRnoZa</th>
<th>SRnoZb</th>
<th>SRnoZc</th>
<th>SRZa</th>
<th>SRZb</th>
<th>SRZc</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Sigma) SM</td>
<td>96 ± 19</td>
<td>29 ± 6</td>
<td>4.4 ± 1.8</td>
<td>249 ± 35</td>
<td>22 ± 5</td>
<td>6.3 ± 1.5</td>
</tr>
<tr>
<td>Data</td>
<td>101</td>
<td>32</td>
<td>5</td>
<td>273</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>(p_0)-value</td>
<td>0.41</td>
<td>0.37</td>
<td>0.40</td>
<td>0.23</td>
<td>0.44</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Simplified model limits are extended w.r.t. 13 fb\(^{-1}\) result

**Via intermediate Sleptons**

\[
\int L \, dt = 20.7 \, fb^{-1}, \sqrt{s} = 8\, TeV
\]

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

\[
m_{\tilde{\chi}_{1,2}} = (m_{\tilde{l}} + m_{\tilde{l}})/2
\]

\[
m_0 = 2m_{\tilde{\chi}_1^0}
\]

**Via intermediate W/Z**

\[
\int L \, dt = 13.0 \, fb^{-1}, \sqrt{s} = 8\, TeV
\]

\[
\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^{\pm} l \tilde{l}, Z^{0} l \tilde{l}
\]

\[
m_{\tilde{\chi}_{1,2}} = (m_{\tilde{l}} + m_{\tilde{l}})/2
\]

\[
m_0 = 2m_{\tilde{\chi}_1^0}
\]
4 Lepton Search (e/mu/tau)

- Sensitive to both R-parity conserving and R-parity violating scenarios.
- RPC through simplified models
  - $\tilde{\chi}^0_2 \tilde{\chi}^0_3$ produced and decay through sleptons.
  - Assume 100% BR to insure 4 lepton signal.
- RPC through gauge mediation
  - Gravitino is the LSP.
  - Higgsino-like NLSP considered
    - dominant decays include gravitino and either Z or h
- RPV
  - Lepton number violation for decays with light leptons ($\lambda_{121}$) and taus ($\lambda_{133}$).
  - LSP can decay via off-shell sleptons, leading to high lepton multiplicity events
  - Covered in dedicated RPV talk

Note: $\lambda_{ijk}$ represent the coupling. In this search, single coupling dominance is assumed. All couplings set to zero except for the two mentioned above.
4 Lepton Results (e/mu/tau)

Signal Region Choices:

Dominant Irreducible background ttbarZ (MC)

No significant excess is seen over SM backgrounds.

<table>
<thead>
<tr>
<th>SR</th>
<th>N(\ell = e, \mu)</th>
<th>N(\tau)</th>
<th>Z Candidate</th>
<th>E_{\text{miss}} [GeV]</th>
<th>m_{\text{eff}} [GeV]</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR0noZa</td>
<td>\geq 4</td>
<td>\geq 0</td>
<td>extended veto</td>
<td>&gt;50</td>
<td></td>
<td>RPC</td>
</tr>
<tr>
<td>SR0noZb</td>
<td>\geq 4</td>
<td>\geq 0</td>
<td>extended veto</td>
<td>&gt;75 or &gt;600</td>
<td></td>
<td>RPV</td>
</tr>
<tr>
<td>SR1noZ</td>
<td>=3</td>
<td>\geq 1</td>
<td>extended veto</td>
<td>&gt;100 or &gt;400</td>
<td></td>
<td>RPV</td>
</tr>
<tr>
<td>SR0Z</td>
<td>\geq 4</td>
<td>\geq 0</td>
<td>request</td>
<td>&gt;75</td>
<td></td>
<td>GGM</td>
</tr>
<tr>
<td>SR1Z</td>
<td>=3</td>
<td>\geq 1</td>
<td>request</td>
<td>&gt;100</td>
<td></td>
<td>GGM</td>
</tr>
</tbody>
</table>

No significant excess is seen over SM backgrounds.
Conclusions

- A summary of the current status and results for direct EW production of charginos, neutralinos, and sleptons has been shown.
  - No significant excess above SM has been observed in any of the multi-lepton searches.
- Developed new signal regions to probe available parameter space.
  - For the first time, a SUSY EW production search with a two tau final state has been completed using the ATLAS detector.
  - For the first time in ATLAS a dedicated analysis probing WW+Met mode in the context of chargino pair production without sleptons has been completed.
- All of the exclusion limits have been extended for simplified models in the context of RPC, RPV, and GGM.
BONUS SLIDES
Dominant Systematics Per Analysis

• 2 Lepton Dominant Uncertainties:
  • Theory and modeling (43%)
  • Jet energy scale and resolution (17%)

• 3 Lepton Dominant Uncertainties:
  • Irreducible background – cross-section, jet energy resolution and missing energy resolution and scale (7-15%)
  • Reducible background – missing energy dependence of mis-id probability (40-60%)

• 2 Tau Dominant Uncertainties:
  • ABCD uncertainty (35%)
  • Theory and modeling for diboson background (10-30%)
  • Tau related uncertainties such as energy scale and resolution, ID and trigger efficiencies (5-15%)

• 4 Lepton Dominant Uncertainties:
  • Theory and modeling uncertainty (~50%).
2 Lepton Exclusion Plots (e/mu)

- Exclusion limits are set for direct slepton production and chargino-chargino production with intermediate sleptons using SR-mT2.

- For chargino-chargino without intermediate sleptons, no exclusion set.
2 Lepton Exclusion Plots (tau)

- 95% CL exclusion limits for simplified models with chargino-neutralino (left) and chargino-chargino production.

- Exclusion limits are set also in the plane of mu-M$_2$ in pMSSM with $M_1=50$ GeV.

- No sensitivity to direct stau production due to EW background overwhelming signal.
3 Lepton Exclusion Plots (e/mu)

Decays via Sleptons

Decays via Gauge Bosons

Funny Dip due to Z turn on, where signal becomes very WZ like
4 Lepton Exclusion Limits (e/mu/tau)

- R-parity conserving limits from SR0noZa

**Assumptions:**

\[ \Delta m(\tilde{\chi}_3^0, \tilde{\chi}_2^0) = 5 \text{ GeV} \text{ and } \Delta m(\tilde{\chi}_3^0, \tilde{\chi}_1^0) = 80 \text{ GeV.} \]

\[ \Delta m(\tilde{\chi}_3^0, \tilde{\chi}_2^0) = 0 \text{ GeV and } m(\tilde{\ell}_R) = \frac{1}{2} [m(\tilde{\chi}_1^0) + m(\tilde{\chi}_3^0)]. \]
4 Lepton Exclusion Limits (e/mu/tau)

- R-parity violating limits
  - For $\lambda_{133}$ limits taken from region SR0noZb
  - For $\lambda_{133}$ limits taken from the statistical combination of SR0Z, ZR0noZb, SR1Z and SR1noZ regions.
4 Lepton Exclusion Limits (e/mu/tau)

- R-parity conserving limits in the context of GMSB are taken from signal region SR0Z
Useful Variable Definitions

- **Relative Missing Energy:**
  - Used by 2-lep analyses. Useful for separating genuine missing energy and missing energy from mis-measurement of objects (jets or leptons).

\[
E_{T}^{\text{miss,rel.}} = \begin{cases} 
E_{T}^{\text{miss}} & \text{if } \Delta \phi_{\ell, j} \geq \pi/2 \\
E_{T}^{\text{miss}} \times \sin \Delta \phi_{\ell, j} & \text{if } \Delta \phi_{\ell, j} < \pi/2 
\end{cases}
\]

- **Stransverse mass (mT2):**
  - Used by 2-lep analyses. Useful for separating signal and background, as SM backgrounds (eg. WW) has a kinematic endpoint.

\[
m_{T2} = \min_{q_{T}} \left[ \max \left( m_{T}(p_{T}^{\ell 1}, q_{T}), m_{T}(p_{T}^{\ell 2}, p_{T}^{\text{miss}} - q_{T}) \right) \right]
\]

- **Effective mass:**
  - Used by 4-lep analysis. Useful for separating signal and background in the tails of the distribution.

\[
m_{\text{eff}} = E_{T}^{\text{miss}} + \sum_{\mu} p_{T}^{\mu} + \sum_{e} p_{T}^{e} + \sum_{\tau} p_{T}^{\tau} + \sum j p_{T}^{j}
\]