High mass diphoton resonance search at CMS

Josh Bendavid (Caltech)
for the CMS Collaboration

Caltech

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New resonances at high mass might decay to photons

- Fully reconstructed mass peak with excellent detector resolution in this case
- Standard Model backgrounds are relatively low
- SM Higgs $\rightarrow$ demonstrates our ability to observe such a signal even with relatively low S/B at lower mass

\[ m_{\gamma\gamma} = \sqrt{2E_1 E_2 (1 - \cos \theta_{12})} \]
The CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals

SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A

STEEL RETURN YOKE
~13000 tonnes

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

PRESHOWER
Silicon strips
~16m² ~137k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

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The CMS Detector

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g. Pion)
- Light green: Neutral Hadron (e.g. Neutron)
- Blue dashed: Photon

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
ECAL crystals lose and recover transparency under exposure to radiation
Monitored in situ with laser monitoring system, but still a major challenge for calibration
Lots of material in front of the ECAL
Diphoton Analysis Overview

- Diphoton search at CMS simple in principle: Search for a possibly narrow mass peak on a smoothly falling background
- Irreducible background from QCD di-photon production, reducible background from QCD $\gamma+\text{jets}$ and multi-jet production with one or more jets faking a photon
- Analysis categorized in EBEB and EBEE categories (EBEB category dominates expected sensitivity for all reasonable signal hypotheses)

\[
\begin{align*}
\bar{q} & \quad \gamma & \quad g & \quad \gamma & \quad q \\
q & \quad \gamma & \quad g & \quad \gamma & \quad q
\end{align*}
\]
Reminder: CMS 2015 (+8 TeV) Results

<table>
<thead>
<tr>
<th>Most Significant Excess</th>
<th>2015</th>
<th>2015 +8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (GeV)</td>
<td>760</td>
<td>750</td>
</tr>
<tr>
<td>Local Significance</td>
<td>2.9σ</td>
<td>3.4σ</td>
</tr>
<tr>
<td>Global Significance</td>
<td>&lt; 1σ</td>
<td>1.6σ</td>
</tr>
</tbody>
</table>

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From these results, need more data to exclude a statistical fluctuation

Interpreting as a signal, narrow resonance interpretation (slightly) favoured

Search analysis not designed to disentangle spin 0 vs spin 2 hypotheses
And now we have it! (more data that is)

(f) 2016

(g) Comparison across years

- Spectacular LHC performance in 2016
- Data for this (and most ICHEP) results included up to July 14-15 overnight fill $\rightarrow 12.9$ fb$^{-1}$ certified for physics
Diphoton search at CMS simple in principle: Search for a possibly narrow mass peak on a smoothly falling background

Simple event selection with two isolated high $p_T$ photons

Background modelling with parametric fit to the $m_{\gamma\gamma}$ distribution in data with appropriate functional form

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

and residual uncertainties

Modelling of a possible signal from simulation with data-driven corrections for selection efficiency and energy resolution

- Gluon-produced scalar and RS graviton models used as proxies for possible signal
- Several widths considered ranging from $\Gamma_X/m_X = 1.4 \times 10^{-4}$ (negligible compared to detector resolution) up to $5.6 \times 10^{-2}$

Search carried out for signal hypotheses between $m_X = 0.5$ and 4.5 TeV

Results extracted from maximum likelihood fit to $m_{\gamma\gamma}$ distribution
Event Selection

- Two isolated high $p_T$ photons:
  - $p_T > 75$ GeV offline,
  - $p_T > 60$ GeV at High Level Trigger
- Cut-based photon identification based on shower shapes and isolation (plus electron-veto)
- Photons selected in ECal Barrel ($|\eta| < 1.44$) and Endcap ($1.56 < |\eta| < 2.5$) regions
- Events split into barrel-barrel and barrel-endcap categories given different energy resolution and S/B
- Selection essentially unchanged from 2015 (no significant improvements found in blinded studies on 2016 data)

Beyond difference in acceptance, analysis is essentially insensitive to spin/parity of a possible signal
Photon Energy Reconstruction

- Reconstruction forms Superclusters extended in \( \phi \) to collect conversion legs/bremsstrahlung spread out by magnetic field
- After all crystal-level calibrations, BDT-based regression algorithm corrects energy for gaps/cracks/showering/pileup based on cluster position, shower shapes, and pileup inputs
Event Selection

- Photon identification efficiency measured with tag and probe from $Z \rightarrow ee$ events
- Electron veto efficiency measured in $Z \rightarrow \mu\mu\gamma$ events
- Scale factors flat in $p_T$, a few % below 1, used to correct signal MC
- Systematic uncertainty on efficiency of 6%
Energy Scale and Resolution Corrections

- Energy scale and resolution measured in $Z \rightarrow ee$ events
- Energy scale correction applied to data
- Energy resolution correction applied to signal MC
- Systematic uncertainties for energy scale and resolution included in signal model (1% uncertainty on energy scale given extrapolation in energy)

![Graphs showing distribution of events](a) EBEB

![Graphs showing distribution of events](b) EBEE
Background fit with $g(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\log(m_{\gamma\gamma})}$ as previously.

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Excess of 2015 not confirmed

Results well-consistent with background-only given LEE
Combination with 2015

Excess of 2015 not confirmed
Significance strongly diluted by combination with 2016 data
Combination with $2015 + 8$ TeV

- Surviving excess in full combination of 8 TeV and 13 TeV data is fairly modest
- Will continue to shrink if further data is consistent with background on average
“Having observed no statistically significant excess, we proceed to set limits”

This is ultimately what remains as the physics result
Compatibility estimated using profile likelihood ratio, assuming $\chi^2$ distribution with $N - 1$ degrees of freedom:

- Two-way compatibility for 2016 vs 2015: 2.7\sigma
- Three-way compatibility for 2016 vs 2015 vs 8 TeV: 2.4\sigma

These numbers can be considered “local” compatibilities, and have a LEE associated with them similar to that of the search (effectively looking for least compatible point across the whole mass range)

- Fitted signal cross sections compared in 2016 vs 2015 vs 8 TeV for a narrow spin-0 hypothesis with $m_\chi = 750$ GeV
Conclusions

- Diphoton resonance search performed for 12.9 fb⁻¹ of 13 TeV data from 2016
- Results compatible with background expectation
- Excess around 750 GeV from 2015 not confirmed
- Set exclusion limits for using both 13 TeV data and 13 TeV+8 TeV combination (8 TeV data now has negligible weight with assumed production cross section ratios)
Backup: 2016 Data vs 2015+8 TeV Signal

2016 data shown compared to plotted signal with $m_X = 750$ GeV and cross section fit from 2015+8 TeV combination

Background fit and associated uncertainties shown integrated over data bins.
Backup: 2016 Exclusion Limits (Spin-0)

(a) Narrow

(b) Medium

(c) Wide
Backup: 13 TeV (2015+2016) Exclusion Limits (Spin-0)

(a) Narrow

(b) Medium

(c) Wide
Backup: Background Composition (2015)

(a) EBEB

(b) EBEE

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Backup: Background Data vs MC (2015 $\gamma\gamma$ component)

(a) EEBEB

(b) EBEF

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Crystals are approximately $1 R^2_M$ at front face $\rightarrow \sim 95\%$ containment in 3x3 grid, $> 99\%$ in 5x5 grid.
\( R_9 = \frac{E_{3x3}}{E_{SC}} \) is an effective, but not 100% pure conversion tagging variable (electrons and photons treated separately, no explicit converted vs unconverted distinction)

Correction vs \( \eta \) has a non-trivial correlation with \( R_9 \) (and other shower profile variables)
Strong, but non-trivial relationship between size of correction and post-correction resolution (size of effect vs photon-to-photon fluctuations)

Per-photon resolution estimate mapped with the full granularity of the multidimensional space used to derive the corrections