Search for di-Higgs production at 13 TeV and prospects for HL-LHC with the ATLAS detector

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on behalf of the ATLAS Collaboration

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Higgs pair production at the LHC

Higgs-boson pairs can be produced at the LHC via gluon-gluon fusion (ggF), accounting for more than 90% of the total cross section, via two Standard Model (SM) diagrams at LO:

- **box diagram (B)** with top-quark Yukawa coupling and **triangle diagram (T)** with also the trilinear Higgs self-coupling

\[
\sigma^{SM}_{ggF}(pp \rightarrow HH) = 33.5 \text{ fb at } 13 \text{ TeV}
\]

- Needs very high statistics to be observed, but interesting to set an upper limit on the overall cross section and direct constraints on the Higgs self-coupling \( \lambda_{HHH} = \frac{m_H^2}{2v} \)

- Beyond Standard Model (BSM) physics could manifest as modifications of the couplings changing the production rate and the kinematics
Higgs pair production at the LHC

Considering variations of the couplings, with two diagrams contributing at LO:

- **B** = box diagram, amplitude proportional to $\kappa_t^2$, $\kappa_t = y_t/y_t^{SM}$
- **T** = triangle diagram, amplitude proportional to $\kappa_t \kappa_\lambda$, $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

Amplitude: $A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$

Cross section

$$\sigma(\kappa_t, \kappa_\lambda) \sim \kappa_t^4 |B|^2 + \kappa_t^3 \kappa_\lambda (BT + TB) + \kappa_t^2 \kappa_\lambda^2 |T|^2$$

- cross section: 2nd order polynomial in $\kappa_\lambda$
- kinematics depends on relative contributions and interference of the two diagrams modifying the $m_{HH}$ distribution

→ information used in the double-Higgs analyses to set constraints on $\kappa_\lambda$
Higgs pair decay and ATLAS di-Higgs analyses

Many different final states in the Higgs pair decay

di-Higgs decay BRs given by all possible combinations of observed Higgs decays:

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

ATLAS di-Higgs searches performed in 6 decay channels using 36 fb$^{-1}$ of LHC 13 TeV $pp$ collisions data:

- $b\bar{b}b\bar{b}$: highest BR
- $b\bar{b}\tau^+\tau^-$: good compromise between high BR and clean signature
- $b\bar{b}\gamma\gamma$: clean signature from the $\gamma$s

3 most sensitive channels

- $b\bar{b}W^+W^-$
- $W^+W^\gamma\gamma$
- $W^+W^\gamma\gamma$

3 channels exploiting high BR and clean signature of the $\gamma$s, but difficult reconstruction of the Higgs candidate in $W^+W^-$
ATLAS di-Higgs analyses: $b\bar{b}b\bar{b}$

- $b$-jet triggers
- At least 4 $b$-tagged jets
- 4 jets $b$-tagged jets used to build the Higgs candidates, with pairing based on angular and invariant mass information
- Signal region defined by 2D requirements in the Higgs boson candidate’s mass plane
- Largest background: QCD → data-driven from control regions
- Final discriminant variable: $m_{HH}$

SM double-Higgs signal

Multijet background

- Signal region inside the inner red dashed curve
- Validation region outside the signal region and within the orange circle
- Control region outside the validation region and within the yellow circle
ATLAS di-Higgs analyses: $b\bar{b}\tau^+\tau^-$

- Divided in two channels depending on $\tau$-lepton pair decay mode: $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$

  - $\tau_{lep}\tau_{had}$:
    - single-lepton (SLT) and lepton-$\tau_{had}$ (LTT) triggers
    - 1 light lepton ($e/\mu$) and 1 $\tau_{had}$ with opposite charge

  - $\tau_{had}\tau_{had}$:
    - single-$\tau_{had}$ and di-$\tau_{had}$ triggers
    - 2 $\tau_{had}$ with opposite charge

- 2 $b$-tagged jets

- Main backgrounds: $t\bar{t}$, $Z \rightarrow \tau\tau$ + heavy flavour jets and QCD
  -> data-driven backgrounds with jets faking $\tau_{had}$

- Final discriminant variable: Boosted Decision Tree (BDT) score distribution

- Simultaneous fit of 3 categories: $\tau_{lep}\tau_{had}$ SLT, $\tau_{lep}\tau_{had}$ LTT and $\tau_{had}\tau_{had}$

ATLAS di-Higgs analyses: $b\bar{b}\gamma\gamma$

- Di-photon triggers
- At least 2 $\gamma$ and at least 2 jets
- 2 categories: 2 $b$-tagged jets and 1 $b$-tagged jet
- Signal region defined by: $105 < m_{\gamma\gamma} < 160$ GeV, $90 < m_{jj} < 140$ GeV
- Final discriminant variable: $m_{\gamma\gamma}$
- Continuum $\gamma\gamma +$ jets background modelled in $m_{\gamma\gamma}$ with a functional form obtained from a fit to the data and single Higgs background described by a double-sided Crystal Ball determined from a fit to simulated samples
- Simultaneous fit of 2 categories: 1 $b$-tag and 2 $b$-tags

ATLAS di-Higgs analyses: $b\bar{b}W^+W^-$, $W^+W^-W^+W^-$, $W^+W^-\gamma\gamma$

$b\bar{b}W^+W^-$:

- $b\nu\nu qq$ final state
- Event-counting analysis (1 category)

$W^+W^-W^+W^-$:

- Three channels:
  - $l\nu l\nu 4q$ (2 leptons),
  - $l\nu l\nu l\nu 2q$ (3 leptons)
  - and $l\nu l\nu l\nu l\nu$ (4 leptons)
- Divided in categories according to the lepton flavour, the number of same-flavour and opposite charge lepton pairs and invariant mass
- Event-counting analysis with a simultaneous fit of 9 categories

$W^+W^-\gamma\gamma$:

- $l\nu qq$ final state
- Final discriminant variable: $m_{\gamma\gamma}$ (1 category)
6 decay channels included in the di-Higgs combination with 36 fb$^{-1}$ to set a 95% C.L. upper limit on the ggF di-Higgs production cross section.

Observed (expected) combined upper limit of $6.9 \times \sigma_{ggF}^{SM}$ $(10 \times \sigma_{ggF}^{SM})$

Results dominated by statistical uncertainties on data,
~10% impact of systematics on expected limit.
ATLAS di-Higgs analyses: $b\bar{b}l\nu l\nu$

New analysis recently performed with full Run-2 dataset of 139 fb$^{-1}$

- Looking for the HH decays with $H \to b\bar{b}$ and $H \to WW, ZZ, \tau\tau \to l\nu l\nu$
- At least two $b$-tagged jets and exactly two leptons ($e/\mu$) with opposite charge
- 2 categories: same-flavour (SF) and different-flavour (DF) for the lepton pair
- Signal region defined by: $20 < m_{ll} < 60$ GeV, $110 < m_{bb} < 140$ GeV and a cut on a discriminant built from the output of a multiclass deep neural network (DNN) classifier ($d_{HH} > 5.45(5.55)$ for SR-SF (SR-DF))
- Event-counting analysis with a simultaneous fit of 2 signal regions: SF and DF

Set a 95% C.L. upper limit on the ggF di-Higgs production cross section:
- Observed (expected) upper limit of $40 \times \sigma_{SM}^{ggF} (29 \times \sigma_{SM}^{ggF})$
- Limits comparable to the previous leading searches for di-Higgs production
→ interesting new channel to include in the full Run-2 di-Higgs combination!

<table>
<thead>
<tr>
<th>$\sigma (gg \to HH)$ [pb]</th>
<th>$\sigma (gg \to HH) / \sigma_{SM} (gg \to HH)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2$\sigma$</td>
<td>-1$\sigma$</td>
</tr>
<tr>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
</tr>
</tbody>
</table>
Combined results: Higgs self-coupling

3 most sensitive channels included in the di-Higgs combination with 36 fb\(^{-1}\) to set 95% C.L. upper limits on the ggF di-Higgs production cross section as a function of \(\kappa_\lambda\):

- Shape determined by the inverse of the signal acceptance
- Comparing to the theoretical cross section predictions, 95% C.L. allowed \(\kappa_\lambda\) range: \(-5 < \kappa_\lambda < 12\)

\[
\kappa_\lambda = \begin{array}{c}
\text{Allowed } \kappa_\lambda \text{ interval at 95% CL} \\
\text{Final state} & \text{Obs.} & \text{Exp.} & \text{Exp. stat.} \\
\text{b\bar{b}b\bar{b}} & -10.9 & -11.6 & -9.8 \\
\text{b\bar{b}\tau^+\tau^-} & -7.4 & -8.9 & -7.8 \\
\text{b\bar{b}\gamma\gamma} & -8.1 & -8.1 & -7.9 \\
\text{Combination} & -5.0 & -5.8 & -5.3 \\
\end{array}
\]
Combination of di-Higgs and single-Higgs analyses

- Analysis to constrain $\kappa_\lambda$ using single-Higgs measurements with up to 80 fb$^{-1}$ also performed ATL-PHYS-PUB-2019-009 (see talk by Eleonora Rossi)
- Di-Higgs $\kappa_\lambda$ analysis very recently combined with the single-Higgs $\kappa_\lambda$ analysis,

NEW RESULTS:

$\kappa_\lambda$-only model:

\begin{align*}
\kappa_\lambda &\sim -2.3 < \kappa_\lambda < 10.3, \\
\kappa_\lambda &\sim -3.7 < \kappa_\lambda < 11.5,
\end{align*}

assuming all other SM couplings

Constraints on $\kappa_\lambda$ set in a more generic model with less assumptions on the other Higgs couplings:

- Significant improvement in constraining $\kappa_\lambda$:
  \begin{align*}
  -2.3 < \kappa_\lambda < 10.3, \\
  -3.7 < \kappa_\lambda < 11.5,
  \end{align*}

in the generic model

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  \end{align*}

in the generic model

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Model & $\kappa_W^{+1\sigma}$ & $\kappa_Z^{+1\sigma}$ & $\kappa_l^{+1\sigma}$ & $\kappa_b^{+1\sigma}$ & $\kappa_t^{+1\sigma}$ & $\kappa_\lambda^{+1\sigma}$ & $\kappa_\lambda$ [95% CL] \\
\hline
$\kappa_\lambda$-only & 1 & 1 & 1 & 1 & 1 & 4.6$^{+3.2}_{-3.8}$ & [-2.3, 10.3] \\
& & & & & & 1.0$^{+7.3}_{-3.8}$ & [-5.1, 11.2] \\
Generic & 1.03$^{+0.08}_{-0.08}$ & 1.10$^{+0.09}_{-0.09}$ & 1.00$^{+0.12}_{-0.11}$ & 1.03$^{+0.20}_{-0.18}$ & 1.06$^{+0.16}_{-0.16}$ & 5.5$^{+3.5}_{-5.2}$ & [-3.7, 11.5] \\
& 1.00$^{+0.08}_{-0.08}$ & 1.00$^{+0.08}_{-0.08}$ & 1.00$^{+0.12}_{-0.12}$ & 1.00$^{+0.21}_{-0.19}$ & 1.00$^{+0.16}_{-0.15}$ & 1.0$^{+7.6}_{-4.5}$ & [-3.7, 11.5] \\
\hline
\end{tabular}
\end{table}
Prospects measurements at the HL-LHC

Prospect study for the search for di-Higgs production at the HL-LHC performed assuming 3000 fb\(^{-1}\) at 14 TeV, using the combination of the 3 most sensitive channels: \(b\bar{b}b\bar{b}\), \(b\bar{b}\tau^+\tau^-\), \(b\bar{b}\gamma\gamma\)

- \(b\bar{b}b\bar{b}\) and \(b\bar{b}\tau^+\tau^-\) analyses based on extrapolating the Run-2 analyses
- \(b\bar{b}\gamma\gamma\) dedicated new analysis using simulations at 14 TeV


**Expected significance for \(\kappa_\lambda = 1\):**

3\(\sigma\), evidence!

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured (\mu) (Statistical-only)</th>
<th>Measured (\mu) (Statistical + Systematic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HH \to b\bar{b}b\bar{b})</td>
<td>1.0 ± 0.6</td>
<td>1.0 ± 1.6</td>
</tr>
<tr>
<td>(HH \to b\bar{b}\tau^+\tau^-)</td>
<td>1.0 ± 0.4</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td>(HH \to b\bar{b}\gamma\gamma)</td>
<td>1.0 ± 0.6</td>
<td>1.0 ± 0.6</td>
</tr>
<tr>
<td>Combined</td>
<td>1.00 ± 0.31</td>
<td>1.0 ± 0.4</td>
</tr>
</tbody>
</table>

**Expected \(-0.4 < \kappa_\lambda < 7.3\) at 95% C.L. for \(\kappa_\lambda = 1\)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1(\sigma) CI</th>
<th>2(\sigma) CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainties only</td>
<td>(0.4 \leq \kappa_\lambda \leq 1.7)</td>
<td>(-0.10 \leq \kappa_\lambda \leq 2.7 \cup 5.5 \leq \kappa_\lambda \leq 6.9)</td>
</tr>
<tr>
<td>Systematic uncertainties</td>
<td>(0.25 \leq \kappa_\lambda \leq 1.9)</td>
<td>(-0.3 \leq \kappa_\lambda \leq 7.3)</td>
</tr>
</tbody>
</table>

4\(\sigma\) from ATLAS+CMS combination
Latest ATLAS results on di-Higgs production and the Higgs self-coupling

Combination of 6 decay channels to set an upper limit on the di-Higgs production cross section: $6.9 \times \sigma_{ggF}^{SM}$

Combination of the 3 most sensitive channels to set constraints on the Higgs self-coupling modifier $\kappa_\lambda$: $-5 < \kappa_\lambda < 12$

New results from the combination of di-Higgs and single-Higgs analyses to set constraints on $\kappa_\lambda$: $-2.3 < \kappa_\lambda < 10.3$

Future prospects for the search for di-Higgs production and test $\kappa_\lambda$ at the HL-LHC: possible to reach evidence for di-Higgs production at the end of the HL-LHC

ATLAS di-Higgs analyses with full Run-2 dataset ongoing!
SM di-Higgs signal:

- Generated at NLO in QCD with MADGRAPH5_aMC@NLO
- Using the CT10 NLO PDF set
- Parton shower and hadronisation simulated with HERWIG++
- Using parameter values from the UE-EE-5-CTEQ6L1 tune

- FTApprox method used to include finite top-quark mass effects in the real-radiation NLO corrections, virtual loop corrections realised assuming infinite top-quark mass
- Generator level bin-by-bin reweighting of the $m_{HH}$ distribution applied to take into account the finite top-quark mass effect in full NLO corrections

Signal normalised to $\sigma_{ggF}^{SM} = 33.5$ fb,
calculated at NLO in QCD with finite top-quark mass effects and corrected at NNLO in QCD matched with the NNLL resummation in the heavy top-quark limit
Signal simulation

di-Higgs signal with $\kappa_\lambda$ variations:

$bb\bar{b}\bar{b}$ and $bb\tau^+\tau^-$:

- Generated at LO with MADGRAPH5_aMC@NLO
- Using the NNPDF 2.3 LO PDF set
- Showered using PYTHIA 8.2
- Using the A14 tune

- 3 LO samples generated with $\kappa_\lambda = 0, 1, 20$
- Used in linear combinations to obtain LO signal distributions for any $\kappa_\lambda$
- Weights derived in $m_{HH}$ bins from the ratio of any $\kappa_\lambda$ to the SM and used to reweight the NLO SM sample
- Reweighted NLO signal samples used to compute signal acceptance and distributions for any $\kappa_\lambda$

$bb\gamma\gamma$:

- Shape of $m_{\gamma\gamma}$ described by the double-sided Crystal Ball function (Gaussian core with power-law tails)
- Signal acceptance parameterised from MC simulated samples

Normalisation for any $\kappa_\lambda$ obtained by multiplying the SM cross section by the ratio $\frac{\sigma_{ggF}(\kappa_\lambda)}{\sigma_{ggF}^{SM}}$ computed at NNLO+NNLL in the heavy top-quark approximation
Combination of di-Higgs and single-Higgs analyses: single-Higgs $\kappa \lambda$ analysis theoretical framework

Single-Higgs processes do not depend on $\kappa \lambda$ at LO, but the Higgs trilinear self-coupling enters in the NLO electroweak corrections via Higgs self energy loop corrections and additional diagrams.

→ an indirect constraint on $\kappa \lambda$ can be set comparing precise measurements of single-Higgs production yields to the SM predictions with $\kappa \lambda$-dependent NLO EW effects.


Single-Higgs $\kappa \lambda$ analysis based on this framework.
Combination of di-Higgs and single-Higgs analyses: single-Higgs $\kappa_\lambda$ analysis theoretical framework

Higgs production cross sections and decay BRs modified by parameters representing their ratio to the SM values as a function of $\kappa_\lambda$

For a given production process $i$ the cross section modifier as a function of $\kappa_\lambda$ can be written as:

$$
\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma_{BSM}^{i}}{\sigma_{SM}^{i}} = \left. Z_H^{BSM}(\kappa_\lambda) \left[ \kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{EW}^i} \right] \right.,
$$

where $Z_H^{BSM}(\kappa_\lambda)$ is defined as:

$$
Z_H^{BSM}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H} \quad \text{with} \quad \delta Z_H = -1.536 \times 10^{-3},
$$

For a given decay channel $f$ the BR modifier as a function of $\kappa_\lambda$ can be written as:

$$
\mu_f(\kappa_\lambda, \kappa_f) = \frac{\text{BR}_f^{BSM}}{\text{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \text{BR}_j^{SM} \left[ \kappa_j^2 + (\kappa_\lambda - 1)C_1^j \right]}.
$$

- $\kappa_{i, EW}^i = \frac{\sigma_{NLO, i}^{SM}}{\sigma_{LO, i}^{SM}}$ accounts for the NLO EW corrections to the cross section for $\kappa_\lambda = 1$
- $C_1^i$ is a process- and kinematic-dependent coefficient
- $\kappa_i = \frac{\sigma_{BSM, LO, i}^{SM}}{\sigma_{LO, i}^{SM}}$ represent the modifiers to other Higgs boson couplings that can also be considered
Double-Higgs and single-Higgs cross sections and Higgs decay branching fractions as a function of $\kappa_\lambda$
Combination of di-Higgs and single-Higgs analyses: data and input measurements

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated luminosity (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$ (excluding $t\bar{t}H, H \rightarrow \gamma\gamma$)</td>
<td>79.8</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$ (including $t\bar{t}H, H \rightarrow ZZ^* \rightarrow 4\ell$)</td>
<td>79.8</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow e\nu\mu\nu$</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>36.1</td>
</tr>
<tr>
<td>$VH, H \rightarrow b\bar{b}$</td>
<td>79.8</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow b\bar{b}$</td>
<td>36.1</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow multilepton$</td>
<td>36.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}bb$</td>
<td>27.5</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\tau^+\tau^-$</td>
<td>36.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>36.1</td>
</tr>
</tbody>
</table>

Same input analyses used in the HH combination and in the H combination, except the $ttH, H \rightarrow \gamma\gamma$ analysis that has been removed from this combination because of large overlap in the events between the $ttH, H \rightarrow \gamma\gamma$ and $HH \rightarrow bb\gamma\gamma$ analyses (50%)

- Removing $ttH, H \rightarrow \gamma\gamma$ worsens the expected constraint on $\kappa_\lambda$ by 4%, removing $HH \rightarrow bb\gamma\gamma$ instead would worsen it by 15%
- The remaining categories have a maximum overlap of less than 2% of the events in the double-Higgs categories and the impact of the overlapping categories on the final result is of about 1% so they are kept
Combination of di-Higgs and single-Higgs analyses: results

- For the $\kappa_\lambda$-only model where all couplings are set to SM values except $\kappa_\lambda$

Likelihood scan as a function of $\kappa_\lambda$

New! ATLAS-CONF-2019-049
Combination of di-Higgs and single-Higgs analyses: results

- For more generic models: model where all coupling modifiers are set to the SM values except $\kappa_\lambda$ and $\kappa_t$

Contours in the $\kappa_\lambda - \kappa_t$ plane

New! ATLAS-CONF-2019-049
Combination of di-Higgs and single-Higgs analyses: results

- For more generic models: model where $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_l$ and $\kappa_\lambda$ are fitted simultaneously

Likelihood scan as a function of $\kappa_\lambda$ with $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_l$ profiled, compared to the likelihood scan from the $\kappa_\lambda$-only fit

New! ATLAS-CONF-2019-049
Likelihood split per production mode and decay mode

New! ATLAS-CONF-2019-049

-2 ln $\Lambda$

**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 27.5 - 79.8 fb$^{-1}$
- Expected ($\kappa_\lambda = 1$)

- $pp\to H, \text{ggF}$
- $pp\to H, \text{VBF}$
- $pp\to H, \text{VH}$
- $pp\to H, \text{ttH}$
- $pp\to HH, \text{ggF}$

**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 27.5 - 79.8 fb$^{-1}$
- Expected ($\kappa_\lambda = 1$)

- $H \to ZZ^*$
- $H \to \gamma\gamma$
- $H \to b\bar{b}$
- $H \to WW^*$
- $H \to t\bar{t}$
- $HH \to b\bar{b}b\bar{b}$
- $HH \to b\bar{b}t\bar{t}$
- $HH \to b\bar{b}\gamma\gamma$

- $95\% \text{ CL}$
- $68\% \text{ CL}$
Prospects measurements at the HL-LHC: extrapolation method

$\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ analyses based on extrapolating the Run-2 analyses:

- Scaling of the distributions used in the fit of the published analyses
- Signal normalisation scaled to account the increase of collision energy from 13 TeV to 14 TeV (using recommendations from the LHCXSWG)
- Background normalisations corrected to account the increase of collision energy from 13 TeV to 14 TeV (scaling the normalisation by 1.18 accounting for the change in gluon-luminosity)
- Experimental systematic uncertainties kept constant with their Run-2 values
- Statistical uncertainties on data-driven backgrounds scaled following Poisson statistics corresponding to the target dataset size
- MC statistical uncertainties neglected

$b\bar{b}\gamma\gamma$ dedicated new analysis using simulations at 14 TeV:

- Truth-level simulations with smearing applied to emulate the upgraded ATLAS detector response
- Systematic uncertainties kept constant with their Run-2 values
- Signal region defined applying a cut on the output of a BDT and $123 < m_{\gamma\gamma} < 127$ GeV
- Final discriminant: $m_{HH}$ distribution

\[ ATLAS \text{ Simulation Preliminary} \]
\[ \sqrt{s} = 14 \text{ TeV, } 3000 \text{ fb}^{-1} \]

\[ 123 \text{ GeV} < m_{\gamma\gamma} < 127 \text{ GeV} \]

- SM HH $\rightarrow b\bar{b}\gamma\gamma$
- Single Higgs
- $b\bar{b}\gamma\gamma$
- Reducible
- Others
- Stat. unc.

\[ m_{HH}[\text{GeV}] \]

\[ \text{Events / 20 GeV} \]
Expected $4\sigma$ for $\kappa_\lambda = 1$

Expected allowed $0.1 < \kappa_\lambda < 2.3$ at 95% C.L.
Prospects measurements at the HL-LHC: double-Higgs ans single-Higgs combination

- $\kappa_{\chi}$-only fit and global fit possible in single-Higgs
- Double-Higgs is driving the bound, but single-Higgs data allow to perform a global fit and to remove the degenerate minima around $\kappa_{\chi} = 5$