SUSY Strong production

Search for gluino-mediated stop and bottom pair production in events with $b$-jets and large missing transverse momentum

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Motivation

- Supersymmetry (SUSY) at the LHC: high gluino cross section @ 13 TeV
  - Stops and sbottoms decay to corresponding quark + LSP (neutralino)
- Typical signature for 3rd generation, R-parity conserving, Supersymmetry (3G RPC SUSY) models
  - Large number of $b$-jets
  - High missing transverse energy (MET)
  - Lorentz-boosted W bosons and top quarks in certain regions of parameter space
- Prior analyses done: Run 1, 2015 paper, ATLAS-CONF-2016-052, and ATLAS-CONF-2017-021
Parameterizing the model

- Looked for SUSY here and did not find it.
- Mass of neutralino: $m_{\tilde{\chi}_0}$
- Mass of gluino: $m_{\tilde{g}}$

- $m_{\tilde{g}} \sim 2 \times m_{\tilde{\chi}_0}$: more jets, less energy per jet.
- $m_{\tilde{g}} \gg m_{\tilde{\chi}_0}$: fewer jets, more energy per jet.
- Mergered decays.
Run I results

\[ \tilde{g}\tilde{g} \text{ production, } \tilde{g} \rightarrow t\bar{t}+\tilde{\chi}_1^0, m(\tilde{q}) \gg m(\tilde{g}) \]

\[ L^{\text{int}} = 20.1 \text{ fb}^{-1}, \ S = 8 \text{ TeV} \]

**ATLAS**

0 and 1 lepton + 3 b-jets channels

Excluded up to 1.4 TeV

10.1007/JHEP10(2014)024
Objects of Interest

Signal: 4 top quarks

- Small energetic jets
- Large reclustered jets
- Leptons: electrons and muons
- High missing transverse energy
- MET trigger

Background: 2 top quarks

![Graph showing data for ATLAS Preliminary analysis with 0L Preselection, showing events vs. number of jets with various backgrounds and signal points at different mass values.](image-url)
Data/Simulation Comparison

\textbf{ATLAS Preliminary}
\(\sqrt{s}=13\ \text{TeV}, \ 36.1\ \text{fb}^{-1}\)

0L Preselection

\begin{itemize}
  \item Data
  \item Total background
  \item \(t\bar{t}\)
  \item Single top
  \item \(t\bar{t} + X\)
  \item \(Z+\text{jets}\)
  \item \(W+\text{jets}\)
  \item Diboson
  \item Multijet
\end{itemize}

- \(b\)-jets
- \(0\) leptons

\textbf{ttbar-enhanced}
\(\text{MET} > 200\ \text{GeV}\)
\(\geq 4\) signal jets
\(\geq 2\) \(b\)-jets
\(0\) leptons
# Multi-bin Strategy

Define orthogonal **signal** regions using jet multiplicity and effective mass
- allow for model-dependent interpretations (e.g. low jet multiplicity probes Gbb-like models)

Then define orthogonal regions dominated by $t\bar{t}$: **control**
- Likelihood fit using MC
- Derive normalization factors by fitting to data

Lastly, define orthogonal regions: **validation**
- Verify that our control region derives normalization correctly
- Check variable extrapolations between **signal** and **control**

Open the box (unblind)!

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Selections optimized for **SUSY exclusion**

simultaneously fit multiple parts of phase space together

[ATLAS-CONF-2017-021]
**High-jet-multiplicity regions**

- Signal regions are orthogonal using lepton multiplicity
- Control regions flip the transverse mass cut to be **orthogonal** to 1-lepton SRs

| Criteria common to all high-$N_{\text{jet}}$ regions: $N_{\text{b-jets}} \geq 3$ |
|---------------------------------|---|---|---|
| Variable                        | SR-0L | SR-1L | CR |
| $N_{\text{lepton}}$             | 0     | $\geq 1$ | $\geq 1$ |
| $\Delta \phi_{\text{min}}^{ij}$ | $> 0.4$ | – | – |
| $m_T$                           | – | $> 150$ | $< 150$ |

- **High-$m_{\text{eff}}$** (HH) (Large $\Delta m$)
  - $N_{\text{jet}} \geq 7$ $\geq 6$ $\geq 6$
  - $m_{\text{eff}} > 2500$ $> 2300$ $> 2100$
  - $m_{T,\text{b-jets}} > 100$ $> 120$ $> 60$
  - $E_T^{\text{miss}} > 400$ $> 500$ $> 300$

- **Intermediate-$m_{\text{eff}}$** (HI) (Intermediate $\Delta m$)
  - $N_{\text{jet}} \geq 9$ $\geq 8$ $\geq 8$
  - $m_{\text{eff}} [1800,2500]$ $[1800,2300]$ $[1700,2100]$
  - $m_{T,\text{b-jets}} > 140$ $> 140$ $> 60$
  - $E_T^{\text{miss}} > 300$ $> 300$ $> 200$

- **Low-$m_{\text{eff}}$** (HL) (Small $\Delta m$)
  - $N_{\text{jet}} \geq 9$ $\geq 8$ $\geq 8$
  - $m_{\text{eff}} [900,1800]$ $[900,1800]$ $[900,1700]$
  - $m_{T,\text{b-jets}} > 140$ $> 140$ $> 130$
  - $E_T^{\text{miss}} > 300$ $> 300$ $> 250$

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**ATLAS Preliminary**

$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$

**OL-HI Multi-bin analysis**

- **Data**
- Total background
- $t\bar{t}$
- Single top
- $t\bar{t} + X$
- $Z+$jets
- $W+$jets
- Diboson
- Multijets

Apply all selections for a signal region, except for MET
Systematic Uncertainties

- **Systematics on objects**
  - For example, the measurement of a jet’s momentum

- **Statistical uncertainties**
  - For example, statistical uncertainty on the normalization of ttbar in the control regions

- **Theory uncertainties**: systematic comparisons with alternatively-produced samples
  - radiation (two-sided), parton shower, generator
  - combine in quadrature for each region

- Total background systematics are between 30-50% for all regions

- Dominant uncertainties:
  - normalization — due to our data/MC fit in the control region for ttbar normalization
  - theory systematics — sensitive to radiation effects and MC generator chosen
  - jet energy scale/resolution (JES/JER) — due to corrections in energy/momentum of jets measured in the calorimeter [JES = 13-25%, JER=6-16%]
  - statistical
Results
Validating our work

No significant mismodeling between observation and theory
Signal Regions Unblinded

\( \sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \)

Multi-bin analysis

\[ \text{Events} \]

\[ 10^3 \]

\[ 10^2 \]

\[ 10^1 \]

\[ 10^{-1} \]

\[ \text{Data} \]

\[ \text{t\bar{t}} \]

\[ \text{t\bar{t} + X} \]

\[ \text{Z+jets} \]

\[ \text{W+jets} \]

\[ \text{Multijet} \]

\[ \text{Total background} \]

\[ \text{Single top} \]

\[ \text{Diboson} \]

\[ \text{[ATLAS-CONF-2017-021]} \]

no large difference between observation and theory
Set strong limits given no large difference

The limits

\[ \tilde{\tilde{g}} \text{ production, } \tilde{\tilde{g}} \to t\bar{t}+\tilde{\chi}_1^0, \ m(\tilde{g}) >> m(\tilde{g}) \]

**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \)

Multi-bin analysis

Expected limit in 2015

Observed limit in 2015

Expected limit \( \pm 1 \sigma_{\text{exp}} \)

Observed limit \( \pm 1 \sigma_{\text{SUSY}} \)

All limits at 95% CL

\[ m_\tilde{g} < m_{\tilde{\chi}_1^0} + 2m_t \]

[ATLAS-CONF-2017-021]

\[ \text{exclude up to } \sim 1.95 \text{ TeV} \]
Conclusion

- A search for supersymmetry at the ATLAS detector was performed and no excess was observed above the predicted background
  - A cut-and-count analysis was optimized for discovery
  - No excess was observed, so the multi-bin analysis was performed and optimized for exclusion
- Stronger limits were set on gluino masses excluded at the 95% CL in simplified models involving the pair production of gluinos that decay via top (bottom) squark

Next paper coming out soon!
Backup
**Baseline small-R**
- **R**=0.4, **pT** > 20 GeV, |**η**| < 2.8
- Calibrated: EM+JES+GSC
- **JVT** > 0.59 & **pT** < 60 GeV & |**η**| < 2.4

**Signal**
- OR’ed
- **pT** > 30 GeV

**b-jets**
- **MV2c10**, 77% OP
- |**η**| < 2.5

**Baseline large-R**

**Signal**
- reclustering from signal small-R jets
- Anti-Kt, **R**=0.8, **f_cut** = 10%*
- **pT** > 100 GeV

*remove subjects with **pT** < 10% of total jet **pT**

**Leptons**

**Baseline Electrons**
- **ID**: LooseLHBLayer
- **pT** > 20 GeV, |**η**| < 2.47

**Signal**
- Overlap Removal, **ID**: MediumLLH
- LooseTrackOnly isolation
- |z_0|sinθ| < 0.5 mm, |d_0/σ_d_0| < 5

**Baseline Muons**
- **ID**: Medium Track
- **pT** > 20 GeV, |**η**| < 2.5

**Signal**
- Overlap Removal
- LooseTrackOnly isolation
- |z_0|sinθ| < 0.5 mm, |d_0/σ_d_0| < 3

**Objects**

**Jets**

**Baseline small-R**
- **R**=0.4, **pT** > 20 GeV, |**η**| < 2.8
- Calibrated: EM+JES+GSC
- **JVT** > 0.59 & **pT** < 60 GeV & |**η**| < 2.4

**Signal**
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**Trigger and MET**

MET reconstructed using Track Soft Terms

2015 **trigger**: HLT_xe70

2016 **trigger**: HLT_xe(100|110)_mht_L1XE50
Variables of Interest

\[ \Delta \phi_{\text{min}}^{4j} = \min(|\phi_1 - \phi_{E_T}^{\text{miss}}|, \ldots, |\phi_4 - \phi_{E_T}^{\text{miss}}|) \]  
QCD suppression

minimum \( \Delta \Phi \) between leading 4 jets and MET

\[ m_{\text{incl}} = \sum_{i \leq n} p_T^{j_i} + \sum_{j \leq m} p_T^{\ell_j} + E_T^{\text{miss}} \]  
Only signal objects used

Inclusive effective mass

\[ m_{\text{b-jets}}^{T, \text{min}} = \min_{i \leq 3} \sqrt{\left( E_T^{\text{miss}} + p_T^{j_i} \right)^2 - \left( E_T^{\text{miss}} + p_T^{\ell_j} \right)^2 - \left( E_T^{\text{miss}} + p_T^{j_i} \right)^2} \]  
Transverse mass of MET and \( b \)-jets (leading 3 \( b \)-jets)

\[ m_T = \sqrt{2 p_T E_T^{\text{miss}} \left( 1 - \cos \Delta \phi \left( E_T^{\text{miss}}, \text{lepton} \right) \right)} \]  
Regions with \( \geq 1 \) lepton

Transverse mass leptonic W

\[ M_{\sum, 4}^J = \sum_{i \leq 4} m_{J,i} \]  
Sum of 4 leading reclustered jets

Total jet mass
Strategy

- Define signal regions based on Gtt/Gbb models
  - Goal: enhance signal/background
  - Define ttbar control regions
    - Likelihood fit using MC
    - Derive normalization factors
  - Define validation regions
    - Kinematically close
    - Orthogonal to SRs / CRs
    - Validate extrapolations between CR and SR
- Open the box (unblind)!

⚠️ All regions optimized for discovery

Used the root_optimize optimization framework
Systematic Uncertainties

- **Systematics on objects**
  - For example, the measurement of a jet’s momentum

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  - jet energy scale (JES) — due to corrections in energy/momentum of jets measured in the calorimeter
  - statistical

### Gtt 0L C

<table>
<thead>
<tr>
<th>Uncertainty of channel</th>
<th>SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background expectation</td>
<td>36.23</td>
</tr>
<tr>
<td>Total statistical ($\sqrt{N_{\exp}}$)</td>
<td>±6.02</td>
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<tr>
<td>Total background systematic</td>
<td>±10.36 [28.59%]</td>
</tr>
<tr>
<td>ttbar normalization</td>
<td>±9.60</td>
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<tr>
<td>theory systematics</td>
<td>±9.12</td>
</tr>
<tr>
<td>jet energy scale</td>
<td>±6.13</td>
</tr>
</tbody>
</table>
Likelihood fits

- inputs to likelihood fits in control regions of cut-and-count and multi-bin analysis
jet multiplicity
$b$-jet multiplicity

**0L**

**1L**
missing transverse momentum
total jet mass
transverse mass

\(m_T\) vs. recoil mass for 0L and 1L preselections.
Validating our work

ATLAS Preliminary

$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$

Cut-and-count analysis

no significant mismodeling between observation and theory
Did we find SUSY? (no)

**ATLAS** Preliminary

**Case Study**

<table>
<thead>
<tr>
<th>Events</th>
<th>Data</th>
<th>$t\bar{t}$</th>
<th>$t\bar{t} + X$</th>
<th>$Z +$jets</th>
<th>W+jets</th>
<th>Multijet</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^3$</td>
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<td>$10$</td>
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<td>$1$</td>
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<tr>
<td>$10^{-1}$</td>
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Cut-and-count analysis

no large difference between observation and theory