SUSY searches with multiple b-jets at CMS

KEITH ULMER
UNIVERSITY OF COLORADO
**Motivation for heavy flavor searches**

- SUSY remains prime candidate for BSM physics
  - Solve hierarchy problem, unify gauge couplings, dark matter candidate in LSP, etc.
- Very strong limits on generic searches now from CMS/Atlas
- Less stringent on 3rd generation searches
- Natural SUSY to solve the hierarchy problem really only needs light stops, sbottoms and gluinos
Search strategies

- Natural SUSY signatures can be approached with varied searches
- Gluino-mediated stop production gives a 4W+4b final state
  - Signal efficiency with 0-4 final state leptons depending on the W decays
  - Nice complementarity in non-overlapping signatures
- Cover here
  - 1 lepton + b-tags: SUS-13-007
  - 2 same-sign leptons + b-tags: SUS-13-013
- See also
  - Sezen Sekmen for all hadronic searches
  - Christian Autermann for ≥3 lepton + b search results
- All results based on the full 2012 CMS dataset (19 fb⁻¹)
**Search in 1 lepton + b-tags**

- **Baseline requirements**
  - 1 isolated $\mu^-$ or $e^-$
    - $p_T > 20$ GeV
    - $|\eta| < 2.4/2.5$
  - $\geq 6$ jets
  - $\geq 2$ b-jets
  - $H_T$ (sum of jet $p_T$) > 500 GeV

- **Two independent searches**
  - MET search: measures backgrounds in bins of MET 250-350, 350-450, > 450 GeV
  - Delta Phi: predict dominant $tt$ background with angular kinematics

---

**Graphical Data**

- **Events/50 GeV**
- **CMS Preliminary**
- **$\sqrt{s} = 8$ TeV**
- **19.4 fb$^{-1}$**
- **Data**
- **Sum predicted**
- **Single Tau**
- **Dilepton**

- **Normalized residuals**
- **$H_T > 500$ GeV**
- **$N_{jet} \geq 6$, $N_b \geq 2$**

---

**Graphical Data Notes**

- **$m_{g \rightarrow LSP}$ = (1100 GeV, 100 GeV)**
MET search for 1L+b

- Measure backgrounds in data
  - Single lepton $t\bar{t}$
    - Dominant background
    - Use lepton spectrum and known $W$ polarization to predict neutrino spectrum
  - Double lepton $t\bar{t}$: MET shape from MC and normalized to 2L control sample in data
  - Tau backgrounds: measured from 1 and 2 lepton control samples and tau response templates from MC
- Report results for different HT cuts:
  - $> 500$, $> 750$, and $> 1000$ GeV

### Table

<table>
<thead>
<tr>
<th>$E_T$</th>
<th>[150,250)</th>
<th>[250,350)</th>
<th>[350,450)</th>
<th>$\geq 450$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $\ell$</td>
<td>304.0±17.4±16.4</td>
<td>49.9±7.7±6.0</td>
<td>13.4±4.8±3.1</td>
<td>0.3±1.9±0.8</td>
</tr>
<tr>
<td>Dilepton</td>
<td>54.7±4.2±9.0</td>
<td>9.6±1.5±4.4</td>
<td>2.3±1.3±1.0</td>
<td>0.1±1.8±0.3</td>
</tr>
<tr>
<td>Single tau</td>
<td>60.1±2.1±5.1</td>
<td>11.8±0.9±3.6</td>
<td>2.7±0.5±1.9</td>
<td>0.3±0.1±0.1</td>
</tr>
<tr>
<td>Z+jets (from MC)</td>
<td>0.5±0.1±0.5</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>1.6 ± 3.1 ± 3.1</td>
<td>0.0 ± 1.2 ± 1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (predicted):</td>
<td>419.3±18.0±19.4</td>
<td>71.3±7.9±8.3</td>
<td>18.4±5.0±3.8</td>
<td>0.7±2.0±0.3</td>
</tr>
<tr>
<td>Data (observed), total ($\mu, e$):</td>
<td>437 (237, 200)</td>
<td>72 (38, 34)</td>
<td>12 (7, 5)</td>
<td>1 (0, 1)</td>
</tr>
<tr>
<td>SMS ($m_{\tilde{g}} = 1150$ GeV, $m_{\text{LSP}} = 500$ GeV)</td>
<td>5.1±0.2</td>
<td>5.6±0.2</td>
<td>3.7±0.2</td>
<td>3.0±0.2</td>
</tr>
<tr>
<td>SMS ($m_{\tilde{g}} = 1100$ GeV, $m_{\text{LSP}} = 100$ GeV)</td>
<td>6.5±0.3</td>
<td>7.6±0.3</td>
<td>7.3±0.3</td>
<td>9.1±0.3</td>
</tr>
</tbody>
</table>
Δφ search for 1L+b

- Reject single-lepton $tt$ by building $W$ candidate from lepton and MET
- Construct $Δφ(l^{-}, W)$
  - Peaks at 0 for $tt \rightarrow 1L$ bkg.
  - Flat for signal (and 2L $tt$ bkg.)
- Measure $Δφ>1/Δφ<1$ ratio in 1b sample and scale $Δφ<1$ yield by ratio for 2b and $≥3b$ signal regions
- Bin in $S_T = \text{MET} + p_T(\text{lep})$: 250-350, 350-450, > 450 GeV

<table>
<thead>
<tr>
<th>$N_b \geq 3$</th>
<th>$S_T^{lep}$ [GeV]</th>
<th>control reg. data</th>
<th>prediction</th>
<th>observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elect.</td>
<td>$[250,350]$</td>
<td>45</td>
<td>$1.89 \pm 1.03 (0.94)$</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>$[350,450]$</td>
<td>7</td>
<td>$0.85 \pm 0.80 (0.70)$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$&gt;450$</td>
<td>0</td>
<td>$0.0 \pm 0.08 (0.08)$</td>
<td>0</td>
</tr>
<tr>
<td>Muons</td>
<td>$[250,350]$</td>
<td>28</td>
<td>$1.92 \pm 0.95 (0.84)$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$[350,450]$</td>
<td>13</td>
<td>$0.57 \pm 0.58 (0.52)$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$&gt;450$</td>
<td>2</td>
<td>$0.0 \pm 0.22 (0.22)$</td>
<td>0</td>
</tr>
</tbody>
</table>
1 lepton + b results

- No excess observed with either approach
- Interpret results in gluino-mediated stop simplified model
  - Assume 100% branching fraction for gluino→t,t,χ°
- Best limits from Δφ approach
  - Simultaneous fit to 12 search bins
  - Total efficiency ~1-10%
- Limits out to 1.3 TeV in gluino mass

![Graph showing m(χ°) vs. m(\tilde{g}) with CMS Preliminary limits for single-lepton search S_T, N_b search.](image-url)
Same-sign dilepton

- Same-sign + b-tag search updated to full 2012 dataset
- Require
  - 2 same-sign isolated leptons (μ or e)
    - $p_T > 10$ or $20$ GeV (see backup for details)
    - ≥ 2 jets with $p_T > 40$ GeV
- Multiple, exclusive selection regions to maximize sensitivity to many models

<table>
<thead>
<tr>
<th>$N_{b-jets}$</th>
<th>$E_T^{miss}$ (GeV)</th>
<th>$N_{jets}$</th>
<th>$H_T \in [200, 400]$ (GeV)</th>
<th>$H_T &gt; 400$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 0</td>
<td>50-120</td>
<td>2-3$^{\geq 4}$</td>
<td>SR01</td>
<td>SR02</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SR03</td>
<td>SR04</td>
</tr>
<tr>
<td></td>
<td>&gt; 120</td>
<td>2-3$^{\geq 4}$</td>
<td>SR05</td>
<td>SR06</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SR07</td>
<td>SR08</td>
</tr>
<tr>
<td>= 1</td>
<td>50-120</td>
<td>2-3$^{\geq 4}$</td>
<td>SR11</td>
<td>SR12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SR13</td>
<td>SR14</td>
</tr>
<tr>
<td></td>
<td>&gt; 120</td>
<td>2-3$^{\geq 4}$</td>
<td>SR15</td>
<td>SR16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SR17</td>
<td>SR18</td>
</tr>
<tr>
<td>≥ 2</td>
<td>50-120</td>
<td>2-3$^{\geq 4}$</td>
<td>SR21</td>
<td>SR22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SR23</td>
<td>SR24</td>
</tr>
<tr>
<td></td>
<td>&gt; 120</td>
<td>2-3$^{\geq 4}$</td>
<td>SR25</td>
<td>SR26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SR27</td>
<td>SR28</td>
</tr>
</tbody>
</table>

SUS-13-013
SS background estimation

- Backgrounds estimated from combination of data-driven methods and simulation
- Non-prompt lepton backgrounds
  - From heavy flavor decays, hadron misID, decay in flight, photon conversions
  - “tight/loose” ratio for lepton isolation measured in data control sample and used to scale loose lepton event yields
- Rare backgrounds
  - $t\bar{t}W$, $t\bar{t}Z$, diboson, $qqW^+W^+$ etc.
  - Taken from MC with 50% uncertainty
- Charge mis-ID backgrounds
  - MisID rate measured in $Z \rightarrow ee$ data

CMS Preliminary $\sqrt{s} = 8$ TeV, $L_{\text{int}} = 19.5$ fb$^{-1}$

Events / 25 GeV

Data
Rare SM processes
Charge misID
Non-prompt $e/\mu$
Total bkg uncertainty

Events / 40 GeV

Data
Rare SM processes
Charge misID
Non-prompt $e/\mu$
Total bkg uncertainty
SS+b interpretation

- No excess observed over predicted SM backgrounds
- Use results to set limits for many models that predict same-sign events
- Most sensitive bins combined for result for each model

![Diagram showing particle interactions](image)

CMS Preliminary, 19.5 fb⁻¹, √s = 8 TeV

pp → g~g, g~ → btWχ⁺, NLO+NLL exclusion

- Observed ± 1σ_{theory}
- Expected ± 1σ_{experiment}

mχ⁺ = 150 GeV, mχ⁻ = 50 GeV

95% C.L. upper limit on cross section (fb)

Keith Ulmer - University of Colorado
SS+b limits: sbottom production

- sbottom production can also give a 4W final state
- Show limits with two different options for intermediate $\chi^1_1$ mass

CMS Preliminary, 19.5 fb$^{-1}$, $\sqrt{s} = 8$ TeV

$pp\rightarrow \tilde{b}_1\tilde{b}^*_1, \tilde{b}_1 \rightarrow tW\tilde{\chi}^0_1$ NLO+NLL exclusion

- Observed $\pm 1\sigma_{\text{theory}}$
- Expected $\pm 1\sigma_{\text{experiment}}$ $m_{\tilde{\chi}}/m_{\tilde{\chi}} = 0.5$

CMS Preliminary, 19.5 fb$^{-1}$, $\sqrt{s} = 8$ TeV

$pp\rightarrow \tilde{b}_1\tilde{b}^*_1, \tilde{b}_1 \rightarrow tW\tilde{\chi}^0_1$ NLO+NLL exclusion

- Observed $\pm 1\sigma_{\text{theory}}$
- Expected $\pm 1\sigma_{\text{experiment}}$ $m_{\tilde{\chi}} = 50$ GeV

7/20/13

Keith Ulmer - University of Colorado

11/15
SS+b limits: gluino production

- Gluino-mediated stop production with off shell (left) and on shell (right) stops

CMS Preliminary, 19.5 fb⁻¹, √s = 8 TeV

SS+b limits: gluino production

- Gluino-mediated stop production with off shell (left) and on shell (right) stops

CMS Preliminary, 19.5 fb⁻¹, √s = 8 TeV
SS limits: gluino production

- Use 0b signal regions for gluino decay to $q,q, \tilde{\chi}^{\pm}$ ($W^{\pm}$, LSP)
- Consider two intermediate $\tilde{\chi}^{\pm}$ masses
  - Similar reach at $m(\text{LSP}) = 0$, but much reduced reach in compressed regions

---

**Model C1**

$P_1 \rightarrow \tilde{g} \tilde{g}, \tilde{g} \rightarrow q\bar{q}W^{0} \tilde{\chi}^{0}_1$ NLO+NLL exclusion

- Observed $\pm 1\sigma_{\text{theory}}$
- Expected $\pm 1\sigma_{\text{experiment}}$

## Limits

- $m_{\tilde{\chi}_1} = 0.8m_{\tilde{\chi}_0} + 0.2m_{\tilde{g}}$

---

CMS Preliminary, 19.5 fb$^{-1}$, $\sqrt{s} = 8$ TeV

---

**Model C1**

$P_1 \rightarrow \tilde{g} \tilde{g}, \tilde{g} \rightarrow q\bar{q}W^{0} \tilde{\chi}^{0}_1$ NLO+NLL exclusion

- Observed $\pm 1\sigma_{\text{theory}}$
- Expected $\pm 1\sigma_{\text{experiment}}$

## Limits

- $m_{\tilde{\chi}_1} = 0.5m_{\tilde{\chi}_0} + 0.5m_{\tilde{g}}$
SS+b limits: RPV and same-sign tops

- Additional search regions designed for same-sign top and RPV SUSY production

<table>
<thead>
<tr>
<th>(N_{\text{jets}})</th>
<th>(N_{b-\text{jets}})</th>
<th>(E_T^{\text{miss}}) (GeV)</th>
<th>(H_T) (GeV)</th>
<th>charge</th>
<th>SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\geq 2)</td>
<td>(\geq 0)</td>
<td>&gt; 0</td>
<td>&gt; 500</td>
<td>++/--</td>
<td>RPV0</td>
</tr>
<tr>
<td>(\geq 2)</td>
<td>(\geq 2)</td>
<td>&gt; 0</td>
<td>&gt; 500</td>
<td>++/--</td>
<td>RPV2</td>
</tr>
<tr>
<td>(\geq 2)</td>
<td>= 1</td>
<td>&gt; 30</td>
<td>&gt; 80</td>
<td>++/--</td>
<td>SStop1</td>
</tr>
<tr>
<td>(\geq 2)</td>
<td>= 1</td>
<td>&gt; 30</td>
<td>&gt; 80</td>
<td>++ only</td>
<td>SStop1++</td>
</tr>
<tr>
<td>(\geq 2)</td>
<td>(\geq 2)</td>
<td>&gt; 30</td>
<td>&gt; 80</td>
<td>++/--</td>
<td>SStop2</td>
</tr>
<tr>
<td>(\geq 2)</td>
<td>(\geq 2)</td>
<td>&gt; 30</td>
<td>&gt; 80</td>
<td>++ only</td>
<td>SStop2++</td>
</tr>
</tbody>
</table>

- Same-sign top production:
  95% CL UL = 0.72 pb
- 4 top production:
- 95% CL UL = 0.047 pb
- Also consider gluino\(\rightarrow\)tbs RPV decay

CMS Preliminary L=19.5 fb\(^{-1}\), \(\sqrt{s} = 8\) TeV

\[pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow tbs, \lambda_{323}^{*}\]

- Observed 95% CLs Limits
- Expected 95% CLs Limits
  - Expected \(\pm 1\sigma\)
  - Expected \(\pm 2\sigma\)
  - Theoretical \(\sigma_{\text{NLO}}\)
  - Theoretical \(\pm 1\sigma\)

\[m_{\tilde{g}}\] (GeV) \[\sigma\] (fb)
Summary

- Varied search program for natural SUSY at CMS
- Many complementary searches all yield null results thus far
- Pushing into territory that challenges a natural solution to the hierarchy problem
- Higher energy and more luminosity after the LHC shutdown will open new possibilities...

\[ \tilde{g}-\tilde{g} \text{ production, } \tilde{g} \rightarrow t \bar{t} \chi_1^0 \]

CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} \)
EPSHEP 2013

- Observed
- Observed -1 \( \sigma_{\text{SUSY}} \)
- Expected

\( m(\text{gluino}) - m(\text{LSP}) = 2 m(\text{top}) \)
\( m(\text{gluino}) - m(\text{LSP}) = m(W) + m(\text{top}) \)

LSP mass [GeV] vs. gluino mass [GeV]
What’s “natural” about SUSY

- A main appeal of SUSY is cancelation of quadratic divergences in radiative corrections to the Higgs mass
  - Naturalness arguments (small fine tuning) require light stop to cancel top loop contribution
  - Gluino enters at 2-loop corrections, so need it fairly light, too

- Natural SUSY gets out of tight squark mass limits if 3\textsuperscript{rd} generation squarks are lighter than 1\textsuperscript{st} and 2\textsuperscript{nd} generation
  - Requires flavor dependence in SUSY breaking

- Without naturalness, much of SUSY’s appeal is lost
What 3rd gen SUSY looks like

- Need light stops, sbottoms and slightly heavier gluinos
  - Pair produce 3rd generation squarks
  - Pair produce gluinos that decay to 3rd generation squarks
- Generally feature b jets + missing energy
- Different decay topologies give varied final states
  - Lots of jets from longer cascade decays
  - High $p_T$ leptons from W’s from top or chargino decays
3 b-jet, 1 light jet + MET all hadronic event
Leptons are selected in a “high $p_T$” and “low $p_T$” configuration

- “high $p_T$” uses $e/\mu$ with $p_T > 20$ GeV and triggers entirely on the leptons allowing a search down to 0 MET
- “low $p_T$” uses $e/\mu$ with $p_T > 10$ GeV and triggers on the leptons plus HT $> 175$ GeV to allow sensitivity to phasespace with softer leptons at the expense of added hadronic activity
### SS+b results tables

<table>
<thead>
<tr>
<th>SR</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low-$p_T$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>1</td>
<td>44 ± 16</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>12 ± 4</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>12 ± 5</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>9.1 ± 3.4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>21 ± 8</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>13 ± 5</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>3.5 ± 1.4</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>5.8 ± 2.1</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>32 ± 13</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>6.0 ± 2.2</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>17 ± 7</td>
<td>15</td>
</tr>
<tr>
<td>14</td>
<td>10 ± 4</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>13 ± 5</td>
<td>9</td>
</tr>
<tr>
<td>16</td>
<td>5.5 ± 2.0</td>
<td>5</td>
</tr>
<tr>
<td>17</td>
<td>4.2 ± 1.6</td>
<td>3</td>
</tr>
<tr>
<td>18</td>
<td>6.8 ± 2.5</td>
<td>11</td>
</tr>
<tr>
<td>21</td>
<td>7.6 ± 2.8</td>
<td>10</td>
</tr>
<tr>
<td>22</td>
<td>1.5 ± 0.7</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td>7.1 ± 2.7</td>
<td>6</td>
</tr>
<tr>
<td>24</td>
<td>4.4 ± 1.7</td>
<td>11</td>
</tr>
<tr>
<td>25</td>
<td>2.8 ± 1.1</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>1.3 ± 0.6</td>
<td>2</td>
</tr>
<tr>
<td>27</td>
<td>1.8 ± 0.8</td>
<td>0</td>
</tr>
<tr>
<td>28</td>
<td>3.4 ± 1.3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>high-$p_T$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>1</td>
<td>51 ± 18</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>9.0 ± 3.5</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>8.0 ± 3.1</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>5.6 ± 2.1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>20 ± 7</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>9 ± 4</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>2.4 ± 1.0</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>3.6 ± 1.5</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>36 ± 14</td>
<td>29</td>
</tr>
<tr>
<td>12</td>
<td>3.8 ± 1.4</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>10 ± 4</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>5.9 ± 2.2</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>11 ± 4</td>
<td>11</td>
</tr>
<tr>
<td>16</td>
<td>3.9 ± 1.5</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>2.8 ± 1.1</td>
<td>3</td>
</tr>
<tr>
<td>18</td>
<td>4.0 ± 1.5</td>
<td>7</td>
</tr>
<tr>
<td>21</td>
<td>7.1 ± 2.5</td>
<td>12</td>
</tr>
<tr>
<td>22</td>
<td>1.0 ± 0.5</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td>3.8 ± 1.4</td>
<td>3</td>
</tr>
<tr>
<td>24</td>
<td>2.8 ± 1.2</td>
<td>7</td>
</tr>
<tr>
<td>25</td>
<td>2.9 ± 1.1</td>
<td>4</td>
</tr>
<tr>
<td>26</td>
<td>0.8 ± 0.5</td>
<td>1</td>
</tr>
<tr>
<td>27</td>
<td>1.2 ± 0.6</td>
<td>0</td>
</tr>
<tr>
<td>28</td>
<td>2.2 ± 1.0</td>
<td>2</td>
</tr>
</tbody>
</table>

**Model**

- **A1**
- **A2**
- **B1**
- **B2**
- **C1**
- **B**
- **C**
- **RPV**

**Model parameter**

- $m_{\chi^0} = 50$ GeV
- $m_{\chi^0} = 50$ GeV
- $x = m_{\chi^0} / m_{\chi^0} = 0.5$
- $x = m_{\chi^0} / m_{\chi^0} = 0.8$
- $m_{\chi^0} = 50$ GeV, $m_{\chi^0} = 150$ GeV
- $x = 0.5$
- $x = 0.8$

**Analysis**

- high-$p_T$
- high-$p_T$
- high-$p_T$
- high-$p_T$
- low-$p_T$
- low-$p_T$
- low-$p_T$
- high-$p_T$
- RPV

**Signal Regions used**

- 21–28
- 11–18, 21–28
- 11–18, 21–28
- 21–28
- 01–08
- 01–08
- SStop1, SStop2
- SStop1++, SStop2++
- 21–28

**Legend**

- Red = 0b
- Blue = 1b
- Green = ≥2b