Searches for direct pair production of third generation squarks with the ATLAS detector

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on behalf of the ATLAS collaboration

3rd International Conference on New Frontiers in Physics
28th July – 6th August 2014, Crete, Greece
Outline

1 Introduction

2 Direct top squark pair production

3 Direct bottom squark pair production

4 Summary plots
Supersymmetry is one of the theories beyond the Standard Model offering a solution to many open issues such as the hierarchy problem and dark matter.

The Higgs boson mass can be regularized by the scalar top mass. Therefore, light 3rd generation squarks (stop and sbottom) are theoretically favoured ($m_{\tilde{t}}, m_{\tilde{b}} < 1$ TeV).

This talk will focus on direct top/bottom squark pair production searches.

Results are interpreted with

- R-parity-conserving models (lightest supersymmetric particle (LSP) is stable)
- simplified models (100% BF to given final state is assumed)
Production

- direct production cross-section smaller than light squark and gluino

Direct sbottom production

- \( \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 \)
- \( \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \)
- \( \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm \)

Direct stop production

- more decay modes possible depending on the point in \( \tilde{t}_1 - \tilde{\chi}_1^\pm - \tilde{\chi}_1^0 \) parametric space
- different analyses target different topologies

Typical 3\textsuperscript{rd} generation signatures

- large \( E_T^{\text{miss}} \) (due to LSP)
- multiple jets (mainly \( b \) and \( c \)-tag)
- possible leptons
Introduction

SUSY search strategy

- SM processes measured with high precision
- SUSY searches target usually different phase space (high $E_T^{\text{miss}}$ etc)
  ⇒ reliable SM background estimation crucial

### Standard Model background

- top
- $V, VV, VVV$
- multijets
- fake leptons

### Irreducible bkg

**Dominant sources**
- normalized to data in dedicated CRs
- $t\bar{t}, W+\text{jets}, ...$

**Sub-dominant sources**
- estimated with MC simulated data

### Reducible bkg

- data-driven techniques (analysis dependent)
- QCD: "Smearing method"
- fake leptons: "Matrix method"

### Validation regions

- all predictions validated in validation regions

### SIGNAL REGIONS

- look for excess of data over SM prediction
Direct top squark pair production
0 lepton + 6 (2 b-) jets + $E^\text{miss}_T$

(arXiv:1406.1122)

**Main target**

- fully hadronic final state search
- targeting high stop mass
- high/medium $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$

a) $\tilde{t} \rightarrow t\tilde{\chi}_1^0$
b) $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW(\ast)\tilde{\chi}_1^0$

Selection

- hadronic $t\bar{t} + E^\text{miss}_T$ selection
- $\geq 2$ b-tagged jets (70% eff)
- $E^\text{miss}_T > 150$ GeV
- SRs with different jet multiplicities
  - SRA: $\geq 6$ jets (both modes)
  - SRB: 4-5 jets reclustered into large-$R$ jets (boosted $W$ in a)
  - SRC: 5 jets (one lost jet in $b$ due to small $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$)

**Main background**

- semi-leptonic $t\bar{t}$ with 1 lepton not reconstructed or misidentified: 1l $t\bar{t}$ CR
- $Z(\nu\bar{\nu}) +$jets: $Z(\ell\ell) +$jets CR
- $W +$jets: 1l CR (for SRB only)
- $t\bar{t} + W/Z$: MC

Direct top squark pair production

$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

Figure: $\tilde{t} \rightarrow t\tilde{\chi}_1^0$

Figure: $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$

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Main target

- one lepton final state allows to target several stop decay chain scenarios
- 15 separate signal regions for different \( \tilde{t}_1 - \tilde{\chi}_1^0 - \tilde{\chi}_1^0 \) masses
- high/medium/low \( \Delta m(\tilde{t}, \tilde{\chi}_1^0) \)

Selection

- semi-leptonic \( t\bar{t} + E_T^{\text{miss}} \) selection
- \( \geq 4 \) jets
- \( \geq 1 \) \( b \)-tagged jet (80/70/60\% eff)
- \( E_T^{\text{miss}} \geq 100 \) GeV
- SRs cover various signal categories
  - models with high \( m_{\tilde{t}} \): large-\( R \) jets (boosted \( W \))
  - models with small \( \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \): soft leptons

Main background

- dileptonic \( t\bar{t} \) with a misidentified/lost lepton or hadronic \( \tau \) and \( W + \)jets
- normalized using control regions
- reduced by requiring a threshold on \( m_{T_1} \) and on variations of \( m_{T_2} \)

Expected limits Observed limits All limits at 95\% CL

\[ t \bar{t} \] production, \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\nu \tilde{\chi}_1^0, m_\nu = 2 m_\chi \]

\[ t \bar{t} \] production, \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\nu \tilde{\chi}_1^0, m_\nu = 2 m_\chi \]
2 leptons + (b-)jets + $E_T^{\text{miss}}$

Main target

1) high $\Delta m(\tilde{t}, \tilde{\chi}^0_1)$
   ▶ $\tilde{t} \to t\tilde{\chi}^0_1$
2) medium $\Delta m(\tilde{t}, \tilde{\chi}^0_1)$
   a) $\Delta m(\tilde{\chi}^{\pm}_1, \tilde{\chi}^0_1) > m(W)$: $\tilde{t} \to b\tilde{\chi}^{\pm}_1 \to bW\tilde{\chi}^0_1$
   b) $\Delta m(\tilde{\chi}^{+}_1, \tilde{\chi}^0_1) < m(W)$: $\tilde{t} \to b\tilde{\chi}^{+}_1 \to bW^*\tilde{\chi}^0_1$
   c) $\Delta m(\tilde{t}, \tilde{\chi}^0_1) < m(t)$: $\tilde{t} \to bW\tilde{\chi}^0_1$

Selection

- leptonic $m_{T2}$ selection (target 2a model)
  - high $m_{T2}$ to cut off bkg
- hadronic $m_{T2}$ selection (target 2b model)
  - high $m_{T2}^{b-jet}$ and 2 $b$-jets (70% eff) to cut off bkg
- MVA selection (target 1 model)

Main background

- data-driven: fake leptons
- MC driven: normalized in CRs
  - leptonic selection: $t\bar{t}$, $WW$
  - hadronic selection: $t\bar{t}$, $Wt$, $Z/\gamma^* +$jets
  - MVA selection: $t\bar{t}$
Direct top squark pair production

\[ 0 \text{ lepton} + \text{mono-jet/c-jet} + E_T^{\text{miss}} \]

(arXiv:1407.0608)

Main target

- compressed spectra: \( \Delta m (\tilde{t}, \tilde{\chi}_1^0) < m_W + m_b \)
- use ISR jets to boost squark-pair system leading to larger \( E_T^{\text{miss}} \) and to extract signal from multijet background

\[ \begin{align*}
\text{a)} & \quad \tilde{t} \rightarrow c\tilde{\chi}_1^0 \\
\text{b)} & \quad \tilde{t} \rightarrow bff'\tilde{\chi}_1^0
\end{align*} \]

Monojet-like selection

- small \( \Delta m (\tilde{t}, \tilde{\chi}_1^0) \)
- c-jets too soft to be identified
- \( \leq 3 \) jets, high \( p_T \) leading jet
- large \( E_T^{\text{miss}} \)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure}
\caption{a)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure}
\caption{b)}
\end{figure}

\[ \begin{align*}
\text{c-tagged selection} & \quad \text{moderate} \; \Delta m (\tilde{t}, \tilde{\chi}_1^0) \gtrsim 20\text{GeV} \\
& \quad \text{c-jets are tagged} \\
& \quad \geq 4 \text{ jets, high } p_T \text{ untagged leading jet} \\
& \quad \text{large } E_T^{\text{miss}}
\end{align*} \]
Direct top squark pair production

\[ Z + b\text{-jet} + \text{jets} + E_T^{\text{miss}} \]

(Main target)

- \( \tilde{t}_2 \rightarrow Z \tilde{t}_1 \)
- sensitive to scenarios where \( \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \approx m_t \)
- in this region, \( \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \) searches have similar kinematics with SM \( t\bar{t} \) production → poor sensitivity

Selection

- SFOS lepton pair with \( Z \) mass window
- \( \geq 3 \) jets
- \( \geq 1 \) \( b \)-tagged jet (60% eff)
- large \( E_T^{\text{miss}} \)
- possibly additional lepton

Main background

- fake leptons
- two lepton SRs: \( Z + \text{jets}, t\bar{t} \)
- three lepton SRs: \( t\bar{t}V, tZ, VV \)

\[ \tilde{t}_1 \tilde{t}_2 \text{ production}, \tilde{t}_2 \rightarrow Z \tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \]
Direct bottom squark pair production

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ATLAS 3rd generation $\bar{q}$ searches

ICNFP2014, 28th July – 6th August 2014
Direct bottom squark pair production

Main target

- $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$
- fully hadronic final state search
- high $\Delta m(\tilde{t}/\tilde{b}, \tilde{\chi}_1^0)$: SRA
- low $\Delta m(\tilde{t}/\tilde{b}, \tilde{\chi}_1^0)$: SRB

SRA selection

- 2 jets (3rd jet veto)
- leading two jets $b$-tagged (60% eff)
- $E_T^{\text{miss}} > 150$ GeV
- $m_{CT}$ cut to reduce $t\bar{t}$ bkg
- main bkg: $Z(\nu\bar{\nu}) + b$-Jets

SRB selection

- $\geq 3$ jets
- leading jet not $b$-tagged: ISR jet recoiling against $\tilde{t}\tilde{t}$
- 2nd and 3rd leading jets $b$-tagged
- $E_T^{\text{miss}} > 250$ GeV
- main bkg: $t\bar{t}$
Direct bottom squark pair production

$0 \text{ lepton} + \geq 3 b\text{-jets} + E_T^{\text{miss}}$

(arXiv:1407.0600)

Main target

- analysis targets several SUSY signals
- $\tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$
- mainly sensitive to events $h \rightarrow bb$

Selection for $\tilde{b} \rightarrow b\tilde{\chi}_2^0$

- 0 lepton channel
- $\geq 4/7$ jets
- $\geq 3 b$-jets (70% eff)
- large $E_T^{\text{miss}}$ and $m_{\text{eff}}$

Main background

- irreducible bkg (MC driven)
  - real $b$-jets: $t\bar{t} + b/b\bar{b}$
- reducible bkg (data-driven)
  - fake $b$-jets

![Figure: $m_{4j}^{\text{eff}} = E_T^{\text{miss}} + \sum_{i=1}^{4} p_T^i$](image)

![Figure: No sensitivity for low $m_{\tilde{\chi}_2^0}$ due to soft $E_T^{\text{miss}}$](image)
Direct bottom squark pair production

2 same-sign/3-leptons + 0-3 b-jets + $E_T^{miss}$

(Main target)

- analysis covers a lot of SUSY processes
- low SM background allows to reach also compressed spectrum
- $\tilde{b} \rightarrow t\tilde{\chi}_1^\pm \rightarrow tW^(*)\tilde{\chi}_1^0$

Selection for $\tilde{b} \rightarrow t\tilde{\chi}_1^\pm$ (SR1b)

- 2 same-sign
- $\geq 3$ jets
- $\geq 1b$-jets (70% eff)
- $E_T^{miss} > 150$GeV
- $m_T(l, E_T^{miss}) > 100$GeV

Main background

- irreducible bkg (MC driven)
  - real leptons: $t\bar{t} + V, VV$
- reducible bkg (data-driven)
  - fake leptons and charge-flips
  - dominated by $t\bar{t}$

<table>
<thead>
<tr>
<th>SR1b</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>10</td>
</tr>
<tr>
<td>Expected background events</td>
<td>$4.7 \pm 2.1$</td>
</tr>
</tbody>
</table>

Components of the background

- $t\bar{t}V, t\bar{t}H, tZ, t\bar{t}t\bar{t}$: $2.5 \pm 1.7$
- $VV, VVV$: $0.9 \pm 0.4$
- Fake leptons: $0.8^{+1.2}_{-0.8}$
- Charge-flip electrons: $0.5 \pm 0.1$

$p(s = 0)$: $0.07$
Summary plots

- several 8 TeV ATLAS analyses excluded large part of $m_{\tilde{t}} - m_{\tilde{\chi}^0_1}$ mass plane
- 5 decay modes considered separately with 100% BR
  - $\tilde{t} \rightarrow t\tilde{\chi}^0_1$
  - $\tilde{t} \rightarrow bW\tilde{\chi}^0_1$
  - $\tilde{t} \rightarrow c\tilde{\chi}^0_1$
  - $\tilde{t} \rightarrow bff'\tilde{\chi}^0_1$
  - $\tilde{t} \rightarrow b\tilde{\chi}^{\pm}_1 \rightarrow bW\tilde{\chi}^0_1$
- gap around $m_{\tilde{t}} - m_{\tilde{\chi}^0_1} \approx m_t$ can be covered by $\tilde{t}_2 \rightarrow Z\tilde{t}_1$ (slide 10)

**Observed limits**

<table>
<thead>
<tr>
<th>$m_{\tilde{\chi}^0_1}$ [GeV]</th>
<th>$m_{\tilde{t}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.3 fb⁻¹ $\sqrt{s}$=8 TeV</td>
</tr>
<tr>
<td>1</td>
<td>20.3 fb⁻¹ $\sqrt{s}$=7 TeV</td>
</tr>
<tr>
<td>2</td>
<td>20.3 fb⁻¹ $\sqrt{s}$=6 TeV</td>
</tr>
</tbody>
</table>

**Status:** ICHEP 2014

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ATLAS 3rd generation $\tilde{q}$ searches

ICNFP2014, 28th July – 6th August 2014
Summary plots

Summary plot for \( \tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW\tilde{\chi}_1^0 \)

- several different assumptions on the mass of chargino \( \tilde{\chi}_1^\pm \)
  - \( m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 5/20 \text{ GeV} \)
  - \( m_{\tilde{\chi}_1^\pm} = 150/106 \text{ GeV} \)
  - \( m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0} \)
  - \( m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} - 10 \text{ GeV} \)

\[ \chi \sim < m_{\tilde{\chi}_1^\pm} \quad m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} + 5 \text{ GeV} \]

\[ \chi \sim ( = 150 \text{ GeV}) \]

\[ \chi \sim ( = 106 \text{ GeV}) \]

\[ \chi \sim < 103.5 \text{ GeV} \]

\[ \chi \sim + 5 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim - 10 \text{ GeV} \]

\[ \chi \sim + 5 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim - 10 \text{ GeV} \]

\[ \chi \sim + 5 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

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\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim - 10 \text{ GeV} \]

\[ \chi \sim + 5 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim + 20 \text{ GeV} \]

\[ \chi \sim - 10 \text{ GeV} \]
results and their interpretations were presented for various SUSY models  
no statistically significant evidence of stop or sbottom discovery yet  
i improved mass limits wrt previous ATLAS analyses  
looking forward to Run II with increased center of mass energy
THANK YOU FOR ATTENTION!
Backup slides
ATLAS experiment

- general purpose detector at the LHC
- $21 \text{fb}^{-1}$ recorded at $\sqrt{s} = 8 \text{ TeV}$
- more than 95% of delivered data good for physics
- large luminosity results in large pileup → pileup suppression strategies developed

![Diagram of ATLAS experiment](attachment:image.png)

**Graph:**
- ATLAS Preliminary LHC Delivered
- $\sqrt{s} = 8 \text{ TeV}$
- Total Delivered: 22.8 fb$^{-1}$
- Total Recorded: 21.3 fb$^{-1}$
- Good for Physics: 20.3 fb$^{-1}$

**Legend:**
- LHC Delivered
- ATLAS Recorded
- Good for Physics

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Prospects for RunII $\sqrt{s} = 14$ TeV

Figure: Assuming $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay chain scenario with BR=100% (ATL-PHYS-PUB-2013-011)
Definitions of transverse masses

- Kinematic variables defined in order to reduce background

**Transverse mass \( m_T \)**

- \( m_T^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [p_T(v_1) + p_T(v_2)]^2 \)

1. \( m_T \equiv m_T(l, E_T^{\text{miss}}) \) for \( W \to l \nu \) bounded by \( W \) mass (reduce \( WW, Wt, t\bar{t} \) background)
   - used in 1 lepton + jets + \( E_T^{\text{miss}} \) and 2 same-sign/3-leptons + jets + \( E_T^{\text{miss}} \) analyses
   - \( m_T = \sqrt{2p_T^{l}E_T^{\text{miss}}[1 - \cos \Delta \phi(p_T^{l}, p_T^{\text{miss}})]} \)

2. \( m_T^{b,\text{min}} \equiv m_T(b^{\text{min}}, E_T^{\text{miss}}) \) for \( t \to bW \) bounded by top mass (reduce \( t\bar{t} \) background)
   - used in 0 lepton + jets + \( E_T^{\text{miss}} \) analysis
   - \( m_T^{b,\text{min}} = \sqrt{2p_T^{b}E_T^{\text{miss}}[1 - \cos \Delta \phi(p_T^{b}, p_T^{\text{miss}})]} \)

**Contransverse mass \( m_{CT} \)**

- Used to measure the masses of pair-produced semi-invisibly decaying heavy particles

- \( m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [p_T(v_1) - p_T(v_2)]^2 \)

- Bounded from above by an analytical combination of particle masses

- Used in 0 lepton + 2 \( b \)-jets + \( E_T^{\text{miss}} \) analysis

- Bound for \( t\bar{t} \) production \( m_{CT}^{\text{max}} = \frac{m(t)^2 - m(W)^2}{m(t)} = 135 \text{GeV} \)
Definitions of transverse masses II

Stransverse mass $m_{T2}$

- generalization of $m_T$ to pair decay with final state consisting of 2 visible objects and $E_T^{miss}$
  
  $m_{T2}(p_T^1, p_T^2, q_T) = \min \{ \max [m_T(p_T^1, q_T^1), m_T(p_T^2, q_T^2)] \}$

1) $m_{T2} \equiv m_{T2}(p_T^l_1, p_T^l_2, p_T^{miss})$ for $W \rightarrow l \nu$ bounded by $W$ mass (reduce $WW, Wt, t\bar{t}$ bkg)
   - used in 2 leptons + jets + $E_T^{miss}$ analysis

2) $m_{T2}^{b-jet} \equiv m_{T2}(p_T^b_1, p_T^b_2, p_T^l_1 + p_T^l_2 + p_T^{miss})$ for $t \rightarrow bW$ bounded by $t$ mass (reduce $t\bar{t}$ bkg)
   - used in 2 leptons + jets + $E_T^{miss}$ analysis

- variations used in 1 lepton + jets + $E_T^{miss}$ analysis
  1) $am_{T2}$ bounded by $t$ mass (reduce dileptonic $t\bar{t}$ bkg with a lost lepton)
  2) $m_{T2}^\tau$ bounded by $W$ mass (reduce $\tau_{hadr}$ $t\bar{t}$ bkg)
B-tagging

Performance

- **efficiency** $\varepsilon = \frac{N_{b\text{-truth,tagged}}^{b\text{-jets}}}{N_{b\text{-truth}}^{b\text{-jets}}}$
- **rejection**:
  - light jet rejection $r_{\text{light jet}} = \frac{N_{\text{uds\text{-truth,non\text{-tagged}}}}^{\text{jets}}}{N_{\text{uds\text{-truth}}^{\text{jets}}}}$
  - $c$-jet rejection $r_{c\text{-jet}} = \frac{N_{c\text{-truth,non\text{-tagged}}}}{N_{c\text{-truth}}^{\text{jets}}}$

**Figure:** ATLAS-CONF-2012-043

- b-tag efficiency 70% (MV1) with 0.7% light-flavor jet and 20% $c$-jet
$t\bar{t}$ background

- rejected by introducing a discriminant variable
- $m_{T}^{b,min} = \sqrt{2p_{T}^{b}E_{T}^{miss}[1-\cos\Delta\phi(p_{T}^{b},p_{T}^{miss})]} > m_t$

Control regions

- background enriched regions of phase-space
- used to estimate background yield correction in signal regions

Interpretation

1) $\tilde{t} \rightarrow t\tilde{\chi}_1^0$
2) $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^*\tilde{\chi}_1^0$
   - $B(\tilde{t} \rightarrow t\tilde{\chi}_1^0) \text{ varies from 0\% to 100\%}$
1 lepton + 4 (1 b-) jets + $E_T^{\text{miss}}$ (arXiv:1407.0583)

$t\bar{t}$ and $W+$jets background

- separated from signal using transverse mass
- $m_T = \sqrt{2p_T E_{T}^{\text{miss}} [1 - \cos \Delta \phi(p_T, p_{T}^{\text{miss}})]} > m_W$

SM bkg validation

- correction factors for SM background estimated in control regions checked with dedicated validation regions

Limits on cross-section

- $t\bar{t}_1 \rightarrow t\tilde{\chi}_1^0$ decay scenario with $m_{\tilde{\chi}_1^0} = 50\text{GeV}$
- $t\bar{t}_1$ being a pure $\tilde{t}_L$ or mostly $\tilde{t}_R$
2 leptons + (b-)jets + $E_T^{\text{miss}}$ (arXiv:1403.4853)

Background rejection

- variable used to measure the masses of pair-produced semi-invisibly decaying heavy particles

$$m_{T2}(p_T^1, p_T^2, q_T) = \min \{\max[m_T(p_T^1, q_T^1), m_T(p_T^2, q_T^2)]\}$$

Leptonic $m_{T2}$ selection

- $m_{T2}(l, l, E_T^{\text{miss}})$

Hadronic $m_{T2}$ selection

- $m_{T2}^{b-jet}(b, b, l + l + E_T^{\text{miss}})$
c-tagged selection

- multivariate algorithm provides weights for jets from light quarks or gluons \( (P_u) \), c quarks \( (P_c) \) and b quarks \( (P_b) \)
- form discriminators: anti-u ≡ log\( (P_c/P_u)_1 \), anti-b ≡ log\( (P_c/P_b) \)
- cut on anti-u and anti-b to separate c jets from light jets and b jets

**c-tagging performance**

- **medium tagger**
  - 20% efficiency
  - rejection factor 200/8/10 against light/b/\( \tau \) jets

- **loose tagger**
  - 95% efficiency
  - rejection factor 2.5 against b
GMSB

- gauge-mediated SUSY breaking model
- LSP is gravitino $\tilde{G}$ ($m_{\tilde{G}} < 1\text{keV}$)
- NLSP is neutralino $\tilde{\chi}_1^0$
0 lepton + 2 $b$-jets + $E_T^{\text{miss}}$ (arXiv:1308.2631)

Background rejection

- variable used to measure the masses of pair-produced semi-invisibly decaying heavy particles
- $m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\vec{p}_T(v_1) - \vec{p}_T(v_2)]^2$

$$\tilde{b}\tilde{b}$$ bound for production of sbottom pairs: $m_{CT}^{\text{max}} = \frac{m(\tilde{b})^2 - m(\tilde{\chi}_1^0)^2}{m(\tilde{b})}$

$t\bar{t}$ bound for production of top pairs: $m_{CT}^{\text{max}} = \frac{m(t)^2 - m(W)^2}{m(t)} = 135\text{GeV}$

Background estimation

- $Z(\nu\nu) + b$-jets normalized in $Z(ll) + b$-jets CR
- $t\bar{t}$ normalized in single lepton CR for SRB and in two leptons (DFOS) CR for SRA
- $W$ + jets normalized in single lepton CR

![Graph showing data vs. theory](image-url)