SUSY searches in photon final states with the CMS detector

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Pheno2016: Forging new physics
University of Pittsburgh

1. Physikalisches Institut B

[Logo of CMS]

[Logo of RWTH Aachen University]
Motivation

Gauge Mediated Supersymmetry Breaking (GMSB)

- Gravitino $\tilde{G}$ is lightest SUSY particle
- Assume neutralino $\tilde{\chi}_1^0$ is next-to-lightest SUSY particle
- $\tilde{\chi}_1^0$ decays to massless $\tilde{G}$ and a neutral SM boson
- Assume R-parity conservation: $\tilde{G}$ stable, SUSY pair production

$\tilde{\chi}_1^0$ decays

**Bino/Wino:**
- Decay to $\gamma$ or $Z$
- Branching fraction mass dependent

$$BF(\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}) \xrightarrow{m \rightarrow \infty}$$

$$\begin{cases} 
\cos^2 \theta_W & \text{Bino} \\
\cos^2 \theta_W & \text{Wino}
\end{cases}$$

**Higgsino:**
- Decay to $H$ (use di-$\gamma$ decay to tag $H$)

Interpretation

**General Gauge Mediation (GGM):**
- Natural decay probabilities
- Mixture of different processes
- Closer to reality

**Simplified models:**
- Branching fractions set to fixed value (usually 100%)
- Simulate only one production model
- Easier to reinterpret
Overview

- Variety of analyses probing many SUSY processes with different analysis strategies
- Covering bino, wino and higgsino neutralino mixtures
- Search for third generation, strong and electroweak production
- Full 2012 dataset (8 TeV) and first results for 13 TeV are published

<table>
<thead>
<tr>
<th>Signature</th>
<th>Publication links</th>
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<tbody>
<tr>
<td>CMS-SUS-13-014 $H\rightarrow\gamma\gamma + \text{bb} + E_T^{\text{miss}}$</td>
<td>PRL 112 (2014) 161802</td>
</tr>
<tr>
<td>CMS-SUS-14-004 $\gamma + \text{jets} + E_T^{\text{miss}}$</td>
<td>PRD 92 (2015) 072006</td>
</tr>
<tr>
<td>CMS-SUS-14-008 $\gamma\gamma + \text{Razor}$</td>
<td>PRD 92 (2015) 072006</td>
</tr>
<tr>
<td>CMS-SUS-14-009 $\gamma\gamma/e^\pm\mu^\mp + \text{jets}, E_T^{\text{miss}}$ inclusive</td>
<td>PLB 743 (2015) 503</td>
</tr>
<tr>
<td>CMS-SUS-14-013 $\gamma + e/\mu + E_T^{\text{miss}}$</td>
<td>PLB 757 (2016) 6</td>
</tr>
<tr>
<td>CMS-SUS-14-016 $\gamma + E_T^{\text{miss}}$</td>
<td>Submitted to PLB (arxiv:1602.08772)</td>
</tr>
<tr>
<td>CMS-SUS-14-017 $H\rightarrow\gamma\gamma + \text{Razor}$</td>
<td>CDS:2047472</td>
</tr>
<tr>
<td>CMS-SUS-15-012 $\gamma\gamma + E_T^{\text{miss}}$ (13 TeV)</td>
<td>CDS:2143897</td>
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See next talk by Arka Santra after the coffee break
Common background estimation for electrons being misidentified as photons

**Method**

Use pixel hits to distinguish between photons and electrons

- Calculate the probability that a real electron does not leave hits in the pixel detector
- Use tag&probe method on the $Z \rightarrow ee$ resonance to find real electrons
  \[ f_{e \rightarrow \gamma} \approx 1.5\% \]

Usage in the analysis:

- Select event similar to the signal selection, except that the photon object has hits in the pixel detector (electron control sample)
- Scale this sample using the misreconstruction probability

⇒ Use this sample as prediction for electrons misreconstructed as photons

**Validate the method using simulation**

- Apply the same methods to simulation
- Compare to generated electrons reconstructed as photons
- Good agreement, method works well

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Events / GeV

<table>
<thead>
<tr>
<th>Events / GeV</th>
<th>Sim. / Pred.</th>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>-10</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Simulation CMS (8 TeV)

-19.7 fb$^{-1}$ (8 TeV)

≥ 1 $\gamma$, ≥ 2 jets

**SUS-14-004**

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γ SUSY searches at CMS
SUS-14-004: $\gamma + \text{jets} + E_T^{\text{miss}}$

**Selection**
- $\geq 1\gamma$, $p_T^{*} > 110$ GeV
- $H_T > 500$ GeV, $\geq 2\text{jets}$
- no e/\mu
- $E_T^{\text{miss}} > 100$ GeV

**Z\gamma, W\gamma, t\bar{t}\gamma$ background**

Use MadGraph simulation, scaled to NLO cross section using MCFM

**Multijet and $\gamma$+Jet background**
- Select control sample with unisolated photon candidates (jets) instead of photons
- Normalize in $E_T^{\text{miss}} < 100$ GeV to photon (signal) selection
- Do this in bins of $H_T$ and the hadronic recoil to minimize correlations

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**Validation of the multijet background estimation method**

- Data
- Prediction $\pm \sigma_{\text{total}}$ $\pm \sigma_{\text{syst}}$ $\pm \sigma_{\text{stat}}$

**Right: Data to background comparison**

- CMS Simulation
  - Multijet, $\gamma$+jet
  - Direct simulation
  - $\geq 1\gamma$, $\geq 2$ jets

- CMS
  - Data
  - Prediction $\pm \sigma_{\text{total}}$
  - $\pm \sigma_{\text{syst}}$ $\pm \sigma_{\text{stat}}$
  - Multijet (+$\gamma$)
  - $Z\gamma, W\gamma, t\bar{t}\gamma$
  - EW $e\rightarrow\gamma$
  - GGMwino $m_{\tilde{v}}=1700$ GeV
  - GGMwino $m_{\tilde{v}}=720$ GeV
SUS-14-004: $\gamma + \text{jets} + E_T^{\text{miss}}$: Interpretation

GGM

Squark or gluino production, $\tilde{\chi}_1^0$ decay depends on mixing

- $\bar{g} \to \tilde{\chi}_1^0 \tilde{\chi}_{10}^- q$ (mSUGRA)
- $\bar{g} \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 q$ (NMSSM)

Simplified model

Gluino production, $BF(\tilde{g} \to qq\tilde{\chi}_1^0) = 100/50\%$

- $\tilde{g} \to \tilde{\chi}_2^0 \tilde{\chi}_1^- q$ (mSUGRA)
- $\tilde{g} \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 q$ (NMSSM)
SUS-14-013: $\gamma + e/\mu + E_T^{\text{miss}}$

**Selection**
- $\geq 1\gamma$, $p_T > 40$ GeV
- $\geq 1e/\mu$, $p_T > 25$ GeV
- $\Delta R(\gamma, \ell) > 0.8$
- $|m_{e\gamma} - m_Z| > 10$ GeV
- $E_T^{\text{miss}} > 120$ GeV
- $M_T(\gamma, E_T^{\text{miss}}) > 100$ GeV

**Jets misreconstructed as photons**
- Fit two templates to distribution of photon-shower width to data with low $E_T^{\text{miss}}$
  - Real-photon template: Select real photons with $m_{\mu\mu\gamma} \approx m_Z$
  - Fake-photon template: Unisolated photon candidates
- $f_{\text{jet} \rightarrow \gamma} = 0.08 - 0.25$
- Prediction: Scale control sample with unisolated photons using this factor

**Misidentified leptons and electroweak processes**
- Fit two templates to distribution of $\Delta \Phi(\ell, E_T^{\text{miss}})$ to data with medium $E_T^{\text{miss}}$
  - Misidentified lepton template: Inverted lepton isolation for leptons (red dashed line)
  - Electroweak process template: Simulation (blue dashed line)
Data to background comparison:

19.7 fb$^{-1}$ (8 TeV)

- CMS
  - $E_T^{\text{miss}} > 120$ GeV, $M_T > 100$ GeV

Interpreted in bins of $H_T$, $E_T^{\text{miss}}$ and $p_T^\gamma$

\begin{align*}
\text{Simplified model of } \tilde{\chi}^0_1 \tilde{\chi}^\pm_0 \text{ production} \\
\text{GGM model with gluino and electroweak production}
\end{align*}
SUS-14-016: $\gamma + E_T^{\text{miss}}$

Selection

- $\geq 1\gamma$, $p_T > 40$ GeV
- $E_T^{\text{miss}} > 100$ GeV
- $M_T > 300$ GeV
- $E_T^{\text{miss,signif}} > 80$ (low for events with large particle uncertainties and therefore prone to mismeasurement)

Major backgrounds

- $\gamma + \text{Jet}$
- $V\gamma = W\gamma$, $Z(\nu\nu)\gamma$, $t\bar{t}\gamma$

Scale background simulation to data in control region, extrapolate to signal region

**Diboson/$t\bar{t}\gamma$ background**

Direct simulation

Divide signal region in low/high $E_T^{\text{miss}} / S_T$ to increase sensitivity

$$S_T = E_T^{\text{miss}} + p_T^{\gamma}$$

$$M_T(\text{GeV})$$

**Signal region:**

- $E_T^{\text{miss,signif}}$
- $100$ to $300$ GeV

**Control region:**

- $10$ to $80$ GeV

Events / bin

$7.4$ fb$^{-1}$ (8 TeV), $\geq 1\gamma + \text{MET}$

Data / bkg

$\sigma = \sigma^{\text{stat}} + \sigma^{\text{syst}}$

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$\gamma$ SUSY searches at CMS
Mixed $\tilde{\chi}_1^0 \tilde{\chi}^\pm$ and $\tilde{\chi}^\pm \tilde{\chi}^\pm$ production, where $\tilde{\chi}_1^0$ and $\tilde{\chi}^\pm$ are mass degenerate

Same model as $\gamma + e/\mu$ analysis

Dominant process for GGM, but also other $\tilde{\chi}_1^0$ production allowed

Very sensitive to electroweak production
Selection

- $\geq 2\gamma$, $p_T > 40(25)\ \text{GeV}$
- $m_{\gamma\gamma} \approx m_H$
- $\geq 1\ \text{jet}$
- Razor variables ($M_R, R$): Discriminates SM versus pair-produced heavy particles
- Categorization according to:
  
  - $P_T^{YY} > 110\ \text{GeV}$: HighPt Box
  - $110 < m_{bb} < 140\ \text{GeV}$: Hbb Box
  - $76 < m_{bb} < 106\ \text{GeV}$: Zbb Box
  - $2\gamma; \sigma_B/E < 1.5\%$: HighRes Box
  - $\text{No}$: LowRes Box

Background estimation for each category

Combinatorics:

- Fit exponential in sideband above and below the expected $H \rightarrow \gamma\gamma$ peak ($M_R, R$ inclusive)
- Extrapolate from sidebands to $H \rightarrow \gamma\gamma$ peak in high $M_R, R$

SM $H$ from simulation
Summary

Status at 8 TeV

- Searched for SUSY with final states containing photons
- Studied bino-, wino- and higgsino-like neutralino mixtures
- Interpretation in GMSB and simplified models
- No hint for SUSY found yet

Are there photons at the end of the tunnel?

- Cross section for heavy (SUSY) particles increases significantly with $\sqrt{s}$
- With this years data, sensitive increases especially for high sparticle masses
Razor variables

The variable $M_R$ is defined as

$$M_R \equiv \sqrt{\left( \left| \vec{p}^{j_1} \right| + \left| \vec{p}^{j_2} \right| \right)^2 - \left( p^{j_1}_z + p^{j_2}_z \right)^2},$$

(1)

where $\vec{p}^{j_i}$ and $p^{j_i}_z$ are, respectively, the momentum of the $i$th megajet and the magnitude of its component along the beam axis. The $p_T$ imbalance in the event is quantified by the variable $M^R_T$, defined as

$$M^R_T \equiv \sqrt{E_{T\text{miss}}^{\text{miss}} \left( \left| \vec{p}^{j_1}_T \right| + \left| \vec{p}^{j_2}_T \right| \right) - \vec{p}_{T\text{miss}} \cdot (\vec{p}^{j_1}_T + \vec{p}^{j_2}_T) / 2},$$

(2)

where $\vec{p}^{j_i}_T$ is the transverse component of $\vec{p}^{j_i}$. The razor ratio $R$ is defined as

$$R \equiv \frac{M^R_T}{M_R}.$$
**Selection**

- $\geq 2\gamma, p_T > 40(25)\text{ GeV}$
- $m_{\gamma\gamma} \approx m_H$
- $\geq 2$ b-tagged jets
- bins in $E_{T}^{\text{miss}}$

**In each category (i), (ii) and (iii):**

**Background**

- Fit sidebands above and below $H \rightarrow \gamma\gamma$ peak
- Use events from sideband to predict $E_{T}^{\text{miss}}$

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**Graphs**

- CMS, $\sqrt{s} = 8$ TeV, $\int L \, dt = 19.7 \text{ fb}^{-1}$

### Observed 95% Cross Section Exclusion (pb)

<table>
<thead>
<tr>
<th>$m_{\chi}$ (GeV)</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (pb)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Natural GMSB Higgsino model**

- $\text{Br}(\chi^0_{i} \rightarrow \gamma\gamma) = 1$, Strong and EW Production
- $m_{\chi^0_i} = m_{\chi_{i}} - 5 \text{ GeV}$, $m_{\chi_1} = m_{\chi_2} + 5 \text{ GeV}$

**Expected 95% CLs Limits**

- Observed 95% CLs Limits
- Theory uncertainty
- Expected 95% CLs Limits
- Expected ±1σ experimental

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**Observational Data**

- Data
- Background
- Signal ($m_{\chi}/m_{\chi}$): 350 / 135 GeV, 400 / 300 GeV, 300 / 290 GeV

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**\(\gamma\) SUSY searches at CMS**

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Stealth SUSY

- New hidden sector at EWK scale
- Small mass splitting between $\tilde{S}$ and $S$
  $\Rightarrow$ LSP carries little momentum
  $\Rightarrow$ low $E_T^{\text{miss}}$

Selection

- $\geq 2\gamma$, $p_T > 40(25)$ GeV
- $N_{\text{jets}} \geq 4$
- $S_T = \sum \gamma, e, \mu, \text{jet}, E_T^{\text{miss}} p_T > 1200$ GeV

Graphs showing cuts on signal and background regions.

 CMS

Graph showing observable vs. $S_T$ with different cuts on $N_{\text{jets}}$.