Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

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The $\kappa_\lambda$

The Higgs potential: $V(\Phi) = \mu^2 \Phi^* \Phi + \lambda |\Phi^* \Phi|^2$

Expanding around the minimum:

$$V(h) \approx \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots$$

The $\kappa_\lambda$ is defined as $\lambda / \lambda_{SM}$
HH production in SM

- The di-Higgs is dominantly produced by the $ggH$ and VBF processes.
- Di-Higgs production in SM is dominated by non-resonant gluon-fusion process.
  - The triangle diagram involves the Higgs self-coupling and is sensitive to $\kappa_A$.
  - The box diagram involves the Top Yukawa coupling and $\kappa_t$.
  - Destructive interference between the triangle and box diagram results in small cross section.
- The vector boson fusion (VBF) process also contributes to the di-Higgs production.
  - Smaller cross section compared with $ggF$.
  - VBF involves trilinear, $HHVV$ and $VVH$ diagrams.
  - Sensitive to $\kappa_A$ and $\kappa_{vv}$.
- Small cross-section compared with single Higgs production. Hard to measure.
**HH decay channels**

- **bbbb**: largest branching ratio, large QCD multi-jets and ttbar backgrounds.


- **bbττ**: relatively small BR and background.

- **bbγγ**: small BR, good mass resolution, small background.


In this talk ATLAS measurement on HH production in **bbγγ**, **bbττ** and **bbbb** channel using full Run 2 data will be reported.
$HH \rightarrow bb\gamma\gamma$
**$HH \to bb\gamma\gamma$**

- Signature of the $bb\gamma\gamma$ channel:
  - A clean channel with small background.
  - $H \to \gamma\gamma$ decay provides excellent mass resolution.
  - Small branching ratio, $\sim 0.26\%$.

- Analysis strategy and event selection:
  - Multivariate method (BDT) is used to separate signal from backgrounds.
  - Two photons with invariant mass in the Higgs mass window $[120, 130]$ GeV.
  - Exactly 2 $b$-tagged jets.
  - No leptons (electron or muon).

\[
m_{bb\gamma\gamma}^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV}
\]
**BDT in $HH \rightarrow bb\gamma\gamma$**

- Events are split into the low and high mass region according to $m_{bb\gamma\gamma}$.
- Events are further split into the loose and tight BDT region in both high and low mass region.

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**Low mass region:** targets to large $\kappa_\lambda = 10$ (BSM)

**High mass region:** targets to $\kappa_\lambda = 1$ (SM)
Results of $HH \to bb\gamma\gamma$

- The statistical fitting is performed on $m_{\gamma\gamma}$ distribution in each category.
- Limits are set on $\mu_{\text{SM}}$ and $\kappa_\lambda$.
- Observed (expected) $\mu_{\text{SM}} : 4.2 (5.7)$. 

Phys. Rev. D 106, 052001
$HH \rightarrow b\bar{b}c\bar{c}$
**HH → bbττ**

- Signature of the $bbττ$ channel:
  - Relative clean background.
  - Moderate branching ratio, $\sim 7.3\%$
  - Dominate background comes from fake $τ$, hard to estimate.

- Analysis strategy and event selection:
  - Backgrounds from fake $τ$ are estimated using fake factor method.
  - Events are split into different categories according to the $τ$ decay mode (leptonic or hadronic), based on the type of trigger accepted the event.
  - Exactly 2 b-tagged jets.
  - Require two hardonic $τ$ or $τ + e/μ$.
  - $m_{ττ} > 60$ GeV.

*arXiv:2209.10910*
MVA and result of $HH \to bb\tau\tau$

• To improve signal/background ratio, boosted decision tree (BDT) is used in the $\tau_{had}\tau_{had}$ category and neural network is used in the $\tau_{had}\tau_{lep}$ category.

• The statistical fitting is performed on BDT and NN predicted score.

• Observed (expected) upper limits of $\mu_{SM}$ : 4.7 (3.9).

arXiv:2209.10910
$HH \rightarrow bbbb$
**HH → bbbb**

- Signature of the $bbbb$ channel:
  - Large background comes from QCD.
  - Largest branching ratio, ~33%

- Analysis strategy and event selection:
  - Both VBF and ggH are included.
  - Fake b-jet backgrounds are estimated using data driven method from a 2b control region.
  - Exactly 4 b-tagged jets.
  - Events are split into six categories according to $\Delta \eta_{HH}$ and $X_{HH}$ in ggH channel, while events are split into two categories according to $\Delta \eta_{HH}$ in VBF channel.
Results of $HH \rightarrow bbbb$

- The statistical fitting is performed on $m_{HH}$ distribution in each category.
- Limits are set on $\mu_{\text{SM}}$ and $\kappa_{\lambda}$.
- Observed (expected) upper limit on $\mu_{\text{SM}}$: 5.4 (8.1)

arXiv:2301.03212
**HH combination**

- Combined three most sensitive channel: $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$.
- Combined 95% upper limits on $\mu_{HH}$: 2.4

![Diagram showing 95% CL upper limit on HH signal strength $\mu_{HH}$](image)

arXiv:2211.01216
**HH combination, $\kappa_{2\nu}$**

**Diagram 1:**

- Observed limit (95% CL)
- Expected limit (95% CL)
- $H_\mu = 0$ hypothesis
- Expected limit $\pm 1\sigma$
- Expected limit $\pm 2\sigma$
- Theory prediction
- SM prediction

**Diagram 2:**

- $\sqrt{s} = 13$ TeV, 126–139 fb$^{-1}$
- $HH \rightarrow b\bar{b}\tau^+ \tau^- + b\bar{b}\gamma\gamma + b\bar{b}b\bar{b}$
- Observed
- Combined: $68\%: k_{2\nu} \in [0.4, 1.7]$
- $95\%: k_{2\nu} \in [0.1, 2.0]$

**ArXiv:** arXiv:2211.01216
**HH combination, $\kappa_\lambda$**

\[ \sqrt{s} = 13 \text{ TeV}, \ 126 - 139 \text{ fb}^{-1} \]

**HH \rightarrow b\bar{b}\tau^+\tau^- + b\bar{b}\gamma\gamma + b\bar{b}\bar{b}\bar{b}**

- **ATLAS**
- Observed limit (95% CL)
- Expected limit (95% CL) ($\mu_{HH} = 0$ hypothesis)
- Expected limit ±1σ
- Expected limit ±2σ
- Theory prediction
- SM prediction

\[ -2 \ln \Lambda \]

**HH + $H \ k_\lambda$ only:**
- 95%: $k_\lambda \in [-0.4, 6.3]$
- HH + $H \ k_\lambda$ generic:
- 95%: $k_\lambda \in [-1.4, 6.1]$

arXiv:2211.01216
**H + HH combination**

- Single Higgs boson production is also sensitive to $\kappa_\lambda$ when loop corrections are included.
- Combined limits from single and double Higgs production:

```
<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$\sqrt{s} = 13$ TeV, 126—139 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All other $\kappa$ fixed to SM</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
</tr>
</tbody>
</table>

```

arXiv:2211.01216
Projected result at HL-LHC ($bb\gamma\gamma + bb\tau\tau$)

- Measurement from Run 2 data with integrated luminosity of 139 fb$^{-1}$ at 13 TeV are projected to the HL-LHC at 14 TeV and total integrated luminosity of 3000 fb$^{-1}$.
- The estimated significance of the SM HH production is $3.2\,\sigma$ with systematic uncertainties included.
Projected result at HL-LHC ($b\bar{b}\gamma\gamma + b\bar{b}\tau\tau + b\bar{b}b\bar{b}$)

- The estimated significance of the SM HH production is $3.4 \sigma$ with systematic uncertainties included after the including the $b\bar{b}b\bar{b}$ channel.
Summary

• Searches for HH production in the three most sensitive channels by ATLAS are reported.
  • $bb\gamma\gamma$: observed (expected) upper limit on $\mu_{HH}$: 4.2 (5.7).
  • $bb\tau\tau$: observed (expected) upper limit on $\mu_{HH}$: 4.7 (3.9).
  • $bbb\bar{b}$: observed (expected) upper limit on $\mu_{HH}$: 5.4 (8.1).

• Combined HH measurement result is also reported:
  • Combined upper limit on $\mu_{HH}$: 2.4.

• Projected measurement result of HH production on the HL-LHC is also reported.
Back up
$HH \rightarrow b\bar{b}\gamma\gamma$
**HH → bbγγ**

(a) High mass BDT tight selection

(b) High mass BDT loose selection

(c) Low mass BDT tight selection

(d) Low mass BDT loose selection
\[ HH \rightarrow bb\tau\tau \]

\( \tau_{\text{lep}}\tau_{\text{had}} \) channel

\[ m_{bb} < 150 \text{ GeV} \]

ID

SR

Anti-ID

SR Template

MJ CR: Anti-Iso

\[ FF_{\text{MJ}} \]

\[ FF_{\text{comb}} = r_{\text{MJ}} \times FF_{\text{MJ}} + (1 - r_{\text{MJ}}) \times FF_{t\bar{t}} \]

\[ t\bar{t} \text{ CR: } m_{bb} > 150 \text{ GeV} \]

ID

Anti-ID

True-\( \tau_{\text{had-vis}} \) subtracted

\( r_{\text{MJ}} \) Fraction of multi-jet events in the template
$HH \rightarrow bb\tau\tau$

$\tau_{\text{had}}\tau_{\text{had}}$ channel

- **OS, 2 $b$-tagged jets**
  - ID
  - Anti-ID
  - SR
  - SR Template

- **SS, 1 $b$-tagged jet**
  - ID
  - Anti-ID
  - $\text{FF}_1$ $b$-tag

- **SS, 2 $b$-tagged jets**
  - ID
  - Anti-ID
  - $\text{TF}_{1\rightarrow 2}$ $b$-tags

$\text{FF} = \text{FF}_1$ $b$-tag $\times$ $\text{TF}_{1\rightarrow 2}$ $b$-tags

Non-multi-jet subtracted
**$HH \rightarrow b\bar{b}t\bar{t}$**

$\tau_{\text{had}}\tau_{\text{had}}$ channel

$\tau_{\text{lep}}\tau_{\text{had}}, t\bar{t}$ CR

$\text{SF(}\text{fake-}\tau_{\text{had-vis}}\text{)}$
(from template fits to the $m_T^W$ distribution)

$t\bar{t}$ with fake-$\tau_{\text{had-vis}}$
(corrected simulation)

$\tau_{\text{had}}\tau_{\text{had}}$ SR

$t\bar{t}$ with fake-$\tau_{\text{had-vis}}$
(simulation)

$\tau_{\text{had}}\tau_{\text{had}}$ SR
**HH → bbbb categories**

**VBF Selection**

1. Pass trigger class
   - (1) Pass trigger class
   - Yes

2. ≥ 4 central jets
   - (2) ≥ 4 central jets
   - Yes

3. ≥ 4 b-tagged central jets
   - (3) ≥ 4 b-tagged central jets
   - Yes

4. ≥ 6 central or forward jets
   - (4) ≥ 6 central or forward jets
   - Yes

5. VBF Jets
   - (5) VBF Jets
   - Yes

6. (Σp_T) < 65 GeV
   - (6) (Σp_T) < 65 GeV
   - Yes

7. VBF
   - (7) VBF
   - Yes

8. VBF
   - (8) VBF
   - Yes

9. VBF
   - (9) VBF
   - Yes

**ggF Selection**

1. (7. ggF)
   - (7. ggF)
   - Yes

2. (8. ggF)
   - (8. ggF)
   - Yes

3. (9. ggF)
   - (9. ggF)
   - Yes

**VBF SR**

**ggF SR**
$HH \rightarrow bbbb$

$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4 \text{ GeV}}{0.1 \ m_W}\right)^2 + \left(\frac{m_t - 172.5 \text{ GeV}}{0.1 \ m_t}\right)^2}$$

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124 \text{ GeV}}{0.1 \ m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117 \text{ GeV}}{0.1 \ m_{H2}}\right)^2}$$
**$H + HH$ combination**

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**Diagram 1:**
- $H$ to $q$
- $q$ to $H$
- $H$ to $q$

**Diagram 2:**
- $g$ to $t$
- $t$ to $H$
- $H$ to $t$

**Diagram 3:**
- $g$ to $t$
- $t$ to $H$
- $H$ to $t$

**Diagram 4:**
- $g$ to $q$
- $q$ to $V$
- $V$ to $H$
- $H$ to $H$