HH/HY and VH Resonant Searches in ATLAS and CMS

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on behalf of ATLAS and CMS Collaborations

INFN Roma Tre

Higgs2022 - Pisa

11th November 2022
Physics Motivations

**Gluon-gluon fusion (ggF) resonant mode allows to probe heavy resonances produced through quark and gluon interactions**

- Production of a heavy spin 0 resonance X:
  - Can be e.g. a Randall-Sundrum radion or the 2HDM heavy CP-even Higgs boson
  - Narrow width (compared to experimental resolution) assumed as a signal benchmark
- Production of a heavy spin 2 resonance $G^x_{\text{KK}}$ (or X in CMS convention)
  - Spin-2 Kaluza-Klein gravitons with model-dependent width (3%-20% of $m_X$)
- Resonant production of HH in association with a vector boson

**New heavy resonances decaying into SM Higgs boson and a vector boson**

- These resonances are assumed to be either a new heavy vector boson ($Z'/W'$), or a heavy CP-odd scalar boson $A$
- A generic two-Higgs-doublet model (2HDM)
- Heavy Vector Triplet (HVT) [arXiv:1402.4431]

**X heavy particle decaying to the SM Higgs boson and a scalar particle**

- (Y in CMS convention or S in ATLAS convention)
- Results are interpreted in the context of the next-to-minimal supersymmetric standard model (NMSSM) and also in an extension of the SM with two additional singlet scalar fields (TRSM)

**VBF HH resonant production not covered in this talk, bonus reference**

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**Disclaimer**: covering only a limited set of analyses, focussing on the most recent ATLAS and CMS results, for more details refer to ATLAS and CMS public pages.

The non-resonant HH analyses covered in the presentation by Jason, Nicola, and resonant HH (ATLAS) by Bill.
**Experimental Overview**

### HH decay modes

<table>
<thead>
<tr>
<th></th>
<th>bb</th>
<th>WW</th>
<th>ττ</th>
<th>ZZ</th>
<th>WW</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb</td>
<td>33%</td>
<td>25%</td>
<td>7.4%</td>
<td>3.1%</td>
<td>0.26%</td>
</tr>
<tr>
<td>WW</td>
<td>25%</td>
<td>4.6%</td>
<td>2.5%</td>
<td>1.2%</td>
<td>0.10%</td>
</tr>
<tr>
<td>ττ</td>
<td>7.4%</td>
<td>2.5%</td>
<td>0.39%</td>
<td>0.34%</td>
<td>0.029%</td>
</tr>
<tr>
<td>ZZ</td>
<td>3.1%</td>
<td>1.2%</td>
<td>0.34%</td>
<td>0.076%</td>
<td>0.013%</td>
</tr>
<tr>
<td>WW</td>
<td>0.26%</td>
<td>0.10%</td>
<td>0.029%</td>
<td>0.013%</td>
<td>0.0005%</td>
</tr>
</tbody>
</table>

### HY decay modes

- **ATLAS**
  - HH to $bb\gamma\gamma$ final state: *Phys. Rev. D 106 (2022) 052001*
  - HH to $bb\pi\pi$ final state: *arXiv:2209.10910*
  - HH to $bbbb$ final state: *Phys. Rev. D 105 (2022) 092002*
  - Combination: *ATLAS-CONF-2021-052*

- **CMS**
  - HH to multilepton final state: *arXiv:2206.10268*
  - HH/HY to $bb\gamma\gamma$ final state: *CMS-PAS-HIG-21-011*

### VH decay modes

- **ATLAS**
  - Semi-leptonic VH search: *arXiv:2207.00230*
  - Vhh search: *arXiv:2210.05415*
  - Generic search for Y to XH: *ATLAS-CONF-2022-045*

- **CMS**
  - All hadronic VH search: *arXiv:2210.00043*
  - HY to $bbbb$ final state: *arXiv:2204.12413*

- **Extended Higgs sector**
  - Search for new particles in an extended Higgs sector with four b quarks in the final state: *arXiv:2203.00480*
HH to $b\bar{b}\gamma\gamma$ search - **ATLAS**

**Candidate event HH to $b\bar{b}\gamma\gamma$**

Two reconstructed photons ($\gamma\gamma$) coming from a Higgs candidate

Two reconstructed bottom quark jets ($b\bar{b}$) coming from a Higgs candidate

4 body mass = 625 GeV

**Fully reconstructable final state**
HH to $b\gamma\gamma$ search - **ATLAS**

- Di-photon triggers used to allow to probe low $m_X$ values, lepton veto

**Object Selection**
- Excellent $m_{\gamma\gamma}$ resolution
- Tight and isolated, $m_{\gamma\gamma}$ in [105-160] GeV
- Large BR
- 2 b-jets, b-jets corrections applied
- Muon in jet + BCal

**Event Categorisation**
- $m^{*}_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV

**MVA approach**
- Single BDT for all signal hypotheses (mass dependent cut)

**Modelling**
- Simultaneous likelihood fit to all categories
- $\sigma$ vs $m_X$
- Statistically limited with the current dataset

**Spurious signal systematic uncert.**
- Potential bias coming from the choice of the background modelling accounted for in systematic uncertainties

- ATLAS Preliminary
  - $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
  - $m_{H} = 300$ GeV
  - $m_{b\gamma\gamma}$
  - $m_{\gamma\gamma}$
  - $m_{bb\gamma\gamma}$
  - $m_{bb}$
  - $m_{\gamma\gamma}$
  - $m_{bb\gamma\gamma} + 250$ GeV

- Event categorisation
  - Data
  - HH: Single Higgs
  - $\gamma\gamma$: Single Higgs
  - jet: Single Higgs
  - $\gamma\gamma$: Single Higgs
  - jet: Single Higgs
  - $m_{bb\gamma\gamma}$

- ATLAS Simulation
  - $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
  - $m_{H} = 300$ GeV
  - $m_{b\gamma\gamma}$
  - $m_{\gamma\gamma}$
  - $m_{bb\gamma\gamma}$
  - $m_{bb}$
  - $m_{\gamma\gamma}$
  - $m_{bb\gamma\gamma} + 250$ GeV

**Phys. Rev. D 106 (2022) 052001**
HH/HY to $b\bar{b}\gamma\gamma$ search - CMS

Candidate event HH to $b\bar{b}\gamma\gamma$

Fully reconstructable final state
**HH/HY to $b\bar{b}\gamma\gamma$ search - CMS**

- Di-photon triggers used to allow to probe low $m_X$ values, lepton veto

- Excellent $m_{\gamma\gamma}$ resolution
- Tight and isolated $b$-jets
- Large BR
- Energy corrections applied

**Object Selection**

- $70 < m_0 < 190$ (1200) GeV
- MVA approach
- Using $b$-jet ID, photon ID and kinematic variables

**Event Categorisation**

- Statistical analysis
  - $\sigma$ vs $m_X - m_Y$
- Modelling discriminating variable
- Extract signal from 2D fit: $m_Y$ vs $m_{H1}$, in windows of $m_X$

- Resonant $m_X$ and $m_Y$ hypotheses differ in kinematics
  - BDT is trained for six different mass ranges, based on boost factor $m_X/(m_{H1} + m_Y)$:
    - 3 ranges in $m_X$ ($m_X < 500$ GeV, $500 < m_X < 700$ GeV and $m_X > 700$ GeV)
    - 3 ranges in $m_Y$ ($m_Y < 300$ GeV, $300 < m_Y < 500$ GeV, and $m_Y > 500$ GeV)

- Statistically limited with the current dataset
### Results: HH to $b\bar{b}\gamma\gamma$ final state

**ATLAS**
- X resonance decaying to HH
- Narrow width approximation
- Spin 0 hypothesis
- Upper limit on $\sigma(pp\rightarrow X\rightarrow HH)$

The expected limit on the cross section improves overall by a factor of 2-3 wrt the partial Run 2 analysis.

<table>
<thead>
<tr>
<th>Mass Hypothesis</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>640 fb</td>
<td>391 fb</td>
</tr>
<tr>
<td>Min</td>
<td>44 fb</td>
<td>46 fb</td>
</tr>
</tbody>
</table>

25 mass hypothesis for $251 < m_X < 1000$ GeV

**CMS**
- X resonance decaying to HH or SH (results in the next slide)
- Spin 0 (narrow width approximation) and spin 2 hypotheses

Upper limit on $\sigma(pp\rightarrow X\rightarrow HH) \times BR( HH \rightarrow b\bar{b}\gamma\gamma)$

<table>
<thead>
<tr>
<th>Spin</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>0.06 fb</td>
<td>0.06 fb</td>
</tr>
<tr>
<td>Min</td>
<td>0.78 fb</td>
<td>0.65 fb</td>
</tr>
</tbody>
</table>

These results exclude masses up to 600 GeV for spin 0 bulk radion signal at $\Lambda_R = 6$ TeV and up to 850 GeV for spin 2 bulk KK graviton signal with coupling factor $\kappa/M_{pl} = 0.5$. 

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**Graphs**

ATLAS Preliminary

*Phys. Rev. D 106 (2022) 052001*

CMS Preliminary

*CMS-PAS-HIG-21-011*
Results: HY to $b\bar{b}\gamma\gamma$ final state - CMS

Excess observed:
$M_X = 650$ GeV $M_Y = 90$ GeV
3.8σ local 2.6σ global
HH to $bb\tau\tau$ search - **ATLAS**

**Candidate event HH to $bb\tau\tau$**

4 body mass = 680 GeV

Good compromise between BR and clean final state
HH to $bb\tau\tau$ search - ATLAS

Complex trigger strategy using a mixture of hadronic single-/di-$\tau$ triggers and lepton/lepton+ $\tau$ triggers

- Single Tau Trigger & Di-Tau Trigger for $\tau_{\text{had}}\tau_{\text{had}}$, Single Lepton Trigger (SLT) and Lepton+Tau Trigger (LTT) in $\tau_{\text{lep}}\tau_{\text{had}}$

Object Selection

Hadronic and semi-leptonic

b-jets corrections applied

Compromise

MV A in 3 categories:
1. $\tau_{\text{had}}\tau_{\text{had}}$
2. $\tau_{\text{lep}}\tau_{\text{had}}$ (e/$\mu$ & opp. charged $\tau$) LTT SLT
3. Control region for $Z$+HF (m$ll$)

Event Categorisation

Backgrounds are estimated using a mix of simulation and control samples in data

Object Selection

Hadronic and semi-leptonic

b-jets corrections applied

Compromise

MV A in 3 categories:
1. $\tau_{\text{had}}\tau_{\text{had}}$
2. $\tau_{\text{lep}}\tau_{\text{had}}$ (e/$\mu$ & opp. charged $\tau$) LTT SLT
3. Control region for $Z$+HF (m$ll$)

Event Categorisation

Backgrounds are estimated using a mix of simulation and control samples in data

Neural Network (NN) to construct a discriminant, which is then fitted

NN is parameterized on m$HH$ for optimal performance across the whole range

arXiv:2209.10910

HH and VH Resonant Searches - Higgs2022

Adele D’Onofrio - INFN Roma Tre - 11th November 2022
Results: HH to $b\tau\tau$ final state

**ATLAS**
- X resonance decaying to HH
- Narrow width approximation
- Spin 0 hypothesis

Upper limit on $\sigma(pp\rightarrow X\rightarrow HH)$

Mass hypothesis for $251 < m_X < 1600\text{GeV}$

The largest (very broad) excess is observed at a resonance mass of 1 TeV, with a local (global) significance of $3.1\sigma (2.0\sigma)$

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Expected</th>
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<tbody>
<tr>
<td>Max</td>
<td>900 fb</td>
<td>840 fb</td>
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<tr>
<td>Min</td>
<td>21 fb</td>
<td>12 fb</td>
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</table>

**CMS**
- (Not covered here) Semi-boosted analysis: JHEP11(2021)057
- NMSSM framework

Upper limit on $\sigma(pp\rightarrow X\rightarrow Hh_s)$

<table>
<thead>
<tr>
<th></th>
<th>CL$_{\text{exp}}$ (m(X)=320 GeV)</th>
<th>CL$_{\text{exp}}$ (m(X)=1000 GeV)</th>
<th>CL$_{\text{exp}}$ (m(X)=1600 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>986 fb</td>
<td>44 fb</td>
<td>117 fb</td>
</tr>
</tbody>
</table>
HH to $b\bar{b}b\bar{b}$ search - *ATLAS*

*ATLAS Experiment*

Candidate event HH to $b\bar{b}b\bar{b}$

Run: 350013  
Event: 1556168518  
2018-05-11 01:39:26 CEST

4 body mass = 1023 GeV

Highest BR but challenging backgrounds in the final state

*Phys. Rev. D 105 (2022) 092002*
HH to $bbbb$ search - **ATLAS**

- Largest BR, but large multi-jet backgrounds and challenging combinatorics
- 12 different b-jet & trigger settings for resolved (eff up to 80%), single jet trigger for boosted (eff ~80%)
- Resolved and boosted analyses, combined in the overlap region

**Resolved**
(251 GeV – 1.5 TeV) 4 b-tagged $b\bar{b}$

**Boosted**
(900 GeV – 3 TeV) VR
track-jets for b-tagging, topo cluster jets for large R jets with $\Delta R = 1.0$

b-jets corrections applied

**Object Selection**
- Resolved
  ($251$ GeV – 1.5 TeV) 4 b-tagged $b\bar{b}$, 4 jets, $\Delta R = 0.4$
- Boosted
  ($900$ GeV – 3 TeV) VR
  track-jets for b-tagging, topo cluster jets for large R jets with $\Delta R = 1.0$
  b-jets corrections applied

**BDT to pair jets from Higgs (65-100% eff)**
- $4b$ category is used for signal hypotheses with $m(X/G^*_X) \leq 3$ TeV
- $2b$ category is used for signal hypotheses with $m(X/G^*_X) \geq 2$ TeV
- For resonance masses in the range 900 GeV–1.5 TeV, the resolved and boosted channels are fitted simultaneously

**Event Categorisation**
- Resolved
  - $4b$ category is used for signal hypotheses with $m(X/G^*_X) \leq 3$ TeV
- Boosted
  - $2b$ category is used for signal hypotheses with $m(X/G^*_X) \geq 2$ TeV

**Background Modelling**
- Dominated by multi-jet + $tt$
- Data-driven multi-jet & MC-driven $tt$
- Fit $m_{H^+}$ spectrum to search for a resonant bump

**Statistical analysis**
- Phys. Rev. D 105 (2022) 092002

Adele D’Onofrio - INFN Roma Tre - 11th Novembre 2022
Results: HH to $b\bar{b}b\bar{b}$ final state

**ATLAS**
- Narrow width approximation for spin 0 search
- Widths ranging from 3% to 20% spin 2 hypothesis

Upper limit on $\sigma(pp\rightarrow X\rightarrow HH)$

Mass hypothesis for $251 < m_X < 5000$ GeV
- For signal masses up to 3 TeV, the limits are computed using asymptotic formulae
- At higher masses the limits are computed by sampling pseudo-experiments

The largest excess is observed at a resonance mass of 1.1 TeV, with a local (global) significance of $2.3\sigma (0.4\sigma)$ for spin 0 signal and a local (global) significance of $2.5\sigma (0.8\sigma)$ for spin 2 signal

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Obs. (fb)</th>
<th>Exp. lim. (fb)</th>
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<tbody>
<tr>
<td>1000</td>
<td>9.74</td>
<td>5.12</td>
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<tr>
<td>1100</td>
<td>3.37</td>
<td>2.20</td>
</tr>
<tr>
<td>1200</td>
<td>2.80</td>
<td>1.72</td>
</tr>
<tr>
<td>1300</td>
<td>3.24</td>
<td>1.10</td>
</tr>
<tr>
<td>1500</td>
<td>1.46</td>
<td>0.53</td>
</tr>
<tr>
<td>2000</td>
<td>0.47</td>
<td>0.42</td>
</tr>
<tr>
<td>2500</td>
<td>0.26</td>
<td>0.46</td>
</tr>
<tr>
<td>3000</td>
<td>0.29</td>
<td>0.31</td>
</tr>
</tbody>
</table>

**CMS**
- (Not covered here) Semi-boosted analysis: CMS-B2G-20-004
- Narrow width approximation for spin 0 search
- Spin 2 hypothesis

Upper limit on $\sigma(pp\rightarrow X\rightarrow HH) \times \text{BR}(HH\rightarrow b\bar{b}b\bar{b})$

Mass hypothesis for $1000 < m_X < 3000$ GeV

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>Obs. (fb)</th>
<th>Exp. lim. (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>4.4</td>
<td>3.47</td>
</tr>
<tr>
<td>1100</td>
<td>2.13</td>
<td>2.12</td>
</tr>
<tr>
<td>1200</td>
<td>1.42</td>
<td>1.54</td>
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<tr>
<td>1300</td>
<td>1.76</td>
<td>1.20</td>
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<td>1500</td>
<td>1.37</td>
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<td>2000</td>
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<td>0.28</td>
</tr>
<tr>
<td>3000</td>
<td>0.19</td>
<td>0.31</td>
</tr>
</tbody>
</table>
HY to $b\bar{b} b\bar{b}$ search - *CMS*

Candidate event HH to $b\bar{b} b\bar{b}$

Highest BR but challenging backgrounds in the final state
HY to $bbbb$ search - CMS

- Large BR, but large multi-jet backgrounds and challenging combinatorics
- Hadronic triggers

Object Selection

- Boosted event topology: X and Y reconstructed as large-radius jets (R=0.8)

Event Categorisation

1. ParticleNet convolutional graph neural network for H/Y $\rightarrow$ bb vs. QCD jet classification for large-R jets
2. Mass de-correlation with dedicated training techniques $\rightarrow$ no mass sculpting

Background Modelling

- Background dominated by multi-jet and < 10% $tt$
- Modeling of QCD bkg from data and of $tt$ from simulation
  - Data control regions for validation & to improve data/MC agreement

Statistical analysis & Results

- 2D fit to reconstruct $m_X$ and $m_Y$ of signal candidates
HH to multi lepton search - *CMS*

Candidate event HH

*arXiv:2206.10268*
HH to multi lepton search - CMS

- Reasonable BR, very good at low mass
- Combination of lepton and tau triggers

HH → VVVV, HH → VVττ and HH → ττττ final states

1. Seven channels with multiple l = e, μ, τ
2. Signal extraction on BDT classifier output:
   - Parametrized BDT on resonant mass for spin 0/spin 2 scenarios
   - 19 resonant masses in range 250 – 1000 GeV

Signal extraction
- Fit to 7 BDT outputs/year for given mass
- Two control regions/year for WZ/ZZ backgrounds included
- No signal yet → Asymptotic limits

Event Categorisation

HH (1 pb) → X (13 TeV)

- Observed (expected) limits on \( \sigma(pp \rightarrow X \rightarrow HH) \): 0.18 to 0.90 (0.08 to 1.07) pb

Results
**X to HH search - Summary - ATLAS**

**Upper limit on \( \sigma(pp \to X \to HH) \)**

\[ \sigma(X \to HH) \]  

- \( b\bar{b}\gamma\gamma \) dominates the sensitivity at low \( m_X \)
- \( bbb\bar{b} \) dominates the sensitivity for high values of \( m_X \)
- \( b\bar{b}\tau\tau \) dominates the sensitivity for medium values of \( m_X \)
$Vhh$ & $VH$ searches
**Vhh search - ATLAS**

- First analysis targeting Vhh final state. Two signal scenarios are considered:
  1. BDT categorisation
  2. Fit on BDT output

**Event Categorisation & Fit strategy**

**Results & Interpretations**

1. **VH, H—>hh results**
   - No significant excess.
   - Largest deviation:
     - WH at 315 GeV: local (global) significance 2.5 (1.3) $\sigma$.
     - ZH at 550 GeV: local (global) significance 2.7 (1.3) $\sigma$.

**Object Selection**

- 0L, 1L, 2L channels targeting vvbvbv, lvbvbv, llbvbv final states
- Lepton triggers

**0 & 2 Leptons**

- $\ell^+ \ell^-$ hypothesis
- Data points and fitted distributions

**1Lepton**

- $\ell^+$ hypotesis
- Data points and fitted distributions

**HH and VH Resonant Searches - Higgs2022**

ArXiv:2210.05415
Vhh search - ATLAS

First analysis targeting Vhh final state. Two signal scenarios are considered:

2. A to ZH, H→hh
   - Narrow width A boson
     Largest deviation: \((m_A, m_H) = (800, 300)\) Local: 3.6 \(\sigma\) Global: 1.6 \(\sigma\)
   - Large-width (20\%) A boson
     Largest deviation: \((m_A, m_H) = (420, 320)\) Local: 3.8 \(\sigma\) Global: 2.8 \(\sigma\)

3. A to ZH results are interpreted as constraints in the 2HDM parameter space
   - \(m_A\) – mass of the A boson.
   - \(m_H\) – mass of the heavy H boson.
   - \(\tan \beta\) – ratio of the vacuum expectation values of the two doublets.
   - \(\cos(\beta - \alpha)\) – with \(\alpha\) as the mixing angle of H and h.
VH search - **ATLAS**

**Object Selection**

**Analysis Strategy**

**Results**

*ATLAS*

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

\( Z' \) combined (0L+2L) limit

- 95% CL limit
- Observed limit
- Expected limit
- Expected \( \pm 1 \) s.d.
- Expected \( \pm 2 \) s.d.
- HVT Model A, \( g_3 = 1 \)
- HVT Model B, \( g_3 = 3 \)
- Expected limit (0L)
- Expected limit (2L)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

\( W' \) combined (0L+1L) limit

- 95% CL limit
- Observed limit
- Expected limit
- Expected \( \pm 1 \) s.d.
- Expected \( \pm 2 \) s.d.
- HVT Model A, \( g_3 = 1 \)
- HVT Model B, \( g_3 = 3 \)
- Expected limit (0L)
- Expected limit (1L)

*arXiv:2207.00230*

HVT and 2HDM Interpretations
(All had.) VH search - **CMS**

- This search covers also VV channels, not discussed here

Object Selection

- Tagging (2q) final states (w. bb category) using DeepAK8 tagger

Analysis Strategy

- QCD model adapts to data, uses MC-based gaussian kernel templates with increased statistics

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**Results**

Most stringent limits on V' up to 4.8 TeV.

Also, first VBF limits (no exclusion) on all-hadronic search - see backup.

Up to 60% better sensitivity than 2016+2017 analysis
Generic search for Y to XH - **ATLAS**

**Analysis Strategy**

Tested signals with \(m_Y\) between 1.5 and 6 TeV and \(m_X\) between 65 and 3000 GeV

**Results**

- **ATLAS Preliminary**
  \(\sigma = 13\) TeV, 139 fb\(^{-1}\)
  - Expected CLs

- **56\% WP \((\sqrt{s}=13\) TeV, 139 fb\(^{-1}\)**
  - Observed CLs

**Object Selection**

\[D_{Hbb} = \ln \frac{p_{\text{Higgs}}}{f_{\text{top}} \cdot p_{\text{top}} + (1 - f_{\text{top}}) \cdot p_{\text{multijet}}}\]

**X/H Candidate Large-R Jet Selection**

- X-Tagging
- H-Tagging & Background Estimation

- **Anomaly**
  - Two-prong (merged)
  - Two-prong (resolved)

**All hadronic final state**

**ATLAS-CONF-2022-045**

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Extended Higgs sector searches $bbbb$ - CMS

The analysis is restricted to the case where the mass ratio of the resonance and the scalar bosons is such that each pair of $b$ quarks is reconstructed as a single large-radius jet.

These are the first limits on this process, and range between 30 and 1 fb for a $\phi$ mass in the range 25-100 GeV and an $X$ mass in the range 1-3 TeV.
Conclusions

- Full Run 2 results presented for ATLAS and CMS
- HH/HY and Vh searches presented
- Great complementarity among the channels
- No significant excess observed
- Stay tuned for Legacy Run 2 results
- Run 3 just started!!!
Back - up Slides
HH to $b\bar{b}γγ$ search - ATLAS

- At least 2 photons: Identified (Tight WP)
- Calo- and Track-isolated within a cone of $ΔR = 0.2$ $E_T^{\text{ISO}} < 0.065 \cdot E_T$ and $p_T^{\text{ISO}} < 0.05 \cdot E_T$
- $105$ GeV < $m_{γγ}$ < $160$ GeV
- $E_T/m_{γγ}$ > 0.35 and 0.25
- $γγ$ vertex

- Less than 6 central jets
- PFlow jets, anti-kt R=0.4, tight JVT applied
- Exactly 2 $b$-jets
  - DL1r 77% WP, b-jet energy corrections applied

BDT Input Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon-related kinematic variables</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\gamma\gamma}$</td>
<td>Transverse momentum and rapidity of the diphoton system</td>
</tr>
<tr>
<td>$Δφ_{γγ}$ and $ΔR_{γγ}$</td>
<td>Azimuthal angle and $ΔR$ between the two photons</td>
</tr>
<tr>
<td>Jet-related kinematic variables</td>
<td></td>
</tr>
<tr>
<td>$m_{b\bar{b}}, p_T^{b\bar{b}}$ and $γ_{b\bar{b}}$</td>
<td>Invariant mass, transverse momentum and rapidity of the $b$-tagged jets system</td>
</tr>
<tr>
<td>$Δφ_{b\bar{b}}$ and $ΔR_{b\bar{b}}$</td>
<td>Azimuthal angle and $ΔR$ between the two $b$-tagged jets</td>
</tr>
<tr>
<td>$N_{jets}$ and $N_{b-jets}$</td>
<td>Number of jets and number of $b$-tagged jets</td>
</tr>
<tr>
<td>$H_T$</td>
<td>Scalar sum of the $p_T$ of the jets in the event</td>
</tr>
<tr>
<td>Diphon+di-jet-related kinematic variables</td>
<td></td>
</tr>
<tr>
<td>$m_{bbγγ}$</td>
<td>Invariant mass of the diphoton plus $b$-tagged jets system</td>
</tr>
<tr>
<td>$ΔX_{γγ,b}\bar{b}$, $Δφ_{γγ,b\bar{b}}$ and $ΔR_{γγ,b\bar{b}}$</td>
<td>Distance in rapidity, azimuthal angle and $ΔR$ between the diphoton and the $b$-tagged jets system</td>
</tr>
<tr>
<td>Missing transverse momentum variables</td>
<td></td>
</tr>
<tr>
<td>$E_{miss}$</td>
<td>Missing transverse momentum</td>
</tr>
</tbody>
</table>

2 BDTs to separate signal vs continuum and single Higgs backgrounds, scores combined in BDT$_{\text{tot}}$

$$BDT_{\text{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{\left(\frac{BDT_{\text{loose}} + 1}{2}\right)^2 + \left(\frac{BDT_{\text{singleH}} + 1}{2}\right)^2}$$
HH to $bb\gamma\gamma$ search - ATLAS

- Fit $m_{\gamma\gamma}$ distribution to a double-sided Crystal Ball (for both single Higgs backgrounds and di-Higgs signal)
- Continuum $\gamma\gamma$ background modelled as exponential function in $m_{\gamma\gamma}$
- Potential bias coming from the choice of the background modelling accounted for in systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Nonresonant analysis $HH$</th>
<th>Resonant analysis $m_X = 300$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
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<td></td>
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<tr>
<td>Photon energy resolution</td>
<td>Norm. + Shpe</td>
<td>0.4</td>
<td>0.6</td>
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<tr>
<td>Jet energy scale and resolution</td>
<td>Normalization</td>
<td>&lt; 0.2</td>
<td>0.3</td>
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<tr>
<td>Flavor tagging</td>
<td>Normalization</td>
<td>&lt; 0.2</td>
<td>0.2</td>
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<tr>
<td>Theoretical</td>
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<tr>
<td>Factorization and renormalization scale</td>
<td>Normalization</td>
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<td>&lt; 0.2</td>
</tr>
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<td>Parton showering model</td>
<td>Norm. + Shpe</td>
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<td>Heavy-flavor content</td>
<td>Normalization</td>
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<td>&lt; 0.2</td>
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<tr>
<td>$B(H\rightarrow \gamma\gamma, bb)$</td>
<td>Normalization</td>
<td>0.2</td>
<td>&lt; 0.2</td>
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<tr>
<td>Spurious signal</td>
<td>Normalization</td>
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<td>3.3</td>
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</table>
HH/HY to $b\phi\gamma\gamma$ search - **CMS**

### Event pre-selection

<table>
<thead>
<tr>
<th>Variable</th>
<th>Requirement</th>
<th>Variable</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>leading photon $p_T$</td>
<td>$m_{\gamma\gamma}/3$</td>
<td>$p_T$</td>
<td>$&gt; 25$ GeV</td>
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<tr>
<td>subleading photon $p_T$</td>
<td>$m_{\gamma\gamma}/4$</td>
<td>$\Delta R_{\gamma\gamma}$</td>
<td>$&gt; 0.4$</td>
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<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
<td>$&lt; 2.5$</td>
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<tr>
<td>$m_{\gamma\gamma}$</td>
<td>100–180 GeV</td>
<td>$n_{jets}$</td>
<td>$&gt; 1$</td>
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<tr>
<td>tfH discriminant</td>
<td>$\geq 0.26$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Event selection

- **$M_X < 500$ GeV**
  - CAT 0 = 0.63–1.0
  - CAT 1 = 0.33–0.63
  - CAT 2 = 0.17–0.33
- **$M_X = [500–700]$ GeV**
  - CAT 0 = 0.60–1.0
  - CAT 1 = 0.35–0.60
  - CAT 2 = 0.18–0.35
  - MX > 700 GeV
    - CAT 0 = 0.40–1.0
    - CAT 1 = 0.29–0.40
    - CAT 2 = 0.13–0.29
- **$M_X > 700$ GeV**
  - CAT 0 = 0.50–1.0
  - CAT 1 = 0.30–0.50
  - CAT 2 = 0.21–0.30

---

**Modelling discriminating variable**

- Fit $m_\phi$ distribution to a double-sided Crystal Ball (for both single Higgs backgrounds and di-Higgs signal)
- Non-resonant background from envelope-method
- Resonant background from gaussian model
Backgrounds are estimated using a mix of simulation and control samples in data:

- **Top with real $\tau_{\text{had}}$**: Use MC simulation
- **Top/multijet with fake $\tau_{\text{had}}$**: Use a “fake factor” method to extrapolate from control regions
  - Inverting the $\tau_{\text{ID}}$ and/or other cuts for samples enriched in “fakes”
- **$Z + \text{heavy flavor}$**: Use MC simulation, but correct it using a data control region with $Z \rightarrow \ell\ell$ selection
- **Other small backgrounds (single Higgs, diboson, etc.)**: Use MC simulation
HH to $b\bar{b}b\bar{b}$ search - ATLAS

- Largest BR, but large multi-jet backgrounds and challenging combinatorics
- 12 different b-jet & jet triggers for resolved, single jet trigger for boosted
- Resolved and boosted analyses, combined in the overlap region

**Object Selection**

1. b-tag using variable-radius subjets constructed from their associated tracks
2. At very high resonance masses, even these get merged.
3. Most of the procedure follows the resolved strategy closely

**Event Categorisation**

- Learn in CR
- Predict in SR

**Boosted (900 GeV – 3 TeV) VR track-jets for b-tagging, topo cluster jets for large R jets with $\Delta R=1.0$

**Background Modelling**

- Bkg dominated by multi-jet + up to 30% $t\bar{t}$
- Data-driven multi-jet & MC-driven $t\bar{t}$ (data-driven corrections in 2/3 b region)

**Statistical analysis**

- fit $m_{HH}$ spectrum to search for a resonant bump

---

HH and VH Resonant Searches - Higgs2022

Adele D’Onofrio - INFN Roma Tre - 11th November 2022
HH to $bbbb$ search - ATLAS

- Largest BR, but large multi-jet backgrounds and challenging combinatorics
- 12 different b-jet & jet triggers for resolved (eff up to 80%), single jet trigger for boosted (eff ~80%)
- Resolved and boosted analyses, combined in the overlap region

1. 4b signal region (based on the $H$ candidate masses)
2. 2b category for bkg estimate
3. BDT to pair jets from Higgs (65-100% eff)

Resolved
(251 GeV – 1.5 TeV) 4 b-tagged $\Delta R=0.4$ jets
b-jets corrections applied

Object Selection

Background Modelling

Bgection Categorisation

Resolved

Phys. Rev. D 105 (2022) 092002
HY to $bbbb$ search - CMS

- Large BR, but large multi-jet backgrounds and challenging combinatorics
- Hadronic triggers

1. ParticleNet convolutional graph neural network for $H/Y \rightarrow bbb$ vs. QCD jet classification for large-R jets
2. Mass de-correlation with dedicated training techniques $\rightarrow$ no mass sculpting

Event Categorisation
HH Combination - CMS

Resonant HH comb with 2016 data (~36 fb⁻¹)

- No significant excess found

Upper limit on $\sigma(pp \rightarrow X \rightarrow HH)$

spin 0 resonance

spin 2 resonance
# Searches in the $b\bar{b}b\bar{b}$ final state

<table>
<thead>
<tr>
<th></th>
<th>Resolved (2+2 jets)</th>
<th>Boosted (1+1 jets)</th>
<th>Semi-resolved (2+1 jets)</th>
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<tbody>
<tr>
<td>$ggF \rightarrow YH$</td>
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<tr>
<td>CMS</td>
<td>–</td>
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<td></td>
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<td></td>
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<td>$ggF \rightarrow HH$</td>
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<td></td>
<td>260 GeV to 1.2 TeV</td>
<td>1-3 TeV</td>
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<td>[JHEP 08 (2018) 152]</td>
<td>[CMS-B2G-20-004]</td>
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HH/HY to multi lepton search - CMS

**HH/HY to multi lepton search - CMS**

**HH → Multilepton 138 fb⁻¹ (13 TeV)**

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>4τₜ</th>
<th>1ℓ + 3τₜ</th>
<th>2ℓss</th>
<th>2ℓ + 2τₜ</th>
<th>3ℓ</th>
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</tbody>
</table>

Solid (dashed) lines: observed (median expected) limits

---

**HH → Multilepton 138 fb⁻¹ (13 TeV)**

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<thead>
<tr>
<th>Hypothesis</th>
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