“Elusive & Exclusive - Highlights from Recent SUSY Searches with ATLAS”

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Outline

• What I will be talking about:
  – Motivation to still search for elusive SUSY
  – 3 select ATLAS searches (exclusive or excessive?)
  – Outlook to the future

• What I will not be talking about (lack of time):
  – Details of detector performance 😞
Open Questions of the Standard Model

- **Hierarchy problem**: Higgs mass subject to quadratically divergent loop corrections. → Unnatural fine-tuning

- **Grand unification**: Standard Model coupling constants do not unify at high scales. → SM does not imply a Grand Unified Theory

- **Dark matter**: Cosmological data suggest presence of dark matter → No explanation within Standard Model
“The Higgs has a snowman’s chance in hell”
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Surface areas by chance within ~ 1% (151,153 km$^2$).
Imagine the difference to be of the size of an atom!
“The Higgs has a snowman’s chance in hell”

Surface areas by chance within ~ 1% (151,153 km²).
Imagine the difference to be of the size of an atom!

Give me a real number between -1 and 1!

0.74683... + -0.00069... + ... + -0.37194... + 0.11489... = 0.00000000000000000000000000001

Analogy by M. Mangano
Never tired of analogies...

Yeah right!

Give me a real number between -1 and 1!

Friend 1: 0.74683...
Friend 2: -0.00069...
...
Friend 9: -0.37194...
Friend 10: 0.11489...

= 0.0000000000000001

Surface areas by chance within ~1% (151,153 km$^2$).

Imagine the difference to be of the size of an atom!

"The Higgs has a snowman's chance in hell"

Analogy by M. Mangano

Yeah right!
We need... Supersymmetry (SUSY)

- **Fundamental symmetry** between fermions and bosons introducing a set of new partner particles to the SM particles with half-spin difference.

- Opposite-sign loop corrections from SUSY particles. **Quadratic divergencies cancel.** → No (little) fine-tuning.

- If R-parity conserved: Lightest SUSY Particle (LSP) stable. → **Natural candidate** for dark matter.

- **Unification** of gauge couplings at $M_{\text{GUT}} \approx 10^{16}$ GeV

\[
\text{R-parity = } (-1)^{3(B-L)+2s}
\]
- SM particles: +1
- SUSY particles: -1

$\sum_{i=1}^{3} 1/\alpha_{i}$
• Higgs boson discovery and strong experimental bounds have put vanilla SUSY under pressure
• Search efforts focus around “Natural SUSY” (e.g. arXiv:1110.6926) as a possible (the last?) way out
• Within the MSSM stop and gluino masses enter at 1 and 2 loop level into the Higgs mass matrix, the Higgsino mass parameter $\mu$ at tree level!
→ Requires relatively light gluinos, stops, higgsinos, remaining SUSY particles decoupled at high masses
How to search for SUSY at the LHC

- If SUSY particles exist at LHC accessible energies and R-parity is conserved:
  - Pair-production
  - Direct or cascade decays to the stable lightest SUSY particle (LSP).

- Experimental signature of inclusive searches:
  - Significant missing transverse energy ($E_T^{\text{miss}}$)
  - Multiple high-$p_T$ jets
  - Other objects, e.g. leptons, photons

- Search strategy @ 13 TeV:
  - Early data: Gluino & 1$^{\text{st}}$/2$^{\text{nd}}$ generation squark searches have the largest potential due to high cross-sections (increase)
  - Beyond ~ 10fb$^{-1}$: Searches for third generation squarks start to exceed Run-1 sensitivity
  - The future: Electro-weak SUSY searches need large amounts of data due to low cross-sections
Searches discussed in this Seminar

• If SUSY particles exist at LHC accessible energies and R-parity is conserved:
  - Pair-production
  - Direct or cascade decays to the stable lightest SUSY particle (LSP).

• Experimental signature of inclusive searches:
  - Significant missing transverse energy ($E_{T,\text{miss}}$)
  - Multiple high-$p_T$ jets
  - Other objects, e.g. leptons, photons

• Search strategy @ 13 TeV:
  - Early data: Gluino & 1st/2nd generation squark searches have the largest potential due to high cross-sections (increase)
  - Beyond ~ 10 fb$^{-1}$: Searches for third generation squarks start to exceed Run-1 sensitivity
  - The future: Electro-weak SUSY searches need large amounts of data due to low cross-sections

• Will present a selection of 3 interesting recent results with up to ~14.8 fb$^{-1}$:
  - Inclusive searches for gluinos & squarks:
    - 1-lepton + jets + $E_{T,\text{miss}}$ ("Inclusive 1-lepton")
    - $Z$ + jets + $E_{T,\text{miss}}$ ("Inclusive $Z$ + MET")
  - 3rd generation quarks:
    - 1-lepton + (b-)jets + $E_{T,\text{miss}}$ ("Stop 1-lepton")
  - Outlook to electro-weak searches

• Important areas of activity that I will not touch upon:
  - R-parity violating models
  - Long-lived particles
What happened so far...

Largest local significance

Run-1 / 8 TeV

- arXiv:1501.03555
  SR: 3J
- arXiv:1407.0583
  SR: bCa_low
- arXiv:1503.03290
  SR: Z

Run-2 / 13 TeV

- arXiv:1605.04285
  SR: 6J
- arXiv:1606.03903
  SR: SR1
- ATLAS-CONF-2015-082
  SR: Z
- ATLAS-CONF-2016-054
  SR: 6J

This talk!
Inclusive 1-lepton Search

- Target final state: 1 lepton (soft/hard) + jets + $E_T^{\text{miss}}$

- Benchmark scenario:
  - Simplified model with gluino production and 1-step decay via chargino to LSP (100% branching ratio)
  - Simplified model parameter space defined in terms of three parameters: gluino / squark mass, neutralino mass, mass ratio parameter x

- Define two model planes to probe optimal slices of parameter space
  - $(m_{\tilde{g}/\tilde{q}}, m_{\tilde{\chi}_1^0})$ with fixed mass ratio parameter $x = \frac{1}{2}$
  - $(m_{\tilde{g}/\tilde{q}}, $ mass ratio parameter $x$) with $m_{\tilde{\chi}_1^0}$ fixed to 60 GeV
Inclusive 1-lepton: Gluino Signal Regions

- Targeting small mass differences, difficult to distinguish from SM backgrounds

**Initial State Radiation**
- SUSY system recoils against hard initial state radiation jet
  - LSPs more aligned
  - Enhanced $E_{T,\text{miss}}$
  - Hard (ISR) jet
- Soft-lepton useful to discriminate against multijet background

**GG 2J**

<table>
<thead>
<tr>
<th>$N_{gg}$ (preselected)</th>
<th>$p_T$ (GeV)</th>
<th>$N_{gg}$</th>
<th>$p_T$ (GeV)</th>
<th>$m_T$ (GeV)</th>
<th>$E_{T,\text{miss}}$ (GeV)</th>
<th>$E_{T,\text{miss}}/m_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>10</td>
<td>4</td>
<td>250</td>
<td>0.1</td>
</tr>
<tr>
<td>[7(6), 35]</td>
<td>30</td>
<td>100</td>
<td>&gt; 125</td>
<td>&gt; 0.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS**

- GG 2J soft-lepton
- Observed limit at 95% CL
- Expected limit at 95% CL
- 1-lepton alone
- 0-lepton alone
- All limits at 95% CL

**Signal Regions**

- 0L + 1L combination
- $s=8\text{ TeV}, 20\text{ fb}^{-1}$

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Inclusive 1-lepton: Gluino Signal Regions

*Many high pT jets from the first decay step. Tight cuts on:*
- Missing transverse energy
- Effective mass: $m_{\text{eff}} = E_{\text{T}}^{\text{miss}} + \sum p_{\text{T}}^{\text{jet}} + \sum p_{\text{T}}^{\text{lepton}}$
- Jet aplanarity (measure of the sphericity of the event)

### GG 2J
- $N_{\text{had}}$ (preselected) = 1
- $p_{\text{T}}^{\text{jet}}$ (GeV) ≥ 2
- $m_{\text{g}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}$ (GeV) > 460
- $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$ > 0.35

### GG 4J low-x
- $N_{\text{had}}$ (preselected) = 1
- $p_{\text{T}}^{\text{jet}}$ (GeV) ≥ 4
- $m_{\text{g}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$ > 0.35

### GG 4J low-x b-jet
- $N_{\text{had}}$ (preselected) = 1
- $p_{\text{T}}^{\text{jet}}$ (GeV) ≥ 4
- $m_{\text{g}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$ > 0.35

### GG 4 high-x
- $N_{\text{had}}$ (preselected) = 1
- $p_{\text{T}}^{\text{jet}}$ (GeV) ≥ 6
- $m_{\text{g}}$ (GeV) > 125
- $E_{\text{T}}^{\text{miss}}$ (GeV) > 225
- $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$ > 0.35

### GG 6 low mass
- $N_{\text{had}}$ (preselected) = 1
- $p_{\text{T}}^{\text{jet}}$ (GeV) ≥ 6
- $m_{\text{g}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$ > 0.35

### GG 6 bulk
- $N_{\text{had}}$ (preselected) = 1
- $p_{\text{T}}^{\text{jet}}$ (GeV) ≥ 6
- $m_{\text{g}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}$ (GeV) > 100
- $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$ > 0.35

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Inclusive 1-lepton: Gluino Signal Regions

**GG 2J**

- $N_{\text{lep}}$ (preselected) = 1
- $p_T > 7(6)$
- $N_{\text{jet}}^2 \geq 2$
- $p_T > 100$
- $E_T^{\text{miss}} > 100$
- $E_T^{\text{miss}} / m_{\text{eff}} > 0.35$

**GG 4J low-x**

- $N_{\text{lep}} = 1$
- $p_T > 7(6)$
- $N_{\text{jet}} \geq 4$
- $p_T > 100$
- $E_T^{\text{miss}} > 100$
- $E_T^{\text{miss}} / m_{\text{eff}} = 0$

- $p_T > 125$
- $p_T > 250$
- $p_T > 2000$
- $E_T^{\text{miss}} > 0.06$

**GG 4J low-x b-veto**

- Same as GG 4J low-x with b-jet veto to enhance sensitivity for exclusion

**GG 4J high-x**

- $N_{\text{lep}} = 1$
- $p_T > 35$
- $N_{\text{jet}} \geq 4$
- $p_T > 100$
- $E_T^{\text{miss}} > 100$
- $E_T^{\text{miss}} / m_{\text{eff}} > 0.3$

- $p_T > 475$
- $p_T > 225$
- $p_T > 1600$
- $E_T^{\text{miss}} > 0.3$

**GG 6J high-mass**

- $N_{\text{lep}} = 1$
- $p_T > 35$
- $N_{\text{jet}} \geq 4$
- $p_T > 100$
- $E_T^{\text{miss}} > 100$
- $E_T^{\text{miss}} / m_{\text{eff}} > 0.3$

- $p_T > 225$
- $p_T > 250$
- $p_T > 2000$
- $E_T^{\text{miss}} > 0.1$

**GG 6J bulk**

- $N_{\text{lep}} = 1$
- $p_T > 35$
- $N_{\text{jet}} \geq 4$
- $p_T > 100$
- $E_T^{\text{miss}} > 100$
- $E_T^{\text{miss}} / m_{\text{eff}} > 0.3$

- $p_T > 225$
- $p_T > 250$
- $p_T > 1000$
- $E_T^{\text{miss}} > 0.2$

- $m_T > 0.4$

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**ATLAS**

- **GG 2J soft-lepton**

- **GG 4J low-x b-veto**

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Inclusive 1-lepton: Gluino Signal Regions

- Lower jet $p_T$ thresholds due to small mass differences in first decay step
- One energetic jet and one hard lepton from second decay step (hadronic / leptonic W decay)
- Tight cut on transverse mass between lepton and $E_{T}^{\text{miss}}$
- No aplanarity requirement
Inclusive 1-lepton: Gluino Signal Regions

- Targets high mass scenario
- Many jets with high $p_T$ thresholds
- Tight cuts on effective mass: $m_{\text{eff}} = E_T^{\text{miss}} + \sum p_T^{\text{jet}} + \sum p_T^{\text{lepton}}$
- Aplanarity cut (many high $p_T$ objects in the event)

### GG 6J high-mass

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{jet}}$ (preselected)</td>
<td>$&gt; 100$</td>
</tr>
<tr>
<td>$p_T^{\text{jet}}$ (GeV)</td>
<td>$&gt; 100$</td>
</tr>
<tr>
<td>$m_T$ (GeV)</td>
<td>$&gt; 460$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ (GeV)</td>
<td>$&gt; 0.35$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} / m_{\text{eff}}$</td>
<td>$&gt; 125$</td>
</tr>
<tr>
<td>$p_T^{\text{lepton}}$ (GeV)</td>
<td>$&gt; 250$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ (GeV)</td>
<td>$&gt; 0.65$</td>
</tr>
<tr>
<td>$N_{\text{jet}}^{\text{inc}}$</td>
<td>$&gt; 300$</td>
</tr>
<tr>
<td>$N_{\text{lepton}}$</td>
<td>$&gt; 1000$</td>
</tr>
</tbody>
</table>

### GG 6J high-x

- $N_{\text{jet}}^{\text{inc}}$ (GeV)
- $p_T^{\text{jet}}$ (GeV)
- $m_T$ (GeV)
- $E_T^{\text{miss}}$ (GeV)
- Aplanarity cut

### GG 4J high-x b-veto

### GG 4J low-x

- $N_{\text{jet}}^{\text{inc}}$ (GeV)
- $p_T^{\text{jet}}$ (GeV)
- $m_T$ (GeV)
- $E_T^{\text{miss}}$ (GeV)
- Aplanarity cut

### GG 2J soft-lepton

### GG 6J high-mass

- $N_{\text{jet}}$ (preselected)
- $p_T^{\text{jet}}$ (GeV)
- $m_T$ (GeV)
- $E_T^{\text{miss}}$ (GeV)
- Aplanarity cut

### GG 4J high-x

- $N_{\text{jet}}^{\text{inc}}$ (GeV)
- $p_T^{\text{jet}}$ (GeV)
- $m_T$ (GeV)
- $E_T^{\text{miss}}$ (GeV)
- Aplanarity cut

### GG 4J low-x b-veto

- $N_{\text{jet}}^{\text{inc}}$ (GeV)
- $p_T^{\text{jet}}$ (GeV)
- $m_T$ (GeV)
- $E_T^{\text{miss}}$ (GeV)
- Aplanarity cut
### Inclusive 1-lepton: Gluino Signal Regions

**E_{T}^{miss} trigger**

- Targeting intermediate region
- Many jets with medium/loose p_T thresholds
- Medium cuts on all discriminating variables
- 2.6σ data surplus in 3.2fb⁻¹@13TeV result

<table>
<thead>
<tr>
<th>GG 2J</th>
<th>GG 4J</th>
<th>GG 6J high-mass</th>
<th>GG 6J bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{by} (preselected)</td>
<td>= 1</td>
<td>= 1</td>
<td>= 1</td>
</tr>
<tr>
<td>p_T (GeV)</td>
<td>≥ 7</td>
<td>≥ 7</td>
<td>≥ 35</td>
</tr>
<tr>
<td>m_{T} (GeV)</td>
<td>≥ 100</td>
<td>≥ 100</td>
<td>≥ 225</td>
</tr>
<tr>
<td>ΔM (GeV)</td>
<td>≥ 6</td>
<td>≥ 6</td>
<td>≥ 6</td>
</tr>
<tr>
<td>Δχ (GeV)</td>
<td>≥ 4</td>
<td>≥ 4</td>
<td>≥ 4</td>
</tr>
</tbody>
</table>

**Targeting intermediate region**

- Many jets with medium/loose p_T thresholds
- Medium cuts on all discriminating variables
- 2.6σ data surplus in 3.2fb⁻¹@13TeV result

**GG 2J soft-lepton**

- gg → qqqqWW, x=1/2
- Observed limit @8 TeV, 20 fb⁻¹
- All limits at 95% CL

**GG 6J bulk**

- Signal
- Regions
- 1-lepton alone
- 0-lepton alone
- ATLAS
- Observed limit (w/1 σ)
- Expected limit (w/1 σ)
- All limits at 95% CL

**GG 4J high-x**

- Decay forbidden

**GG 4J low-x b-veto**

- Atlas result

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# Inclusive 1-lepton: Squark Signal Regions

**E_{T}^{miss} trigger**

\[ m_{q} \]

\[ \Delta M \]

\[ \Delta m \]

\[ m_{\tilde{q}} \]

\[ m_{\tilde{x}^{\pm}} \]

\[ m_{\tilde{x}^{0}} \]

<table>
<thead>
<tr>
<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>( N_{lep} ) (preselected)</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>
</tr>
<tr>
<td>( N_{H} )</td>
<td>( &gt; 0 )</td>
<td>( = 0 )</td>
<td>( &gt; 0 )</td>
</tr>
<tr>
<td>( m_{T}^{(GeV)} )</td>
<td>[150, 400]</td>
<td>&gt; 400</td>
<td>&gt; 175</td>
</tr>
<tr>
<td>( E_{T}^{miss} ) (GeV)</td>
<td>&gt; 250</td>
<td>&gt; 400</td>
<td>&gt; 300</td>
</tr>
<tr>
<td>( m_{T}^{ll} ) (GeV)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( m_{T}^{ll}/m_{T} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Models:**

- SS 4J low-x
- SS 5J high-x
- SS 4J x=1/2
- SS 5J x=1/2

**Plot:**

ATLAS

\( \tilde{q} \tilde{q} \rightarrow qW_{L}W_{L}^{*} \tilde{\chi}_{1}^{0}, m(\tilde{\chi}_{1}^{0}) = 60 \text{ GeV} \)

\[ x = \frac{\Delta m^{2}}{m_{\tilde{q}}^{2}} \]

\[ \Delta m^{2} \]

\[ m_{\tilde{q}} \]

\[ m_{\tilde{x}^{0}} \]

**Graphs:**

ATLAS

- Observed limit (± 1 \( \sigma_{\text{exp}} \))
- Expected limit (± 1 \( \sigma_{\text{exp}} \))
- Hard 1-lepton obs./exp.
- Soft 1-lepton obs./exp.
- All limits at 95% CL

**Data:**

- \( s = 8 \text{ TeV}, 20 \text{ fb}^{-1} \)

**References:**

- PRD 86 (2012) 092002

**Author:**

Moritz Backes

**Date:**

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Major backgrounds: \(tt & W+jets\) (diboson for squark signal regions)

1. Define control regions (CRs) that are enriched in the process of interest & normalise simulation
2. Extrapolation based on simulation from CRs to validation regions (VRs) and eventually to the SRs

\[\rightarrow\] Optimization of CR and VR selections:
- Theoretical uncertainties (proximity to the SRs)
- Statistics in CRs
- Signal contamination

Smaller backgrounds:
- \(tt+V\), single-top, (di-boson for gluino signal regions), \(Z+jets\), etc. taken from simulation
- Fake-lepton background negligible
Inclusive 1-lepton: Validation & Results

Background estimates well validated!

No significant deviations from SM 😞
Previously observed $2.1\sigma$ excess in GG 6J bulk reduced to $1.2\sigma$ ($2.6\sigma \rightarrow 1.8\sigma$ in muon channel).
Inclusive 1-lepton: Interpretation
• Looking for SUSY models with Z-boson production along the decay chains

• Has been a hot topic for a while following interesting 8 TeV & first 13 TeV results

• Signature: $l^+l^- + \text{jets} + E_{T,\text{miss}}$

Benchmark simplified model

Signal region ("SRZ")

\[
\begin{array}{cccccc}
E_{T,\text{miss}} & H_{T,\text{incl}} & n_{\text{jets}} & m_{\ell\ell} \\
[\text{GeV}] & [\text{GeV}] & & [\text{GeV}] \\
> 225 & > 600 & \geq 2 & 81 < m_{\ell\ell} < 101 \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{SF/DF} & \Delta \phi(\text{jet}_{12}, p_{T,\text{miss}}) & m_T(\ell_3, E_{T,\text{miss}}) & n_{b,\text{jets}} \\
\text{[GeV]} & & [\text{GeV}] & \\
\text{SF} & > 0.4 & - & - \\
\end{array}
\]

\[
\rightarrow \text{SRZ essentially unchanged since Run-1}
\]
Z+MET: Backgrounds

- **Flavour symmetric** background:
  - Backgrounds with ee / μμ final states
  - Dominated by t\(\bar{t}\) (50-70%), Wt, Z \(\rightarrow\) ττ
  - Constitutes 60% of total backgrounds
  - Estimated using the so-called “flavour symmetry” method based on eμ control sample

- **Z/gamma* + jets** background:
  - Arises from met mismeasurements
  - Well suppressed due to met requirements (constitutes around 5% of total background)
  - However: Difficult to model and can mimic signal
  - Estimated using photon + jets control sample

- **WW/ZZ diboson** background:
  - Constitutes 30% of total backgrounds,
  - Estimated with simulation and cross-checked in validation regions

- **Rare top** background (ttW,ttZ,ttWW processes):
  - Constitutes ~ 5% of total backgrounds → From simulation

- **Fake / non-prompt lepton** background:
  - Sub-% level → Estimated with data-driven matrix method
• Flavour-symmetric backgrounds have 2 leptons from separate W decays

• Estimate background with opposite flavour events based on \( N_{ee} + N_{\mu\mu} = N_{e\mu} \)

• Apply corrections for:
  – Contamination of non flavour-symmetric backgrounds
  – Electron vs. muon reconstruction and identification efficiencies
  – Di-electron / di-muon vs. e\(\mu\) trigger efficiencies
Z+MET: Flavour-Symmetry Method

Correction for contamination of non flavour-symmetric processes in eµ control sample

\[ N_{ee}^{\text{est}} = \frac{1}{2} \cdot f_{FS} \cdot f_{Z-\text{mass}} \sum_{i} k_{e}(p_{T}^{i,\mu}, \eta^{i,\mu}) \cdot \alpha(p_{T}^{i,\mu}, \eta^{i,\mu}), \]

\[ N_{\mu\mu}^{\text{est}} = \frac{1}{2} \cdot f_{FS} \cdot f_{Z-\text{mass}} \sum_{i} k_{\mu}(p_{T}^{i,e}, \eta^{i,e}) \cdot \alpha(p_{T}^{i,e}, \eta^{i,e}), \]

Sum over eµ control data with lepton \((p_{T}, \eta)\) – dependent correction factors:

* e vs. µ offline reconstruction and identification efficiency
* di-e / di-µ vs. eµ trigger efficiencies

Fraction in eµ control data that is contained within the SR’s invariant mass window

(invariant mass window widened in CR to triple control region statistics)
Perform likelihood fit in Z-mass sidebands (CRT) which is dominated by tT (~75%)

- All BG processes from MC
- tT normalisation floating (norm factor = 0.64)
- Extrapolation of prediction to signal region (CRT \rightarrow SRZ)

- Fit & flavour symmetry method repeated also in lower MET region to validate extrapolation

→ Excellent agreement in both regions:

<table>
<thead>
<tr>
<th>Region</th>
<th>Flavour-symmetry</th>
<th>Sideband fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRZ</td>
<td>33 ± 4</td>
<td>29 ± 7</td>
</tr>
<tr>
<td>VR-S</td>
<td>99 ± 8</td>
<td>92 ± 25</td>
</tr>
</tbody>
</table>

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Z+MET: Z/\gamma* + jets background

- Exploit similar kinematics between Z+jets and photon+jets events
  - Both have $E_{T,\text{miss}}$ from jet mis-measurements

- Smearing of photon $p_T$ according to $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ resolution function

- Reweighting of $p_T(\gamma)$ to match $p_T(Z)$
Z+MET: Validation: Z/gamma* + jets

- Validation of predictions in dedicated validation region VRZ:
  - $e^+e^-/\mu^+\mu^-$ leptons, $p_T > (50,25)$ GeV, $m_{ll} 81-101$ GeV
  - 2 jets, $p_T > 30$ GeV, $H_T > 600$ GeV, $\Delta\phi$ (jet$_{1,2}$, $E_{T,\text{miss}}$ cut) > 0.4

→ Excellent agreement on MC closure test and validation on data
Perfect agreement with the expectation in the SR

The previously observed excess has disappeared
ATLAS Preliminary

Gluino production

Squark production

ATLAS Preliminary

Gluino production
Stop Production & Decay

• $t^-$ $t^*$ production:
  – Cross-section suppressed w.r.t. to gluino and light squark production

• Decay modes:
  – Only $t^-$ and $X^0$ accessible: $t^- \rightarrow t + X^0$ with on- / off-shell $t$
    and W or loop-suppressed decay with charm
  – If $X^\pm$ in reach: $t^- \rightarrow b + X^\pm \rightarrow W + X^0$ with on- / off-shell W

→ To cover all interesting ground need searches for **light & heavy** stops

→ Compressed off-shell scenarios require large amounts of data:
  Not an early search (but competitive 8 TeV results)
Stop 1-lepton Search

- Latest 13 TeV search considers heavy stop production with stop → top neutralino and stop → b + chargino decays

- In addition dedicated signal regions for dark matter production via spin-0 mediator

- Signature: **1-lepton + (b-)jets + E_{T,miss}**

→ First serious direct stop production search with ATLAS @ 13 TeV
Stop 1-lepton: Discriminating Variables

- Standard variables to discriminate against multi-jets (misid. & non-prompt leptons), W+jets & semi-lepton tT: $E_{T,\text{miss}}$, $m_T$, $\Delta\phi (\text{jet}_{1,2}, E_{T,\text{miss}})$

- $H_{T,\text{miss}}$ significance: Effective against multi-jets

- $m_{\chi^*}\text{top}$: Invariant mass of the 3 jets most compatible with hadronic top decay leg

- **Asymmetric $a m_{T2}$ and $m_{T2}^T$:** Generalization of the transverse mass applied to signatures where two particles are not directly detected: $a m_{T2}$ (dileptonic tT & one lepton not reconstructed), $m_{T2}^T$ (dileptonic tT with hadronic tau).

- **Topness:** $\chi^2$ minimization quantifying the compatibility with a dileptonic tT event where one lepton is not reconstructed.

- $E_{T,\text{miss}}^{\perp}$: In semi-leptonic top decays $E_{T,\text{miss}}$ component perpendicular to the top decay leg larger in SUSY events due to $E_{T,\text{miss}}$ from LSP.

(a) SM $t\bar{t}$ decay

(b) $t\bar{t}^*$ decay
Stop 1-lepton: Signal Regions

- Targets stop $\rightarrow$ top + LSP

- **SR1**: low mass splitting $\Delta m$ where all decay products are resolved
  $\rightarrow$ a 2.3σ excess was observed in this region in the 3.2fb$^{-1}$ @ 13TeV analysis.

- **tN_high**: large mass splitting $\Delta m$ with very boosted top quarks where decay products are very close by and can be reconstructed in a single jet
• Targets stop → b + chargino

\[ \text{bC2x}\_\text{diag} \quad \text{&} \quad \text{bC2x}\_\text{med}: \]
Covering models with \( m_{\tilde{\chi}^\pm} = 2m_{\tilde{\chi}^0} \) with small and large mass splittings

• bCbv: Designed for models where \( \Delta M \) is small (10 GeV) & \( \Delta m \) is large
  
  – Soft b-jets cannot be reconstructed → b-veto to suppress t\( T \)
  
  – W very boosted → W-mass cut on large-R jet mass
Stop 1-lepton: Signal Regions

- **Targets dark matter production**

![](image)

- **DM_low & DM_high**: Designed to be sensitive to low-mass and high-mass dark matter production in associated with top quarks

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR1</th>
<th>tN_high</th>
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</thead>
<tbody>
<tr>
<td>Number of (jets, b-tags)</td>
<td>(≥ 4, ≥ 1)</td>
<td>(≥ 4, ≥ 1)</td>
</tr>
<tr>
<td>Jet $p_T &gt;$ [GeV]</td>
<td>(80 50 40 40)</td>
<td>(120 80 50 25)</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>≥ 260</td>
<td>≥ 450</td>
</tr>
<tr>
<td>$E_T,_{\perp}$ [GeV]</td>
<td>≥ 14</td>
<td>≥ 22</td>
</tr>
<tr>
<td>$H_{T,\text{sig}}$</td>
<td></td>
<td>≥ 180</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>≥ 170</td>
<td>≥ 210</td>
</tr>
<tr>
<td>$amT_2$ [GeV]</td>
<td>≥ 175</td>
<td>≥ 175</td>
</tr>
<tr>
<td>topness</td>
<td>≥ 6.5</td>
<td></td>
</tr>
<tr>
<td>$m^{\ell}_{\text{top}}$ [GeV]</td>
<td>≤ 270</td>
<td></td>
</tr>
<tr>
<td>$\Delta R(b, \ell)$</td>
<td>≤ 3.0</td>
<td>≤ 2.4</td>
</tr>
<tr>
<td>Leading large-R jet $p_T$ [GeV]</td>
<td></td>
<td>≥ 290</td>
</tr>
<tr>
<td>Leading large-R mass [GeV]</td>
<td></td>
<td>≥ 70</td>
</tr>
<tr>
<td>$\Delta \phi(P_T^{\text{miss}}, 2_{\text{ndlarge-R jet}})$</td>
<td></td>
<td>≥ 0.6</td>
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</table>

<table>
<thead>
<tr>
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<th>bC2x_med</th>
<th>bCbv</th>
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<td>(≥ 4, ≥ 2)</td>
<td>(≥ 4, ≥ 2)</td>
<td>(≥ 2, = 0)</td>
</tr>
<tr>
<td>$b$-tagged jet $p_T &gt;$ [GeV]</td>
<td>(25 25)</td>
<td>(105 100)</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>≥ 230</td>
<td>≥ 210</td>
<td>≥ 360</td>
</tr>
<tr>
<td>$H_{T,\text{sig}}$</td>
<td>≥ 14</td>
<td>≥ 7</td>
<td>≥ 16</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>≥ 170</td>
<td>≥ 140</td>
<td>≥ 200</td>
</tr>
<tr>
<td>$amT_2$ [GeV]</td>
<td>≥ 170</td>
<td>≥ 210</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi(jet, P_T^{\text{miss}})(i = 1)</td>
<td>$</td>
<td>≥ 1.2</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi(jet, P_T^{\text{miss}})(i = 2)</td>
<td>$</td>
<td>≥ 0.8</td>
</tr>
<tr>
<td>Leading large-R jet $p_T$ [GeV]</td>
<td></td>
<td></td>
<td>[70, 100]</td>
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<tr>
<td>$\Delta \phi(P_T^{\text{miss}}, \ell)$</td>
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<td></td>
<td>≥ 1.2</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>DM_low</th>
<th>DM_high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of (jets, b-tags)</td>
<td>(≥ 4, ≥ 1)</td>
<td>(≥ 4, ≥ 1)</td>
</tr>
<tr>
<td>Jet $p_T &gt;$ [GeV]</td>
<td>(60 60 40 25)</td>
<td>(50 50 50 25)</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>≥ 300</td>
<td>≥ 330</td>
</tr>
<tr>
<td>$H_{T,\text{sig}}$</td>
<td>≥ 14</td>
<td>≥ 9.5</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>≥ 120</td>
<td>≥ 220</td>
</tr>
<tr>
<td>$amT_2$ [GeV]</td>
<td>≥ 140</td>
<td>≥ 170</td>
</tr>
<tr>
<td>$\min(</td>
<td>\Delta \phi(P_T^{\text{miss}}, \text{jet}))(i \in {1 \cdots 4})</td>
<td>$</td>
</tr>
<tr>
<td>$\Delta \phi(P_T^{\text{miss}}, \ell)$</td>
<td>≥ 0.8</td>
<td></td>
</tr>
</tbody>
</table>
Stop 1-lepton: Background Estimation

- Dominant backgrounds isolated in dedicated control regions
  - \( W+\text{jets} / tT \rightarrow \text{WCR/TCR} \):
    - Standard approach of b-veto / 1 b-jet control regions with associated validation regions
    - Purity 75% / 50-90%
  - \( \text{Single-top Wt} \rightarrow \text{STCR} \):
    - 2 b-jets requirement (additional b from intial state), high \( m_{T2} \) since mass from Wb system higher than from top-quark
    - Purity \( \sim 40-50\% \)
  - \( \text{tt+Z(} \rightarrow \nu \nu) \rightarrow \text{TZCR} \):
    - Irreducible background, estimation based on \( \text{tt+}\gamma \) events with \( \gamma \) to \( E_{T,\text{miss}} \) (approximation valid at large boson \( p_T \))
    - Purity \( \sim 90\% \)
Stop 1-lepton: Validation & Results

- Excellent agreement in all validation regions
- Deviations of 3.3/2.6/2.2 $\sigma$ observed in SRs DM_low, bC2x_diag, SR1 $\rightarrow$ signal regions are correlated
- Small excess of 2.3 from 3.2@13TeV results persists
Stop 1-lepton: Interpretations

ATLAS Preliminary

26/10/16

Moritz Backes
To summarize...

Largest local significance

Run-1 / 8 TeV
- 4σ
  - arXiv:1503.03290
    SR: Z
  - arXiv:1407.0583
    SR: bCa_low
- 3σ
  - arXiv:1501.0355
    SR: 3J
- 2σ
- 1σ

Run-2 / 13 TeV
- 4σ
  - ATLAS-CONF-2016-050
    SR: DM_low
  - ATLAS-CONF-2016-054
    SR: 6J
- 3σ
  - ATLAS-CONF-2015-082
    SR: Z
- 2σ
  - ATLAS-CONF-2016-050
    SR: 6J
  - ATLAS-CONF-2016-098
    SR: Z

Inclusive 1-lepton
Stop 1-lepton
Inclusive Z+MET

Luminosity [fb⁻¹]

26/10/16 Moritz Backes
Can we ever kill SUSY?

- **SUSY is a many headed monster!**
- **Our currently best attempt to broadly attack the monster are pMSSM scans:**
  - Reinterpretation of many ATLAS SUSY searches in a 19 parameter pMSSM model
  - Assumptions: R-parity conservation, minimal flavor violation, no additional CP violation, degeneracy of 1\textsuperscript{st} /2\textsuperscript{nd} generation squarks and sleptons
  - For Run-1 result: 500 millions pMSSM points randomly sampled, with $\sim$ 300 000 models surviving theory & non-LHC experimental constraints

First results on 13 TeV scan: Barr & Liu
pMSSM $\tilde{\chi}_1^0$ LSP
13 TeV, 3.2 fb$^{-1}$

1S = 8 TeV, 20.3 fb$^{-1}$
• Electro-weak SUSY searches:
  – The future !
  – Out last chance (?)

• Suppressed production cross-sections for electroweak SUSY particles at hadron colliders thus small signal acceptance

→ Mass limits significantly weaker than in strong production searches

→ Light SUSY still possible ?
• Natural SUSY seems in trouble:
  – Strong bounds from the LHC on gluinos (~ 2 TeV) and stop (~ 800 GeV)

• No further significant jump in center of mass energy foreseen in a long time thus little prospect of significantly enhanced limits

• Reminder: Higgsino mass parameter $\mu$ enters at tree level into the Higgs mass matrix!

→ Searches for Higgsinos at the LHC may be our last experimental window to natural Supersymmetry!

→ LEP limits @ $m_\chi > 92$ GeV are currently still our strongest bounds!

LEP SUSY Working Group:
http://lepsusy.web.cern.ch/lepsusy/Welcome.html
Search Strategies

- Final state:
  - Multiple **very soft leptons** from virtual $W/Z$ decays $\rightarrow$ Very difficult to distinguish from SM

- Need experimental handles:
  - Initial or final state radiation (jet, photon)
  - VBF
Experimental Challenges

• What do we need for this:
  – **Lots of data**: Strong physics case for Run-3 / HL-LHC
  – **Excellent detector performance**: Ultra low-$p_T$ lepton reconstruction to maximize acceptance
  – **Advanced analysis techniques** (e.g. machine learning techniques) to get the maximum out of the data
  – **Low trigger thresholds** vs. high-luminosity high pile-up environment
    • Multi-object triggers with topological requirements (L1Topo)
    • Reconstruction of charged tracks and their vertex associations in e.g. $E_{T,\text{miss}}$ triggers (FTK and phase1/2 trigger upgrades)

→ A long-term project!
Conclusions

- Vast search program at the LHC in order to make a conclusive statement about the existence of weak-scale SUSY

- Strong effort concentrating around natural SUSY to find traces of:
  - Gluinos
  - 3rd generation squarks
  - Higgsinos

- Despite several mild deviations from the SM no convincing signs of SUSY yet at 13 TeV

- However, searches for gluinos and 3rd generation squarks remain interesting!

- Eventually only a long term Higgsino search program may be able to answer the question:

  **Do we live in fine-tuned or a natural supersymmetric universe?**