A theoretical review of triple Higgs coupling studies at the LHC

Deep Inelastic Conference 2014, Warsaw, Poland

Julien Baglio | 2014, April 30th
Outline

1. Introduction
2. SM Higgs pair production at the LHC
3. Status of the studies of the triple Higgs coupling in the SM
4. BSM studies of the triple Higgs coupling (bibliography)
5. Outlook
Motivation: probing the Brout-Englert-Higgs potential

- From the scalar potential before EWSB: with a scalar $SU(2)$–doublet field $\phi$, $Y_\phi = 1$:

$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

- $V(\phi)$ after EWSB, with $M_H^2 = 2m^2$, $v^2 = m^2/\lambda$:

$$\phi = \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2H^2 + \frac{1}{2}M_H^2vH^3 + \frac{1}{8}M_H^2v^2H^4 + \text{constant}$$
Motivation: probing the Brout-Englert-Higgs potential

- **Quartic Higgs coupling**: not accessible at current or foreseen collider energies ($\leq 100$ TeV) \cite{PlehnRauch}

- **Triple Higgs coupling**: the ultimate probe of the shape of the SM Brout-Englert-Higgs potential

- **BSM physics**: triple Higgs coupling can depend on gauge parameters (for example in SUSY) and be enhanced
Historical recap: the early studies

- **Early studies at lepton colliders:**
  - Studies at a 2 TeV $e^+e^-$ collider: SM triple Higgs coupling could be measured with a 10% accuracy for a light Higgs, in $\nu_e\bar{\nu}_eHH$ and $W^+W^-HH$ modes (VBF modes) 
    [Boudjema, Chopin, Z.Phys. C73 (1996) 85]
  - Complementary SM and MSSM studies: in addition to weak boson fusion, associated Higgs production with a weak gauge boson and triple Higgs production; 500 GeV $e^+e^-$ collider could be enough for a 20% accuracy on the triple Higgs coupling 
    [Djouadi, Kilian, Muhlleitner, Zerwas, Eur.Phys.J. C10 (1999) 27]

- **Early studies at the LHC:**
  - First study at the LHC: theoretical predictions for $HH$ production in the main channels, in the SM and MSSM 
    [Djouadi, Kilian, Muhlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45]
  - Comprehensive analysis of the $b\bar{b}\gamma\gamma$ channel: with a very high luminosity (6000 fb$^{-1}$) $\lambda = 0$ can be excluded at 90% CL 
    [Baur, Plehn, Rainwater, Phys.Rev.Lett. 89 (2002) 151801; Phys.Rev. D67 (2003) 033003; Phys.Rev. D69 (2004) 053004]
SM Higgs pair production at the LHC
The main production channels

- gluon fusion
  \[ g + g \rightarrow H + H \]

- vector boson fusion
  \[ \text{W, Z} + q \rightarrow H + H \]

- double Higgs–strahlung
  \[ \bar{q} + q \rightarrow W + H + H \]

- associated production with top quark
  \[ g + g \rightarrow t + \bar{t} + H + H \]

\[ \sigma(pp \rightarrow HH + X) \text{ [fb]} \]

- LO QCD
- NLO QCD
- NNLO QCD

\[ M_H = 125 \text{ GeV} \]

- \( q\bar{q}' \rightarrow HHq\bar{q}' \)
- \( q\bar{q}/gg \rightarrow t\bar{t}HH \)
- \( q\bar{q}' \rightarrow WHH \)
- \( q\bar{q} \rightarrow ZHH \)

\[ \sqrt{s} \text{ [TeV]} \]

SM Higgs pair production at the LHC

\[ \sim 1000 \text{ times smaller than } \sigma(pp \rightarrow H + X) \]

J. Baglio – \( HHH \) coupling at the LHC: theory review

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Gluon fusion: the largest cross section

LO inclusive cross section known exactly \((t + b \text{ loops})\) \([\text{Eboli et al., Phys.Lett. B197 (1987) 269; Glover, v.d. Bij, Nucl.Phys. B309 (1988) 282; Dicus, Kao, Willenbrock, Phys.Lett. B203 (1988) 457; Plehn, Spira, Zerwas, Nucl.Phys. B479 (1996) 46}]\)

**QCD corrections to inclusive rate in the low energy limit** \(\sqrt{s} \ll m_t\): NLO corrections \([\text{Dawson, Dittmaier, Spira, Phys.Rev. D58 (1998) 115012}] + NNLO corrections (new in 2013!), +20\% on top of NLO rate \([\text{De Florian, Mazzitelli, Phys.Lett. B724 (2013) 306; Phys.Rev.Lett. 111 (2013) 201801}]\)

**NLO (NNLO) \(K\)-factor \(\simeq 2\) \((2.3)\)**

\[
\begin{array}{|c|c|c|}
\hline
\sqrt{s} [\text{TeV}] & \sigma^{\text{NLO}} [\text{fb}] & \sigma^{\text{NNLO}} [\text{fb}] \\
\hline
8 & 8.2 & 9.8 \\
14 & 33.9 & 40.2 \\
33 & 207.3 & 242 \\
100 & 1417.8 & 1638 \\
\hline
\end{array}
\]

**NNLL resummation**: \(\simeq +20 - 30\%\) on top of NLO cross section, scale dependence stabilized

\([\text{Shao, C.S. Li, H.T. Li, Wang, JHEP 1307 (2013) 169}]\)
Gluon fusion: theoretical uncertainties

$gg \rightarrow HH$ affected by sizeable uncertainties:

- **Scale uncertainty:** calculated at NLO with $\frac{1}{2} \mu_0 \leq \mu_R, \mu_F \leq 2 \mu_0, \mu_0 = M_{HH}$
  
  $\Delta^{\text{scale}} \simeq +20\%(+12\%)/-17\%(−10\%)$ at $\sqrt{s} = 8(100) \text{ TeV}$

- **PDF uncertainty:** gluon PDF at high $-x$ less constrained, $\alpha_s(M_Z^2)$ uncertainty
  
  $\Delta^{\text{PDF+}\alpha_s}_{90\%CL} \simeq \pm 9\% \,(\simeq \pm 6\% \text{ at } 100 \text{ TeV})$ uncertainty

- **EFT approximation:** NLO correction only known in a top mass expansion (new 2013!)
  
  ⇒ estimate of $\pm 10\%$ uncertainty [Grigo, Hoff, Melnikov, Steinhauser, Nucl.Phys. B875 (2013) 1]

![Graph of $\sigma(gg \rightarrow HH)$ [fb] vs. $\sqrt{s}$ [TeV]]

**Total uncertainty:** $\simeq \pm 40\% \,(\simeq \pm 30\% \text{ at } 100 \text{ TeV})$ [J.B. et al, JHEP 1304 (2013) 151]

With recent NNLO calculation, scale uncertainty reduced to $\pm 9\%(\pm 6\%) \text{ at } 8 \,(100) \text{ TeV}$

[De Florian, Mazzitelli, Phys.Rev.Lett. 111 (2013) 201801]
Vector boson fusion at NLO

\[ pp \rightarrow qq \rightarrow qq\, WW/ZZ \rightarrow qqHH: \] the second production channel at the LHC

**LO inclusive cross section known for a while** [Keung, Mod.Phys.Lett. A2 (1987) 765; Eboli *et al*, Phys.Lett. B197 (1987) 269; Dicus, Kao, Willenbrock, Phys.Lett. B203 (1988) 457; Dobrovolskaya, Novikov, Z.Phys. C52 (1991) 427]

**QCD corrections:** NLO corrections to inclusive rates and differential distributions [J.B. *et al*, JHEP 1304 (2013) 151] implemented in VBFNLO (and now publicly available!) [Arnold *et al* Comput.Phys.Comm. 180 (2009) 1661; J.B. *et al*, arXiv:1404.3940]

\[ \approx +7\% \text{ correction} \]

(similar to single Higgs case)

| \( \sqrt{s} \) [TeV] | \( \sigma^\text{NLO} \) [fb] |
|--------------------|------------------|
| 8                  | 0.49             |
| 14                 | 2.01             |
| 33                 | 12.05            |
| 100                | 79.55            |

SM Higgs pair production at the LHC

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Vector boson fusion: theoretical uncertainties

qq → HHqq is a clean process:

- Scale uncertainty: calculated at NLO with $\frac{1}{2} \mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$, $\mu_0 = Q_W/Z$;
  $\Delta^{\text{scale}} \sim +3\% (+2\%) / -2\% (-1\%)$ at $\sqrt{s} = 8\, (33) \text{ TeV}$
  Good precision compared to LO $\Delta^{\text{scale}} \sim \pm 10\%$

- PDF uncertainty: total $\Delta^{\text{PDF}+\alpha_s}_{90\%CL} \sim +7\% / -4\%$ ($\sim +5\% / -4\%$ at 33 TeV)

**Total uncertainty:** $\sim +8\% / -5\%$ (14 TeV) [J.B. et al, JHEP 1304 (2013) 151]

**NNLO QCD corrections in the structure function approach:** +0.5% on top of the NLO result, scale uncertainty at the percent level [L. Liu-Sheng et al, Phys.Rev. D89 (2014) 073001]
**Monte Carlo tools and parton shower**

**Progress in 2014: Monte-Carlo tools including parton shower:**

- $gg \rightarrow HH$ merged to 1 jet: HERWIG++ implementation of $HH + 1j$ production with real radiation merged to parton shower ⇒ 10% theoretical uncertainty on the efficiencies of the cuts, much better than unmerged samples [Maierhöfer, Papaefstathiou, JHEP 1403 (2014) 126]

- All main processes interfaced with parton shower in the ac@NLO framework: fully differential predictions at NLO for all channels [Frederix et al, Phys.Lett. B732 (2014) 142]

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**HH production at the LHC14, NLO+PS**

**Unmerged**

| Process                        | Theory       | Experiment |
|--------------------------------|--------------|------------|
| $pp \rightarrow HH$ (EFT loop-improved) | PY8          | HW6        |
| $pp \rightarrow HHj$ (VBF)        |              |            |
| $pp \rightarrow Whh$              |              |            |
| $pp \rightarrow Whh$              |              |            |
| $pp \rightarrow Zhh$              |              |            |

**Merged**

| Process                        | Theory       | Experiment |
|--------------------------------|--------------|------------|
| $pp \rightarrow HH$ (EFT loop-improved) | NLO+PY8      | NLO+HW6    |
| $pp \rightarrow WHH$            |              |            |
| $pp \rightarrow ZHH$            |              |            |

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**SM Higgs pair production at the LHC**

J. Baglio – $HHH$ coupling at the LHC: theory review

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Status of the studies of the $HHH$ coupling in the SM
Parton level analysis: overview of the main channels

Where to look for HH production? production cross section small $\Rightarrow$ use $H \rightarrow b\bar{b}$ decay channel at least once to retain some signal; foreseen luminosity at the LHC of $3000 \text{ fb}^{-1}$

4 interesting final states \textit{a priori}:

- $b\bar{b}W(\rightarrow \ell\nu)W(\rightarrow \ell\nu)$: difficult because of MET, not promising \cite{J.B. et al, JHEP 1304 (2013) 151}
- $b\bar{b}W(\rightarrow \ell\nu)W(\rightarrow 2j)$: difficult because of MET, but less than above, worth doing it?
- $b\bar{b}\gamma\gamma$: rates very small, lots of fake photon identification, still promising?
- $b\bar{b}\tau\tau$: rates small, but quite promising and under consideration by experimental collaborations

see also CMS projections at HL-LHC \cite{CMS Collaboration, arXiv:1307.7135} and ATLAS projections \cite{ATLAS Collaboration, ATL-PHYS-PUB-2012-004, 2013-007, 2013-014}

\textbf{Remark:} analyses presented in the following have been performed using the $gg \rightarrow HH$ production channel, $HH + 2j$ (using also VBF process) analyses have just started

\cite{Dolan, Englert, Greiner, Spannowsky, Phys.Rev.Lett. 112, 101802 (2014)}
Triple Higgs coupling sensitivity in the production channels

How sensitive are the three main channels to $HHH$ coupling?

- VBF mode is the most sensitive channel
- Identical shape when increasing the center–of–mass energy but reduced sensitivity

\[ \sigma(pp \rightarrow HH + X) \ [fb] \]
\[ \sqrt{s} = 8 \text{ TeV}, \ M_H = 125 \text{ GeV} \]

![Graph showing the sensitivity of different production channels to the $HHH$ coupling.](image)

\[ \frac{\sigma(pp \rightarrow HH + X)}{\sigma^{SM}} \]
\[ \sqrt{s} = 8 \text{ TeV}, \ M_H = 125 \text{ GeV} \]

\[ gg \rightarrow HH \]
\[ qq \rightarrow HHqq \]
\[ q\bar{q} \rightarrow HHW \]
\[ q\bar{q} \rightarrow HHZ \]

\[ \lambda_{HHH}/\lambda_{SM}^{HHH} \]

\( \lambda_{HHH} \)

\( \lambda_{SM}^{HHH} \)

\[ \begin{array}{c}
1000 \\
100 \\
10 \\
1 \\
0.1 \\
0.01
\end{array} \]

\[ \begin{array}{c}
40 \\
35 \\
30 \\
25 \\
20 \\
15 \\
10 \\
5 \\
0
\end{array} \]

\( \begin{array}{c}
gg \rightarrow HH \\
qq \rightarrow HHqq \\
q\bar{q} \rightarrow HHW \\
q\bar{q} \rightarrow HHZ
\end{array} \)

\[ \text{[J.B. et al, JHEP 1304 (2013) 151; see also Djouadi, Kilian, M"uhlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45-49]} \]

Status of the studies of the triple Higgs coupling in the SM

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Triplet Higgs coupling sensitivity in the production channels

How sensitive are the three main channels to HHH coupling?

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- Identical shape when increasing the center–of–mass energy but reduced sensitivity

\[ \sigma(pp \rightarrow HH + X) \ [fb] \]
\[ \sqrt{s} = 14 \text{ TeV}, M_H = 125 \text{ GeV} \]

\[ \sigma(pp \rightarrow HH + X) / \sigma^{SM} \]
\[ \sqrt{s} = 14 \text{ TeV}, M_H = 125 \text{ GeV} \]

\[ \lambda_{HHH}/\lambda_{HHH}^{SM} \]

\[ \lambda_{HHH}/\lambda_{HHH}^{SM} \]

[J.B. et al, JHEP 1304 (2013) 151; see also Djouadi, Kilian, Mühlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45-49]
Triple Higgs coupling sensitivity in the production channels

How sensitive are the three main channels to HHH coupling?

- VBF mode is the most sensitive channel
- Identical shape when increasing the center–of–mass energy but reduced sensitivity

\[ \sigma(pp \to HH + X) \text{ [fb]} \]
\[ \sqrt{s} = 33 \text{ TeV, } M_H = 125 \text{ GeV} \]

\[ \frac{\sigma(pp \to HH + X)}{\sigma^{SM}} \]
\[ \sqrt{s} = 33 \text{ TeV, } M_H = 125 \text{ GeV} \]

[J.B. et al, JHEP 1304 (2013) 151; see also Djouadi, Kilian, Mühlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45-49]
Jet substructure analysis, the major improvement: fatjet analysis with boosted kinematics to distinguish in jet substructure the signal from large QCD backgrounds

[Butterworth, Davison, Rubin, Salam, Phys.Rev.Lett. 100 (2008) 242001]

the idea: define a large cone size (“fatjet”) and then work backward through the jet to define and separate softer subjets

Cut strategy: kinematic acceptance cuts + boosted topology cuts + Fat jet cuts

Results with a SHERPA/MADEVENT+HERWIG++ simulation:

\[ S/B \approx 0.5, \quad 95 \text{ signal events for } 1000 \text{ fb}^{-1} \]

- Adding one jet in the final state \((hhj \rightarrow b\bar{b}\tau\tau j)\): with the same techniques, \( S/B \approx 1.5 \)
- With the addition of kinematic bounding variables: 60\% accuracy in trilinear Higgs coupling determination at 3 ab\(^{-1}\) [Barr, Dolan, Englert, Spannowsky, Phys.Lett. B728 (2014) 308]
- With kinematic acceptance cuts + boosted topology cuts only and more optimistic \(M_{\tau\tau}\) window: [J.B. et al, JHEP 1304 (2013) 151]

Optimistic expected significance at 14 TeV, \(\mathcal{L} = 3000 \text{ (300) fb}^{-1}\):

\[ S/\sqrt{B} = 9.37 \text{ (2.97)}, \quad 330 \text{ (33) signal events} \]
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**Signal analysis in $b\bar{b}\tau\tau$ final state** [Dolan, Englert, Spannowsky, JHEP 1210 (2012) 112]

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$S/B \simeq 0.5$, 95 signal events for 1000 fb$^{-1}$

- **Adding one jet in the final state ($hhj \rightarrow b\bar{b}\tau\tau j$):** with the same techniques, $S/B \simeq 1.5$
- **With the addition of kinematic bounding variables:** 60% accuracy in trilinear Higgs coupling determination at 3 ab$^{-1}$ [Barr, Dolan, Englert, Spannowsky, Phys.Lett. B728 (2014) 308]
- **With kinematic acceptance cuts + boosted topology cuts only and more optimistic $M_{\tau\tau}$ window:** [J.B. et al, JHEP 1304 (2013) 151]

Optimistic expected significance at 14 TeV, $\mathcal{L} = 3000$ (300) fb$^{-1}$:

$S/\sqrt{B} = 9.37$ (2.97), 330 (33) signal events
Parton level analysis: Pythia 6 using $gg \rightarrow HH$ matrix elements from HPAIR, rates rescaled to (N)NLO through $K$–factors, tag efficiency of 70% ($b$), fake photons with a rough detector simulation (Delphes)

Cut strategy: kinematic acceptance cuts + boosted topology cuts

Rough detector level expected significance at 14 TeV, $\mathcal{L} = 3000$ fb$^{-1}$:

$$S/\sqrt{B} = 6.46, 47$$ signal events

See also a study at high energy LHC (33 and 100 TeV) in [Yao, arXiv:1308.6302]

Status of the studies of the triple Higgs coupling in the SM

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**Signal analysis in** \( \bar{b}bW(\rightarrow \ell\nu)W(\rightarrow jj) \) **final state**

[\(\text{Papaefstathiou, Yang, Zurita, Phys.Rev. D87 (2013) 011301}\)]

**Parton level analysis:** \textsc{MADGRAPH} using \( gg \rightarrow HH \) matrix elements from \textsc{HPAIR}, \textsc{HERWIG++} and \textsc{ALPGEN} for background processes, rates normalized to \((N)\)NLO total cross section

**Cut-based analysis with jet substructure technique, improved with BDT multivariate analysis** + specific cuts to this channel, e.g. \( p_{T,H} > 240 \text{ GeV} \) and \( m_{W_h} > 65 \text{ GeV} \) (hadronically decaying \( W \))

![Signal (test) Background (test) Signal (training) Background (training)]

**promising result of** \( S/\sqrt{S+B} = 2.4 \) **with 9 events at** \( 600 \text{ fb}^{-1} \)
More improvements

- **Using ratio of cross sections**: similar structure for higher-order corrections in $\sigma(gg \to H)$ and $\sigma(gg \to HH)$ \iffalse\Rightarrow\fi uncertainties on their ratio $C_{HH}$ much more reduced

\[ \Delta^\mu C_{HH} \simeq \pm 2\%, \Delta^{PDF} C_{HH} \simeq \pm 2\% \] [Goertz, Papaefstathiou, Yang, Zurita, JHEP 1306 (2013) 016]

Very promising confidence interval of $\simeq +30\% / -20\%$ on the reduced triple Higgs coupling $\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ when the three previous search channels are naively combined

- **Multivariate analysis in $b\bar{b}\gamma\gamma$**: improved significance and probe of $\lambda_{HHH}$ within 40% uncertainty at LHC 14 TeV with 3 ab$^{-1}$ [Barger, Everett, Jackson, Shaugnessy, Phys.Lett. B728 (2014) 433]

- **New from this morning, 4$b$ analysis!** with jet substructure analysis, set a 95% CL limit $\lambda_{HHH} \leq 1.2$ at 3 ab$^{-1}$ [de Lima, Papaefstathiou, Spannowsky, arXiv:1404.7139]
A (short) selection of BSM studies

Disclaimer: there has been a lot of activities in $HH$ production regarding to BSM theories in the past few years. I apologize here for the missing papers, this is a limited selection

- **Strong sector and anomalous Higgs couplings** [Contino et al, JHEP 1005 (2010) 089, JHEP 1208 (2012) 154; Kribs, Martin, Phys.Rev. D86 (2012) 095023]

- **Anomalous $ttH$ coupling effects** [Nishiwaki, Niyogi, Shivaji, JHEP 1404 (2014) 011]

- **Two Higgs Doublet Model analyses:** large enhancement possible for non-SM-like triple Higgs couplings [Moretti et al, JHEP 0502 (2005) 024; Arhrib et al, JHEP 0908 (2009) 035; J.B., Eberhardt, Nierste, Wiebusch, arXiv:1403.1264]

- **MSSM studies:** 1.45 enhancement factor for $gg \rightarrow H_{SM-like}H_{SM-like}$ in the most favored parameter space region, see [Cao, Heng, Shang, Wan, Yang, JHEP 1304 (2013) 134]

- **NMSSM studies:**
  - 0.7 to 2.4 enhancement factor for $gg \rightarrow H_{SM-like}H_{SM-like}$ in the most favored parameter space region [Cao, Heng, Shang, Wan, Yang, JHEP 1304 (2013) 134]
  - sizeable enhancement in $\sigma \times BR$ predictions in $gg \rightarrow h_i h_j \rightarrow b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$ for 1 SM-like Higgs boson and a lighter Higgs state [Ellwanger, JHEP 1308 (2013) 077]
  - One-loop corrections to trilinear Higgs couplings in the real NMSM [Nhung, Mühlleitner, Streicher, Walz, JHEP 1311 (2013) 181]

- **Resonant new physics in $HH$ production:**
  - generic new physics [Dolan, Englert, Spannowsky, Phys.Rev. D87 (2013) 5, 055002]
  - new Higgs states analysis [Liu, Wang, Zhu, arXiv:1310.3634; Arhrib, Ferreira, Rui Santos, JHEP 1403 (2014) 053; J.B., Eberhardt, Nierste, Wiebusch, arXiv:1403.1264]
  - jet substructure technique, case study of massive KK graviton [Gouzevitch et al, JHEP 1307 (2013) 148]

- **SM + 2 singlets:** large enhancement in $gg \rightarrow H_{SM}H_{SM}$ [Ahriche, Arhrib, Nasri, JHEP 1402 (2014) 042]

- **Exotics:** pair production with color-octet scalars [Heng, Shang, Zhang, Zhu, JHEP 1402 (2014) 083], Minimal Dilaton Model [Cao, He, Wu, Zhang, Zhu, JHEP 1401 (2014) 150], etc.
Summary and outlook

Trilinear Higgs coupling at the LHC:

- **Major news from 2012:** the observation of a scalar particle at the LHC compatible with the SM Higgs boson

- Higgs couplings measurements era has began:
  - **HHH coupling of utmost importance for the scalar potential measurement**

- **HH production channels status:** 2013 has seen major improvements in the QCD corrections
  - VBF process now at NLO (total rates and differential distributions) and NNLO in the approximation of the structure function, Higgs–strahlung at NNLO (total rates)
    - ⇒ total theoretical uncertainty < 10% in VHH and VBF channels
  - Gluon fusion channel at NNLO+NNLL in the infinite top mass limit for the total rate, top mass expansion at NLO
    - ⇒ scale uncertainty reduced to ±8% at 14 TeV

- **HH Parton level analysis:** jet substructure technique is the 2013 major improvement
  - $b\bar{b}\tau\tau$ channel really promising even already at $\mathcal{L} = 300 \text{ fb}^{-1}$
  - $b\bar{b}\gamma\gamma$ may also be very interesting at $\mathcal{L} = 3000 \text{ fb}^{-1}$
  - $b\bar{b}W(\to \ell\nu)W(\to 2j)$ shows good prospects with multivariate analysis at 600 fb$^{-1}$

- Stay tuned, more to come with improvements towards a full NLO calculation for $gg \to HH$ including the differential distributions!
Thank you!
More details on the analyses presented

- **Signal analysis in $b\bar{b}\tau\tau$:**
  Main backgrounds considered:
  - continuum production: $pp \rightarrow b\bar{b}\tau\tau$; $b\tau^+\nu\bar{\tau} b\tau^-\bar{\nu}\tau$ (mainly from $t\bar{t}$ production)
  - $ZH \rightarrow b\bar{b}\tau\tau$ production

  Define the subjet separation in the fat jet: using mass-drop condition,
  $$m_{j_1} \leq 0.66m_j \& \min(p^2_{T,j_1}, p^2_{T,j_2})/m_j^2 \Delta R^2_{j_1,j_2} > 0.09$$
  $\tau$ reconstruction efficiency of 80%

- **Signal analysis in $b\bar{b}\gamma\gamma$:**
  Main backgrounds considered:
  - continuum production: $pp \rightarrow b\bar{b}\gamma\gamma$
  - $t\bar{t}H$ production with $H \rightarrow \gamma\gamma$ and $t \rightarrow W^+b$ decays, $ZH \rightarrow b\bar{b}\gamma\gamma$ production

- **Signal analysis in $b\bar{b}W(\rightarrow \ell\nu)W(\rightarrow jj)$:**
  Main backgrounds considered:
  - largest background: $pp \rightarrow t\bar{t}$ with semi-leptonic decays
  - $W(\rightarrow \ell\nu)bb + 2j$ production, $H(\rightarrow WW)b\bar{b}$ production and $H + jj$ with misidentified jets