Search and prospects for HH production

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Non-resonant HH production

\[ \sigma_{\text{gg}\rightarrow HH} = 33.49^{+4.3}_{-6.0} \text{ (scale)} \pm 2.1 \text{ (PDF)} \pm 2.3 \text{ (}\alpha_s\text{) fb} \]

- \( \sigma_{\text{HH}} \): main way to extract Higgs trilinear coupling \( \lambda_{\text{HHH}} \)
  - direct information on the shape of the scalar Higgs potential
  - dominated by gg fusion, other production modes out of reach with current data
- Destructive interference of the two diagrams \( \rightarrow \) small \( \sigma_{\text{HH}} \)
- Effective lagrangian used to model BSM effects: anomalous \( \lambda_{\text{HHH}} \) and \( y_t \) couplings and three new contact interactions
  - large modification of \( \sigma_{\text{HH}} \)

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19/03/2017
Many different theories predict resonant Higgs pair production $X \rightarrow HH$
- just a few examples quoted in the scheme!

Very different theoretical motivation, but similar experimental signature

Full coverage of a broad $m_X$ range is crucial to maximize the sensitivity to different models
- no “golden” channel, multiple analysis techniques

Resonant HH production would be evidence for a new state, not predicted by the SM
Phenomenologically rich set of final states

One $H \rightarrow bb$ or $H \rightarrow WW$ decay required to keep BR high enough
- common techniques across analyses (e.g. b-tagging) + channel-specific challenges

Complementarity of the channels
- similar sensitivity to non-resonant production
- different coverage in $m_X$

BR $HH \rightarrow xxyy$
($m_H = 125$ GeV)
Four channels explored and combined in ATLAS

- $\gamma\gamma\gamma\gamma$ and $bb\tau\tau$ with similar sensitivity at low mass, $bb\gamma\gamma$ dominant at high mass
- $bb\gamma\gamma + bb\tau\tau + bbbb$ explored in CMS but not combined yet
- exclude 58 $X$ SM ($bb\tau\tau$), 74 $X$ SM ($bb\gamma\gamma$)
- High BR, large contamination from multijet background
  - estimated from data
- Two event topologies explored
  - resolved: four separate jets
  - boosted: jets from $H \rightarrow bb$ decay overlap, use jet with radius 0.8/1.0 + substructure techniques
- Crucially relies on b-tagging
  - b-tag at trigger level for resolved analyses
  - double b-tagging on 0.8 radius jet based on multivariate method for CMS boosted analysis
- Invariant masses of selected jets used to search for a signal
### ATLAS:
- 13.3 fb$^{-1}$ analyzed
- non-resonant search excludes 29 X SM

### CMS
- 2.3/2.7 fb$^{-1}$ analyzed
- non resonant search excludes 324 x SM
- search for both spin-0 and spin-2 resonances
**HH → bbWW**

- $WW \rightarrow \ell \nu \ell \nu$ ($\ell = e, \mu$) $\Rightarrow$ bbew, bbew, bbew
- Dominant background: tt (same final state)
  - constrained from $m_{bb}$ sideband
- Exploit event kinematics to select signal using BDT
  - used as final discriminant
- Updated results on 35.9 fb$^{-1}$ are coming for Moriond QCD!
- 3 $\tau\tau$ final states: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$
  - require the presence of $\mu$, $e$, $\tau_h$ candidates and 2 jets in the event
  - $m_{\tau\tau}$ (from likelihood technique) and $m_{bb}$ must be compatible with $m_H = 125$ GeV

- Main backgrounds:
  - $tt$: from MC simulation
  - Drell-Yan: MC simulation corrected in data $Z \rightarrow \mu\mu$ sideband
  - multijet: from data sideband

- Categorization on the selected $H \rightarrow bb$ jet candidates
  - 2b-tagged jet category
  - 1b-tagged jet + 1 untagged jet category
  - "boosted" category with a $R=0.8$ jet to improve reconstruction $H$ decays at high $m_X$
- tt background rejected with BDT method in $\mu\tau_h$ and $e\tau_h$ final states
  - based on angular separation of leptons and reconstructed H candidates and $m_T$
- Fitted observables:
  - resonant search: kinematic reconstruction of HH decay
  - non-resonant search: “stransverse mass” $M_{T2}$ that has optimal separation of signal from background

$$m_{T2} \equiv \min_{p_{T1}+p_{T2}=p_T^{\tau\tau}} \{ \max[m_T(m_{b1}, p_T^{b1}, m_{vis}, p_{T1}), m_T(m_{b2}, p_T^{b2}, m_{vis}^{\tau2}, p_{T2})] $
Non-resonant search excludes 28 times the SM
- anomalous $\lambda_{HHH}$ and $y_t$ couplings tested
- sensitive to the sign of $y_t$

Resonant production tested up to $m_X = 900$ GeV, and interpreted in the hMSSM
- Rare but very clean final states
  - large signal acceptance
  - main background from continuum $jj\gamma\gamma (+\ell)$ production estimated from data
  - exploit excellent resolution on $m_{\gamma\gamma}$ to look for a signal

- Two photons and two jets in the event for $bb\gamma\gamma$
- One additional lepton for $WW\gamma\gamma\rightarrow jj\ell\nu\gamma\gamma$
- Dedicated methods to improve $m_{bb}$ resolution
- Additional categories with 2 and 1 b-tagged jets for CMS $bb\gamma\gamma$
Results overview

- Complementarity in different mass ranges
- much to gain from a combination!

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS Obs. (exp.) 95% C.L. limit on $\sigma/\sigma_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>29 (38) 342 (308)</td>
</tr>
<tr>
<td>bbWW</td>
<td>- 410 (227)</td>
</tr>
<tr>
<td>bb$\tau\tau$</td>
<td>28 (25)</td>
</tr>
<tr>
<td>bb$\gamma$</td>
<td>117 (161) 91 (90)</td>
</tr>
<tr>
<td>WW$\gamma$</td>
<td>747 (386) -</td>
</tr>
</tbody>
</table>

![Graph showing limits on various channels for ATLAS and CMS](image)

**NOTE:** ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses
Measurement of $\sigma_{HH}$ and determination of $\lambda_{HHH}$ are one of the main points of the physics programme at the HL-LHC (3 ab$^{-1}$ of data)

Two alternative approaches to estimate the sensitivity to HH production

- parametric simulation of upgraded detector response
- extrapolation of results from 13 TeV, 2.3/2.7 fb$^{-1}$ to HL-LHC (conservative: current results not optimal for high luminosity)

Future prospects

- $bb\gamma\gamma$, $bb\tau\tau$ and $bbbb$ studied

Best significance is 1.05$\sigma$ from $bb\gamma\gamma$

Combination of final states and of ATLAS and CMS will be crucial to observe HH production.
Conclusions

- What can we learn from HH production?
  - search for new physics via resonant production
  - probe the 5-dimensional structure of the BSM effective Lagrangian
  - access the shape of the scalar Higgs field via $\lambda_{HHH}$

- Where do we stand?
  - several HH final states explored at 13 TeV by ATLAS and CMS
  - no sign of (B)SM HH production yet: best limit is $28 \times$ SM

- What’s next?
  - more updated results with full 2016 luminosity
  - new HH final states and a combination are coming soon
  - projections show that in the long term (HL-LHC) we can have some sensitivity to SM HH, but analyses are evolving quickly, and we expect to do better!
HH is (almost) at reach!

HH → bbττ or background?

We expect to have already recorded a few HH events
Additional material
Effective Lagrangian parametrization

- Effective Lagrangian obtained by adding dim-6 operators to the SM Lagrangian
- Results in a modification of the SM $\lambda_{HHH}$ and $y_t$ couplings and introduces three new contact interactions
  - changing these 5 couplings affect $\sigma_{HH}$ and the HH kinematics
- Analyses are exploring the 5-dimensional space of these couplings
  - a parametrization of $\sigma_{HH}(\lambda_{HHH}, y_t, c_2, c_g, c_{2g})$ is used

![Feynman diagrams](image)
In the Standard Model (SM), after the EWSB, the Higgs potential can be written with the following form.\(^76\)

- **Limit set as a function of the ratio** \(k_\lambda/k_t\) with \(k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}\) and \(k_t = y_t/y_t^{SM}\)
- **The shape of the signal depends only on the ratio of the couplings for the gg fusion mechanisms**
  - under the assumption that the other BSM couplings \(c_2, c_g, c_2g\) are zero

\[\text{Combined channels} \quad \text{Observed} \quad \text{Expected} \quad \text{Theory prediction}\]

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19/03/2017
- 13.3 fb⁻¹ (ATLAS) and 2.3 fb⁻¹ (CMS) analyzed
- Different set of triggers used: require 1 or 2 b-tagged jets (ATLAS) or 3 b-tagged jets (CMS)
- Different definition of control regions: both use a mass sideband, but ATLAS also inverts the b-tag requirement
- Require two jets with cone 1.0 (ATLAS) / 0.8 (CMS)
  - trigger: one R=1.0 jet (ATLAS), jets+ H_T sums (CMS)
- b-tag criteria applied
  - ATLAS: categories with 2/3/4 b-tagged track-jets matched
  - CMS: two separate methods
    1) b-tag on sub-jets + 3-4 tag categorization
    2) double-b tagging MVA algorithm on R=0.8 jet
- Background from data
  - ATLAS: multijet+tt yield simultaneous fit to jet-mass distribution in sideband. Multijet shape from data.
  - CMS: two separate methods
    1) simultaneous functional fit of signal and bkg to data
    2) interpolation of b-untagged/b-tagged event ratio vs. m_{lead} into the signal region
Some details on the selections and techniques used in the two analyses

- $2 \gamma$ of $E_T/m_{\gamma\gamma} > 0.35 \ (0.25)$
- $2$ jets of $p_T > 55 \ (35)$ GeV, both b-tagged
- signal selection efficiency is 5-8% (resonant with $m_X < 400$ GeV) and 10% (non-resonant)
- $bb$ 4-momentum rescaled by $m_H/m_{bb}$
- fit over $m_{\gamma\gamma}$ for non-resonant search, counting experiment in $m_{\gamma\gamma bb}$ window in resonant search

- $2 \gamma$ of $E_T > 30 \ (20)$ GeV and $E_T/m_{\gamma\gamma} > 0.33 \ (0.25)$
- $2$ jets of $p_T > 25$ GeV, 1 and 2 b-tag categories
- signal selection efficiency is $\sim 20\%$ for $m_X < 400$ GeV
- multivariate regression method to estimate $m_{bb}$
- improved 4-body mass resolution using $m_X = m_{jj\gamma\gamma} - m_{jj} + 125$ GeV
- $2D$ fit over $(m_{\gamma\gamma}, m_{bb})$ in a window around $m_{bb\gamma\gamma}$ (resonant search) and for $m_{bb\gamma\gamma} > 350$ GeV (non-resonant search)