HH measurements in ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

HL-LHC and HE-LHC workshop

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Motivation for HH studies

- HH cross-section and differential distributions sensitive to
  
  the Higgs boson trilinear coupling ($\lambda_{HHH}$)

  → Probe ElectroWeak Symmetry Breaking
  
  → Measure the shape of Higgs potential

- Possible deviations or limits can be parametrised
  
  by low-energy effective Lagrangian (EFT)
Non-resonant double Higgs cross section

$\sigma_{gg\rightarrow HH}^{\text{SM}}(14 \text{ TeV})=39.56 \text{ fb @ NNLO\_NNLL with top mass effects, (arXiv.1610.07922)}$

with relative error in %: $^{+4.4}_{-6.0}$ (scale)$\pm 2.1$ (PDF)$\pm 2.2(\alpha_s)$

$\rightarrow \sim 120k \text{ events at HL-LHC}$

$\sigma_{gg\rightarrow HH}\sim 33 \text{ fb @ 13 TeV} \rightarrow O(1200) \text{ events in 2017 LHC data (40 fb}^{-1})$

ATL-PHYS-PUB-2014-019

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

- LO $\rightarrow$ NNLO\_NNLL: Factor $\sim 2$
- Shape almost independant on $\sqrt{s}$

More in G. Heinrich talk

S. Jézéquel, HL-LHC/HE-LHC Workshop 2017
Final state particles mainly produced in the central part of the detectors
→ Within acceptance of current trackers
→ Direct extrapolation from Run2 to HL-LHC : Good first approximation
HH decay channels

- **bbbb**:
  - Large number of signal events
  - Large QCD and t\(\bar{t}\) background

- **bbWW**:
  - Large number of signal events
  - Large t\(\bar{t}\) background

- **bb\(\tau\)\(\tau\)**
  - Balance between purity and efficiency

- **bb\(\gamma\)\(\gamma\)**
  - Low number of signal events
  - Narrow H \(\rightarrow \gamma\gamma\) mass window with low background

- **WW\(\gamma\)\(\gamma\)**
Background contamination

Example: \( HH \rightarrow bb\gamma\gamma \)

- Irreducible background (Cross-section: 1000 * signal)
- Single H (Cross-section: 10-1000 * signal)
- Reducible (Cross-section: Up to \( 10^9 \) * signal)

Can be worse for other HH decay channels
Analysis strategy

Main selection criteria
- Particle identification
- Single particle $P_T/\eta$ acceptance
- Invariant mass
- Angles between particles

Cut flow vs MVA selection
+ Count vs fit methods

HH significance expected at HL-LHC
$S/\sqrt{B} \sim O(2-0.3)$ per channel
HH : self-coupling sensitivity

- Current analysis selection optimised to maximise significance for SM
- \( m_{HH}, Pt(H), \ldots \) distributions sensitive to coupling

\[ \rightarrow \text{Optimal selection cuts not identical to maximise significance versus minimise coupling limits} \]

Selection efficiency depends on \( \kappa_\lambda \)
Technical challenges

- Detector operation in HL-LHC environment
  → Adressed now with detector optimisation and R&D

- Full simulation and reconstruction of signal/background not possible at HL-LHC scale (nb background events, CPU and memory consumption / event)
  - Solution 1: Extrapolate from Run2 results
    - Issue: Estimation of pileup effect and performances of new detector
  - Solution 2: Events described at particle level convoluted with parametrised detector response (efficiency, resolution, fake rate): 'smearing function'
    - Issue: Usually QCD background level/shapes not well modeled

- Large datasets → systematic uncertainty can become critical
  - How to estimate future systematics?
    - ✓ Extrapolate from current Run-1/Run-2 systematics
    - ✓ Background control with data driven methods
Run1/2 results

- ATLAS: $\sigma/\sigma_{SM} < 48$ @ 95% C.L.
- CMS: $\sigma/\sigma_{SM} < 43$ @ 95% C.L.

95% C.L. limits on $\mu = \sigma/\sigma_{SM}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbbbb</td>
<td>29 (38)</td>
<td>342 (308)</td>
</tr>
<tr>
<td>bbbVV</td>
<td></td>
<td>79 (89)</td>
</tr>
<tr>
<td>bb\tau\tau</td>
<td>28 (25)</td>
<td></td>
</tr>
<tr>
<td>bb\gamma\gamma</td>
<td>117 (161)</td>
<td>19 (17)</td>
</tr>
<tr>
<td>WW\gamma\gamma</td>
<td>747 (386)</td>
<td></td>
</tr>
</tbody>
</table>

2015-2016 Run-2 data: Better limit than Run1

Run-1

Run-2


CMS-PAS-HIG-15-013
HH → bbγγ (B.R. ~0.3%)
HH $\rightarrow$ bb$\gamma\gamma$ : Selection

2 b-tagged jets + 2 photons:
Narrow $\gamma\gamma$ mass peak, $m(bb)$, $\Delta R(\gamma\gamma)$, $\Delta R(bb)$
**HH → bbγγ : Significance**

*Smearing function approach*
- Cut and count method
- 2.9 % signal efficiency
- No syst. uncertainty

<table>
<thead>
<tr>
<th>Channel</th>
<th>Nb events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single H</td>
<td>15.8</td>
</tr>
<tr>
<td>Irreducible bbγγ</td>
<td>21.8</td>
</tr>
<tr>
<td>Reducible (bbjγ,...)</td>
<td>53.4</td>
</tr>
<tr>
<td>Signal</td>
<td>9.5</td>
</tr>
</tbody>
</table>

→ Significance : 1.05 σ

Extrapolation from Run2 analysis/data (*CMS-PAS-HIG-16-032*)
- 2D fit of \( m(γγ) - m(bb) \) distributions
- **Syst. uncertainty**: S2+ scenario

→ Significance : 1.43 σ
HH → bbbb (B.R. ~33%)
HH → bbbb : Selection

4 b-tagged jets:
m(4 jets), b pairings matching $m_H$

Extrapolation from Run2 analysis/data (ATLAS+CMS)

Main background: multijet, $t\bar{t}$

$\langle \mu_{PU} \rangle = 200$

→ Significance: 0.39 $\sigma$
HH → bbbb : Significance degradation

Wrong/correct pairing assignment

- Run 2 : 30 GeV
- HL-LHC : 50-70 GeV
→ Up to 30% loss in sensitivity
HH $\rightarrow$ bb$\tau\tau$ (B.R. $\sim$7.3%)
HH → bbττ: Selection

2 b-tagged jets + 2 τ (fully hadronic or semi-leptonic):
m(bb), m(ττ)

Main backgrounds:

- had-e/μ: tt
- had-had: Z → ττ + jets, tt

Smearing function approach

Extrapolation from Run2

CMS-PAS-HIG-16-012
HH → bbττ: Significance

ATLAS Projection (3 ab⁻¹)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>e/μ + jets</td>
<td>0.43</td>
<td>0.60</td>
</tr>
<tr>
<td>τ_{had}τ_{had}</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

Syst. Uncertainty: Run 1

→ Significance: 0.39 σ
Coupling limits (@ 95% C.L.)

\[-0.8 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 7.7 \text{ (no syst.)}\]

\[-3.5 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 11 \text{ (Run2 syst.)}\]

\[-4 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 12 \text{ (Run1 syst.)}\]

ATLAS combination expected in 2018

S. Jézéquel, HL-LHC/HE-LHC Workshop 2017
HH → bbVV → bbℓνℓν (B.R. ~1.8%)
HH $\rightarrow$ bbVV $\rightarrow$ bblννν

2 b-tagged jets + 2 leptons + missing E_T

Main background (estimated from data): t¯t, Drell-Yan

$\rightarrow$ Significance: 0.45 $\sigma$
HH $\rightarrow$ bbWW $\rightarrow$ bb$\ell\nu qq$ (B.R. $\sim 2.5\%$)
**HH → bbWW → bblvqq**

2 b-tagged jets + ≥ 2 jets + 1 e/μ + missing $E_T$

- Parametrised studies with fast simulation (DELPHES)
- $\sqrt{s}=14$ TeV with $\mu=200$
- Main background: $t\bar{t}$ (cross section $10^5$ higher than signal)
- Boosted Decision Tree (BDT) based on kinematic variables
  → 68 signal events for 8696 background ones

**Relative uncertainty on fitted signal strength (%)**

**95% CL upper limit on $\sigma / \sigma_{\text{SM}}$**
HH : Associated production

Lower cross sections than HH by at least factor 10

No destructive interference $\rightarrow \sigma_{ttHH} \sim 1$ fb
Final states:
- $t\bar{t}$ : semileptonic
- $HH \rightarrow 4b$
  $\rightarrow 6$ b-jets + 2 light jets + $e$ or $\mu$ + missing-$E_T$

Cut based analysis:
- Main variables: Nb b-tagged jets, angle between jets
- For $\geq 5$ b-tag jets: 25 signal events and 7100 background (mainly $t\bar{t}b\bar{b} +$ jets)

$\Rightarrow$ Significance: 0.35 $\sigma$
Expected HH results at HL-LHC

<table>
<thead>
<tr>
<th>HH final state</th>
<th>ATLAS Significance</th>
<th>CMS Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coupling limit (95 % C.L.)</td>
<td></td>
</tr>
<tr>
<td>HH → bb\gamma</td>
<td>1.05 σ, -0.8 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 7.7</td>
<td>1.43 σ</td>
</tr>
<tr>
<td>HH → bb\tau\tau</td>
<td>0.6 σ, -4.0 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 12.0</td>
<td>0.39 σ</td>
</tr>
<tr>
<td>HH → bbbb</td>
<td>-3.5 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 11.0</td>
<td>0.39 σ</td>
</tr>
<tr>
<td>HH → bbVV</td>
<td></td>
<td>0.45 σ</td>
</tr>
<tr>
<td>ttHH, HH→ bbbb</td>
<td>0.35 σ</td>
<td></td>
</tr>
</tbody>
</table>

Improved results already in the pipeline (especially for HL-LHC TDRs)
Conclusion

HH physics is one of the benchmark channels for HL-LHC program

Current expected significance per experiment at the level of 0.5-1.5 $\sigma$

Improvement foreseen driven by:

- Detector optimisation documented in the coming TDRs
- Analysis algorithms developed for Run2
- Combination of channels and experiments
- Optimisation of analysis for coupling limits

Many improvements foreseen for the Yellow Report
Posters

- Prospects on HH production at the HL-LHC with the CMS experiment  
  S. Wertz

- HH->bbyy and triple H coupling in ATLAS  
  D. Briglin
Backup slides
\[ \mathcal{L}_h = \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v} (v + \kappa_t h + \frac{c_2}{v} h h) (t_L t_R + h.c.) + \frac{1}{4} \frac{\alpha_s}{3\pi v} (c_g h - \frac{c_{2g}}{2v} h h) G^{\mu\nu} G_{\mu\nu}. \]
**ATLAS analysis strategy**

- **Parametrised performances of upgraded detector layout**
  - Use fully simulated events with pile-up to parametrise efficiency/resolution for particle/object ($e, \gamma, \mu, \tau, \text{jet, missing-}E_T$)
  - Particles at event-generator level smeared according to these functions
  - Overlay with pile-up jets

- **Extrapolation from Run-2 results**
  - Assume similar detector performances and analysis approach as Run-2
  - Scale signal and background level to higher luminosity/CM

- **Theoretical systematics**: Implement the ones used for Run-2 publications (will have decreased by HL-LHC time)

- **Experimental systematics**: Scaled to best guess for ATLAS upgraded detector at HL-LHC
CMS analysis strategy

- Assuming $\sqrt{s}=13$ TeV and just extrapolate to HL-LHC luminosity
  $\rightarrow$ Underestimate significance by 15%
- Data driven analysis from 2015 data ($O(2 \text{ fb}^{-1})$)

**ECFA S1:**
- Same CMS detector performance as in reference note
- All systematic uncertainties kept constant with luminosity

**ECFA S2:**
- Same CMS detector performances as in reference note
- Theoretical uncertainties scaled down by factor 2
- Experimental systematics scaling down with $\sqrt{L}$ untill some limits

**ECFA S2+:**
- Higher pileup and detector upgrades taken into account
- Same treatment for systematic uncertainties as S2
HH : CMS detailed numbers

CMS Projection $\sqrt{s} = 13$ TeV SM gg → HH

$\mathcal{L} = 3$ ab$^{-1}$

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<table>
<thead>
<tr>
<th>Channel</th>
<th>Median expected limits in $\mu_t$</th>
<th>Z-value</th>
<th>Uncertainty as fraction of $\mu_t = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg → HH → $\gamma\gamma$bb (S2+)</td>
<td>ECFA16 S2: 1.44</td>
<td>ECFA16 S2: 1.43</td>
<td>ECFA16 S2: 0.72</td>
</tr>
<tr>
<td>gg → HH → $VV$bb</td>
<td>ECFA16 S2: 5.2</td>
<td>ECFA16 S2: 0.39</td>
<td>ECFA16 S2: 2.6</td>
</tr>
<tr>
<td>gg → HH → $V$bb</td>
<td>ECFA16 S2: 4.8</td>
<td>ECFA16 S2: 0.45</td>
<td>ECFA16 S2: 2.4</td>
</tr>
<tr>
<td>gg → HH → $bb$bb</td>
<td>ECFA16 S2: 7.0</td>
<td>ECFA16 S2: 0.39</td>
<td>ECFA16 S2: 2.5</td>
</tr>
</tbody>
</table>
ATLAS Preliminary

ATLAS Preliminary

Systematic uncertainty from Run2 data
### Run1 results

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\gamma\gamma bb$</th>
<th>$\gamma\gamma WW^*$</th>
<th>$bb\tau\tau$</th>
<th>$bbbb$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upper limit on the cross section [pb]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td>1.0</td>
<td>6.7</td>
<td>1.3</td>
<td>0.62</td>
<td>0.47</td>
</tr>
<tr>
<td>Observed</td>
<td>2.2</td>
<td>11</td>
<td>1.6</td>
<td>0.62</td>
<td>0.69</td>
</tr>
</tbody>
</table>

| **Upper limit on the cross section relative to the SM prediction** |
| Expected   | 100                 | 680                  | 130          | 63     | 48       |
| Observed   | 220                 | 1150                 | 160          | 63     | 70       |


CMS (CMS-HIG-15-013) : $\sigma/\sigma_{SM} < 43$ @ 95% C.L. ($bb\gamma\gamma + bb\tau\tau$)
HH → $b\bar{b}γγ$ : all mass distributions
HH → bbττ : Selection (backup)

Run2 plots

S. Jézéquel, HL-LHC/HE-LHC Workshop 2017
ATLAS : 95% C.L. limits :

-0.2< $\lambda_{HHH}/\lambda_{SM}$< 7 (negligible syst.)

-3.5< $\lambda_{HHH}/\lambda_{SM}$< 11 (current syst.)

-3.4< $\lambda_{HHH}/\lambda_{SM}$< 12 (Trigger $p_T$ > 75 GeV)

<$\mu_{PU}$>=200
ttHH production

S. Jézéquel, HL-LHC/HE-LHC Workshop 2017