Higgs boson pair production in non-linear EFT with full mt-dependence at NLO QCD

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1806.05162

built on results from
Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke
1604.06447, 1608.04798

LHC HXSWG HH subgroup meeting

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MAX-PLANCK-GESELLSCHAFT

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Max-Planck-Institut für Physik
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non-linear EFT framework

Electro-weak chiral Lagrangian (EWChL) [Buchalla et al. ’13]

Lagrangian relevant for $gg \to HH$ (at chiral dimension 4)

$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

note:

- Higgs boson is EW singlet; Goldstone fields $U = \exp\left(2i\varphi^a T^a / v\right)$

$$V(h) = v^4 \sum_{n=2}^{\infty} f_{V,n} \left(\frac{h}{v} \right)^n \qquad \text{SM:} \quad f_{V,2} = f_{V,3} = \frac{m_h^2}{2v^2}, \quad f_{V,4} = \frac{m_h^2}{8v^2}$$

- 3 scales: EW scale v, scale f of Higgs sector dynamics, cut-off scale $\Lambda = 4\pi f \;\; \Rightarrow$
- expansion parameters $\xi = v^2/f^2$ and $f^2/\Lambda^2 = 1/(16\pi^2)$ (loop factor)
- SMEFT assumes $\xi \ll 1$, expansion in powers of ξ

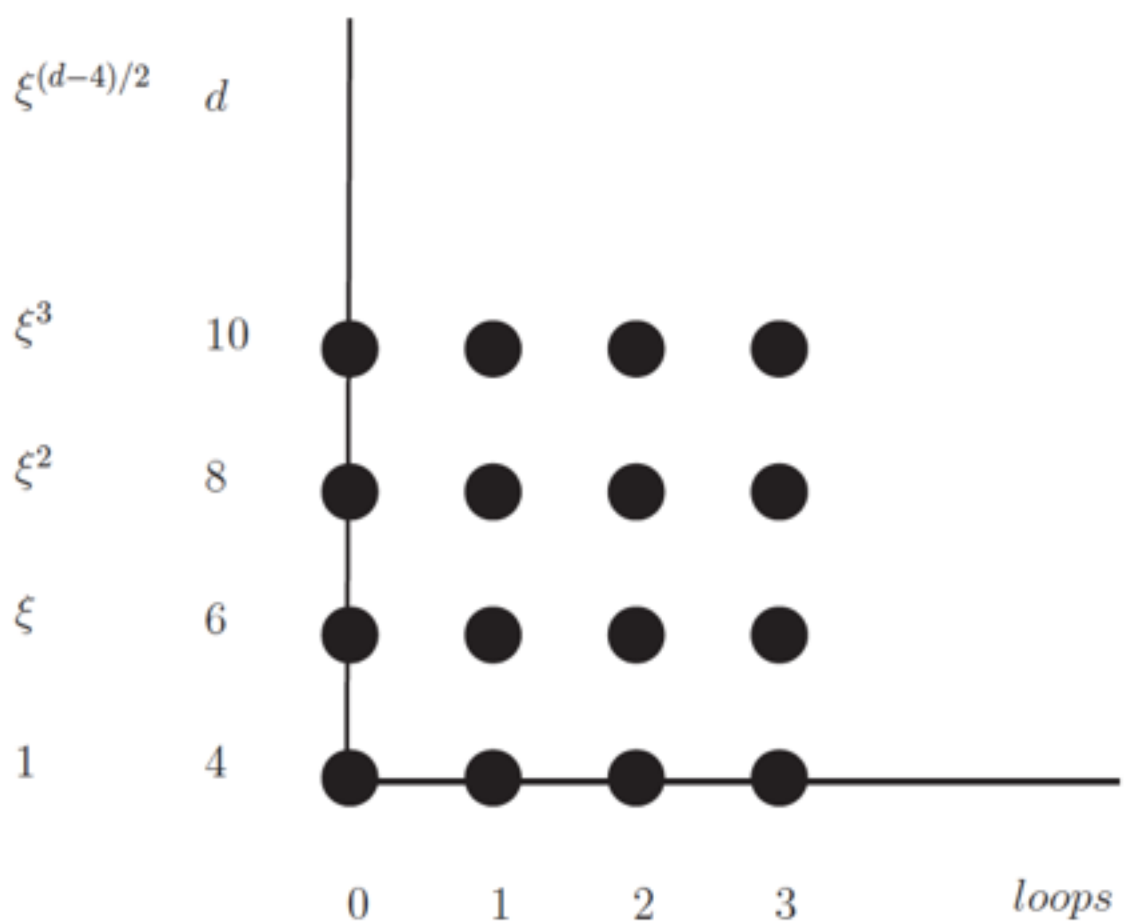
non-linear EFT framework

EWChL: “loop expansion”

based on chiral dimension $d_\chi = 2L + 2$ with

$$d_\chi(A_\mu, \varphi, h) = 0, \quad d_\chi(\partial, \bar{\psi}\psi, g, y) = 1$$

expansion in canonical dimension $1/\Lambda^2$



loop expansion

Relation to SMEFT

(restricted to Higgs sector + QCD)

SMEFT:

$$\Delta\mathcal{L}_{\mathrm{dim6}} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \mathrm{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3 + \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}t_R + \mathrm{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\,G^a_{\mu\nu}G^{a\mu\nu}$$

EWChL:

$$\Delta\mathcal{L}_{d\chi\le 4} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

relations: $c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u\,, \quad c_{tt} = -\frac{\bar{c}_H + 3\bar{c}_u}{2}\,, \quad c_{hhh} = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6\,,$

$$c_{ggh} = 2c_{gghh} = 128\pi^2\bar{c}_g\,.$$

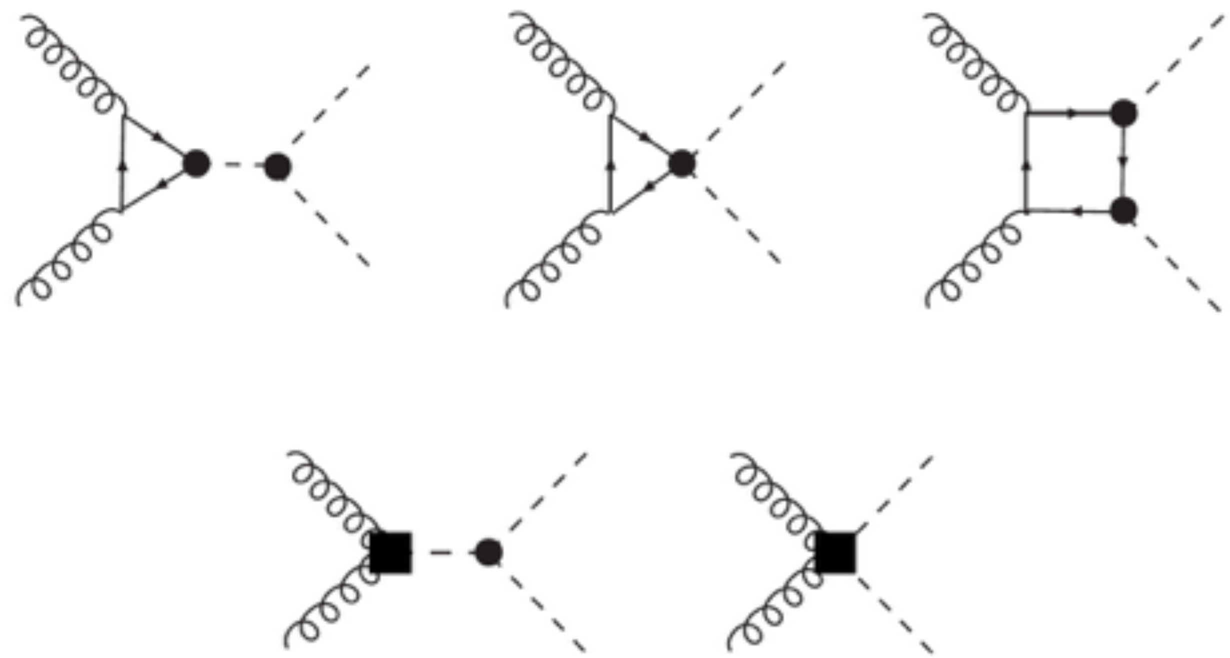
in both cases 5 independent couplings

examples of diagrams

LO diagrams:

$d\chi \leq 4$

and $\mathcal{O}(g_s^2)$

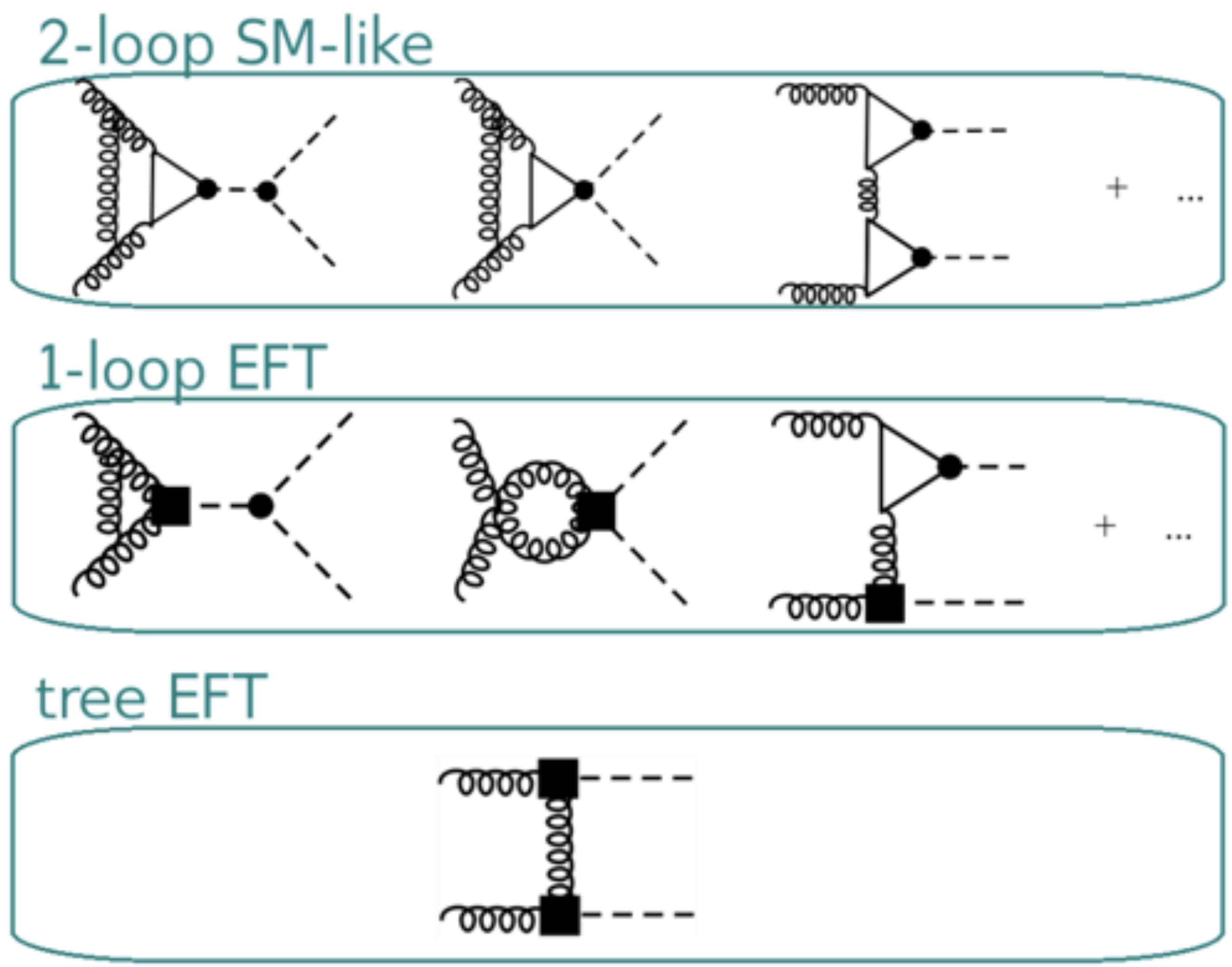


NLO diagrams:

(virtual corrections)

$d\chi \leq 6$ and

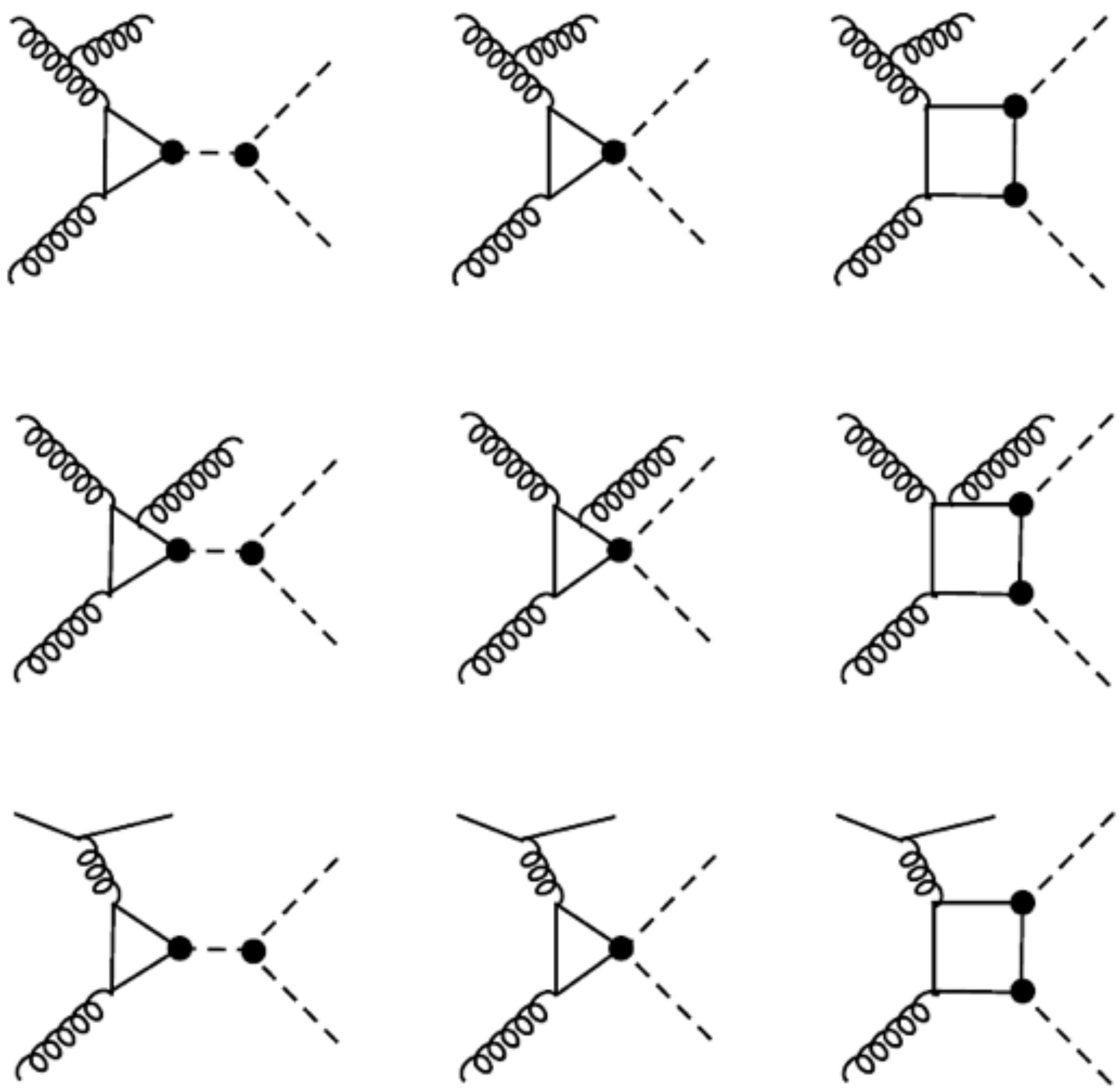
$\mathcal{O}(g_s^4)$ at diagram level



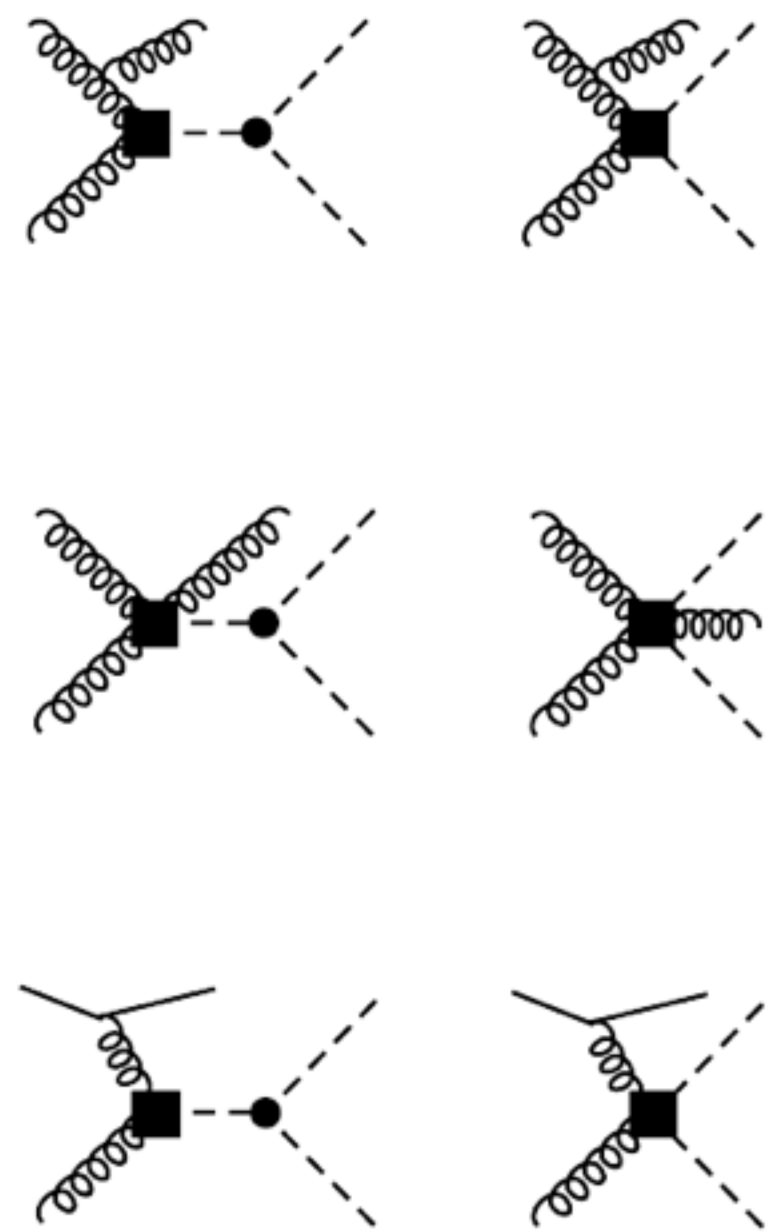
examples of diagrams

NLO diagrams: real radiation corrections

5-point 1-loop diagrams



tree diagrams $\propto c_{ggh},\ c_{gghh}$

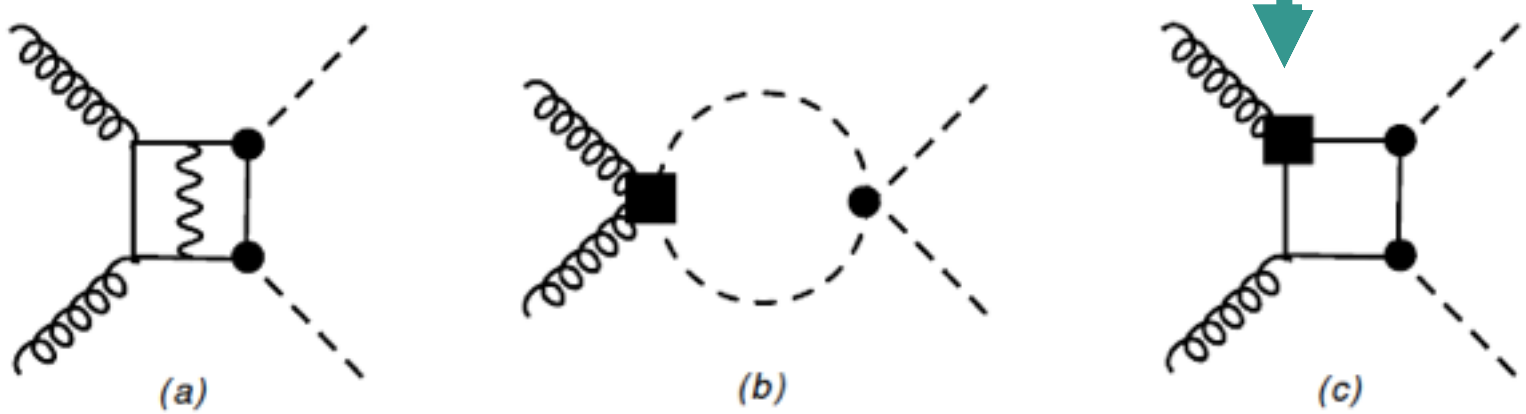


thanks: Ludovic Scyboz

Chromomagnetic operator

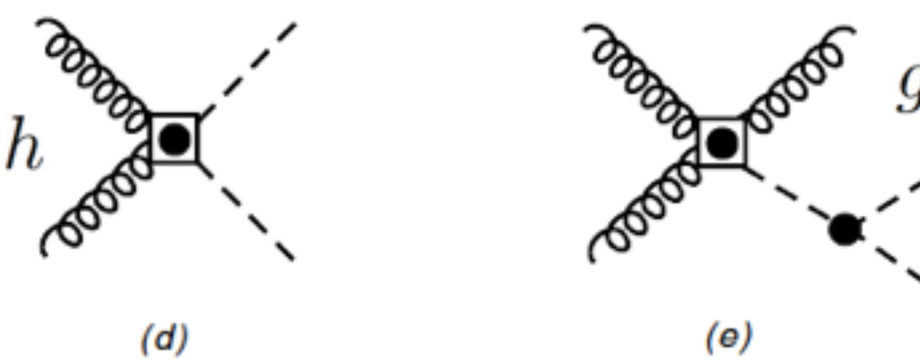
not contributing diagram types:

$y_t g_s \bar{t}_L \sigma_{\mu\nu} G^{\mu\nu} t_R$



$g_s^2 G^a_{\mu\nu} G^{a,\mu\nu} \partial_\lambda h \partial^\lambda h$

$g_s^3 f^{abc} G^a_{\mu\nu} G^{b,\nu}{}_\lambda G^{c,\lambda\mu} h$



(a),(b): $d\chi = 6$ but of order $g_s^2 g_w^2$ (a), $g_s^2 c_{4h}$ (b)

(c),(d): not of order g_s^4, suppressed by $1/16\pi^2$
(operator must come from contracted loop, see hep-ph/9405214)

(e): *L*=2 interfered with real emission $\Rightarrow$ higher order

Parametrisation of the NLO cross section

$$\sigma^{\rm NLO}/\sigma^{\rm NLO}_{SM} =$$

$$A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh}$$
$$+ A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh}$$
$$+ A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh}$$
$$+ A_{16}\, c_t^3 c_{ggh} + A_{17}\, c_t c_{tt} c_{ggh} + A_{18}\, c_t c_{ggh}^2 c_{hhh} + A_{19}\, c_t c_{ggh} c_{gghh}$$
$$+ A_{20}\, c_t^2 c_{ggh}^2 + A_{21}\, c_{tt} c_{ggh}^2 + A_{22}\, c_{ggh}^3 c_{hhh} + A_{23}\, c_{ggh}^2 c_{gghh}\,.$$

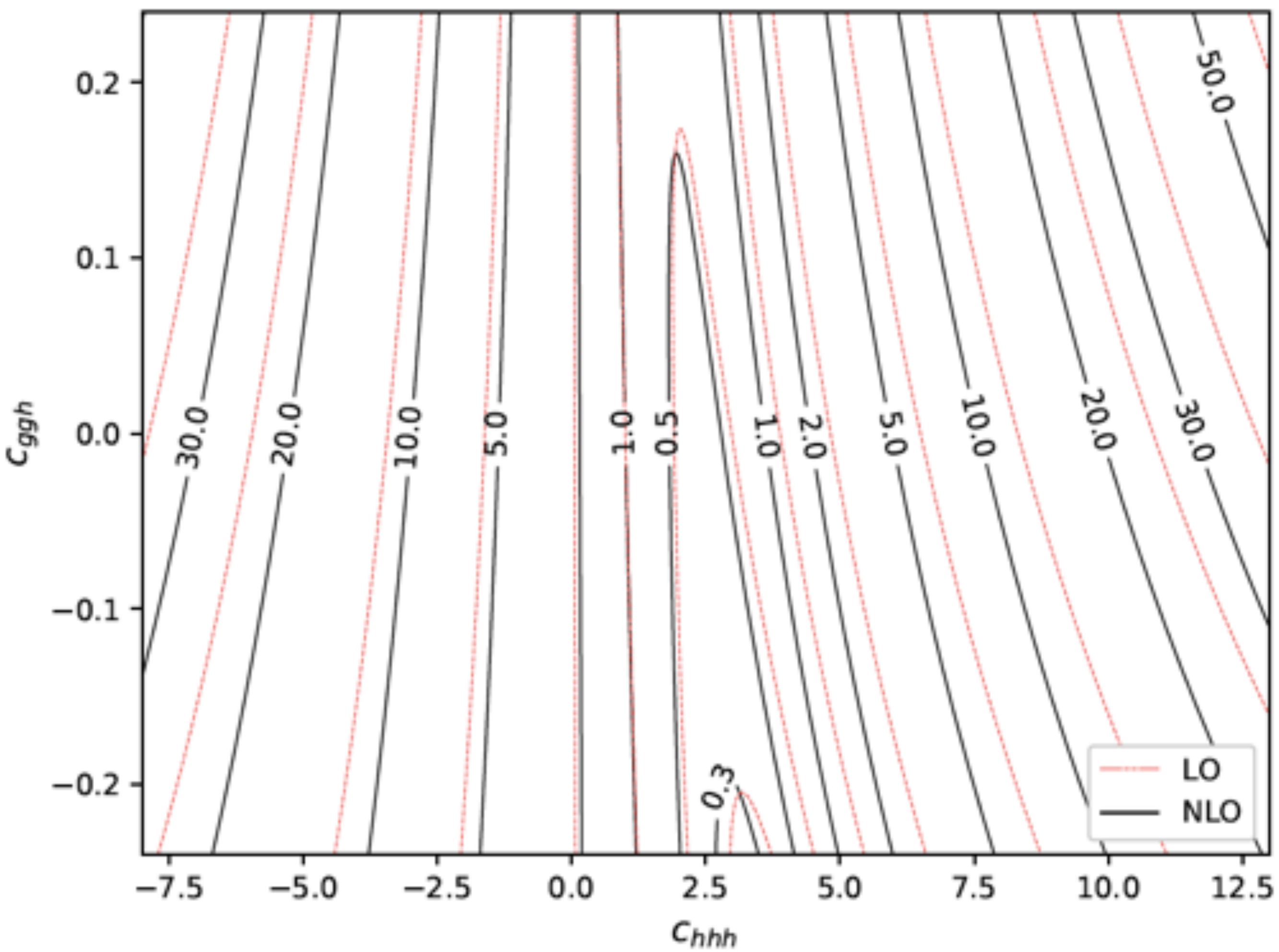
only present at NLO

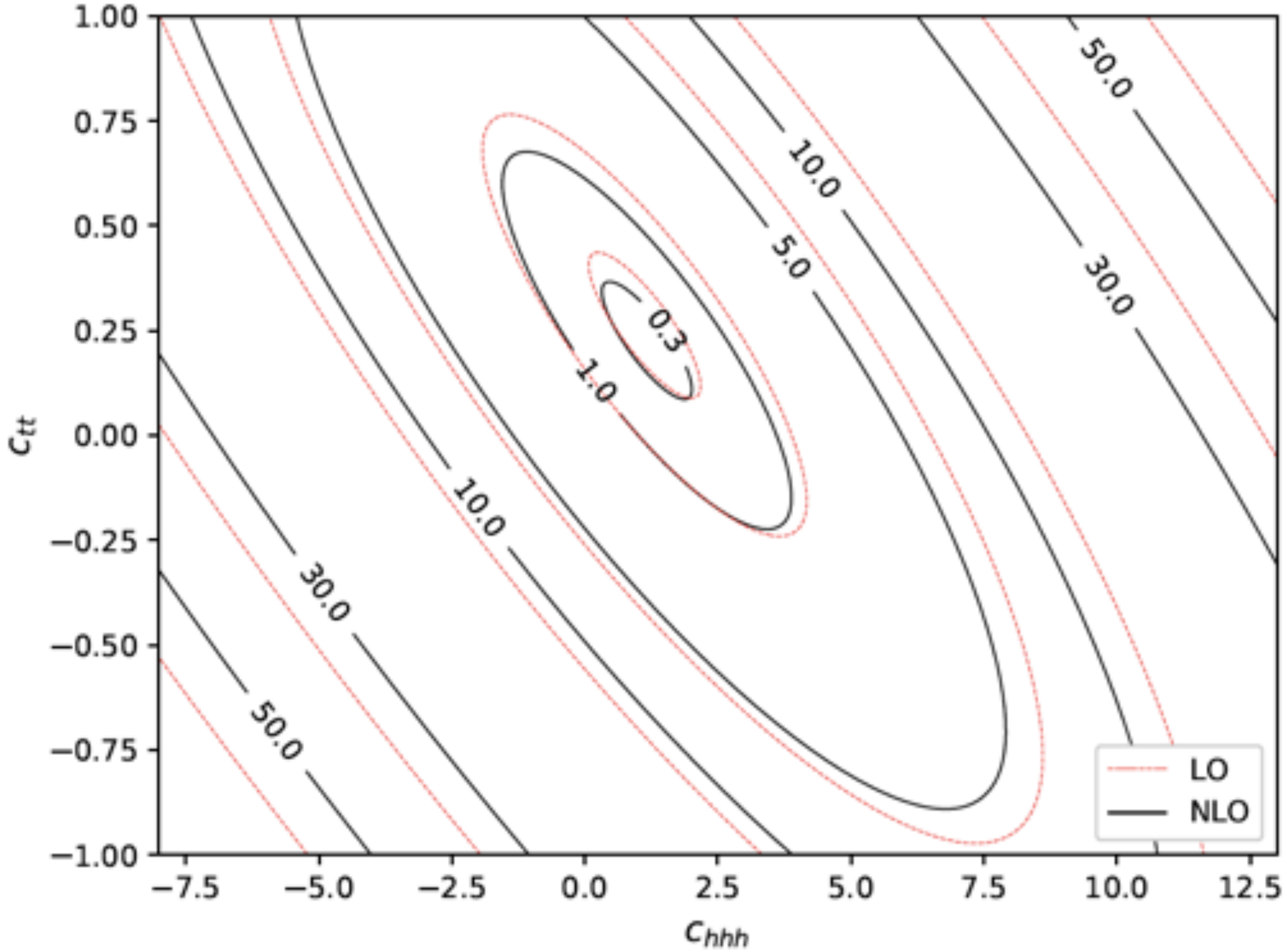
A_i coefficients allow to reconstruct the total cross section for arbitrary values of the couplings

- also available in differential form for m_{hh} distribution
- for 14 TeV on https://arxiv.org/abs/1806.05162v1 as .csv tables
- for 13 and 27 TeV available on request

iso-contours LO/NLO

$$\sigma/\sigma_{\rm SM}$$

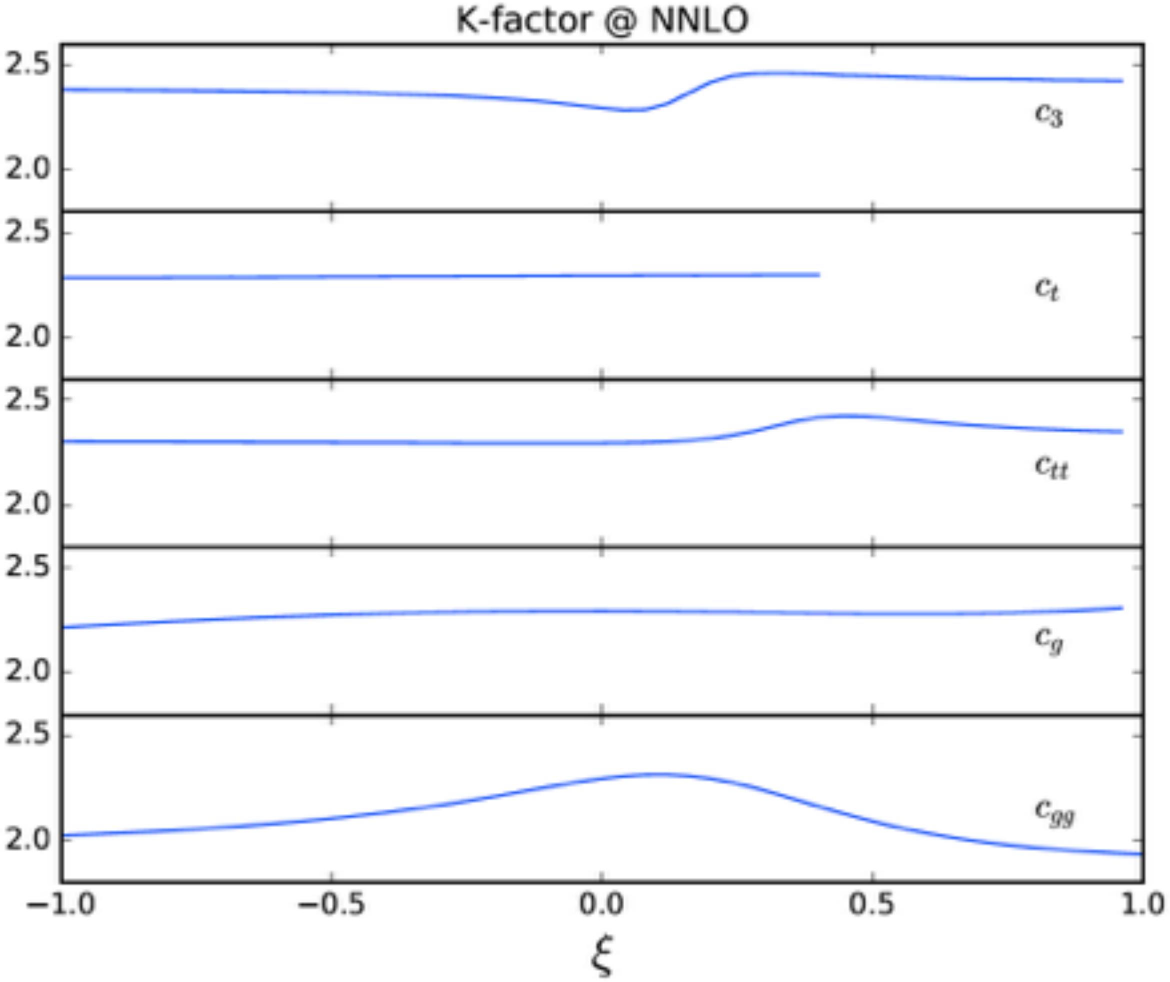


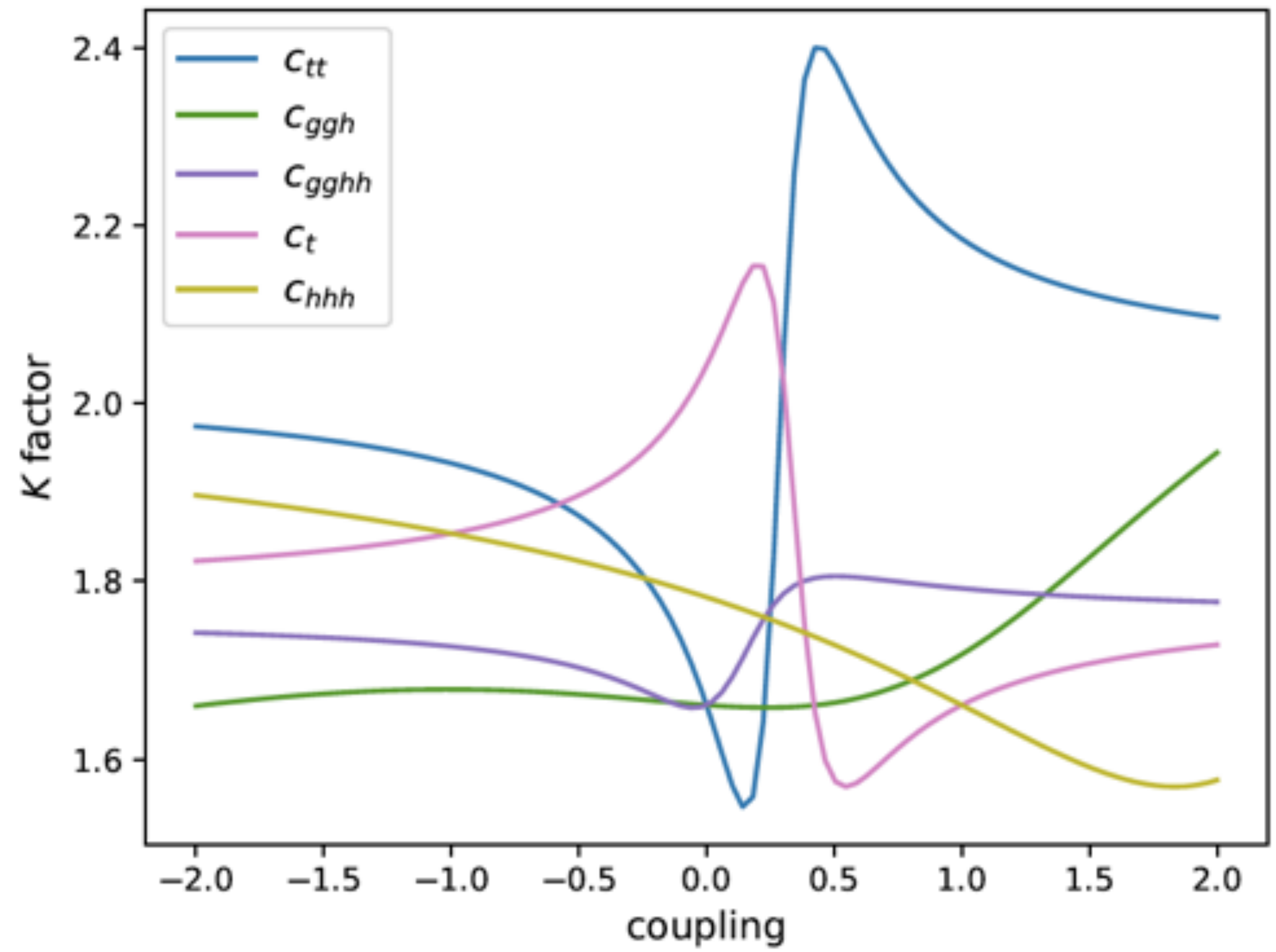


- sizeable distortions at NLO for larger values of $|c_{hhh}|$
- allow to identify degeneracies with SM

K-factors

K-factors as functions of the BSM couplings





NNLO rescaled HEFT

De Florian, Fabre, Mazzitelli '17

NLO with full mt dependence

Buchalla, Capozi, Celis, GH, Scyboz '18

$$
\begin{aligned}
c_3 &= 1 + 10\,\xi\,, \\
c_t &= 1 + 0.35\,\xi\,, \\
c_{tt} &= 1.5\,\xi\,, \\
c_g &= 0.15\,\xi\,, \\
c_{gg} &= 0.15\,\xi\,.
\end{aligned}
$$

SM values: $\xi = 0$

top mass effects very important!

benchmark points

benchmarks characterising "clusters" of BSM scenarios according to distribution shapes

Carvalho, Dall'Osso, Dorigo, Goertz, Gottardo, Tosi '15;
Carvalho, Goertz, Mimasu, Gouzevitch, Aggarwal '17

Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	$-\frac{1.6}{3}$	-0.2
3	1.0	1.0	-1.5	0.0	$\frac{0.8}{3}$
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	$\frac{1.6}{3}$	$\frac{1.0}{3}$
6	2.4	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
7	5.0	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
9	1.0	1.0	1.0	-0.4	-0.2
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	$\frac{2.0}{3}$	$\frac{1.0}{3}$
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

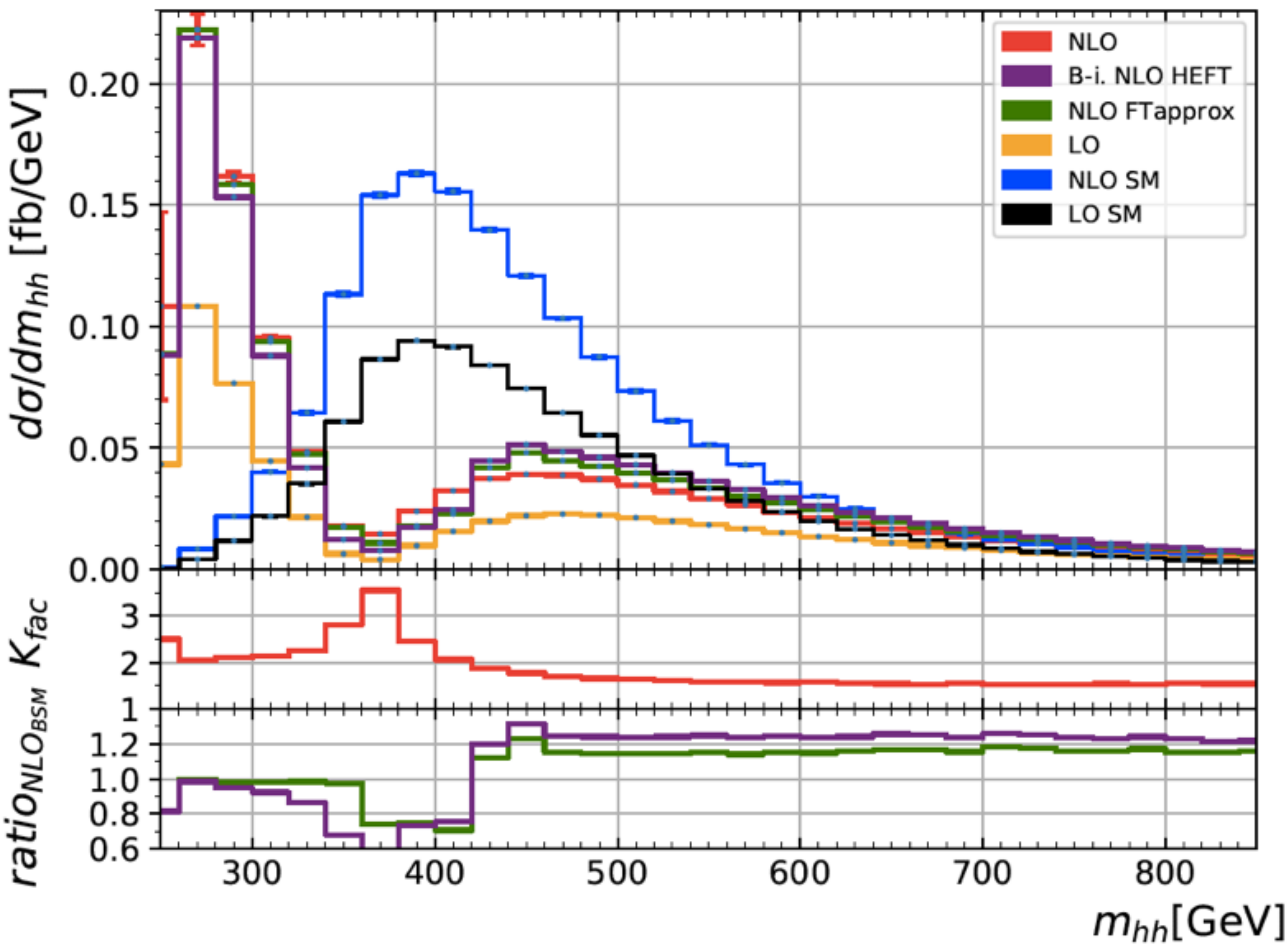
choosing 2 examples

results are for $\sqrt{s} = 14\,\mathrm{TeV}$

Benchmark	σ_{NLO} [fb]	K-factor	scale uncert. [%]	stat. uncert. [%]	$\frac{\sigma_{NLO}}{\sigma_{NLO,SM}}$
B_6	24.69	1.89	$^{+2}_{-11}$	2.1	0.7495
B_{8a}	41.70	2.34	$^{+6}_{-9}$	0.63	1.266
SM	32.95	1.66	$^{+14}_{-13}$	0.1	1

mhh distribution for benchmark point 6

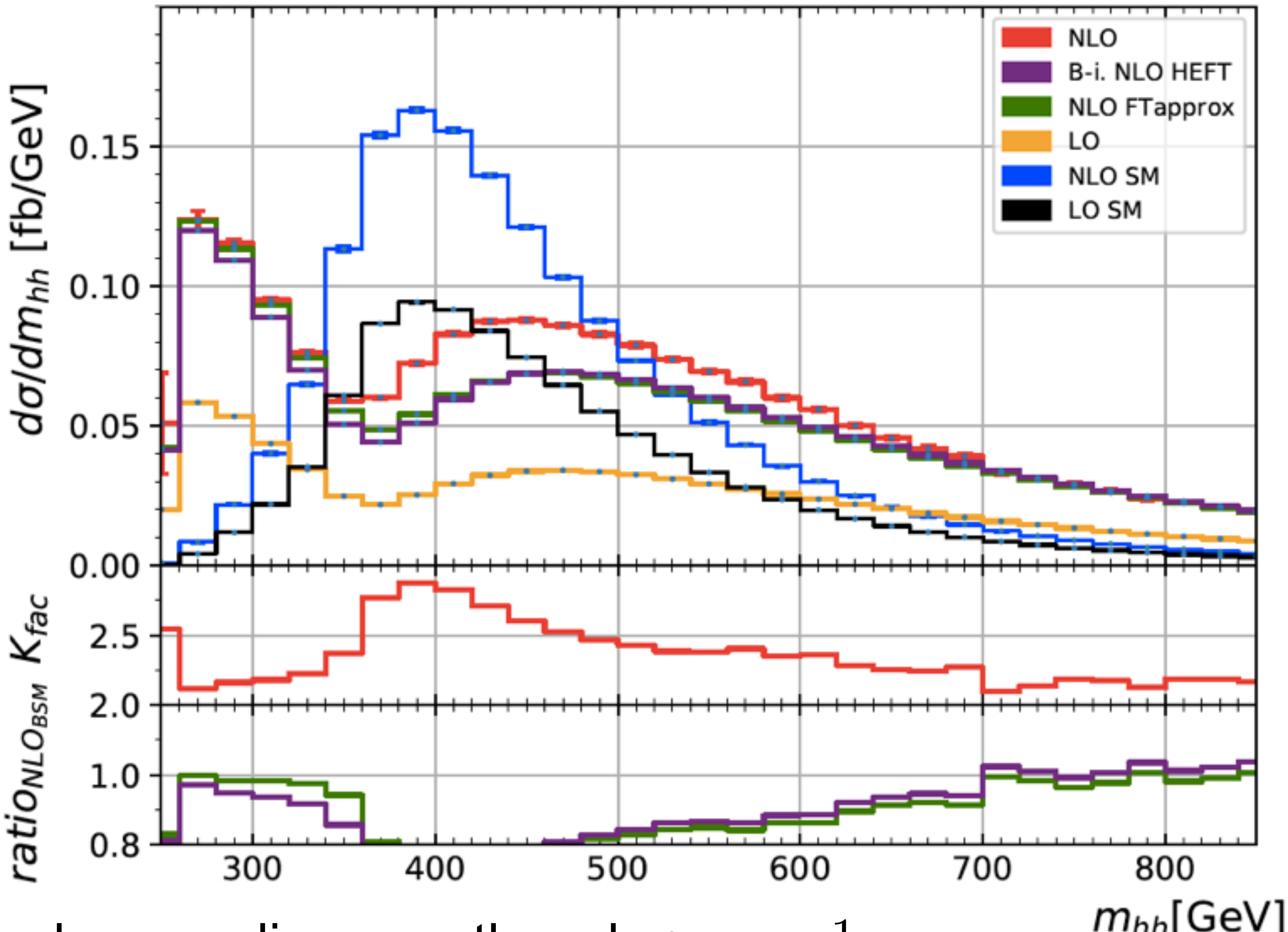
$c_{hhh} = 2.4,\ c_t = 1.0,\ c_{tt} = 0,\ c_{ggh} = \frac{2}{15},\ c_{gghh} = \frac{1}{15}$



very different shape, highly non-homogeneous K-factor

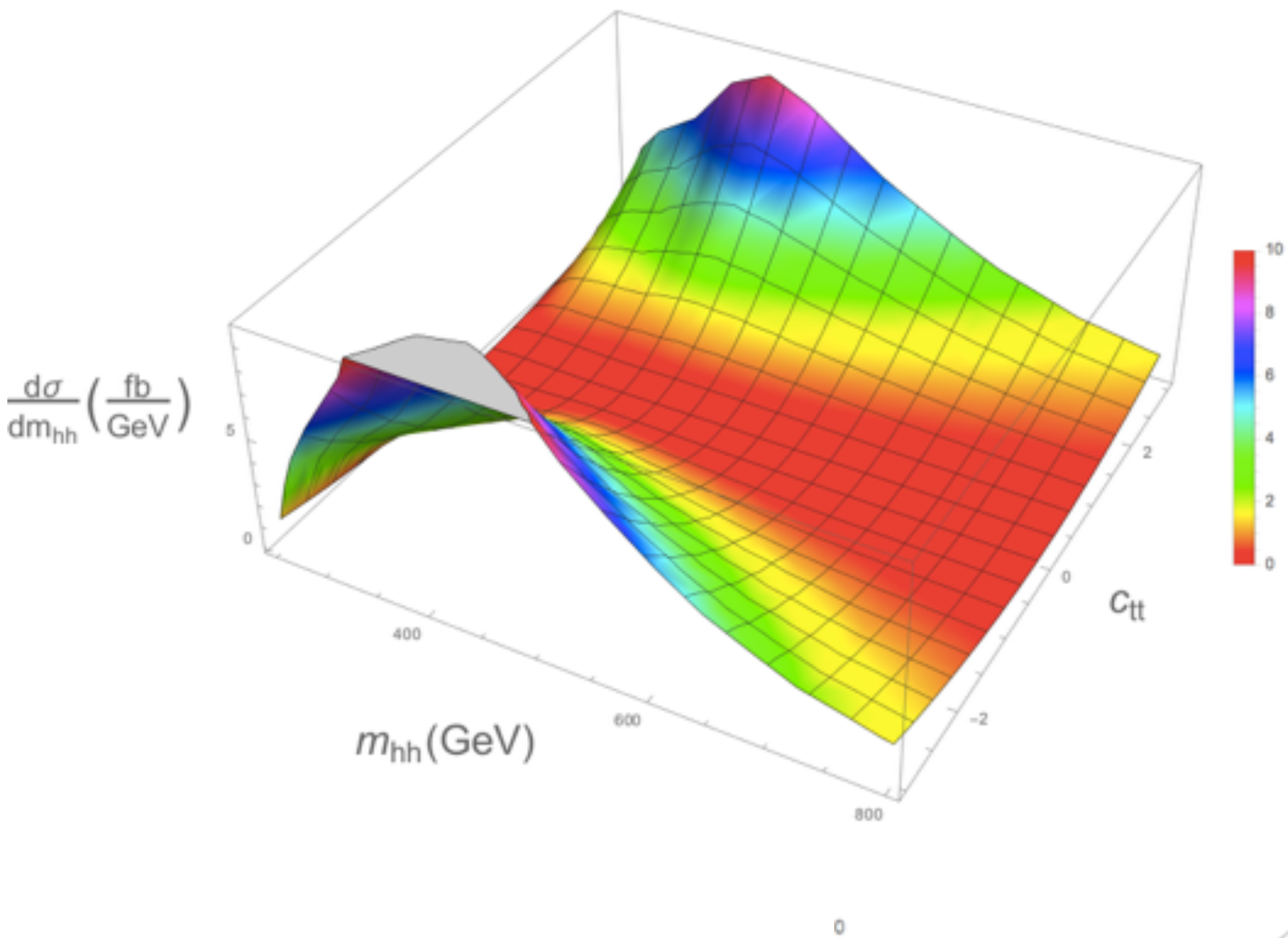
mhh distribution for benchmark point 8a

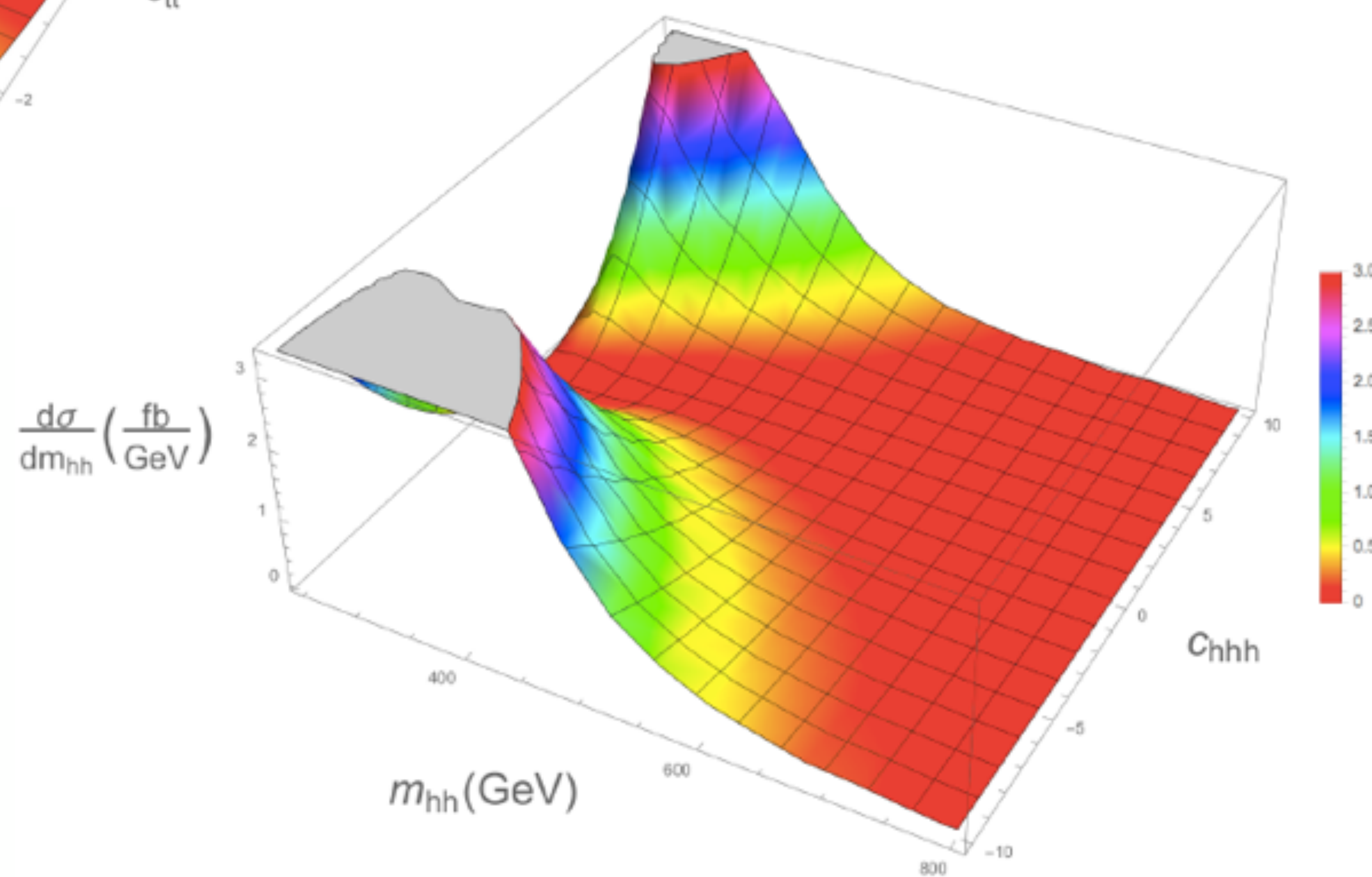
$$c_{hhh} = 1, c_t = 1, c_{tt} = 0.5, c_{ggh} = 4/15, c_{gghh} = 0.$$



- also shows a dip, even though $c_{hhh} = 1$
- approximations (purple, green) quite different from full

3D mhh distributions

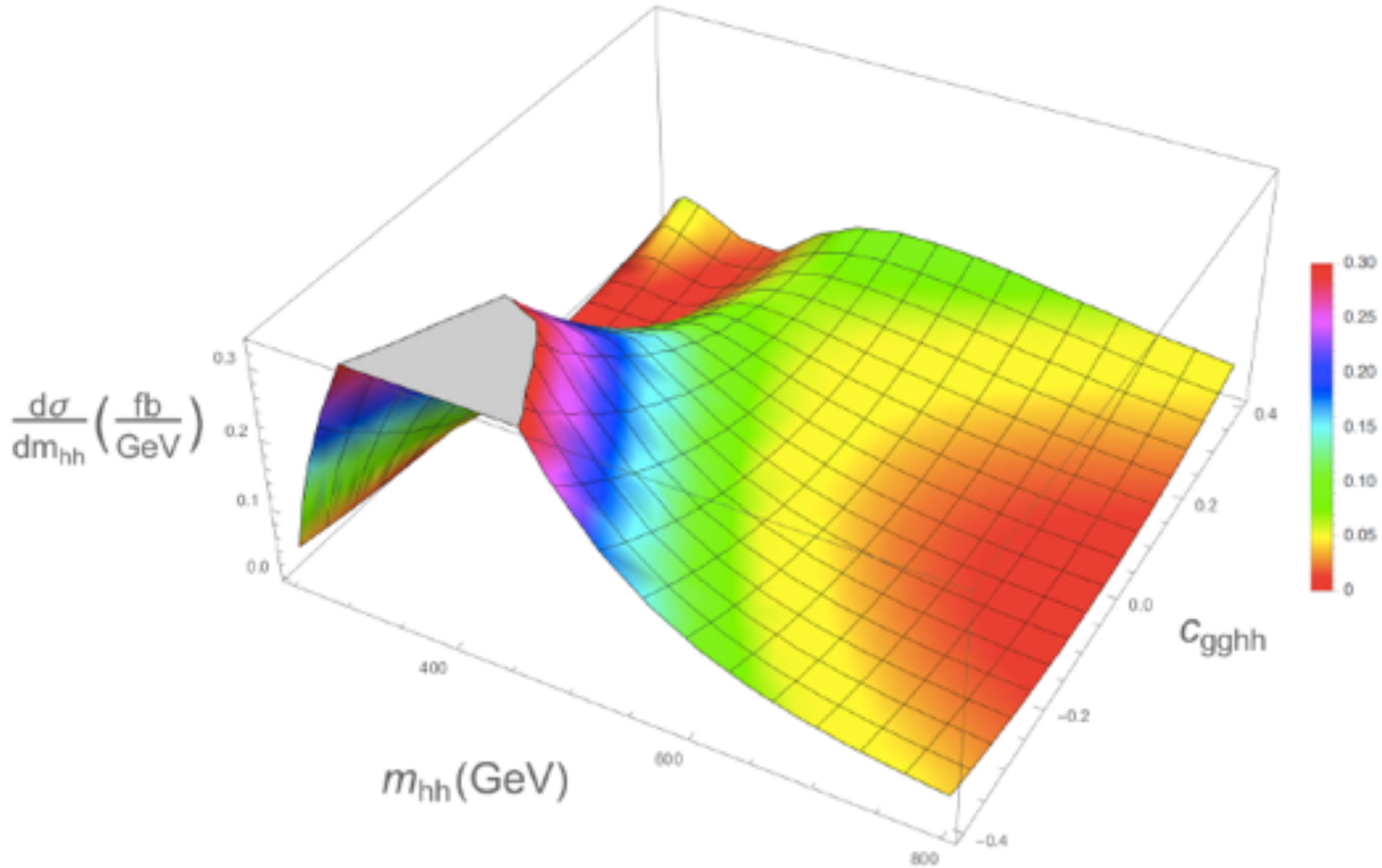




other couplings
fixed to their SM values

thanks: Matteo Capozi

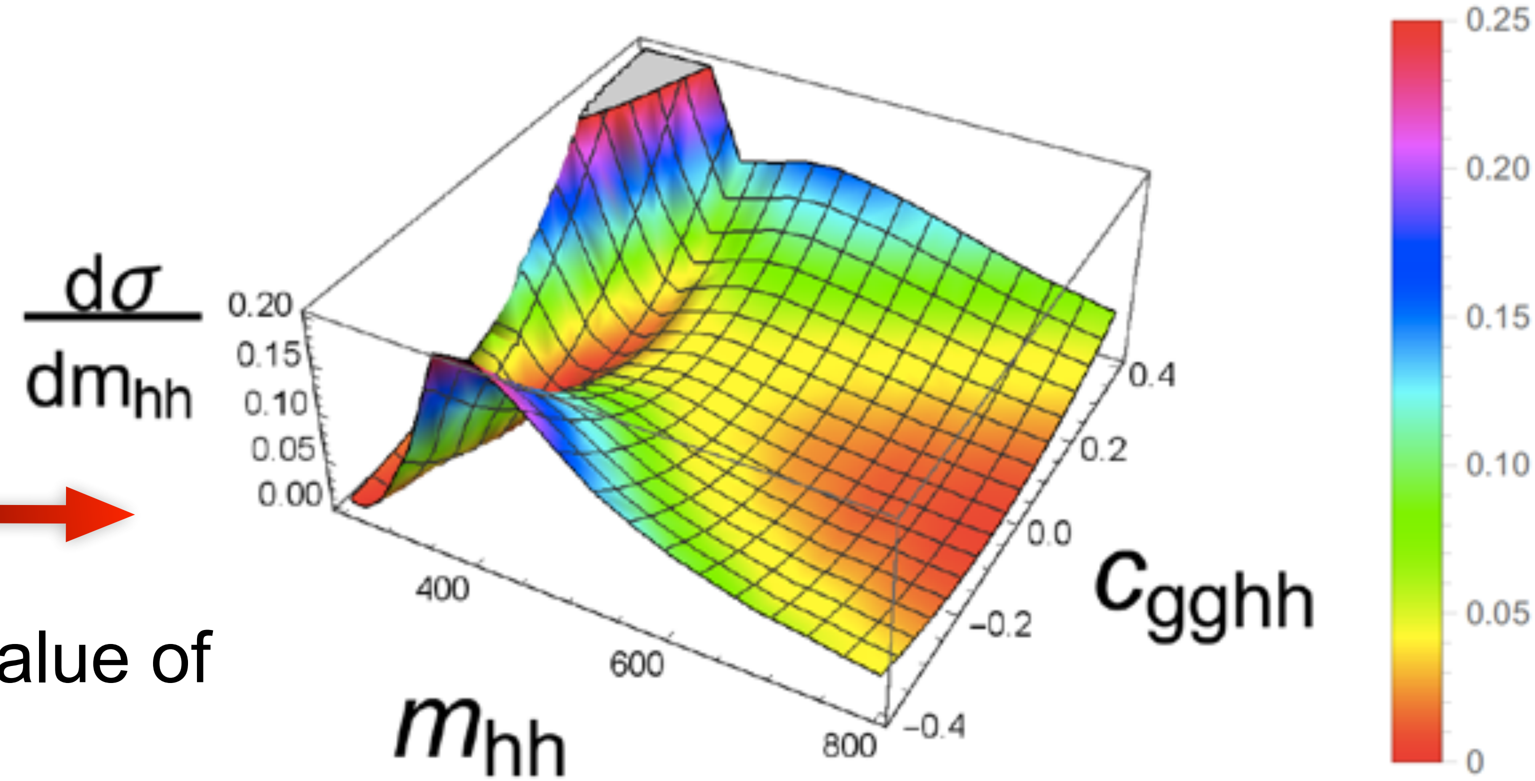
change of shape with c_{hhh} and c_{gghh}



here $c_{hhh} = 1$

here $c_{hhh} = 2.4$

depth of dip depends on value of c_{gghh}



Summary & Outlook

- 5 anomalous couplings within non-linear EFT framework in Higgs sector, $c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}$ at order $d_\chi = 6, \alpha_s^3$
- NLO corrections can be sizeable and distort the shape of the m_{hh} distribution
- total cross sections degenerate with SM usually are very different at distribution level
- benchmark analysis of limited constraining power in coupling parameter space
- varying only c_{hhh}, c_{tt} might be more useful

  $\rightarrow$ implementation in POWHEG coming soon

  (will be same setup as SM POWHEG/ggHH)
- coefficients A_i for m_{hh} distribution already publicly available

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Thanks for your attention

Backup slides

$$\mathcal{L}_2 = -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{\psi=q_L,l_L,u_R,d_R,e_R} \bar{\psi} i \not{D} \psi$$
$$+\frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle\,(1+F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$
$$-v\left[\bar{q}_L\left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)}\left(\frac{h}{v}\right)^n\right) U P_+ q_R + \bar{q}_L\left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- q_R\right.$$
$$\left. + \bar{l}_L\left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- l_R + \text{h.c.}\right] \quad \text{(II}$$