ATLAS and CMS diphoton resonance searches at 13 TeV

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Overview

• ATLAS
  ✓ https://cds.cern.ch/record/2114853
  
  Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

  The ATLAS Collaboration

  Abstract
  This note describes a search for new resonances decaying to two photons, with invariant mass larger than 200 GeV. The search is optimized for scalars such as those expected, for example, in models with an extended Higgs sector. The dataset consists of 3.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider. The data are consistent with the expected background in most of the mass range. The most significant deviation in the observed diphoton invariant mass spectrum is found around 750 GeV, with a global significance of about 2 standard deviations. A limit is reported on the fiducial production cross section of a narrow scalar boson times its decay branching ratio into two photons, for masses ranging from 200 GeV to 1.7 TeV.

• CMS
  ✓ https://cds.cern.ch/record/2114808
  
  Search for new physics in high mass diphoton events in proton-proton collisions at $\sqrt{s} = 13$ TeV

  The CMS Collaboration

  Abstract
  We report on a search for new physics using high mass diphoton events. The search employs 2.6 fb$^{-1}$ of $pp$ collision data collected by the CMS experiment in 2015 at a center-of-mass energy of 13 TeV and it is aimed at extradimensional models leading to resonant production of two photons. Limits on the production cross section of Randall-Sundrum gravitons decaying to two photons are obtained in the range 500-4500 GeV.

✓ 3.2 fb$^{-1}$
✓ Optimized for scalars

✓ 2.6 fb$^{-1}$
✓ Optimized for spin-2
What are we talking about?

- **ATLAS**

  - ATLAS and CMS high-mass diphoton resonance searches at 13 TeV

  ![ATLAS Plot](image1)

  - Data
  - Background-only fit

  \[ \sqrt{s} = 13 \text{ TeV, 3.2 fb}^{-1} \]

  ![ATLAS Graph](image2)

  - Data
  - Fitted background

- **CMS**

  - CMS Preliminary

  ![CMS Plot](image3)

  - Data
  - Fit model
  - \( \pm 1 \sigma \)
  - \( \pm 2 \sigma \)

  ![CMS Graph](image4)

  - Data - fitted background

  \[ \text{Events / 20 GeV} \]

  \[ m_{\gamma\gamma} \text{ (GeV)} \]
Selections

• **ATLAS**

  ✓ **Trigger**
  - $E_{T}^{Y1} > 35 \text{ GeV}, E_{T}^{Y2} > 25 \text{ GeV}$
  - Loose quality
  - Fully efficient for $E_{t}^{Y} > 40 \text{ GeV}$

  ✓ **Offline**
  - $|\eta| < 2.37, 1.37-1.52$ excluded
  - $E_{T}^{Y1} > 40 \text{ GeV}, E_{T}^{Y2} > 30 \text{ GeV}$
  - $E_{T}^{Y1} > 0.4 \ m_{YY}, E_{T}^{Y2} > 0.3 \ m_{YY}$
    - Effectively deplete EndCaps
  - Tight quality (cuts) + isolation
  - Select $m_{YY} > 150 \text{ GeV}$
  - **Search** $m_{YY} > 200 \text{ GeV}$

  ✓ **Efficiency** (ggF Scalar)
  - $m_{X} \sim 200 \text{ GeV} \rightarrow \sim 35\%$
  - $m_{X} > 600 \text{ TeV} \rightarrow > 40\%$

• **CMS**

  ✓ **Trigger**
  - $E_{T}^{Y1} > 60 \text{ GeV}, E_{T}^{Y2} > 60 \text{ GeV}$
  - $H/E < 0.15$
  - Fully efficiency for $m_{G} > 600 \text{ GeV}$

  ✓ **Offline**
  - $|\eta| < 2.5, 1.44-1.57$ excluded
    - At least one $\gamma$ with $|\eta| < 1.44$
    - No E-E combination
  - $E_{T}^{Y1} > 75 \text{ GeV}, E_{T}^{Y2} > 75 \text{ GeV}$
  - Tight quality (cuts) + $H/E < 0.05$ + isolation
  - Select $m_{YY} > 230 \text{ GeV}$ (320 if EC $\gamma$)
  - **Search** $m_{YY} > 500 \text{ GeV}$

**Efficiency** (RS Gravitons)
- $m_{G} \sim 600 \text{ GeV} \rightarrow \sim 30\%$
- $m_{G} \sim 2 \text{ TeV} \rightarrow \sim 45\%$
Signal modeling

**ATLAS**

- **Signal properties**
  - **Higgs-like scalar**
    - $m_X = [200 \text{ GeV} - 2 \text{ TeV}]$
  - Different production modes
    - $ggF$ (Powheg-box), $VBF$ (Powheg-box+Pythia), $VH$, $ttH$ (Pythia)
    - systematic uncertainties to avoid “model” dependence
  - **Narrow Width Approximation (NWA)**
    - Full Simulation
    - Width ~ 4 MeV for all $m_X$
  - **Large Width Approximation (LWA)**
    - Width 1%-10% $m_X$
    - Theoretical line shape convoluted to detector response
    - Powheg implementation of a large-width scalar resonance when assuming SM-like couplings (BW distribution with a mass-dependent width + dependence of propagator on the gg parton lumi)

- **Implementation**
  - Double-Sided Crystal Ball parameterization
    - Simultaneous fit of parameter parameterization

**CMS**

- **Signal properties**
  - **RS Graviton**
    - $m_X = [500 \text{ GeV} - 4.5 \text{ TeV}]$
    - $\bar{\kappa} = \sqrt{8\pi\kappa/m_{Pl}}$
    - $0.01 < \bar{\kappa} < 0.2$

- **Implementation**
  - Moment morphing

<table>
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<th>$m_G$ (GeV)</th>
<th>category</th>
<th>$\bar{\kappa}$</th>
<th>FWHM (GeV)</th>
<th>$\bar{\kappa}$</th>
<th>FWHM (GeV)</th>
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</table>
Background modeling

• **ATLAS**
  
  ✓ Data driven $\gamma\gamma$ purity (wrt $\gamma\gamma$, $\gamma j$)
    - ~ 90%
  
  ✓ **Functional form**
    
    $$x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$$
    
    $$f(k)(x; b, \{a_k\}) = (1 - x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}$$
    
    $$f_0(x; b, a_0) = (1 - x^{1/3})^b x^{a_0}$$
  
  ✓ Bias evaluated on MC
    - “Spurious signal”
    - S+B fits to high-statistics of background MC
    - Fitted S component must be smaller than 20% of expected background uncertainty at given mass
  
  ✓ **F-test on data to evaluate need for higher order in background function**

• **CMS**
  
  ✓ Data driven $\gamma\gamma$ purity (wrt $\gamma\gamma$, $\gamma j$)
    - ~ 90% ~ 80% (BB, BE)
  
  ✓ **Functional form**
    
    $$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a + b \cdot \log(m_{\gamma\gamma})}$$
  
  ✓ Bias evaluated on MC
    - Additional uncertainty assigned to background parameterization
    - From fit MC pseudo-experiment (toys)
    - Assigned if median of pull distributions from toy fits toys is larger than 0.5
Systematic uncertainties

**ATLAS**

- Bias term on parametric background model (no size given)
- Luminosity : 4.6%
- Trigger and photon ID : 10%
- Signal PDF : 6% (not in ATLAS, several production processes)
- Photon energy scale : 1% (negligible in ATLAS)

**CMS**

- Bias term on parametric background model (no size given)
- Luminosity : 4.6%
- Trigger and photon ID : 10%

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### Background modeling

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
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<tbody>
<tr>
<td><strong>Spurious signal</strong></td>
<td>$2 \times 10^{-3}$ events, mass-dependent</td>
</tr>
<tr>
<td>Background fit</td>
<td>$\leq 50% - \leq 20%$ of the total signal yield uncertainty, mass- and signal-dependent</td>
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### Signal modeling

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy resolution</td>
<td>$^{+5%}_{-2%}$, mass-dependent</td>
</tr>
<tr>
<td>Signal yield</td>
<td>$^{\pm 3%}_{\pm 2%}$, mass-dependent</td>
</tr>
</tbody>
</table>

### $C\times$ factors

- Photon identification : $^{\pm (3-2)\%}_{\pm (4-1)\%}$, mass-dependent
- Photon isolation : $^{\pm (3-2)\%}_{\pm (4-1)\%}$, mass-dependent
- Production process : $\pm 3.1\%$
Statistical treatment

• **ATLAS**
  - ✓ Profile likelihood ratio
    \[ q_0(m_X, \alpha) = -2 \log \frac{L(0, m_X, \alpha, \hat{\nu})}{L(\hat{\sigma}, m_X, \alpha, \hat{\nu})} \]
  - ✓ Look Elsewhere Effect
    - 1D \(\rightarrow\) several mass hypothesis in NWA scan
    - 2D \(\rightarrow\) several mass and width hypothesis

• **CMS**
  - ✓ Profile likelihood ratio
    \[ q(\mu) = -2 \log \frac{L(\mu \cdot S + B | \hat{\theta}_\mu)}{L(\hat{\mu} \cdot S + B | \hat{\theta})} \]
  - ✓ Look Elsewhere Effect
    - 2D \(\rightarrow\) several mass and width hypothesis
Spectrum

• ATLAS

ATLAS Preliminary

Events / 40 GeV

ATLAS Preliminary

Data

Background-only fit

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

CMS Preliminary

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

EBEB category

Events / (20 GeV)

EBEE category

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

CMS plots have different m scale!

Data

Fit model

\( \pm 1 \sigma \)

\( \pm 2 \sigma \)

Data - fitted background

\( \sigma_{\text{stat}} \)

\( \sigma_{\text{fit}} \)
Significance

- **ATLAS**
  - ✓ NWA
  - • Pull on resolution NP
  - ✓ Local $p_0 \sim 3.6 \sigma$ at $\sim 750$ GeV
  - ✓ Global $p_0 \sim 2.0 \sigma$

- **CMS**
  - ✓ $\tilde{\kappa} = 0.01$
  - • FWHM(500 GeV) BB = 14 GeV
  - ✓ Local $p_0 \sim 2.6 \sigma$ at $\sim 760$ GeV
  - ✓ Global $p_0 \sim 1.2 \sigma$
Significance

• **ATLAS**
  - ✓ LWA
  - Minimum $p_0$ for width $\sim 6\%$

• **CMS**
  - ✓ $\tilde{\kappa} = 0.2$
    - FWHM(500 GeV) BB = 36 GeV ($\sim 7\%$)
    - 760 GeV $\sim 6\%$ (EOYE seminar)

µ LWA
- Minimum $p_0$ for width $\sim 6\%$

CMS Preliminary

Local $p_0$ $\sim 2.6\sigma$

Global $p_0$ $\sim 2.3\sigma$

✓ Local $p_0$ $\sim 3.9\sigma$

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ATLAS and CMS high-mass diphoton resonance searches at 13 TeV
Limits

• **ATLAS**
  - Fiducial limit!
    - Isolation in fiducial volume definition
  - NWA

• **CMS**
  - RS Graviton

✓ Validity for LWA
  - Bias smaller than 10% (20%) for width
    0.4% (1.4%) $m_\chi$

**ATLAS Preliminary**

\[ \gamma_5 = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]

95% CL Upper Limit on $\sigma_{\text{fid}} \times \text{BR}$ [fb]

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**CMS Preliminary**

\[ \bar{\kappa} = 0.01 \]

95% CL limit on $\sigma(pp \rightarrow G \gamma \gamma)$ (fb)

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Conclusions (and perspectives?)

- **ATLAS and CMS reported mild excess in 13 TeV diphoton spectrum**
  - Around 750 (760) GeV
  - Largest local significance ~ 3.9 $\sigma$ ATLAS for width ~6%
  - **Global significance is really small! No reason to get (too) excited!**
    - ATLAS: 2.3 $\sigma$, CMS: 1.2 $\sigma$
    - CMS significance largest for smaller width

- **Analyses targeting different signal**
  - ATLAS $\rightarrow$ scalar ; CMS $\rightarrow$ graviton
  - Both analyses have (sub-optimal) sensitivity to other signal

- **What can we expect before 2016 data taking?**
  - ATLAS has graviton-like analysis still to be made public…
  - Scalar analysis from CMS?
  - Better calibration in both experiments
    - energy scale (mass and significance), resolution (significance)
  - Extended compatibly/combination with 8 TeV results?

- **Otherwise, more data needed to establish excess origin**
Compatibility/combination with 8 TeV results

- e.g. s-channel gluon-initiated process $\rightarrow$ parton-luminosity ratio = 4.7
8 TeV results for compatibility/combination

**ATLAS**
- arXiv:1407.6583
- Scalar NWA
- $m_X = [65-600]$ GeV
- Preliminary extension of analysis to estimate compatibility...

**CMS**
- CMS-PAS-EXO-12-045
- Graviton
- $m_G = 300$ GeV, 2.5 TeV
- Change in statistical treatment to enable combination

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ATLAS and CMS high-mass diphoton resonance searches at 13 TeV
Compatibility/combination with 8 TeV results

- **ATLAS**
  - 8 TeV analysis → scalar
  - Compatibility
    - NWA → 2.2
    - LWA (6%) → 1.4 σ

- **CMS**
  - 8 TeV analysis → graviton
  - Combination 8 TeV + 13 TeV
    - Local $p_0 \sim 3 \sigma$
    - Global $p_0 < 1.7 \sigma$

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![Graph showing compatibility and combination with 8 TeV results](image-url)