Higgs pair production at the LHC

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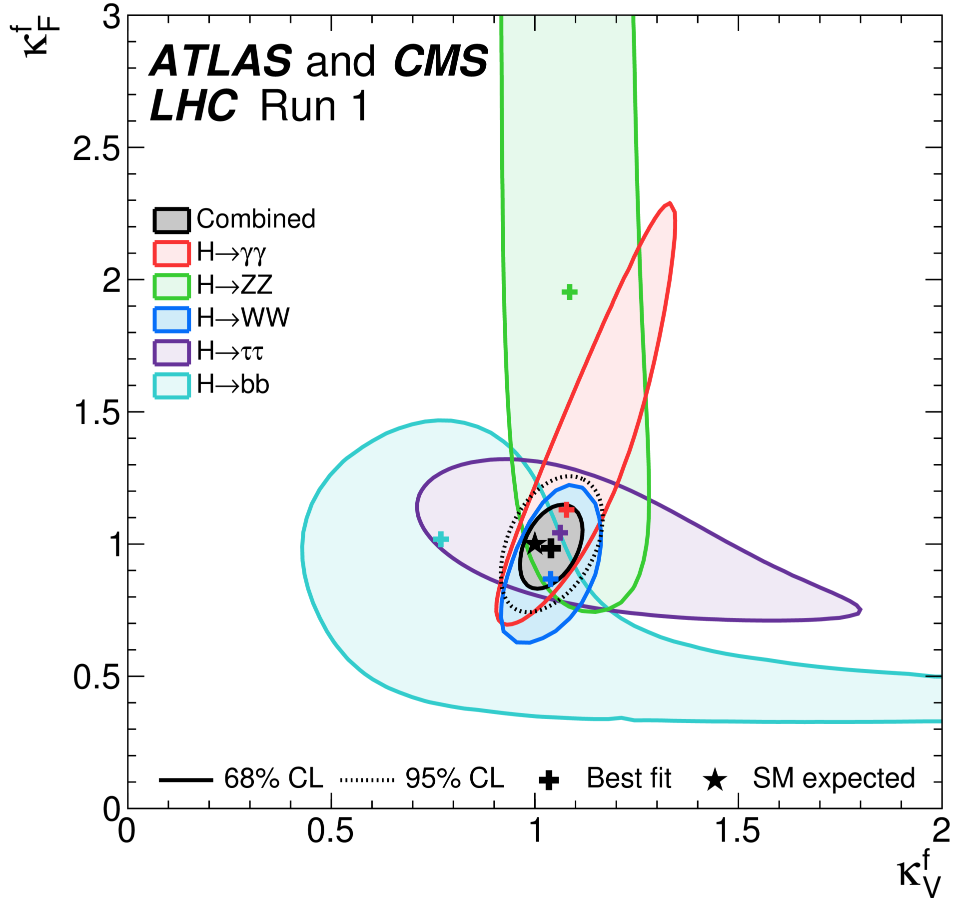
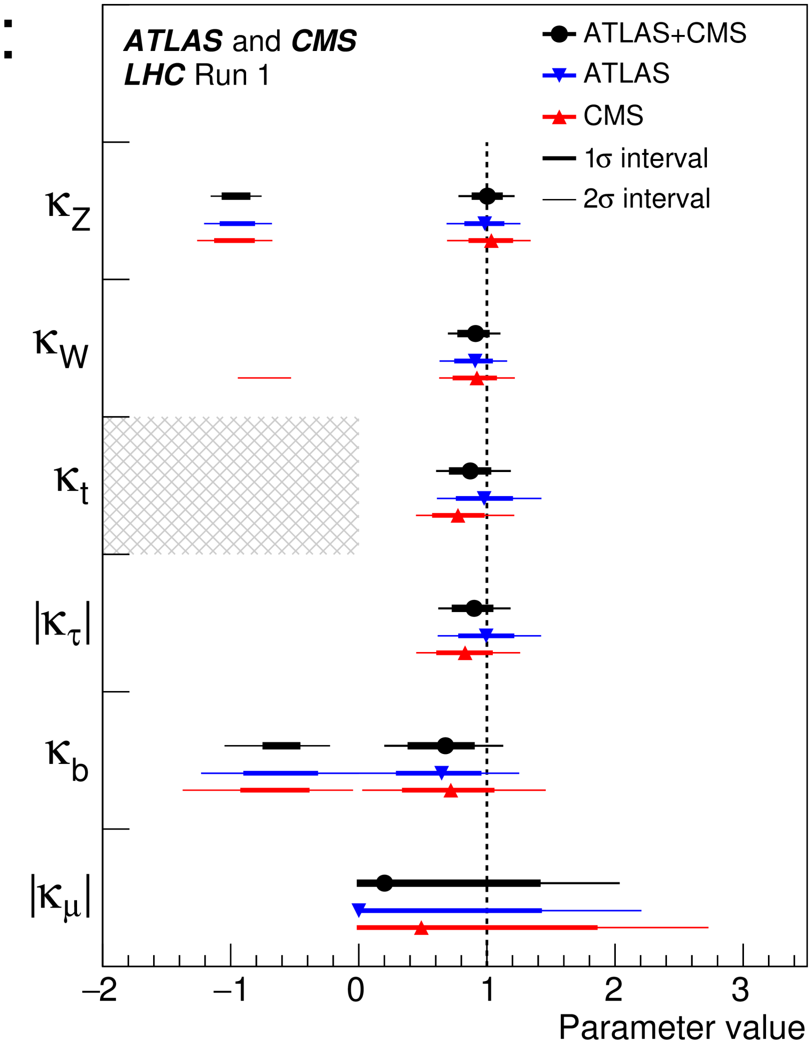
Why HH?

- SM Higgs?
- Higgs couplings measurements:



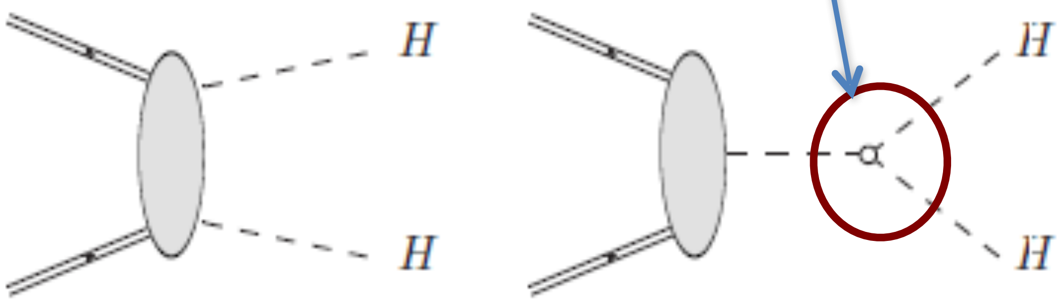


ATLAS and CMS Run I combination
Good agreement with the SM

Why HH?

- **Higgs self couplings: The missing piece**
  - Higgs potential:

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

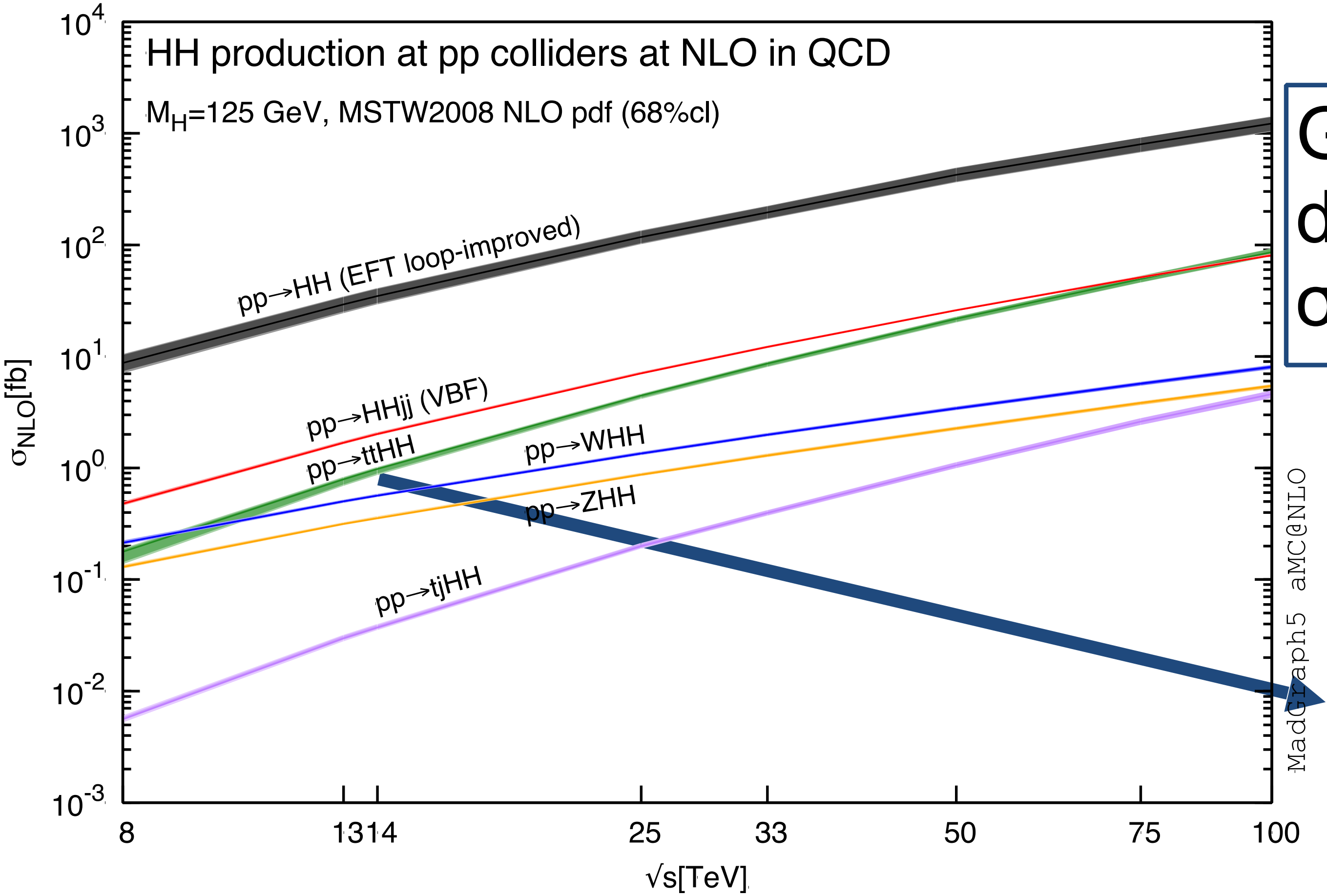


Triple Higgs production:
$\sigma < 0.1$fb at 14TeV

Fixed values in the SM after Higgs mass measurement

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

HH total cross-section results



Gluon gluon fusion dominates
σ~35fb at 14TeV

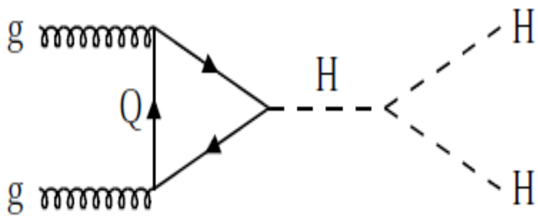
Small difference from single Higgs at 14 TeV: Vector boson associated production and ttHH hierarchy reversed

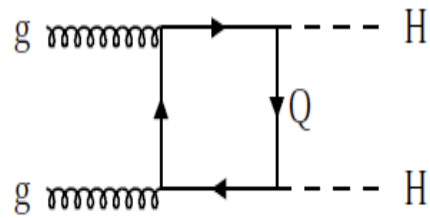
Frederix et al. arxiv:1401.7340

See also Baglio et al. arxiv:1212.5581 for a survey of all channels

HH in gluon-gluon fusion...

At LO:

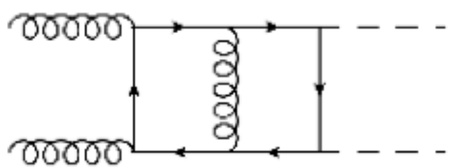




Biggest cross section
The only loop induced channel

Glover, Van der Bij Nucl.Phys. B309 (1988) 282
Plehn, Spira, Zerwas, Nucl.Phys. B479 (1996) 46

- Exact NLO computation requires:
  - Real emissions: HHj one loop
  - Virtual corrections: Include 2-loop amplitudes



The bottleneck of the NLO calculation

Use a low energy theory as in single H

Effective Lagrangian (top quark integrated out)

$$\mathcal{L}_{\text{eff}} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

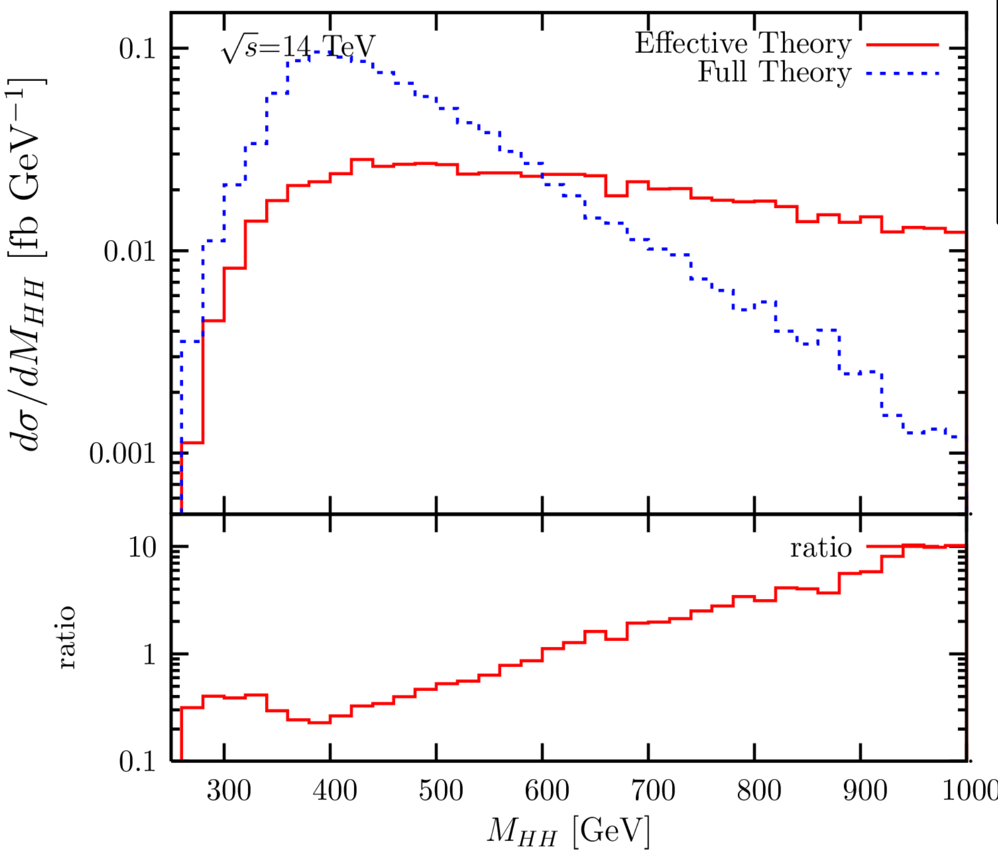
$$\mathcal{L} \supset +\frac{1}{4}\frac{\alpha_s}{3\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h - \frac{1}{4}\frac{\alpha_s}{6\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 .$$

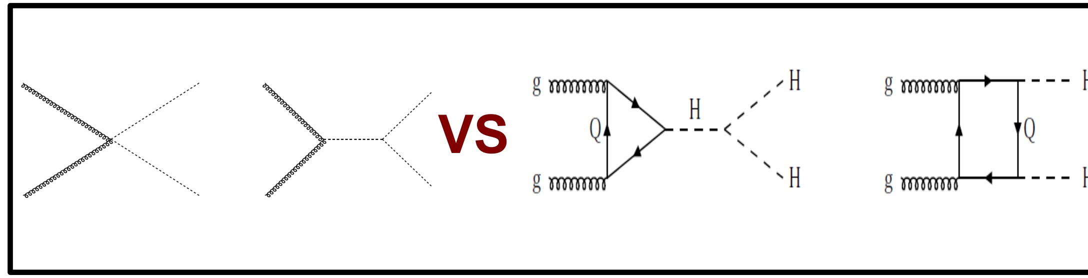
HH in gluon-gluon fusion beyond LO

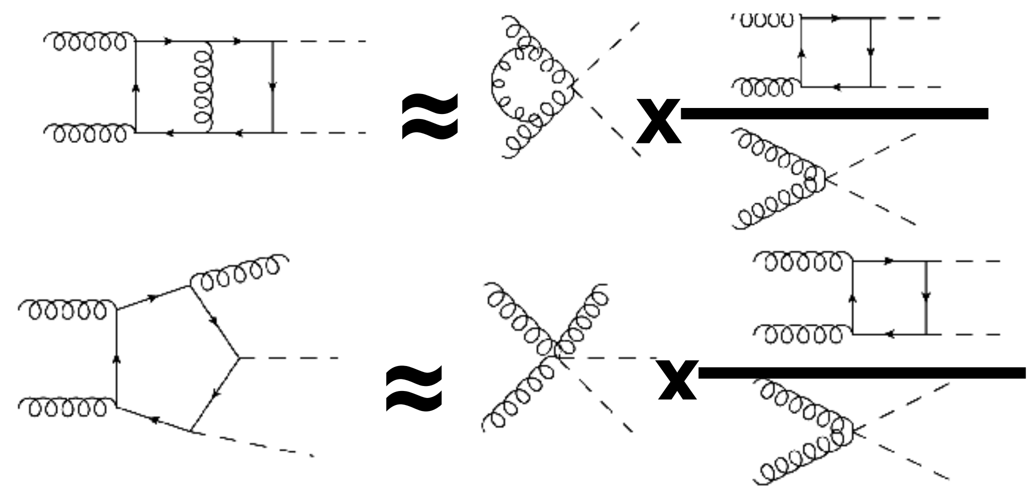
Beyond LO: The early times (1998-2013)

Hpair approach: Dawson, Dittmaier, Spira hep-ph/9805244

NLO corrections in the EFT







HEFT fails to reproduce the differential distributions

Includes LO cross-section with full top-mass dependence

HH in gluon-gluon fusion beyond LO

Beyond LO: The recent past (2013-2015)

An effort to better include top-mass effects

$1/m_t$ expansion for the NLO results:

Grigo et al. arxiv:1305.7340

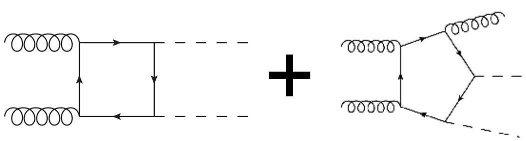
Computation of an $1/m_t$ expanded k-factor combined with the exact Born cross section
Expansion reliable up to the $2m_t$ threshold

$$\sigma^{\mathrm{NLO}}_{\mathrm{expanded}} \to \sigma^{\mathrm{LO}}_{\mathrm{exact}} \frac{\sigma^{\mathrm{NLO}}_{\mathrm{expanded}}}{\sigma^{\mathrm{LO}}_{\mathrm{expanded}}}$$

Improved by soft-virtual factorisation: Grigo et al arXiv:1508.00909

Result: +/-10% compared to Born improved

Including the exact real corrections



Exact real emission matrix elements

Virtual corrections in the HEFT-rescaled by the exact born

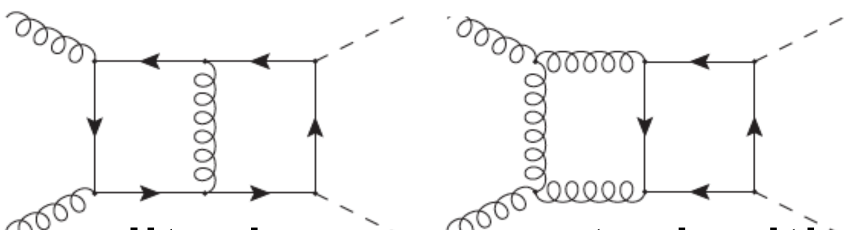
arxiv:1401.7340 and 1408.6542 within MG5_aMC@NLO framework

Result: -10% compared to Born improved

Exact NLO computation

HH@NLO: The present (2016)

Borowka et al 1604.06447 and 1608.04798
NLO computation with the exact top mass dependence

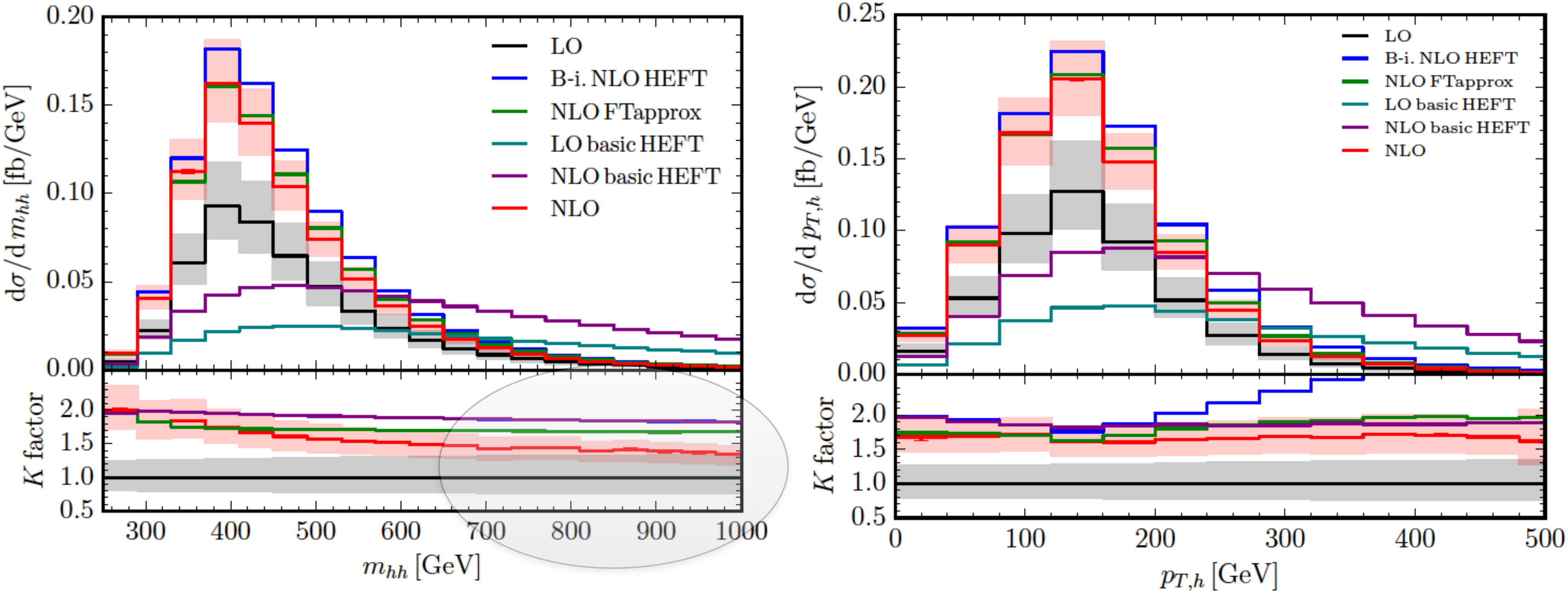


2-loop amplitudes computed with
GOSAM-2L → REDUZE → SECDEC 3
Numerical evaluation of integrals

$\sqrt{s}$	LO	B-i. NLO HEFT	NLO FT_{approx}	NLO
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$

-14% -4%

Differential distributions at NLO



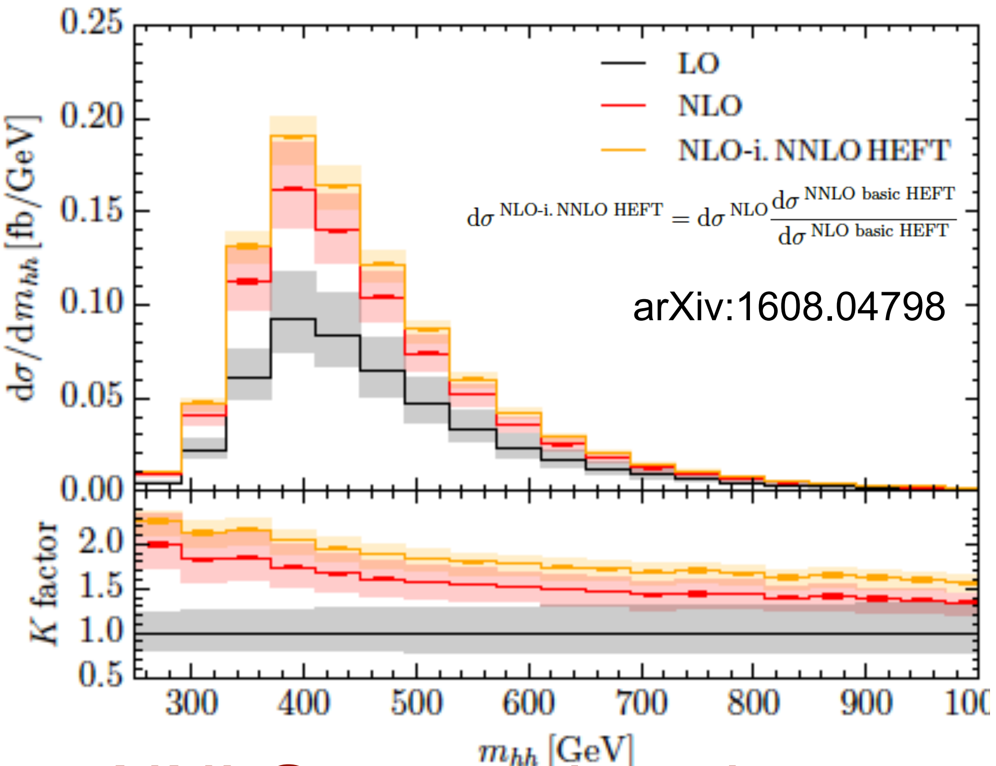
Borowka et al arXiv:1604.06447 and 1608.04798

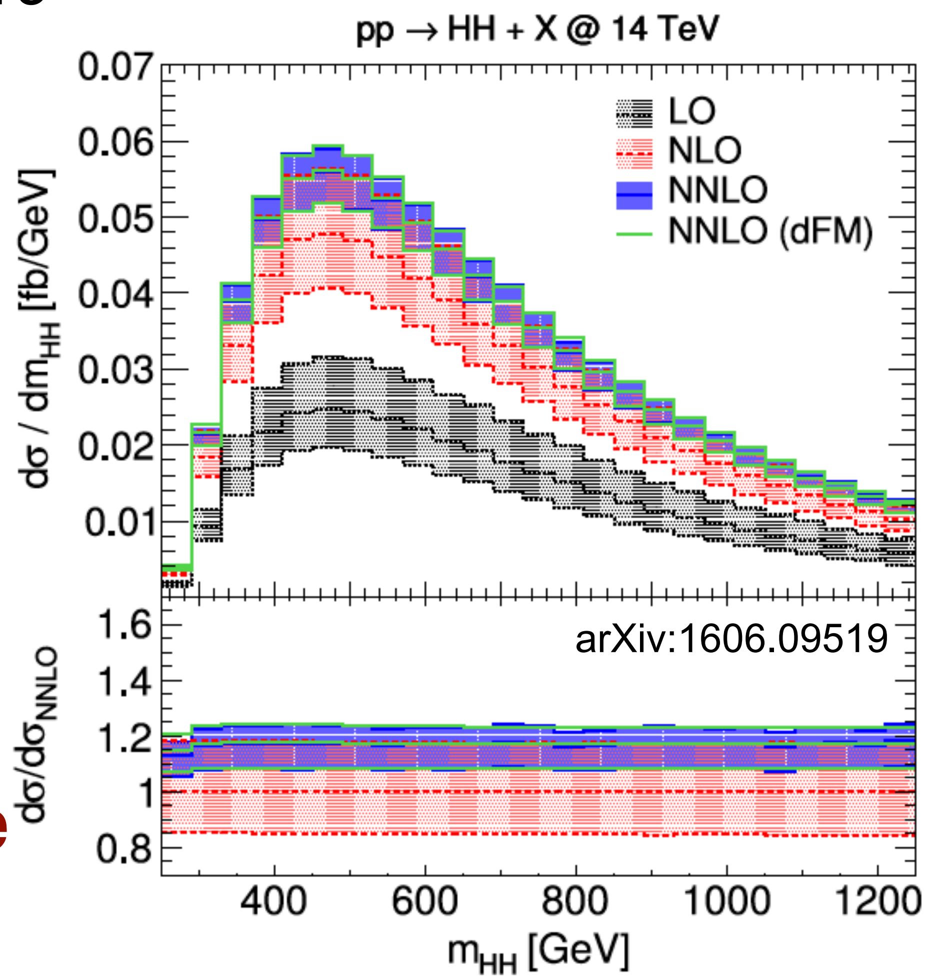
Exact NLO result softer than all other approximations in high m_{hh} region (up to ~20% difference)

To be investigated by a high-energy expansion?

HH beyond NLO

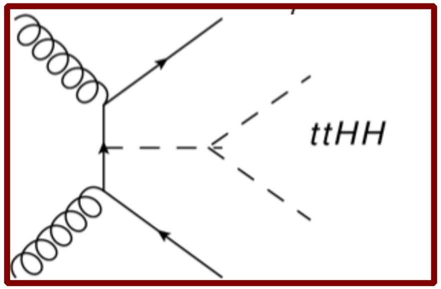
- NNLO calculation in the EFT: De Florian, Mazzitelli (arXiv: 1305.5206,1309.6594)
- NNLO+NNLL resummation (arXiv:1505.07122)
- Differential distributions at NNLO with q_T subtraction: De Florian et al arXiv:1606.09519

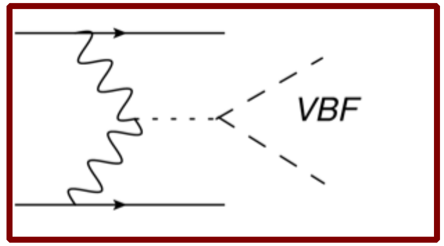


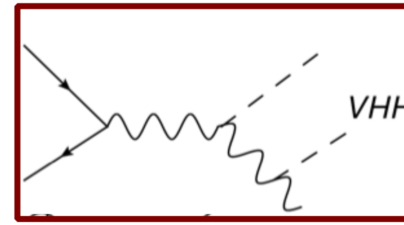


NNLO corrections increase the cross section by 20%

HH in other channels







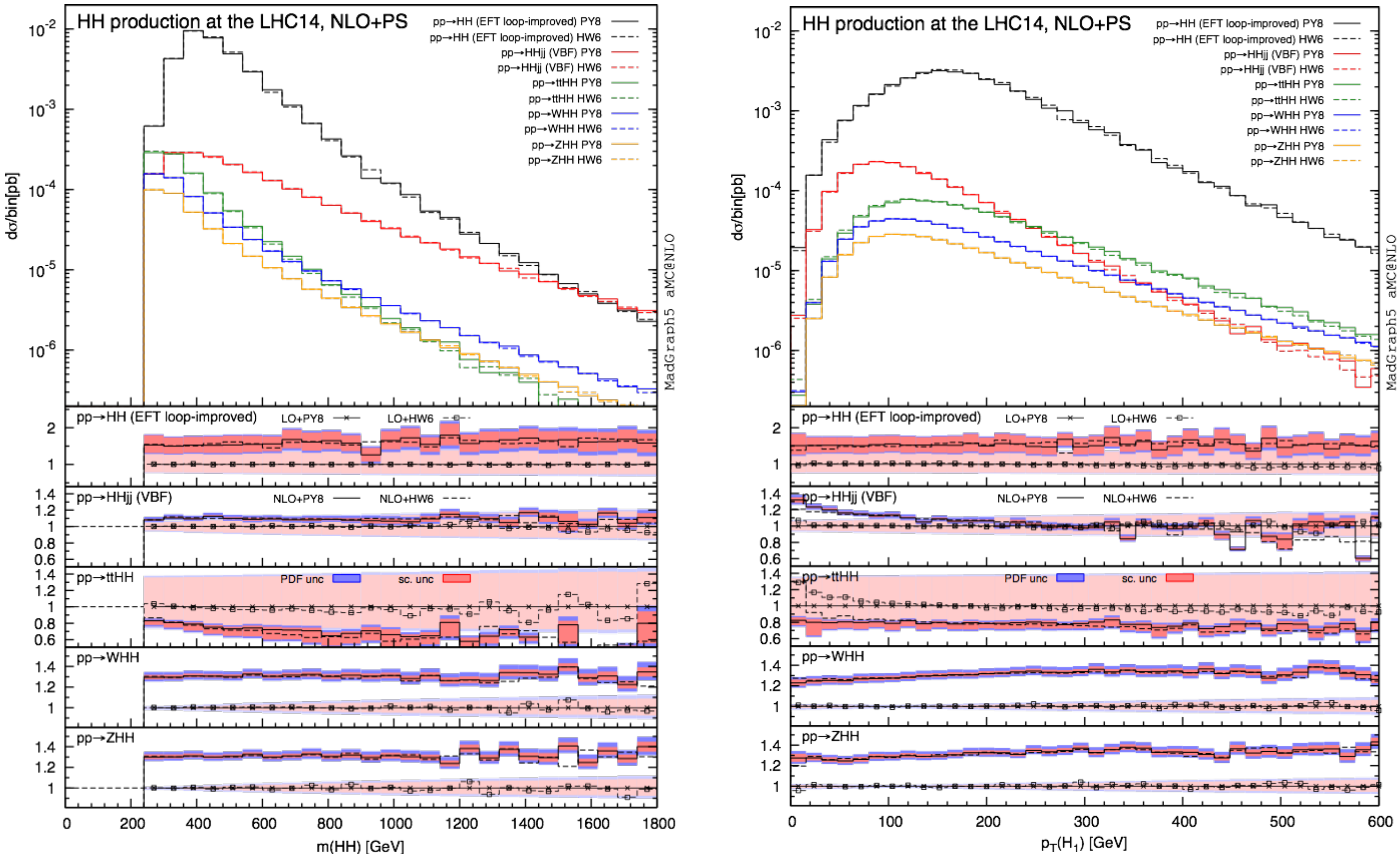
Total cross-section results

Alwall et al. arxiv:1405.0301

	Process Higgs pair production	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
h.1	$pp \to HH$ (Loop improved)	`p p > h h`	$1.772 \pm 0.006 \cdot 10^{-2}$	$^{+29.5\%}_{-21.4\%}$ $^{+2.1\%}_{-2.6\%}$	$2.763 \pm 0.008 \cdot 10^{-2}$	$^{+11.4\%}_{-11.8\%}$ $^{+2.1\%}_{-2.6\%}$
h.2	$pp \to HHjj$ (VBF)	`p p > h h j j $$ w+ w- z`	$6.503 \pm 0.019 \cdot 10^{-4}$	$^{+7.2\%}_{-6.4\%}$ $^{+2.3\%}_{-1.6\%}$	$6.820 \pm 0.026 \cdot 10^{-4}$	$^{+0.8\%}_{-1.0\%}$ $^{+2.4\%}_{-1.7\%}$
h.3	$pp \to HHW^{\pm}$	`p p > h h wpm`	$4.303 \pm 0.005 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$5.002 \pm 0.014 \cdot 10^{-4}$	$^{+1.5\%}_{-1.2\%}$ $^{+2.0\%}_{-1.6\%}$
h.4*	$pp \to HHW^{\pm}j$	`p p > h h wpm j`	$1.922 \pm 0.002 \cdot 10^{-4}$	$^{+14.2\%}_{-11.7\%}$ $^{+1.5\%}_{-1.1\%}$	$2.218 \pm 0.009 \cdot 10^{-4}$	$^{+2.7\%}_{-3.3\%}$ $^{+1.6\%}_{-1.1\%}$
h.5*	$pp \to HHW^{\pm}\gamma$	`p p > h h wpm a`	$1.952 \pm 0.004 \cdot 10^{-6}$	$^{+3.0\%}_{-3.0\%}$ $^{+2.2\%}_{-1.6\%}$	$2.347 \pm 0.007 \cdot 10^{-6}$	$^{+2.4\%}_{-2.0\%}$ $^{+2.1\%}_{-1.6\%}$
h.6	$pp \to HHZ$	`p p > h h z`	$2.701 \pm 0.007 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$3.130 \pm 0.008 \cdot 10^{-4}$	$^{+1.6\%}_{-1.2\%}$ $^{+2.0\%}_{-1.5\%}$
h.7*	$pp \to HHZj$	`p p > h h z j`	$1.211 \pm 0.001 \cdot 10^{-4}$	$^{+14.1\%}_{-11.7\%}$ $^{+1.4\%}_{-1.1\%}$	$1.394 \pm 0.006 \cdot 10^{-4}$	$^{+2.7\%}_{-3.2\%}$ $^{+1.5\%}_{-1.1\%}$
h.8*	$pp \to HHZ\gamma$	`p p > h h z a`	$1.397 \pm 0.003 \cdot 10^{-6}$	$^{+2.4\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.604 \pm 0.005 \cdot 10^{-6}$	$^{+1.7\%}_{-1.4\%}$ $^{+2.3\%}_{-1.7\%}$
h.9*	$pp \to HHZZ$	`p p > h h z z`	$2.309 \pm 0.005 \cdot 10^{-6}$	$^{+3.9\%}_{-3.8\%}$ $^{+2.2\%}_{-1.7\%}$	$2.754 \pm 0.009 \cdot 10^{-6}$	$^{+2.3\%}_{-2.0\%}$ $^{+2.3\%}_{-1.7\%}$
h.10*	$pp \to HHZW^{\pm}$	`p p > h h z wpm`	$3.708 \pm 0.013 \cdot 10^{-6}$	$^{+4.8\%}_{-4.5\%}$ $^{+2.3\%}_{-1.7\%}$	$4.904 \pm 0.029 \cdot 10^{-6}$	$^{+3.7\%}_{-3.2\%}$ $^{+2.2\%}_{-1.6\%}$
h.11*	$pp \to HHW^{+}W^{-}$ (4f)	`p p > h h w+ w-`	$7.524 \pm 0.070 \cdot 10^{-6}$	$^{+3.5\%}_{-3.4\%}$ $^{+2.3\%}_{-1.7\%}$	$9.268 \pm 0.030 \cdot 10^{-6}$	$^{+2.3\%}_{-2.1\%}$ $^{+2.3\%}_{-1.7\%}$
h.12	$pp \to HHt\bar{t}$	`p p > h h t t~`	$6.756 \pm 0.007 \cdot 10^{-4}$	$^{+30.2\%}_{-21.6\%}$ $^{+1.8\%}_{-1.8\%}$	$7.301 \pm 0.024 \cdot 10^{-4}$	$^{+1.4\%}_{-5.7\%}$ $^{+2.2\%}_{-2.3\%}$
h.13	$pp \to HHtj$	`p p > h h tt j`	$1.844 \pm 0.008 \cdot 10^{-5}$	$^{+0.0\%}_{-0.6\%}$ $^{+1.8\%}_{-1.8\%}$	$2.444 \pm 0.009 \cdot 10^{-5}$	$^{+4.5\%}_{-3.1\%}$ $^{+2.8\%}_{-3.0\%}$
h.14*	$pp \to HHb\bar{b}$	`p p > h h b b~`	$7.849 \pm 0.022 \cdot 10^{-8}$	$^{+34.3\%}_{-23.9\%}$ $^{+3.1\%}_{-3.7\%}$	$1.084 \pm 0.012 \cdot 10^{-7}$	$^{+7.4\%}_{-10.8\%}$ $^{+3.1\%}_{-3.7\%}$

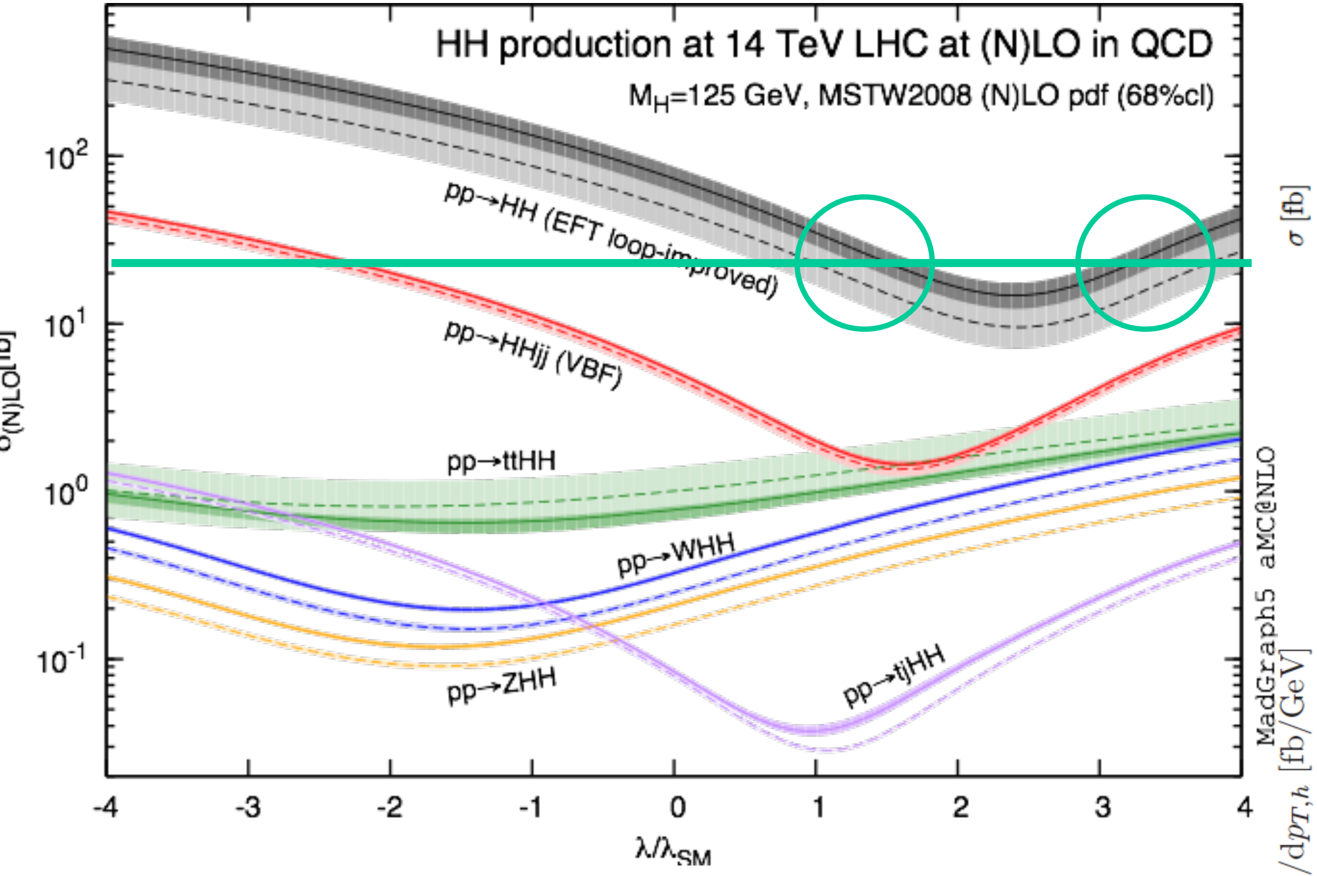
Gluon gluon fusion dominating by an order of magnitude over the other channels, all <fb

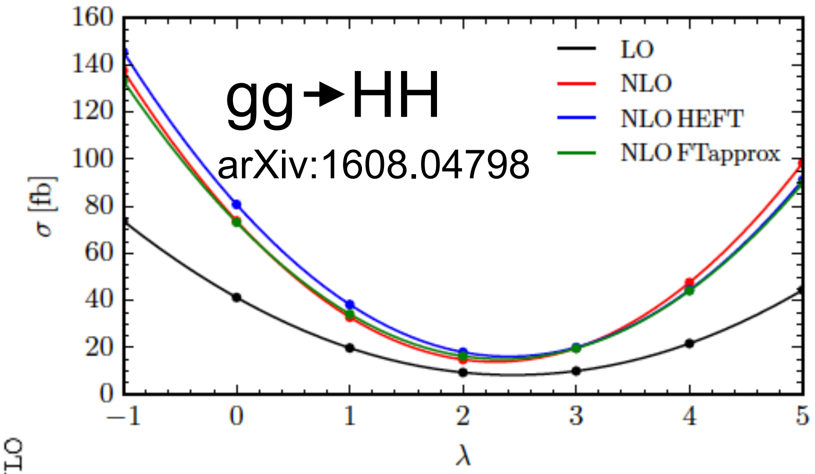
Differential distributions for the LHC

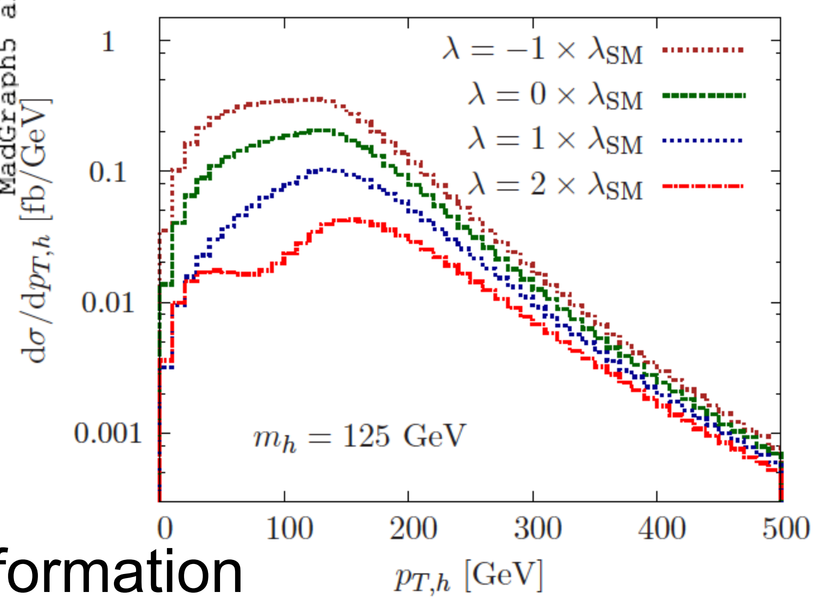


NLO plus PS available in MG5_aMC@NLO

Dependence on the trilinear Higgs coupling







More than one order of magnitude variation can be achieved

degenerate solutions ⇨ use differential information

Dolan et al arXiv:1206.5001

Higgs pair production beyond the SM

BSM physics enhancements

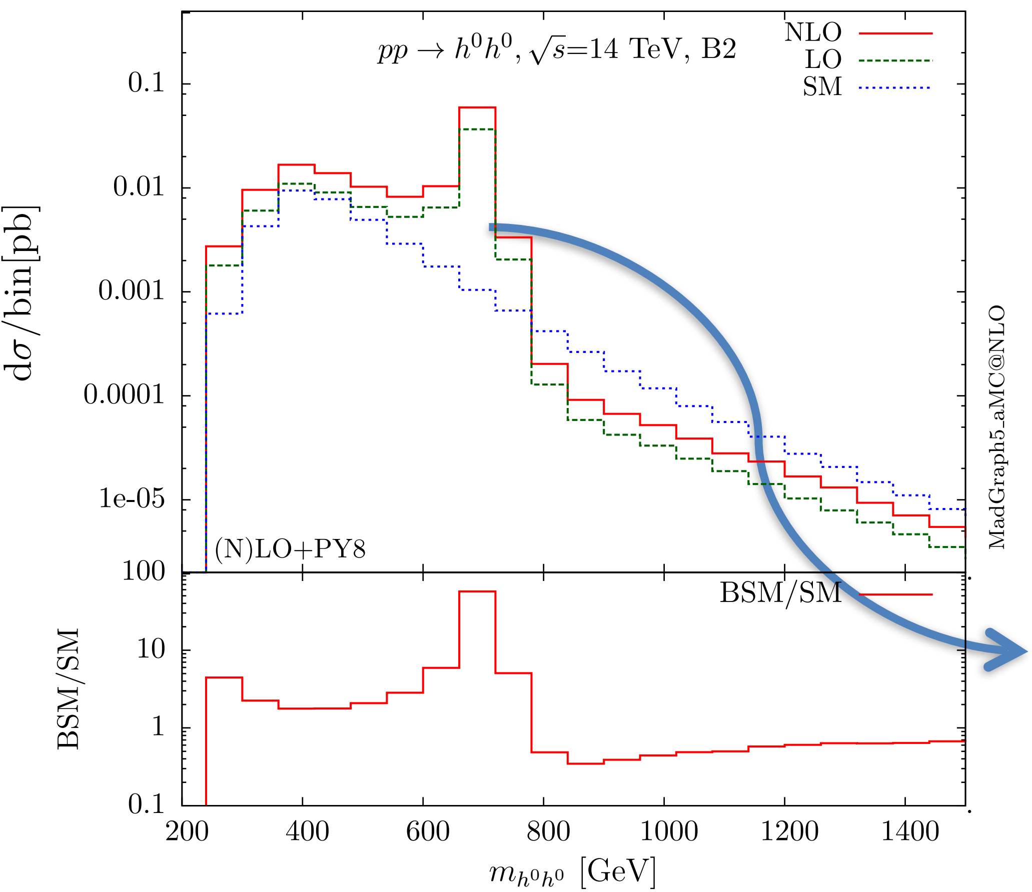
New particles
Resonances

EFT: Higher dimension operators

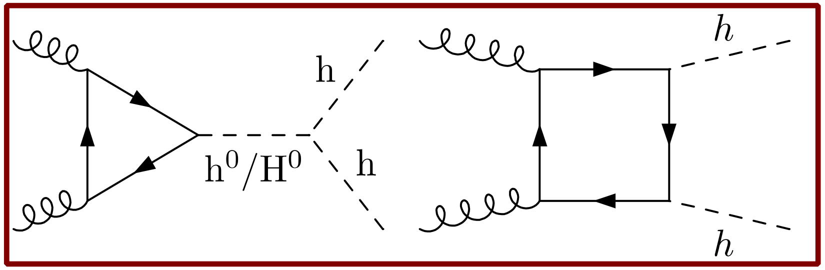
- Non SM Yukawa couplings (1205.5444, 1210.6663)
- ttHH interactions (1205.5444)
- Resonances from extra dimensions (1303.6636)
- Vector-like quarks (1009.4670, 1210.6663)
- Light coloured scalars (1207.4496,1504.05596)
- Dimension-6 operators (hep-ph/0609049, 1410.3471, 1502.00539, 1504.06577)
- Higgs Singlet Model (1508.05397)
- 2HDM (1403.1264, 1407.0281)

An obvious possibility: Resonant enhancement in HH

Heavy scalar decay



Hespel, Lopez-Val, EV arxiv:1407.0281



2HDM input: Type-ii

tan β	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
1.50	-0.2162	700	701	670	180000

- Significant resonant enhancement from H→hh
- Distinctive resonance peak
- Bigger enhancements can be achieved with smaller H masses
- See also Baglio et al. arxiv: 1403.1264

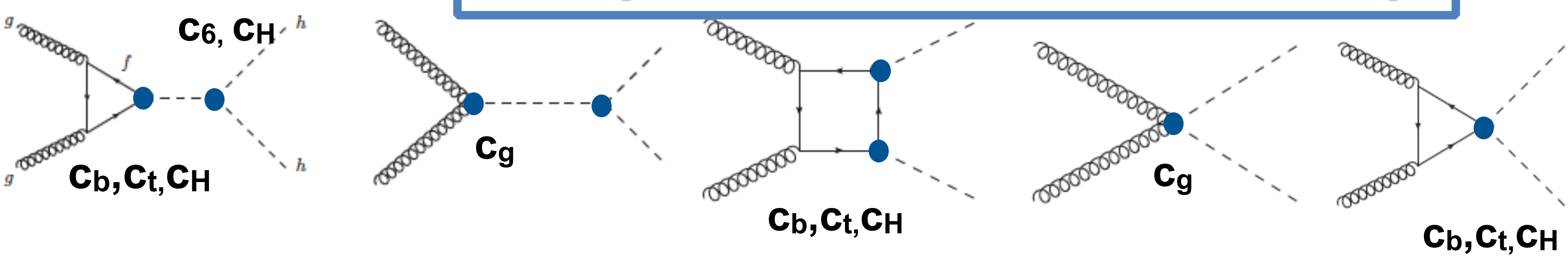
HH production in the EFT

EFT approach: No additional light states
Dimension-6 operators suppressed by scale Λ

$$
\begin{aligned}
\mathcal{L}_{h^n} =& -\mu^2|H|^2 - \lambda|H|^4 - \left(y_t\bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R + \text{h.c.}\right) \\
&+ \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda|H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu}G^{\mu\nu}_a \\
&- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \text{h.c.}\right),
\end{aligned}
$$

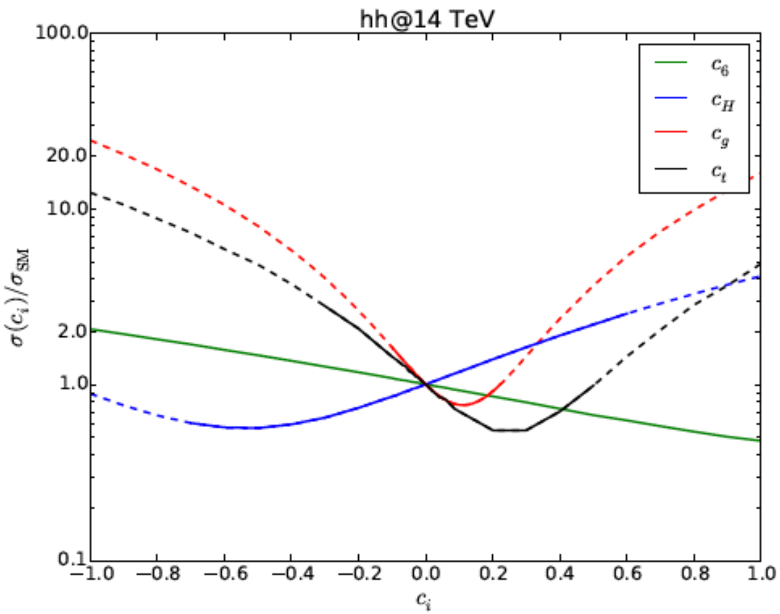
Goertz et al. arxiv:1410.3471
Contino et al. arXiv:1502.00539

$$
\begin{aligned}
\mathcal{L}_{hh} =& -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1 - \frac{25}{3}c_H + 6c_6\right)h^4 \\
&+ \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right) G^a_{\mu\nu}G^{\mu\nu}_a \\
&- \left[\frac{m_t}{v}\left(1 - \frac{c_H}{2} + c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1 - \frac{c_H}{2} + c_b\right)\bar{b}_L b_R h + \text{h.c.}\right] \\
&- \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2} - \frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right],
\end{aligned}
$$



5 parameters: c_6, c_H, c_b, c_t, c_g

HH cross-section in the EFT

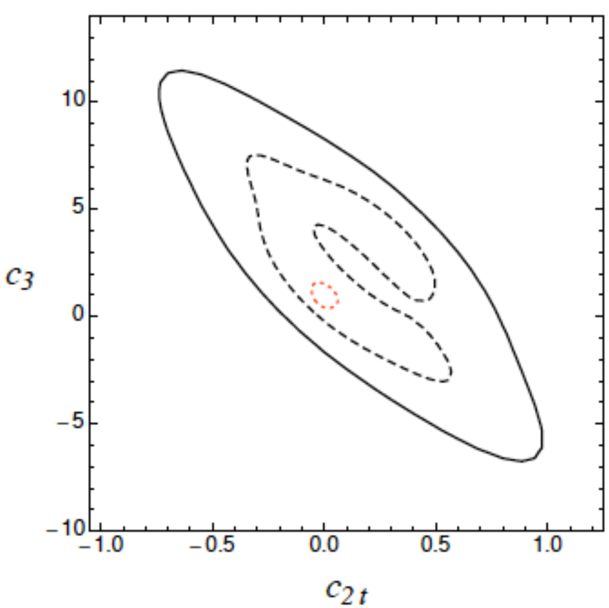


arxiv:1410.3471

Dashed lines: excluded by single Higgs measurements

c_6 only accessible through HH production

model	$L = 600\ \text{fb}^{-1}$	$L = 3000\ \text{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$
$c_6 - c_t - c_\tau - c_b$	$c_6 \gtrsim -2.0$	$c_6 \in (-1.8, 2.3)$



Similarly in Azatov et al. arxiv:1502.00539

$$\mathcal{L}_{non-lin} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{a\,\mu\nu}$$

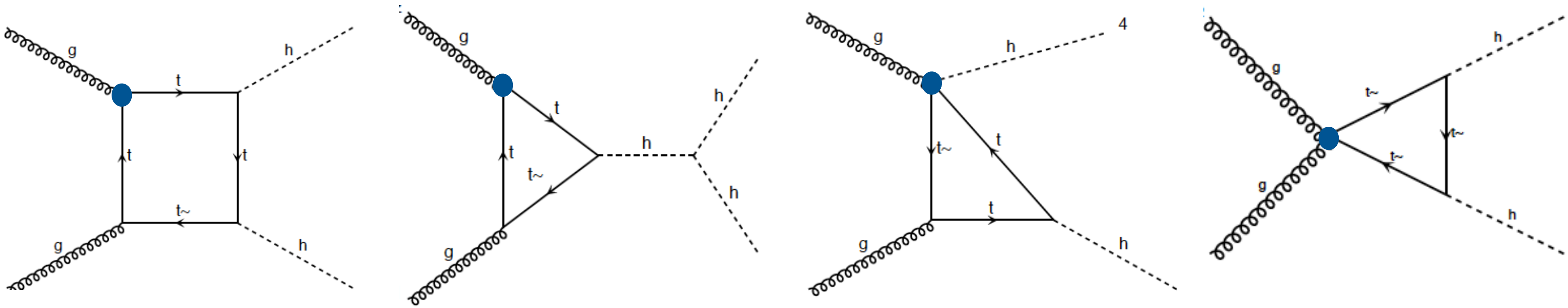
Prospects for HH measurement:

	LHC_{14}	HL-LHC	FCC_{100}
68% interval on μ	$[-0.41, 3.0]$	$[0.50, 1.6]$	$[0.92, 1.1]$
$\mu = \sigma/\sigma_{SM}$	$300\ \text{fb}^{-1}$	$3\ \text{ab}^{-1}$	$3\ \text{ab}^{-1}$

The missing dimension-6 part

Chromomagnetic operator also contributing

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$



Needs to be taken into account in the context of a global EFT analysis for HH
Constraints from top pair production at NLO:

$C_{tg}=$ [-0.42,0.30] Zhang and Franzosi arxiv:1503.08841

How much does this operator contribute to HH?

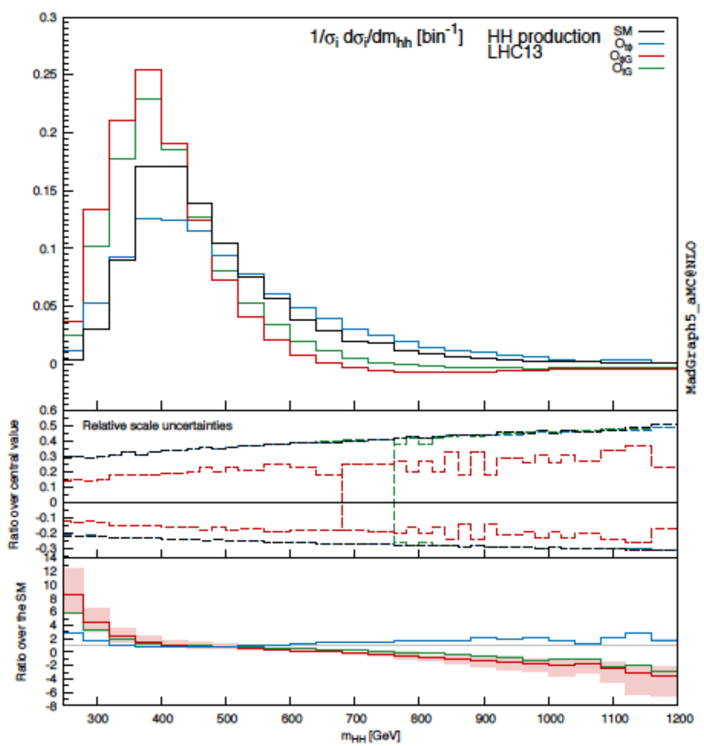
EFT in HH

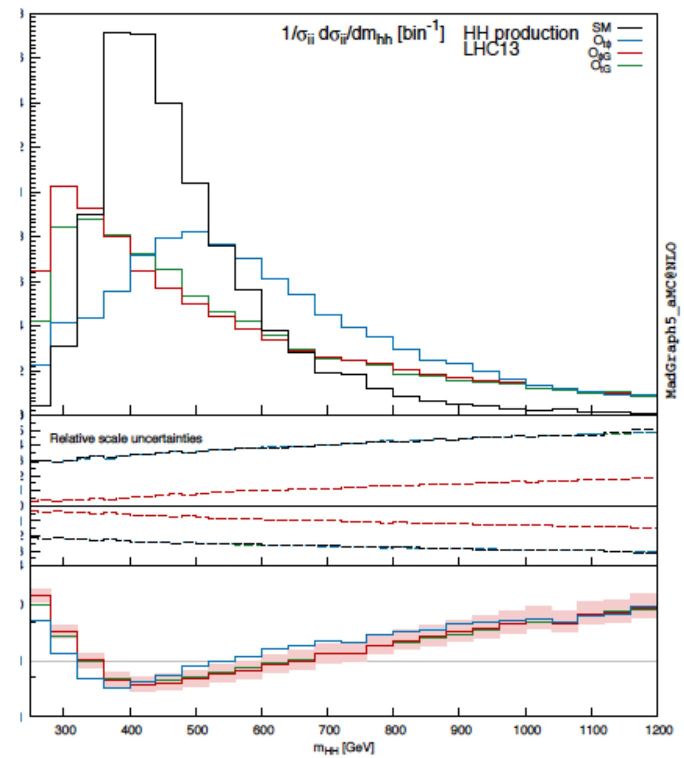
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

13 TeV	σ/σ_{SM} LO
σ_{SM}	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\sigma_{tG,tG}$	$1.940^{+0.0650+0.198}_{-0.0477-0.493}$
$\sigma_{t\phi,\phi G}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$



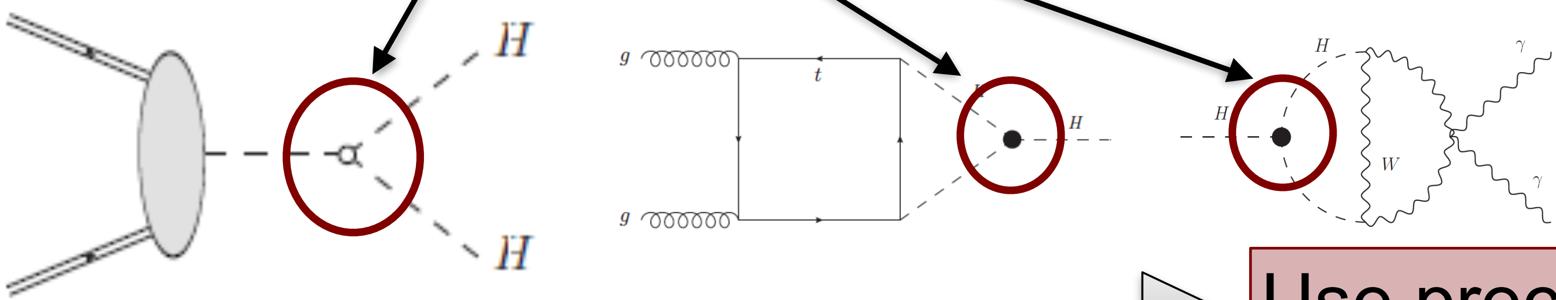


Maltoni, EV, Zhang: arXiv:1607.05330

To be investigated: the impact of the chromomagnetic operator in EFT analyses that focus on the extraction of the triple Higgs coupling λ (e.g. arXiv:1502.00539 and arXiv:1410.3471)

A new way to extract λ

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$



Use precision in single Higgs:

- Degrassi et al.: arXiv:1607.04251

Contribution of lambda to all Higgs production and decay modes, one parameter fit κ_λ ratio over SM coupling

$$V_{H^3} = \lambda_3 \, v \, H^3 \equiv \kappa_\lambda \lambda_3^{\text{SM}} \, v \, H^3$$

- Gorbahn and Haisch: arXiv:1607.03773

contribution to $gg \to h$ and $h \to \gamma\gamma$ assuming one dim-6 operator:

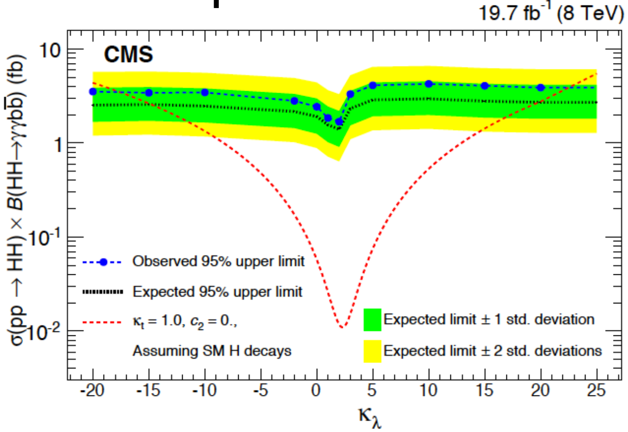
$$O_6 = -\lambda \left(H^\dagger H\right)^3$$

See also McCullough arXiv:1312.3322 for a similar idea for a lepton collider

Prospects for higgs self-coupling

Present

HH: Experimental limit:



exclusion $(-\infty, -17.5] \cup [22.5, \infty)$

Single Higgs:
arXiv:1607.04251 $\chi^2(\kappa_\lambda)$ fit

$$\kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$$

arXiv:1607.03773
$\kappa_g = 0.98 \pm 0.08 \quad \kappa_\gamma = 1.07 \pm 0.09$

$$\bar{c}_6 \in [-12.7, 9.9]$$

Future

HH: Experimental projection
ATL-PHYS-PUB-2014-019 3000fb^{-1}
exclusion at 95% CL

$$\lambda/\lambda_{SM} \lesssim -1.3 \text{ and } \lambda/\lambda_{SM} \gtrsim 8.7$$

CMS PAS FTR-15-002 3000fb^{-1}
expected significance 1.9σ for HH
+various rather optimistic pheno studies

Single Higgs:
arXiv:1607.04251

"CMS-II" (300 fb^{-1})

$$\kappa_\lambda^{1\sigma} = [-1.8, 7.3]\,, \qquad \kappa_\lambda^{2\sigma} = [-3.5, 9.6]\,.$$

"CMS-HL-II" (3000 fb^{-1})

$$\kappa_\lambda^{1\sigma} = [-0.7, 4.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-2.0, 6.8]$$

arXiv:1607.03773
3000fb^{-1} $\kappa_g = 1.00 \pm 0.03 \quad \kappa_\gamma = 1.00 \pm 0.02$

$$\bar{c}_6 \in [-8.0, 5.1]$$

H and HH constraints comparable

Summary and conclusions

- HH gluon-fusion cross section now known at NLO with the exact top mass dependence
- Precision achieved in total cross-section and distributions
- New Physics in HH: plethora of BSM possibilities
- EFT a model independent framework in the absence of light NP states
- Important to obtain current and future limits for the Wilson coefficients in a global way - including all relevant operators
- Information on the trilinear coupling can be obtained also using precision in single Higgs - current limits competitive with HH limits

Thanks for your attention