Searches for squarks and gluinos in final states with
1 lepton+jets+Missing ET
with the ATLAS detector
(Based on ATL-CONF-2016-054)

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on behalf of ATLAS Collaboration
Epiphany 2017 @Jagiellonian University, Krakow
Why SUSY search is important?

- **Homework of the Standard Model:**
  - Dark matter candidate.
  - Higgs mass divergence
  - GUT etc...

- **Super-symmetry can solve them,**
  and the schemes works particularly successful when SUSYs are $O(1-10\text{TeV})$.

- **SUSY is also anticipated from formalism side:**
  - Renormalizability.
  - Potential clue to reconcile gravity with QFT? (e.g. SUGRA)
Gluino/squark search in ATLAS

- Gluino/squark $\rightarrow$ high xsec in LHC.
- First Run2 result published in 2015 ($L=3.2\,fb^{-1}$).
  No significant excess so far.
- Sensitivity is always limited by data stat.

New result in 2016 summer with $\times 5$ statistics.

Open up the probe to unexplored heavier gluino & squarks.
How do we search gluino/squark in ATLAS?

Gluino/light squark can decay into many final states...

e.g. Gluino decays

→ Divide the analysis by different final state. ("Topology-based searches")

1 lepton + jets + MET analysis:
- One of the most inclusive search channel.
- Major focus on “1-step” signatures + some of “direct decays”

※ There are also some “signature-based searches” aiming specific type of decays (e.g. stop search).
How do we search gluino/squark in ATLAS?

Gluino/light squark can decay into many many final states...

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→ Divide the analysis by different final state. ("Topology-based searches")

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Strategy of signal region definition

- Signals typically leave large missing ET (MET). \( \rightarrow \) Large MET, use MET trigger.
- Signal regions (SRs) are split by \( N_{\text{jet}}, \text{jetPt}, \text{leptonPt} (M_T) \) etc. to deal with different scenarios of mass spectra.

10 SRs are set in total (6 for gluino “GG”, 4 for squark “SS”).
- Further cuts for BG rejection are carefully optimized in respective SR, so that they are not too much fine-tuned to particular decays/masses.
Background rejection

Main BG: TT, W+jets, (Di-boson in squark SR)

Typical cuts

- \( M_T(\ell, \text{MET}) > 125\,\text{to}\,400\,\text{GeV} \). SM 1LBG has a cut-off at \( M_W \).
- \( \text{MET} > 250\,\text{to}\,460\,\text{GeV} \), \( M_{\text{eff}} > 1\,\text{to}\,2\,\text{TeV} \) etc.

Representing that particles in final state are hard.

- SM remnants are “unbalanced” events due to ISR activity
  - Make use of event shape variables (\( \text{MET}/M_{\text{eff}}, \text{aplanarity} \))

\[ M_T(\ell, \text{MET}) = \sqrt{2p_T^\ell E_T^\text{miss}(1 - \cos(\Delta\phi(p_T^\ell, E_T^\text{miss}))}. \]

\[ m_{\text{eff}} = \sum_{j=1}^{N_{\text{jets}}} p_{T,j} + E_T^\text{miss}. \]

\[ M_{\text{aplay}} = \sqrt{\frac{1}{2} \sum_{j=1}^{N_{\text{jets}}} p_{T,j}^2 - \sum_{j=1}^{N_{\text{jets}}} p_{T,j}^2}. \]
Background estimation

- Most important part in discovery oriented search analysis
- BG lays in the SM “tail”.
  
  MC is not always well-modeling in such extreme phase space.
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⇒ In-situ correction using control regions (CR).
  - Scale MC to data in CR
  - Extrapolate CR to SR using “well-modeled” shape. (\(M_T\), aplanarity etc.)
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⇒ In-situ correction using control regions (CR).
  - Scale MC to data in CR
  - Extrapolate CR to SR using “well-modeled” shape. ($M_T$, aplanarity etc.)
Background estimation

- CR: Low $M_T$, low aplanarity
- SR: High $M_T$, high aplanarity
- The correction method is tested in validation regions (VRs).
- No significant deviation from estimation in VR :)

※MET, MET/meff etc. are used instead apl. in some regions.
Drum roll ...
Result (Gluino signal regions)

<table>
<thead>
<tr>
<th></th>
<th>GG 2J</th>
<th>GG 4J high x</th>
<th>GG 4J low-x</th>
<th>GG 4J low-x bveto</th>
<th>GG 6Jbulk</th>
<th>GG 6JhighM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. BG</td>
<td>46 ± 7</td>
<td>3.4 ± 0.9</td>
<td>6.0 ± 1.6</td>
<td>3.3 ± 1.2</td>
<td>24 ± 5</td>
<td>3.8 ± 1.2</td>
</tr>
<tr>
<td>Data (L=14.8 fb(^{-1}))</td>
<td>47</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>32</td>
<td>3</td>
</tr>
</tbody>
</table>

- No significant excess.
- The largest deviation is in 6Jbulk (1.6σ).
Result (Squark signal regions)

<table>
<thead>
<tr>
<th></th>
<th>SS 4J low-x</th>
<th>SS 5J high-x</th>
<th>SS 4J x=1/2</th>
<th>SS 5J x=1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. BG</td>
<td>11.1 ± 2.7</td>
<td>4.6 ± 1.4</td>
<td>5.4 ± 1.7</td>
<td>13.2 ± 2.5</td>
</tr>
<tr>
<td>Data (L=14.8 fb⁻¹)</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

Pull

No significant excess.
Limit on simplified models @L=14.8fb⁻¹

Gluino→1step, chargino med.

Chargino mass is set to exactly the middle between gluino and the lightest neutralino here.
Summary

- You don’t have to believe in SUSY, but have to admit SUSY search is important!!
- One of the key analysis in ATLAS: “1L+jets+MET analysis”
  - Main target: gluino/light squark → chargino → LSP
- No significant excesses are found @14.8fb⁻¹.
  - Exclusion limit grew upto: ~ 1.7 TeV of gluino mass (@low m_{LSP}),
  - ~ 1.0 TeV of light squark mass (@low m_{LSP}).

This is still not the end!!
Sensitivity will keep getting improved with larger statistics.
We will keep ramping up for heavier SUSY.

Stay tuned!!
Backup
Producing strongly interacting particles is what LHC is best at :) 
$O(10-100\text{fb})$ for $g\sim g\sim$ production @1-2TeV gluino which is current exclusion limit.
Gluino signal regions

<table>
<thead>
<tr>
<th></th>
<th>GG 6J bulk</th>
<th>GG 6J high-mass</th>
<th>GG 4J low-x</th>
<th>GG 4J low-x b-veto</th>
<th>GG 4J high-x</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{\text{lep}}) (preselected)</td>
<td>(&gt; 35)</td>
<td>(&gt; 35)</td>
<td>(= 1) for electron (muon)</td>
<td>(&gt; 7(6)) for electron (muon)</td>
<td>(&gt; 35)</td>
</tr>
<tr>
<td>(p_T^{\text{F}}) (GeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N_{\text{jet}}) (GeV)</td>
<td>(\geq 6)</td>
<td>(\geq 6)</td>
<td>(\geq 4)</td>
<td>(\geq 4)</td>
<td>(\geq 4)</td>
</tr>
<tr>
<td>(p_T^{\text{F,2,3}}) (GeV)</td>
<td>(&gt; 125)</td>
<td>(&gt; 125)</td>
<td>(&gt; 100)</td>
<td>(&gt; 100)</td>
<td>(&gt; 400)</td>
</tr>
<tr>
<td>(p_T^{\text{miss}}) (GeV)</td>
<td>(&gt; 30)</td>
<td>(&gt; 30)</td>
<td>(&gt; 100)</td>
<td>(&gt; 100)</td>
<td>(\geq 30)</td>
</tr>
<tr>
<td>(p_T^{\text{jet},5,6}) (GeV)</td>
<td>(&gt; 30)</td>
<td>(&gt; 30)</td>
<td>(&gt; 100)</td>
<td>(&gt; 100)</td>
<td>([30, 100])</td>
</tr>
<tr>
<td>(N_{\text{b-jet}})</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(m_T) (GeV)</td>
<td>(&gt; 225)</td>
<td>(&gt; 225)</td>
<td>(&gt; 125)</td>
<td>(&gt; 125)</td>
<td>(&gt; 475)</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}) (GeV)</td>
<td>(&gt; 250)</td>
<td>(&gt; 250)</td>
<td>(&gt; 250)</td>
<td>(&gt; 250)</td>
<td>(&gt; 250)</td>
</tr>
<tr>
<td>(m_{\text{inc}}) (GeV)</td>
<td>(&gt; 1000)</td>
<td>(&gt; 2000)</td>
<td>(&gt; 2000)</td>
<td>(&gt; 2000)</td>
<td>(&gt; 1600)</td>
</tr>
<tr>
<td>(E_T^{\text{miss}}/m_{\text{inc}})</td>
<td>(&gt; 0.2)</td>
<td>(&gt; 0.1)</td>
<td>-</td>
<td>-</td>
<td>(&gt; 0.3)</td>
</tr>
<tr>
<td>Jet aplanarity</td>
<td>(&gt; 0.04)</td>
<td>(&gt; 0.04)</td>
<td>(&gt; 0.06)</td>
<td>(&gt; 0.03)</td>
<td>-</td>
</tr>
</tbody>
</table>

**SR6J @2015.12**

**SR6Jbulk @2016.8**

- "SR 6J" in 2015 result is kept ("GG 6Jbulk") to monitor the mild excess.
Squark signal regions

- Target: light squark@0.8-1TeV
  - Looser cuts than gluino SRs.
- B-veto is applied as light squarks rarely decay with b-jets.
- Main BGs are W+jets and diboson.

<table>
<thead>
<tr>
<th></th>
<th>SS 4J x=1/2</th>
<th>SS 5J x=1/2</th>
<th>SS 4J low-x</th>
<th>SS 5J high-x</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{lep}$ (preselected)</td>
<td>$= 1$</td>
<td>$= 1$</td>
<td>$= 1$</td>
<td>$= 1$</td>
</tr>
<tr>
<td>$p_T^{l}$ (GeV)</td>
<td>$&gt; 35$</td>
<td>$&gt; 35$</td>
<td>$&gt; 35$</td>
<td>$&gt; 35$</td>
</tr>
<tr>
<td>$N_{jet}^{1,2}$</td>
<td>$\geq 4$</td>
<td>$\geq 5$</td>
<td>$\geq 4$</td>
<td>$\geq 5$</td>
</tr>
<tr>
<td>$p_T^{jet3,4}$</td>
<td>$&gt; 50$</td>
<td>$&gt; 50$</td>
<td>$&gt; 250$</td>
<td>$&gt; 30$</td>
</tr>
<tr>
<td>$p_T^{jet5}$</td>
<td>$&gt; 50$</td>
<td>$&gt; 50$</td>
<td>$&gt; 30$</td>
<td>$&gt; 30$</td>
</tr>
<tr>
<td>$N_{b-jet}$</td>
<td>$= 0$</td>
<td>$= 0$</td>
<td>$= 0$</td>
<td>$= 0$</td>
</tr>
<tr>
<td>$m_T$ (GeV)</td>
<td>$&gt; 175$</td>
<td>$&gt; 175$</td>
<td>$[150, 400]$</td>
<td>$&gt; 400$</td>
</tr>
<tr>
<td>$E_T^{miss}$ (GeV)</td>
<td>$&gt; 300$</td>
<td>$&gt; 300$</td>
<td>$&gt; 250$</td>
<td>$&gt; 400$</td>
</tr>
<tr>
<td>$m_{eff}$ (GeV)</td>
<td>$&gt; 1200$</td>
<td>$-$</td>
<td>$&gt; 250$</td>
<td>$&gt; 400$</td>
</tr>
<tr>
<td>$E_T^{miss}/m_{eff}$</td>
<td>$- - -$</td>
<td>$- - -$</td>
<td>$- - -$</td>
<td>$- - -$</td>
</tr>
<tr>
<td>Lepton aplanarity</td>
<td>$&gt; 0.08$</td>
<td>$-$</td>
<td>$&gt; 0.03$</td>
<td>$&gt; 0.03$</td>
</tr>
</tbody>
</table>

**SS 5J x=1/2**

**SS 4J low-x**
Systematic uncertainties

- Experimental uncertainties are well-controlled (<10%) since CRs have similar cuts in meff, jetPt, MET etc. which are sensitive to them.
- Largest uncertainty is from theory uncertainty of unconstrained “minor” BG:
  Especially single top, which has significant interference with TT in this phase space

### Gluino SRs:

<table>
<thead>
<tr>
<th></th>
<th>2J</th>
<th>4J highx</th>
<th>4J lowx</th>
<th>6J bulk</th>
<th>6J highMass</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC normalization factor (CR stat.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets</td>
<td>1.1%</td>
<td>5.0%</td>
<td>5.6%</td>
<td>1.2%</td>
<td>5.8%</td>
</tr>
<tr>
<td>TT</td>
<td>5.6%</td>
<td>6.5%</td>
<td>16.3%</td>
<td>9.3%</td>
<td>8.5%</td>
</tr>
<tr>
<td>Exp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JES</td>
<td>5.1%</td>
<td>2.4%</td>
<td>3.0%</td>
<td>4.7%</td>
<td>5.5%</td>
</tr>
<tr>
<td>JER</td>
<td>0.4%</td>
<td>6.4%</td>
<td>3.4%</td>
<td>3.9%</td>
<td>5.9%</td>
</tr>
<tr>
<td>MET resol.</td>
<td>0.4%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>0.6%</td>
<td>2.0%</td>
</tr>
<tr>
<td>others</td>
<td>4.4%</td>
<td>12.3%</td>
<td>14.2%</td>
<td>5.4%</td>
<td>17.1%</td>
</tr>
<tr>
<td>Theo.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W+jets</td>
<td>5.9%</td>
<td>9.6%</td>
<td>3.9%</td>
<td>1.6%</td>
<td>6.8%</td>
</tr>
<tr>
<td>TT</td>
<td>5.0%</td>
<td>8.5%</td>
<td>17.5%</td>
<td>15.9%</td>
<td>20.5%</td>
</tr>
<tr>
<td>others</td>
<td>12.7%</td>
<td>20.7%</td>
<td>16.9%</td>
<td>9.2%</td>
<td>16.3%</td>
</tr>
<tr>
<td>Total</td>
<td>15.9%</td>
<td>26.1%</td>
<td>26.9%</td>
<td>19.6%</td>
<td>30.6%</td>
</tr>
</tbody>
</table>