Search for BSM physics in di-photon final states at CMS

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On behalf of the CMS Collaboration

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Why di-photon searches

Fully reconstructed resonances: simplest way to discover new particles

Statistically significant peak over a smooth background
• experimentally robust
• small systematics
• difficult for unknown backgrounds to mimic
⇒ simple yet striking signature!

Final states with high $p_T$ photons:
• relatively low background at hadron colliders
• good mass resolution

Many theoretical motivations
Recap of 2015 results

**Phys.Rev.Lett. 117(2016), no. 5, 051802**

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<td>750</td>
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<td>3.4σ</td>
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Recap of 2015 results

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CMS 2016 dataset

CMS Integrated Luminosity, pp, 2016, \( \sqrt{s} = 13 \) TeV

Data included from 2016-04-22 22:48 to 2016-07-25 21:26 UTC

LHC Delivered: 19.41 fb\(^{-1}\)
CMS Recorded: 17.89 fb\(^{-1}\)

CMS Online Luminosity

This analysis: 13/fb

Preliminary lumi uncertainty: 6.2%

Wonderful LHC performance!
Analysis in a nutshell

Search for a localized excess in the di-photon invariant mass spectrum

Events selection: 2 high $p_T$ isolated photons
- Robust criteria

Signal modeling with data-driven inputs
- Efficiencies, energy scale and resolution
- Good detector understanding needed

Background modeling
- Parameterization from data

$M = \sqrt{2E_1E_2(1 - \cos \theta)}$

Number of events

$m_{\gamma\gamma}$
Analysis in a nutshell

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Solid techniques exploited

Potential improvements investigated while keeping the 2016 analysis blind

No significant gain found
- No selection change applied: basically same analysis as last year
Photons in CMS

ECAL: homogeneous PbW04 crystals calorimeter

Photons reconstructed from energy deposits in clusters of ECAL crystals
- No associated track

97% energy contained in a 5x5 matrix
Clustering optimized to collect radiated energy
- up to $2X_0$ distributed material in front of ECAL
Energy from multivariate regression

2015 data
High Level Trigger
2 photons, $p_T > 60$ GeV

Offline kinematic selection
- Fixed $p_T$ cut, $p_T > 75$ GeV
- ECAL fiducial region ($|\eta| < 2.5$)

2 event categories
- EBEB: both $\gamma$s in the barrel
- EBEE: one $\gamma$ in barrel, one in endcap
- Based on S/B ratio

Identification requirements:
- Shower shape and isolation
- No associated track
- $\gamma\gamma$ selection efficiency:
  - $\sim 85\%$ in EBEB
  - $\sim 80\%$ in EBEE

Small differences due to different Kinematics for different spin hypothesis
Efficiency measurement

Tuned in MC and validated in data
• Z->ee events
• Z->μμγ events for electron veto requirement

Data/MC scale factors
• computed for EB and EE
• almost constant in $p_T$
• non compatible with 1
  • included in signal modeling
Photon energy scale and resolution

Measured with Z in data at O(0.1%) level in bins of η and cluster shape
- simultaneously adjust scale and resolution

Good agreement in term of shape and normalization after all corrections

Energy scale stability vs $E_T$ checked with boosted Zs up to $\sim 150\text{GeV}$
- Deviations within a few permilles
- 1% uncertainty to account for extrapolation to larger momenta
Signal modeling

Statistical interpretation from simultaneous fit to $m_{\gamma\gamma}$ distribution in the two analysis categories.

Signal shape: convolution of intrinsic line-shape and detector resolution

- $\sigma_m/m \sim 1\%$ (EBEB), $1.5\%$ (EBEE)
- Spin-0 and spin-2
- $m_X : 0.5 - 4.5$ TeV
- $\Gamma/m = 1.4 \times 10^{-4}, 1.4 \times 10^{-2}, 5.6 \times 10^{-2}$ (k=0.01, 0.1, 0.2 for RS Graviton)

Detector resolution dominates Comparable resolution and width Resonance width dominates
Background modeling

Statistical interpretation from simultaneous fit to $m_{\gamma\gamma}$ distribution in the two analysis categories

Background model

- Parametric fit to data with empirical function $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$
- Independent shape for each category
- Model coefficients: nuisance parameters in the hypothesis test
- Possible mis-modeling studied on MC and included as a “bias term”

Extra uncertainty implemented adding a signal-like component to the background model.

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• Accurate background estimate to not bias signal extraction - signal can be overestimate (or even fake excess) - signal can be missed

• Two techniques
  - background shape from MC and normalize in control region (usually low mass) + theory/experimental systematics
  - parameterize background shape and fit parameters directly on data

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**EXPERIMENTAL ISSUES: BACKGROUND**

GOOD

SIGNAL OVERESTIMATED

SIGNAL HIDDEN
2016 mass spectra

CMS Preliminary 12.9 fb\(^{-1}\) (13 TeV)

- Data
- Fit model
- ± 1 s.d.
- ± 2 s.d.

Events / 20 GeV

EBEB

\(m_{\gamma\gamma}\) (GeV)

\(\frac{(\text{data-fit})/\sigma_{\text{stat}}}{\text{(data-fit)}}\)

12.9 fb\(^{-1}\) (13 TeV)
2016 mass spectra

Data consistent with Standard Model expectations
No significant excess in proximity of 750 GeV

Largest excess now observed for $m_X \sim 620$ GeV
Local significance (narrow width): 
~2.4-2.7$\sigma$

Showing only plots for selected width and spin hypothesis.
All other plots available in backup
2016 exclusion limits

Exclusion limits for RS Graviton (LO cross-sections)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Exclusion</th>
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<tbody>
<tr>
<td>0.01</td>
<td>$m_G &lt; 1.75$ TeV</td>
</tr>
<tr>
<td>0.1</td>
<td>$m_G &lt; 3.75$ TeV</td>
</tr>
<tr>
<td>0.2</td>
<td>$m_G &lt; 4.35$ TeV</td>
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Spin-2

- $\Gamma_x / m_x = 1.4 \times 10^{-4}$
- $\Gamma_x / m_x = 5.6 \times 10^{-2}$
8TeV + 13TeV

Combination of results from
- 19.7/fb at √s = 8TeV
- 3.3/fb at √s = 13TeV (2015)
- 12.9/fb at √s = 13TeV (2016)

<table>
<thead>
<tr>
<th>CMS publications</th>
<th>√s [TeV]</th>
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<tbody>
<tr>
<td>CMS-PAS-EX0-16-027 (new)</td>
<td>8 / 13</td>
</tr>
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<td>PRL 117, 051802 (2016)</td>
<td>8 / 13</td>
</tr>
<tr>
<td>PLB750 (2015) 494–519</td>
<td>8</td>
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@750GeV:
σ(13TeV)/σ(8TeV) = 4.5 spin-0
= 4.2 spin-2
Run1+Run2 significance

\[ \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4}, \text{ J}=0 \]

- Combined
- 2015 (3.3 fb\(^{-1}\))
- 2016 (12.9 fb\(^{-1}\))

Spin-0, \( \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4} \) hypothesis

Local excesses around 750 GeV:
- 2015 only: \( 2.9\sigma \) → 2015+2016: <1σ
- 8 TeV+2015: 3.4σ → 8 TeV+2015+2016: <2σ
Compatibility among results

A signal with cross-section as the largest excess in 2015+8TeV would look like this

Compatibility of data at $m_\chi=750$GeV tested with a likelihood ratio test.

Compatibility at the level of
- 13TeV data only: 2.7$\sigma$
- 8TeV+13TeV data: 2.4$\sigma$
Run1+Run2 limits

Sensitivity driven by 2016 dataset

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<td>0.01</td>
<td>(m_G &lt; 1.95 \text{TeV}) except for [1.75, 1.85]</td>
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<td>0.1</td>
<td>(m_G &lt; 3.85 \text{TeV})</td>
</tr>
<tr>
<td>0.2</td>
<td>(m_G &lt; 4.45 \text{TeV})</td>
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8TeV contribution:
~10% at low mass, negligible at high mass

\[
\frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4}, \ J=2
\]

\[
\frac{\Gamma_x}{m_x} = 5.6 \times 10^{-2}, \ J=2
\]
Conclusions

Search for new resonances decaying to di-photon pairs presented, based on 12.9/fb of 13TeV CMS 2016 data

- Mass region between 0.5 and 4.5 TeV
- Tested hypothesis: spin-0 and spin-2 resonances with different widths

Data consistent with Standard Model expectations
Modest excess presented based on 2015 (+ 8TeV) data in the region around 750 GeV not confirmed by the new data

- Results at 750GeV compatible at level of 2.4σ

2016 data combined with 2015 and 8TeV data
Limits set on the production cross section times di-photon branching ratio

- Negligible contribution of the 8TeV dataset
- 2016 data dominating limits and significances
Backup
Photon selection efficiencies

CMS Preliminary

12.9 fb⁻¹ (13 TeV)

EE

$\eta < 1.4442$

$| \eta | < 2.5$

$pt (GeV)$

$12.9 \text{ fb}^{-1} (13 \text{ TeV})$

$Z \rightarrow ee$

Data

Simulation

Scale Factor

$0.8$

$0.9$

$1.0$

$1.1$

$1.2$

$0.8$

$0.9$

$1.0$

$1.1$

$1.2$

$0.8$

$0.9$

$1.0$

$1.1$

$1.2$

$0.8$

$0.9$

$1.0$

$1.1$

$1.2$

$0.8$

$0.9$

$1.0$

$1.1$

$1.2$
Energy calibration

- Simulation
- Calibrations used here applied to 2015 data
Background purities

2015 plots. Consistent purities measured this year

Dominant contribution: 2 prompt photons

QCD and photon+jets: <10% (20%) in EEBEB (EBEE)
Background composition, closure test

Data driven prediction for the prompt-prompt component compared with theory
✓ Sherpa generator rescaled to $2\gamma$NNLO

2015 plots. Consistent purities measured this year
Vertex determination

Interaction vertex identified using recoiling tracks and conversions when present: $\text{Sum}(p_T^2)$, $p_T(\gamma\gamma)$ vs $p_T(\text{tracks})$, $Z(\text{conv})$

Combined in a BDT

Same as in H-$\gamma\gamma$ analysis
Vertex ID performance

Probability to assign the correct vertex in H->γγ analysis
Background model

Parametric 1dim fit to data in the 2 categories, \( f(m) = m^{a+b \log(m)} \)
- Model coefficients treated as unconstrained nuisance parameters in the hypothesis test

Goodness of background fit assessed locally in \( m_{\gamma\gamma} \) using MC
- Study pull of mean number of background events
- Model ok if \( b = |\text{median}(p)| < 0.5 \) for all windows
  - Uncertainty on mean number of B events underestimated by < 10%
  - If not => error increased with a bias term

Bias term = signal like component added to the model
- negligible impact on sensitivity
Systematics

Signal model:
• Luminosity: 6.2%
• Trigger and photon selection: 6%
• Photon energy scale: 1%
• Photon energy resolution: 0.5%
• PDF: 6%

Background model:
• Bias term only
• [ Parameter coefficients: unconstrained nuisance parameters
  • contribute to statistical error ]
2016 exclusion limits

$\frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4}$

$\frac{\Gamma_x}{m_x} = 1.4 \times 10^{-2}$

Spin-0
2016 exclusion limits

\[ \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4} \]

\[ \frac{\Gamma_x}{m_x} = 5.6 \times 10^{-2} \]

Spin-2
2015 + 2016 exclusion limits

\[ \Gamma_x / m_x = 1.4 \times 10^{-4} \]

\[ \Gamma_x / m_x = 1.4 \times 10^{-2} \]

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Spin-0
2015 + 2016 exclusion limits

\[ \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4} \]

\[ \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-2} \]

\[ \frac{\Gamma_x}{m_x} = 5.6 \times 10^{-2} \]

Spin-2
8TeV + 13TeV exclusion limits

\[ \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4}, \text{J}=0 \]

Expected limit
- ± 1 s.d.
- ± 2 s.d.
- Observed limit

\[ \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-2}, \text{J}=0 \]

Expected limit
- ± 1 s.d.
- ± 2 s.d.
- Observed limit

\[ \frac{\Gamma_x}{m_x} = 5.6 \times 10^{-2} \]

Expected limit
- ± 1 s.d.
- ± 2 s.d.
- Observed limit

Spin-0
8TeV + 13TeV exclusion limits

- $\gamma\gamma \rightarrow G \rightarrow (pp \sigma_{95\% \text{ CL limit}}$)

- Expected limit
  - $\pm 1 \text{ s.d.}$
  - $\pm 2 \text{ s.d.}$
- Observed limit
  - $G_{RS} \rightarrow \gamma\gamma$ (LO)

Spin-2

- $\Gamma_x/m_x = 1.4 \times 10^{-4}$
- $\Gamma_x/m_x = 1.4 \times 10^{-2}$
- $\Gamma_x/m_x = 5.6 \times 10^{-2}$
2016 p-value (intermediate width)

\[ \frac{\Gamma_x}{m_x} = 1.4 \times 10^{-2} \]

CMS Preliminary

Observed J=0

Observed J=2

\[ 12.9 \text{ fb}^{-1} (13 \text{ TeV}) \]
2015 + 2016 p-value

\[ \frac{\Gamma_X}{m_X} = 1.4 \times 10^{-4}, \quad J=0 \]

Combined

2015 (3.3 fb⁻¹)

2016 (12.9 fb⁻¹)

\[ \frac{\Gamma_X}{m_X} = 5.6 \times 10^{-2}, \quad J=0 \]

Combined

2015 (3.3 fb⁻¹)

2016 (12.9 fb⁻¹)

Spin-0
2015 + 2016 p-value

Spin-2

CMS Preliminary

$\frac{\Gamma_X}{m_X} = 1.4 \times 10^{-4}$, J=2

Combined

$\frac{\Gamma_X}{m_X} = 5.6 \times 10^{-2}$, J=2

Combined

$16.2 \text{ fb}^{-1}$ (13 TeV)
\(8\text{TeV} + 13\text{TeV} \ p\text{-value}\)

\[
\frac{\Gamma_X}{m_X} = 1.4 \times 10^{-4} , \ J=0
\]

Spin-0
8TeV + 13TeV p-value

\( \frac{\Gamma_X}{m_X} = 1.4 \times 10^{-4}, J=2 \)

Combined

13TeV (16.2fb\(^{-1}\))

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

\[ \sigma_1, \sigma_2, \sigma_3, J=2 \]

\( \frac{\Gamma_X}{m_X} = 5.6 \times 10^{-2}, J=2 \)

Combined

13TeV (16.2fb\(^{-1}\))

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

Spin-2
$\Gamma_x/m_x = 1.4 \times 10^{-4}$, spin-0, $m_x = 750$ GeV
The expected median 95% C.L. exclusion limits on $s G \cdot B_{gg}$ for the three analyses entering the combination are shown in Figure 8. For this comparison, the limits obtained by the 8 TeV analyses are scaled by the cross section ratios described above.

Figure 8: Comparison of the median expected upper limits of the analyses entering the combination. The 8 TeV results are scaled by the expected ratio of cross sections predicted for an RS graviton.

The expected and observed median 95% C.L. exclusion limits on $s G \cdot B_{gg}$ for the combined analysis are shown in Figure 9. For the signal hypotheses below roughly 1.5 TeV, the exclusion limits obtained with the combined analysis improves those obtained with the single analyses by 20-30%.

Figure 9: Upper limit on the production of a narrow RS graviton obtained with the combined analysis. For $m_G < 850$ GeV, the results obtained at $p_T = 8$ TeV with the analysis described in Ref. [10] are combined with those obtained at $p_T = 13$ TeV. For $m_G > 850$ GeV the results of the analysis described in Ref. [11] obtained at 8 TeV are combined with those obtained at $p_T = 13$ TeV.

The background only $p_0$-value, $p_0$, for the combined analysis is shown, as a function of $m_G$, in Figure 10. The largest excess is observed for $m_G = 750$ GeV and has a local significance of roughly 3 standard deviations. Using the procedure described in Ref. [37] to take into account the probability to observe an excess more significant than this for at least one of the mass hypotheses tested with the combined analysis, the significance of the excess is estimated to be less than 1.7 standard deviations.

To further qualify the compatibility of the results obtained with 8 TeV and 13 TeV datasets, we compute the likelihoods of the fits to a signal plus background hypothesis as a function of the...
2015 data spectra, 3.8T

2.7 fb⁻¹ (13 TeV, 3.8 T)

EBEB
- Data
- Fit model
  - ± 1 s.d.
  - ± 2 s.d.

CMS

Events / 20 GeV

(data-fit)/σ_stat

m_{\gamma\gamma} (GeV)
2015 data spectra, 0T
8TeV data spectra
8TeV + 2015 limits

CMS

$\frac{\Gamma_x}{m_x} = 1.4 \times 10^{-4}$

$3.3 \text{ fb}^{-1} (13 \text{ TeV}) + 19.7 \text{ fb}^{-1} (8 \text{ TeV})$

$\Gamma_x = 1.4 \times 10^{-2}$

$G_{RS} \rightarrow \gamma \gamma, \tilde{\kappa} = 0.01$ (LO)

$G_{RS} \rightarrow \gamma \gamma, \tilde{\kappa} = 0.1$ (LO)

$G_{RS} \rightarrow \gamma \gamma, \tilde{\kappa} = 0.2$ (LO)
$\Gamma_x/m_x = 1.4 \times 10^{-4}, J=0$

$\Gamma_x/m_x = 5.6 \times 10^{-2}, J=0$
Crystals transparency