Di-Photons At CMS

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on behalf of the CMS collaboration
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After the discovery of a particle compatible with the Higgs boson, the LHC program has 2 clear directions to look for new physics.

**Indirect: precision measurements of the Higgs properties**
- Higgs couplings
- Higgs differential cross-sections
...

**Direct: look for new particles and rare final states**
- new center of mass-of-mass energy 13 TeV significantly extends reach of Run I

In either of these, di-photon final state plays a major role!
**Di-Photon Searches**

Di-photon is a clean experimental signature to look for new physics. Fully reconstructed final state is a golden search mode for new particles.

![Diagram](image)

**Yang theorem:**

\[ X \text{ either } J=0 \text{ or } J=2 \]

<table>
<thead>
<tr>
<th><strong>STEP</strong></th>
<th><strong>ISSUES</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 2 isolated photons with high ( p_T )</td>
<td>Photon identification to reject QCD background</td>
</tr>
</tbody>
</table>
| 2) di-photon mass reconstruction | Energy scale and resolution  
Vertex determination in presence of multiple interactions pile-up (PU) |
| 3) signal extraction | Background determination: can be estimated directly with a fit to the mass spectrum |

\[ m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\theta_{12})} \]
First di-photon distribution ever shown by CMS (Nov 2009)
First LHC collisions, \( \sqrt{s} = 900 \) GeV, B=0T
Raw energy used (no energy corrections)


Now: Looking for high mass resonances decaying in 2 photons in 13 TeV Collisions
ECAL is THE crucial detector for di-photon analyses

CMS ECAL: Lead tungstate (PbWO$_4$) homogenous calorimeter designed to discover the Higgs boson in the $\gamma\gamma$ final state: $\sigma_E/E @ E>100$ GeV $\sim$0.5%

Most critical aspects (constant term of the energy resolution)
- in-situ calibration
- crystal transparency variations

More details in R. Teixeira De Lima’s talk
Relative crystals response to laser light
EB average signal loss ~6%

Energy scale stability at 0.15% level (EB) already in prompt reconstruction
**Di-Photon Analyses In CMS**

H→γγ analysis

After discovery focus on measuring Higgs properties
- couplings, mass, differential cross-section

Very optimised analysis: signal hypothesis well known (SM Higgs), systematics controlled with extrapolation from not so far Z→ee

X→γγ search (500<m_{γγ}<4500)

Generic search for a high mass di-photon resonance as predicted in several BSM models:
- **Spin0**: e.g. heavy scalar in non minimal Higgs sector
- **Spin2**: e.g. graviton, as predicted in several extra-dimensions model (RS, ADD)

Requires robust analysis tools, since performed over a large mass range more difficult to extrapolate from Z→ee
**COMMON INGREDIENTS FOR DI-PHOTON ANALYSES**

**Photon reconstruction**
- ECAL clustering
- Energy reconstruction and corrections

**Photon identification**
- Cut based or multivariate

**Vertex identification**

**Data driven approach to measure energy scale, resolution and efficiency**
- main control samples: $Z \rightarrow e e$ and $Z \rightarrow l l \gamma$

Paolo Meridiani
ECAL clustering optimised to collect energy radiated from conversions and bremsstrahlung (tracker material up to 2X₀)

- dynamic “Supercluster” algorithm recollects additional energy along φ
- material effects are smaller at high p_T (>100 GeV)

Energy estimate from a MC trained multivariate regression

- further correct material effects, gaps, PU contamination
- can provide also a per photon resolution estimate

More details in J. Bendavid’s talk
Energy scale and resolution measured in data at O(0.1%) level

MC used as a template to fit the data $E_{MC} \times Gauss(1 + \Delta P, \Delta \sigma)$

fit performed in bins of $\eta$ and cluster shape

Linearity checked with boosted $Z \rightarrow ee$ up to $p_T \sim 200$ GeV

deviations within 0.5%(0.7%) in barrel/endcap

Energy resolution for $H \rightarrow \gamma \gamma$ photons

Energy resolution $\sim 1\%$ for uncoverted photons

$R9 = \frac{E_{3x3}}{E_{\text{SuperCluster}}}$

measures the spread in $\phi$ of the energy deposition

- discriminate unconverted/converted photons
Isolated photons can be distinguished from jets by means of shower shape and isolation variables.

- Cut-based selection (more robust for high $p_T$ photons) used for high mass search.
- Multivariate techniques (BDT) to exploit correlation among several variables used in $H \rightarrow \gamma\gamma$ analysis.

**Electron rejection:** veto EM cluster with matching prompt electron, keeping reconstructed conversions.
Cut based selection adopted in $X \to \gamma \gamma$ search has $\sim 90\%$ efficiency for $p_T > 100$ GeV
  
  efficiency checked in data ($Z \to ee$)

Electron veto efficiency measured with $Z \to \mu \mu \gamma$

Shower shape variables, isolation variables and their correlations are well reproduced by the MC
  
  nice data/MC agreement on the BDT output on $Z \to ee$ and $Z \to \mu \mu \gamma$ events
**Vertex Identification**

Mass reconstruction depends on the position of the primary vertex.

In current pile-up conditions, the di-photon production vertex has to be selected among ~20 vertices.

Interaction vertex identified using recoiling tracks (and reconstructed conversions when present)

\[ \sum p_T^2, p_T(\gamma\gamma) \text{ vs } p_T(\text{tracks}), z_{\text{conv}} \]

variables combined in a BDT

Probability to assign the correct vertex also determined using a BDT.
Probability to assign the correct vertex depends on the $p_T(\gamma\gamma)$

for $H \rightarrow \gamma\gamma$ efficiency to find correct vertex within 1cm $\sim 80\%$

for $X \rightarrow \gamma\gamma$ efficiency is $\sim 90\%$

BDT output validated using

$Z \rightarrow \mu\mu$

$\gamma$+jets events used for events with a conversion
Events split in 11(7 TeV) + 14(8 TeV) categories

H→γγ can measure each Higgs production mode

special event categories to tag associated production with jets, lepton, MET

CMS H→γγ mass measure is the single most precise (340 MeV)
extrapolation from Z→ee allows to control photon energy scale systematics at 0.1-0.2%
(150 MeV)
# High Mass Di-Photon Searches

<table>
<thead>
<tr>
<th>Title</th>
<th>$m_X$ range [GeV]</th>
<th>interpretation</th>
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<tbody>
<tr>
<td>PLB 750 (2015) 494</td>
<td>150-850</td>
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<tr>
<td>Search for diphoton resonances in mass range 150 to 850 GeV in pp collisions at $\sqrt{s}=8$ TeV</td>
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<tr>
<td>EXO-16-008</td>
<td>500-4500</td>
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<tr>
<td>Search for new physics in high mass diphoton events in 3.3fb$^{-1}$ of pp collisions at $\sqrt{s}=13$ TeV and combined interpretation of searches at $\sqrt{s}=8$ TeV and $\sqrt{s}=13$ TeV</td>
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<td></td>
</tr>
</tbody>
</table>
New result (EXO-16-008) based on full 13 TeV luminosity $3.3 \text{ fb}^{-1}$

includes $0.6 \text{ fb}^{-1}$ of additional data recorded at 13 TeV at B=0T
analysis sensitivity improves by 10%

data reconstruction with improved ECAL inter-calibration completed over winter shutdown
30% improvement in mass resolution for a narrow resonance $m_X > 500$ GeV
10% improvement in analysis sensitivity

Results interpreted in terms of spin0 and spin2 resonances
J=0 gluon fusion production, J=2 RS-graviton
3 widths considered: $\Gamma/m=1.4\times10^{-4}$, $1.4\times10^{-2}$, $5.6\times10^{-2}$
combination with 8 TeV results
All analysis ingredients had to be re-thought to use data without magnetic field
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No informations on tracks momenta 😞
weakens isolation power
more difficult to identify correct vertex

Energy spread for conversions/brem reduced 😊
better energy resolution, easier e/γ extrapolation
shower shape discrimination more powerful

Dedicated channel inter-calibration

Dedicated photon identification
 photon identification efficiency in EB~80% (less efficient ele-veto)

Dedicated vertex identification
 probability to find correct vertex ~60% (only track count can be used)
Simple and robust selection

- 2 isolated photons, $p_T > 75$ GeV
- Split events into (EB-EB, EB-EE) x (3.8T, 0T)
- Background composition (measured in data with template fits) dominated by irreducible SM $\gamma\gamma$ production: ~90%
**MASS SPECTRA**

**EB-EB categories at 3.8T and 0T**

**B=3.8T**

![Graph for B=3.8T]

**B=0T**

![Graph for B=0T]

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

**CMS Preliminary** 0.6 fb⁻¹ (13 TeV, 0T)
INTERPRETATION

Statistical interpretation from simultaneous fit to $m_{\gamma\gamma}$ distribution 0.5-4.5TeV in the 4 analysis categories (EB-EB,EB-EE)x(3.8T,0T)

**Background model:** parametric fit to the data with empirical function $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b \cdot \log(m_{\gamma\gamma})}$
- possible mis-modelling assessed with MC and included as a “bias-term”

**Signal model:** MC prediction including energy resolution corrections interpolated between several mass points
- $(\text{Spin0}, \text{Spin2}) \times (3 \text{ widths})$ signal hypotheses
Combination of 13 TeV 3.8T and 0T dataset

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

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

\[ \Gamma/m = 5.6 \times 10^{-2} \]
Largest excess observed for $m_X=760$ GeV $\Gamma/m=1.4E-2$

Local significance: $2.8-2.9\sigma$ depending on spin hypothesis
similar significance for narrow width

Global significance $<1\sigma$
trial factors obtained considering all 6 signal hypotheses (spin x width) in the 500-4500 GeV mass range
Excess mostly driven by EBEB 3.8T category
One event in the 0T dataset compatible with 3.8T excess
Combination With 8 TeV

2 analyses performed on 8 TeV data


EXO-12-045: 500-3000 GeV, spin2 only

Combination in all 6 signal hypotheses with 13 TeV
pick most sensitive analysis: 500-850 GeV HIG-14-006, EXO-12-005 otherwise

Cross section ratios:
spin0 (gg→S): $\sigma_{13 \text{ TeV}}/\sigma_{8 \text{ TeV}}=4.7$
spin2 (RS): $\sigma_{13 \text{ TeV}}/\sigma_{8 \text{ TeV}}=4.2$
Compared to single analyses, sensitivity improved by 20-40%.

Largest excess observed at $m_X=750$ GeV for narrow width

Local significance: $3.4\sigma$

Global significance $1.6\sigma$, considering all signal hypotheses in 500-3500 GeV mass range.
Evaluated looking at likelihood profile for equivalent $\sigma_{13\text{ TeV}}$ at 750 GeV for both spin hypotheses

Excess is compatible between the 2 datasets
CONCLUSIONS

Di-photon is a robust and powerful final state to look for new physics and explore the Higgs boson properties. It relies heavily on excellent CMS ECAL performance.

13 TeV center-of-mass energy is a new unexplored territory. Not only limits, a modest excess has been observed at mass ~ 750 GeV.

10 fb⁻¹ at 13 TeV are required to assess the nature of this excess:
- statistical fluctuation
- new physics

OR

OR

?
BACKUP
### CMS Unpublished

<table>
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<tr>
<th>Category</th>
<th>Expected Signal</th>
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<tr>
<td>Combined</td>
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</tr>
</tbody>
</table>

#### Signal Fraction (%)

- ggH
- qqH
- WH
- ZH
- ttH

#### Width (GeV)

- FWHM/2.35

#### S/(S+B) in ± σ_{eff}

- 19.7 fb⁻¹ (8 TeV)
H $\rightarrow \gamma\gamma$ Event Categories

**CMS**

H $\rightarrow \gamma\gamma$

19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)

$\hat{\mu}_{\text{combined}} = 1.14^{+0.26}_{-0.23}$

[m$_H = 124.7$ GeV]

Combined ± 1 σ

Per-channel ± 1 σ