Diphoton resonance search with CMS

**LHCP 2016**: Fourth annual Large Hadron Collider Physics

**Giuseppe Fasanella** on behalf of the CMS Collaboration
Overview

• Introduction and motivation
• Analysis strategy
• Mass spectra
• Combination with the 8 TeV results
• Conclusions

Analyzed datasets:
• $L=2.7 \text{ fb}^{-1}$ collected with $B=3.8 \text{ T}$:  
  $\rightarrow$ re-load of the December '15

• $L=0.6 \text{ fb}^{-1}$ collected with $B=0\text{ T}$:  
  $\rightarrow$ first time in CMS 
  $\rightarrow$ unique challenges & significant re-thinking of the analysis 
  $\rightarrow$ lead to 10 % improvement in sensitivity

Giuseppe Fasanella, ULB and INFN Roma I
Several BSM theories predict resonant production of high mass diphoton pairs

- **Spin 0**: heavy scalar in non-minimal Higgs sectors (**2HDM**)
- **Spin 2**: models with additional space-like dimensions (**ADD & RS**)

Smoking gun signature:
- Localized excess of events in the diphoton invariant mass spectrum
**RUN2** LHC data taking exploits:
- Increase discovery potential
- Parton luminosity ratio

**Key experimental strategy:**
- Search for a bump over a continuous background
- Although small x-sections, channels with photons have clean final state
Analysis strategy

- Select events with two photons of $p_T > 75$ GeV
- Photons are required to pass two dedicated photon ID:
  - $B= 3.8 \text{ T} \ L=2.7 \ \text{fb}^{-1}$: 90% efficiency
  - $B= 0 \text{ T} \ L=0.6 \ \text{fb}^{-1}$: 80% (EB) – 70% (EE) efficiency

- Split events in categories: (EB-EB, EB-EE) x (3.8 T, 0 T)
- Search region: $M_{\gamma\gamma} > 500$ GeV
- Results interpreted for 3 widths and 2 spin hypothesis

CMS-EX0-16-018; arXiv:1606.04093 [hep-ex]
Vertex selection

@ 3.8 T:
- **Multivariate approach** using recoil and track kinematics, trained for $H \to \gamma\gamma$

@ 0 T:
- New algorithm needed
- Vertex selected with the highest track multiplicity (simple and robust approach)
Data driven inputs

- **Energy scale and resolution** corrections (MC used as a template to fit the data)

- **Efficiency scale factors** from \( Z \to ee \) with TP technique

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**CMS-EX0-16-018**

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Mass spectra @ $B=3.8$ T

$$f(m_{\gamma \gamma}) = m_{\gamma \gamma}^{a+b \cdot \log(m_{\gamma \gamma})}$$

2.7 fb$^{-1}$ (13 TeV, 3.8 T)

EBEB

- Data
- Fit model
- $\pm 1$ s.d.
- $\pm 2$ s.d.

CMS

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

$400$ $600$ $800$ $1000$ $1200$ $1400$ $1600$ $m_{\gamma \gamma}$ (GeV)

$2.7$ fb$^{-1}$ (13 TeV, 3.8 T)

EBEE

- Data
- Fit model
- $\pm 1$ s.d.
- $\pm 2$ s.d.

CMS

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

$400$ $600$ $800$ $1000$ $1200$ $1400$ $1600$ $m_{\gamma \gamma}$ (GeV)

CMS-EX0-16-018; arXiv:1606.04093 [hep-ex]
Mass spectra @ B=0 T

$$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a + b \cdot \log(m_{\gamma\gamma})}$$

0.6 fb\(^{-1}\) (13 TeV, 0 T)

CMS-EX0-16-018; arXiv:1606.04093 [hep-ex]
Exclusion Limits: (3.8 T + 0 T)

- 10% improvement in sensitivity adding 0T

Spin 0; Narrow width

Spin 2; Narrow width
p values @ (3.8 T + 0 T)

Narrow width

Wide width

$\rightarrow$ Global significance < 1 $\sigma$
Combination with 8 TeV results*

* Taking the most sensitive result from 2 different analyses:
  - **EXO 12-045** for M> 850 GeV
Exclusion Limits @ (13 TeV + 8 TeV)

- Largest excess @ ~750 GeV

CMS-EX0-16-018; arXiv:1606.04093 [hep-ex]
p value comparison (13 TeV, 8 TeV)

→ Largest local p-value $\sim 3.4 \sigma$
→ global significance $\sim 1.6 \sigma$

CMS-EX0-16-018; arXiv:1606.04093 [hep-ex]
### Compatibility 8 TeV & 13 TeV

- **Likelihood scan for the cross section corresponding to the largest excess**
- **The equivalent x-sections from the 8 & 13 TeV datasets are compatible with each other (for both J=0 and J=2)**

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**CMS-EX0-16-018**

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@ 13 TeV:
- The largest excess observed @ 760 GeV for narrow width hypothesis
- local p-value is ~2.8-2.9 $\sigma$ (global p-value < 1 $\sigma$)

@ 13 TeV + 8 TeV:
- The largest excess observed @ ~750 GeV for $\Gamma/m = 1.4 \times 10^{-2}$
- local p-value ~3.4 $\sigma$ (global p-value ~ 1.6 $\sigma$)

New analysis of the 2016 dataset on-going: stay tuned!
back-up
ISOγ = \Sigma E_t \text{ of photons inside a cone (}\Delta R < 0.3\text{)}

N_{\text{trk}} = \text{number of tracks inside a cone (}\Delta R < 0.3\text{)}

σ_{\eta\eta} = \text{shower transverse width along } \eta

σ_{\phi\phi} = \text{shower transverse width along } \Phi

N_{\text{missing hits}} = \text{(electron veto)}
Interpretation

• Statistical interpretation from simultaneous fit to $M_{\gamma\gamma}$ distribution in the 4 analysis categories: (EBEB, EBEE) x (3.8T, 0T)

• Background model: **parametric fit to data** → Possible mismodelling assessed with MC and accounted as “bias term”

• Signal model: interpolation of MC prediction (+ energy corrections and scale factors)

• Spin-0 / Spin-2 results interpretation, for 3 width hypotheses
Uncertainties related to possible background shape mismodeling

- Goodness of fit of background model assessed locally (as a function of $m_{\gamma\gamma}$) using MC
  - Study pull of predicted number of background events in several mass windows
    \[ p_i^j = \frac{N_{\hat{g}_i}^{w_j} - N_h^{w_j}}{\sigma(N_{\hat{g}_i}^{w_j})} \]
  - Model acceptable if $b = |\text{median}(p)| < 0.5$ for all windows
  - If not, increase error by “bias term”

\[ \tilde{p}_j^i = \frac{N_{\hat{g}_i}^{w_j} - N_h^{w_j}}{\sqrt{\sigma^2(N_{\hat{g}_i}^{w_j}) + \beta_1^2(w_j)}} \]

Stat. Uncertainty on the fit

Extra uncertainty (“bias term”)
Modeling of the bias term

- Bias term included in hypothesis test adding a signal-like component to the background model

\[
bkg(m_{\gamma\gamma}|\theta_{\text{bias}}) = N_{\text{bkg}} \cdot \left( \frac{N_{\text{bkg}} - \theta_{\text{bias}}}{N_{\text{bkg}}} \right) bkg(m_{\gamma\gamma}) + \frac{\theta_{\text{bias}}}{N_{\text{bkg}}} \cdot \text{sig}(m_{\gamma\gamma}) \cdot Gaus(\theta_{\text{bias}}|0, N_{\text{bias}})
\]

- Normalization of signal-like component constrained from result of bias study

\[
N_{\text{bias}} = \int \text{sig}(m_{\gamma\gamma}) \beta(m_{\gamma\gamma}) \sim \text{FWHM}(\text{sig}) \cdot \beta(m_{G})
\]
### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>3.8T</th>
<th>0T</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Norm</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PDFs</td>
<td>6%</td>
<td>6%</td>
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<tr>
<td>Efficiency</td>
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<td>16%</td>
<td>0</td>
</tr>
<tr>
<td>Luminosity</td>
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<td>0</td>
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<tr>
<td><strong>Shape</strong></td>
<td></td>
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<tr>
<td>Energy scale EBE-E</td>
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<td>1%</td>
<td>1</td>
</tr>
<tr>
<td>Energy scale EBE-E</td>
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<tr>
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<td>0.5%</td>
<td>0</td>
</tr>
<tr>
<td>Energy resolution EBE-E</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0</td>
</tr>
</tbody>
</table>

- The total uncertainty is dominated by the statistical one
Exclusion Limits: (3.8 T + 0 T)

- 10% improvement in sensitivity adding 0T

*Plots from CMS-EX0-16-018*
p values 3.8 T & 0 T superimposed

Spin 0

Narrow width

Wide width

Spin 2
**p-values: summary**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Mass</th>
<th>Local p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8 T</td>
<td>~ 760 GeV</td>
<td>2.6 σ</td>
</tr>
<tr>
<td>0 T</td>
<td>~ 800 GeV</td>
<td>2.5 σ</td>
</tr>
<tr>
<td>3.8 T + 0T</td>
<td>~ 760 GeV</td>
<td>2.8-2.9 σ</td>
</tr>
</tbody>
</table>

Including “look elsewhere effect” for all spin & widths hypotheses:
- Pseudo-experiments to compute bkg-only p-values for full search region for each alternative hypothesis
- $\min(p_0)$ for each pseudo-experiment considering all hypothesis ($\Gamma, J, \text{Mass}$)
- Compare global significance distribution with observed value
- Global significance from observed excess is smaller than 1 σ
Systematic Uncertainties: correlation

- All normalization systematics assumed uncorrelated between 8 and 13TeV dataset
- Correlation model for energy scale and resolution detailed in the table below:

<table>
<thead>
<tr>
<th>Source</th>
<th>13TeV</th>
<th>8T</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale EBEB</td>
<td>1%</td>
<td>0.5%</td>
<td>0.5</td>
</tr>
<tr>
<td>Energy scale EBEE</td>
<td>1%</td>
<td>2%</td>
<td>0.5</td>
</tr>
<tr>
<td>Energy resolution EBEB</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0</td>
</tr>
<tr>
<td>Energy resolution EBEE</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0</td>
</tr>
</tbody>
</table>
Exclusion Limits @ (13 TeV + 8 TeV)

- Largest excess @ ~750 GeV

*Plots from CMS-EX0-16-018*
p value @ (13 TeV + 8 TeV)

- Lowest p-value for narrow width $\sim 3.4 \sigma$

*Plots from CMS-EX0-16-018*
Global significance for (13 TeV + 8 TeV) combination

@ 8 TeV: use sliding window for mass fit (cannot throw correlated toy experiments)

Approximation:
Trails factor = Trails factor(mass) x Trails factor(\Gamma, J | Mass)

Asymptotic formulas (crossings)
(\sim 100)

From toys @ 13 TeV
\sim 1.3

\rightarrow \text{global p-value} \sim 1.6 \sigma
CMS detector for Run2

Tracker:
- ~1 m² Pixels (66M channels)
- ~200 m² Si microstrips (9.6M channels)

Iron Yoke
- 4th muon station
- 4 stations of muon detectors

DAQ and HLT:
- New computers
- Improved Trigger

New Luminosity telescopes

Improvements during Long Shut Down LS1

3.8 T Solenoid

ECAL: Electromagnetic calorimeter - 76K PbWO₄ crystals
- 12,500 tons
- 21 m long
- 15 m diameter

HCAL: hermetic Brass/Scintillator sampling hadronic calorimeter
- HCAL new photosensors