Squark/gluino searches in hadronic channels with CMS

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for the CMS collaboration

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https://indico.cern.ch/event/442390/contributions/1096130/
Squark/gluino searches in hadronic channels with CMS

- Squarks or gluinos production in pp collisions
  - larger cross sections than other sparticle production
  - apt channel in early searches

- Hadronic channels
  - jets and missing energy in final states
  - events with a lepton or photon are vetoed in search regions and are used as control samples

- SMS (simplified model spectra)
  - interpretation of results

- Related talks
  - Parallel: Squark/gluino in leptonic channels with CMS by Artur Lobanov on Thursday
  - Parallel: Third generation SUSY searches in CMS by Eric Chabert on Thursday
  - Plenary: Inclusive searches for gluinos and squarks at the LHC plenary by Mark Hodgkinson on Thursday
  - Parallel: pMSSM studies with ATLAS and CMS by William James Fawcett, today next talk

Production cross sections

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSYSMSSummaryPlots13TeV
Summaries of Run 1 results

**T1tttt**

**g-g production, \(g \rightarrow t \bar{t} \chi^0_1\)**

**CMS Preliminary**

\(\sqrt{s} = 8\) TeV

ICHEP 2014

**T1qqqq**

**g-g production, \(g \rightarrow q \bar{q} \chi^0_1\)**

**CMS Preliminary**

\(\sqrt{s} = 8\) TeV

ICHEP 2014

**T1bbbb**

**g-g production, \(g \rightarrow b \bar{b} \chi^0_1\)**

**CMS Preliminary**

\(\sqrt{s} = 8\) TeV

ICHEP 2014

**T2qq**

**q-\bar{q} production, \(q \rightarrow q \chi^0_1\)**

**CMS Preliminary**

\(\sqrt{s} = 8\) TeV

ICHEP 2014

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSYSMSSummaryPlots8TeV
Run 2 squark/gluino searches in hadronic channels

<table>
<thead>
<tr>
<th>Reference</th>
<th>Search Parameters</th>
<th>Publication Details</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS-15-004</td>
<td>jets + (1 lepton) + razor</td>
<td>CDS:2114815</td>
<td>Dec 2015</td>
</tr>
<tr>
<td>SUS-15-005</td>
<td>jets + $\alpha_T$</td>
<td>CDS:2114880</td>
<td>Dec 2015</td>
</tr>
<tr>
<td>SUS-16-004</td>
<td>further SMS interpretations</td>
<td>CDS:2140312</td>
<td>Mar 2016</td>
</tr>
</tbody>
</table>
Common variables used to define search regions or categories

HT - a measure of how energetic the event was

\[ H_T = \sum_{i \in \text{jets}} |\vec{p}_{T,i}| \]

MET - sensitive to the presence of invisible particles and their total \( p_T \)

\[ \vec{E}_T^{\text{miss}} = \vec{H}_T = - \sum_{i \in \text{particles}} \vec{p}_{T,i} \]

MHT - alternative to MET, defined only by jet \( p_T \)

\[ \vec{H}_T^{\text{miss}} = \vec{H}_T = - \sum_{i \in \text{jets}} \vec{p}_{T,i} \]

\[ H_T^{\text{miss}} = |\vec{H}_T| = |\vec{H}_T^{\text{miss}}| = |\vec{H}_T| \]

\( \Delta \phi \) - the azimuthal angle between jet \( p_T \) and MHT (or MET)

\[ \Delta \phi_i = \Delta \phi(\vec{p}_{T,i}, \vec{H}_T^{\text{miss}}) \]

Jet multiplicity \( n_{\text{jet}} \)

b-jet multiplicity \( n_b \)
An overall SUSY search procedure in hadronic channels

- Define **search (signal) region (SR)**
  - high signal-to-background ratio
  - high hadronic activity and large missing energy
    - e.g., cuts on HT, njet, MHT, MET, Δϕ or dedicated variables, MT2, αT, Razor variables
  - no lepton or photon (**vetos**)
  - primary SM background processes: Z(→νν) + jets, top pair, W(→lν) + jets, QCD
  - **blind analysis**: do not analyze data in the search region until later

- Define **control regions (CR)**
  - by inverting the veto or as sidebands
  - used to predict background
  - dominated by specific SM processes

- Define **categories**
  - events in the SR are categorized, for example, in **bins** of HT, njet, nb, MHT

- Analyze data in CR: compare with MC
- Predict background in each category in the SR
  - validate the predictions, e.g., closure test
- Analyze data in the SR (**unblind**)
  - compare the data in the SR with the prediction
- Interpret the results in SMS unless a significant discrepancy is observed in the comparison
  - place exclusion limits on cross sections and masses, e.g., asymptotic formula [1] and CLS method

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SUS-15-002: HT + MHT

- The first CMS Run 2 SUSY paper  
  **PLB 758 (2016) 152**
- Combination of two strategies used in Run 1  
  **SUS-12-024, SUS-13-012**
- Search region: high jet multiplicity, high HT
- Categorization: bins of HT, MHT, $n_{\text{jet}}$, $n_{\text{b}}$
- Interpretation: T1tttt, T1bbbb, T1qqqq, T1qqqqVV

**Background composition**

- $n_{\text{jet}} \geq 4$, HT > 500 GeV, MHT > 200 GeV
- no isolated e, $\mu$, or track
- $\Delta \phi$(MHT, jet) > 0.5, 0.5, 0.3, 0.3

**Categorization**

- Each bin in the figure is further binned in $n_{\text{jet}}$, $n_{\text{b}}$  
  $n_{\text{jet}}$: 4-6, 7-8, $\geq$9  
  $n_{\text{b}}$: 0, 1, 2, $\geq$3

**Run-1 results**

- SUS-13-012, JHEP 06 (2014) 055
- SUS-12-024, PLB 725 (2013) 243
- SUS-12-011, PRL 109 (2012) 171803
- SUS-10-005, JHEP 08 (2011) 155
Results

Observed number of events and predictions in each of the 72 search region bins

![Graph showing CMS results for various search region bins with expected and observed events, and background predictions.](image)

**Background predictions**

- top pair, $W(\to l\nu) +$ jets:
  - lost lepton
  - hadronically decaying tau - a template method
- $Z(\to \nu\nu) +$ jets from $Z(\to ll) +$ jets, $\gamma +$ jets
- QCD from sideband of $\Delta\phi$
Submitted to JHEP, arXiv.org:1603.04053

Use the variable MT2 in defining search region and categorization

Low $n_{\text{jet}}$, HT thresholds

Interpretations
- T1tttt, T1bbbb, T1qqqq, T2qq

Search region
- $n_{\text{jet}} \geq 1$
- HT $> 200 \, \text{GeV}$, MET $> 200 \, \text{GeV}$
  - or HT $> 1000 \, \text{GeV}$, MET $> 30 \, \text{GeV}$
- for $n_{\text{jet}} \geq 2$
  - MT2 $> 200 \, \text{GeV}$
  - $\Delta \phi(\text{MET, jet}) > 0.3$ for 4 leading jets
  - $|\text{MET} - \text{MHT}| / \text{MET} < 0.5$
- no isolated $e$, $\mu$, or track

Run-1 results with MT2
- SUS-14-015, arXiv:1602.03169
- SUS-13-019, JHEP 05 (2015) 078
- SUS-12-002, JHEP 10 (2012) 018

**MT2 - stransverse mass**

$$M_{T2} = \min_{\vec{q}_T + \vec{r}_T - \vec{E}_{\text{miss}}} \left[ \max \left( M_T(\vec{p}_T^{j1}, \vec{q}_T), M_T(\vec{p}_T^{j2}, \vec{r}_T) \right) \right]$$

$$M_T(\vec{p}_T, \vec{q}_T) = \sqrt{2(\vec{p}_T||\vec{q}_T| - \vec{p}_T \cdot \vec{q}_T)}$$

$p_T^{j1}, p_T^{j2}$: $p_T$ of each of two pseudo-jets which are formed to maximize their invariant mass

While MT2 is small for QCD events, it can be large for signal events
Categorization

- 5 bins in HT, 11 bins in $n_{\text{jet}}$ and $n_b$
- bins of MT2 for $n_{\text{jet}} \geq 2$
- bins of jet $p_T$ for $n_{\text{jet}} = 1$

The boundaries of HT and MT2 bins for $n_{\text{jet}} \geq 2$

![Diagram of HT and MT2 boundaries]

The boundaries of jet $p_T$ bins for $n_{\text{jet}} = 1$

![Diagram of jet $p_T$ boundaries]
SUS-15-004: Razor

- **CMS-PAS-SUS-15-004**
- Use *razor variables* in the definition of the search region and the background prediction
- 0 or 1 lepton and 4 or more jets
- Interpretation
  - T1bbbb, T1tttt, T1qqqq, T1ttbb

### Razor variables

Use longitudinal momenta to find an approximate center-of-mass frame of patron-level process

<table>
<thead>
<tr>
<th>$M_R$</th>
<th>$R^2$</th>
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<tbody>
<tr>
<td>for SUSY models</td>
<td></td>
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<tr>
<td>- $M_R$ has a broad peak</td>
<td></td>
</tr>
<tr>
<td>- $R^2$ has a long tail</td>
<td></td>
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<tr>
<td>for SM processes</td>
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<tr>
<td>- both exponentially decrease, which is used to model the background shape</td>
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</tbody>
</table>

### Search region

- for muon + multijet categories
  - 1 muon, 4 or more jets
  - $M_R > 400$ GeV, $R^2 > 0.15$, $MT > 120$ GeV
- for electron + multijet categories
  - 1 electron, 4 or more jets
  - $M_R > 400$ GeV, $R^2 > 0.15$, $MT > 120$ GeV
- for multijet categories
  - 4 jets with $p_T > 40$ GeV or 2 jets with $p_T > 80$ GeV
  - $M_R > 500$, $R^2 > 0.25$
  - $\Delta \phi < 2.8$ (angle between two razor hemispheres)

### Run-1 results with razor variables

- **SUS-14-007**, arXiv:1602.02917 (accepted by PRD)
- **SUS-14-004**, PRD 92 (2015) 072006
- **SUS-13-004**, PRD 91 (2015) 052018
- **SUS-12-005**, PRD 90 (2014) 112001
- **SUS-11-024**, PRL 111 (2013) 081802
- **SUS-10-009**, PRD 85 (2012) 012004
SUS-15-005: $\alpha_T$

- **CMS-PAS-SUS-15-005**
- Use $\alpha_T$ and $\Delta \phi_{\text{min}}$ to suppress QCD to a negligible level
- Low njet, HT thresholds
- Interpretations: T1tttt, T1bbbb, T1qqqq

**Search region**
- $n_{\text{jet}} (p_T > 40 \text{ GeV}) \geq 1$
- lead jet $p_T > 100 \text{ GeV}$
- $HT > 200 \text{ GeV}, MHT > 130 \text{ GeV}$
- $MHT/MET < 1.25$
- $\Delta\phi_{\text{min}} > 0.5$
- $\alpha_T > 0.52 \sim 0.65$ only for $HT < 800 \text{ GeV}$

**Categorization**
- $n_{\text{jet}}$ bins
  - **monojet bins**: $n_{\text{jet}} = 1$
  - **asymmetric jet bins**: $n_{\text{jet}} \geq 2$
    - lead jet $p_T > 100 \text{ GeV}$
    - 2nd lead jet $p_T$ between 40 and 100 GeV
  - **symmetric jet bins**: $n_{\text{jet}} \geq 2$
    - lead and 2nd lead jets with $p_T > 100 \text{ GeV}$
    - each $n_{\text{jet}}$ bin further in bins of $n_\Delta$, HT, MHT

**alphaT**

$$\alpha_T = \frac{\sum_i E_T^{j_i} - \Delta E_T}{2 \sqrt{\left(\sum_i E_T^{j_i}\right)^2 - H_T^{\text{miss}}^2}}$$

$\Delta E_T$: the jets in the event are combined into two **pseudo-jets** such that $\Delta E_T$, the difference in $E_T$ of two pseudo-jets, is minimized

$\alpha_T \leq 0.5$ for QCD events, $\alpha_T$ can be greater than 0.5 for events with invisible particles

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**Run-1 results with $\alpha_T$**
- SUS-14-006, arXiv:1605.08993
- SUS-12-028, EPJC 73 (2013) 2568
- SUS-11-022, JHEP 01 (2013) 077
- SUS-11-003, PRL 107 (2011) 221804
- SUS-10-003, PLB 698 (2011) 196
Gluino searches

**T1qqqq**

\[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_0^0 \]

**T1tttt**

\[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_0^0 \]

**T5qqqVV**

\[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q} V\tilde{\chi}_0^0 \]

**T1bbbb**

\[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_0^0 \]
Squark searches

T2qq

CMS

2.3 fb⁻¹ (13 TeV)

pp → \bar{q} q, \bar{q} → q \tilde{\chi}^0

NLO+NLL exclusion

- Observed ± \sigma_{theory}
- Expected ± \sigma_{experiment}

95% CL upper limit on cross section [pb]

SUS-15-003
Summary

• We have searched hadronic final states in 2.3 fb\(^{-1}\) of data collected with the CMS detector in 2015 for deviations from the standard model prediction. We interpreted the results in SMS for squarks or gluinos production and extended the exclusion regions on the mass planes from the Run 1 results.

• The data collection in 2016 has been successful. CMS has recorded 3.2 fb\(^{-1}\) of data as of June 14th. We are actively analyzing these new data and continue searching for signature of production of squarks, gluinos, and other sparticles.
End