Searches for Higgs boson pair production with the full LHC Run 2 dataset and HL-LHC prospects in ATLAS

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On behalf of ATLAS collaboration
2022.01.11
Introduction

\[ \mathcal{L}_{\text{Higgs}} = (D_\mu \Phi) \dagger (D^\mu \Phi) - \left( \mu^2 \Phi \dagger \Phi + \lambda (\Phi \dagger \Phi)^2 \right) \]

After EW symmetry breaking

\[ \mathcal{L} \supset - \left( \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 \right) \]

**ggF** \( \sigma_{\text{SM}} = 31.05 \text{ fb} \)

Challenging cross section:

~ 1k smaller than 1H

**VBF** \( \sigma_{\text{SM}} = 1.73 \text{ fb} \)
HH decay channels & Run 2 publications

<table>
<thead>
<tr>
<th></th>
<th>bb</th>
<th>WW</th>
<th>ττ</th>
<th>ZZ</th>
<th>YY</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb</td>
<td>34%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td></td>
<td>25%</td>
<td>4.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ττ</td>
<td>7.3%</td>
<td>2.7%</td>
<td>0.39%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>3.1%</td>
<td>1.1%</td>
<td>0.33%</td>
<td>0.069%</td>
<td></td>
</tr>
<tr>
<td>YY</td>
<td>0.26%</td>
<td>0.10%</td>
<td>0.028%</td>
<td>0.012%</td>
<td>0.0005%</td>
</tr>
</tbody>
</table>

*Latest results include improvements on b-tagging and τ-ID. Fruitful on-going work on the other channels not presented.

**Early results (36 fb\(^{-1}\)):**
bbbb, bbττ, bbγγ, 4W, WWγγ, bbWW

**Full Run 2 (126-139 fb\(^{-1}\)):**
- bb γγ: HDBS-2018-34
**Signal regions (SRs) defined with:**
- Multi-class Deep Neural Network outputs
- Lepton flavor (ee/μμ or eμ)

**Main backgrounds:**
- top
- Z/γ*+HF
- diboson, single Higgs

**Event topology:**
- At least 2 b-jets
- 2 opposite-sign leptons (e, μ)
- Missing $E_T$
- $m_{ll} \in [20, 60]$ GeV
- $m_{bb} \in [110, 140]$ GeV

**Signal regions (SRs) defined with:**
- Multi-class Deep Neural Network outputs
  $$d_{HH} = \ln \left( \frac{p_{HH}}{p_{Top} + p_{Z\ell\ell} + p_{Z\tau\tau}} \right)$$
- Lepton flavor (ee/μμ or eμ)

**Dedicated control regions (CRs) for top and Z/γ* normalization**

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<thead>
<tr>
<th>SM HH</th>
<th>obs</th>
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<tr>
<td>$\sigma_{\text{limit}} / \sigma_{\text{SM}}$</td>
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<td>29</td>
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**Target signal:**
- Non-resonant: ggF

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**Non-resonant event:**

**Primary processes:**
- $\nu l l \nu$ (WW, $\tau\tau$, ZZ)

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**Non-resonant event:**

**Primary processes:**
- $\nu l l \nu$ (WW, $\tau\tau$, ZZ)
VBF $\rightarrow$ HH $\rightarrow$ bbbb

**Target signal:**
- Non-resonant: VBF $\kappa_{2V}$
- Resonant: VBF spin-0

**Event topology:**
★ 2 forward jets
★ exactly 4 b-jets (2b paired to have similar mass as Higgs)

**Main backgrounds:**
- multi-jets (~95%, data-driven)
- ttbar
- single Higgs

Using $m_{4b}$ as discriminant variable

![Graphs showing ATLAS simulation results for non-resonant and resonant signals.](image)

- non-resonant
  - $\kappa_{2V}$ distribution with observed $-0.43 < \kappa_{2V} < 2.56$
  - expected $-0.55 < \kappa_{2V} < 2.72$

- resonant
  - $m_{4b}$ distribution with observed and expected limits

JHEP07(2020)108

$\text{BR}(\text{HH} \rightarrow \text{bbbb}) = 34\%$

126 fb$^{-1}$
ggF→HH→bbbb

**Target signal:**
- Resonant: ggF spin-0, spin-2

**b-jets topology:**
- **resolved:** 4 separated b-jets (R=0.4)
- **boosted:** 2 large-R jets (R=1)

**Event topology:**

**Resolved** ($m_X \in [251, 1500]$ GeV):
- Boosted Decision Tree (BDT) used to pair 4b into 2H
- top-veto

**Boosted** ($m_X \in [900, 3000]$ GeV):
- b-tagging using track jets within large-R jet
- 4b, 3b, 2b categories

**Main backgrounds:**
- multi-jets (dominant)
- ttbar

*Data-driven bkg: use lower b-tag CRs*
**ggF→HH→bbbb results**

**Discriminant variable:** $m_{HH(4b)}$

**Limits on cross section for spin-0 and KK graviton.**

**KK graviton** ($k/M_{Pl}=1$): $m_G$, lower (bigger) than 298 (1440) GeV excluded

Small excess near 1.1 TeV

spin-0: 2.6 (1) $\sigma$ local (global)  
spin-2: 2.7 (1.2) $\sigma$ local (global)
**HH→bbττ**

**Target signal:**
- Non-resonant: ggF+VBF
- Resonant: ggF spin-0

**Event topology:**
- ★ exactly 2 b-jets
- ★ 2 opposite sign τ
- ★ categories: $\tau_{had} \tau_{lep}$, $\tau_{had} \tau_{had}$
  - $\tau_{had}$: decay into 1 (or 3) charged pions, neutral pions and neutrino (specific features in track and calorimeters)
- ★ 3 SRs defined with τ decay modes and triggers

**Main backgrounds:**
- • multi-jets
- • ttbar
- • V+jet, diBoson, single Higgs

*Fake $\tau_{had}$ from multi-jets and ttbar by data-driven*

**Parametrized Neural Network (PNN) trained for resonant**

**BDT and Neural Network trained for non-resonant**

MVA output as discriminant variable

139 fb$^{-1}$

BR(HH→bbττ) = 7.3%

Non-resonant & Resonant

ATLAS-CONF-2021-030
HH → bbττ results

\[ \sigma_{\text{limit}}/\sigma_{\text{SM}} \]

<table>
<thead>
<tr>
<th>SM HH</th>
<th>obs</th>
<th>exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.65</td>
<td>3.87</td>
<td></td>
</tr>
</tbody>
</table>

\(~ \text{factor 4 improvement w.r.t } 36.1 \text{ fb}^{-1} (~ \text{factor 2 from lumi increase})\)

Small excess around 1 TeV:
3 (2) σ local (global)

non-resonant

resonant

Resonant \( m_X = 1 \text{ TeV} \)
HH→bbττ (boosted)

Target signal:
- Resonant: ggF spin-0

Event topology:
- boosted di-b jet
- boosted di-τ jet

di-τ tagger: first use in ATLAS ($\epsilon_{\text{reco}}=80\%$, $\epsilon_{\text{ID}}=60\%$)

Backgrounds:
- Z+HF
- multi-jets fake di-τ (data-driven)
- ZH

visible $m_{HH}>900$ (1200) GeV for $m_X>1.6$ (2.5) TeV
### Target signal:
- Non-resonant: ggF+VBF
- Resonant: ggF spin-0

### Event topology:
- ★ exactly 2 b-jets
- ★ 2 photons (tight, isolated)
- ★ $m_{\gamma\gamma} \in [105, 160]$ GeV

### Main backgrounds:
- γγ+jets (dominant, data SB)
- single Higgs

### Discriminant: $m_{\gamma\gamma}$

#### Resonant
1 category per $m_X$ benchmark:
- BDT output
- $m_X$-dependent $m_{HH}$ cut

#### Non-resonant

### 4 SRs defined with:
- High or low mass
- Tight or loose cut on BDT

### Data & Signal

- HH→bbγγ

### HDBS-2018-34

- 139 fb$^{-1}$
- BR(HH→bbγγ)=0.26%
HH→bbγγ results

<table>
<thead>
<tr>
<th>SM HH</th>
<th>obs</th>
<th>exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_{limit}/σ_{SM}</td>
<td>4.2</td>
<td>5.7</td>
</tr>
</tbody>
</table>

~ factor 5 improvement w.r.t 36.1 fb⁻¹ (~ factor 2 from lumi increase)

non-resonant

resonant
Non-resonant HH combination

Combination with two channels (ggF+VBF modes): \( b\bar{b}\gamma\gamma \) and \( b\bar{b}\tau\tau \)

\( ATLAS \) Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
\( \sigma_{\text{ggF+VBF}}^{\text{SM}} = 32.78 \text{ fb} \)

- \( b\bar{b}\gamma\gamma \):
  - Observed: \( \Lambda_{b\bar{b}\gamma\gamma} \in [-1.5, 6.7] \) (obs)
  - Expected: \( \Lambda_{b\bar{b}\gamma\gamma} \in [-2.4, 7.7] \) (exp)
- \( b\bar{b}\tau\tau \):
  - Observed: \( \Lambda_{b\bar{b}\tau\tau} \in [-2.4, 9.2] \) (obs)
  - Expected: \( \Lambda_{b\bar{b}\tau\tau} \in [-2, 9] \) (exp)
Resonant HH combination

Combination with 3 channels:
(Spin-0 (ggF): $m_X \in [251, 3000]$ GeV)

- $b\bar{b}\gamma\gamma$: best at low $m_X$
- $b\bar{b}\tau\tau$ (only resolved): best at mid $m_X$
- $b\bar{b}b\bar{b}$: best at high $m_X$

Combined:
small excess $\sim 1.1$ TeV $3.2\sigma$ ($2.1\sigma$) local (global)
HL-LHC extrapolation: 36 fb\(^{-1}\)→3000 fb\(^{-1}\)

Run2(partial)→HL-LHC:

- 36 fb\(^{-1}\)→3000 fb\(^{-1}\)
- 13 TeV→14 TeV: ~18% increase of \(\sigma_{HH}\)

Extrapolated significance of SM HH:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HH \to bbbb)</td>
<td>1.4</td>
<td>0.61</td>
</tr>
<tr>
<td>(HH \to b\bar{b}\tau^+\tau^-)</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>(HH \to b\bar{b}\gamma\gamma)</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Combined</td>
<td>3.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Extrapolation based on previous analysis (36 fb\(^{-1}\))

Better results foreseen by extrapolating the current results

Expect to measure \(\kappa_\lambda\) with uncertainty<1
Conclusion

Latest ATLAS Run 2 published results presented for:

- 4 decay channels: $b_b b_b, b_b l_v l_v, b_b \tau \tau, b_b \gamma \gamma$
- Non-resonant search: SM HH, $\kappa_\lambda^\lambda$, $\kappa_2^\nu$
- Resonant search: spin-0 and spin-2 resonance
- Combination of a few channels
- HL-LHC prospects

More results on the way!
backup
Previous HH results (36.1 fb$^{-1}$)
B-tagging and $\tau$-ID improvements

- **MV2**: BDT-based (used for 36 fb$^{-1}$ results)
- **DL1R**: DNN-based (new approach)

All HH channels are able to move 70%→77% working point

- **BDT** used for 36 fb$^{-1}$ results
- **RNN** new approach

Moved from medium to loose: 75%→85% (60%→75%) for 1-prong (3-prong)
$ggF \rightarrow bbbb$: acceptance \times efficiency

ATLAS Simulation Preliminary
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
Boosted channel, spin-0 signal

ATLAS Simulation Preliminary
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
Boosted channel, spin-0 signal

ATLAS Simulation Preliminary
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
Resolved channel, spin-0 signal

ATLAS Simulation Preliminary
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
Resolved channel, spin-2 signal
**bbττ**: acceptance × efficiency

**ATLAS** Simulation Preliminary

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- $\tau_{\text{had}}\tau_{\text{had}}$
- $\tau_{\text{lep}}\tau_{\text{had}}$
- $\tau_{\text{lep}}\tau_{\text{had}}$ (SLT)
- $\tau_{\text{lep}}\tau_{\text{had}}$ (LTT)

Variation in function of $m_\chi$

Full signal region selection
ggF→bbbb: background estimation

Background dominated by QCD multi-jets, estimated with data-driven method with low b-tag CRs

**Resolved**

using 2b regions to estimate bkg shape in 4b SR, with a NN-based kinematic reweighting

\[ w(\vec{x}) = \frac{p_{4b}(\vec{x})}{p_{2b}(\vec{x})} \]

2b-SR with kinematic reweighting is used to estimate multi-jets bkg shape

**Boosted**

CRs defined with less b-tagged sub-jets

VR used to validate kinematic reweighting, and for its systematic estimation
Fake Factor (FF), Transfer Factor (TF) derived with data in CRs, then applied on SR template.
**bbττ (boosted): di-τ tagger performance**

Di-τ ID is trained by BDT with 2015 data as background.

Insensitivity of pileup allows to apply it to full datasets.
VBF→HH→b4b results

Using $m_{4b}$ as discriminant variable

obs: $-0.43 < \kappa_{2\nu} < 2.56$
exp: $-0.55 < \kappa_{2\nu} < 2.72$
bbττ: PNN score and $m_{HH}$ distributions

PNN ($m_x=1$ TeV)

$m_{HH}$

No excess observed at $m_{HH}$ near 1 TeV
HH→bbγγ statistical interpretation

Discriminant variable: $m_{\gamma\gamma}$

- HH signal and 1H background modelled by double sided crystal ball function
- $\gamma\gamma$+jets continuum background modelled by exponential function

Non-resonant high mass BDT tight

Resonant $m_x=500$ GeV
## HH → bbγγ: systematic impact on limits

<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><strong>Experimental</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>Norm. + Shape</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>Normalization</td>
<td>&lt; 0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>Normalization</td>
<td>&lt; 0.2</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Theoretical</strong></td>
<td></td>
<td></td>
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<tr>
<td>Factorization and renormalization scale</td>
<td>Normalization</td>
<td>0.3</td>
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<td>Parton showering model</td>
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<td>0.6</td>
<td>2.6</td>
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</tr>
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<td>$\mathcal{B}(H \rightarrow \gamma\gamma, b\bar{b})$</td>
<td>Normalization</td>
<td>0.2</td>
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<tr>
<td>Spurious signal</td>
<td>Normalization</td>
<td>3.0</td>
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HL-LHC prospects

Probing HH

Probing $\kappa_\lambda$