Search for high mass resonances in the diphoton and $Z\gamma$ channels at LHC

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Diphoton and flavor anomalies
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LHC Run2 started one year ago at 13 TeV (unexplored √s)

ATLAS and CMS presented 2015 preliminary results in mid-december with an update at Moriond conference

Excess of events in the diphoton channel at ~750 GeV invariant γγ mass shown by both experiments
2015 end-of-year event

ATLAS NOTE
ATLAS-CONF-2015-081

December 13, 2015

Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

CMS Physics Analysis Summary

Search for new physics in high mass diphoton events in proton-proton collisions at $\sqrt{s} = 13$ TeV
Number of $\gamma\gamma$-related arXiv submissions after the Run2 seminar @ CERN

Stable slope (~1.6 day$^{-1}$) during last 3 months!

Credits:
http://jsfiddle.net/adavid/bk2tmc2m/show/
Looking for fully reconstructed resonances at higher center-of-mass energy (→LHC Run2) is the golden way to new particle discoveries.

Very clear signature at hadron collider (signal over smooth well known background)

- Model independent probe to new physics
  - several extensions of the Standard Model predict high-mass states decaying to $\gamma \gamma$
- Inspired to the Higgs→$\gamma \gamma$ Run1 analysis
  - very solid techniques (e.g. cut based selection)
- Small systematic effects
1) Define the event selection: 2 isolated photons
   ✓ must be loose and model-independent

2) Reconstruct the $\gamma \gamma$ invariant mass

$$M = \sqrt{2E_1 E_2 (1 - \cos \theta)}$$
   ✓ photon reconstruction
   ✓ energy resolution and scale
   ✓ dedicated vertex identification technique

3) Signal extraction

Clean final state at hadron colliders

Electromagnetic calorimeter performances are crucial for the analysis achievement.

Fully blind analysis.
LHC operations @ 13TeV

2015 Luminosity

CMS Integrated Luminosity, pp, 2015, $\sqrt{s} = 13$ TeV

Data included from 2015-06-03 08:41 to 2015-11-03 06:25 UTC

Offline Luminosity

~ 25% of the data recorded by CMS with the magnet @ 0 T

2016 Luminosity

ATLAS Online Luminosity $\sqrt{s} = 13$ TeV

- Total Delivered: 0.693 fb$^{-1}$
- Total Recorded: 0.639 fb$^{-1}$

Expected ~1 fb$^{-1}$ for LHCP and ~5-10 fb$^{-1}$ for ICHEP conference
ATLAS Electromagnetic Calorimeter

Lead – liquid Argon sampling calorimeter with accordion geometry

Longitudinal segmentation for particle ID and vertexing.

- S1 (Strips) \(\gamma/\pi^0\) separation \(4.3 X_0\)
- S2 (Middle) Main energy deposit \(16 X_0\)
- S3 (Back) High energy showers \(2 X_0\)

High granularity: almost 200k channels

Design energy resolution: **0.5-0.7% constant term**

- Critical issues:
  - Material in front of the calorimeter
  - Temperature and HV dependence
CMS Electromagnetic Calorimeter

Lead Tungstate (PbWO$_4$) homogeneous crystal calorimeter

Crystal qualification and module construction in Rome (Casaccia) and at Cern

Design energy resolution:

**0.5% for E > 100 GeV**
(as measured at Test Beam)

**Low stochastic term (< 3%)**

- Critical issues:
  - Transparency loss due to radiation damage
  - Precision of in-situ calibration
Energy resolution

The diphoton invariant mass resolution:

\[
\Delta m_\gamma = \frac{1}{2} \left[ \frac{\Delta E_{\gamma_1}}{E_{\gamma_1}} \oplus \frac{\Delta E_{\gamma_2}}{E_{\gamma_2}} \oplus \frac{\Delta \theta_\gamma}{\tan(\theta_\gamma/2)} \right]
\]

\[
\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
\]

- **a**: stochastic term from Poisson-like fluctuations
- **b**: noise term from electronic and pile-up
- **c**: constant term dominant at high energy

[ Angular contribution is negligible: primary vertex position from high momentum tracks ]
Crystal transparency loss in CMS

Cycle of response loss during irradiation and recovery in beam-off periods

Stable energy scale achieved after laser correction

Stability (RMS):
- Barrel ~ 0.1%
- Endcap ~ 0.3%
Effect of Calibration in CMS

- Crystal LY spread ~ 20% → 0.5-1.0% after calibration
- Transparency losses in the crystals up to ~60% (strong position dependence) → 0.1-0.3% stability with laser corrections

Effect of calibration on Zee invariant mass distribution in data:
- raw data
- channel Inter-Calibration
- Inter-Calibration and Laser Monitoring corrections
Photon = energy deposits in clusters of ECAL channels
✓ clustering optimized to collect energy radiated from conversions and bremsstrahlung (best energy resolution)
✓ clusters are then associated with inner tracker and classified as electrons, $\gamma$ or $\gamma_{\text{converted}}$

Final energy corrections from multivariate regression trained on MC
– further correct material effects, gaps, PU contamination
– can provide also a per photon resolution estimate
Response stability

- Energy calibration determined in Run1 $Z\to\text{ee}$ events and corrected for the 13 TeV data taking conditions.
- Energy scale stability with electrons from $Z$ and $W$ as a function of the number of reconstructed vertices (left) and vs time (right).
  - peak of the dielectron invariant mass distribution with $Z$ event selection
  - MPV of $E/p$ distribution with $W$ event selection
Photon reconstruction performance

- Energy scale and resolution corrections estimated using 13 TeV $Z \rightarrow e e$ with electrons reconstructed as photons.
- Photon energy smeared on MC to match data.
- Linearity checked with boosted $Z \rightarrow e e$ up to $p_T \sim 200$ GeV and with high mass DY events.
Diphoton vertex identification

- Spread of primary vertex position is ~ 5 cm in z
- If vertex is located within 1 cm, contribution to the mass resolution from angle negligible
- The vertex is selected using recoiling tracks (and reconstructed conversion when present)
- Multivariate approach for optimal performance
  \[ \Sigma p_T^2, p_T(\gamma\gamma) \text{ vs } p_T(\text{tracks}), z_{\text{conv}} \]
- Probability to assign the correct vertex depends on the \( p_T(\gamma\gamma) \).
- Average probability is ~ 90%.
- Performance validated in data with \( Z \rightarrow \mu\mu \) events
Diphoton vertex identification

- $\gamma$ trajectories measured exploiting the calorimeter longitudinal segmentation
- The vertex is selected among the reconstructed vertices with a neural network (NN) algorithm
  - Inputs: $z$ position of extrapolation, sum $p_T$, sum $p_T$, $\delta \phi$ between di-photon system and vector sum of track momenta

Efficiency of identifying a vertex within 0.3 mm for the true one is 80-95%, depending on the number of reconstructed vertices in the event
ATLAS and CMS diphoton preliminary results already shown here in Sapienza in a seminar in January.

Focus of this presentation on diphoton updates at Moriond conference (March 2016) and recent Z+photon results.

**Analysis update (Moriond)**

<table>
<thead>
<tr>
<th><strong>ATLAS</strong></th>
<th><strong>CMS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin 2 interpretation added</td>
<td>Spin 0 interpretation added</td>
</tr>
<tr>
<td>(was only Spin 0 in december)</td>
<td>(was only Spin 2 in december)</td>
</tr>
<tr>
<td>diphoton 8 TeV data re-analysis and</td>
<td>0.6 fb(^{-1}) of additional data recorded</td>
</tr>
<tr>
<td>compatibility with 13 TeV analysis</td>
<td>without magnetic field</td>
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<tr>
<td>p-value scan in 2D (mass-width, was</td>
<td>re-reconstruction of data with the</td>
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<tr>
<td>only mass in december)</td>
<td>new ECAL calibration</td>
</tr>
<tr>
<td>Kinematic properties of events in the</td>
<td>combination with 8 TeV results</td>
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<tr>
<td>excess region w.r.t. sidebands</td>
<td></td>
</tr>
<tr>
<td><strong>Z(_γ) → eeγ/μμγ/jjγ channels at 13 TeV</strong></td>
<td><strong>Z(_γ) → eeγ/μμγ channels at 13 TeV</strong></td>
</tr>
</tbody>
</table>
Diphoton event display

Run: 280673
Event: 1273922482
2015-09-29 15:32:53 CEST
Central photon ID efficiency at 13 TeV

**Cut-based event selection**

- **Trigger:** $E_{1T} > 35$ GeV and $E_{2T} > 25$ GeV
- **Offline pre-selection:**
  - $E_{1T} > 40$ GeV and $E_{2T} > 30$ GeV
  - ECAL fiducial region
  - dedicated photon selection (isolation, H/E, shower shape)

- **two event selections:**

  **Spin-0 analysis**
  (extended Higgs sector)

  - Higgs-like signal optimization
    - $E_T(\gamma_1) > 0.4 \ m_{\gamma\gamma}$, $E_T(\gamma_2) > 0.3 \ m_{\gamma\gamma}$ → +20% significance for $m_X > 600$ GeV
  - Search range
    - $m_X : [0.2, 2]$ TeV and $\Gamma_X/m_X : [0\% - 10\%]$  

  **Spin-2 analysis**
  (Randall-Sundrum graviton)

  - Looser selection
    - $E_T(\gamma_1) > 55$ GeV, $E_T(\gamma_2) > 55$ GeV → preserve acceptance at high mass
  - Search range
    - $m_G : [0.5, 3]$ TeV and $\Gamma_G/m_G : [0.01\% - 11\%]$
Diphoton event display

$m(\gamma\gamma) = 745$ GeV
Cut-based event selection
(same selection for both benchmark models)

- HLT: 2 photons, $E_T > 60$ GeV
- Offline selection:
  - $E_T > 75$ GeV
  - ECAL fiducial region
  - dedicated photon selection
    (isolation, H/E, shower shape)
- 2 event categories:
  - EBEB: both $\gamma$ in the barrel
  - EBEE: one $\gamma$ in EB, one in EE

10-15% improvement from adding the barrel-endcap category

Per-photon efficiency in the barrel (endcaps): ~90%(~85%).

Zee to check efficiencies

- data/MC scale factors compatible with 1, constant at high $p_T$
Backgrounds

Direct $\gamma\gamma$ SM production irreducible

Dijet and $\gamma+$jet production reducible

Background composition measured in data using template fits

**Dominant contribution:** 2 prompt photons

**QCD and photon+jets:** 10%-20%
Signal modelling

- **Shape of the signal**: combination of the intrinsic width of the resonance and the calorimeter detector response.

- **Benchmark model**: spin0 and spin2
  - scan of the mass in the range 500-5000 GeV
  - spin 0: scan of the width up to ~10%
  - spin 2: scan of the RS graviton coupling: $0.01-0.2 \rightarrow \Gamma_G/m_G = 0\%-6\%

- **Detector response modeled on fully simulated signal sample with negligible intrinsic width**

<table>
<thead>
<tr>
<th>$m$ (GeV)</th>
<th>$\sigma_{FWHM}^{3.8T}/m$ EBEB</th>
<th>$\sigma_{FWHM}^{3.8T}/m$ EBEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>$0.94 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>1000</td>
<td>$0.94 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>2000</td>
<td>$0.96 \times 10^{-2}$</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>4500</td>
<td>$1.11 \times 10^{-2}$</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

**ATLAS Simulation Preliminary**

- $\sqrt{s} = 13$ TeV, $G^* \rightarrow \gamma \gamma$
- $m_{G^*} = 1000$ GeV
- $k/M_{Pl} = 0.20$ ($\Gamma_G/m_{G^*} = 5.8\%$)
Background modelling

Background $m_{\gamma\gamma}$ shape:
✓ parametric fit to data (several function tested)
✓ model coefficients: nuisance parameters in the hypothesis test

\[
f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a + b \cdot \log(m_{\gamma\gamma})},
\]

CMS

\[
f = (1 - x^{1/3})^b x^a, \text{ with } x = m_{\gamma\gamma}/\sqrt{s}
\]

ATLAS (Spin 0)

ATLAS (Spin 2)

**Irreducible** $\gamma\gamma$ background from MC

**Reducible** ($\gamma+$jets, jj) background from data

Accuracy of the background determination is assessed using MC simulations and quantified by studying the difference between the true and predicted number of background events
CMS improved the analysis for Moriond conference thanks to:
1. re-reconstruction of data with the new ECAL calibration
2. 0.6 fb\(^{-1}\) of additional data recorded without magnetic field (next slide).

Both the improvements rely on a deep ability to make the best usage of data taken with the Electromagnetic Calorimeter.

New ECAL calibration derived with the full 2015 data sample:
- \(~30\%\) improvement in mass resolution
- \(~10\%\) improvement in expected sensitivity
Data with B=0 Tesla

- No measurement of charged particle momenta
- Reduced energy spread from conversion/brem.

- Significant re-thinking of the analysis needed to use data without magnetic field (very first case in CMS)
- Dedicated calibration and photon ID
- Identification of production vertex by counting the associated tracks.
Diphoton mass spectra

$m_{\gamma\gamma}$ distribution @ 13 TeV - Moriond updates
Expected and observed limits on cross section x diphoton BR based on simultaneous unbinned likelihood fit in all analysis categories. (ATL-PHYS-PUB-2011-11 / CMS NOTE-2011/005):

- Spin 2 results very similar (in the backup).
- Observed limit deviation from expected due to excess in data
Interpretation: exclusion limits

Spin-0 analysis

Limit on fiducial cross section

Spin-2 analysis

Limit on production cross section

Expected and observed limits on cross section x diphoton BR

(ATL-PHYS-PUB-2011-11 / CMS NOTE-2011/005):

✔ Observed limit deviation from expected due to excess in data
Event kinematic properties: sidebands and excess region

Spin-0 analysis

- No additional activities (with the current size of the data sample) in the diphoton events belonging to the excess region with respect to the events in sidebands.
- No additional activities also in ATLAS spin 2 and in CMS selections.
Comparison with 8 TeV results

8 TeV data re-analyzed: latest run1 calibration, run1 selection, 13 TeV analysis methods

1.9 \sigma at the same m_X, \Gamma_X combination
- Compatible with 13 TeV results at 1.2\sigma

No significant excess
- Compatible with 13 TeV results at 2.7\sigma
Combination with 8 TeV results

- Combination with 8 TeV results in narrow width hypothesis
  - different acceptance and categorizations
- Consistency between 8 and 13 TeV results evaluated with likelihood scan at 750 GeV.
  - 8 TeV results rescaled by the expected cross-section ratio (4.7/4.2 for spin 0/2)
- Compatible results in both spin hypotheses.
\[ \text{Largest excess for } m_X = 750 \text{ GeV in both experiments} \]

\[ \text{Local significance } 3.4\sigma \text{ (CMS) and } 3.9\sigma \text{ (ATLAS)} \]

\[ \text{Significance reduced to } 1.6\sigma \text{ (CMS) and } 2.0\sigma \text{ (ATLAS) when accounting for Look Elsewhere Effect in mass and width} \]

(trial factor derived as in \texttt{arXiv:1005.1891v3})
## ATLAS vs CMS

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calorimeter (complementary technology)</strong></td>
<td>Lead – Argon sampling Ionization Longitudinal segmentation</td>
<td>PbWO homogeneous Scintillation light Excellent stochastic term</td>
</tr>
<tr>
<td><strong>13 TeV Luminosity</strong></td>
<td>3.2 fb(^{-1})</td>
<td>2.7 fb(^{-1})+0.6 fb(^{-1}) (B=0T)</td>
</tr>
<tr>
<td><strong>Benchmark models</strong></td>
<td>Spin 0 + Spin 2</td>
<td>Spin 0 + Spin 2</td>
</tr>
<tr>
<td><strong>diphoton selection</strong></td>
<td>spin 0: scaling (E_T) cut spin 2: fixed (E_T) cut (55 GeV)</td>
<td>fixed (E_T) cut (75 GeV)</td>
</tr>
<tr>
<td><strong>efficiency x acceptance</strong></td>
<td>55%-70% @ 200-700 GeV 45%-60% @ 0.5-3.0 TeV</td>
<td>spin0: 60% @ 750 GeV spin2: 55% @ 750 GeV</td>
</tr>
<tr>
<td><strong>compatibility with 8TeV</strong></td>
<td>OK: small excess with spin0 selection</td>
<td>OK: combination</td>
</tr>
<tr>
<td><strong>Significance @750GeV</strong></td>
<td>3.9(\sigma) local 2.0(\sigma) global</td>
<td>3.4(\sigma) local 1.6(\sigma) global</td>
</tr>
</tbody>
</table>
Complementary search: high mass resonances in $Z\gamma$ channels

- Assuming no extra tree-level decays other than an effective coupling to gluons and to SM gauge bosons implies a large contribution to the $Z\gamma$ decay

Search for scalar resonances in $Z\gamma \rightarrow e\gamma, \mu\mu\gamma, jj\gamma$ final states at $\sqrt{s} = 13$ TeV (and 8 TeV) in ATLAS and CMS (additional channels investigated – e.g. ZZ, dijets,… - and no excess observed)

- The dominant background process is SM production of non-resonant $Z+\gamma$ in the leptonic channel and $Z$+jet with the latter misidentified as photon in the hadronic channel.

- Mass range:
  - ATLAS $e\gamma/\mu\mu\gamma \rightarrow 250$ GeV – 1.5 TeV
  - ATLAS $e\gamma/\mu\mu\gamma @ 8$ TeV → 200 GeV – 1.6 TeV
  - ATLAS $jj\gamma \rightarrow 720$ GeV – 2.75 TeV
  - CMS $e\gamma/\mu\mu\gamma \rightarrow 350$ GeV – 2.0 TeV
  - CMS $e\gamma/\mu\mu\gamma @ 8$ TeV → 200 GeV – 1.2 TeV
Considered separately leptonic and hadronic Z decays: very different detector resolution

- $Z\gamma \rightarrow ll\gamma$: 2 same flavor, opposite sign leptons consistent with a Z
- $Z\gamma \rightarrow J\gamma$: jet-pair reconstructed as a large radius single jet (J) with $p_T > 200$ GeV
In both cases the smoothing falling background is fitted with the analytical function \( F = N(1-x^k)^{p_1+\delta p^2 x^{p_2}} \) (\( x = m_{Z\gamma}/\sqrt{s} \)).

Signal benchmark: generic Higgs-like resonance with a narrow width (\( \Gamma_X = 4 \text{ MeV} \)) simulated using POWHEG+PYTHIA.
ATLAS Z\gamma \rightarrow ee\gamma/\mu\mu\gamma/jj\gamma

- No significant excess over the background-only hypothesis (largest deviation in m_X \sim 350 GeV at the level of 2 \sigma)
- The observed limits (narrow-width) are between \sim 8 and 260 fb
The photon is required to have a distance $\Delta R > 0.4$ from each of the two leptons, to minimize the effect of lepton FSR.

The SM background is described by the function $f(m_{Z\gamma}) = m_{Z\gamma}^{a+b \log m_{Z\gamma}}$ with a fit on data events.
CMS $Z\gamma \rightarrow e\gamma/\mu\gamma$

- No significant excess over the background-only hypothesis.
- The observed limits (narrow-width) are between ~20 and 250 fb.
CMS and ATLAS results of $Z\gamma\rightarrow ee\gamma/\mu\mu\gamma$ @ 8 TeV

- No significant excess over the background-only hypothesis.
- The observed limits (on $ll\gamma$) in the mass range 200 GeV – 1.2 TeV are between 0.1 and 3.8 fb
Conclusions

- Observed diphoton and Z+photon mass spectrum in agreement with Standard Model expectations
- Strongest constraint on production cross-section set
- Simple and robust analysis strategy
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Clouds will thin out with the next ~10 fb⁻¹