Theoretical status of the triple Higgs coupling studies at the LHC

GDR Terascale meeting, LAPTh Annecy, France

Julien Baglio | 2013, October 28th

Karlsruhe Institute of Technology

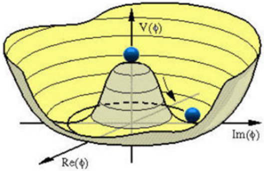
INSTITUT FÜR THEORETISCHE PHYSIK

Outline

Motivation: probing the Brout-Englert-Higgs potential

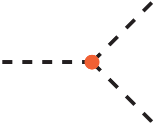
- **From the scalar potential before EWSB:** with a scalar $SU(2)$–doublet field ϕ, $Y_\phi = 1$:

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

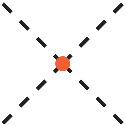


- **$\mathbf{V(\phi)}$ after EWSB, with $\mathbf{M_H^2 = 2m^2}$, $\mathbf{v^2 = m^2/\lambda}$:**

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



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



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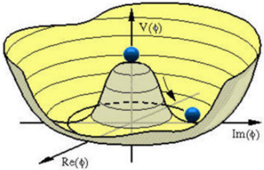

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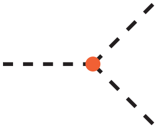

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Motivation: probing the Brout-Englert-Higgs potential

- Quartic Higgs coupling: not accessible at current or foreseen collider energies ($\lesssim$ 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

- SUSY extensions: triple Higgs coupling depends on gauge couplings and can be enhanced:

$$
\begin{aligned}
V = & \frac{1}{2} m_1^2 \left((v_d + h_d^0)^2 + {G_d^0}^2 + 2|h_d^-|^2 \right) + \frac{1}{2} m_2^2 \left((v_u + h_u^0)^2 + {G_u^0}^2 + 2|h_u^+|^2 \right) - \\
& \frac{1}{2} B\mu \left((v_u + h_u^0 + \imath G_u^0)(v_d + h_d^0 + \imath G_d^0) + \text{ c.c. } - 2 h_u^+ h_d^- + \text{ c.c.} \right) + \\
& \frac{1}{4} g^2 \left| (v_d + h_d^0 + \imath G_d^0) h_u^+ + (v_u + h_u^0 + \imath G_u^0) h_d^- \right|^2 + \\
& \frac{1}{32} \left(g^2 + g_Y^2 \right) \left((v_d + h_d^0)^2 + {G_d^0}^2 + 2|h_d^+|^2 - (v_u + h_u^0)^2 - {G_u^0}^2 - 2|h_u^-|^2 \right)^2
\end{aligned}
$$

Historical recap: the early studies

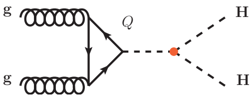
- Early studies at lepton colliders:
  - Studies at a 2 TeV e^+e^- collider: SM triple Higgs coupling could be measured with a 10% accuracy for a light Higgs, in $\nu_e\bar{\nu}_eHH$ and W^+W^-HH modes (VBF modes)
    [Boudjema, Chopin, Z.Phys. C73 (1996) 85]
  - Complementary SM and MSSM studies: included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

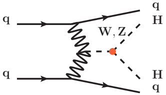
The main production channels

- gluon fusion



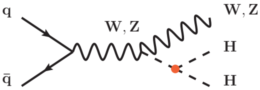
NLO in QCD

- vector boson fusion

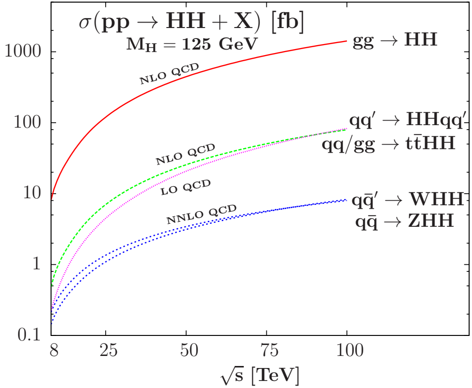


NLO in QCD

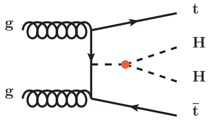
- double Higgs–strahlung



NNLO in QCD



- associated production with top quark



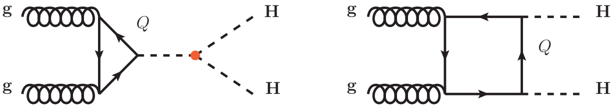
LO in QCD

$\sim$ 1000 times smaller than $\sigma(pp \to H + X)$

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

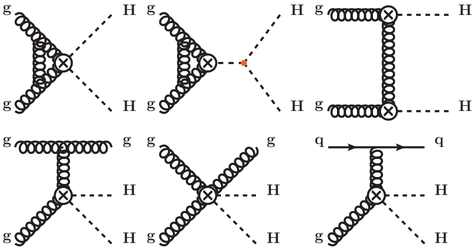
Gluon fusion: the largest cross section

pp → gg → HH: the largest production channel at hadron colliders



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: NLO corrections in the low energy limit $\sqrt{\hat{s}} \ll m_t$ [Dawson, Dittmaier, Spira, Phys.Rev. D58 (1998) 115012]+ NNLO corrections (see next slide)



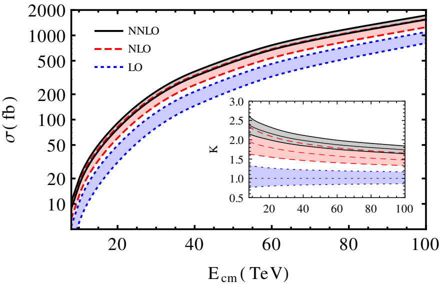
K–factor $\simeq 2$

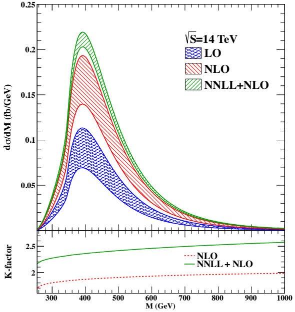
$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}$ [fb]
8	8.2
14	33.9
33	207.3
100	1417.8

Recent improvements on gluon fusion process

2013: the QCD revolution in the $gg \to HH$ inclusive rate

NNLO QCD corrections in the low energy limit: $\simeq +20\%$ compared to NLO prediction
[De Florian, Mazzitelli, Phys.Lett. B724 (2013) 306-309; arXiv:1309.6594]





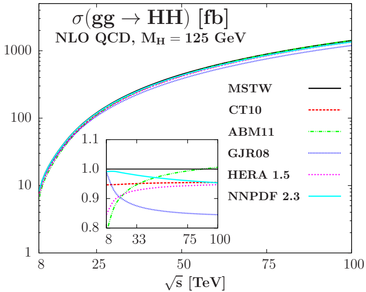
NLO QCD corrections with top mass expansion: mass effects of the order of 10% when exact LO cross section is used [Grigo, Hoff, Melnikov, Steinhauser, Nucl.Phys. B875 (2013) 1]

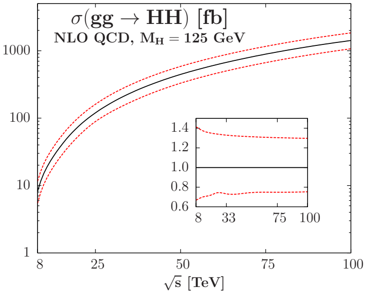
NNLL resummation both for total cross sections and differential distributions: $\simeq +20-30\%$ increase on top of NLO cross section, scale dependence stabilized
[Shao, C.S. Li, H.T. Li, Wang, JHEP 1307 (2013) 169]

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
  $\Rightarrow$ large discrepancy between PDFs predictions
  $\Delta^{\rm PDF+\alpha_s}_{\rm 90\%CL} \simeq \pm 9\%$ ($\simeq \pm 6\%$ at 100 TeV) uncertainty
- EFT approximation: NLO correction only known in a top mass expansion
  $\Rightarrow$ estimate of $\pm 10\%$ uncertainty [Grigo, Hoff, Melnikov, Steinhauser, Nucl.Phys. B875 (2013) 1]



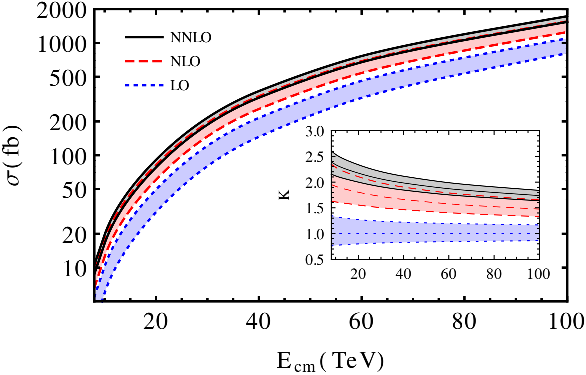


Total uncertainty: $\simeq \pm 40\%$ ($\simeq \pm 30\%$ at 100 TeV) [J.B. *et al*, JHEP 1304 (2013) 151]

Gluon fusion: theoretical uncertainties

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

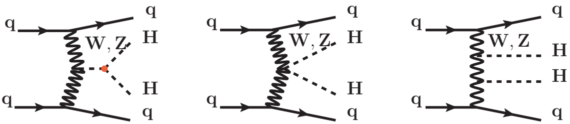
[De Florian, Mazzitelli, arXiv:1309.6594]



$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}$ [fb]
8	$9.8^{+0.9}_{-1.0}$
14	$40.2^{+3.2}_{-3.5}$
33	242^{+17}_{-18}
100	1638^{+96}_{-95}

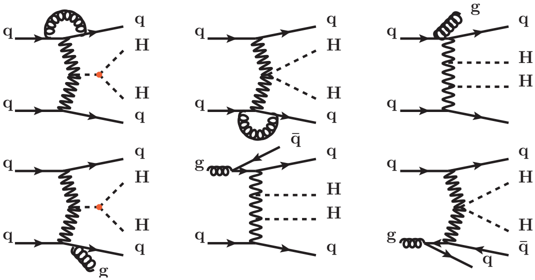
Vector boson fusion at NLO

$pp \to qq \to qq\,WW/ZZ \to qqHH$: 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 to inclusive rate: **NLO corrections in the structure function approach** [J.B. *et al*, JHEP 1304 (2013) 151] **implemented in** `VBFNLO` [Arnold *et al* Comput.Phys.Comm. 180 (2009) 1661]



$\simeq +7\%$ 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

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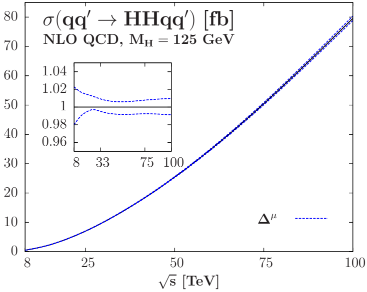
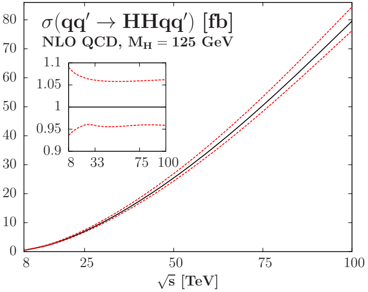
qq $\to$ HHqq is a clean process:

- 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 $\Delta^{\rm PDF+\alpha_s}_{90\%\rm CL} \simeq +7\%/-4\%$
  ($\simeq +5\%/-4\%$ at 33 TeV)





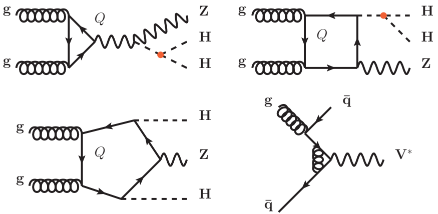
Total uncertainty: $\simeq +8\%/-5\%$ (14 TeV) [J.B. *et al*, JHEP 1304 (2013) 151]

Associated W/Z + Higgs pair production

pp $\to$ Z*/W* $\to$ Z/W + HH: clean but very small rates

[Barger, Han, Phillips, Phys.Rev. D38 (1988) 2766]

- NLO QCD corrections: Drell-Yan $\sigma(pp \to V^*)$ corrections $\simeq +20\%$ [J.B. *et al*, JHEP 1304 (2013) 151]
- NNLO QCD corrections: Drell-Yan $\simeq +4\%$ [J.B. *et al*, JHEP 1304 (2013) 151]
- NNLO QCD corrections (II): specific $gg \to ZHH$ channel $\Rightarrow \simeq +20$ - 30%, sharp contrast with $\simeq +5\%$ in ZH production [J.B. *et al*, JHEP 1304 (2013) 151]



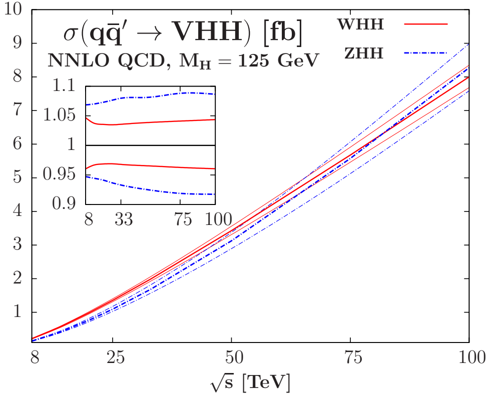
$\sqrt{s}$ [TeV]	$\sigma^{\text{NNLO}}_{WHH}$ [fb]	$\sigma^{\text{NNLO}}_{ZHH}$ [fb]
8	0.21	0.14
14	0.57	0.42
33	1.99	1.68
100	8.00	8.27

Theoretical uncertainties in double Higgs–strahlung

$pp \to VHH$ is also a very clean process:

- Scale uncertainty: calculated at NNLO with $\frac{1}{2}\mu_0 \le \mu_R, \mu_F \le 2\mu_0$, $\mu_0 = M_{VHH}$;
  $\Delta^{\rm scale} < 1\%$ in *WHH* channel
  In *ZHH* channel, worse due to $gg \to ZHH$: $\Delta^{\rm scale}_{ZHH} \simeq \pm 3\%$

- PDF uncertainty: total $\Delta^{\rm PDF+\alpha_s}_{\rm 90\%CL} \simeq \pm 4\%$ ($\simeq \pm 3\%$ at 100 TeV)



Total uncertainty:

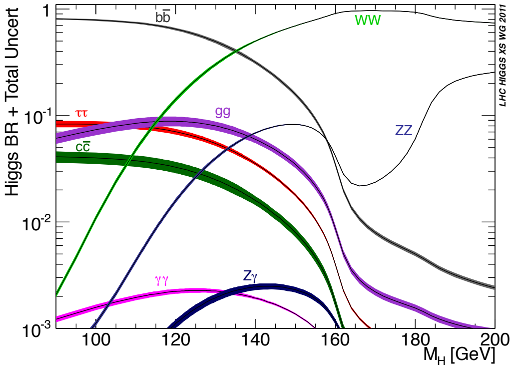
$\Delta^{\rm tot}_{\rm WHH} \simeq \pm 4\%$, $\Delta^{\rm tot}_{\rm ZHH} \simeq \pm 7\%$

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

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?
- $b\bar{b}\tau\tau$: clean leptonic channel, rates small, but promising

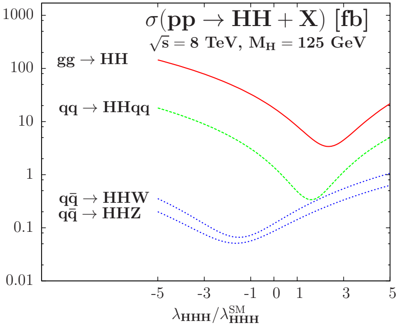
see also CMS projections at HL-LHC [CMS Collaboration, arXiv:1307.7135] and ATLAS projections [ATLAS Collaboration, ATL-PHYS-PUB-2012-004, 2013-007, 2013-014]

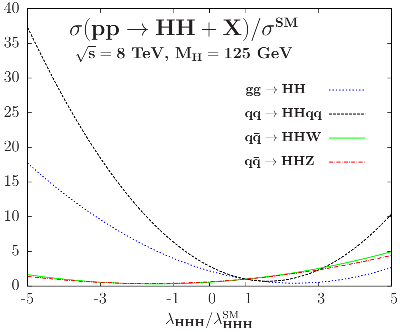
Remark: analyses presented in the following have been performed using the $gg \to HH$ production channel, $HH + 2j$ (using also VBF process) analyses have just started [Dolan, Englert, Greiner, Spannowsky, arXiv:1310:1084]

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 sensibility





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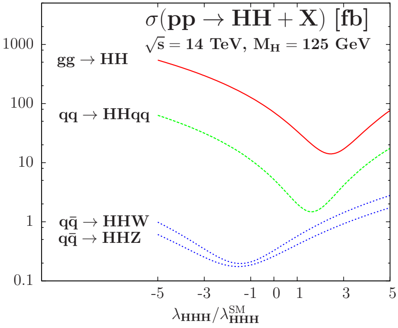

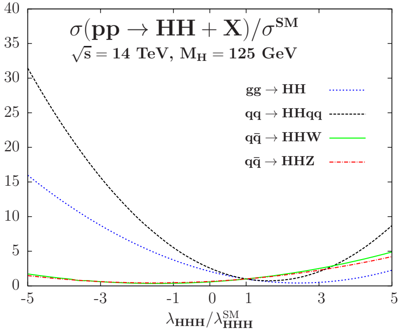

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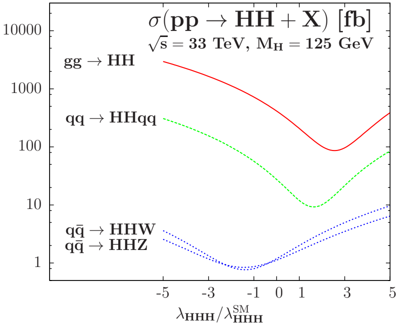

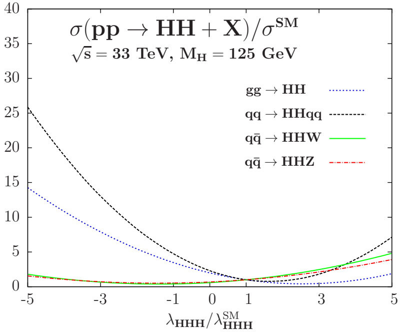

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Signal analysis in $b\bar{b}\tau\tau$ final state [Dolan, Englert, Spannowsky, JHEP 1210 (2012) 112]

Jet substructure analysis, the revolution : 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 using mass-drop condition,

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

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

Cut strategy: kinematic acceptance cuts + boosted topology cuts (considering a τ reconstruction efficiency of 80%):

- $p_T(b/\tau) > 20$ GeV, $|\eta(b/\tau)| < 2.5$, $115 \text{ GeV} < M_{b\bar{b}} < 135$ GeV
- $M_{HH} > 350$ GeV, $p_T(H) > 100$ GeV, $100 \text{ GeV} < M_{\tau\tau} < 150$ GeV
- $R_{bb} < 1.5$, $p_T(bb, \tau\tau) \geq 100$ GeV

Fat jet cuts: at least one fatjet with $R = 1.5$, $p_{T,j} > 150$ GeV, BDRS approach to analyze the fatjet

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

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

Adding one jet in the final state ($hhj \to b\bar{b}\tau\tau j$): with the same techniques, $S/B \simeq 1.5$

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Fat jet cuts: at least one fatjet with $R = 1.5$, $p_{T,j} > 150$ GeV, BDRS approach to analyze the fatjet

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

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

With the addition of kinematic bounding variables: 60% accuracy in trilinear Higgs coupling determination at 3 ab^{-1} [Barr, Dolan, Englert, Spannowsky, arXiv:1309.6318]

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

Jet substructure analysis, the revolution : 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 using mass-drop condition,

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

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

Cut strategy: kinematic acceptance cuts + boosted topology cuts (considering a τ reconstruction efficiency of 80%):

- $p_T(b/\tau) > 20$ GeV, $|\eta(b/\tau)| < 2.5$, 115 GeV $< M_{b\bar{b}} <$ 135 GeV
- $M_{HH} > 350$ GeV, $p_T(H) > 100$ GeV, 100 GeV $< M_{\tau\tau} <$ 150 GeV
- $R_{bb} < 1.5$, $p_T(bb, \tau\tau) \geq 100$ GeV

With kinematic acceptance cuts + boosted topology cuts only: [J.B. *et al*, JHEP 1304 (2013) 151]

$M_{HH} > 350$ GeV, $p_T(H) > 100$ GeV in addition to the cut strategy, no fatjet technique, more optimistic $M_{\tau\tau}$ window with 112.5 GeV $< M_{\tau\tau} <$ 137.5 GeV

Optimistic expected significance at 14 TeV, $\mathcal{L} = 3000\ (300)\ \text{fb}^{-1}$:
$S/\sqrt{B} = 9.37\ (2.97)$, 330 (33) signal events

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`)

	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}H$	ZH [NNLO]
LHC 14 TeV K–factor	1.88	1.0	1.10	1.33

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

Cut strategy: kinematic acceptance cuts + boosted topology cuts:

- $p_T(b/\gamma) > 30$ GeV, $|\eta(b/\gamma)| < 2.4$, $\Delta R(b/\gamma, b/\gamma) > 0.4$
- $120 \text{ GeV} < M_{\gamma\gamma} < 130$ GeV, $112.5 \text{ GeV} < M_{b\bar{b}} < 137.5$ GeV
- $M_{HH} > 350$ GeV, $p_T(H) > 100$ GeV, $|\eta_H| < 2$, $\Delta R(b, b) < 2.5$

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`)

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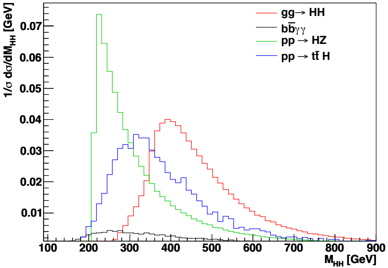

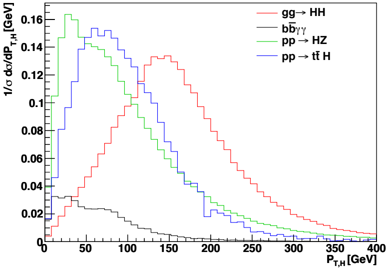

Rough detector level expected significance at 14 TeV, $\mathcal{L} = 3000$ fb^{-1}:
$S/\sqrt{B} = 6.46$, 47 signal events

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

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

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

Cut-based analysis with jet substructure technique, improved with BDT multivariate analysis

Specific cuts to this channel:

- $p_{T,\ell} > 10$ GeV (isolated lepton), $|\eta_\ell| < 2.5$, $\not{E}_T > 10$ GeV
- Fat b-jet with $|\eta_j| < 2.5$, $p_{T,j} > 180$ GeV, $115 \text{ GeV} \leq m_j \leq 135$ GeV
- Fat jet with the hadronically decaying W where $p_{T,j} > 40$ GeV, $m_j > 5$ GeV
- $p_{T,H} > 240$ GeV, $120 \text{ GeV} \leq m_H \leq 130$ GeV (H from fat b-jet), $m_{W_h} > 65$ GeV (hadronically decaying W)

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

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

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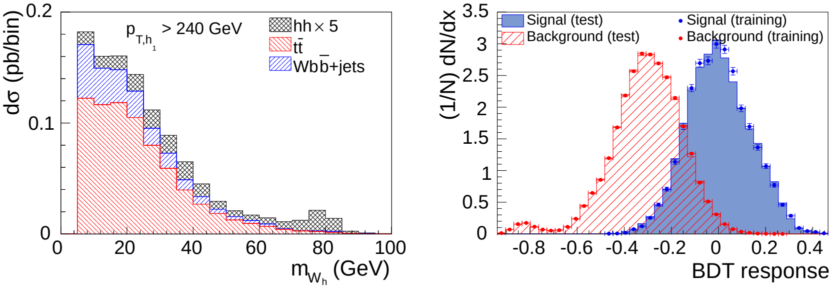
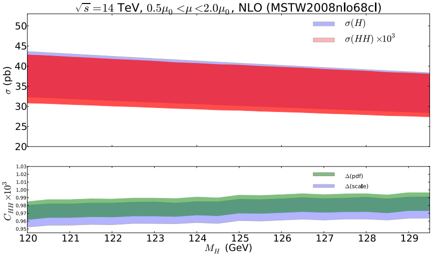


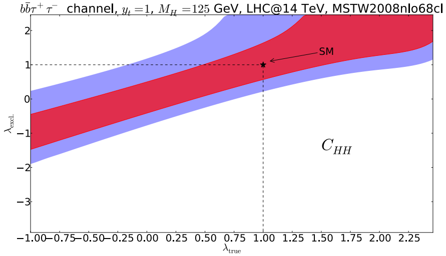
promising result of $S/\sqrt{S+B} = 2.4$ with 9 events at 600 fb^{-1}

Improving limits using ratio of cross sections

Similar structure for higher-order corrections in single and double Higgs production cross sections ⇒ **uncertainties on $\mathbf{C_{HH} = \sigma(gg \to HH)/\sigma(gg \to H)}$ much more reduced**

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





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

A (short) selection of BSM studies

KIT Karlsruhe Institute of Technology

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 analysis and anomalous Higgs couplings** [Contino *et al*, JHEP 1005 (2010) 089; Contino *et al*, JHEP 1208 (2012) 154; Kribs, Martin, Phys.Rev. D86 (2012) 095023]
- **Anomalous ttH coupling effects** [Nishiwaki, Niyogi, Shivaji, arXiv:1309.6907]
- **Two Higgs Doublet Model analyses:** large enhancements are possible for the triple Higgs couplings [Moretti *et al*, JHEP 0502 (2005) 024; Arhrib *et al*, JHEP 0908 (2009) 035]
- **MSSM studies:** 1.45 enhancement factor for $gg \to H_{\rm SM}H_{\rm SM}$ 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 $gg \to H_{\rm SM}H_{\rm SM}$ 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 available in the real NMSM [Nhung, Mühlleitner, Streicher, Walz, arXiv:1306.3926]
- **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]
  - jet substructure technique in resonant production of heavy particles with the case study of massive KK graviton production [Gouzevitch et al, JHEP 1307 (2013) 148]
- **SM + 2 singlets:** large enhancement found in $gg \to H_{\rm SM}H_{\rm SM}$ [Ahriche, Arhrib, Nasri, arXiv:1309.5615]
- **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 is the QCD revolution**
  - VBF process now at NLO (total rates and differential distributions), 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 revolution**
  $b\bar{b}\tau\tau$ 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!