HH production at the HL-LHC with CMS

Sylvie Braibant
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on behalf of the CMS Collaboration
In the Standard Model (SM), the Brout-Englert-Higgs (BEH) self-coupling $\lambda$ is **uniquely determined** by the structure of the **scalar potential**

$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

where

$$\lambda_3 = \lambda_4 = \frac{m_h^2}{2v^2}$$

depends only on BEH field VEV and mass

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**Experimental measurement of the trilinear BEH coupling $\lambda_3$**

- Crucial **test of the ESB mechanism**
- Unique way to probe the **existence of BSM physics** as a modification of $\lambda_3$
  - Anomalous trilinear coupling
  - New resonance decaying to HH
HH Production

- Production dominated by **gluon-gluon fusion mode**

  ![Diagram showing gluon-gluon fusion](image)

- **Small inclusive cross section** due to negative interference between the two diagrams

  $$\sigma = 36.59^{+2.1\%}_{-4.9\%} \text{ fb at } \sqrt{s} = 14 \text{ TeV}$$

  Value at the NNLO of the perturbative QCD calculation, including NNLL corrections and finite top quark mass effects

  ![Diagram showing small inclusive cross section](image)

  → need **HIGH LUMINOSITY**
HH Decay

- $H \rightarrow bb$ chosen for one $H$ boson to keep $BR$ high enough
- Five decay channels for the other $H$: $H \rightarrow bb, WW, \tau\tau, ZZ, \gamma\gamma$

Trade off between $BR$ and purity

- $H \rightarrow \gamma\gamma/ZZ$ channels: small $BR$ but strong sensitivity given their low-background level

<table>
<thead>
<tr>
<th>Channel</th>
<th>$B$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>33.6</td>
</tr>
<tr>
<td>bb$\tau\tau$</td>
<td>7.3</td>
</tr>
<tr>
<td>bb$WW(\ell\ell\ell\ell)$</td>
<td>1.7</td>
</tr>
<tr>
<td>bb$\gamma\gamma$</td>
<td>0.26</td>
</tr>
<tr>
<td>bbZZ($\ell\ell\ell\ell$)</td>
<td>0.015</td>
</tr>
</tbody>
</table>

BR $HH \rightarrow xxyy$ ($m_H = 125$ GeV)
**LHC → HL-LHC**

**LS3 (2024-2026): LHC major upgrade**

**Pileup [PU]:** average number of proton-proton collisions per bunch crossing → major challenge for the experiments

**HL-LHC**

$L = 5 \times (7.5) \cdot 10^{34} \text{ cm}^2 \text{ s}^{-1}$

$\sqrt{s} = 14 \text{ TeV}$

$\text{PU} = 200$

~3000 fb$^{-1}$ per experiment

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LHC major upgrade:
- **LS1**: 2011-2014
  - 7 TeV
  - Experiment beam pipes
  - 76% nominal luminosity
  - 30 fb$^{-1}$
- **LS2**: 2015-2018
  - 13 TeV
  - Injector upgrade
  - 150 fb$^{-1}$
- **LS3**: 2019-2023
  - 14 TeV
  - Experiment upgrade phase 1
  - 2 x nominal luminosity
  - 300 fb$^{-1}$

HL-LHC major upgrade:
- **LS3**: 2024-2026
  - 14 TeV
  - 5 to 7 x nominal luminosity
  - 3000 fb$^{-1}$
Performance compromised by radiation damage and increased pileup

Detector upgrades crucial to maximise physics potential and maintain a good object reconstruction in this harsh environment → increased radiation hardness, increased forward acceptance, higher granularity ...

New Tracker
- Increased radiation hardness
- Higher granularity
- Increased forward acceptance up to $\eta = 4$
- Reduced material in the tracker volume
- Tracks in hardware trigger (L1)

New Endcap Calorimeter
- Radiation tolerant
- High granularity (HGCAL)
- Timing information

Muons
- In the forward region, improved RPC
  + new GEM detectors → Increased acceptance up to $\eta \sim 3$
- Front-end electronics upgrade for DT’s and CSC’s

On-going efforts:
- MIP Timing Detector TDR (Oct 2019)
- L1/HLT TDR (2019/2020)

See Pallabi Das’s talk
CMS Upgraded Detector Simulation

DELPHES
- Fast *parametric* simulation software
  - Simulate the *response of the CMS upgraded detector*
  - Account for the **PU: +200** minimum bias interactions simulated with PYTHIA8
  - Extensively compared and tuned from full simulation based on GEANT4

Projections
- Use DELPHES samples
  - Optimised for a projected integrated luminosity of 3000 fb⁻¹
  - Ultimate collider scenario with \( \mathcal{L} = 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) might provide up to 4000 fb⁻¹
Largest $BR$ amongst the HH final states
Large contamination from the multijet background $\rightarrow$ experimentally challenging

“Resolved” event topology
- 4 b-jets all reconstructed separately

Event selection:
- $\geq 4$ b-jets with $p_T > 45$ GeV and $|\eta| < 3.5$
- Jet pairing based on combination minimising difference in invariant mass of the two jet pairs

Use of BDT to identify the signal contribution in the overwhelming background

Event Yields

<table>
<thead>
<tr>
<th>Event</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH signal</td>
<td>1370</td>
</tr>
<tr>
<td>Background</td>
<td>$1.1 \cdot 10^7$</td>
</tr>
</tbody>
</table>
**HH → bbττ**

- Sizeable $BR = 7.3\%$ → experimentally favourable

- Events exclusively selected into 3 final states with $\geq 1 \tau_{had}$ (85%):
  $e\tau_{had}, \mu\tau_{had}, \tau_{had}\tau_{had}$

- $\geq 2$ b-jets with $p_T > 30$ GeV and $|\eta| < 2.4$

**Event Yields**

<table>
<thead>
<tr>
<th></th>
<th>$\mu\tau_{had}$</th>
<th>$e\tau_{had}$</th>
<th>$\tau_{had}\tau_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HH signal</strong></td>
<td>100</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>$4.3\cdot10^6$</td>
<td>$2.9\cdot10^6$</td>
<td>$1.25\cdot10^3$</td>
</tr>
</tbody>
</table>

- **Neural-network based discriminant** to separate the signal from the background

52 input variables

Transverse mass
HH $\rightarrow$ bbWW $\rightarrow$ bb$\ell\nu\ell\nu$

- bb$\ell\nu\ell\nu$ final states with $\ell = e, \mu$

**Dominant backgrounds** are irreducible:
- tt production in fully leptonic decay mode
- Drell-Yan production of lepton pairs + jets

<table>
<thead>
<tr>
<th>Event Yields</th>
<th>$ee$</th>
<th>$\mu\mu$</th>
<th>$e\mu+\mu e$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HH signal</strong></td>
<td>50</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>$2.9\cdot10^6$</td>
<td>$8.4\cdot10^6$</td>
<td>$7.5\cdot10^6$</td>
</tr>
</tbody>
</table>

- Kinematic properties combined in a **Neural Network** (NN) discriminant to enhance sensitivity (9 input variables)

- **Very powerful discrimination** against background
HH → bbγγ

Tiny $\mathcal{B}$ but experimentally very clean → large sensitivity

Backgrounds:

- **Non-resonant** di-photon events
- **Resonant background**: Higgs boson production in association with two top quarks (ttH):
  - suppressed by a dedicated multivariate discriminant with 12 variables
  - rejection of 75% of the ttH contamination for a signal efficiency of 90%

<table>
<thead>
<tr>
<th>Event Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH signal</td>
</tr>
<tr>
<td>Res. bckg</td>
</tr>
<tr>
<td>Non-res. bckg</td>
</tr>
</tbody>
</table>

$Pseudo\text{-}data$

Nonresonant backgr.

Full backgr.

Sig. + Full backgr.

CMS Phase-2

Simulation Preliminary

$pp \rightarrow HH \rightarrow \gamma\gamma b\bar{b}$

HP, 480 GeV < $M_X$

3000 fb$^{-1}$ (14 TeV)

Events/(1.6 GeV)

Sylvie Braibant  HH production at the HL-LHC with CMS  11/07/2019
HH → bbZZ → bb\(\ell\ell\ell\ell\)

- Very rare but clean final states: 4e, 4\(\mu\), 2e2\(\mu\) channels
- Background processes are mostly single H production
  - ttH, ggH, ZH, WH, VBF
- Other backgrounds: ttZ, ttZZ

**Events selection:**
- \(\geq 4\) isolated muons (electrons) with \(p_T > 5(7)\) GeV and \(|\eta| < 2.8\)
- Z candidates from pairs of \(\ell^+\ell^-\)→ Z\(_1\) and Z\(_2\)
- \(50 \leq Z_1 \leq 100\) GeV and \(12 \leq Z_2 \leq 60\) GeV
- \(\geq 1\) \(\ell\) with \(p_T > 20\) GeV and \(\geq 1\) \(\ell\) with \(p_T > 10\) GeV
- \(120 \leq m_{4\ell} \leq 130\) GeV

**Event Yields**

<table>
<thead>
<tr>
<th>(HH \rightarrow bb4\ell)</th>
<th>Event Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH signal</td>
<td>1.0</td>
</tr>
<tr>
<td>Background</td>
<td>6.8</td>
</tr>
</tbody>
</table>
Combined Results on Signal Strength

- Statistical combination of the 5 decay channels
- Both systematic and statistical uncertainties considered
- In analyses using DELPHES and $L = 3000$ fb$^{-1}$: systematic uncertainties are “floor” values

Signal strength:

$$\mu = \frac{\sigma_{HH}}{\sigma_{SM}^{HH}} < 0.77 \ @ \ 95\% \ C.L.$$ 

$\rightarrow$ with a corresponding significance of $2.6\ \sigma$

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<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance Stat. + syst.</th>
<th>Significance Stat. only</th>
<th>95% CL limit on $\sigma_{HH}/\sigma_{SM}^{HH}$ Stat. + syst.</th>
<th>95% CL limit on $\sigma_{HH}/\sigma_{SM}^{HH}$ Stat. only</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>0.95</td>
<td>1.2</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>bb$\tau\tau$</td>
<td>1.4</td>
<td>1.6</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>bbWW($\ell\nu\ell\nu$)</td>
<td>0.56</td>
<td>0.59</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>bb$\gamma\gamma$</td>
<td>1.8</td>
<td>1.8</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>bbZZ($\ell\ell\ell\ell\ell\ell$)</td>
<td>0.37</td>
<td>0.37</td>
<td>6.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Combination</td>
<td><strong>2.6</strong></td>
<td><strong>2.8</strong></td>
<td><strong>0.77</strong></td>
<td><strong>0.71</strong></td>
</tr>
</tbody>
</table>
Prospects for the measurement of $\lambda_3$

Scan of the likelihood as a function of the coupling modifier $K_\lambda$:

$$K_\lambda = \frac{\lambda_3}{\lambda_3^{\text{SM}}}$$

Projected confidence interval on $K_\lambda$:

- [0.35, 1.9] at the 68% CL
- [-0.18, 3.6] at the 95% CL
Constraint on $k_\lambda$ from Differential Cross Section

- Differential cross section measurement using Higgs $p_T$ can disentangle the H self-coupling effects from anomalous top-Higgs coupling
- $ttH$ and $tH$ events with $H \rightarrow \gamma\gamma$ decay selected in hadronic or leptonic final states depending on top decay

Projected confidence interval on $K_\lambda$:
- $[-4.1, 14.1]$ at the 95% CL
Summary

- HL-LHC will **significantly increase physics reach** of LHC experiments BUT
  - **Challenging experimental conditions** for experiments (unprecedented pileup)
  - **Extensive detector upgrades** will preserve performance and provide new capabilities

- HH production: **a top priority research subject**
  - Rate limited due to the small HH cross-section → **excellent case for the HL-LHC**
  - Direct access to the shape of the scalar potential
  - Sensitive to BSM physics effects

- **Current prospects**
  - Importance of **exploring and combining many decay channels**
  - Projected sensitivity to SM HH is $\sim 3\sigma$
  - Projected confidence interval on the $K_\lambda$ coupling modifier:
    - $[0.35, 1.9]$ at the 68% CL
    - $[-0.18, 3.6]$ at the 95% CL
Backup
- HH@LHC Run2 (2016): not yet sensitive to SM HH production because of small cross section and large backgrounds

- Observed (expected) signal strength:
  \[ \mu = \frac{\sigma_{HH}}{\sigma_{SM}} < 22.2 \ (12.8) @ 95\% \text{ C.L.} \]

→ Decay channel combination essential for an evidence of HH production
Event and Detector Simulation

**Parton level generation**
- Madgraph5_aMC@NLO for signal and most backgrounds
- POWHEG for top processes (i.e., ttH)

**PYTHIA8**
- Parton shower and decay

**DELPHES**
- Fast *parametric* simulation software
- Simulate the *response of the CMS upgraded detector*
- Account for the PU: +200 minimum bias interactions simulated with PYTHIA8
- Extensively compared and tuned from full simulation based on GEANT4

**Analyses**
- Optimised for a projected integrated luminosity of 3000 fb\(^{-1}\)
- Ultimate collider scenario with \(\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\) might provide up to 4000 fb\(^{-1}\)
Feynman diagrams that contribute to HH production by gluon-gluon fusion (LO):

- Gluon fusion HH production described by 5 parameters: $\kappa_\lambda$, $\kappa_t$, $c_g$, $c_{2g}$ and $c_2$
- Deviations from SM values parametrized with multiplicative factors $\kappa_\lambda$ and $\kappa_t$
- Contact interactions $ggH$, $gg2H$, $ttHH$ parametrized with absolute couplings $c_g$, $c_{2g}$, and $c_2$
- Relevant part of the Lagrangian then takes the form

$$
\mathcal{L}_h = \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v} (v + \kappa_t h + \frac{c_2}{v} h h) (\bar{t}L \tau_R + h.c.) + \frac{1}{4} \frac{\alpha_s}{3\pi v} \left( c_g h - \frac{c_{2g}}{2v} h h \right) G^{\mu\nu} G_{\mu\nu}.
$$
Parameter values of the 12 benchmarks and the SM point

Expected upper limits for non-resonant $HH \rightarrow bbbb$ in the SM and shape benchmarks (1–12)

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$\kappa_\lambda$</th>
<th>$\kappa_t$</th>
<th>$c_2$</th>
<th>$c_g$</th>
<th>$c_{2g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5</td>
<td>1.0</td>
<td>-1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>-0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>1.0</td>
<td>-1.5</td>
<td>0.0</td>
<td>-0.8</td>
</tr>
<tr>
<td>4</td>
<td>-3.5</td>
<td>1.5</td>
<td>-3.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.8</td>
<td>-1</td>
</tr>
<tr>
<td>6</td>
<td>2.4</td>
<td>1.0</td>
<td>0.0</td>
<td>0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>7</td>
<td>5.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>8</td>
<td>15.0</td>
<td>1.0</td>
<td>0.0</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>-0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>10</td>
<td>10.0</td>
<td>1.5</td>
<td>-1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>11</td>
<td>2.4</td>
<td>1.0</td>
<td>0.0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>12</td>
<td>15.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SM</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
HH → bbbbb

- **Largest $BR$ amongst** the HH final states
- Large contamination from the multijet background → **experimentally challenging**

**Two complementary strategies:**

**“Resolved” event topology**
- 4 b-jets **all reconstructed** separately

**“Boosted” event topology:**
- Large $m_{HH}$ → high Lorentz boost of both Higgs bosons
- 2 b-jets overlap → **single large-area jet**

**Event selection:**
- $\geq 4$ b-jets with $p_T > 45$ GeV and $|\eta| < 3.5$
- Jet pairing based on combination minimising difference in invariant mass of the two jet pairs

**Event selection:**
- 2 boosted $H\rightarrow bb$, each associated with a single AK8 jet
- 2 leading-$p_T$ AK8 jets with $p_T > 300$ GeV and $|\eta| < 3.0$
- Events classified as having exactly 3 or exactly 4 b-tagged subjets
“Resolved” event topology

<table>
<thead>
<tr>
<th></th>
<th>Event Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH signal</td>
<td>1370</td>
</tr>
<tr>
<td>Background</td>
<td>1.1·10⁷</td>
</tr>
</tbody>
</table>

Use of BDT to identify the signal contribution in the overwhelming background

“Boosted” event topology

- Use AK8 $m_{JJ}$ invariant mass

<table>
<thead>
<tr>
<th></th>
<th>Event Yields</th>
<th>3b cat</th>
<th>4b cat</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH signal</td>
<td>95</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>1.08·10⁶</td>
<td>1.4·10⁵</td>
<td></td>
</tr>
</tbody>
</table>

CMS Phase-2

Simulation Preliminary

**HH → bbbb**
“Boosted” event topology

- Most sensitive to EFT shape benchmark 2 → contact interactions

<table>
<thead>
<tr>
<th>Event Yields</th>
<th>$3b$ cat</th>
<th>$4b$ cat</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH signal</td>
<td>95</td>
<td>15</td>
</tr>
<tr>
<td>Benchmark 2</td>
<td>537</td>
<td>61</td>
</tr>
<tr>
<td>$\sigma = 10$ fb</td>
<td>1.08·10$^6$</td>
<td>1.4·10$^5$</td>
</tr>
<tr>
<td>Background</td>
<td>1.08·10$^6$</td>
<td>1.4·10$^5$</td>
</tr>
</tbody>
</table>

$AK8 m_{JJ}$ (GeV)
In analyses using DELPHES and an integrated luminosity at the HL-LHC of 3000 fb\(^{-1}\), systematic uncertainties are the “floor” values reported in table.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Working point/ component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron ID</td>
<td>All WPs, (p_T &gt; 20) GeV</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>All WPs, (10 &lt; p_T &lt; 20) GeV</td>
<td>2.5%</td>
</tr>
<tr>
<td>Photon ID</td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Muon ID</td>
<td>All WPs</td>
<td>0.5%</td>
</tr>
<tr>
<td>Tau ID</td>
<td>All WPs</td>
<td>2.5%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Total</td>
<td>1–2.5%</td>
</tr>
<tr>
<td></td>
<td>Absolute scale</td>
<td>0.1–0.2%</td>
</tr>
<tr>
<td></td>
<td>Relative scale</td>
<td>0.1–0.5%</td>
</tr>
<tr>
<td></td>
<td>PU</td>
<td>0–2%</td>
</tr>
<tr>
<td></td>
<td>Jet flavor</td>
<td>0.75%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td></td>
<td>3–5% as a function of (\eta)</td>
</tr>
<tr>
<td>b-tagging</td>
<td>b jets (all WPs)</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>c jets (all WPs)</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Light jets, loose WP</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Light jets, medium WP</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Light jets, tight WP</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Subjet b tagging</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>Double c tagging</td>
<td></td>
</tr>
<tr>
<td>(p_T^\text{miss})</td>
<td>Propagate jet energy corrections uncertainties (must)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Propagate jet energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>resolution uncertainties (recommended)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vary unclustered</td>
<td></td>
</tr>
<tr>
<td></td>
<td>energy by 10% (recommended)</td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td></td>
<td>1%</td>
</tr>
</tbody>
</table>
Assuming no HH signal, 95% CL upper limits on the SM HH production cross section as a function of the coupling modifier $K_\lambda$:

$$K_\lambda = \frac{\lambda_3}{\lambda_{3,\text{SM}}}$$

Total HH cross section has a quadratic dependence on $K_\lambda$ with a minimum at $K_\lambda = 2.45$.

Variation of the excluded cross section directly related to changes in the HH kinematic properties.

Combined Results on HH Production Cross section

CMS Phase-2

3000 fb$^{-1}$ (14 TeV)

95% CL upper limits - Median expected

- $b\bar{b}b\bar{b}$
- $b\bar{b}VV(l\nu l\nu)$
- $b\bar{b}\gamma\gamma$
- $b\bar{b}ZZ^*(4l)$
- Combination

Theoretical prediction

- Simulation Preliminary
  Assumes no HH signal
A simple combination is performed of the measurements from the ATLAS and CMS collaborations.

The significances are added in quadrature and the negative-log-likelihood are simply added together.

<table>
<thead>
<tr>
<th></th>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATLAS</td>
<td>CMS</td>
</tr>
<tr>
<td>$HH \to b\bar{b}bb$</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>$HH \to b\bar{b}\tau\tau$</td>
<td>2.5</td>
<td>1.6</td>
</tr>
<tr>
<td>$HH \to b\bar{b}\gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>$HH \to b\bar{b}VV (ll\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
</tr>
<tr>
<td>$HH \to b\bar{b}ZZ (4l)$</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>combined</td>
<td>3.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Combined significance of 4 $\sigma$ achieved with all systematic uncertainties included.

Combined

4.5

Combined

4.0
Projected confidence interval on the $K_\lambda$ coupling modifier:

- $[0.52, 1.5]$ at the 68% CL