Search for SUSY in hadronic final states with the $\alpha_T$ variable at CMS

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Search for SUSY in hadronic final states with the $\alpha_T$ variable at CMS

- **Hadronic final states**
  - jets and missing energy
  - events with a lepton or photon are vetoed

- **The $\alpha_T$ variable**
  - A dimensionless variable used to reject QCD multijet events

- Related talks: CMS searches in hadronic final states with other variables
  - **MT2**: *Search for supersymmetry in hadronic final states with the MT2 variable* by Mario Masciovecchio, today
  - **Razor**: *Inclusive searches for SUSY using the razor variables in CMS* by Javier Mauricio Duarte, tomorrow
  - **MHT**: *Search for supersymmetry in the multijet and missing transverse momentum channel in pp collisions at 13 TeV* by Kevin Pedro, tomorrow

[Image of graph showing production cross sections vs. particle mass in GeV]
Run 2 SUSY searches with the $\alpha_T$ variable

<table>
<thead>
<tr>
<th>SUS-15-005</th>
<th>2.2 fb$^{-1}$ 13 TeV</th>
<th>CDS:2114880</th>
<th>Dec 2015</th>
</tr>
</thead>
</table>

Run 1 SUSY searches with the $\alpha_T$ variable

<table>
<thead>
<tr>
<th>SUS-14-006</th>
<th>18.5 fb$^{-1}$ 8 TeV</th>
<th>arXiv:1605.08993 (submitted to PLB)</th>
<th>May 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS-12-028</td>
<td>11.7 fb$^{-1}$ 8 TeV</td>
<td>EPJC 73 (2013) 2568</td>
<td>Mar 2013</td>
</tr>
<tr>
<td>SUS-11-022</td>
<td>4.98 fb$^{-1}$ 7 TeV</td>
<td>JHEP 01 (2013) 077</td>
<td>Oct 2012</td>
</tr>
<tr>
<td>SUS-11-003</td>
<td>1.14 fb$^{-1}$ 7 TeV</td>
<td>PRL 107 (2011) 221804</td>
<td>Sep 2011</td>
</tr>
<tr>
<td>SUS-10-003</td>
<td>35 pb$^{-1}$ 7 TeV</td>
<td>PLB 698 (2011) 196</td>
<td>Jan 2011</td>
</tr>
</tbody>
</table>

SUSY production at LHC

A typical SUSY production at LHC predicted by SUSY models with conserved R-parity

SUSY particles will be pair-produced

Each SUSY particle successively decays to another SUSY particle and SM particle (the cascade decay)

Each cascade decay chain ends with the LSP, invisible and causes missing transverse momentum (MET)

The final states contain large MET, jets, and possibly leptons or photons
A SMS contains two (or three) new particles in addition to the SM particles:
- new particles are named after sparticles with the same quantum numbers, e.g., gluinos, neutralinos
- the heavier particles are produced in pair. Each decay chain ends with the lighter particle (LSP).
- the masses of the new particles are the only new parameters if the couplings are specified by a particular SUSY model.
- relevant for "natural" SUSY models, in which only a few particles are light enough to be produced at LHC.

We use the data to exclude the possible range of the masses of the new particles in SMS as long as the data agrees with the SM predictions.
Common variables used to define search regions or categories

**HT** - a measure of how energetic the event was

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

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

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

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

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

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

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

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

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

**b-jet multiplicity** \( n_b \)
Two dedicated variables to suppress QCD events

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

\( \Delta E_T \): 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

\[ \Delta \phi^*_\text{min} = \min_{i \in \text{jets}} \Delta \phi(\vec{p}_T^{i}, \vec{H}_{\text{miss}}^T + \vec{p}_T^{i}) \]

The angle between jet \( p_T \) and MHT that is calculated without the jet

\[ \Delta \phi \]
An overall search procedure in hadronic final states

- Define **search (signal) region (SR)**
  - high signal-to-background ratio
    - high hadronic activity and large missing energy
e.g., cuts on HT, $n_{\text{jet}}$, MHT, $\alpha_T$, $\Delta\phi^*$
  - no lepton or photon (vetos)
  - primary SM background processes: $Z(\rightarrow\nu\nu) + \text{jets}$, top pair, $W(\rightarrow l\nu) + \text{jets}$, 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 in **bins** of HT, $n_{\text{jet}}$, $n_b$, 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 CL$_S$ method

CRs and dominant SM processes:
- double lepton: $Z(\rightarrow ll) + \text{jets}$
- single photon: $\gamma + \text{jets}$
- single lepton: $W(\rightarrow l\nu) + \text{jets}$, top pair
- sideband of cuts: QCD

SUS-15-005: overview

- **CMS-PAS-SUS-15-005**
- 2.2 fb\(^{-1}\), pp collisions, 2015, LHC Run 2
- Use \(\alpha_T\) and \(\Delta\phi^{*\text{min}}\) to suppress QCD to a negligible level
- **Search region**: low \(n_{\text{jet}}\), HT thresholds
- **Categorization**: bins of \(n_{\text{jet}}, n_b, HT, MHT\)
- **Interpretations**: T1tttt, T1bbbb, T1qqqq


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

**Categorization**
- \(n_{\text{jet}}\) bins
  - **monojet bins**: \(n_{\text{jet}} = 1\)
  - lead jet \(\rho_T > 100 \text{ GeV}\)
  - 2nd lead jet \(\rho_T\) between 40 and 100 GeV
  - **asymmetric jet bins**: \(n_{\text{jet}} \geq 2\)
    - lead and 2nd lead jets with \(\rho_T > 100 \text{ GeV}\)
  - each \(n_{\text{jet}}\) bin further in bins of \(n_b, HT, MHT\)
Table 1: Summary of the selection criteria and categorisation for signal candidate events.

<table>
<thead>
<tr>
<th>Baseline selection:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets selection</td>
<td>Select jets satisfying $p_T &gt; 40$ GeV and $</td>
</tr>
<tr>
<td>Forward jet veto</td>
<td>Veto events containing jet satisfying $p_T &gt; 40$ GeV and $</td>
</tr>
<tr>
<td>Lepton/photon vetoes</td>
<td>$p_T &gt; 10$ GeV and $</td>
</tr>
<tr>
<td>Lead jet acceptance</td>
<td>$p_T &gt; 100$ GeV and $</td>
</tr>
<tr>
<td>Second jet acceptance</td>
<td>$p_T &gt; 100$ GeV (symmetric), $40 &lt; p_T &lt; 100$ GeV (asymmetric), $p_T &lt; 40$ GeV (monojet)</td>
</tr>
<tr>
<td>Energy sums</td>
<td>$H_T &gt; 200$ GeV and $H_T^{miss} &gt; 130$ GeV</td>
</tr>
<tr>
<td>$E_T^{miss}$ cleaning</td>
<td>Various filters related to beam and instrumental effects</td>
</tr>
</tbody>
</table>

(n$_{jet}$,n$_{b}$) categorisation and $H_T$ binning:

| $n_{jet}$ binning  | 1 (monojet), 2, 3, 4, ≥5 (both symmetric and asymmetric) |
| $n_{b}$ binning    | 0, 1, 2, ≥ 3 ($n_{b} \leq n_{jet}$) |
| $H_T$ (GeV) binning| 200, 250, 300, 350, 400, 500, 600, >800 GeV (bins can be merged depending on $n_{jet}$, $n_{b}$) |

Signal region:

| QCD suppression | $\alpha_T > 0.65$ to $\alpha_T > 0.52$ ($H_T$-dependent, for the region $H_T < 800$ GeV) |
| QCD suppression | $\Delta\phi_{min}^{*} > 0.5$ |
| QCD suppression | $H_T^{miss} / E_T^{miss} < 1.25$ |

Control regions

**Single muon:** one isolated muon with $M_T$ compatible with the W mass

**Double muon:** two isolated muons with the dimuon mass compatible with the Z mass

**Single photon:** one isolated photon and $H_T > 400$ GeV

**Hadronic:** sideband of MHT/MET, $\Delta\phi_{min}^{*}$ cuts
The data and the prediction (labeled as “prefit background”) in the MHT bins in two $n_{\text{jet}}$, $n_{b}$, HT bins.
SUS-15-005: interpretations in SMS

The color scale - the upper limit on the cross section derived from the acceptance, the observed and predicted number of events in the signal region and their uncertainties.

The thick black line - the observed lower mass limit, the contour at which the theoretical cross sections calculated in SUSY NLO+NLL intersect with the upper cross section limit.

The thin black lines - the contours at which 1 sigma variations of the theoretical cross sections intersect with the upper cross section limit.

The thick red dotted line - the expected lower mass limit, the contour at which the theoretical cross sections intersect with the expected upper cross section limit, the limit that would be obtained if the predicted number of the events were actually observed.

The signal acceptance is evaluated with signal MC samples generated at each point in the grid of the mass plane.
**T1qqqq**

\[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 \]

**T1bbbb**

\[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0 \]

**T1tttt**

\[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0 \]

CMS Preliminary

\[ m_{\tilde{g}} \text{ [GeV]} \]

Expected

Observed

- SUS-15-002 (Higgsino), 2.3 fb\(^{-1}\) (13 TeV)
- SUS-15-003 (M\(_{1/2}\)), 2.3 fb\(^{-1}\) (13 TeV)
- SUS-15-004 (Razor), 2.1 fb\(^{-1}\) (13 TeV)
- SUS-15-005 (\(\chi_1\)), 2.2 fb\(^{-1}\) (13 TeV)
- SUS-15-006, 1-lep (\(\Delta\tilde{g}\)), 2.3 fb\(^{-1}\) (13 TeV)
- SUS-15-007, 1-lep (M\(_{1/2}\)), 2.2 fb\(^{-1}\) (13 TeV)
- SUS-15-008, 2-lep (SS), 2.2 fb\(^{-1}\) (13 TeV)
- SUS-15-009, 3-lep (13 TeV)
- SUS-14-010, 0+1+2+3-lep, 19.5 fb\(^{-1}\) (8 TeV)

CMS Preliminary

\[ m_{\tilde{g}} \text{ [GeV]} \]

Expected

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- SUS-15-003, 0-lep (M\(_{1/2}\)), 2.3 fb\(^{-1}\) (13 TeV)
- SUS-15-004, 0-lep (Razor), 2.1 fb\(^{-1}\) (13 TeV)
- SUS-15-005, 0-lep (\(\chi_1\)), 2.2 fb\(^{-1}\) (13 TeV)
- SUS-15-006, 1-lep (SS), 2.2 fb\(^{-1}\) (13 TeV)
- SUS-15-007, 2-lep (SS), 2.2 fb\(^{-1}\) (13 TeV)
- SUS-15-008, 3-lep (13 TeV)
- SUS-14-010, 0+1+2+3-lep, 19.5 fb\(^{-1}\) (8 TeV)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
• With the variable $\alpha_T$, we have searched hadronic final states in 2.2 $\text{fb}^{-1}$ of data collected with the CMS detector in 2015 for deviations from the standard model prediction. We interpreted the results in SMS for 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 8.2 $\text{fb}^{-1}$ of data as of July 3rd. We are actively analyzing these new data and continue searching for signature of production of squarks, gluinos, and other sparticles.
End