Search for supersymmetry in events with photons and missing transverse energy

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on behalf of CMS collaboration

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April 8, 2017
Analysis Overview

Search for General gauged mediated (GGM) supersymmetry breaking in final state involving photons. The data sample corresponds to an integrated luminosity of $2.32 \text{ fb}^{-1}$ of proton proton collisions at $\sqrt{s} = 13\,\text{TeV}$ was collected with the CMS detector at the LHC in 2015.

GGM supersymmetry breaking can produce events with double photons, jets and significant missing energy ($E_T^{\text{miss}}$).

We assume gluino pair production where the NLSP neutralino decays to a gravitino and photon ($\tilde{\chi}_1^0 \to \tilde{G}\gamma$), resulting in characteristic events with jets, two photons and large $E_T^{\text{miss}}$. 
Backgrounds

Quantum Chromodynamics (QCD) background
- Most significant background due to huge QCD cross section
- Can have real photons in the final state or we can get electromagnetically-rich jet fragmentation mimicking the response of a photon
- $E_T^{\text{miss}}$ comes from mis-measured hadronic activity.

Electroweak (EWK) background
- Includes $W\gamma$ and $W + \text{jet}$ events
  - $W \rightarrow e\nu$ and the electron is misidentified as a photon
  - $W + \text{jet}$ events, one of the jets fakes a photon
- Genuine $E_T^{\text{miss}}$ from the neutrino

Other backgrounds-small and studied with Monte Carlo (MC).
- $Z\gamma\gamma \rightarrow \nu\nu\gamma\gamma$
- $W\gamma\gamma \rightarrow l\nu\gamma\gamma$
- $t\bar{t}\gamma\gamma$
Primary analysis trigger:

\[ \text{HLT\_Diphoton30\_18\_R9Id\_OR\_IsoCaloId\_AND\_HE\_R9Id\_Mass95} \]

- Lead Photon \( p_T > 30 \text{GeV} \) and trail for photon \( p_T > 18 \text{GeV} \)
- \( M_{\gamma\gamma} > 95 \text{GeV} \)

HLT efficiency is calculated by a tag and probe method and is 98.6\% for photon \( p_T > 40 \text{GeV} \)

Trigger requires two photons passing the sub-leading filter and one photon passing the leading filter, so that the total efficiency \( \epsilon_{\text{tot}} = \epsilon_{\text{lead,lead}} \times \epsilon_{\text{lead,sub}} \times \epsilon_{\text{sub,sub}} \)
Object Selection

Muons
- $P_T > 30\text{GeV}$
- $|\eta| < 1.4442$
- Passes medium muon ID
- Passes loose muon isolation

Electrons
- From PF photon collection
- $P_T > 40\text{GeV}$
- $|\eta| < 1.4442$
- Passes medium photon ID
- Fails pixel seed veto
- Remove electrons that overlap within $\Delta R < 0.4$ of a muon

Photons
- From PF photon Collection
- $P_T > 40\text{GeV}$
- $|\eta| < 1.4442$
- Passes medium photon ID
- Passes Pixel seed veto

Jets
- $P_T > 30\text{GeV}$
- $|\eta| < 2.4$
- Passes PF Loose ID
- Remove jets that overlap within $\Delta R < 0.4$ of a muon, electron, or a photon
Fake Selection

'Fake Photons' are photons that fail isolation or shape requirements. Primarily composed of electromagnetically rich jets reconstructed as photons.

- Control Sample with fakes are used to model the QCD background.
- Make Fakes orthogonal to Photons by inverting charged hadron isolation or $\sigma_{\eta\eta}$ requirements of the medium photon ID. 
  \[
  (1.33 \text{GeV} < \text{charged hadron isolation} < 15 \text{GeV} \ XOR \ 0.0102 < \sigma_{\eta\eta} < 0.0150)
  \]

Events are sorted into four categories depending on the selection of their highest-$p_T$ electromagnetic objects:
- $\gamma\gamma$
- $ee$
- $ff$
- $e\gamma$
**Event Selection**

**Control and Candidate Sample**

Double electron Sample (ee)
- Used to model EM objects in the QCD background
- Require $75\text{GeV} < m_{ee} < 105\text{GeV}$ to collect $Z \rightarrow ee$ events
- Require $\Delta R > 0.3$ between electrons

Double fake sample (ff)
- Passes the primary trigger
- Used to model EM objects in the QCD background
- require $m_{ff} > 105\text{GeV}$
- require $\Delta R > 0.3$ between fakes.

Candidate DiPhoton Sample ($\gamma\gamma$)
- passes primary trigger
- Require $m_{\gamma\gamma} > 105\text{GeV}$
- $\Delta R > 0.3$ between photons

Signal Region is $E_T^{\text{miss}} > 100\text{GeV}$
QCD Background Estimation - Backgrounds without true $E_T^{\text{miss}}$

Strategy

- Processes that lack from genuine $E_T^{\text{miss}}$, but can emulate GGM signal topologies if the hadronic activities in the event are poorly measured.
- Used double electrons and double fakes control samples to estimate the $E_T^{\text{miss}}$ distribution of QCD backgrounds.
- But this samples have different amounts of hadronic activity than the candidate $\gamma\gamma$ sample.

- Model the hadronic recoil of the event with the di-EM $p_T$ of the event, where di-EM $p_T$ is the vector sum of the $P_T$ of the two electromagnetic object.
- Reweight the control samples to correct for the differences in hadronic activity.
Reweight $E_T^{\text{miss}}$ backgrounds

Unweighted (left) and di-EM $p_T$ reweighted (right) $E_T^{\text{miss}}$ distributions of the ee and ff samples

Samples are normalized to $E_T^{\text{miss}} < 50$ GeV of the $\gamma\gamma$ (signal contamination < 1% )
Comparison to Candidate $\gamma\gamma$ Sample

Comparing the candidate $E_T^{miss}$ distribution to the distributions for the ee (left) and ff (right) control samples.

Samples are normalized to $E_T^{miss} < 50$ GeV of the $\gamma\gamma$
Estimation of pure QCD background

- The primary background estimate comes from the double electron sample.
- We use the prediction from double fake as a systematic uncertainty on the estimate from the ee sample.
- Low statistics from ff sample in $E_T^{miss} > 100$ GeV signal region.

- Tight fake and loose fake samples match well in $E_T^{miss} < 100$ GeV region.
- Loose fake samples can be used to model the shape in high $E_T^{miss}$ region.
- Determine ff sample in signal region from looser fake definition.
Systematic Uncertainty from Shape Difference

- Fit reweighted ee and loose ff samples for $70 \text{ GeV} < E_T^{\text{miss}} < 300 \text{ GeV}$ with a function $\chi^{p0}\exp(p1\chi^{p2})$ with fit parameters $p0$, $p1$, $p2$
- Integrate fits in each $E_T^{\text{miss}}$ bin for $E_T^{\text{miss}} > 100 \text{ GeV}$.
- Difference between ee and loose ff result gives shape uncertainties in that bin.
- Largest uncertainty in the last bin due to the large bin width.
**Final QCD Estimate**

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
<th>Bkg Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-110</td>
<td>1.85 ± 0.96</td>
</tr>
<tr>
<td>110-120</td>
<td>1.53 ± 0.63</td>
</tr>
<tr>
<td>120-140</td>
<td>0.97 ± 0.62</td>
</tr>
<tr>
<td>&gt; 140</td>
<td>0.61 ± 2.15</td>
</tr>
</tbody>
</table>

- Di-EM $p_T$ reweighting uncertainty comes from propagating toy Di-EM $p_T$ plots to the reweighted $E_T^{\text{miss}}$ distribution.
- Additional systematic comes from the differences between reweighting with the di-EM $p_T$ only and reweighting with di-EM $p_T$ and jet multiplicity.

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
<th>Systematic Uncertainty</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-110</td>
<td>Di-EM $p_T$ reweighting</td>
<td>15.11</td>
</tr>
<tr>
<td></td>
<td>Jet multiplicity reweighting</td>
<td>33.77</td>
</tr>
<tr>
<td></td>
<td>Shape difference between ee and ff</td>
<td>18.18</td>
</tr>
<tr>
<td></td>
<td>Statistical uncertainty of ee sample</td>
<td>30.81</td>
</tr>
<tr>
<td>110-120</td>
<td>Di-EM $p_T$ reweighting</td>
<td>16.60</td>
</tr>
<tr>
<td></td>
<td>Jet multiplicity reweighting</td>
<td>14.87</td>
</tr>
<tr>
<td></td>
<td>Shape difference between ee and ff</td>
<td>12.07</td>
</tr>
<tr>
<td></td>
<td>Statistical uncertainty of ee sample</td>
<td>33.33</td>
</tr>
<tr>
<td>120-140</td>
<td>Di-EM $p_T$ reweighting</td>
<td>33.31</td>
</tr>
<tr>
<td></td>
<td>Jet multiplicity reweighting</td>
<td>29.39</td>
</tr>
<tr>
<td></td>
<td>Shape difference between ee and ff</td>
<td>14.40</td>
</tr>
<tr>
<td></td>
<td>Statistical uncertainty of ee sample</td>
<td>41.75</td>
</tr>
<tr>
<td>&gt; 140</td>
<td>Di-EM $p_T$ reweighting</td>
<td>39.75</td>
</tr>
<tr>
<td></td>
<td>Jet multiplicity reweighting</td>
<td>20.34</td>
</tr>
<tr>
<td></td>
<td>Shape difference between ee and ff</td>
<td>150.36</td>
</tr>
<tr>
<td></td>
<td>Statistical uncertainty of ee sample</td>
<td>70.98</td>
</tr>
</tbody>
</table>
**EWK Background in the Signal Region**

In the signal region ($E_T^{\text{miss}} > 100\text{GeV}$), EWK background comes mainly from $W\gamma \rightarrow e\nu\gamma$, where the electron is misidentified as a photon.

- Calculate the ratio of the electrons faking photons, $f_{e\rightarrow\gamma}$, using the $Z \rightarrow ee$ invariant mass peak in both an ee sample and an $e\gamma$ sample.

- To get the final EWK background estimate, we weight the $e\gamma E_T^{\text{miss}}$ distribution by $f_{e\rightarrow\gamma}/(1 - f_{e\rightarrow\gamma})$ to get the number of $e\gamma$ events that sneak into the candidate $\gamma\gamma$ sample.

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### Table: Estimation of total EWK background for $E_T^{\text{miss}} > 100 \text{ GeV}$

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ bin (GeV)</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 – 110</td>
<td>0.11 ± 0.09</td>
</tr>
<tr>
<td>110 – 120</td>
<td>0.07 ± 0.06</td>
</tr>
<tr>
<td>120 – 140</td>
<td>0.14 ± 0.11</td>
</tr>
<tr>
<td>140 – $\infty$</td>
<td>0.27 ± 0.22</td>
</tr>
</tbody>
</table>

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HEP 2017, Ioannina

April 8, 2017  14 / 20
## Observed vs Expected

<table>
<thead>
<tr>
<th>$E_T^{miss}$ (GeV)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-110</td>
<td>2.26 ± 0.96</td>
<td>4</td>
</tr>
<tr>
<td>110-120</td>
<td>1.79 ± 0.64</td>
<td>2</td>
</tr>
<tr>
<td>120-140</td>
<td>1.51 ± 0.64</td>
<td>2</td>
</tr>
<tr>
<td>&gt; 140</td>
<td>1.64 ± 2.16</td>
<td>1</td>
</tr>
</tbody>
</table>

The CMS Preliminary graph shows the comparison of data and background with theoretical predictions. The data points are compared to the expected distributions for different processes and models. The combined uncertainty is shown for the theoretical predictions at $0.6$ TeV and $1.4$ TeV, with $M_{T5gg} = 0.6$ TeV and $M_{T5gg} = 1.6$ TeV, respectively. The CMS measurement is preliminary and based on $2.3$ fb$^{-1}$ of data at 13 TeV.
Results

Limits

- An expected exclusion reach for the analysis was done using the modified frequentist CLs methods.
- This is based on long-likelihood test statistic that compares the likelihood of the SM-only hypothesis to the likelihood of the presence of signal in addition to the SM conditions.
- The likelihood functions are based on the expected shape of the $E_T^{miss}$ distribution for signal and background in four separate bins.
- For typical values of neutralino mass, we expect to exclude gluino masses out of 1.5 TeV, improving the reach of previous searches performed at center-of-mass energies of 8 TeV.
Conclusions

- Full analysis has been done on 13 TeV data
- Even with $2.3fb^{-1}$ of data, we are able to extend our reach from 8TeV analysis
- No evidence of SUSY seen, but we expect to probe even higher mass scales this year with a larger dataset.
Back Up
Jet multiplicity Reweighting

The difference in jet multiplicity between the candidate sample and the control sample can also affect the overall $E_T^{\text{miss}}$ resolution of the background estimation.

The jet multiplicity distribution for the candidate and the $\text{ff}$ samples are similar, but the candidate and $\text{ee}$ are different.

To investigate the effect of jet multiplicity reweighting, we plotted the $eeE_T^{\text{miss}}$ distribution reweighting by the jet multiplicity in bins of di-EM $p_T$.

The difference between them is small.

Choose not to reweight by the jet multiplicity, but we take the difference as a systematic uncertainty.
Contributions to control samples

There is a small contribution to the ee control sample from $t\bar{t}$ events and the contribution to the ff sample from $Z \to \nu\bar{\nu}$.

$t\bar{t}$ events will contribute $17.27 \pm 0.98$. and $Z \to \nu\bar{\nu}$ contribution is almost negligible. To get rid of the contamination we substract the shape of $t\bar{t}$ from our ee control sample.