SUSY searches with ATLAS

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QFTHEP - Samara
ATLAS and the LHC are zooming in on the world to understand the unknown.

- Supersymmetry (SUSY) = theory that can explain some of the holes in the Standard Model
- Summarise status of ATLAS searches for SUSY:
  - Bulk and small corners of phase space
  - Variety of different combinations of objects in final states
  - Statistical exclusion limits on some models
  - Searches with hints of new physics
Supersymmetry

- SM particles $\rightarrow$ 1/2 spin $\rightarrow$ SUSY particles
- R-Parity conservation: SUSY particles come in pairs
  - Lightest supersymmetric particle (LSP) is a dark matter candidate $\rightarrow$ missing energy
- Scalar top $\rightarrow$ hierarchy problem / fine tuning
Supersymmetry with ATLAS

Classify searches based on:

- Production cross-section
- Final states after decays
- Decay chain
- Lifetime
- R-parity conservation/breaking

- Simplified models
- LSP = $\tilde{\chi}_1^0$ or $\tilde{G}$ or ...
- Assume prompt decays unless specified otherwise

- Frequently main backgrounds: $t\bar{t}$ & single top, $W$+jets, $Z$+jets, and multijets

- Discriminating variables: $p_T$ of objects, number of leptons, number of jets, scalar sums of $p_T$ (e.g. $m_{\text{eff}}$, $E_T^{\text{miss}}$, $E_T^{\text{miss}}/m_{\text{eff}}$, $m_T$, $m_{T2}$)
Many searches performed but SUSY not (yet?) discovered
Strong Direct Production

\[ \sigma_{tot}[pb]: pp \rightarrow \text{SUSY} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ m_{\text{average}} \text{ [GeV]} \]

\[ \tilde{H}_u \tilde{H}_d \tilde{W}^0 \tilde{B}^0 \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_2 \tilde{\chi}^0_3 \tilde{\chi}^0_4 \]

neutralinos

\[ \tilde{H}_u \tilde{H}_d \tilde{W}^+ \tilde{W}^- \rightarrow \tilde{\chi}^{\pm}_1 \tilde{\chi}^{\pm}_2 \]

charginos
Strong Production: Search for gluinos ($\tilde{g}$) and 1st, 2nd generation scalar quarks ($\tilde{q}$) - $0\ell$ and $\geq 1\ell$ analyses

- Searches cover a wide range of signal models
- Important discriminating variables: $m_{\text{eff}}$, $E_{\text{T}}^{\text{miss}}$, number of leptons, number of jets, lepton $p_T$

Strong Production: Search for $\tilde{g}$ and 1st, 2nd generation $\tilde{q}$ - recently combined $0\ell$ and $\geq 1\ell$ analyses

Combination extends exclusion reach
Z+MET+jets has $3\sigma$ excess

- Of the many strong production searches, this one saw an excess of $3\sigma$
- Gauge Mediated model above = example signal model that can produce this excess
- $Z \rightarrow \ell^+\ell^- : 81 < m_{\ell\ell} < 101$ GeV
- Main backgrounds estimated using data. E.g. $Z$+jets: produce $E_T^{\text{miss}}$ by smearing jets in $p_T, \phi$
Third Generation Direct Production

\[ \sigma_{\text{tot}} \text{[pb]}: pp \rightarrow \text{SUSY} \]
\[ \sqrt{s} = 8 \text{ TeV} \]

SUSY particles

- \( \tilde{u} \), \( \tilde{c} \), \( \tilde{t} \)
- \( \tilde{d} \), \( \tilde{s} \), \( \tilde{b} \)
- \( \tilde{\nu}_e \), \( \tilde{\nu}_\mu \), \( \tilde{\nu}_\tau \)
- \( \tilde{\nu}_\tau \), \( \tilde{\nu}_\mu \), \( \tilde{\nu}_e \)
- \( \tilde{\tau} \), \( \tilde{\mu} \), \( \tilde{\tau} \)

\[ \tilde{H}_u \tilde{H}_d \tilde{W}^0 \tilde{B}^0 \rightarrow \tilde{\chi}_1 \tilde{\chi}_2 \tilde{\chi}_3 \tilde{\chi}_4 \]

neutralinos

\[ \tilde{H}_u \tilde{H}_d \tilde{W}^+ \tilde{W}^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^\pm \]

charginos
3rd Generation: Search for scalar tops summary

- 0 – 2ℓ searches
- Some important discriminating variables:
  \( m_T, m_{T2}, E_T^{\text{miss}} \)
  b-quark jet tagging
- 2-4 body decays
3rd Generation: Search for scalar tops summary structure

Diagonal lines
\[ = \text{kinematic boundaries:} \]
\[ m(\tilde{t}) = \sum_i m(\text{child } i) \]

ATLAS Preliminary
L_{int} = 20 \text{ fb}^{-1} | s = 8 \text{ TeV}

0L [1406.1122]
1L [1407.0583]
2L [1403.4853], 2L [1412.4742]
1L [1407.0583], 2L [1403.4853]
0L [1407.0608]
0L [1407.0608], 1L [1407.0583]
3rd Generation: Scalar tops - Specialised Tools for Specific Features

Boosted parent particles

- Large sized jets
  (top figure: heavy $\tilde{t}$, light $\tilde{\chi}_1^0$)
  (doi: JHEP11(2014)118)

Scalar top masses just above top quark mass

- Spin correlation
  (top figure inset)
  (doi: PhysRevLett.114.142001)

- Re-interpret $t\bar{t}$ cross-section measurement
  (bottom figure)
  (doi: EPJC/s10052-014-3109-7)
3rd Generation: Scalar top - scalar tau $2\ell$

- Many additional signatures possible → check all the different corners of phase space
- Re-interpretation of a $2\ell$ search + additional signal region
- LSP = $\tilde{G} \sim$ massless
- Targets diagonal boundary
- Signal regions:
  Vary jet $p_T$, $m_{T^2}$
3rd Generation: Search for scalar tops - recently combined 0$\ell$ and 1$\ell$ analyses

Statistically combining results extends exclusion

Test different branching ratios for $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$
Electroweak Direct Production

\[ \sigma_{\text{tot}}[\text{pb}]: \text{pp} \to \text{SUSY} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

**SUSY particles**
- \( \tilde{u} \), \( \tilde{c} \), \( \tilde{t} \)
- \( \tilde{d} \), \( \tilde{s} \), \( \tilde{b} \)
- \( \tilde{g} \)
- \( \tilde{H} \)
- \( \tilde{W} \)
- \( \tilde{Z} \)
- \( \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau \)

**Neutralinos and Charginos**
- \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \)
- \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm \)
Electroweak Summary

- Small cross-sections
- Clean multi-lepton final states
- Low hadronic activity
- Searches using $e$, $\mu$, $\tau$
Electroweak: Search for Charginos (\(\tilde{\chi}^{\pm}_{1}\)) and next-to-lightest Neutralinos (\(\tilde{\chi}^{0}_{2}\))

- Hadronically decaying taus (0 e/\(\mu\))
- Not the best search channel; included for variety
- Minimize number of jets
- Some discriminating variables: \(E_{T}^{\text{miss}}\), \(m_{T2}\), and \(m_{T}(\tau_1) + m_{T}(\tau_2)\)

10.1007/JHEP10(2014)096
What about if SUSY particles can decay into SM particles (R-parity violating)?

→ final state without SUSY particles ~ no stable LSP.

What about if the SUSY particles have long lifetimes?
- SUSY particles with long lifetimes (e.g. $\tilde{g}$ or $\tilde{\chi}_1^0$)
- Analyses depend on where in the detector the decay occurs

**ATLAS** Preliminary

95% CL limits, $\sigma_{\text{susy}}$ not included
18.4-20.3 fb$^{-1}$, $\sqrt{s}=8$ TeV

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20 / 23
What’s next?

What is coming up in the near future?

- LHC 2015 = 13 TeV
- How much data is needed before we publish?
13 TeV Strong Direct Production

Production cross-section
8 TeV → 13 TeV:
- Main backgrounds: × 2 – 3
- Gluino pairs: × ~ 10

Discovery sensitivity:
~ 3σ with 2 – 10 fb⁻¹ for masses heavier than those excluded at 8 TeV
Conclusions

- ATLAS has probed a significant amount of phase space
- No SUSY particles discovered ... yet?
- Study the $Z + E_T^{\text{miss}} + \text{jets}$ excess further with 13 TeV data
- First signs of SUSY at 13 TeV could be seen with just $2 - 10 \text{fb}^{-1}$

13 TeV data taking has started!
### Z+MET details

<table>
<thead>
<tr>
<th>On-Z Region</th>
<th>( E_{T}^{\text{miss}} ) [GeV]</th>
<th>( H_T ) [GeV]</th>
<th>( n_{\text{jets}} )</th>
<th>( m_{\ell\ell} ) [GeV]</th>
<th>SF/DF</th>
<th>( E_{T}^{\text{miss}} ) sig. [( \sqrt{\text{GeV}} )]</th>
<th>( f_{\text{ST}} )</th>
<th>( \Delta\phi(\text{jet}<em>{12}, E</em>{T}^{\text{miss}}) )</th>
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<td>SR-Z</td>
<td>( &gt; 225 )</td>
<td>( &gt; 600 )</td>
<td>( \geq 2 )</td>
<td>( 81 &lt; m_{\ell\ell} &lt; 101 )</td>
<td>SF</td>
<td>-</td>
<td>-</td>
<td>( &gt; 0.4 )</td>
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<td><strong>Control regions</strong></td>
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<td>Seed region</td>
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<td>( &gt; 600 )</td>
<td>( \geq 2 )</td>
<td>( 81 &lt; m_{\ell\ell} &lt; 101 )</td>
<td>SF</td>
<td>(&lt; 0.9 )</td>
<td>(&lt; 0.6 )</td>
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<td>CR( \mu )</td>
<td>( &gt; 225 )</td>
<td>( &gt; 600 )</td>
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<td>( 81 &lt; m_{\ell\ell} &lt; 101 )</td>
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<td>CRT</td>
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<td>( &gt; 600 )</td>
<td>( \geq 2 )</td>
<td>( m_{\ell\ell} \notin [81, 101] )</td>
<td>SF</td>
<td>-</td>
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<td>( &gt; 0.4 )</td>
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<td>SF</td>
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<td>VRT</td>
<td>150–225</td>
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<td>( \geq 2 )</td>
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<td>-</td>
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<td>( &gt; 0.4 )</td>
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</tbody>
</table>

\[
H_T = \sum_i p_T^{\text{jet } i} + p_T^{\text{lepton } 1} + p_T^{\text{lepton } 2}
\]

\( p_T^{\text{lepton } 1} > 25 \text{ GeV}, p_T^{\text{lepton } 2} > 10 - 14 \text{ GeV}, p_T^{\text{jet}} > 35 \text{ GeV} \)

Other cuts for \( 10 \text{ GeV} < p_T^{\text{lepton}} < 25 \text{ GeV} \) leptons are tighter than for \( p_T^{\text{lepton}} > 25 \text{ GeV} \) leptons

Other cuts for \( 35 \text{ GeV} < p_T^{\text{jet}} < 50 \text{ GeV} \) jets are tighter than for \( p_T^{\text{jet}} > 50 \text{ GeV} \) jets
Sensitivity at $\sim 2\sigma$ with $5 - 10\text{ fb}^{-1}$ for masses heavier than those excluded at 8 TeV
Variable definitions

\[ m_T(a) = \sqrt{2p_T^a p_T^{miss}} \left(1 - \cos(\Delta \phi)\right) \]

where \( a = e/\mu/\tau \) (assumed massless).

\[ m_{T2}(b, c) = \sqrt{\min_{q_T^b + q_T^c = p_T^{miss}}} \left(\max\left[m_T^2(p_T^b, q_T^b), m_T^2(p_T^c, q_T^c)\right]\right) \]

where \( b, c = \text{hadronic tau, jet, lepton+jet, etc.} \)

\[ H_T = \sum_i p_T^{\text{jet } i} \]

\[ m_{eff} = E_T^{miss} + \sum_i p_T^{\text{jet } i} + \sum_j p_T^{\text{lepton } j} + \sum_k p_T^{\text{hadronic tau } k} \]

Exact definitions are highly analysis dependent (number of jets, pt cut off, etc.).