Search for high mass diphoton resonances at CMS

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Motivation

Search for high mass diphoton resonances in proton-proton collisions motivated by several models of physics beyond SM.

For example:

- Models with extended Higgs sectors predict appearance of spin-0 resonances.
- Extra-dimensional models predict appearance of spin-2 resonances.
- Many more models than I thought predict the appearance of diphoton resonance, given the recent number of phenomenological papers on arXiv.
Experimental signature

Very clean final state:

- Two **high $p_T$ photon candidates**. Reconstructed as high energy deposits in EM calorimeters.

- **Isolated**. No additional activity in the direction of the two photons candidates.

- Signature of **resonant production**: localized **excess** of events in the diphoton invariant mass spectrum.
### High mass diphoton searches at 8 and 13 TeV

<table>
<thead>
<tr>
<th>Ref</th>
<th>Title</th>
<th>( M_x )</th>
<th>interpreted as</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLB 750 (2015) 494</td>
<td>Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at ( \sqrt{s} = 8 \text{ TeV} )</td>
<td>150-850 GeV</td>
<td>✓</td>
</tr>
<tr>
<td>EXO-12-045</td>
<td>Search for High-Mass Diphoton Resonances in pp Collisions at ( \sqrt{s} = 8 \text{ TeV} ) with the CMS Detector</td>
<td>0.5-3 TeV</td>
<td>✓</td>
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<tr>
<td>EXO-15-004</td>
<td>Search for new physics in high mass diphoton events in proton-proton collisions at ( \sqrt{s} = 13 \text{ TeV} )</td>
<td>0.5-4.5 TeV</td>
<td>✓</td>
</tr>
<tr>
<td>EXO-16-018</td>
<td>Search for new physics in high mass diphoton events in ( 3.3 \text{ fb}^{-1} ) of proton-proton collisions at ( \sqrt{s}=13 \text{ TeV} ) and combined interpretation of searches at ( \sqrt{s}=8 \text{ TeV} ) and 13 TeV.</td>
<td>0.5-4.5 TeV</td>
<td>✓</td>
</tr>
</tbody>
</table>
Analysis strategy

- Select diphoton pairs and search for a **local excess** of events in the $m_{\gamma\gamma}$ spectrum.
  - Simple selection criteria, categorize events according to S/B ratio to enhance sensitivity.

- **Measure** energy scale, resolution and efficiency **in data**.
  - Using $Z \rightarrow ee$ and $Z \rightarrow ll\gamma$

- Parametrize **background** mass spectrum **from data**.

- Test compatibility of data with resonant diphoton production.

- **Blind** analysis:
  - Selection criteria and **signal width hypotheses fixed a-priori**.
  - All analysis inputs (energy calibration, efficiency, etc..) checked before box-opening.
  - December dataset re-blinded to study analysis improvements.
What's new?

Results presented at the CERN-LHC Seminar in December 2015 based on 2.6fb\(^{-1}\) (which became 2.7fb\(^{-1}\) due to an update in the luminosity measurement).

- Based on channel-to-channel ECAL calibration extrapolated from Run 1 data.

Data re-reconstruction, using updated channel-to-channel calibration, completed over the winter shutdown.

- Constants to equalize channel-to-channel response obtained on 2015 data.
- In the high mass region, resolution improved by \(~30\%\) (leading to a \(~10\%\) improvement in analysis sensitivity).
ECAL channel-to-channel calibration crucial for energy resolution.

Over the winter shutdown data were re-reconstructed using new channel-to-channel calibration obtained on the 2015 dataset.

![Graph showing energy resolution before and after calibration improvements](image)
New ECAL channel-to-channel calibration crucial for energy resolution.

Over the winter shutdown data were re-reconstructed using new channel-to-channel calibration obtained on the 2015 dataset. This lead to a 30% improvement in mass resolution above 500GeV. Resolution correction is assumed to be constant vs energy. (in run 1 observed decrease vs energy, but not possible to run fit in run 2 yet).
What's new?

- Results presented at the December Jamboree based on 2.6 fb$^{-1}$ (which became 2.7 due to an update in the luminosity measurement).
  - Based on channel-to-channel calibration extrapolated from Run 1 data.

- Data re-reconstruction, using updated channel-to-channel calibration, completed over the winter shutdown.
  - Constants to equalize channel-to-channel response obtained on 2015 data.
  - In the high mass region, resolution improved by $\sim 30\%$ (leading to a $\sim 10\%$ improvement in analysis sensitivity).

- An additional 0.6 fb$^{-1}$ dataset, recorded at $B=0\text{T}$ was analyzed.
  - Lead to a further 10% improvement on top of the re-calibration.
Analyzing B=0T data

- Significant re-thinking of the analysis needed to use data without magnetic field.

No information on tracks momenta
- Weakens power of isolation requirements
- Complicates primary vertex selection (based on recoiling tracks)

No energy spread due to brem/conversions
- Better intrinsic energy resolution and simpler e/γ extrapolation.
- Use more information on lateral shower profile.
Analyzing $B=0T$ data

- Major re-thinking of the analysis needed to use data without magnetic field.

Specific detector calibration ✓
Channel-to-channel calibration extrapolated from 3.8T. Dedicated energy scale calibration with 0T $Z \rightarrow ee$ events

Dedicated photon identification. ✓

Dedicated vertex selection. ✓
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- An additional 0.6\,fb$^{-1}$ dataset, recorded at $B=0\,T$ was analyzed.
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- Results interpreted in terms of spin-0 and spin-2 resonances.
  - $J=0$: assumed gluon-fusion production, $J=2$: RS-graviton
  - Three widths ($\Gamma/m=1.4\times10^{-4}$, $1.4\times10^{-2}$, $5.6\times10^{-2}$)
Event selection

- Simple event selection.
  - Two photons with $p_T$ above 75GeV. At least one of which in the barrel ($|\eta|<1.44$).
  - Events split in barrel-barrel (EBEB) and barrel-endcaps (EBEE) categories.
  - Efficient cut-based photon identification criteria.
    - Per-photon efficiency in the barrel: 90(85)% at 3.8(0)T.
    - Per-photon efficiency in the endcaps: 85(70)% at 3.8(0)T.
Energy scale calibration - 3.8T

- Obtained at the Z peak.

- Simultaneously adjust energy scale and resolution of electron candidates as a function of the pseudo-rapidity and cluster shape of the candidates.

- Stability vs $E_T$ checked with boosted events up to ~150GeV.

  Deviations within 0.5(0.7)% in barrel (endcaps).
  Assigned 1% uncertainties to account for further extrapolation.

**Graphs:**

1. **EBEB 3.8T**
   - CMS Preliminary
   - 2.7 fb$^{-1}$ (13 TeV, 3.8T)
   - $Z \rightarrow ee$
   - Data
   - Simulation

2. **EBEE 3.8T**
   - CMS Preliminary
   - 2.7 fb$^{-1}$ (13 TeV, 3.8T)
   - $Z \rightarrow ee$
   - Data
   - Simulation
Energy scale calibration - 0T

- Same procedure as for 3.8T but **no binning in cluster shape** (no radiative losses)
  - Data/MC **scale corrections** found to be **1% larger** than at 3.8T.
  - Energy **resolution corrections** similar at 0T and 3.8T.
  - Assigned 1% uncertainty on knowledge of the relative energy scale in the analysis

- Level of **stability** vs $E_T \sim$ **same** as for the 3.8T dataset.

![Graphs showing data and simulation comparison for $m_{ee}$ (GeV) for Z -> ee at 0T and 0.6 fb$^{-1}$ (13 TeV)]
Vertex identification important to maintain good mass resolution.

- For 3.8T: use BDT (using recoil and tracks $p_T$) trained for $H \rightarrow \gamma\gamma$. *(see I.Kucker in Wed. YSF).*
- For 0T: simpler algorithm based on **track-counting**.
- **Correct** assignments: 90% at 3.8T, 60% at 0T
Vertex identification validation

- Modeling of correct vertex assignment tested in data.
  - Using di-muon and g+jet events for 3.8T. (see Inna's talk for more details)
  - Using di-electron events 0T.
  - (Lepton and jets tracks remove from events)
Photon identification efficiency data/MC scale factor derived on $Z\rightarrow ee$ events.

The **electron veto** requirement is removed from the selection in this measurement and its efficiency is assessed separately using $Z \rightarrow \mu\mu(ee)\gamma$ events at 3.8(0)T.
Mass spectra - 3.8T

CMS Preliminary 2.7 fb⁻¹ (13 TeV, 3.8T)

**EBEB**

- Data
- Fit model
- ± 1 σ
- ± 2 σ

Events / (20 GeV)

(data-fit)/σ_{stat}

m_{γγ} (GeV)
Mass spectra - 0T

CMS Preliminary 0.6 fb⁻¹ (13 TeV, 0T)

Events / (20 GeV)

(data-fit)/σ_{stat}

m_{γγ} (GeV)
Interpretation of the results

Hypothesis test based on simultaneous unbinned likelihood fit to $m_{\gamma\gamma}$ in all four analysis categories.

$$L(\mu, \theta) = \prod_{i=1}^{N_{\text{events}}} \left[ \mu S(m_i|\theta_S) + B(m_i|\theta_B) \right] \cdot \text{Poisson}(N_{\text{events}}|N_B + \mu N_S)$$

Signal model.

- Shape from convolution of detector response and intrinsic line-shape.
- Mass window: 500GeV-4.5TeV.
Interpretation of the results (2)

- **Background model:**
  - Parametric function of $m_{\gamma\gamma}$: 
    $$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot \log(m_{\gamma\gamma})}.$$  
  - Independent shape for each of the category. Coefficients treated as unconstrained nuisance parameters.
  - Possible mismodelling studied on simulation and explicit uncertainty added to the fit.

- **Frequentist hypotheses tests.**
  - Test statistics: based on LHC-type likelihood ratio.
  - Upper limits set based on CLs method.
  - Background hypothesis rejection evaluated through background-only p-value.
  - Asymptotic formulas used throughout (validity tested for a subset of the calculations using sampling distributions).
Upper limits

Shown here for the spin-0 hypotheses

Spin-2 version gives equivalent message (and it's available in backup)

\[ \Gamma/m = 1.4 \times 10^{-4} \]

\[ \Gamma/m = 1.4 \times 10^{-2} \]

\[ \Gamma/m = 5.6 \times 10^{-2} \]
Largest excess observed for \( m_X = 760 \text{GeV} \) and \( \Gamma/m = 1.4 \times 10^{-2} \).

- **Local** significance: 2.8-2.9\( \sigma \) depending on the spin hypothesis.
- Similar significance for narrow-width hypothesis.
- **Trial factors** estimated from sampling distribution of \( \max(p_0) \), taking into account all the 6 signal hypotheses (spin and width).
- “Global” significance < 1\( \sigma \).
Breaking-down the contributions

- Excess at 760GeV comes mostly from EBEB categories.
  - Driven by 3.8T category.
    (where the observed excess is ~unchanged w.r.t. the previous results).
  - Observed one event in the 0T dataset compatible with 3.8T excess.
Combined analysis of 8 and 13TeV data

- CMS presented **two searches** for diphoton resonances at 8TeV.


- **EXO-12-045**: search range 500-3000GeV, spin-2 only interpretation.

Combination in all 6 signal hypotheses tested at 13TeV.

- At **each mass**, pick most sensitive analysis:
  HIG-14-004 in 500-850GeV, EXO-12-045 otherwise.

- **Cross section ratios** at 750GeV.
  - For spin 0 \((gg \rightarrow S)\): \(\sigma(13TeV)/\sigma(8TeV) = 4.7\)
  - For spin 2 \((G_{RS})\): \(\sigma(13TeV)/\sigma(8TeV) = 4.2\)
Upper limits (normalized to 13TeV x-sec)

Compared to single analyses, sensitivity improved by 20-40%.

\[ \Gamma/m = 1.4 \times 10^{-4} \]

\[ \Gamma/m = 1.4 \times 10^{-2} \]

\[ \Gamma/m = 5.6 \times 10^{-2} \]

Switch between 8TeV analyses
Largest excess observed at $m_X = 750\text{GeV}$ and for narrow width.

- **Local** significance: $3.4\sigma$
- Taking into account mass range 500-3500GeV (and all signal hypotheses), “global” significance becomes $1.6\sigma$
Consistency between 8 and 13 TeV datasets

Evaluated through likelihood scan vs equivalent 13 TeV cross-section at $m_X = 750$ GeV under both spin (narrow-width) hypotheses.

Compatible results observed in both datasets.
Showed an update on searches for diphoton resonances in the mass range above 500 GeV at 8 and 13 TeV.

- Used simple and robust analysis strategy.

- Used **improved** detector **calibration** and analyzed dataset recorded at 0T.
  - Compared to previous results, 13 TeV analysis improved **sensitivity** by more than 20%.

- Results interpreted in terms of scalar resonances and RS gravitons production of different widths.
  - Observation generally consistent with SM expectations.
  - **Modest excess** of events observed at $m_X = 750(760) \text{GeV}$ for the 8+13 TeV (13 TeV) dataset.
  - **Local** significance is $3.4(2.9)\sigma$, **reduced to 1.6 (<1)\sigma** after accounting for look-elsewhere-effect.
The CMS detector

PWO homogeneous calorimeter. Ideal energy resolution @E_\gamma = 100\text{GeV} \sim 0.6\%

https://ideas.lego.com/projects/94885
December results – mass spectra

![Graphs showing mass spectra for different categories and models.](image_url)
December results - p-values

![Graph showing CMS Preliminary results with a peak at \( \bar{\kappa} = 0.01 \)]
Background composition

Analyses estimate background process extrapolating from side-bands in $m_{\gamma\gamma}$ spectrum.

- Do not rely on precise prediction of background processes from MC simulation.
- MC simulations used only to determine functional form used.

At 3.8T, background composition measured in data

- Determination do not enter in search result, but important to validate assumption that MC simulation are reliable.
- Irreducible background accounts for 90(80)% of the events in the EBEB(EBEE) category.
Photon identification efficiency for endcap photons.

**CMS Preliminary**

**2.6 fb⁻¹ (13 TeV)**

![Graph 1](image1)

**0.6 fb⁻¹ (13 TeV, 0T)**

![Graph 2](image2)
Background composition (2)

Prediction for $\gamma\gamma$ component checked against theory predictions.

- Obtained using Sherpa-LO reweighted to $2\gamma$NNLO.
- Observation in good agreement with model.
Background modelling

- Background modelled using **parametric fit** to data.
  - Model **coefficients** treated as unconstrained **nuisance parameters** in hypothesis test.

- Choice of background parametrization is arbitrary a-priori.
- Requirement: should not lead to false positives or negatives.
  - Fulfilled making sure that the **bias on** the predicted **background** is **small compared** to the **statistical uncertainties**.
  - Mismodelling required to be $< \frac{1}{2}$ of the background stat. uncertainty.
  - Extra uncertainty added if condition not fulfilled, modelled as signal-like background component ("bias term").
Upper limits - 13 TeV

$$\Gamma/m = 1.4 \times 10^{-4}$$

$$\Gamma/m = 1.4 \times 10^{-2}$$

$$\Gamma/m = 5.6 \times 10^{-2}$$
Upper limits (normalized to 13TeV x-sec) 8+13TeV

\[ \frac{\Gamma}{m} = 1.4 \times 10^{-4} \]

\[ \frac{\Gamma}{m} = 1.4 \times 10^{-2} \]

\[ \frac{\Gamma}{m} = 5.6 \times 10^{-2} \]
P-values – all signal hypotheses
8 TeV data