Search for direct production of the top squark with the ATLAS detector

IoP HEPP & APP Meeting 2013, Liverpool

Josh McFayden
Overview

- Motivation for top squark searches
- Top squark signal
- All-hadronic top squark search
  - Selection
  - Background estimation
    - lepton+jets $t\bar{t}$
    - $Z \rightarrow \nu\nu$
    - Multijets
  - Results and interpretation
Motivation

- Searches for **3rd generation squarks** at the LHC are well motivated by **naturalness** arguments.

- The **exclusion of ~TeV scale first and second generation squarks and gluinos** by previous LHC searches make these searches particularly interesting.

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ATLAS Preliminary

\[ \int L \, dt = 5.8 \, fb^{-1}, \sqrt{s} = 8 \, TeV \]

0-lepton combined

- Observed limit \((\pm 1 \sigma_{\text{SUSY}})\)
- Expected limit \((\pm 1 \sigma_{\text{exp}})\)
- Observed limit \((4.7 \, fb^{-1}, 7 \, TeV)\)
Motivation

- Searches for **3rd generation squarks** at the LHC are well motivated by **naturalness** arguments.

- The **exclusion of ~TeV scale first and second generation squarks and gluinos** by previous LHC searches makes these searches particularly interesting.

- Several **“natural” SUSY scenarios** rely on **“light”** third generation squarks and gauginos.

Unavoidable tunings: $\left(\frac{400}{m_\tilde{t}}\right)^2, \left(\frac{4m_\tilde{g}}{M_\tilde{g}}\right)^2$
Which top squark?

- Production
  - Gluino mediated stop
  - Direct stop production
Which top squark?

- Production
  - Gluino mediated stop
  - Direct stop production

\[ \tilde{g} \rightarrow \tilde{t} \tilde{\chi}_1^0 \]

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

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

\[ \sqrt{S} = 8 \text{ TeV} \]
Which top squark?

- Production
  - Gluino mediated stop
  - Direct stop production

![Diagram showing production mechanisms of top squarks](image-url)
Which top squark?

- Production
  - Gluino mediated stop
  - Direct stop production

- Decay mode
  - $\tilde{t} \rightarrow t + \text{LSP}$
  - $\tilde{t} \rightarrow b + \text{Chargino}$

  and others...
Which top squark?

- Production
  - Gluino mediated stop
  - Direct stop production

- Decay mode
  - $\tilde{t} \rightarrow t + \text{LSP}$
  - $\tilde{t} \rightarrow b + \text{Chargino}$
  - and others...

This talk
Focus of this talk is on all-hadronic direct top squark search in ATLAS with full 2012 8 TeV dataset: **ATLAS-CONF-2013-024**

- The analysis searches for *pair produced* top squarks.
- Assume decay $\tilde{t} \rightarrow t + \text{LSP}$ with BR=100%.
- Consider final state where both top quarks decay *hadronically*.

**Signature** is **6 jets**, **2 b-jets** and **significant $E_T^{miss}$**.

**Signal selection**

- Trigger on $E_T^{miss}$
- Veto events with leptons ($e, \mu$)
- Reject events with fake $E_T^{miss}$
- Require 6 jets and 2 b-jets
- Reconstruct two top quarks
- Veto events if $E_T^{miss}$ and b-jet are consistent with semi-leptonic $t\bar{t}$
- Veto events if a jet close to $E_T^{miss}$ is consistent with hadronic $\tau$
**Selection | Overview**

- **Preselection:**
  - $E_{T}^{\text{miss}}$ trigger, standard event cleaning
  - 6 jets $p_{T} > 80, 80, 35, ..., 35$ GeV

- **Signal region selection:**

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Signal Region I</th>
<th>Signal Region II</th>
<th>Signal Region III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{T}^{\text{miss, track}} &gt; 30$ GeV and $</td>
<td>\Delta\phi(E_{T}^{\text{miss}}, E_{T}^{\text{miss, track}})</td>
<td>&lt; \frac{\pi}{3}$</td>
<td>$E_{T}^{\text{miss}} &gt; 200$ GeV</td>
</tr>
<tr>
<td>$\min</td>
<td>\Delta\phi(\text{jet}^{0-2}, E_{T}^{\text{miss}})</td>
<td>&gt; 0.2\pi$</td>
<td></td>
</tr>
<tr>
<td>$m_{T}(b_{\min[\Delta\phi(b,E_{T}^{\text{miss}})]}, E_{T}^{\text{miss}}) &gt; 175$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Veto events with a $\tau$ candidate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$80$ GeV $&lt; m_{jjj}^{0}, m_{jjj}^{1} &lt; 270$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- QCD and EW rejection
- QCD rejection
- Semileptonic $t\bar{t}$ and EW rejection
- Signal regions
Selection | t\bar{t} & EW rejection

**ATLAS Work in Progress**

\[ \int L \, dt = 20.5 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \]

0-leptons, ≥ 2 bjets

<table>
<thead>
<tr>
<th>Events / 20 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^5</td>
</tr>
<tr>
<td>10^4</td>
</tr>
<tr>
<td>10^3</td>
</tr>
<tr>
<td>10^2</td>
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<tr>
<td>10^1</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.001</td>
</tr>
</tbody>
</table>

**m_T(b-MET) [GeV]**

- \( m_T \left( b_{\min}[\Delta \phi(b,E_T^{\text{miss}})], E_T^{\text{miss}} \right) > 175 \text{ GeV} \)
- Veto events with a \( \tau \) candidate

<table>
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<tr>
<td>10^5</td>
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</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.001</td>
</tr>
</tbody>
</table>

**m_T^{\text{had}} [GeV]**

- \( m_T(b-E_T^{\text{miss}}) \) has an endpoint at \( \sim m_t \) for \( t\bar{t} \)
  - Cutting above 175 GeV removes a huge amount of the semileptonic \( t\bar{t} \) background.
- Reconstruct two hadronic tops from the ≥6 jets
  - Top mass window cut removes a large amount of remaining \( t\bar{t} \) and W/Z+jets backgrounds.

**Semileptonic \( t\bar{t} \) and EW rejection**

Josh McFayden - IoP 2013
Selection | $\bar{t}t$ & EW rejection

- $m_T(b,E_T^{\text{miss}}) > 175$ GeV
- Veto events with a $\tau$ candidate
- $80$ GeV < $m_{jjj}^0$, $m_{jjj}^1$ < $270$ GeV

- $m_T(b,E_T^{\text{miss}})$ has an endpoint at $\sim m_t$ for $t\bar{t}$
  - Cutting above 175 GeV removes a huge amount of the semileptonic $t\bar{t}$ background.
- Reconstruct two hadronic tops from the $\geq 6$ jets
  - Top mass window cut removes a large amount of remaining $t\bar{t}$ and $W/Z+$jets backgrounds - especially on the least well reconstructed hadronic top.

Semileptonic $t\bar{t}$ and EW rejection
**Selection | Discrimination with $E_T^{\text{miss}}$**

![Graph showing $E_T^{\text{miss}}$ vs. $m_{t\bar{t}}$ for three signal regions: I, II, III.](image)

- **Signal Region I**: $E_T^{\text{miss}} > 200$ GeV
- **Signal Region II**: $E_T^{\text{miss}} > 300$ GeV
- **Signal Region III**: $E_T^{\text{miss}} > 350$ GeV

- After extensive optimisation $E_T^{\text{miss}}$ provides the best discrimination between the signal and remaining backgrounds.

- Incremental $E_T^{\text{miss}}$ thresholds define the signal regions.
Analysis strategy

- Control regions defined for important backgrounds:
  - Semileptonic $t\bar{t} +$ jets (hadronic $\tau$ or low $p_T$ e/\mu)
  - $Z \rightarrow \nu\bar{\nu} +$ jets (including heavy flavour jets)
  - Multijets ($E_T^{\text{miss}}$ coming from mis-measured jets)

- Single top, $t\bar{t} +$V and diboson estimated from Monte Carlo.

- A simultaneous fit to each of the signal and $t\bar{t}$ control regions is performed to extract the final limit.
  - The $t\bar{t}$ normalisation is allowed to float in the fit.
  - QCD and Z backgrounds have fixed contributions and uncertainties.
Background estimation | Top

- Background comes from semileptonic $t\bar{t}$
  - Mostly composed of events with hadronic tau leptons
  - Large uncertainties on normalisation
- Use 1-lepton control region

Select events with:
- Exactly 1 good $e/\mu$
- 5 (other) jets, 2 b-tagged
- Large $E_T^{miss}$
- At least 1 well reconstructed top
- Passes cuts to remove fake $E_T^{miss}$
- $40 < m_{T(l,E_T^{miss})} < 120$ GeV
- Consider the lepton to be a jet
  - Mimics the hadronic tau in the signal region

Uncertainties
- JES and theory (generator and parton shower) uncertainties are dominant.
Irreducible background from $Z \rightarrow \nu\nu + (HF)$ jets

Use 2-lepton control region
- Mimic $Z \rightarrow \nu\nu$ with $Z \rightarrow ll$ events by subtracting the lepton $p_T$ from $E_T^{\text{miss}}$.

Select events with:
- Opposite sign ee or $\mu\mu$ pair
- Require $E_T^{\text{miss}} < 50$ GeV (removes $tt$)
- Subtract the lepton $p_T$ from $E_T^{\text{miss}}$
- $81 < m_{ll} < 101$ GeV
- Same jet selection as SR
- Modified $E_T^{\text{miss}} > 70$ GeV
- b-tagging

Uncertainties
- Detector, theory and scale variations are considered, uncertainties of 31-35% are assigned for each SR.
Estimate multijet (and all-hadronic top) background with jet smearing method.

- Select clean multijet events from data.
- Smear jets, sampling from a MC derived response function, to form “pseudo data” that can acquire large $E_T^{miss}$ from fluctuating jets.
- Pass “pseudo data” through SR selection.

Normalisation is taken from a QCD enriched CR:

- Same jet and $E_T^{miss}$ selection as SR.
- Logical or of reversed $\Delta \Phi(j, E_T^{miss})$ and reversed $\Delta \Phi(E_T^{miss}, E_T^{miss,\text{track}})$ regions.

Uncertainties

- 100% uncertainty from variations to the response function Gaussian core and tail shape.
Systematic uncertainties

- Dominant systematic uncertainties come from control region sample size, jet energy scale and $t\bar{t}$ theoretical uncertainties.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>18%</td>
<td>33%</td>
<td>45%</td>
</tr>
<tr>
<td>Background sample sizes (data and simulation)</td>
<td>10%</td>
<td>17%</td>
<td>21%</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>10%</td>
<td>10%</td>
<td>25%</td>
</tr>
<tr>
<td>$t\bar{t}$ theory</td>
<td>10%</td>
<td>19%</td>
<td>22%</td>
</tr>
<tr>
<td>Z+jets theory</td>
<td>4%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>$t\bar{t}$ + $W/Z$ theory</td>
<td>5%</td>
<td>8%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Results

- Observations are consistent with SM expectations.

<table>
<thead>
<tr>
<th>Number of events</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>15</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Expected background</td>
<td>17.5 ± 3.2</td>
<td>4.7 ± 1.5</td>
<td>2.7 ± 1.2</td>
</tr>
<tr>
<td>Expected (tt)</td>
<td>9.8 ± 2.6</td>
<td>1.9 ± 1.3</td>
<td>0.9 ± 0.7</td>
</tr>
<tr>
<td>Expected (tt) + W/Z</td>
<td>1.7 ± 1.0</td>
<td>0.7 ± 0.4</td>
<td>0.51 ± 0.30</td>
</tr>
<tr>
<td>Expected Z+jets</td>
<td>2.1 ± 1.0</td>
<td>1.2 ± 0.5</td>
<td>0.8 ± 0.4</td>
</tr>
<tr>
<td>Expected W+jets</td>
<td>1.2 ± 0.8</td>
<td>0.32 ± 0.29</td>
<td>0.19 ± 0.19 ± 0.19</td>
</tr>
<tr>
<td>Expected single-top</td>
<td>1.5 ± 0.9</td>
<td>0.5 ± 0.4</td>
<td>0.3 ± 0.3</td>
</tr>
<tr>
<td>Expected multijet</td>
<td>0.12 ± 0.12</td>
<td>0.01 ± 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Expected diboson</td>
<td>1.2 ± 1.2</td>
<td>&lt; 0.22</td>
<td>&lt; 0.22</td>
</tr>
</tbody>
</table>

Fit input expectation \(tt\)

\[9.9 \quad 1.7 \quad 0.6\]
Exclusion limits at 95% CL have been set.

- Stop masses between 320 and 660 GeV are excluded for a nearly massless LSP.
- For a LSP mass of 150 GeV stop masses are excluded between 400 and 620 GeV.
Exclusion limits at 95% CL have been set.

Stop masses between 320 and 660 GeV are excluded for a nearly massless LSP.

For a LSP mass of 150 GeV stop masses are excluded between 400 and 620 GeV.
It is possible to interpret the model cross section upper limits in terms of **branching ratio** (BR) limits.

We are able to exclude $BR > 54\%$ for $m_{\text{stop}}=400\text{ GeV}$, $m_{\text{LSP}}=1\text{ GeV}$.
ATLAS \( \tilde{t} \rightarrow t + \text{LSP} \) exclusion limits

- A summary of all the ATLAS stop searches where \( \tilde{t} \rightarrow t + \text{LSP} \)
- This result:
- Extends previous ATLAS limits.
Note that these plots overlay contours belonging to different stop decay channels, different sparticle mass hierarchies, and simplified decay scenarios.

References

[1] arxiv:1208.1447 (0-lepton 7 TeV)
[3] arxiv:1209.4186 (2-lepton 7 TeV)
[8] ATLAS-CONF-2012-167 (2-lepton 8 TeV, 13 fb⁻¹)
[9] ATLAS-CONF-2013-001 (0-lepton, bb+MET 8 TeV, 13 fb⁻¹)
A search for direct pair production of top squarks in final states containing six or more jets and $E_T^{\text{miss}}$ was performed with 20.5 fb$^{-1}$ of $\sqrt{s} = 8$ TeV 2012 data.

Observations are consistent with SM expectations.

The result significantly extends previous limits in the all-hadronic final state and excludes top squarks up to higher masses than in previous searches.

We eagerly await the LHC running with higher $\sqrt{s}$ which will present a thorough test for natural SUSY.
Back-ups
Stop mixing | left/right-handed table

- Cutflow table shows the yields for the T600, L1 signal point with both the right and left-handed stops.
- Note the slight increase in acceptance for the left-handed stop after the b-jet cut.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Right-handed</th>
<th>Left-handed</th>
</tr>
</thead>
<tbody>
<tr>
<td>No selection</td>
<td>507.3</td>
<td>507.3</td>
</tr>
<tr>
<td>Trigger</td>
<td>468.0</td>
<td>467.8</td>
</tr>
<tr>
<td>Primary Vertex</td>
<td>467.8</td>
<td>467.4</td>
</tr>
<tr>
<td>Event cleaning</td>
<td>459.0</td>
<td>459.6</td>
</tr>
<tr>
<td>Muon veto</td>
<td>381.2</td>
<td>382.5</td>
</tr>
<tr>
<td>Electron veto</td>
<td>284.4</td>
<td>292.3</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 130$ GeV</td>
<td>263.1</td>
<td>270.1</td>
</tr>
<tr>
<td>Jet multiplicity and $p_T$</td>
<td>97.7</td>
<td>92.2</td>
</tr>
<tr>
<td>$E_T^{miss,track} &gt; 30$ GeV</td>
<td>96.3</td>
<td>90.5</td>
</tr>
<tr>
<td>$\Delta\phi(E_T^{miss}, E_T^{miss,track}) &lt; \pi/3$</td>
<td>90.3</td>
<td>84.3</td>
</tr>
<tr>
<td>$\Delta\phi(jet, E_T^{miss}) &gt; \pi/5$</td>
<td>77.1</td>
<td>72.0</td>
</tr>
<tr>
<td>Tau veto</td>
<td>67.4</td>
<td>61.9</td>
</tr>
<tr>
<td>$\geq 2b$-tagged jets</td>
<td>29.5</td>
<td>31.5</td>
</tr>
<tr>
<td>$m_T(b-jet, E_T^{miss}) &gt; 175$ GeV</td>
<td>20.2</td>
<td>23.6</td>
</tr>
<tr>
<td>$80$ GeV &lt; $m_{jj}^0$ &lt; 270 GeV</td>
<td>17.8</td>
<td>20.4</td>
</tr>
<tr>
<td>$80$ GeV &lt; $m_{jjj}^0$ &lt; 270 GeV</td>
<td>10.9</td>
<td>11.9</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 150$ GeV</td>
<td>10.8</td>
<td>11.8</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 200$ GeV</td>
<td>10.3</td>
<td>11.2</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 250$ GeV</td>
<td>9.2</td>
<td>10.0</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 300$ GeV</td>
<td>7.8</td>
<td>8.3</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 350$ GeV</td>
<td>6.1</td>
<td>6.6</td>
</tr>
</tbody>
</table>
## Results | Model independent limits table

<table>
<thead>
<tr>
<th>Signal region</th>
<th>$\langle \varepsilon \sigma \rangle_{\text{obs}}^{95}$ [fb]</th>
<th>$S_{\text{obs}}^{95}$</th>
<th>$S_{\text{exp}}^{95}$</th>
<th>$CL_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1</td>
<td>0.49</td>
<td>10.0</td>
<td>10.6$^{+5.5}_{-1.7}$</td>
<td>0.39</td>
</tr>
<tr>
<td>SR2</td>
<td>0.17</td>
<td>3.6</td>
<td>5.3$^{+3.2}_{-1.7}$</td>
<td>0.20</td>
</tr>
<tr>
<td>SR3</td>
<td>0.19</td>
<td>3.9</td>
<td>4.5$^{+1.9}_{-0.7}$</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Top control region figures.

The hashed band represents the statistical uncertainty and the yellow represents to systematic uncertainty.
These plots show a **0-lepton validation region** for the Top background.

Events are selected in $50 < m_T(b, E_{T}\text{miss}) < 150$ GeV window.

The plots show the number of jets with **no tau veto** at all (left), the **tau veto reversed** (middle) and the **tau veto applied** (right).

The good data/MC agreement gives us faith in the MC modelling.
Selection | Optimisation

\[
\overline{t}\overline{t} \text{ production, } \overline{t} \rightarrow t\chi_n^0 (BR=1)
\]

**ATLAS Preliminary**

\[ L_{\text{int}} = 20.5 \text{ fb}^{-1}, \sqrt{S}=8 \text{ TeV} \]

All hadronic channel

Best Signal Region

**ATLAS Work in Progress**

Neutralino1 mass [GeV]

Stop1 mass [GeV]

**ATLAS-CONF-2013-024**
Selection | QCD rejection

\[ \int L \, dt \sim 20.5 \, fb^{-1}, \sqrt{s} = 8 \, TeV \]

**ATLAS Work in progress**

- **SM Total**
- **Multijet Estimate**
- **\( t\bar{t} \)**
- **\( t\bar{t} + V \)**
- **single top**
- **W**
- **Z**

\[ \Delta \phi (E_T^{\text{miss}}, E_T^{\text{miss,track}}) \]

\[ E_T^{\text{miss,track}} > 30 \, GeV \text{ and } |\Delta \phi (E_T^{\text{miss}}, E_T^{\text{miss,track}})| < \frac{\pi}{3} \]

\[ \min |\Delta \phi (\text{jet}^{0-2}, E_T^{\text{miss}})| > 0.2 \pi \]

Cuts on the angle between the track and calorimeter based \( E_T^{\text{miss}} \) and the angle between the leading 3 jets and \( E_T^{\text{miss}} \) reject events with fake \( E_T^{\text{miss}} \).

QCD rejection
$t\bar{t}+V$ Systematics

- $t\bar{t}+Z$ kinematic distributions sensitive to uncertainties.