Searches for Strong Production of SUSY at CMS

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On behalf of the CMS collaboration
DIS2018
Kobe, Japan
● Still looking for SUSY?!
  ○ Motivated by naturalness, cosmological observations of dark matter, and GUT
  ○ SUSY searches can be reinterpreted for other BSM signals

● SUSY parameter space is extremely large
  ○ Simplified Models (SMS) are used to reduce model dependence
  ○ Consider only the lightest SUSY particles, others decoupled
  ○ Simple assumptions on branching fractions are made

● Strong production of SUSY
  ○ In SMS, gluinos and squarks have largest xsecs (for a given mass) at the LHC
  ○ Well-motivated place to look for SUSY

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections
arXiv:1407.5066
Strong Production of SUSY particles at CMS

R-Parity Conserving

Gluino and Squarks ($\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$)

- Largest cross-sections
- Many jet final states
- 0l and 1l searches compatible reach

3rd generation

- Light stops/sbottoms preferred by naturalness
- Jet and leptonic final states

Electroweak

- Also motivated by naturalness arguments
- Leptonic final states

Here I will focus on some of the more recent CMS results (2016 data)
Analyses Covered in this Talk

CMS SUSY Results:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Hadronic Search:

Search for Natural and Split SUSY:
CMS-SUS-16-038 (arXiv:1802.02110)

1 Soft Lepton:
Compressed Stop Search
CMS-PAS-SUS-17-005

2 Lepton search:
Chargino and Stop pair production
CMS-PAS-SUS-17-010

Links include additional material needed for reinterpretations!
Search For Natural and Split SUSY with $\alpha_T$

  - Abandon the hierarchy problem
  - Guided by gauge unification and dark matter constraints
    - Scalar susy particles much heavier than EW scale
    - Gluino decay suppressed (highly virtual squarks)
    - R-Hadron $\rightarrow$ displaced jets

- **All-jet final states with large missing energy**
  - Sensitivity to various signatures by categorization in $N(b), N(j), H_T, H_T^{\text{miss}}$
  - Use clever kinematic variables to fight QCD multijet evts
    - Jet mismeasurement can fake $p_T^{\text{miss}}$ in multijet events
    - Reduced significantly using variables $\alpha_T$ and $\Delta\phi_{\text{min}}^{*}$
    - Use sidebands ($\Delta\phi_{\text{min}}^{*}, H_T^{\text{miss}}/p_T^{\text{miss}}$) to estimate the rest
  - Non-multijet backgrounds:
    - $t\bar{t}$bar and $W$+jets (with a lost lepton)
      - Extrapolate from $\mu$+jets
      - Measure probability for losing the lepton in MC
    - $Z \rightarrow \nu\nu$ (irreducible background)
      - Extrapolate from $\mu\mu$ + jets events
      - Measure the ratio of $Z \rightarrow \nu\nu / Z \rightarrow \mu\mu$ in MC

\[ H_T^{\text{miss}} = \left| \sum_{\text{jets}} p_T^{j} \right| \]
\[ H_T = \sum p_T^{j} \]
Results: Split SUSY

$\alpha_T$ Results: Split SUSY

$\tau_0 = 1 \mu m$

$\tau_0 = 1 mm$

$\tau_0 = 100 m$
α_T Results: Natural SUSY

Gluino production

CMS 35.9 fb⁻¹ (13 TeV)

- \( p p \rightarrow \tilde{g} \tilde{g} \) NLO+NLL exclusion
- \( \tilde{g} \rightarrow b \bar{b} \tilde{\chi}_1^0 \)
- \( \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0 \)
- \( \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0 \) (Prompt decay)
- Metastable \( \tilde{g} \)

1st, 2nd, 3d Gen. squark production

CMS 35.9 fb⁻¹ (13 TeV)

- NLO+NLL exclusion
- \( pp \rightarrow \tilde{b}_1 \tilde{b}_1 \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 \)
- \( pp \rightarrow \tilde{t}_1 \bar{t}_1 \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \)
- \( pp \rightarrow \tilde{t}_1 \tilde{t}_1 \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 \)
- \( pp \rightarrow \tilde{q} \tilde{q} \tilde{q} \rightarrow q \tilde{\chi}_1^0 (q_L + \tilde{q}_R, \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}) \)
- \( pp \rightarrow \tilde{q} \tilde{q} \tilde{q} \rightarrow q \tilde{\chi}_1^0 \) (one light \( \tilde{q} \))

\[ \Delta m_1 = m_{\tilde{t}_1} - m_{\chi_1^0} = m_W \]
\[ \Delta m_2 = m_{\tilde{t}_1} - m_{\chi_2^0} = m_t \]
Compressed Stop 1 soft lepton

- Compressed Region: $\Delta m(m_{\text{Stop}}, m_{\text{LSP}}) < m_W$
  - Relatively light stops still allowed!
  - Coannihilation of stops and LSPs in this region can help predict the correct dark relic density.
  - Challenging region to probe due to soft final state particles (often too soft for trigger threshold) but recoil against ISR jet can help!

**Kinematics** ($P_T(l), M_T, P_T(b), P_T^{\text{miss}}$) strongly depend on $\Delta m$

- Direct decay
- Chargino-mediated

**Compressed Region:**
- $m_{\tilde{t}_1} = m_{\tilde{L}_{1}}$
- $m_{\tilde{t}_1} - m_{\tilde{L}_{1}} = m_W$
- $m_{\tilde{t}_1} - m_{\tilde{L}_{1}} = m_t$

**Graphs:**
- $\Delta m = 10 \text{GeV}$
- $\Delta m = 80 \text{GeV}$

**Plots:**
- $P_T(l)$ vs. $P_T(b)$
- $M_T$ vs. $m_t$
Compressed Stop 1 soft lepton

- **MVA and Cut&Count common baseline:**
  - Require one ISR Jet, moderate $p_T^{miss}$, and $H_T$
  - 1 soft lepton:
    - $p_T(\text{mu}) > 3.5 \text{ GeV}$, $p_T(e) > 5 \text{ GeV}$
    - $p_T(l) < 30 \text{ GeV}$ (not for $\Delta m < 70 \text{ GeV}$ in MVA)
  - Dominant backgrounds: W+jets, ttbar, $Z \rightarrow \nu\nu$

- **Cut&Count**
  - Optimized to be sensitive to range of $\Delta m$
  - Binned in $p_T(l)$, $M_T$ and $p_T^{miss}$, $H_T$, $P_T$(ISR)
  - 0 b-jet or 1+ soft bjet ($p_T(b) < 60\text{GeV}$)
  - 44 total signal regions
  - Results combined with hadronic 0l search

- **MVA (only four body-decay):**
  - 8 BDTs trained for each $\Delta m$: 10-80 GeV
  - Trained against W+jets, ttbar and $Z \rightarrow \nu\nu$
  - Optimized lower boundary for each BDT
  - Trained Variables:
    - $p_T^{miss}$, $p_T(l)$, $M_T$, $p_T(j_1)$, $p_T(b)$, $\eta(l)$, $Q(l)$, $N_{jets}$, $H_T$, $N_b$, $\Delta r(l,b)$, Disc(b)

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**BDT $\Delta m=10\text{GeV}$**

**BDT $\Delta m=80\text{GeV}$**
Background Estimation

- **Prompt Backgrounds (W+jets and ttbar)**
  - Normalization in SR obtained from CRs
  - **MVA CR:** BDT cut reversed
  - **C&C CR:** $p_T(l) > 30$ GeV

- **Nonprompt ($Z\rightarrow\nu\nu +$ jets, QCD)**
  - Data-driven method using the ‘fake rate’ method

- **Rare backgrounds**
  - Taken from simulation

<table>
<thead>
<tr>
<th>$\Delta m$ (GeV)</th>
<th>BDT$&gt;$</th>
<th>$N_{DD_{prompt}}^{SR}$ (W + jets)</th>
<th>$N_{DD_{prompt}}^{SR}$ (tt)</th>
<th>$N_{DD_{fake}}^{SR}$</th>
<th>$N_{SR}^{Other}$</th>
<th>$N_{Pred}^{SR}$</th>
<th>$N_{Data}^{SR}$</th>
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<tr>
<td>10</td>
<td>0.31</td>
<td>18.4 ± 3.6</td>
<td>1.8 ± 4.8</td>
<td>8.0 ± 2.9</td>
<td>2.3 ± 1.4</td>
<td>30.3 ± 6.7</td>
<td>39</td>
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<tr>
<td>20</td>
<td>0.39</td>
<td>9.0 ± 2.0</td>
<td>1.3 ± 1.7</td>
<td>11.2 ± 3.2</td>
<td>3.1 ± 1.9</td>
<td>24.7 ± 4.5</td>
<td>20</td>
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<td>30</td>
<td>0.47</td>
<td>4.0 ± 2.5</td>
<td>1.2 ± 0.6</td>
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<td>1.7 ± 1.2</td>
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<td>40</td>
<td>0.48</td>
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<tr>
<td>50</td>
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<td>7.1 ± 2.0</td>
<td>5.5 ± 3.1</td>
<td>24.5 ± 4.8</td>
<td>36</td>
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<tr>
<td>60</td>
<td>0.50</td>
<td>2.0 ± 0.6</td>
<td>2.4 ± 1.2</td>
<td>3.1 ± 1.1</td>
<td>1.1 ± 0.9</td>
<td>8.7 ± 1.8</td>
<td>12</td>
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<tr>
<td>70</td>
<td>0.46</td>
<td>4.9 ± 1.6</td>
<td>3.4 ± 1.1</td>
<td>5.4 ± 1.6</td>
<td>3.2 ± 1.9</td>
<td>16.8 ± 2.9</td>
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</tr>
<tr>
<td>80</td>
<td>0.44</td>
<td>7.1 ± 1.6</td>
<td>5.1 ± 0.9</td>
<td>5.3 ± 1.6</td>
<td>5.2 ± 3.0</td>
<td>22.8 ± 3.3</td>
<td>26</td>
</tr>
</tbody>
</table>
Compressed Stop 1 soft lepton: Results

**direct-decay**

**chargino-mediated**

**CMS Preliminary 35.9 fb⁻¹ (13 TeV)**

\[ pp \rightarrow \tilde{t}^+_1 \tilde{t}^-_1 \rightarrow b f \tilde{\chi}^0_1 \]

- Observed ± 1 \( \sigma_{\text{theory}} \)
- Expected ± 1 \( \sigma_{\text{experiment}} \)

**NLO-NLL exclusion**

**95% CL upper limit on cross section [pb]**

**\( \Delta m(\tilde{t}^+_1, \tilde{\chi}^0_1) \) [GeV]**

- **MVA**
- **C&C combined with 0L**
- **C&C with 0L**

**\( m_{\tilde{t}_1} = (m_{\tilde{t}_1} + m_{\tilde{\chi}_1}) / 2 \)**

- **Observed ± 1 \( \sigma_{\text{theory}} \)**
- **Expected 1L**
- **Expected 0L**

**CMS Preliminary 35.9 fb⁻¹ (13 TeV)**

**NLO-NLL exclusion**

**95% CL upper limit on cross section [pb]**

**\( \Delta m(\tilde{t}^+_1, \tilde{\chi}^0_1) \) [GeV]**

- **MVA**
- **C&C combined with 0L**
- **C&C with 0L**

**\( m_{\tilde{t}_1} = (m_{\tilde{t}_1} + m_{\tilde{\chi}_1}) / 2 \)**

- **Observed ± 1 \( \sigma_{\text{theory}} \)**
- **Expected 1L**
- **Expected 0L**
2 lepton search

- 2 leptons: opposite charge (OC)
  - Same Flavor, Different Flavors
  - Top squark pair production $m_W < \Delta m < m_{\text{top}}$
    - 3-body decay of the stop
  - Main backgrounds are ttbar, tW, WW
    - Lepton and $p_T^{\text{miss}}$ come from W decay
    - $M_{T2}$ has an end point at W mass

$$M_{T2}(\ell\ell) = \min_{\tilde{p}_T^{\text{miss}1} + \tilde{p}_T^{\text{miss}2} - \tilde{p}_T^{\text{miss}}} \left( \max \left[ M_T(\tilde{p}_T^{\text{vis}1}, \tilde{p}_T^{\text{miss}1}), M_T(\tilde{p}_T^{\text{vis}2}, \tilde{p}_T^{\text{miss}2}) \right] \right)$$

- Search Strategy:
  - $M_{T2}$ shape analysis, binned in $p_T^{\text{miss}}$, N(b), N(j)
  - $p_T^{\text{miss}}$ : 140-200, 200-300, >300
  - N(b) binnings:
    - 0 b-Jet: $\Delta m \sim M(w)$
    - 1+ b-Jet : $\Delta m \sim M(t)$
  - 1 ISR Jet (pt > 150) for MET<300
  - Tail of $M_{T2}$ for main backgrounds:
    - Mostly from detector resolution effects
    - Validated in CRs
2 lepton search: Background

- **Main Backgrounds (ttbar, tW, WW)**
  - Irreducible backgrounds
  - Normalized by a simultaneous fit in $M_{T2}$
  - $M_{T2}$ shape in simulation validated in two CRs
    - 1st CR:
      - $100 < p_T^{\text{miss}} < 140$ GeV
      - Different flavor leptons (to reduce Drell-Yan events)
    - 2nd CR
      - Use $WZ \rightarrow 3\ell\nu$ to emulate $M_{T2}$ shape of WW
        - Take a 1\ell from Z, add to $p_T^{\text{miss}}$ and recalc. $M_{T2}$
  - Nonprompt leptons:
    - Important contribution to the $M_{T2}$ tail of ttbar
    - Corrected from events w/ 2 same sign leptons and a bjet

- **ttZ, WZ, ZZ**
  - Normalization obtained in dedicated regions
    - ttZ and WZ, from $3\ell$ events
    - ZZ from $4\ell$ events
2 lepton search: Some Results

- $140 \leq p_T^{\text{miss}} < 200$
  - $N(\text{b-jet}) = 0$
  - $N(\text{b-jet}) \geq 1$

CMS Preliminary 35.9 fb$^{-1}$ (13 TeV)

- $p_T^{\text{miss}} \geq 300$
  - $N(\text{b-jet}) = 0$
  - $N(\text{b-jet}) \geq 1$

CMS Preliminary 35.9 fb$^{-1}$ (13 TeV)

**Observed ± 1 $\sigma_{\text{theory}}$**

**Expected ± 1 $\sigma_{\text{experiment}}$**

**pp → $\tilde{t}\tilde{t}$, $\tilde{t} \rightarrow t \tilde{t}^0$**

NLO-NLL exclusion

$m_T$ [GeV]

95% CL upper limit on cross section [pb]
Thanks to the great performance of LHC in 2016, CMS was able to probe various regions in the SUSY parameter space!

Still no sign of SUSY…

New signatures are being investigated (long-lived gluinos)

Compressed regions are being probed in search of light stops

Results are provided for reinterpretation of other models:
  - Covariance matrix, efficiency maps, etc

Need to think of new interpretations, new topologies, new signatures!

Analysis of the 2017 data has begun and even more data to come in 2018!
Backup
Mismeasurement of Jet Energies

- Main source of large $P_T^{\text{miss}}$ in QCD multijet events
- Due to possible detection inefficiencies
- Or nonuniformity in the calorimeter calibration

$\alpha_T$

- Robust against jet mismeasurement:
  - $= 0.5$ for perfectly balanced back-to-back dijet event
  - $<0.5$ when there is imbalance between measured $E_T$ of the back to back jets
  - $>0.5$ when jets not back to back (genuine $P_T^{\text{miss}}$)

- When more than 2 jets:
  - n-jet system reduced to dijet by combining jets into two ‘pseudojets’
  - Use the combination that minimizes the $E_T$ difference between the two

$\Delta \phi^{\text{min}}$

- Min. angle between each jet and vector sum $P_T$ of all other jets
- $= 0$ for multi jet events
**Alpha T: Region Definitions**

<table>
<thead>
<tr>
<th>Physics object acceptances</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jet</strong></td>
</tr>
<tr>
<td>$p_T &gt; 40,\text{GeV}$, $</td>
</tr>
<tr>
<td><strong>Photon</strong></td>
</tr>
<tr>
<td>$p_T &gt; 25,\text{GeV}$, $</td>
</tr>
<tr>
<td><strong>Electron</strong></td>
</tr>
<tr>
<td>$p_T &gt; 10,\text{GeV}$, $</td>
</tr>
<tr>
<td><strong>Muon</strong></td>
</tr>
<tr>
<td>$p_T &gt; 10,\text{GeV}$, $</td>
</tr>
<tr>
<td><strong>Single isolated track (SIT)</strong></td>
</tr>
<tr>
<td>$p_T &gt; 10,\text{GeV}$, $</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Baseline event selection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All-jet final state</strong></td>
</tr>
<tr>
<td>Veto events containing photons, electrons, muons, and SITs within acceptance</td>
</tr>
<tr>
<td><strong>$p_T^{miss}$ quality</strong></td>
</tr>
<tr>
<td>Veto events based on filters related to beam and instrumental effects</td>
</tr>
<tr>
<td><strong>Jet quality</strong></td>
</tr>
<tr>
<td>Veto events containing jets that fail identification criteria or $0.1 &lt; f_{j_{i}}^{h} &lt; 0.95$</td>
</tr>
<tr>
<td><strong>Jet energy and sums</strong></td>
</tr>
<tr>
<td>$p_T^{j_{i}} &gt; 100,\text{GeV}$, $H_T &gt; 200,\text{GeV}$, $H_T^{miss} &gt; 200,\text{GeV}$</td>
</tr>
<tr>
<td><strong>Jets outside acceptance</strong></td>
</tr>
<tr>
<td>$H_T^{miss} / p_T^{miss} &lt; 1.25$, veto events containing jets with $p_T &gt; 40,\text{GeV}$ and $</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Signal region</th>
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</thead>
<tbody>
<tr>
<td><strong>$a_T$ threshold ($H_T$ range)</strong></td>
</tr>
<tr>
<td>0.65 (200–250 GeV), 0.60 (250–300), 0.55 (300–350), 0.53 (350–400), 0.52 (400–900)</td>
</tr>
<tr>
<td><strong>$\Delta\phi^{\ast}_{\text{min}}$ threshold</strong></td>
</tr>
<tr>
<td>$\Delta\phi^{\ast}<em>{\text{min}} &gt; 0.5 ,(n</em>{\text{jet}} \geq 2), \Delta\phi^{\ast\ast}<em>{\text{min}} &gt; 0.5 ,(n</em>{\text{jet}} = 1)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nominal categorization schema</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{jet}}$</td>
</tr>
<tr>
<td>1 \quad (monojet)</td>
</tr>
<tr>
<td>$\geq 2a$ \quad ($a$ denotes asymmetric, $40 &lt; p_T^{j_{i}} &lt; 100,\text{GeV}$)</td>
</tr>
<tr>
<td>2, 3, 4, 5, $\geq 6$ \quad (symmetric, $p_T^{j_{i}} &gt; 100,\text{GeV}$)</td>
</tr>
<tr>
<td>$n_{b}$</td>
</tr>
<tr>
<td>0, 1, 2, 3, $\geq 4$ \quad (can be dropped/merged vs. $n_{\text{jet}}$)</td>
</tr>
<tr>
<td><strong>$H_T$ boundaries</strong></td>
</tr>
<tr>
<td>200, 400, 600, 900, 1200 GeV \quad (can be dropped/merged vs. $n_{\text{jet}}, n_{b}$)</td>
</tr>
<tr>
<td><strong>$H_T^{miss}$ boundaries</strong></td>
</tr>
<tr>
<td>200, 400, 600, 900 GeV \quad (can be dropped/merged vs. $n_{\text{jet}}, n_{b}, H_T$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simplified categorization schema</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Topology ($n_{\text{jet}}, n_{b}$)</strong></td>
</tr>
<tr>
<td>Monojet-like \quad $(1 \cap \geq 2a, 0), ,(1 \cap \geq 2a, \geq 1)$</td>
</tr>
<tr>
<td>Low $n_{\text{jet}}$ \quad $(2 \cap 3, 0 \cap 1), ,(2 \cap 3, \geq 2)$</td>
</tr>
<tr>
<td>Medium $n_{\text{jet}}$ \quad $(4 \cap 5, 0 \cap 1), ,(4 \cap 5, \geq 2)$</td>
</tr>
<tr>
<td>High $n_{\text{jet}}$ \quad $(\geq 6, 0 \cap 1), ,(\geq 6, \geq 2)$</td>
</tr>
<tr>
<td><strong>$H_T$ boundaries</strong></td>
</tr>
<tr>
<td>$H_T &gt; 200,\text{GeV}$ ($n_{\text{jet}} \leq 3$), $H_T &gt; 400,\text{GeV}$ ($n_{\text{jet}} \geq 4$)</td>
</tr>
<tr>
<td><strong>$H_T^{miss}$ boundaries</strong></td>
</tr>
<tr>
<td>200, 400, 600, 900 GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control regions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$\mu$+jets (inverted $\mu$ veto)</strong></td>
</tr>
<tr>
<td>$p_T^{\mu_i} &gt; 30,\text{GeV}$, $</td>
</tr>
<tr>
<td><strong>$\mu\mu$+jets (inverted $\mu$ veto)</strong></td>
</tr>
<tr>
<td>$p_T^{\mu_1,\mu_2} &gt; 30,\text{GeV}$, $</td>
</tr>
<tr>
<td><strong>Multijet-enriched</strong></td>
</tr>
<tr>
<td>Sidebands to signal region: $H_T^{miss} / p_T^{miss} &gt; 1.25$ and/or $\Delta\phi_{\text{min}}^{\ast} &lt; 0.5$</td>
</tr>
</tbody>
</table>
## Alpha T Search: Results Summary

<table>
<thead>
<tr>
<th>Model family</th>
<th>Production and decay</th>
<th>Additional assumptions</th>
</tr>
</thead>
</table>

### Production and prompt decay of squark pairs

- **T2bb** \( pp \rightarrow \tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 \) —
- **T2tt** \( pp \rightarrow \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \) —
- **T2cc** \( pp \rightarrow \tilde{c}_1 \tilde{c}_1, \tilde{c}_1 \rightarrow c \tilde{\chi}_1^0 \) \( 10 < m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} < 80 \text{ GeV} \)
- **T2qq-8fold** \( pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0 \) \( m_{\tilde{q}_L} = m_{\tilde{q}_R}, \tilde{q} = \{ \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c} \} \)
- **T2qq-1fold** \( pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0 \) \( m_{\tilde{q}(\tilde{q} \neq \tilde{u}_L)} \gg m_{\tilde{u}_L} \)

### Production and prompt decay of gluino pairs

- **T1bbbb** \( pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}^*_1 \rightarrow b\bar{b} \tilde{\chi}_1^0 \) \( m_{\tilde{b}_1} \gg m_{\tilde{g}} \)
- **T1tttt** \( pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}\tilde{t}^*_1 \rightarrow \tilde{t}\tilde{t} \tilde{\chi}_1^0 \) \( m_{\tilde{t}_1} \gg m_{\tilde{g}} \)
- **T1qqqq** \( pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}^* \rightarrow \tilde{q}\tilde{q} \tilde{\chi}_1^0 \) \( m_{\tilde{q}} \gg m_{\tilde{g}} \)

### Production and decay of long-lived gluino pairs

- **T1qqqqLL** \( pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}^* \rightarrow \tilde{q}\tilde{q} \tilde{\chi}_1^0 \) \( m_{\tilde{q}} \gg m_{\tilde{g}}, 10^{-3} \lessgtr c\tau_0 \lessgtr 10^5 \text{ mm or metastable} \)
CC search: Definition of signal regions and their corresponding control regions (CR). The sub-regions of signal regions are denoted by tags in parentheses described in the text. For jets, the attributes “soft” and “hard” refer to the $p_T$ ranges 30–60 GeV and > 60 GeV, respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Common to all SRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of hard jets</td>
<td>≤ 2</td>
</tr>
<tr>
<td>$\Delta\phi$(hard jets) (rad)</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ (GeV)</td>
<td>&gt; 300</td>
</tr>
<tr>
<td>Lepton rejection</td>
<td>no $\tau$, or additional $\ell$ with $p_T &gt; 20$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR1</th>
<th>SR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_T$ (GeV)</td>
<td>&gt; 400</td>
<td>&gt; 300</td>
</tr>
<tr>
<td>$p_T$(ISR jet) (GeV)</td>
<td>&gt; 100</td>
<td>&gt; 325</td>
</tr>
<tr>
<td>Number of b jets</td>
<td>$\geq 1$ soft, 0 hard</td>
<td>$\geq 1$ soft, 0 hard</td>
</tr>
<tr>
<td>$</td>
<td>\eta(\ell)</td>
<td>$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>SR1a</th>
<th>SR1b</th>
<th>SR1c</th>
<th>SR2a</th>
<th>SR2b</th>
<th>SR2c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_T$ (GeV)</td>
<td>&lt; 60</td>
<td>60–95</td>
<td>&gt; 95</td>
<td>&lt; 60</td>
<td>60–95</td>
<td>&gt; 95</td>
</tr>
<tr>
<td>$Q(\ell)$</td>
<td>-1</td>
<td>-1</td>
<td>any</td>
<td>any</td>
<td>any</td>
<td>any</td>
</tr>
<tr>
<td>$p_T(\mu)$ (GeV)</td>
<td>3.5–5 (VL)</td>
<td>3.5–5 (VL)</td>
<td>any</td>
<td>3.5–5 (VL)</td>
<td>3.5–5 (VL)</td>
<td>any</td>
</tr>
<tr>
<td>$p_T(e, \mu)$ (GeV)</td>
<td>5–12 (L)</td>
<td>5–12 (L)</td>
<td>5–12 (L)</td>
<td>5–12 (L)</td>
<td>5–12 (L)</td>
<td>5–12 (L)</td>
</tr>
<tr>
<td>$C_T$ (GeV)</td>
<td>$300 &lt; C_{T1} &lt; 400$ (X)</td>
<td>$300 &lt; C_{T2} &lt; 400$ (X)</td>
<td>$C_{T1} &gt; 400$ (Y)</td>
<td>$C_{T2} &gt; 400$ (Y)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Compressed Stop 1: C&C vs MVA

Similar results for MVA and C&C at $\Delta m<30$

MVA performs much better for larger $\Delta m$ (partially due to loose lepton $p_T$)
## 2 lepton search: Region Definitions

<table>
<thead>
<tr>
<th>Channel</th>
<th>SR1\textsubscript{0Tag}</th>
<th>SR1\textsubscript{Tags}</th>
<th>SR2\textsubscript{0Tag}</th>
<th>SR2\textsubscript{Tags}</th>
<th>SR3\textsuperscript{ISR}\textsubscript{0Tag}</th>
<th>SR3\textsuperscript{ISR}\textsubscript{Tag}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{jets}}$</td>
<td>$\geq 0$</td>
<td>$\geq 1$</td>
<td>$\geq 0$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>$n_{\text{b jets}}$</td>
<td>0</td>
<td>$\geq 1$</td>
<td>0</td>
<td>$\geq 1$</td>
<td>0</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>$p_{T}^{\text{miss}}$ [GeV]</td>
<td>140-200</td>
<td>140-200</td>
<td>200-300</td>
<td>200-300</td>
<td>$\geq 300$</td>
<td>$\geq 300$</td>
</tr>
<tr>
<td>ISR jets</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td>$\geq 0$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>$M_{T2}(\ell\ell)$</td>
<td>0-20, 20-40, 40-60, 60-80, 80-100, 100-120, $\geq 120$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2 lepton search: $MT_2(\ell\ell)$ dist. (diff. flavor)
2 lepton search: MT2(\(ll\)) dist. (same flavor)
Selected CMS SUSY Results - SMS Interpretation

CMS Preliminary
\(|s = 13\text{ TeV}\)
\(L = 12.9 \text{ fb}^{-1} L = 35.9 \text{ fb}^{-1}\)

*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for \(m_{\text{LSP}} = 0 \text{ GeV}\) unless stated otherwise.
LPCC SUSY Cross Section WG

\[ \sigma(pp \rightarrow \text{SUSY}) \text{[pb]}, \text{NLO-NLL} \]

\[ \sqrt{s} = 13 \text{ TeV} \]

Events in 36 fb\(^{-1}\) 13TeV LHC data

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

arXiv:1407.5066
Typical Search Strategies

- **Designing the Signal Regions (SRs):**
  - Targeted Searches:
    - Search regions optimized with a specific signal in mind
  - Inclusive Searches:
    - Search regions optimized in order to be sensitive to various signals
    - Typically larger numbers of bins
  - Usually SRs are exclusive in CMS.
  - Discriminating variables are used to further bin the SRs

- **Background estimation:**
  - Control Regions (CRs) are defined to be kinematically similar to SRs but not overlapping with them
  - Important backgrounds are estimated in the CRs from data and extrapolated to SRs
  - Validations regions (orthogonal to both SRs and CRs) are used to test the estimation method.

- **Results**
  - Observed yields are compared to the expected background in SRs
  - Pop a champagne bottle! (or set limits)