Three searches for squarks and gluinos with the CMS detector using kinematic variables

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On behalf of the CMS Collaboration

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Introduction

- CMS has a broad range of searches for events with escaping undetected particles from, e.g., SUSY with R-parity conservation. They are organized by numbers of leptons and photons required.

- Described here are three different searches which use primarily all-hadronic events: $\alpha_T$, $M_{T2}$, Razor. Shared features include strong suppression of multi-jet backgrounds and variables related to mass scales. Substantial differences include triggers, signal selection, and background estimation methods.

- Results from analyzing 1.1/fb (35/pb) of data are presented and interpreted in both the CMSSM and “simplified models”.
The CMS Detector

- Excellent performance and live-time in 2011.
- SUSY searches exercise every sub-detector!
The search using $M_{T2}$

$M_{T2}$ is a generalization of transverse mass to a system with two semi-invisibly decaying particles [Lester, Summers, 1999]:

$$M_{T2}(m_\chi) = \min_{p_T^{\chi(1)}+p_T^{\chi(2)}=p_T^{\text{miss}}} \left[ \max(m_T^{(1)}, m_T^{(2)}) \right]$$

Each $m_T$ is the transverse mass of a sparticle decaying to a visible system and LSP; for the correct value of $m_\chi$, $M_{T2}$ has an endpoint at the parent sparticle mass.

Assuming zero masses and no ISR or UTM, $M_{T2}$ assumes a simple form: $(M_{T2})^2 = 2p_T^{\text{vis}(1)}p_T^{\text{vis}(2)}(1 + \cos\phi_{12}) \implies$ apparent that back-to-back visible systems have low $M_{T2}$

For an $n$-jet system, two “pseudo-jets” are formed from reconstructed event hemispheres.
$M_{T2}$ search: trigger, objects, vetoes

Trigger \( H_T > 550 \) GeV

**MET** Built from reconstructed particles.

**Jets** Anti-\( k_T \), \( R = 0.5 \); built from reconstructed particles;
\[ |\eta| < 2.4, \rho_T > 20 \text{ GeV}. \]

**Leptons** Veto events with an iso. muon or electron with \( \rho_T > 10 \) GeV.

**Noise** Veto events with a jet which fails loose ID requirements.

Further:

- \(|MHT - MET| < 70 \) GeV, to protect against several low-\( \rho_T \) jets pointing in the same direction.
- \( \min_j \Delta \phi(\text{jet, } MET) > 0.3 \) to protect against severely mis-mismeasured jets.
$M_{T2}$ search: two signal selections

“High $M_{T2}$” selection

- $H_T > 600$ GeV
- $N_{jets} \geq 3$
- Leading two jets have $p_T > 100$ GeV
- $M_{T2} > 400$ GeV

- Targets models with heavy sparticles.

“Low $M_{T2}$” selection

- $H_T > 650$ GeV
- $N_{jets} \geq 4$; $N_{b-jets} \geq 1$
- Leading (second) jet has $p_T > 150(100)$ GeV
- $M_{T2} > 150$ GeV

- Targets models with large $m_{squark}$ and small $m_{gluino}$. 
$M_{T2}$ search: observed distributions

- **High $M_{T2}$ Analysis**
  - CMS Preliminary, $\sqrt{s} = 7$ TeV, $L = 1.1$ fb$^{-1}$
  - Events vs. $M_{T2}$

- **Low $M_{T2}$ Analysis**
  - CMS Preliminary, $\sqrt{s} = 7$ TeV, $L = 1.1$ fb$^{-1}$
  - Events vs. $M_{T2}$

(numbers are in GeV)

- **signal region:**
  - $400 < M_{T2}$
- **control region:**
  - $200 < M_{T2} < 400$

- **signal region:**
  - $150 < M_{T2}$
- **control region:**
  - $100 < M_{T2} < 150$
$M_{T2}$ search: yields and background estimation

- The QCD background was estimated from a control region using the form
  \[ r(M_{T2}) = \frac{N(\Delta\phi_{min} \geq 0.3)}{N(\Delta\phi_{min} \leq 0.2)} = \exp(a - b \cdot M_{T2}) + c, \]
  validated in MC, tested with variations of fit range and cut values, emulated catastrophic jet loss. Contribution found to be negligible for both analyses ($< 1$ event).

- $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ samples were selected by inverting the lepton vetoes in the $M_{T2}$ control region and used to predict:
  - $W$ and $t\bar{t}$ backgrounds from unobs. leptons (using loss probs.)
  - $Z \rightarrow \nu\bar{\nu}$ background (using $t\bar{t}$ subtraction; $W$-to-$Z$ correction)

- Results (1.1/fb):

<table>
<thead>
<tr>
<th>search</th>
<th>$N_{obs}$</th>
<th>data-driven pred.</th>
<th>MC pred.</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $M_{T2}$</td>
<td>12</td>
<td>$12.6 \pm 1.3$(stat.) $\pm 3.5$(syst.)</td>
<td>11.0</td>
</tr>
<tr>
<td>Low $M_{T2}$</td>
<td>19</td>
<td>$10.6 \pm 1.9$(stat.) $\pm 4.8$(syst.)</td>
<td>15.0</td>
</tr>
</tbody>
</table>
\( M_{T2} \) search: interpretation in the CMSSM

The sensitivities complement each other.
$M_{T2}$ search: interpretation in a simplified model

Two SUSY particles, b-enriched:

\[ P_1, P_2, \tilde{g}, \tilde{\chi}^0, b \]

<table>
<thead>
<tr>
<th>$m_{\tilde{g}}$ (GeV)</th>
<th>$m_{LSP}$ (GeV)</th>
<th>NLO-QCD $\sigma$ (pb)</th>
<th>95% CL upper limit on $\sigma$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CMS Preliminary
$\sqrt{s} = 7$ TeV $L = 1.1$ fb$^{-1}$

lowMT2

CMS - searches with kinematic variables
SUSY '11
The search using Razor variables

- The “Razor” variables $R$, $M_R$ were designed to discover and characterize events with heavy pair-produced particles [Rogan, arXiv:1006.2727].

- Reconstructed objects are grouped into two hemispheres with 3-momenta $\vec{p}$, $\vec{q}$ ($\vec{M}$ denotes MET).

- $M_R$ peaks at $M_\Delta$, whereas $M^R_T$ has a kinematic edge at $M_\Delta$.

- $R \equiv \frac{M^R_T}{M_R}$ provides strong rejection of QCD multi-jet events:

$$M_R = 2 \sqrt{\frac{(|\vec{p}|q_z - |\vec{q}|p_z)^2}{(p_z - q_z)^2 - (|\vec{p}| - |\vec{q}|)^2}}$$

$$M^R_T = \sqrt{|\vec{M}|(|\vec{p}| + |\vec{q}|) - \vec{M} \cdot (\vec{p} + \vec{q})}$$

$$M_\Delta = \frac{m^2_{\tilde{q}} - m^2_{\tilde{\chi}_1^0}}{2m_{\tilde{q}}}$$
Razor search: method and 35/pb results

- Exponent of $M_R$ distribution is measured as function of $R$ cut

- Hadronic box with $\geq 2$ jets and $R > 0.5$ has signal region at $M_R > 500$ GeV

- Muon and electron boxes:
  - provide EWK background prediction (using low $M_R$)
  - provide search sensitivity (at high $M_R$)

- Excellent sensitivity at 35/pb–stay tuned for 2011 results!
The search using $\alpha_T$

- Inspired by the variable $\alpha$ [Randall, Tucker-Smith, 2008]
- For a di-jet system, $\alpha_T \equiv \frac{E_{T,\text{jet}2}}{M_T}$.
- QCD expectation $= 0.5$
- Jet mis-measurements cause $\alpha_T < 0.5$
- Events with genuine MET can have smaller $M_T$, and hence $\alpha_T > 0.5$

- For an $n$-jet system, form two “pseudo-jets” defined by balance in pseudo-jet $H_T \equiv \sum_j E_T$
- $\alpha_T \equiv \frac{1}{2} \frac{H_T - \Delta H_T}{M_T}$.
\( \alpha_T \) search: trigger, objects, vetoes

**Trigger** \( H_T > 250 \ \text{GeV} \) and \( MHT > 90 \ \text{GeV} \).

**MET** Built from calorimeter towers.

**Jets** Anti-\( k_T \), \( R = 0.5 \); built from calorimeter towers; \( |\eta| < 3.0 \), \( p_T > 50 \ \text{GeV} \). The thresholds are scaled at low \( H_T \) to preserve phase space:

<table>
<thead>
<tr>
<th>( H_T ) range</th>
<th>jet ( p_T ) threshold</th>
<th>leading 2 jets ( p_T ) threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>275 &lt; ( H_T ) &lt; 325</td>
<td>36.7</td>
<td>73.3</td>
</tr>
<tr>
<td>325 &lt; ( H_T ) &lt; 375</td>
<td>43.3</td>
<td>86.7</td>
</tr>
<tr>
<td>375 &lt; ( H_T )</td>
<td>50.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Leptons** Veto events with an iso. muon or electron with \( p_T > 10 \) \( \text{GeV} \).

**Photons** Veto events with an iso. photon with \( p_T > 25 \) \( \text{GeV} \).

**Forward** Veto events with a jet with \( |\eta| > 3.0 \).

**Noise** Veto events with a jet which fails loose ID requirements.
\( \alpha_T \) search: hadronic (signal) selection

- \( H_T > 275 \text{ GeV} \) (where trigger becomes fully efficient)
- \( N_{\text{jets}} \geq 2 \)
- Leading jet has \(|\eta| < 2.5.\)
- \( \alpha_T > 0.55 \)
- \( MHT/MET < 1.25 \), to protect against several low-\( p_T \) jets pointing in the same direction.
- \( \Delta \phi^* \equiv \min_j \Delta \phi(\text{jet}, \text{MHT computed w/o the jet}) > 0.5 \)
  or
- \( \min \Delta R(\text{jet}^*, \text{insensitive detector region}) > 0.3 \)
  to protect against severely mis-mismeasured jets due to instrumental inefficiency.
search: some distributions

- Applied cuts: $H_T > 375$ GeV, $MHT > 100$ GeV, $MHT/MET < 1.25$, where the trigger is fully efficient.

- Note: MC is shown simply for guidance; yields not used in the analysis. LM4 and LM6 are benchmark points in the CMSSM.
\( \alpha_T \) search: background estimation

- All-Hadronic (signal) sample, already described
- Photon + jets sample, used to estimate \( Z \rightarrow \nu \bar{\nu} \) background
- Muon + jets sample, used to estimate \( tt+W \) background
- QCD-dominated all-Hadronic sample (invert \( \alpha_T \) cut) used to model \( H_T \) dependence

\[ R_{\alpha_T} \text{ HT-evolution} \]

- Hadronic Control Sample
  - \( \alpha_T < 0.55 \)

- Hadronic Signal Sample
  - \( \alpha_T > 0.55 \)

- MC \( ttW \) had
- MC muon

- MC \( Z\rightarrow\nu\bar{\nu} \) had
- MC photon

- Muon Control Sample
  - \( \mu p_T > 10 \text{ GeV; } \alpha_T > 0.55 \)

- Photon Control Sample
  - \( \text{photon } p_T > 100 \text{ GeV; } \alpha_T > 0.55 \)

- MC used only for ratios of kinematically similar processes
\( \alpha_T \) search: evolution in \( H_T \) of yield ratio

\[ R_{\alpha_T} = \frac{N_{\alpha_T > 0.55}}{N_{\alpha_T < 0.55}} \]. Left: observed values and fit result.

The contribution from EWK backgrounds is modeled as flat, as tested in MC (right).

A possible contribution from QCD is modeled as exponentially falling, as tested with relaxed cuts (to greatly enrich QCD background). Fit contribution compatible with zero.

A signal contribution is expected to rise.
The SM yields result from the simultaneous fit to the hadronic (signal) sample and these control samples.

The control sample yields are connected via MC ratios to the background yields in the hadronic sample [O(30%) sys. unc.].
The background model describes the data over three orders of magnitude in yield, from near the trigger threshold to $O(1 \text{ TeV})$ of visible transverse energy.
\( \alpha_T \) search: interpretation in the CMSSM

\[
\alpha_T \int L dt = 1.1 \ \text{fb}^{-1} \quad \sqrt{s} = 7 \ \text{TeV}
\]

95\% C.L. Limits:
- Observed Limit (NLO), CL
- Observed Limit (NLO), PL
- Median Expected Limit \( \pm 1\sigma \), PL
- Observed Limit (NLO), FC, 35pb\(^{-1}\)

\( \tan \beta = 10, A_0 = 0, \mu > 0 \)

\( m_0 \) (GeV)

\( m_{1/2} \) (GeV)

\( \tilde{g} \) (500) GeV

\( \tilde{g} \) (750) GeV

\( \tilde{g} \) (1000) GeV

\( \tilde{g} \) (1250) GeV

\( \tilde{\chi}_1^\pm \)

\( \tilde{\chi}_1^0 \)

\( \tilde{t} \)

\( \tilde{t} \)
$\alpha_T$ search: interpretation in simplified models

Two models, each with only two SUSY particles:

- Model $P_1$: $\tilde{g}$, $\tilde{q}$, $\tilde{\chi}_0$
- Model $P_2$: $\tilde{g}$, $\tilde{\chi}_0$

**Graphical Representations:**

- For model $P_1$: $\tilde{g}$ and $\tilde{q}$ connected to $\tilde{\chi}_0$.
- For model $P_2$: $\tilde{g}$ and $\tilde{\chi}_0$ connected to $\tilde{\chi}_0$.

**Tables:**

- $m_{\tilde{g}}$ (GeV) vs. $m_{LSP}$ (GeV) with $\sigma_{95\% CL}$ upper limit on $\alpha_T$.
- $m_{\tilde{q}}$ (GeV) vs. $m_{LSP}$ (GeV) with $\sigma_{95\% CL}$ upper limit on $\alpha_T$.

**Legend:**

- $\alpha_T^{\text{prod}} = \sigma_{\text{NLO-QCD}}$
- $\alpha_T^{\text{prod}} = \frac{2}{3} \times \sigma_{\text{NLO-QCD}}$
- $\alpha_T^{\text{prod}} = \frac{1}{3} \times \sigma_{\text{NLO-QCD}}$
Summary

- The outstanding performance of the LHC and CMS has enabled many complementary searches for events with undetected escaping particles.
- Presented are three searches which focus on all-hadronic events.
- The observed event yields are consistent with SM expectations.
- In the CMSSM slice considered, equal squark and gluino masses of 1.1 TeV are excluded at 95% C.L.
- Interpretation in simplified models is well underway.

- Where is SUSY hiding?