BSM physics with photons at ATLAS and CMS: Resonances and BSM Higgs

Chiara Rovelli (INFN Roma)
on behalf of ATLAS and CMS Collaborations
BSM physics at LHC

The discovery of a SM-like Higgs Boson completed the Standard Model

Strong indications that SM is a low-energy expression of a more general theory
• Direct evidence from observation (dark matter, matter-antimatter…)
• Conceptual problems

Huge number of searches ongoing at LHC

2HDM, extra dimensions (resonance bump)
Dark Matter
SUSY
Contact Interactions
BSM Higgs sector
...

Contact Interactions...
BSM physics at LHC

The discovery of a SM-like Higgs Boson completed the Standard Model

Strong indications that SM is a low-energy expression of a more general theory
• Direct evidence from observation (dark matter, matter-antimatter…)
• Conceptual problems

Huge number of searches ongoing at LHC

2HDM, extra dimensions (resonance bump)
Dark Matter
SUSY
Contact Interactions
BSM Higgs sector
...

More on other topics in B.Schumm’s talk
Probing new physics with photons

Photons give a clear experimental signature

Striking signature in the detectors:
- Isolated energy deposit in the electromagnetic calorimeter
- No track associated in the inner detector
- Distinctive shape of the energy deposits

Very good energy resolution
High purity and large reconstruction efficiency
- Can be controlled with data-driven techniques

Relatively low SM backgrounds
- Almost soft QCD production at LHC
- Fake photons from misidentified objects

Perfect “tool” to search for new physics

Details in F. Couderc’s and K. Brendlinger’s yesterday talks
Searches for resonances

Many results available, only selected items here
Resonances at LHC

Generic prediction of several BSM theories

Production: 
- gluon fusion, 
- qq annihilation...

Spin-2: extra-dimensions (e.g. RS Gravitons)
Spin-1: W’, Z’ as in compositeness models
Spin-0: 2HDM (SM extensions with non-minimal Higgs sectors)

Where photons?
Bosonic decay channels
- X -> γγ, X-> Vγ, X->VV
Fermionic decay searches can profit from ISR photons
- E.g. X -> qq + γ
Bump searches

Reconstruct invariant mass of decay products and search for a “bump” on a smooth falling background
- experimentally robust, small systematics
- difficult for unknown backgrounds to mimic
⇒ *simple yet striking signature!*

General strategy:

Signal: simulation with inputs from data
- efficiencies, energy scale, resolution..

Background: directly measured in data
- accounting from mis-modeling in the fit

Among main challenges:
- Background understanding
- Objects reconstruction to maximize signal efficiency (e.g. pileup mitigation, isolation)
  - requiring a very good detector understanding

*ATLAS and CMS approaches leading to similar sensitivities*
High mass $\gamma\gamma$ resonances

Lots of interest in 2015-16 due to the (in)famous excess around 750 GeV

Events with 2 high $p_T$ isolated photons, selected by di-photon triggers

Dedicated photon selection
• tuned to be flat vs di-photon mass

BDT-based vertex reconstruction
• ~90% efficient in selecting the good vertex

Events categorization to enhance analysis sensitivity

Main backgrounds directly fitted from data:
• non-resonant $\gamma\gamma$
• mis-identified jets ($\gamma$+jet, jet+jet)

*Phys. Rev. D 98 (2018) 092001*
High mass X-$\rightarrow$$\gamma\gamma$: Results


Both ATLAS and CMS 2016 data not showing any excess

Interpretation:
Spin0 (extended Higgs sector) and Spin2 resonances (RS Graviton)

Comparable sensitivities for the experiments

CMS (2016 data):
- $m_G < 2.3$–4.6 TeV excluded @95% CL for $k = [0.01$–$0.2]$
- Limits on spin0 resonances ($\Gamma/m = 1.4\times10^{-4}$, $1.4\times10^{-2}$, $5.6\times10^{-2}$)
  and fiducial pp-$\rightarrow$$\gamma\gamma$ cross-section also set

ATLAS (2015 + 2016 data):
- $m_G < 4.1$ TeV excluded @95% CL for $k = 0.1$
- Limits on $\sigma \times BR$ @95%CL:
  Spin0: $11.4$–$0.1$ fb for $m_X = [200, 2700]$ GeV
  Spin2: $4.6$–$0.1$ fb for $m_G = [500, 5000]$ GeV
Low mass $\gamma\gamma$ resonances

Focus on narrow $X$ with $m_X < 110$ GeV

Similar strategy as for the high mass region

Main differences in background estimate:
- $Z/\gamma^* \rightarrow ee$ as additional background
  - electrons faking photons
  - shape and normalization constrained with data-driven $e\rightarrow\gamma$ measurement
- Impact of trigger thresholds at the low bound

Events categorization based on $\gamma$ conversions
- Different DY contamination

Main uncertainties: statistical + background fit
Low mass X -> γγ: Results

Both ATLAS and CMS focused on an additional SM-like Higgs boson

No significant excess observed

CMS (combined 2012 + 2016 data):
Maximum local (global) significance 2.8σ (1.3σ) at 95.3 GeV

<table>
<thead>
<tr>
<th>mX [GeV]</th>
<th>UL@95%CL σ x BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS Run2</td>
<td>65-110</td>
</tr>
<tr>
<td>CMS Run1</td>
<td>80-110</td>
</tr>
<tr>
<td>CMS Run2</td>
<td>70-110</td>
</tr>
</tbody>
</table>
Variety of $X \rightarrow Z/W/H+\gamma$ searches performed by ATLAS and CMS on 2015 + 2016 datasets

**Leptonic channels**

$Z \rightarrow ll$, $l = \text{electron or } \mu$

Good resolution, important at low $m_X$

**Hadronic channels**

Large-radius jet, light or b-quarks

Large BR, important at high $m_X$
X -> Vγ Resonances

Variety of X -> Z/W/H+γ searches performed by ATLAS and CMS on 2015 + 2016 datasets

**Leptonic channels**

Z -> ll, l = electron or μ
Good resolution, important at low m_X

**Hadronic channels**

Large-radius jet, light or b-quarks
Large BR, important at high m_X

*Phys. Rev. D 98 (2018) 032015*

Hadron decays of Z, W, H
Main backgrounds: γ+jets, W/Z (W, Z -> jj) +γ, ttbar+γ
Selection on m_V, fit to m_jγ
Events classification to enhance sensitivity

No significant excess observed
Limits set on a variety of spin 0/1/2 models
Low mass $X \rightarrow qq + \gamma$

Extensive searches for $X\rightarrow qq$ (dijets) performed at ATLAS and CMS

Large multi-jet background
Tight online requirements

Reduced sensitivity to low masses ($m_X < \sim 1$ TeV)

Effort to cover the whole mass range exploring new ideas
• Exploit ISR jet / photon

Lower trigger thresholds
Lower background

CMS-EXO-17-027
Search for a light $Z'$, $10 < m_{Z'} < 125$ GeV

Boosted event topology, $Z'$ recoiling against $\gamma$
• $q/q\bar{q}$ merged in a single large radius jet
• jet sub-structure to reduce backgrounds

Events selected by single photon trigger
• Lower masses accessible

No excess found: limits set
Summary of $X \rightarrow qq$ searches

ATLAS, boosted dijet

CMS, boosted dijet

CMS, boosted dijet + γ

15

CMS Preliminary

LHCP 2019

$Z' \rightarrow q\bar{q}$

$M_{Z'}$ [GeV]
X -> HH Resonances

SM HH production cross section very small
• 34fb, ~1000 times smaller than for single Higgs

Several BSM models predict heavy resonances decaying to HH

Channels with H->γγ are powerful:
small branching ratio
BUT clean signal extraction
• Thanks to narrow H->γγ peak

H->γγbb (CMS/ATLAS)
2 photons and 2 jets in final state
Discriminating variables: mγγ, mjj, mγjj

H->γγWW (ATLAS)
2 photons, 1e/μ, 2 jets (WW->lvqq)
Less sensitive

Main backgrounds: γγ continuum, single Higgs
X→HH→bbγγ results

No significant excess observed

CMS UL @95%CL on σ x BR(pp→X→HH→γγbb): 0.23-4.2 fb (m_X=250-750 GeV) depending on m_X and spin

ATLAS UL @95%CL on σ x BR(pp→X→HH): 0.12-1.14 pb (m_X=260-1000 GeV) for narrow spin-0

bbγγ final state: important role in the combination
BSM Higgs

Many results available, only selected items here
Higgs boson = key for BSM physics?

Higgs boson discovery opened the way to new searches for BSM

*Exotic h(125) decays*
SM Higgs has narrow width (~4 MeV): current limits allow for additional contributions

*Indirect evidence for BSM:* deviations from SM couplings

*Direct evidence for BSM:* observation of Higgs BSM decays
  - Higgs -> invisible
  - Higgs -> light (pseudo)scalars (H -> aa)
  - Flavour violating decays

*Exotic h(125) productions*
  - From new particles decay
  - Originated in SUSY chains
  - ....

*More Higgses?*
  - Additional EW singlet mixing with SM-h
  - Charged Higgs
  - ...
Higgs boson = key for BSM physics?

Higgs boson discovery opened the way to new searches for new physics

Exotic $h(125)$ decays
SM Higgs has narrow width (~4 MeV): current limits allow for additional contributions

Indirect evidence for BSM: deviations from SM couplings
Direct evidence for BSM: observation of Higgs BSM decays
- Higgs -> invisible
- Higgs -> light (pseudo)scalars ($H \rightarrow aa$)
- Flavour violating decays

Exotic $h(125)$ productions
- From new particles decays
  - Originated in SUSY chains
  - ... 

More Higgses?
- Additional EW singlet mixing with SM-h
- Charged Higgs
- ...

More on other topics in B.Schumm’s talk (or final states with photons not relevant)
Higgs decays to SM particles

Important to look at all possible decay modes

Very rare decays:
• Excess would indicate BSM physics
• Precision limited, slow increase with data

No surprise so far

Study of $H \rightarrow J/\psi \gamma$ decay
Probe of charm and bottom Yukawa coupling
Focus on clean di-$\mu$ final state
95%CL UL on BR $\sim 10^{-4}$

Study of $H \rightarrow ll\gamma$
Focus on clean di-$\mu$, di-ele final states
Observed (expected) 95%CL UL on
$\sigma \times$ BR $= 3.9 \ (2.0) \times$ SM

<table>
<thead>
<tr>
<th>channel</th>
<th>BR (SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow Z\gamma \rightarrow ll\gamma$</td>
<td>$1.01 \times 10^{-4}$</td>
</tr>
<tr>
<td>$H \rightarrow J/\psi \gamma$</td>
<td>$3.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\sim 5 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
Higgs exotic decays: h->aa

SM: single Higgs doublet $\Phi \rightarrow 1$ Higgs boson $h$

2HDM: two $\Phi_1\Phi_2$ => 5 Higgs bosons $h, H^0, A, H^+, H^-$

Interesting scenarios with extra singlet (2HDM+S) $a$ with $m_a < m_h$

• Significant $h\rightarrow aa$ possible

Final states with photons explored by ATLAS:

- $H\rightarrow aa\rightarrow 4\gamma$ (Run1)
- $H\rightarrow aa\rightarrow 2\gamma 2b$ (Run2)

Complementary searches

Become relevant when fermionic decays suppressed
Summary

Photons are a primary ingredient in searches for BSM physics thanks to the clean signature in the detector

Many searches for resonances ongoing in final states with photons at ATLAS and CMS

The Higgs Boson discovery opened additional paths to search for new physics, in an extended Higgs sector

So far all observations are compatible with the SM expectations Still O (100fb-1) of data to be analysed for many channels. Many more results coming with full Run2 dataset. Stay tuned!