Karlsruhe Institute of Technology

A theoretical review of triple Higgs coupling studies at the LHC

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Julien Baglio | 2014, April 30th

INSTITUT FÜR THEORETISCHE PHYSIK

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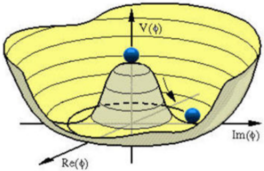
Outline

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

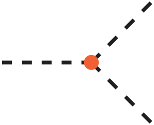
- **From the scalar potential before EWSB:** with a scalar $SU(2)$–doublet field ϕ, $Y_\phi = 1$:

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



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

$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \mathbf{\frac{1}{2}\frac{M_H^2}{v}H^3} + \frac{1}{8}\frac{M_H^2}{v^2}H^4 + \text{constant}$$



$$\frac{3M_H^2}{v} \times (-\imath)$$

$$\frac{3M_H^2}{v^2} \times (-\imath)$$

Motivation: probing the Brout-Englert-Higgs potential

- Quartic Higgs coupling: not accessible at current or foreseen collider energies ($\leq$ 100 TeV) [Plehn, Rauch, Phys.Rev. D72 (2005) 053008]
- 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

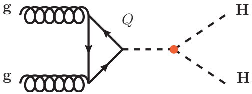
- Early studies at lepton colliders:
  - Studies at a 2 TeV e^+e^- collider: SM triple Higgs coupling could be measured with a 10% accuracy for a light Higgs, in $\nu_e\bar{\nu}_e HH$ and W^+W^-HH modes (VBF modes) [Boudjema, Chopin, Z.Phys. C73 (1996) 85]
  - Complementary SM and MSSM studies: in addition 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

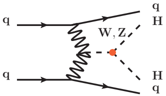
The main production channels

- gluon fusion



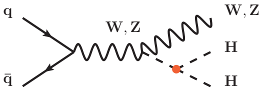
NNLO in QCD
(see next slides)

- vector boson fusion

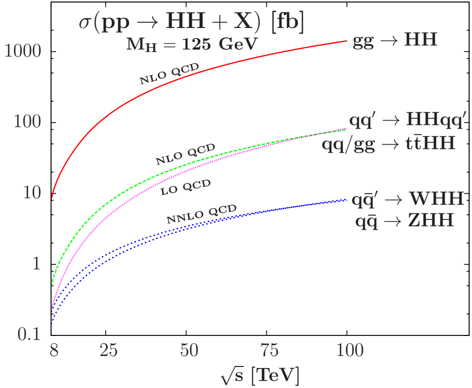


NNLO in QCD
(see next slides)

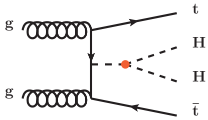
- double Higgs–strahlung



NNLO in QCD
[J.B. *et al*, JHEP 1304 (2013) 151]



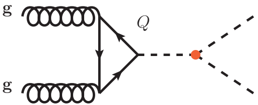
- associated production with top quark

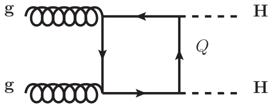


NLO in QCD
[Frederix *et al*, Phys.Lett. B732 (2014) 142]

$\sim$ 1000 times smaller than $\sigma(pp \to H + X)$
[J.B. *et al*, JHEP 1304 (2013) 151]

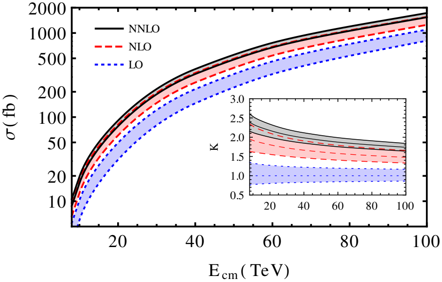
Gluon fusion: the largest cross section





LO inclusive cross section known exactly ($t + b$ loops) [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 $\sqrt{\hat{s}} \ll m_t$: NLO corrections [Dawson, Dittmaier, Spira, Phys.Rev. D58 (1998) 115012]+ **NNLO** corrections (**new in 2013!**), **+20% on top of NLO rate** [De Florian, Mazzitelli, Phys.Lett. B724 (2013) 306; Phys.Rev.Lett. 111 (2013) 201801]



NLO (NNLO) K–factor $\simeq$ 2 (2.3)

$\sqrt{s}$ [TeV]	σ^{NLO} [fb]	σ^{NNLO} [fb]
8	8.2	9.8
14	33.9	40.2
33	207.3	242
100	1417.8	1638

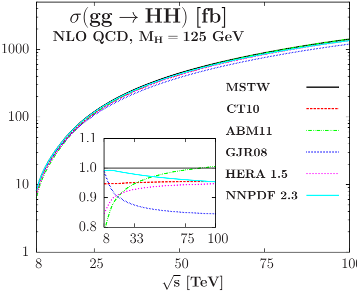
NNLL resummation: $\simeq +20 - 30\%$ on top of NLO cross section, scale dependence stabilized

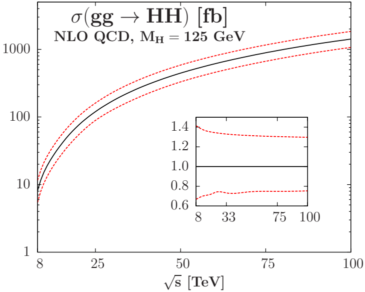
[Shao, C.S. Li, H.T. Li, Wang, JHEP 1307 (2013) 169]

Gluon fusion: theoretical uncertainties

$gg \to HH$ affected by sizeable uncertainties:

- Scale uncertainty: calculated at NLO with $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$, $\mu_0 = M_{HH}$
  $\Delta^{\rm scale} \simeq +20\%(+12\%)/-17\%(-10\%)$ at $\sqrt{s} = 8(100)$ TeV
- PDF uncertainty: gluon PDF at high$-x$ less constrained, $\alpha_s(M_Z^2)$ uncertainty
  $\Delta^{\rm PDF+\alpha_s}_{\rm 90\%CL} \simeq \pm 9\%$ ($\simeq \pm 6\%$ at 100 TeV) uncertainty
- EFT approximation: NLO correction only known in a **top mass expansion (new 2013!)**
  $\Rightarrow$ estimate of $\pm 10\%$ uncertainty [Grigo, Hoff, Melnikov, Steinhauser, Nucl.Phys. B875 (2013) 1]





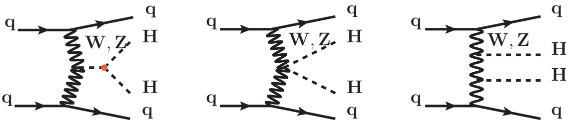
Total uncertainty: $\simeq \pm 40\%$ ($\simeq \pm 30\%$ at 100 TeV) [J.B. *et al*, JHEP 1304 (2013) 151]

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

[De Florian, Mazzitelli, Phys.Rev.Lett. 111 (2013) 201801]

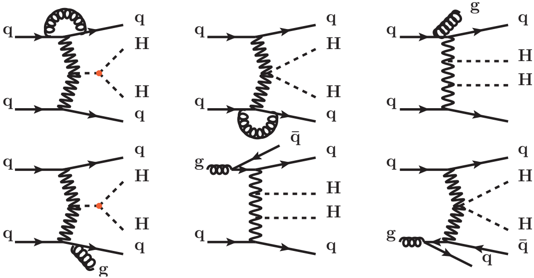
Vector boson fusion at NLO

pp → *qq* → *qq WW/ZZ* → *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]



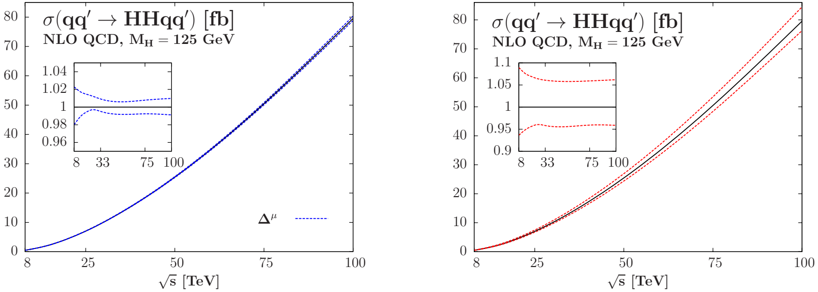
$\simeq +7\%$ correction
(similar to single Higgs case)

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}$ [fb]
8	0.49
14	2.01
33	12.05
100	79.55

Vector boson fusion: theoretical uncertainties

$qq \to HHqq$ is a clean process:

- Scale uncertainty: calculated at NLO with $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$, $\mu_0 = Q_{W/Z}$;
  $\Delta^{\rm scale} \simeq +3\%(+2\%)/-2\%(-1\%)$ at $\sqrt{s} = 8(33)$ TeV
  Good precision compared to LO $\Delta^{\rm scale} \simeq \pm 10\%$
- PDF uncertainty: total $\Delta^{\rm PDF+\alpha_s}_{\rm 90\%CL} \simeq +7\%/-4\%$ ($\simeq +5\%/-4\%$ at 33 TeV)



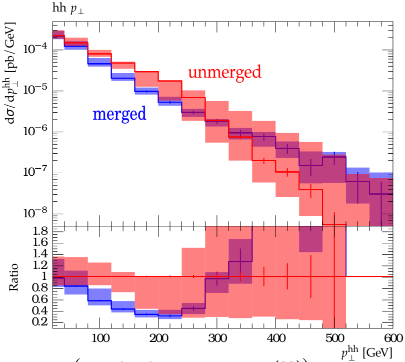
Total uncertainty: $\simeq +8\%/-5\%$ (14 TeV) [J.B. *et al*, JHEP 1304 (2013) 151]

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]

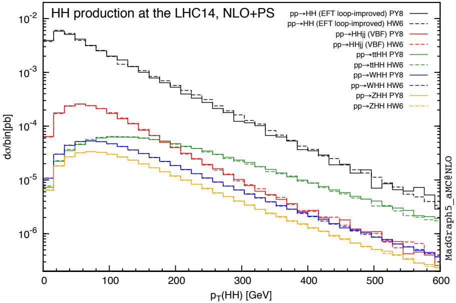
Monte Carlo tools and parton shower

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

- $gg \to HH$ merged to 1 jet: HERWIG++ implementation of $HH + 1j$ production with real radiation merged to parton shower $\Rightarrow$ 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]



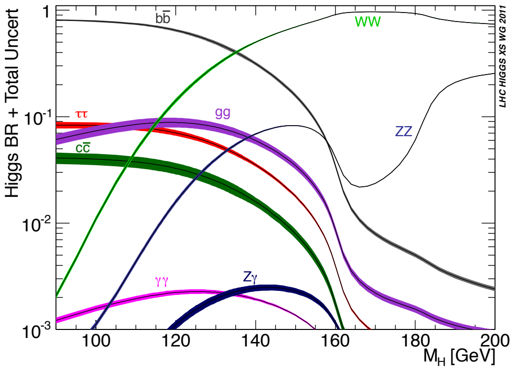
(central scale: $\mu_0 = m_h + p_T(hh)$)



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 $H \to b\bar{b}$ decay channel at least once to retain some signal; foreseen luminosity at the LHC of 3000 fb^{-1}



4 interesting final states *a priori*:

- $b\bar{b}W(\to \ell\nu)W(\to \ell\nu)$: difficult because of MET, not promising [J.B. *et al*, JHEP 1304 (2013) 151]
- $b\bar{b}W(\to \ell\nu)W(\to 2j)$: 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

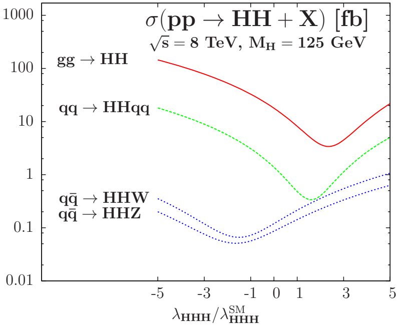
see also CMS projections at HL-LHC [CMS Collaboration, arXiv:1307.7135] and ATLAS projections [ATLAS Collaboration, ATL-PHYS-PUB-2012-004, 2013-007, 2013-014]

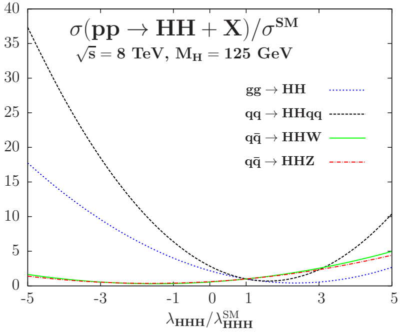
Remark: analyses presented in the following have been performed using the $gg \to HH$ production channel, $HH + 2j$ (using also VBF process) analyses have just started [Dolan, Englert, Greiner, Spannowsky, Phys.Rev.Lett. 112, 101802 (2014)]

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





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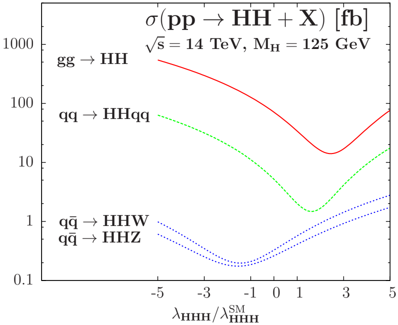

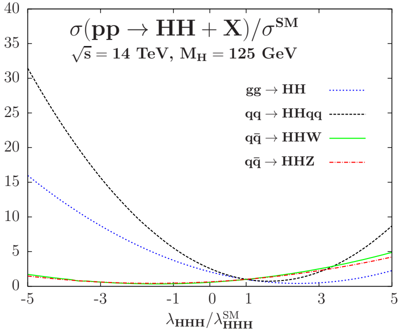

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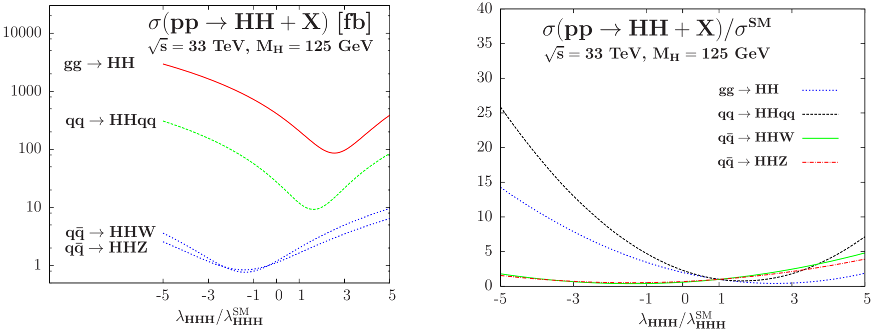

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Signal analysis in $b\bar{b}\tau\tau$ final state [Dolan, Englert, Spannowsky, JHEP 1210 (2012) 112]

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:**

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

- **Adding one jet in the final state ($hhj \to b\bar{b}\tau\tau j$):** 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

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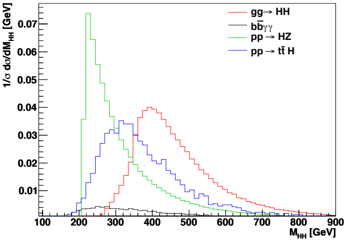
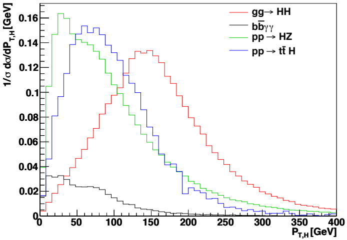
Signal analysis in $b\bar{b}\gamma\gamma$ final state [J.B. *et al*, JHEP 1304 (2013) 151]

Parton level analysis: `Pythia 6` using $gg \to HH$ 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, $\mathcal{L} = 3000\ \text{fb}^{-1}$:
$S/\sqrt{B} = 6.46$, 47 signal events

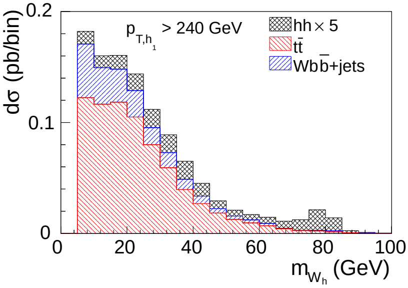
See also a study at high energy LHC (33 and 100 TeV) in [Yao, arXiv:1308.6302]

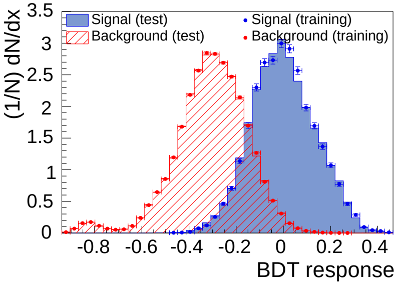
Signal analysis in $b\bar{b}W(\to \ell\nu)W(\to jj)$ final state

[Papaefstathiou, Yang, Zurita, Phys.Rev. D87 (2013) 011301]

Parton level analysis: MADGRAPH using $gg \to HH$ matrix elements from HPAIR, HERWIG++ and 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. $p_{T,H} > 240$ GeV and $m_{W_h} > 65$ GeV (hadronically decaying W)





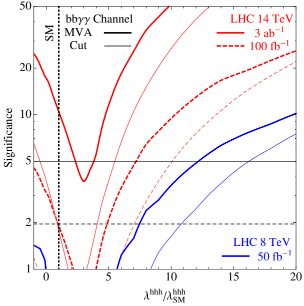
promising result of $\mathrm{S}/\sqrt{\mathrm{S}+\mathrm{B}} = 2.4$ with 9 events at 600 fb^{-1}

More improvements

- **Using ratio of cross sections:** similar structure for higher-order corrections in $\sigma(gg \to H)$ and $\sigma(gg \to HH) \Rightarrow$ **uncertainties on their ratio C_{HH} much more reduced** $\Delta^{\mu} C_{HH} \simeq \pm 2\%$, $\Delta^{\mathrm{PDF}} C_{HH} \simeq \pm 2\%$ [Goertz, Papaefstahiou, Yang, Zurita, JHEP 1306 (2013) 016]

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

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



- **New from this morning, 4b 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 $gg \to H_{\rm SM-like}H_{\rm SM-like}$ 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 $gg \to H_{\rm SM-like}H_{\rm SM-like}$ in the most favored parameter space region [Cao, Heng, Shang, Wan, Yang, JHEP 1304 (2013) 134]
  - sizeable enhancement in $\sigma \times BR$ predictions in $gg \to h_i h_j \to b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$ 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 $gg \to H_{\rm SM}H_{\rm SM}$ [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)
    $\Rightarrow$ **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**
    $\Rightarrow$ **scale uncertainty reduced to $\pm 8\%$ 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 $\mathcal{L} = 300$ fb^{-1}
  $b\bar{b}\gamma\gamma$ may also be very interesting at $\mathcal{L} = 3000$ 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: $pp \to b\bar{b}\tau\tau$; $b\tau^+\nu_\tau\,\bar{b}\tau^-\bar{\nu}_\tau$ (mainly from $t\bar{t}$ production)
  - $ZH \to b\bar{b}\tau\tau$ production

  Define the subjet separation in the fat jet: using mass-drop condition,

  $$m_{j_1} \leq 0.66 m_j \;\&\; \min(p^2_{T,j_1}, p^2_{T,j_2})/m_j^2 \Delta R^2_{j_1,j_2} > 0.09$$

  τ reconstruction efficiency of 80%

- **Signal analysis in $b\bar{b}\gamma\gamma$:**

  Main backgrounds considered:

  - continuum production: $pp \to b\bar{b}\gamma\gamma$
  - $t\bar{t}H$ production with $H \to \gamma\gamma$ and $t \to W^+ b$ decays, $ZH \to b\bar{b}\gamma\gamma$ production

- **Signal analysis in $b\bar{b}W(\to \ell\nu)W(\to jj)$:**

  Main backgrounds considered:

  - largest background: $pp \to t\bar{t}$ with semi-leptonic decays
  - $W(\to \ell\nu)b\bar{b} + 2j$ production, $H(\to WW)b\bar{b}$ production and $H + jj$ with misidentified jets