Non-resonant HH production

- Unique probe of the B.E.H. mechanism
  - provides access to the measurement of the Higgs self-coupling $\lambda$
  - brings information on the shape of the Higgs potential

Gluon Fusion (ggF) dominant production mode

- Process predicted by the SM
- BSM effects can result in anomalous couplings: $\lambda$, $y_t + 3$ contact interactions (EFT approach)

Small variation of the couplings from the prediction

Large modification of the cross section

e.g. $\delta k_\lambda = 1 \rightarrow \frac{\sigma^{BSM}_{ggF}}{\sigma^{SM}_{ggF}} \sim 20$

*State-of-the-art NNLO prediction of ggF cross section at 13 TeV: $31.05^{+2.2%}_{-5.0%}$ fb

JHEP 05 (2018) 059
10.23731/CYRM-2017-002

C. Amendola (LLR)

In the 2016 analyses, $\sigma_{ggF}(13\text{ TeV}) = 33.49^{+4.3%}_{-6.0%}$ fb is used

Higgs Hunting

July 30, 2019

2 / 15
Resonant HH production

Look for a new narrow resonance $X$ with mass $m_X > 2m_H$

- Not predicted in the SM, but in several extensions
- Different theoretical scenarios, but similar signature
- CP-even spin-0 or spin-2 particles predicted
- Need to cover a wide mass range:

  - **MSSM/2HDM**: 250 to 350 GeV  
  - **Singlet Model**: 250 GeV to 1 TeV  
    *J. Z. Phys C 75 (1997) 17*
  - **Warped Extra Dimensions**: 250 GeV to 3 TeV  
    *Phys. Rev. Lett. 83, 3370*
**Final states**

Rich set of final states accessible at the LHC
2016 (35.9 fb$^{-1}$) CMS public analyses:

**bb**
- largest BR, large QCD and $t\bar{t}$ contamination
- (non-res) JHEP04 (2019) 112 NEW!
- (res) JHEP01 (2019) 040 NEW!
- JHEP08 (2018) 152
- PLB 781 (2018) 244

**bbVV**
- large $t\bar{t}$ contamination,
  $BR(2\ell2\nu) = 2.7\%$
- JHEP 01 (2018) 054 NEW!
- bbZZ($2\ell2j$) CMS PAS HIG-18-013 NEW!

**bb$\tau\tau$**
- good compromise between BR and purity
- PLB 778 (2018) 101
- JHEP 1901 (2019) 051 NEW!

**bb$\gamma\gamma$**
- low branching ratio, high purity
- PLB 788 (2019) 7 NEW!

- Trade-off between BR and purity
- coverage of different phase spaces
- different sensitivity in different mass ranges

Combination of the 2016 analyses

Phys. Rev. Lett. 122, 121803 NEW!
**HH→bbbb (non-resonant)**

Two searches performed:
- 4 resolved b-tagged jets (best sensitivity to SM), results shown here
- one bb pair highly boosted (sensitive to specific BSM topologies)

**Main challenge:** QCD background contamination

- b-tag is crucial, used from trigger level (3 bjets)
- BDT technique optimised for SM HH signal
- Dedicated data-driven method for QCD estimation: hemisphere mixing
- Signal extraction from BDT output

**Limits**

\[ \frac{\lambda}{\sigma_{SM}} = k_\lambda = 75 (37) \times \sigma_{SM} \]

95% CL upper limits
- Observed
- Median expected
- 95% expected
- 68% expected

**SM obs (exp):** 75 (37) \( \times \sigma_{SM} \)

\( k_\lambda = \lambda/\lambda_{SM} \) (\( k_t = 1 \)) scan: no exclusion
**Low mass** Resolved
- At least 3 b-tagged jets
- Data-driven QCD estimation from sidebands of Higgs candidates masses

**High mass** Boosted + Semi-boosted
- 2 large-area jets or 1 large-area jet + 2 jets, passing b-tag or double-b discriminator
- QCD background measured from sidebands of large-area jet mass and double-b discriminator

**Excluded mass ranges**
- **Radion**: 260-280 GeV; 300-450 GeV; 480-1120 GeV; no exclusion in high mass region
- **Graviton**: 320-450 GeV; 480-720 GeV; no exclusion in high mass region (backup)
Resonant and non-resonant searches performed

- Event categories: bbee, bbµµ, bbµµ
- Dominant backgrounds: tt (irreducible), DY
  - Data-driven DY estimation
- DNN to improve signal-background separation
  - Output used as final discriminant

Limits

SM obs (exp): 79 (89) × σ_{SM}

\( k_λ - k_t \) scan performed

No exclusion on Radion nor Graviton mass

Also public: bbZZ(2\ell 2j) CMS PAS HIG-18-013

NEW!
Comprehensive set of results on resonant and non-resonant searches

- Final states: \((e\tau_h, \mu\tau_h, \tau_h\tau_h) + 2\) jets
- Categorisation on number (1/2) of b-tagged jets
  - Boosted category: only 1 b-tagged large-area jet + substructure requirements
- BDT technique to reject \(tt\) background in \(e\tau_h, \mu\tau_h\) channels
- Signal extraction from kinematic variables:
  - Resonant search: kinematic fit of HH decay (fit based on 4-momenta of the \(\tau\) and b candidates and on \(\vec{p}_{T}^{miss}\))
  - Non-resonant search: “stransverse mass” \(MT_2\) (largest mass of the parent particle compatible with the kinematic constraints of the event)

**Limits**

- \(SM\) obs (exp): 31 (25) \(\times \sigma_{SM}\)
- \(k_\lambda-k_t\) scan performed
- Additional hMSSM interpretation
- No exclusion on Radion nor Graviton mass
Resonant and non-resonant searches performed: most sensitive channel to SM HH

- Main backgrounds: nγ+jets, single-H
- Categorisation in MVA and reduced mass:
  \[ M_X = m_{\gamma\gamma} bb - (m_{bb} - m_H) - (m_{\gamma\gamma} - m_H) \]

Signal extraction through 2D likelihood \( m_{\gamma\gamma} \times m_{bb} \)

- 10% improvement w.r.t. 1D fit on \( m_{\gamma\gamma} \): better discrimination against single-H

MVA to efficiently discriminate against nγ+jets

Striking improvement at low mass using \( M_X \)

---

**Limits**

**SM obs (exp):** \( 24 \times 19 \times \sigma_{SM} \)

(VBF HH signal inclusion improves sensitivity by 1.3%)

Constrained \( \lambda \) to \(-11 < k_\lambda < 17\)

Radion (\( \Lambda_R = 3 \) TeV): excluded \( m_X < 540 \) GeV
Graviton: excluded \( 290 < m_X < 810 \) GeV (backup)

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C. Amendola (LLR)  Higgs Hunting  July 30, 2019  9 / 15
Combination: resonant searches

Different sensitivities in different regions

- Limits also set for spin-2 hypothesis
- No significant excess observed

NEW! Phys. Rev. Lett. 122, 121803
SM combined limit: 22 (13) \times \sigma_{SM}

- Run I combination obs (exp) limit:
  43 (46) \times \sigma_{SM}

BSM obs (exp) constraints:

-11.8 < k_\lambda < 18.8 (-7.1 < k_\lambda < 13.6)
BSM benchmarks

Producing samples for all the combinations of couplings would be computationally prohibitive.

Anomalous couplings clustering strategy used in all analyses: JHEP 04 (2016) 126

Parameter space divided into 12 regions (+ SM + λ = 0 scenarios) with similar kinematics.

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$k_\lambda$</th>
<th>$k_t$</th>
<th>$c_2$</th>
<th>$c_g$</th>
<th>$c_{2g}$</th>
</tr>
</thead>
<tbody>
<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>7</td>
<td>5.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.2</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

CMS supplementary

95% CL upper limit on $\sigma(pp\rightarrow HH)$ [fb]

Assumes SM Higgs boson branching fractions

35.9 fb$^{-1}$ (13 TeV)

Complementary sensitivity of all analyses

The hierarchy of the analyses sensitivity is different in different BSM scenarios.
Perspectives for HH searches

- Getting closer to the observation of SM Higgs pair production:
  \[ 22 \times (13) \times \sigma_{SM} \text{ with } 35.9 \text{ fb}^{-1} \]
  - the single analyses are constantly improving
  - full Run II statistics: \( \sim 150 \text{ fb}^{-1} \)

**Projection using 2015 data at 13 TeV**

- CMS PAS FTR-16-002
  - \( bb\tau\tau \) already overperformed the projected results
    - result: \( 25 \times \sigma_{SM} \text{ with } 35.9 \text{ fb}^{-1} \)
    - projection: \( 25 \times \sigma_{SM} \text{ with } 100 \text{ fb}^{-1} \)

- Updated projections: CERN-LPCC-2018-04 NEW!
  - CMS PAS FTR-18-019 NEW!
Projected sensitivity of the combination of the 4 existing analyses + rare but clean $bbZZ(4\ell)$

- DELPHES fast parametric simulation: upgraded CMS response (see Elisa Fontanesi’s talk in this conference)
- $PU = 200, \mathcal{L} = 3000 \text{ fb}^{-1}$

<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>$bbWW(\ell\nu\nu)$</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>$bbZZ(\ell\ell\ell\ell)$</td>
<td>0.37</td>
<td>0.37</td>
<td>6.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Combination</td>
<td>2.6</td>
<td>2.8</td>
<td>0.77</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Projected constraints on $k_\lambda$:

- $[0.35, 1.9]$ at 68% CL
- $[-0.18, 3.6]$ at 95% CL

HH searches are an excellent case for HL-LHC
Non-resonant and resonant Higgs pair production searches are performed in 4 different channels with 2016 data. Different channels have different sensitivities. The combination of channels brings a significant improvement: \( \text{obs (exp)} = 22 \pm 13 \times \sigma_{SM} \text{ with } 35.9 \text{ fb}^{-1} \).

The 2016 analyses performed better than the pre-existing predictions! Advanced analysis techniques not fully exploited yet (e.g. DNN). The observation of the SM Higgs pair production is definitely within reach of HL-LHC.
Backup
HH $\rightarrow$ bbbb (non-resonant)

Resolved analysis

Boosted analysis

95% CL upper limits
- Observed
- Median expected
- 68% expected
- 95% expected

CMS (13 TeV)

35.9 fb$^{-1}$

Shape benchmark

C. Amendola (LLR)
HH → bbbb (resonant)

Low mass Resolved
- At least 3 b-tagged jets
- Data-driven QCD estimation from sidebands of Higgs candidates masses

High mass Boosted + Semi-boosted
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$HH \rightarrow bb\tau\tau$

**95% CL on $\sigma \times B(S \rightarrow HH \rightarrow bb\tau\tau)$ [fb]**

<table>
<thead>
<tr>
<th>$m_S$ [GeV]</th>
<th>$95%$ CL upper limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>Observed</td>
</tr>
<tr>
<td>350</td>
<td>Median expected</td>
</tr>
<tr>
<td>400</td>
<td>68% expected</td>
</tr>
<tr>
<td>450</td>
<td>95% expected</td>
</tr>
<tr>
<td>500</td>
<td>Radion $\Lambda_R = 3$ TeV, $k_l = 35$, no R/H mixing</td>
</tr>
</tbody>
</table>

**Combined channels**

$bb\tau\tau + bb\tau\tau + bb\tau\tau$

**95% CL upper limits**

- Observed
- Median expected
- 68% expected
- 95% expected
- Theoretical prediction

**$k_l/k_t$**

$bb\tau\tau + bb\tau\tau + bb\tau\tau + bb\tau\tau$

Combined channels