Third Generation SUSY Searches at the LHC

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on behalf of ATLAS and CMS Collaborations
Third Generation Squarks

- Supersymmetry (SUSY) is one of the theory beyond the SM.
- Third generation squarks are expected to be lighter than other squarks due to mixing of the mass matrix and large Yukawa couplings.
- Moreover, naturalness of Higgs mass requires top squarks (stops) to be light.

- Both ATLAS and CMS showed results for third generation squark searches at $\sqrt{s}=7$ TeV of $\sim5$ fb$^{-1}$ in 2011 and at $\sqrt{s}=8$ TeV of $\sim20$ fb$^{-1}$ in 2012.
- Since then, we have performed more studies on this data for new signatures and with improved methods for better sensitivity.
Production and Decay Processes

• Gluino mediated production
  – Relatively higher cross sections and high multiplicity signatures.
  – The gluino can decay through virtual or real stop/sbottom (depending on the mass hierarchy).

\[ \tilde{g} \rightarrow tt^{(*)} \rightarrow t\tilde{\chi}_1^0 \]
\[ \tilde{g} \rightarrow b\tilde{b}^{(*)} \rightarrow b\tilde{\chi}_1^0 \]

• Direct pair production
  - Cross sections are lower but still larger than EWK production because of strong couplings.
  - The stop/sbottom can decay in different ways depending on the sparticle masses.

\[ \tilde{b} \rightarrow b\tilde{\chi}_1^0 / \tilde{t} \rightarrow t\tilde{\chi}_1^0 \]
\[ \tilde{t} \rightarrow b\tilde{\chi}_1^\pm / \tilde{b} \rightarrow t\tilde{\chi}_1^0 \]
Gluino Mediated Stop/Sbottom Production
Multi-b-jets Search

• High b-jet multiplicity final states are searched for in both ATLAS and CMS for gluino mediated stop/sbottom production.

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>N(leptons)</td>
<td>0</td>
<td>&gt;1</td>
</tr>
<tr>
<td>N(b-jets)</td>
<td>&gt;3</td>
<td>&gt;3</td>
</tr>
<tr>
<td>N(jets)</td>
<td>&gt;4, &gt;7</td>
<td>&gt;6</td>
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</tbody>
</table>

Selection

\[ m_{\text{eff}} = E_T^{\text{miss}} + \sum p_T^{\text{jet}} + (p_T^{\text{lepton}}) \]

\[ S_T^{\text{lep}} = E_T^{\text{miss}} + p_T^{\text{lepton}} \]

arXiv:1311.4937
Exclusion Limits on Gluino Mediated Production

Various searches interpret their results in gluino mediated stop/sbottom production models. More will be shown in the next talk about “Inclusive SUSY Searches at the LHC” by Sezen Sekmen.

\[ m(\tilde{g}) \leq 1.3 \text{ TeV} \] is excluded.
Direct Sbottom Pair Production
For direct sbottom search, both ATLAS and CMS use $m_{CT}$ to reduce the large $ttbar$ background.

**JHEP 10 (2013) 189**

**Leading jet**
- $p_T > 150$ GeV, b-tag
- $p_T > 250$ GeV (b-tag)

**2nd leading jet**
- $p_T > 50$ GeV, b-tag
- $p_T > 30$ GeV, b-tag (b-tag)

**3rd leading jet**
- $p_T < 50$ GeV
- $p_T > 30$ GeV, b-tag
- $p_T < 50$ GeV

**$E_{miss}$**
- $> 150$ GeV
- $> 250$ GeV
- $> 175$ GeV

**$m_{CT}$**
- $> 150, 200, 250, 300, 350$ GeV
- $[0, 250, 350, 450], > 450$ GeV

**NEW!**

CMS-PAS-SUS-13-018
Other Sbottom Searches

• 2 same sign lepton analysis can be interpreted in other scenarios such as sbottom pair production.

• The models in which the sbottom decaying to the neutralino2 are also considered.
  – Then the neutralino2 decays to a Higgs or Z.

Interpretation of the high b-jet multiplicity analyses

Interpretation of 3-lepton b-jets analyses
Direct Stop Pair Production
Direct Stop in All Hadronic Decay

- Top mass reconstruction is used in both ATLAS and CMS for stop in all hadronic decay channel.

### ATLASS-CONF-2013-024

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>N(jet)</td>
<td>$\geq 6$</td>
<td>$\geq 5$</td>
</tr>
<tr>
<td>N(b-jet)</td>
<td>$\geq 2$</td>
<td>$\geq 1, \geq 2$</td>
</tr>
<tr>
<td>$E_{T\text{miss}}$</td>
<td>$&gt;200, 300, 350$ GeV</td>
<td>$&gt;200, 350$ GeV</td>
</tr>
<tr>
<td>$m_{3j}$</td>
<td>[80, 270] GeV (x2)</td>
<td>[80, 270] GeV (x1)</td>
</tr>
<tr>
<td>$m_T(b, E_{T\text{miss}})$</td>
<td>$&gt;175$ GeV</td>
<td></td>
</tr>
<tr>
<td>$m_{T2}$</td>
<td>$&gt;300$ GeV</td>
<td></td>
</tr>
<tr>
<td>$0.5m_{3j}+m_{\text{Rsys}}$</td>
<td></td>
<td>$&gt;500$ GeV</td>
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</table>

3 jet mass distribution in top control region

remnant system mass

### CMS-PAS-SUS-13-015

CMS Preliminary, $L = 19.4$ fb$^{-1}$, $\sqrt{s} = 8$ TeV

3 jet mass distribution in top control region

remnant system mass

26 March 2014

Moriond QCD and High Energy Interactions
Direct Stop in Semi-leptonic Decay

- ATLAS uses cut-based approach and binned shape fit.
  - For shape fit, 2D distributions of $E_T^{\text{miss}}$ vs. $m_T(p_T^{\text{lepton}}, E_T^{\text{miss}})$ are used.
- CMS uses cut-based approach and a BDT multivariate method.
  - $E_T^{\text{miss}}$, $m_T$, $\min\Delta\phi$, Leading b-jet $p_T$ etc. as input for BDT.

Preselection:
- Exactly 1-lepton
- At least 4 jets
- At least 1 b-jet

ATLAS-CONF-2013-037

26 March 2014
Stop in Semiletonic Decay Exclusion Limits

1-lepton analysis is sensitive to stop polarization. ATLAS and CMS use different assumptions here (ATLAS assumes almost stopR-like stop1 scenario).

Different chargino, neutralino mass relation is used for $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$. 
Direct Stop in Di-leptonic Decay

- Leptonic (using 2-lepton) and hadronic (using 2 bjets) $m_{T2}$ analyses and BDT multivariate analysis are performed for di-leptonic decay mode.

$\sum \min_{\alpha_i} \left\{ \max \left[ m_T(p_T^1, q_T^1), m_T(p_T^2, q_T^2) \right] \right\}$ is used to reduce ttbar background.

**Update!**

Multivariate BDT

arXiv:1403.4853
Stop to Stau

- Stop dilepton search is also interpreted in another model in which stop decays to stau and gravitino is LSP.
  - Leptonic $m_{T2}$ analysis interprets this model.
  - For low stop mass signals, one more signal region is added which requires low $m_{T2}^{ll}$.

\[
m_{T2}(p_T^1, p_T^2, q_T) = \min_{q_T + q_T^1 = q_T} \left\{ \max\left[ m_T(p_T^1, q_T^1), m_T(p_T^2, q_T^2) \right] \right\}
\]

\[
p_T^1 = p_T^{lep1} + p_T^{jet1}
\]

\[
p_T^2 = p_T^{lep2} + p_T^{jet2}
\]

with $m^{ll} < 180$ GeV

ATLAS-CONF-2014-014
Summary of Direct Stop Pair Production

- These results are also interpreted in various mass hierarchies for stop, chargino, neutralino.

Razor analysis will be mentioned in the next "Inclusive SUSY Searches at the LHC"
Stop2 Searches

- If \( m(\tilde{t}_2) - m(\tilde{\chi}_1^0) \approx m(t) \), \( \tilde{t}_2 \rightarrow t\tilde{\chi}_1^0 \) signal is very similar to SM top pair production and there is little sensitivity with the existing searches.
- If stop2 is not too heavy, the signature of stop2 can be seen which decays to stop1 via a Z or h.

Etmiss distribution in 3 lepton, on-shell Z channel

**NEW!**

Update!

arXiv.1403.5222

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<tbody>
<tr>
<td>N(leptons)</td>
<td>2 OS ( \geq 3 )</td>
<td>2 OS ( \geq 3 )</td>
</tr>
<tr>
<td>N(jets)</td>
<td>([3,4], \geq 5)</td>
<td>([2,3], \geq 4), (\geq 5)</td>
</tr>
<tr>
<td>N(b-jets)</td>
<td>(\geq 1)</td>
<td>(1, \geq 2)</td>
</tr>
<tr>
<td>(E_t^{\text{miss}}) (&gt;160,200) GeV</td>
<td>(&gt;60) GeV (\geq 50) GeV</td>
<td>([50,120]), (\geq 120) GeV</td>
</tr>
<tr>
<td></td>
<td>on-shell Z</td>
<td>100(\leq M_{bb}) (\leq 150) GeV</td>
</tr>
</tbody>
</table>

Others

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Stop2 Exclusion Limits

Interpretation in different BRs
Stop to Higgsino in GMSB

- Naturalness requires the higgsino to also be light.
- If gravitino is LSP, decay of higgsino to gravitino (accompanied by Z or h) gives another signature.

Event selection for $hh \rightarrow \gamma\gamma + bb$ signal:
- Two photons $p_T > 40, 25$ GeV
- $120$ GeV $< M_{\gamma\gamma} < 131$ GeV
- At least two b-jets $p_T > 30$ GeV

Three categories:
(i) one additional b-jet
(ii) $95$ GeV $< M_{bb} < 155$ GeV
(iii) others

Update!
Summary

- Third generation squarks are expected to be lighter than the other squarks.
- ATLAS and CMS collected \( \sim 20 \text{ fb}^{-1} \) p-p collision data at \( \sqrt{s}=8 \text{ TeV} \) in 2012 and performed searches for third generation squarks.
- Updated results during 2013 are presented in this talk.
  - No excess from SM is found so far.
  - For \( \tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0 \), \( m(\tilde{b}_1) \lesssim 700 \text{ GeV} \) \( (m(\tilde{\chi}_1^0) \approx 0 \text{ GeV}) \) is excluded.
  - For \( \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0 \), \( m(\tilde{t}_1) \lesssim 700 \text{ GeV} \) \( (m(\tilde{\chi}_1^0) \approx 0 \text{ GeV}) \) is excluded.
- LHC run 2 will start soon with \( \sqrt{s}=13-14 \text{ TeV} \! \! \! ! !
  - e.g. discovery reach for the stop mass will be almost 1 TeV at \( \sqrt{s}=14 \text{ TeV} \), 300 fb\(^{-1}\).

ATLAS-PHYS-PUB-2013-011

CMS-CR-2013-255
Backup
In ATLAS, high jet multiplicity (N_{jets}>7-10) with exclusive N(bjets) (0,1,>2) regions are scanned.

In CMS, exclusive signal regions categorized by N(jets), HT, ETmiss are scanned.

Results of exclusive signal regions.
2-lepton Same Sign

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<td>N(b-jets)</td>
<td>0, &gt;1, &gt;3</td>
<td>0,1,&gt;2</td>
</tr>
<tr>
<td>N(jets)</td>
<td>&gt;3, &gt;5</td>
<td>[2,3],&gt;4</td>
</tr>
<tr>
<td>( E_T^{miss} )</td>
<td>&gt;150 GeV</td>
<td>[50,120],&gt;120 GeV</td>
</tr>
<tr>
<td>( H_T )</td>
<td>[200,400],&gt;400 GeV</td>
<td>&gt;500, 80 GeV</td>
</tr>
<tr>
<td>( m_{eff} )</td>
<td>&gt;300 GeV, &lt; 150 GeV</td>
<td></td>
</tr>
</tbody>
</table>

\[
m_{eff} = \sum p_T^{lepton} + \sum p_T^{jet} + E_T^{miss}
\]

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Summary Gluino Mediated Stop Production

- Various searches interpret their results in gluino mediated stop production models.
  - More will be shown in the next talk about “Inclusive SUSY Searches at the LHC” by Sezen Sekmen.
Direct Sbottom MT2 Analysis

- In CMS, $m_{T2}$ which is similar to $m_{CT}$ is also used for sbottom search to reduce ttbar background.

Signal regions are categorized by jet and b-jet multiplicity and $H_T$ and $E_T^{\text{miss}}$ exclusively.

\[
MT2(m_{\chi}) = \min_{p_T^{(1)}+p_T^{(2)}=p_T^{\text{miss}}} \left[ \max \left( M_T^{(1)}, M_T^{(2)} \right) \right]
\]
Stop Polarization

- Composition of stopR, stopL in stop1 affects signal acceptance especially in semi-leptonic decay.
  - Top quark polarization changes the boost of lepton in the decay.
  - Weaker sensitivity is obtained with left-handed top.
Razor Analysis

- Razor analysis also interpret direct stop pair production models.
  - After categorizing events by the number of jets, b-jets, leptons, two “megajets” are formed from jets and leptons to minimize the sum of invariant mass of two megajets.
  - Razor variables are defined from these megajets.

\[
M_R = \sqrt{(p_{j1} + p_{j2})^2 - (p_{j1}^1 + p_{j2}^1)^2}
\]

\[
M_T^R = \sqrt{E_{T}\text{miss} \cdot (p_{T}^1 + p_{T}^2) - E_{T}\text{miss} \cdot (p_{T}^1 + p_{T}^2) \over 2}
\]

\[
R = \frac{M_T^R}{M_R}
\]

SUSY signals have a peak in $R^2-M_R$ plane while SM background fall smoothly.
Stop to Charm

- If \( m(\tilde{t}) - m(\tilde{\chi}_1^0) < m(b) + m(W^\pm) \), dominant stop decay can be via charm quark.
- Both ATLAS and CMS perform mono-jet like searches exploiting ISR jet(s) from signal.
- In ATLAS, charm-tagging is also used to enhance c-jet signal.

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<tr>
<td></td>
<td>Monojet-like</td>
<td>Charm-tagged</td>
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<tr>
<td>( E_{T,\text{miss}} )</td>
<td>&gt; 220 GeV</td>
<td>&gt; 410 GeV</td>
</tr>
<tr>
<td>Leading jet</td>
<td>( p_T &gt; 280 ) GeV</td>
<td>( p_T &gt; 270 ) GeV</td>
</tr>
<tr>
<td>2nd leading jet</td>
<td>( b )-veto</td>
<td>( b )-veto</td>
</tr>
<tr>
<td>3rd leading jet</td>
<td>( b )-veto</td>
<td>( p_T &lt; 60 ) GeV</td>
</tr>
<tr>
<td>4th leading jet</td>
<td>( p_T &lt; 30 ) GeV</td>
<td>( p_T &gt; 30 ) GeV, c-tag</td>
</tr>
</tbody>
</table>

ATLAS-CONF-2013-068

CMS-PAS-SUS-13-009

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