Non-resonant Higgs boson pair production at the LHC

Olivier Bondu
on behalf of the ATLAS & CMS collaboration

CP3 - UC Louvain

2016-11-11 - Higgs Couplings 2016
Motivation (1): access the scalar potential

hh production in the Standard Model

- **Direct access** to the self-coupling $\lambda$
  - SM scalar potential structure:
    \[ V(h) = \frac{m_h^2}{2} h^2 + \lambda vh^3 + \frac{\lambda}{4} h^4 \]

- **Key property measurement** of $h(125)$
- Main production at LHC: gluon fusion

<table>
<thead>
<tr>
<th>LHCHXSWG</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma_{\text{NNLO+NNLL}}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>10.16</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>33.45</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>39.56</td>
</tr>
</tbody>
</table>

$m_h = 125$ GeV

Major setback: very low production cross-section

- Strong destructive interference of the two main diagrams
- By (lack of) chance, SM is almost the most destructive case...
Motivation (2): Effective Field Theories

There is hope yet: we have some leeway...

- Self-coupling $\lambda$ predicted but (loosely) constrained experimentally
  - Experimental constraints of $O(n \times 10 - 100)$
- There exists other couplings in BSM scenarios:
  - $\kappa_\lambda = \lambda/\lambda_{SM}$, $\kappa_t = y_t/y_{t_{SM}}$, $c_2$, $c_g$, $c_{2g}(1502.00539, 1410.3471, 1407.0281)$
  - There exists alternatives (1607.05330) as well as indirect ways (1607.04251)
  - Cross-section can vary sensibly: $[10^{-1}, 10^4] \times \sigma(pp \rightarrow hh)^{SM}$
  - Signal shape can be significantly different from SM
- Model builders manage to accommodate deviations of $O(1)...$ we need to do better!

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Scan 5D parameter space: the clustering method

It is impractical to generate a 5D grid of signal samples

- LO generation and various theoretical arguments: most of the physics is contained in the $m_{hh}$ spectrum
  - and somewhat in $\cos(\theta)^*$
- Extensive discussions in a MITP TH-EXP workshop last year

The cluster analysis (JHEP04(2016)126, LHCHXSWG report 4 pp 202-206)

- Exp. analyses sensibility depend on the signal shape
- Cluster regions of the parameter space with similar kinematics
- Define benchmark points (BM): representative of a cluster
- Injection of the 12 benchmarks in the CMS full-sim MC prod.

O. Bondu (CP3 - UC Louvain)  (Non-res) Higgs boson pairs @ LHC  Higgs Couplings - 2016
Experimental signatures

Ultimate figure of merit: sensitivity

- \( hh \rightarrow b\bar{b}b\bar{b} \): \( BR = 33.3\% \), fully reconstructible, but large QCD background + combinatorics and trigger thresholds
- \( hh \rightarrow b\bar{b}\tau^{-}\tau^{+} \): \( BR = 7.27\% \), fully reconstructible, large \( t\bar{t} \) QCD backgrounds
- \( hh \rightarrow b\bar{b}WW(jj\ell\nu_\ell) \): \( BR = 7.2\% \), irreducible \( t\bar{t} \) background, \( \not{E}_T \)
- \( hh \rightarrow b\bar{b}WW(\ell\nu_\ell\bar{\nu}_\ell) \): \( BR = 1.23\% \), good triggers, irreducible \( t\bar{t} \) background, \( \not{E}_T \)
- \( hh \rightarrow b\bar{b}\gamma\gamma \): \( BR = 0.26\% \), excellent trigger thresholds and acceptance, relatively low background
- \( hh \rightarrow \gamma\gamma WW(jj\ell\nu_\ell) \): \( BR = 0.10\% \), excellent trigger thresholds, relatively low background
# List of LHC HH analyses

## Run I - 8 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( hh \rightarrow bb\gamma\gamma )</td>
<td>20 fb⁻¹ (Phys. Rev. Lett. 114 (2015) 081802)</td>
<td>19.7 fb⁻¹ (Phys. Rev. D 94 (2016) 052012)</td>
<td>XX</td>
<td>19.7 fb⁻¹ (Phys. Rev. D 94 (2016) 052012) (, \kappa_\lambda, c_2, \kappa_t )</td>
</tr>
<tr>
<td>( hh \rightarrow bb\tau^-\tau^+ )</td>
<td>20.3 fb⁻¹ (Phys. Rev. D 92 (2015) 092004)</td>
<td>18.3 fb⁻¹ CMS-PAS-HIG-15-013</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( hh \rightarrow bb)</td>
<td>19.5 fb⁻¹ (Eur. Phys. J. C 75 (2015) 412)</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( hh \rightarrow \gamma\gamma WW(jj, ll) )</td>
<td>20.3 fb⁻¹ (Phys. Rev. D 92 (2015) 092004)</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
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</table>

## Run II - 13 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( hh \rightarrow bb\gamma\gamma )</td>
<td>3.2 fb⁻¹ (ATLAS-CONF-2016-004)</td>
<td>2.70 fb⁻¹ (CMS-PAS-HIG-16-032)</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( hh \rightarrow bb\tau^-\tau^+) (ICHEP16)</td>
<td>XX</td>
<td>12.9 fb⁻¹ (CMS-PAS-HIG-16-028)</td>
<td>XX</td>
<td>12.9 fb⁻¹ (CMS-PAS-HIG-16-028) (, \kappa_\lambda, \kappa_t, BM )</td>
</tr>
<tr>
<td>( hh \rightarrow bb\tau^-\tau^+(Moriond16) )</td>
<td>XX</td>
<td>2.7 fb⁻¹ (CMS-PAS-HIG-16-012)</td>
<td>XX</td>
<td>2.7 fb⁻¹ (CMS-PAS-HIG-16-012) (, \kappa_\lambda )</td>
</tr>
<tr>
<td>( hh \rightarrow bb) (ICHEP16)</td>
<td>13.3 fb⁻¹ (ATLAS-CONF-2016-049)</td>
<td>2.32 fb⁻¹ (CMS-PAS-HIG-16-026)</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( hh \rightarrow bb) (Moriond16)</td>
<td>3.2 fb⁻¹ (Phys. Rev. D 94 (2016) 052002)</td>
<td>2.30 fb⁻¹ (CMS-PAS-HIG-16-024)</td>
<td>XX</td>
<td>2.30 fb⁻¹ (CMS-PAS-HIG-16-024) (, \kappa_\lambda, \kappa_t, c_2, c_1, BM )</td>
</tr>
<tr>
<td>( hh \rightarrow WW(jj, ll) )</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
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</tr>
</tbody>
</table>

## 13 TeV projections

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( hh \rightarrow bb\gamma\gamma )</td>
<td>XX</td>
<td>3000 fb⁻¹ (CMS-DP-2016-064)</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( hh \rightarrow bb\tau^-\tau^+ )</td>
<td>XX</td>
<td>3000 fb⁻¹ (CMS-DP-2016-064)</td>
<td>XX</td>
<td>XX</td>
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<tr>
<td>( hh \rightarrow bb)</td>
<td>XX</td>
<td>3000 fb⁻¹ (CMS-DP-2016-064)</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( hh \rightarrow bb) (ICHEP16)</td>
<td>XX</td>
<td>3000 fb⁻¹ (CMS-DP-2016-064)</td>
<td>XX</td>
<td>XX</td>
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</table>

## 14 TeV projections

<table>
<thead>
<tr>
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<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( tt)</td>
<td>3000 fb⁻¹ (ATL-PHYS-PUB-2016-023)</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( tt)</td>
<td>3000 fb⁻¹ (ATL-PHYS-PUB-2014-019)</td>
<td>3000 fb⁻¹ (CMS-PAS-FTR-15-002)</td>
<td>XX</td>
<td>3000 fb⁻¹ (ATL-PHYS-PUB-2014-019) (, \kappa_\lambda )</td>
</tr>
<tr>
<td>( tt)</td>
<td>3000 fb⁻¹ (ATL-PHYS-PUB-2015-046)</td>
<td>3000 fb⁻¹ (CMS-PAS-FTR-15-002)</td>
<td>XX</td>
<td>3000 fb⁻¹ (ATL-PHYS-PUB-2015-046) (, \kappa_\lambda )</td>
</tr>
<tr>
<td>( tt)</td>
<td>3000 fb⁻¹ (ATL-PHYS-PUB-2016-024)</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>( tt)</td>
<td>3000 fb⁻¹ (ATL-PHYS-PUB-2016-024)</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
</tbody>
</table>

O. Bondu (CP3 - UC Louvain) (Non-res) Higgs boson pairs @ LHC
Higgs boson was discovered in 2012. Since 2014...

- **4 papers** and **1 conference note** on 8 TeV data
- **1 paper** and **8 conference notes** on 13 TeV data
- **1+6 conference notes** on HL-LHC projections at 13 and 14 TeV
- Not to mention many more results on resonant searches
  - see Souvik Das’ talk (CMS) as well as BaoJia Tong’s talk (ATLAS)

Very active area in experimental collaborations
(and growing community)

I apologize for the large tables:
not all informations are provided on public documents
for a proper apple-to-apple comparison of everything...
hh $\rightarrow$ b\bar{b}b\bar{b} analyses (1)

Key points

- Larger BR: 33.9%
- Fully hadronic final state: HUGE QCD bkg

Analysis Strategy

- Set of multi-(b-)jets triggers
- 4 b-tagged, resolved jets
- consistent pairs with the Higgs mass
- Data-driven QCD background estimate
- tt, DY (SMHiggs) backgrounds estimated from simulation ( 10%)
  - yields from data in some cases
- Signal region from mh-mh plane (ellipse, $X_{hh}$)

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13 TeV HL-LHC: CMS-DP-2016-064
14 TeV HL-LHC: ATL-PHYS-PUB-2016-024

O. Bondu (CP3 - UC Louvain) (Non-res) Higgs boson pairs @ LHC

Higgs Couplings - 2016 8 / 19
hh → b-bb analyses (2)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>QCD bkg.</th>
<th>misc.</th>
<th>final discriminant</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS 8 TeV</td>
<td>2btag CR &amp; iter. kin. corrections</td>
<td>veto w/ ( n_{\text{jets}} ) and ( \chi^2 ) trigger, bkg. unc., ( \int L ), min ( p_T ) studies</td>
<td>cut-and-count ( m_{\ell\ell\ell} )</td>
</tr>
<tr>
<td>ATLAS-15 13 TeV</td>
<td></td>
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<tr>
<td>ATLAS-15+16 13 TeV</td>
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<tr>
<td>HL-ATLAS 14 TeV</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CMS-15 13 TeV</td>
<td>data-driven hemisphere mixing</td>
<td>cut on BDT(kin., angles)</td>
<td></td>
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<tr>
<td>HL-CMS 13 TeV</td>
<td></td>
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</tr>
</tbody>
</table>

\[ \sigma (\text{TeV}) \times \sigma^{\text{SM}} \times \text{BR (fb)} \]

<table>
<thead>
<tr>
<th>( \sqrt{s} ) (TeV)</th>
<th>( \sigma^{\text{SM}} \times \text{BR (fb)} )</th>
<th>95% CL upper limit on ( \sigma ) (pb) and ( \sigma \times \text{BR (fb)} ) obs. (exp.)</th>
<th>( \mu_{hh} ) (exp.)</th>
<th>unc. on ( \mu )</th>
<th>significance</th>
<th>anomalous couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>3.45</td>
<td>ATLAS 0.62 202 (0.62) 210 63 (63) 36 (N/A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>11.3</td>
<td>ATLAS-15 3.6 1220 29 (N/A) CMS-15 11.4 3880 (10.3) 3490 343 (308) &lt; 1( \sigma )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>11.3</td>
<td>HL-CMS (7.0) (2.5) (0.39)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>14</td>
<td>13.4</td>
<td>HL-ATLAS (1.5 - 5.2)</td>
<td></td>
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</tr>
</tbody>
</table>

Content in gray is not official

- Trigger, preselection, bkg estimation, signal extraction: **different strategies**
- **Most sensitive result to date (ATLAS):** important final state!

O. Bondu (CP3 - UC Louvain) (Non-res) Higgs boson pairs @ LHC
hh → b$\bar{b}$τ$^-$τ$^+$ analyses (1)

Key points

- BR: 7.27% (all tau decays)
- Fully reconstructible final state
- $t\bar{t}$ bkg dominating for $\tau_e\tau_h, \tau_\mu\tau_h$
- QCD, DY bkg dominating for $\tau_h\tau_h$

Analysis Strategy

- Single lepton and $\tau$ triggers
- $\tau$ ID (HPS, BDT, ...) with lepton veto
- $\tau\tau$ system reco. (MMC, SVfit)
- invariant mass windows
- QCD, fake $\tau$s from data
- DY → $\tau\tau$ with embedding (for 8 TeV)
- $t\bar{t}$, others (W, t, VV, SMH) from MC

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13 TeV: CMS-PAS-HIG-16-012, CMS-PAS-HIG-16-028
13 TeV HL-LHC: CMS-DP-2016-064

O. Bondu (CP3 - UC Louvain)

(Non-res) Higgs boson pairs @ LHC

Higgs Couplings - 2016
hh → b¯bτ−τ+ analyses (2)

Key differences

<table>
<thead>
<tr>
<th>analysis</th>
<th>channels</th>
<th>additional criteria</th>
<th>final discriminant</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS 8 TeV</td>
<td>τeτh, τμτh</td>
<td>n_b &lt; 3, m_{T'} &lt; 60 GeV, angular cuts</td>
<td>m_{T'}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(m_W, m_h) elliptic cut</td>
<td></td>
</tr>
<tr>
<td>CMS 8 TeV</td>
<td>τhτh</td>
<td>kin. fit, ΔR(τ, τ) &lt; 2</td>
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</tr>
<tr>
<td>CMS-15 13 TeV</td>
<td>τeτh, τμτh, τhτh</td>
<td>2jets(0,1,2)tag cat.</td>
<td></td>
</tr>
<tr>
<td>CMS-16 13 TeV</td>
<td>τeτh, τμτh, τhτh</td>
<td>cut on angular cut</td>
<td></td>
</tr>
<tr>
<td>HL-CMS 13 TeV</td>
<td>extrapolation of 2015 analysis, upgrade scenarios studies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HL-ATLAS 14 TeV</td>
<td>τeτh, τμτh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HL-CMS 14 TeV</td>
<td>τeτh, τμτh</td>
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</tbody>
</table>

Benchmark number

<table>
<thead>
<tr>
<th>√S (TeV)</th>
<th>σ^{SM} × BR (fb)</th>
<th>95% CL upper limit on</th>
<th>unc. on μ</th>
<th>significance</th>
<th>anomalous couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>σ (pb) and σ × BR (fb)</td>
<td>(exp.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.74</td>
<td>ATLAS 1.6 116 (1.3)</td>
<td>(94)</td>
<td>160 (130)</td>
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</tr>
<tr>
<td></td>
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<td>CMS 0.59 43 (0.94)</td>
<td>(94)</td>
<td>53 (84)</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.43</td>
<td>CMS-15 8.7 632 (7.2)</td>
<td>(523)</td>
<td>260 (215)</td>
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</tr>
<tr>
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<td>CMS-16 6.99 508 (5.78)</td>
<td>(420)</td>
<td>200 (170)</td>
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</tr>
<tr>
<td>13</td>
<td>2.43</td>
<td>HL-CMS (5.2 - 7.4)</td>
<td>(4.3)</td>
<td>(2.6 - 3.7)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2.88</td>
<td>HL-ATLAS (2.6 - 3.7)</td>
<td>(0.28 - 0.39)</td>
<td>(0.60)</td>
<td>(κ_λ \leq 50)</td>
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<td></td>
<td>HL-CMS (2.6 - 3.7)</td>
<td>(0.28 - 0.39)</td>
<td>(0.60)</td>
<td>(κ_λ \leq 50)</td>
</tr>
</tbody>
</table>

Content in gray is not official

- Very good sensitivity, and **sensitive to signal shape**
- **More data**: categories, variables, bkg estimates, ... **performance will improve**
hh → bbWW(jj\ell\bar{\ell}) analysis

Key points
- **BR**: 7.2%
- **Irreducible t\bar{t} background**
- Not fully reconstructible (1 d.o.f.)

Analysis strategy
- Delphes study with upgraded CMS detector
- Large PU: **importance of combinatorics and jet tools**
- Numerous variables as input to a BDT
- Cut and count analysis

<table>
<thead>
<tr>
<th>( \sqrt{s} ) (TeV)</th>
<th>( \sigma_{SM} \times BR ) (fb)</th>
<th>95% CL upper limit on ( \sigma ) (pb) and ( \sigma \times BR ) (fb) obs.</th>
<th>(exp.)</th>
<th>( \mu_{hh}^{\text{obs.}} ) ( \mu_{hh}^{\exp.} )</th>
<th>unc. on ( \mu )</th>
<th>significance</th>
<th>anomalous couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>2.85</td>
<td></td>
<td></td>
<td>( \frac{\sigma}{\sigma_{SM}} ) if N/A</td>
<td>(5.3)</td>
<td>(2.8)</td>
<td></td>
</tr>
</tbody>
</table>

Promising sensitivity: to be pursued with data analysis (?) soon from ATLAS!
hh → bbWW(ℓν_ℓbar ℓν_ℓbar) analyses

Key points

- BR: 1.23% (h → VV → ℓνℓν leg)
- Irreducible t¯t background
- Not fully reconstructible (2 d.o.f.)

Strategy

- Kin. MVA (no m_{jj})
- 2D fit (13 TeV) – MVA-cut and count (14 TeV)
- Providing numerical limits on 1459 points of the parameter space

- Same O(sensitivity) as other final states

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>σ^{SM} × BR (fb)</th>
<th>95% CL upper limit on σ (pb) and σ × BR (fb)</th>
<th>obs.</th>
<th>exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>0.411</td>
<td>CMS-15 13.6, 166.7 (7.5) (92.8^{+0.9}_{-30.4})</td>
<td>410 (227^{+147}_{-82})</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.411</td>
<td>HL-CMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.487</td>
<td>HL-CMS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Expected: allowed
Observed: allowed
excluded (95% CL)

anomalous couplings

K_λ, K_μ, C_2, C_9, C_{2g}, BM

O. Bondu (CP3 - UC Louvain)
hh → bbγγ analyses (1)

Key points

- Lowe BR (0.26%)
- fully reconstructible and clean final state - low background
- Excellent sensitivity - stat. limited

Analysis strategy

- Collect data with diphoton triggers
- Select 2 photons and 2 b-jets
- Use $m_{\gamma\gamma}$ resolution
- $\gamma\gamma+$ jets , $\gamma+$ jets , multijets directly fit in data, single h from simulation
  - Account for possible background mismodeling
hh → b\bar{b}γγ analyses (2)

Key differences

<table>
<thead>
<tr>
<th>analysis</th>
<th>selection</th>
<th>tools</th>
<th>categories</th>
<th>signal extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS 8 TeV</td>
<td>(p_T &gt; 55, 35 \text{ GeV})</td>
<td>(m_{b}) scaling</td>
<td>b-tag</td>
<td>fit (m_\gamma)</td>
</tr>
<tr>
<td>CMS 8 TeV</td>
<td>(p_T &gt; 25 \text{ GeV})</td>
<td>b-jet regr. ;</td>
<td>(\cos \theta_{th}) cut</td>
<td>b-tag, (m_{\gamma</td>
</tr>
<tr>
<td>ATLAS-15 13 TeV</td>
<td>Similar to ATLAS 8 TeV</td>
<td></td>
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<tr>
<td>CMS-15 13 TeV</td>
<td>b-jet regr. ; (m_{\gamma</td>
<td></td>
<td>}) cut</td>
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<tr>
<td>HL-CMS 13 TeV</td>
<td>Projection of CMS-15 13 TeV</td>
<td></td>
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<tr>
<td></td>
<td>accounting high-pu ((e(\text{ID})), (e(\text{vtx}))) upgrade / aging scenarios studied</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HL-ATLAS 14 TeV</td>
<td>angular cuts, (\leq 6) jets, lepton veto, (p_T^{\gamma}), (p_T^{b\bar{b}} &gt; 110 \text{ GeV})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HL-CMS 14 TeV</td>
<td>(p_T &gt; 40 \text{ GeV}, ) lepton veto, (\leq 4) jets, angular cuts upgrade / aging scenarios studied</td>
<td></td>
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</table>

\(\sqrt{s} \text{ (TeV)} \quad \sigma^{SM} \times \text{BR (fb)}\) | \(95\% \text{ CL upper limit on } \sigma \text{ (pb)} \quad \sigma \times \text{BR (fb)} \text{ obs.} \quad \text{exp.})\) | \(\frac{\text{obs.}}{\text{exp.}} \quad \text{if N/A} \quad \text{unc. on } \mu \quad \text{significance} \quad \text{anomalous couplings} \)

<table>
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<tr>
<td>8</td>
<td>2.64 × 10^{-2}</td>
<td>2.2</td>
<td>0.71</td>
<td>3.9</td>
<td>3.04</td>
<td>7.90</td>
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<td>8.70 × 10^{-2}</td>
<td>5.72</td>
<td>1.85</td>
<td>10.1</td>
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<td>7.90</td>
<td>10.1</td>
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- **Very similar analyses**
- **Very good sensitivity and sensitive to signal shape**, analyses are stat. limited,
- **More on (CMS) hh → b\bar{b}γγ analyses** in Rafael Teixeira De Lima talk

O. Bondu (CP3 - UC Louvain) (Non-res) Higgs boson pairs @ LHC
hh → γγWW(jjℓνℓ) analyses

Key points

- Lowest BR: 0.10%
- à la hh → b¯bbγγ: low BR, good trigger and selection eff., low bkg
- γγ continuum (Wγγ + jets) bkg.

Strategy

- h → γγ triggers
- 2 tight γ, 1 medium ℓ, 0 b-tag jet
- Fit \( m_{γγ} \) to estimate continuum bkg
- Cut on \( m_{γγ} \) and count

Stat. limited: more data coming!

<table>
<thead>
<tr>
<th>( \sqrt{s} ) (TeV)</th>
<th>( σ^{SM} ) × BR (fb)</th>
<th>95% CL upper limit on ( σ ) (pb) and ( σ \times BR ) (fb)</th>
<th>( \mu_{hh} ) obs. (exp.)</th>
<th>unc. on ( μ )</th>
<th>significance</th>
<th>anomalous couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.010</td>
<td>ATLAS 11 (11) (6.7) (6.7)</td>
<td>1150 (680)</td>
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<tr>
<td>13</td>
<td>0.033</td>
<td>ATLAS-16 25.0 (25.0) (12.9) (12.9)</td>
<td>757 (390)</td>
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</tbody>
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O. Bondu (CP3 - UC Louvain) (Non-res) Higgs boson pairs @ LHC

Higgs Couplings - 2016 16 / 19
Combinations: towards the end goal

L’union fait la force

- Not all (not any?) analyses has reached yet it’s full maturity: areas for improvements in each experiment
- Yet all final states have an expected sensitivity within one order of magnitude
- The end game will be to combine them all
- Even if the target seems far away yet, we might be lucky and BSM could be around the (hh-)corner...

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>σ^{SM} (fb)</th>
<th>95% CL upper limit on σ (pb)</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>obs. (exp.)</td>
<td>μ_{hh} (exp.)</td>
<td>unc. on μ</td>
<td>significance</td>
</tr>
<tr>
<td>8</td>
<td>10.16</td>
<td>ATLAS 0.69 (0.47)</td>
<td>70 (48)</td>
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<tr>
<td>14</td>
<td>39.56</td>
<td>HL-CMS</td>
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</tbody>
</table>

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O. Bondu (CP3 - UC Louvain) (Non-res) Higgs boson pairs @ LHC Higgs Couplings - 2016
**Bonus track: what about $t\bar{t}hh$?**

**Key points**

- $t\bar{t}hh \rightarrow b\ell\nu bjj(b\bar{b}b\bar{b})$
- low background, no loops in LO diagrams
- **Very low stat.**, combinatorics

**Strategy**

- Single lepton triggers, $\geq 7$ jets, 1 lepton, $\geq 5-6$ b-tagged jets
- Discriminant variable: $<\eta(b_i, b_j) > \left( \frac{\sum_{jets} p_T}{\sum_{jets} E} \right)$, $H_B = \sum_{b-jets} p_T$ also studied
- Jets combinatorics via $\chi^2$ or scalar sums
- cut and count

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\sigma^{SM}$ (fb)</th>
<th>95% CL upper limit on $\sigma$ (pb)</th>
<th>$\mu_{hh}^{obs.}$ ($\mu_{hh}^{exp.}$)</th>
<th>unc. on $\mu$</th>
<th>significance</th>
<th>anomalous couplings</th>
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</thead>
<tbody>
<tr>
<td>14</td>
<td>0.33</td>
<td>HL-ATLAS</td>
<td>$g_{SM}$</td>
<td>if N/A</td>
<td>(0.35)</td>
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- No hope of a stand-alone discovery (/ not much contribution to total hh rate)
Conclusion

Where we are

- SM $hh$ production is out of reach for the short term
- Experimental effort to make sure all interesting final state are considered, combination is likely the best answer
- Start **probing anomalous couplings**, BSM could be around the $hh$-corner

Where we are going:

- More final states!
  - ATLAS: $hh$, $bbWW$, $(jj\ell\ell)$
  - CMS: $hh$, $hh!bbZZ$

- More production modes!
  - Next stop: VBF ($10\%$ of the total production)

- 4-20 times more data: 40 fb$^{-1}$ to analyse (for the short term!)

- With more data comes improved analyses, we can do better than our own extrapolations: categorisation, data-driven bkg estimates, ...

Stay tuned! More Higgses, more fun!

O. Bondu (CP3 - UC Louvain)
Conclusion

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- **SM hh production is out of reach for the short term**
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- **More final states!**
  - ATLAS: $hh \rightarrow b\bar{b}WW(jj\ell\bar{\ell})$
  - CMS: $hh \rightarrow \gamma\gamma\gamma\gamma$, $hh \rightarrow b\bar{b}ZZ$
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**Stay tuned! More Higgeses, more fun!**
References

**hh → b¯b b¯b**


13 TeV HL-LHC: CMS-DP-2016-064

14 TeV HL-LHC: ATL-PHYS-PUB-2016-024

**hh → b¯b τ− τ+**


13 TeV HL-LHC: CMS-DP-2016-064


**hh → b¯b WW (jjℓ̅ℓ̅)**

14 TeV HL-LHC: CMS-DP-2016-064

**hh → b¯b WW (ℓ̅ν̅ℓ̅ ν̅ℓ)**

13 TeV: CMS-PAS-HIG-16-024

13 TeV HL-LHC: CMS-DP-2016-064

14 TeV HL-LHC: CMS-PAS-FTR-15-002

**hh → b¯b γγ**


13 TeV: CMS-PAS-HIG-16-032, ATLAS-CONF-2016-004

13 TeV HL-LHC: CMS-DP-2016-064


**hh → γγ WW (jjℓ̅ℓ̅)**


13 TeV: ATLAS-CONF-2016-071

**Combinations**


14 TeV HL-LHC: CMS-PAS-FTR-15-002

**tthh**

14 TeV HL-LHC: ATL-PHYS-PUB-2016-023