Anomalous couplings in gg → HH at NLO

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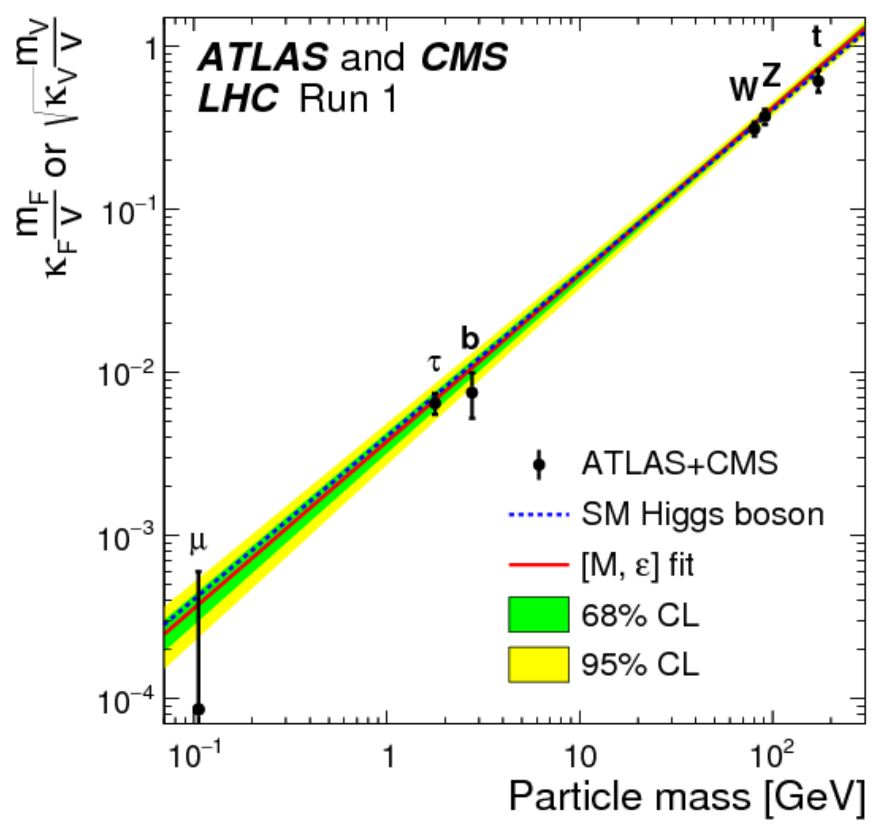
H?



LHC-HH subgroup meeting, January 29, 2020

MAX-PLANCK-GESELLSCHAFT

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Effective Field Theory descriptions of BSM effects

- parametrise ignorance about new physics

  at a scale (much) larger than the electroweak scale

  in a systematic way

- add operators to SM Lagrangian respecting symmetries

  (**gauge**, optionally: lepton number, flavour, CP, custodial, …)

- scheme of power counting for the extra operators is not unique

  basically two schemes:

  - SMEFT (“linear EFT”)
  - HEFT (“non-linear EFT”) (also called “Electroweak Chiral Lagrangian”)

Effective Field Theory descriptions

both respect the SM gauge symmetries

- SMEFT: Higgs field $\Phi(x)$ is complex doublet

  transforms linearly under $SU(2) \times U(1)$

$$\Phi(x) \rightarrow \exp\left[-i\alpha^a(x)\frac{\sigma^a}{2} - i\beta(x)\frac{1}{2}\right]\Phi(x)$$

- HEFT: Goldstone boson fields $\pi^a(x)$ are represented as

$$U(x) = \exp\left[i\pi^a(x)\sigma^a/v\right]$$

linear transformations on $U(x) : U \rightarrow V_L\, U\, V_R^\dagger$

act non-linearly on $\pi^a(x)$ (therefore the name "non-linear EFT")

$$U(x) \rightarrow \exp\left[-i\alpha^a(x)\frac{\sigma^a}{2}\right] U(x)\, \exp\left[i\beta(x)\frac{\sigma^3}{2}\right]$$

Effective Field Theory descriptions

- HEFT:

Goldstone sector has a symmetry $SU(2)_L \times SU(2)_R$ ("chiral")

which is broken to $SU(2)_{L+R}$ ("custodial symmetry", protects the rho-parameter)

Effective Field Theory descriptions

- HEFT:

Goldstone sector has a symmetry $SU(2)_L \times SU(2)_R$ ("chiral")

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Where is the Higgs?

Effective Field Theory descriptions

- HEFT:

Goldstone sector has a symmetry $SU(2)_L \times SU(2)_R$ ("chiral")

which is broken to $SU(2)_{L+R}$ ("custodial symmetry", protects the rho-parameter)

Where is the Higgs?

Physical Higgs field $h(x)$ is $SU(2)_L \times U(1)_Y$ singlet

Therefore Lagrangian can contain polynomials

$$\sum_n c_n \left(\frac{h}{v}\right)^n$$ with no a priori relation among the c_n

UV completion can be strongly coupled

dominant BSM physics is in the Higgs sector

model examples: composite H, H-dilaton, conformal H, induced EWSB, …

Effective Field Theory descriptions

scale hierarchies

E

new physics scale Λ

f : characteristic scale of Goldstone bosons

EW scale $v \sim 246\,\mathrm{GeV}$

- 3 scales, $\Lambda = \min(\Lambda_{\rm BSM}, 4\pi f),\ f,\ v \quad \Rightarrow$
- 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

Two EFT frameworks

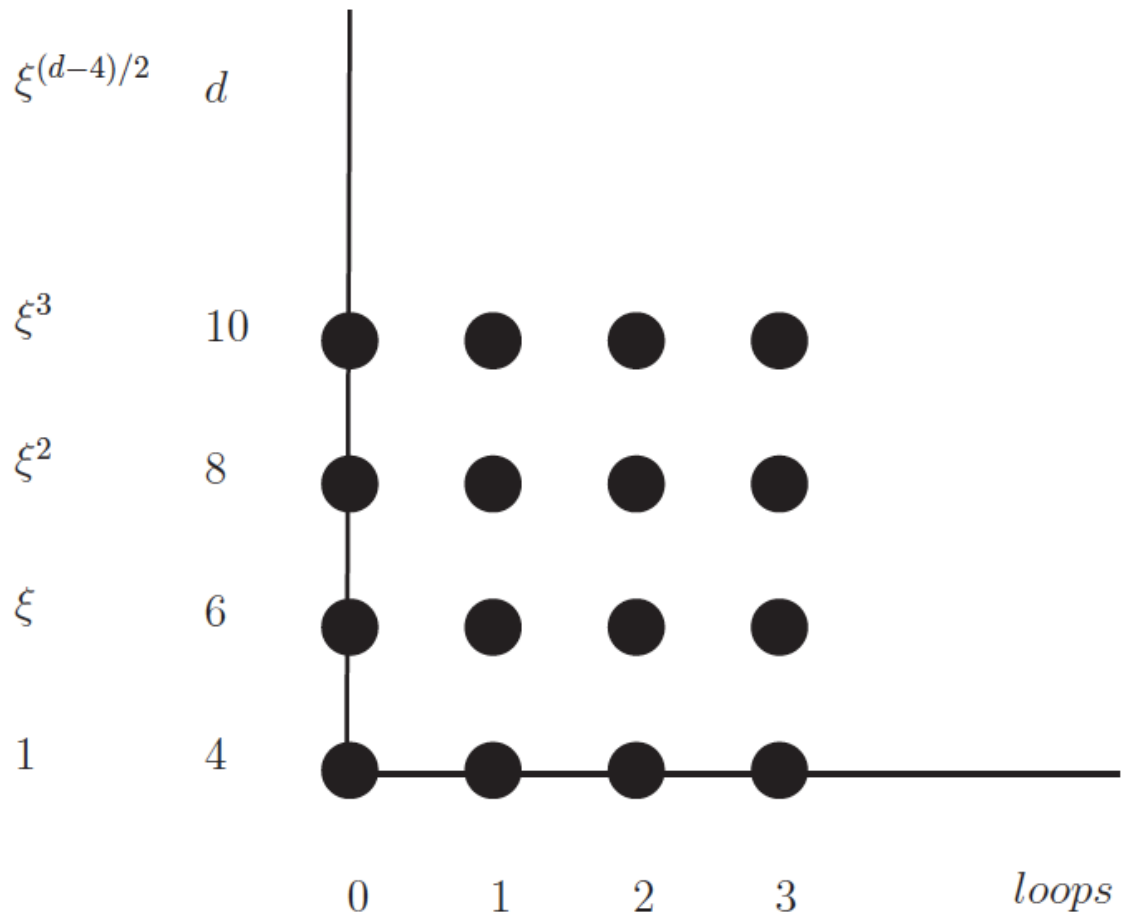
HEFT (EWChL): "loop expansion"

based on chiral dimension $d_\chi = 2L + 2$ L: "Loop"

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

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

SMEFT



loop expansion

HEFT

figure: G.Buchalla

Lagrangian relevant for gg to HH

SMEFT:

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

HEFT:

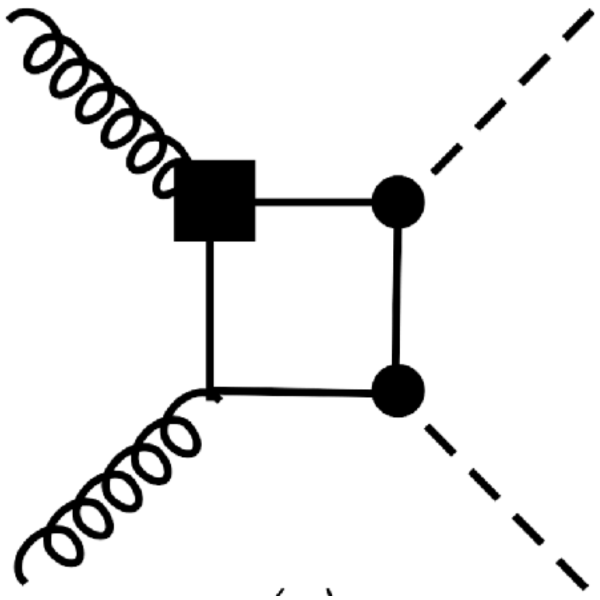
$$\Delta\mathcal{L}_{d\chi\le 4} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

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

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

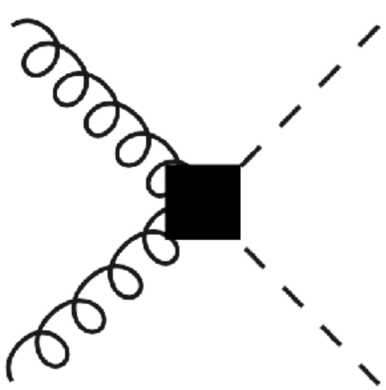
Chromomagnetic operator

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



in weakly coupled theories operator must come from contracted loop
(see Arzt, Einhorn, Wudka hep-ph/9405214)

$\Rightarrow$ suppressed by $1/16\pi^2$



$ggh(h)$ interactions also come from contraction of a loop, but they appear at tree level, while O_{tG} is inserted into a loop diagram and therefore is suppressed

Phenomenology
(gg to HH at NLO)

based on

1903.08137 GH, Jones, Kerner, Luisoni, Scyboz

http://powhegbox.mib.infn.it/User-Process-V2/ggHH

allows variations of c_{hhh} (and c_t)

1806.05162 Buchalla, Capozi, Celis, GH, Scyboz

variations of 5 anomalous couplings

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

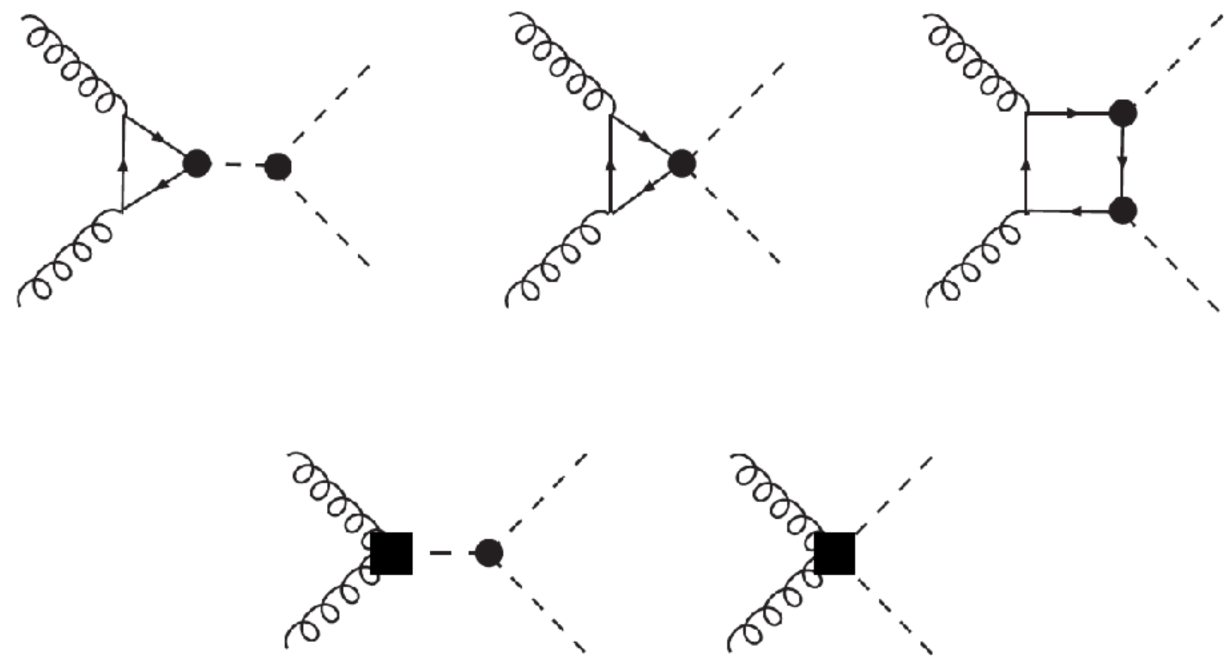
1703.09252 GH, Jones, Kerner, Luisoni, Vryonidou

gg to HH EFT + NLO QCD

LO diagrams:

$d\chi \le 4$

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

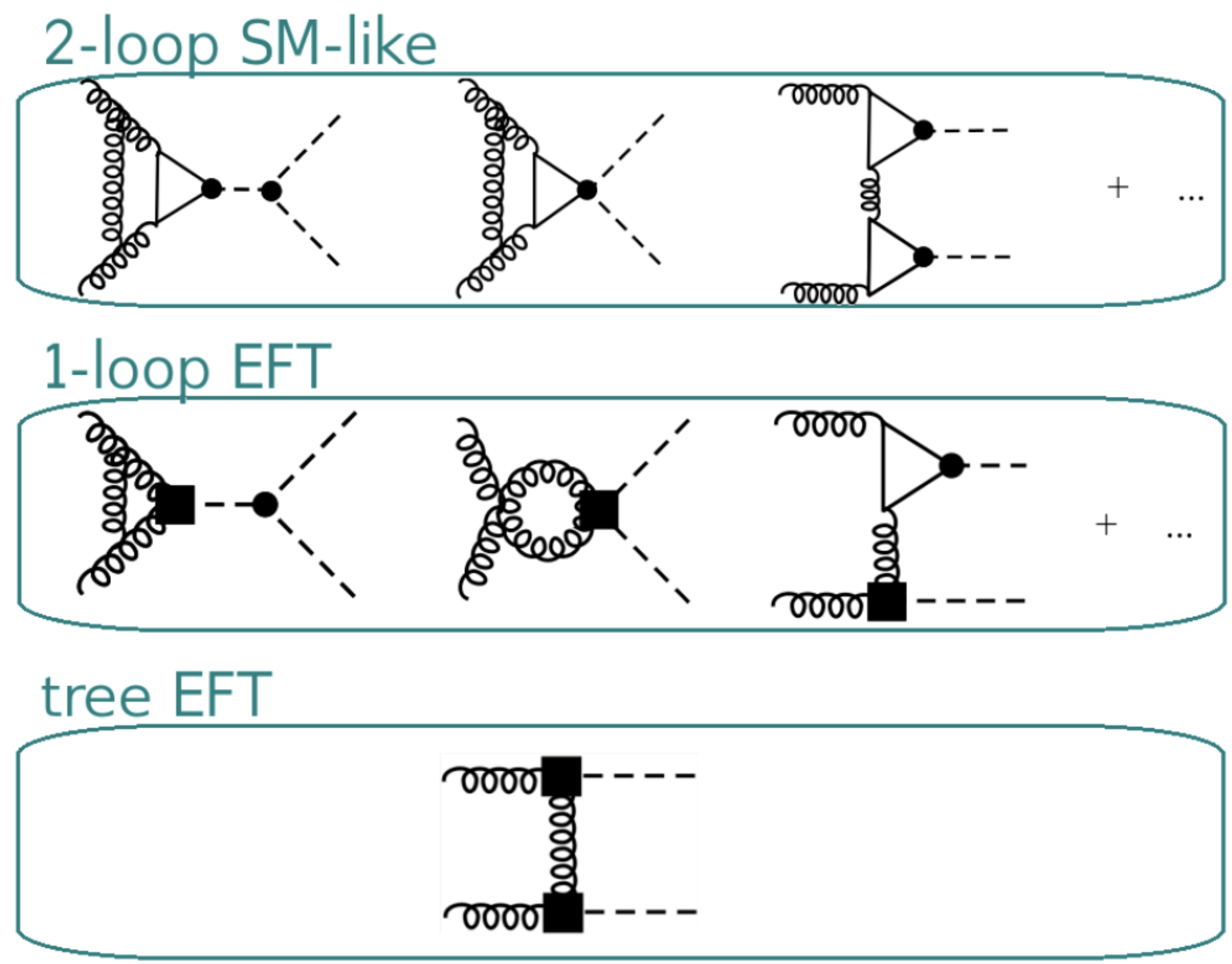


NLO diagrams:

virtual corrections
(example diagrams)

$d\chi \le 6$ and

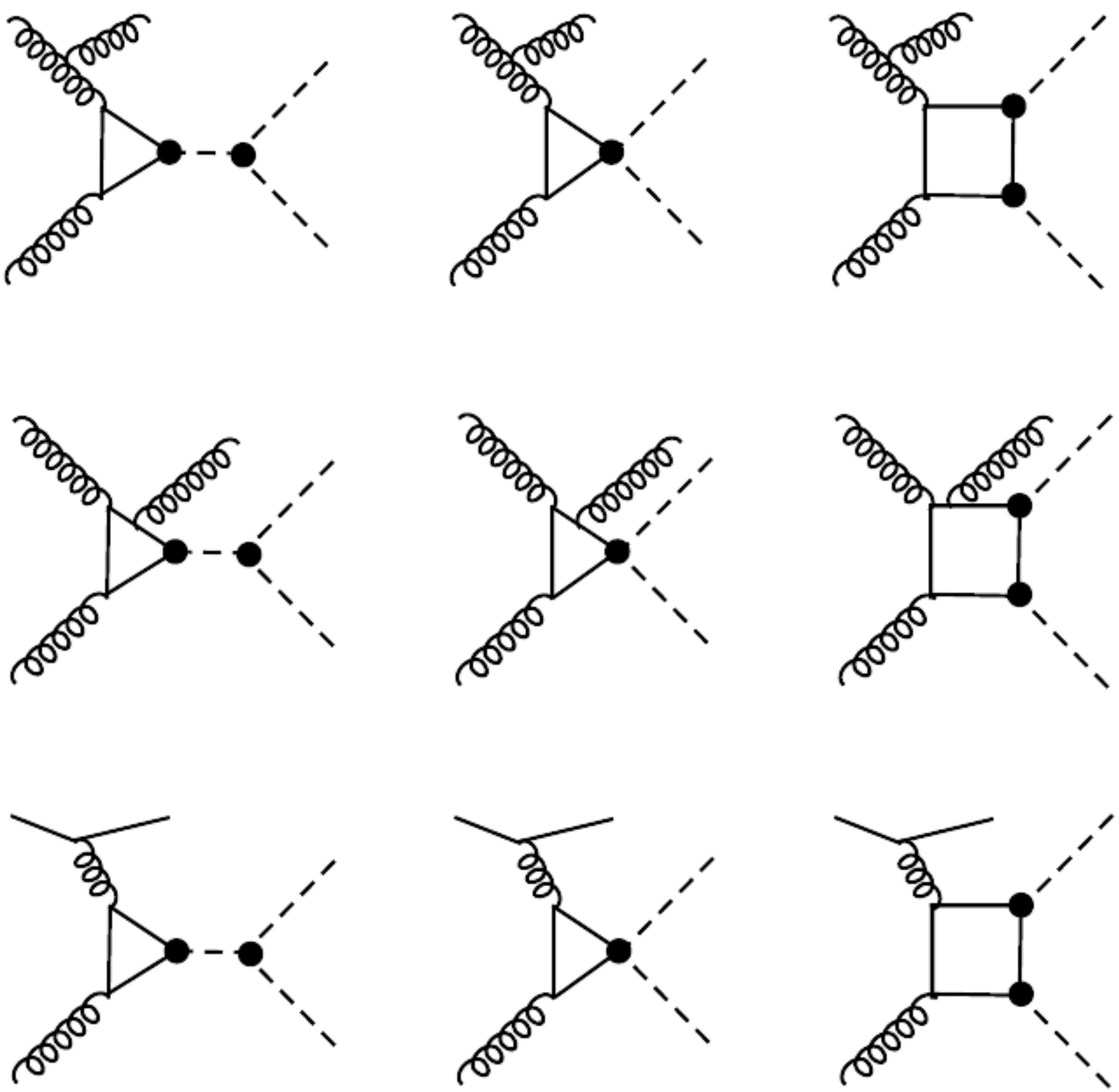
$\mathcal{O}(g_s^4)$ at diagram level



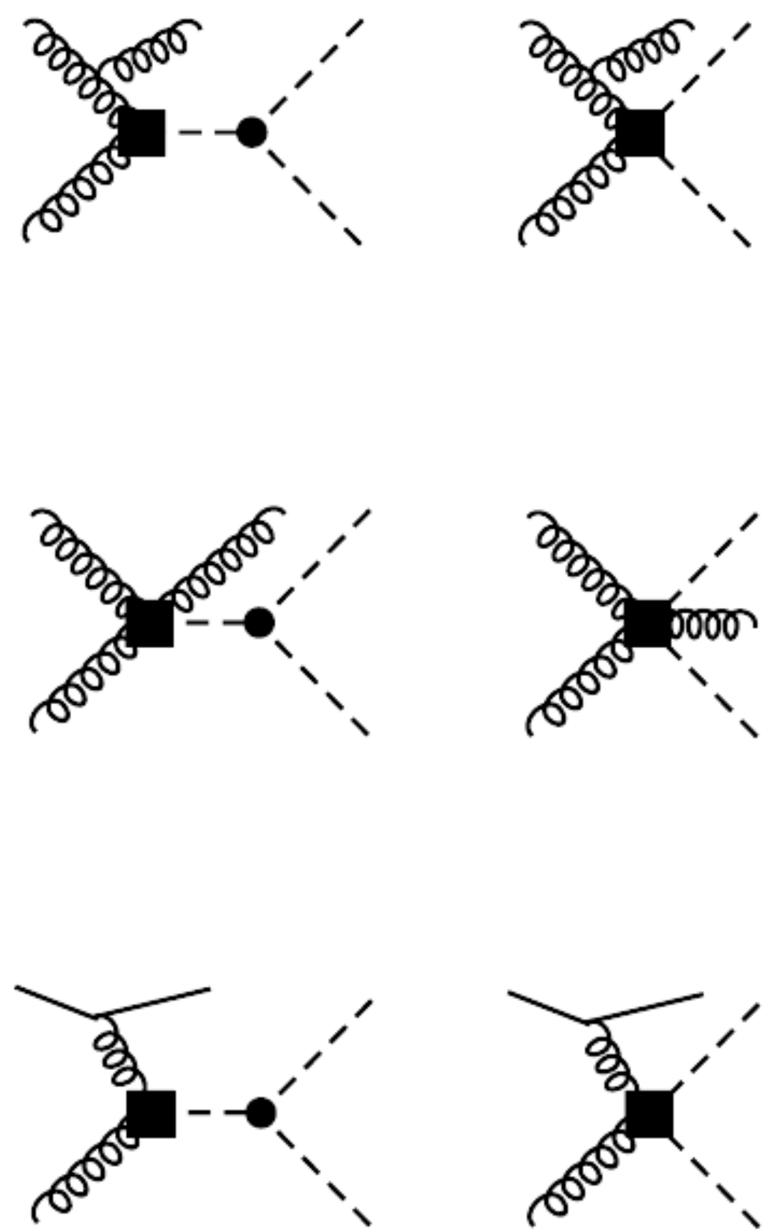
examples of diagrams

NLO diagrams: real radiation corrections

5-point 1-loop diagrams



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



thanks: Ludovic Scyboz

K-factors

K-factors as functions of the BSM couplings

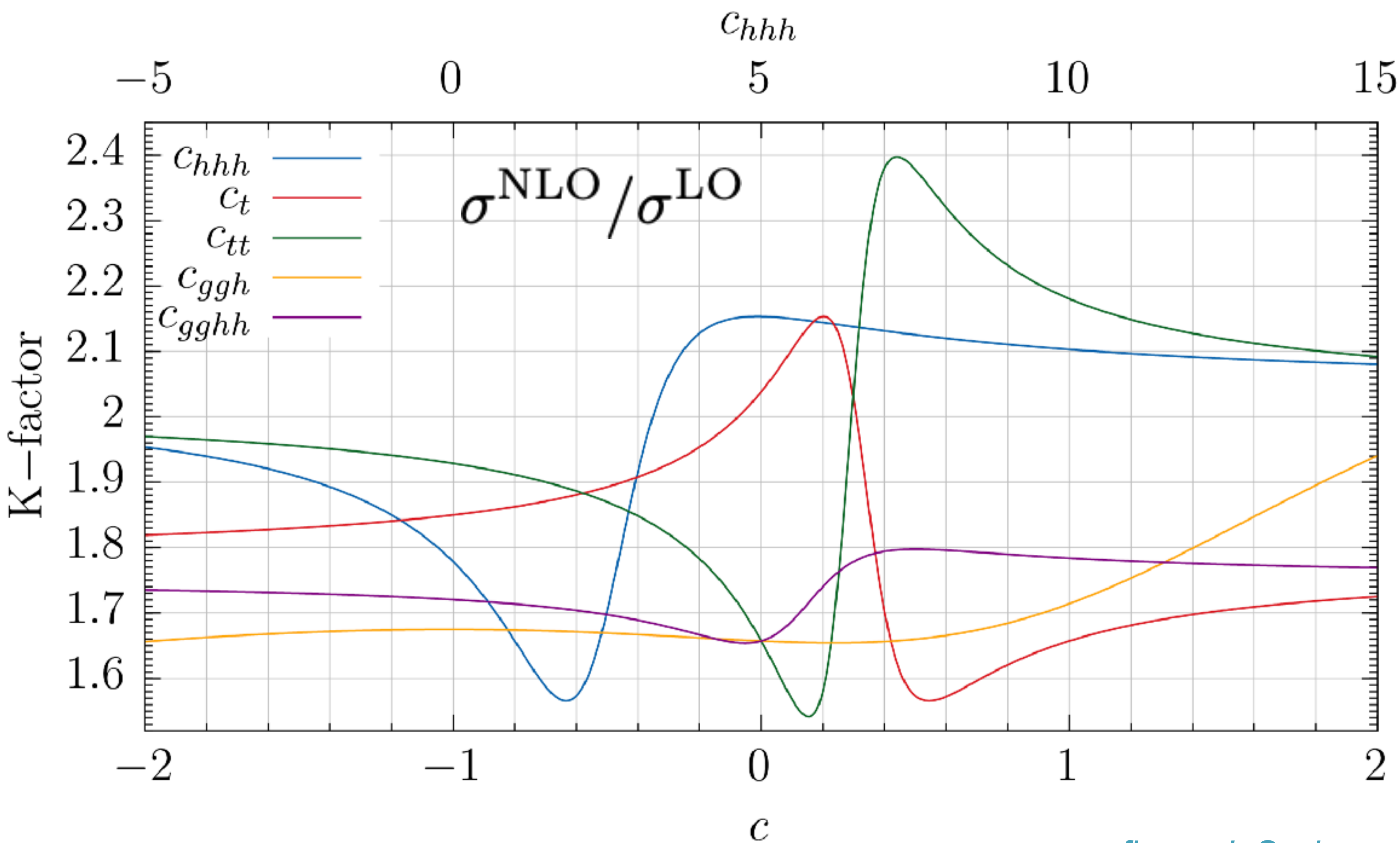


figure: L.Scyboz

vary substantially (much less variation in heavy top limit)

lambda variations: total cross sections

focus on $c_{hhh} = \lambda_{\mathrm{SM}}/\lambda_{\mathrm{BSM}}$

$\lambda_{\mathrm{BSM}}/\lambda_{\mathrm{SM}}$	σ_{NLO}@13TeV [fb]	σ_{NLO}@14TeV [fb]	σ_{NLO}@27TeV [fb]	K-factor@14TeV
-1	$116.71^{+16.4\%}_{-14.3\%}$	$136.91^{+16.4\%}_{-13.9\%}$	$504.9^{+14.1\%}_{-11.8\%}$	1.86
0	$62.51^{+15.8\%}_{-13.7\%}$	$73.64^{+15.4\%}_{-13.4\%}$	$275.29^{+13.2\%}_{-11.3\%}$	1.79
1	$27.84^{+11.6\%}_{-12.9\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	1.66
2	$12.42^{+13.1\%}_{-12.0\%}$	$14.75^{+12.0\%}_{-11.8\%}$	$59.10^{+10.2\%}_{-9.7\%}$	1.56
2.4	$11.65^{+13.9\%}_{-12.7\%}$	$13.79^{+13.5\%}_{-12.5\%}$	$53.67^{+11.4\%}_{-10.3\%}$	1.65
3	$16.28^{+16.2\%}_{-15.3\%}$	$19.07^{+17.1\%}_{-14.1\%}$	$69.84^{+14.6\%}_{-12.1\%}$	1.90
5	$81.74^{+20.0\%}_{-15.6\%}$	$95.22^{+19.7\%}_{-11.5\%}$	$330.61^{+17.4\%}_{-13.6\%}$	2.14

uncertainties: scale variations by factor of 2 around $\mu_0 = m_{hh}/2$

PDFs: PFD4LHC15_nlo30_pdfas

scale uncertainties reduced if combined with NNLO in $m_t \to \infty$ limit

Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli; 1803.02463

combination of full NLO with NNLO for anomalous couplings:

lambda variations: total cross sections

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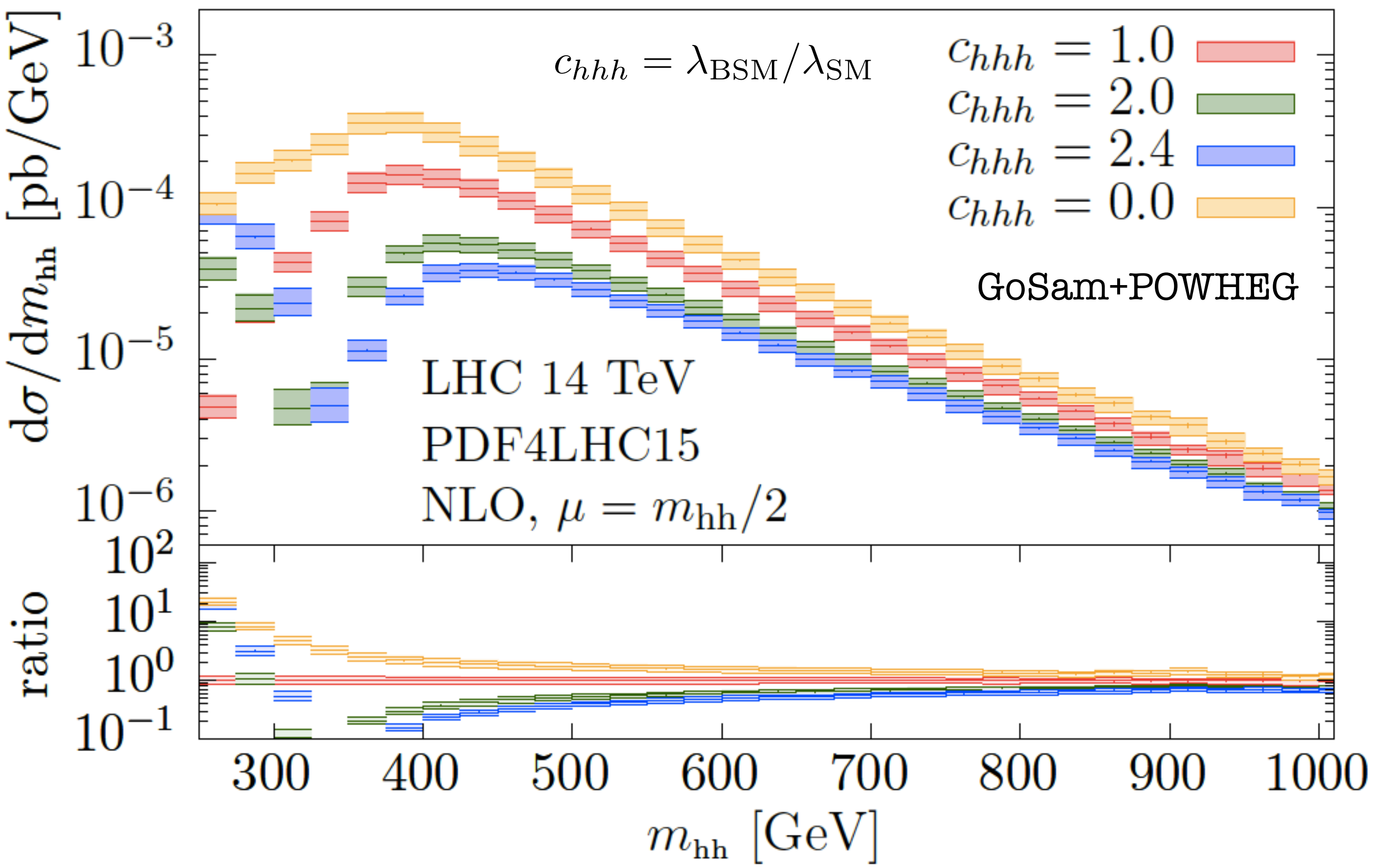
combination of full NLO with NNLO for anomalous couplings:

see talk of Javier Mazzitelli

HH invariant mass with variation of the self-coupling

GH, Jones, Kerner, Luisoni, Scyboz '19



dip in m_{hh} distribution

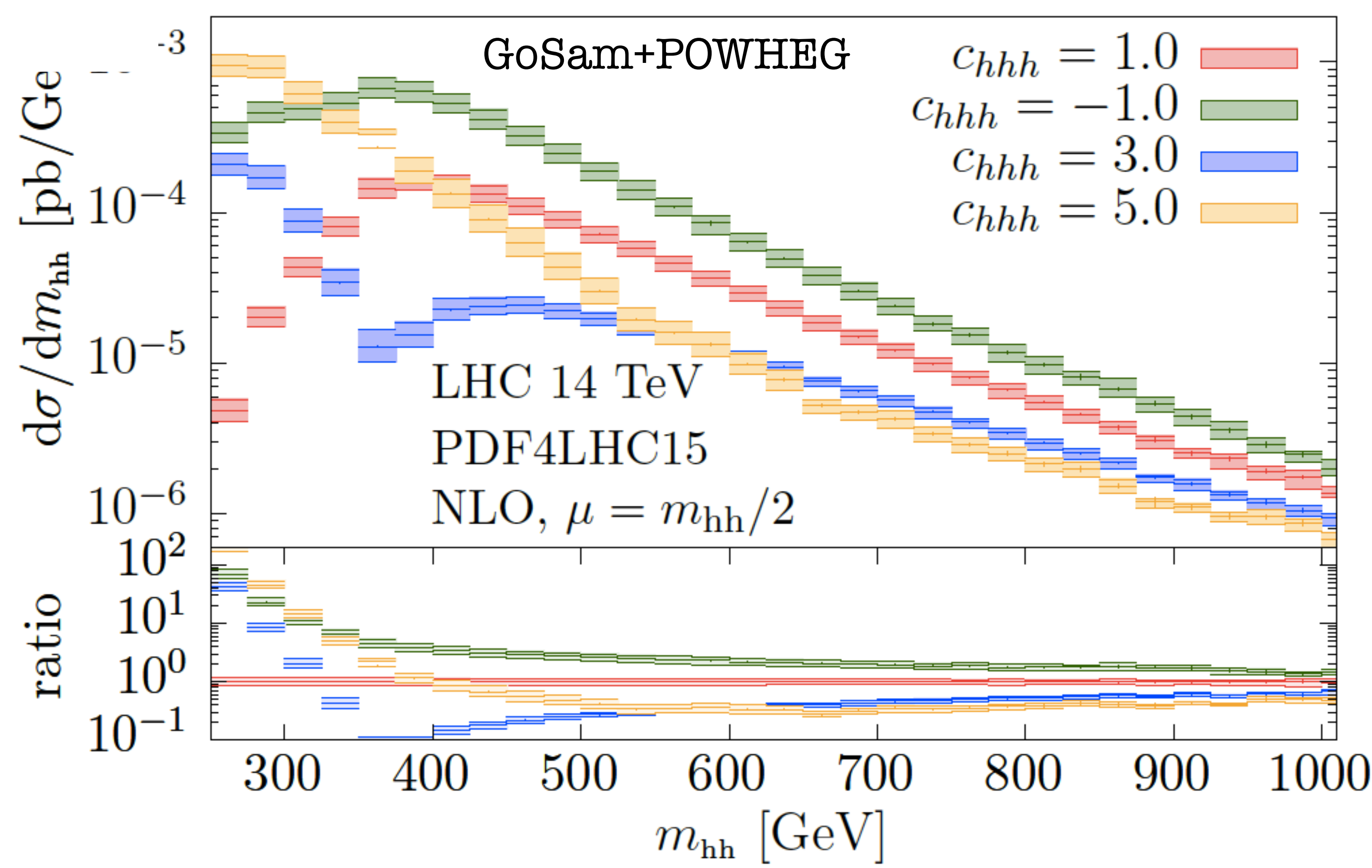
at 350 GeV for c_{hhh} ~ 2.4

↑

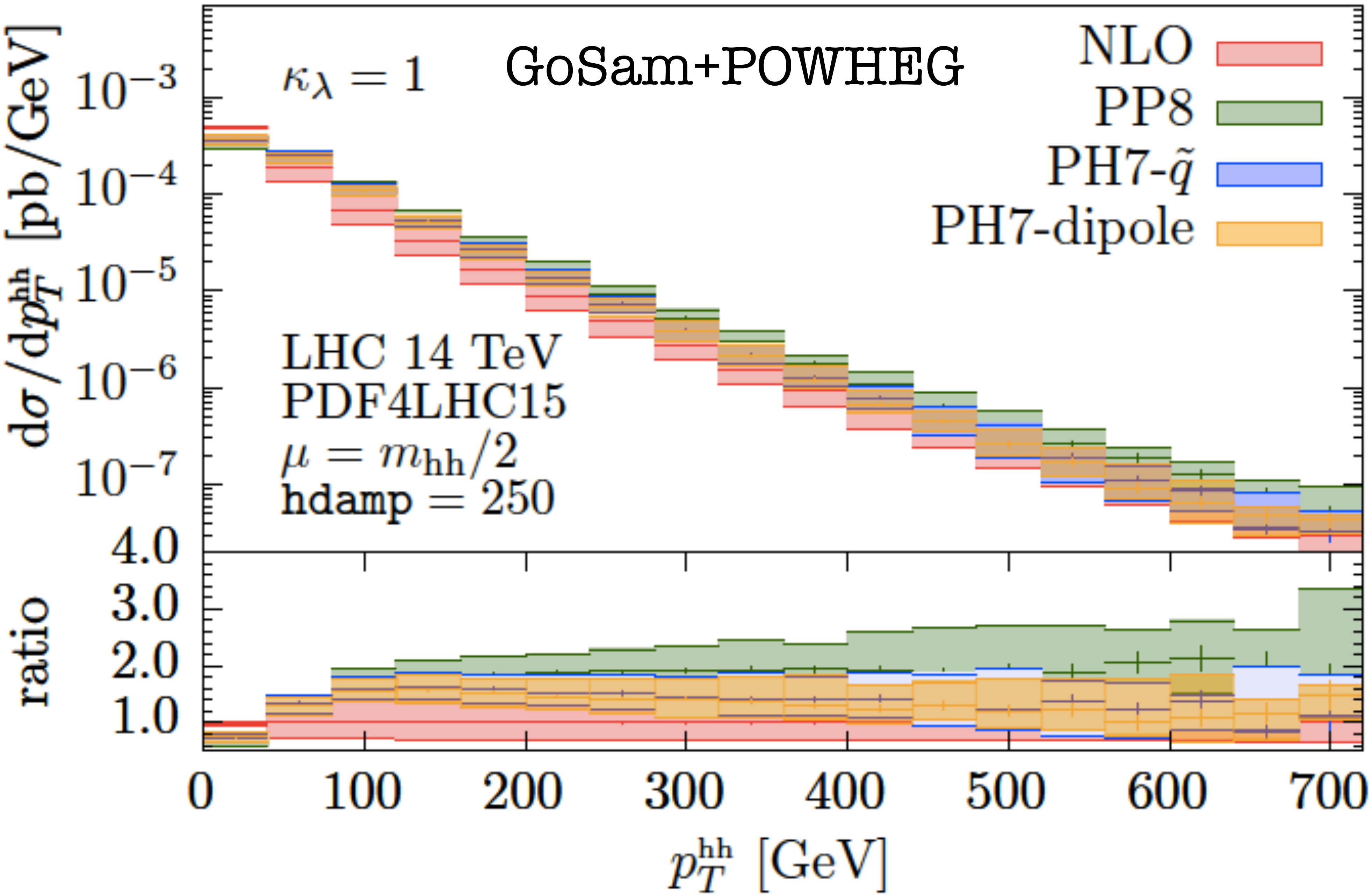
$c_{hhh} = 0$ largest

in this group

bands: 3-point scale variations



HH@NLO + Parton Shower



Pythia8

Herwig7 angular-ordered

Herwig7 dipole

$$p_T^{hh} = \vec{p}_T^{\,h_1} + \vec{p}_T^{\,h_2}$$

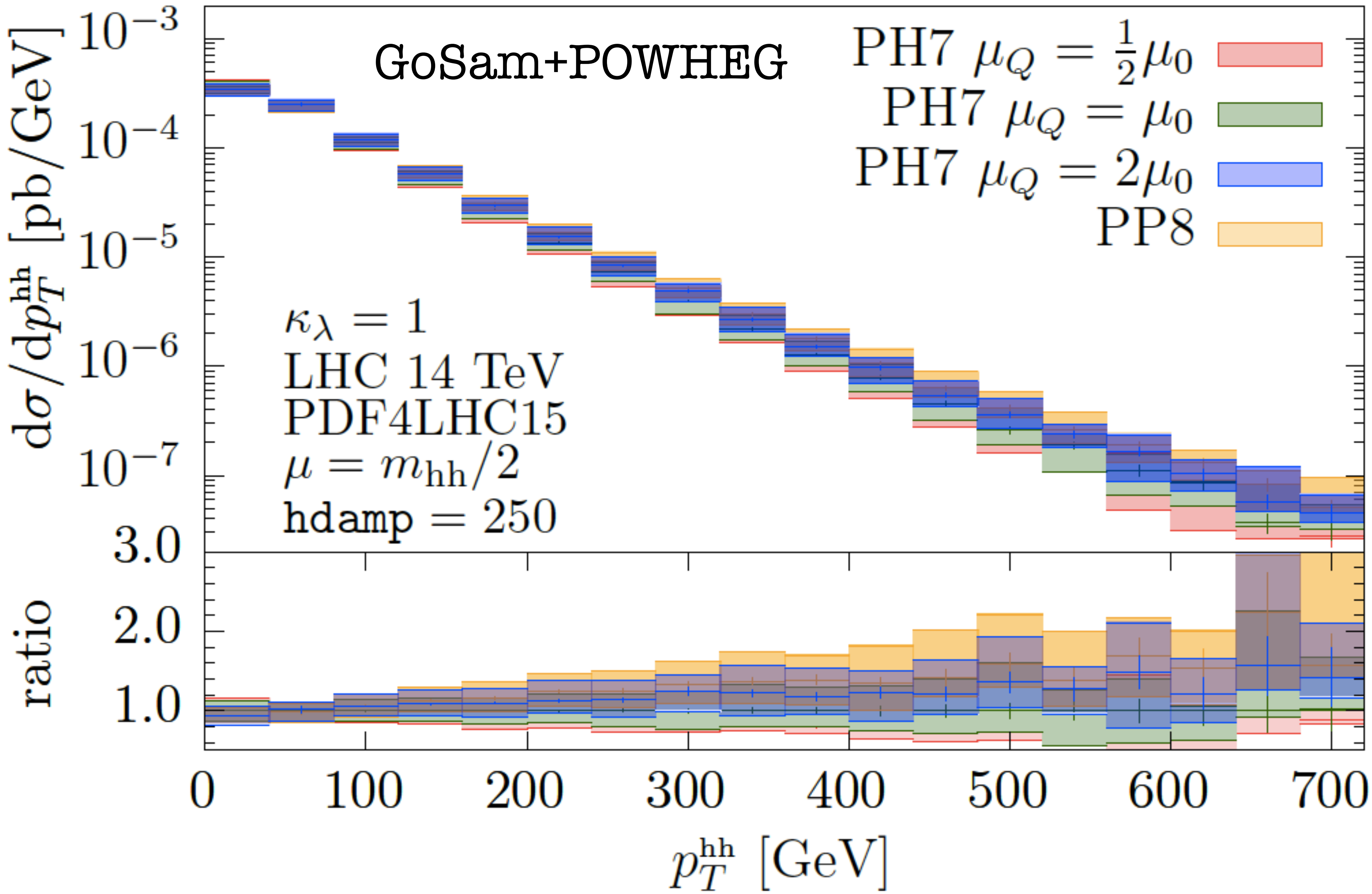
transverse momentum of Higgs boson pair: NLO is first non-trivial order

→ very sensitive to extra radiation

Pythia8 produces relatively hard additional jets (also seen in other processes, e.g. ZZ, WW, H)

HH@NLO + Parton Shower

variation of hard shower scale in Herwig7, compared to Pythia8



differences (almost) covered by large shower matching scale uncertainties

variation of 5 anomalous couplings

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

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

choosing 3 examples

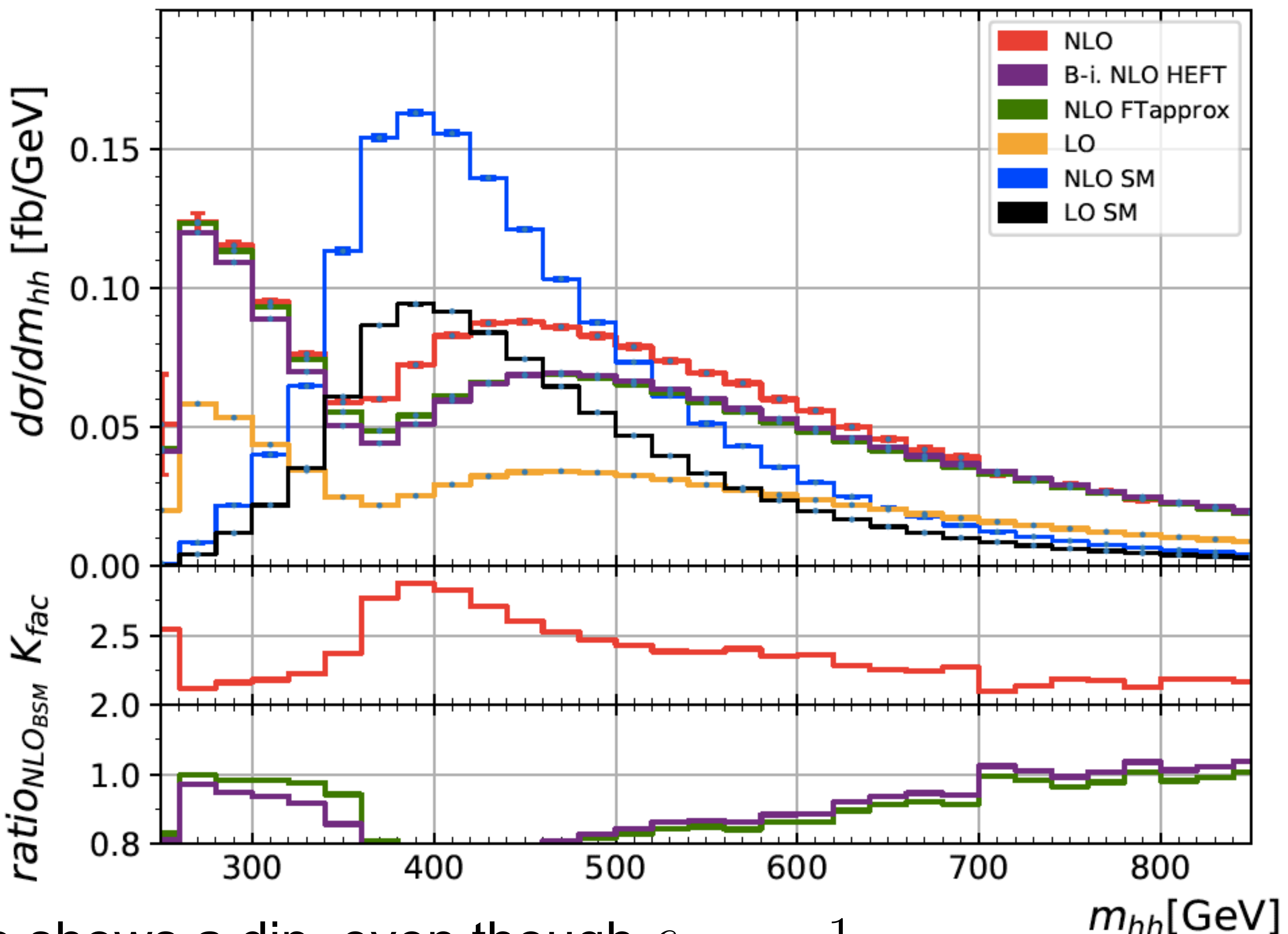
Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	$-\frac{1.6}{3}$	-0.2
3	1.0	1.0	-1.5	0.0	$\frac{0.8}{3}$
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	$\frac{1.6}{3}$	$\frac{1.0}{3}$
6	2.4	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
7	5.0	1.0	0.0	$\frac{0.4}{3}$	$\frac{0.2}{3}$
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

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

Benchmark	σ_{NLO} [fb]	K-factor	$\frac{\sigma_{NLO}}{\sigma_{NLO,SM}}$
B_6	24.69	1.89	0.7495
B_{8a}	41.70	2.34	1.266
B_{11}	174.70	1.92	5.303
SM	32.95	1.66	1

mhh distribution for benchmark point 8a

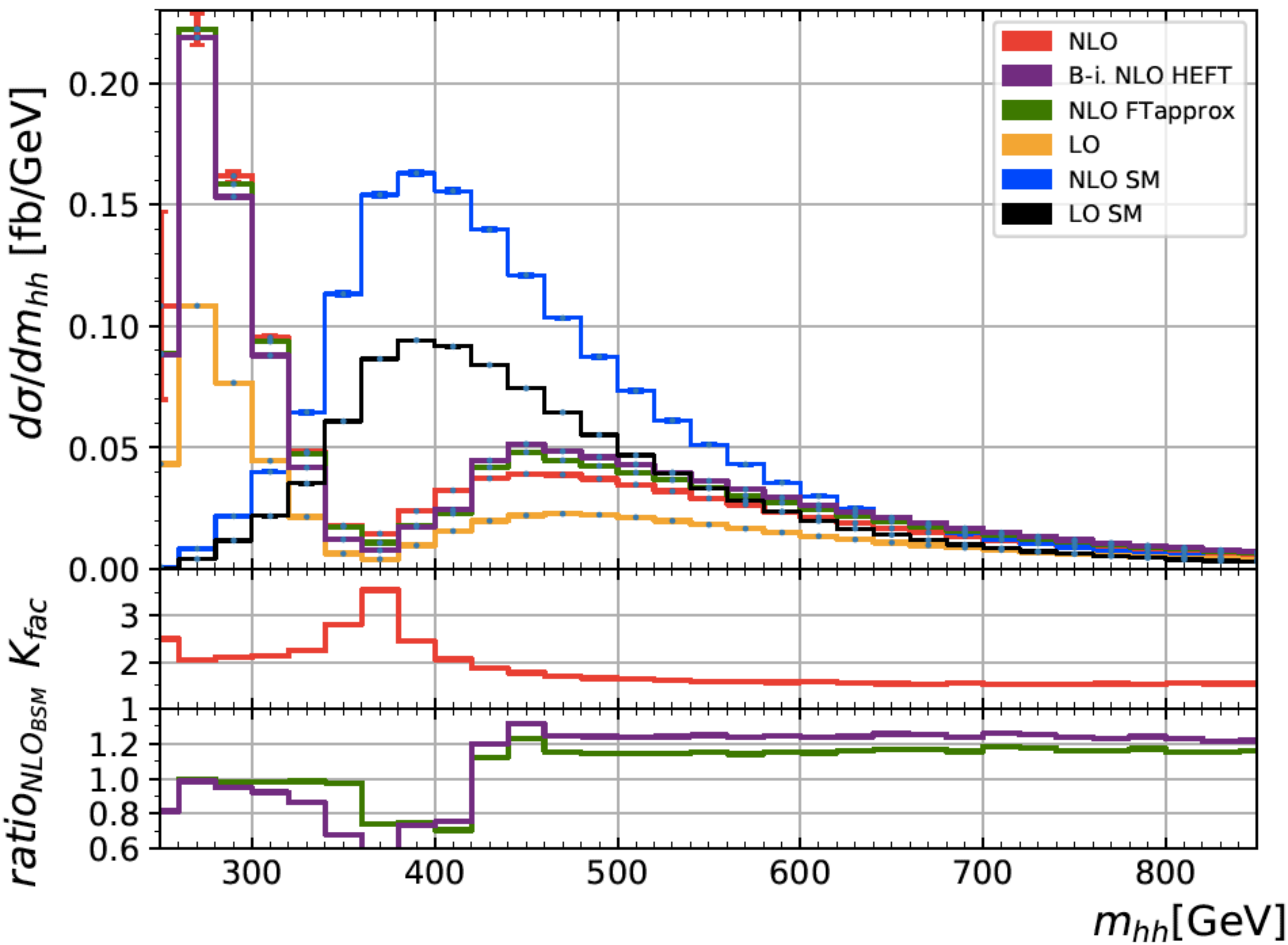
$c_{hhh} = 1, c_t = 1, c_{tt} = 0.5, c_{ggh} = 4/15, c_{gghh} = 0$



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

mhh distribution for benchmark point 6

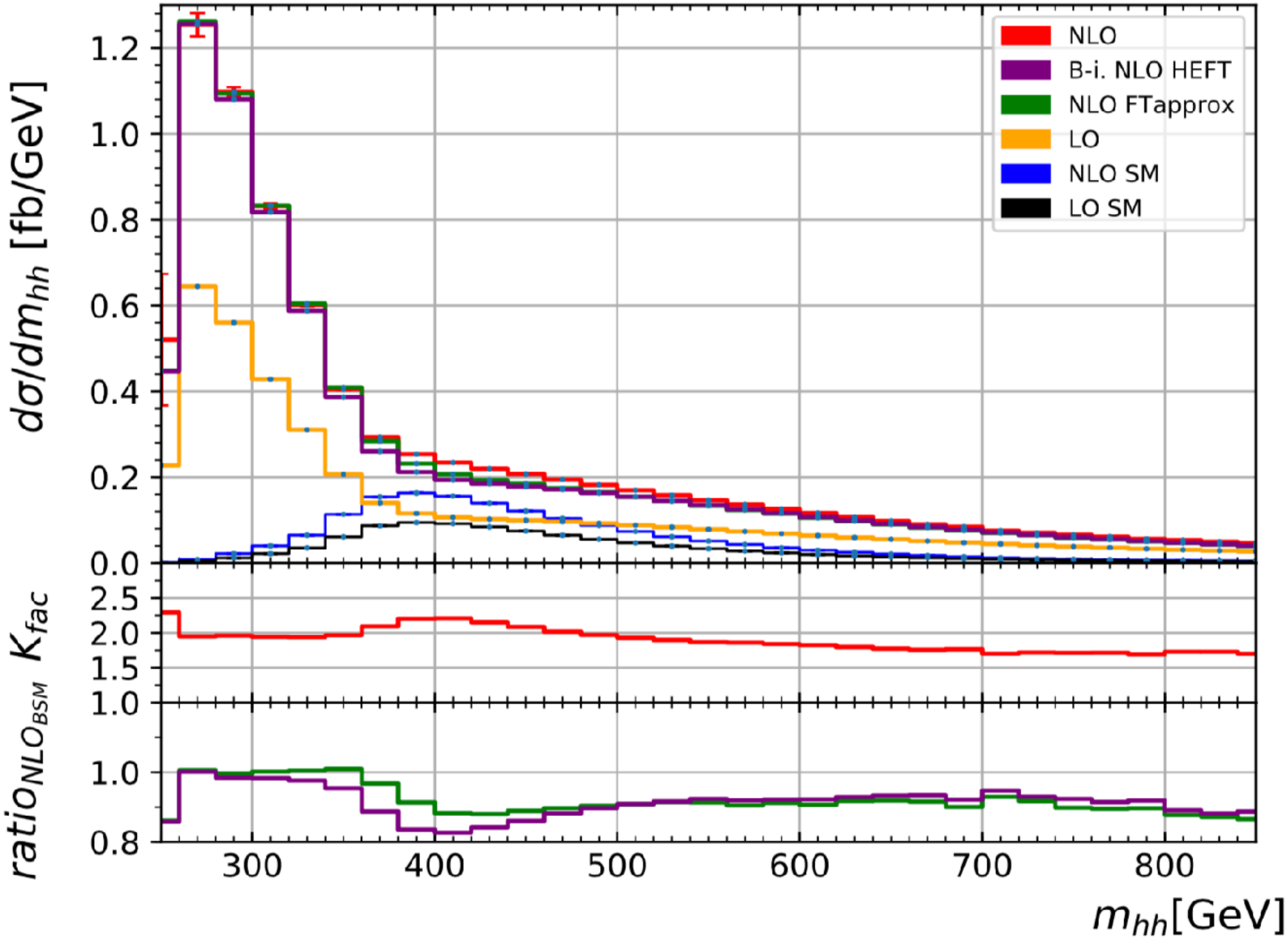
$c_{hhh} = 2.4, \; c_t = 1.0, \; c_{tt} = 0, \; c_{ggh} = \frac{2}{15}, \; c_{gghh} = \frac{1}{15}$



dip, highly non-homogeneous K-factor

mhh distribution for benchmark point

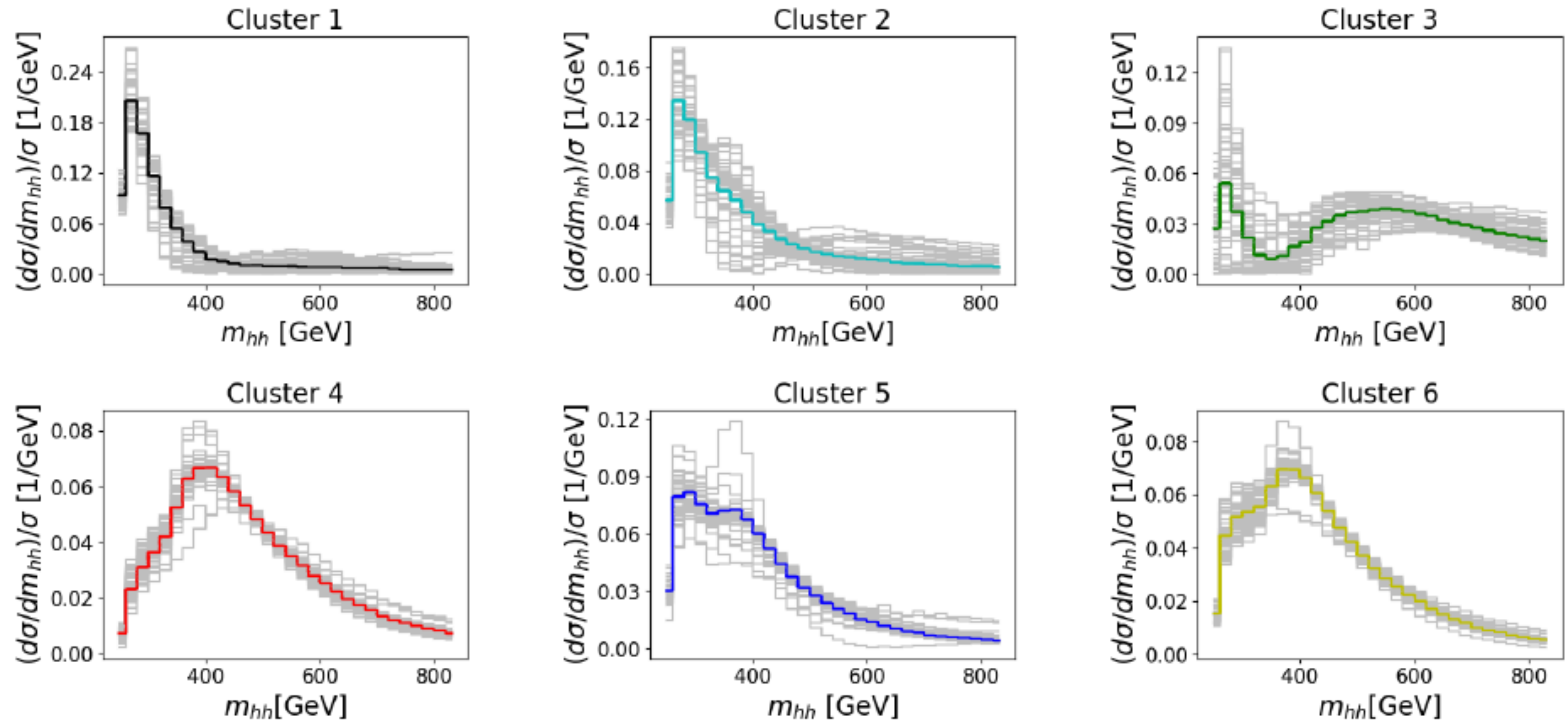
$$c_{hhh} = 2.4, c_t = 1, c_{tt} = 0, c_{ggh} = 2/3, c_{gghh} = 1/3$$

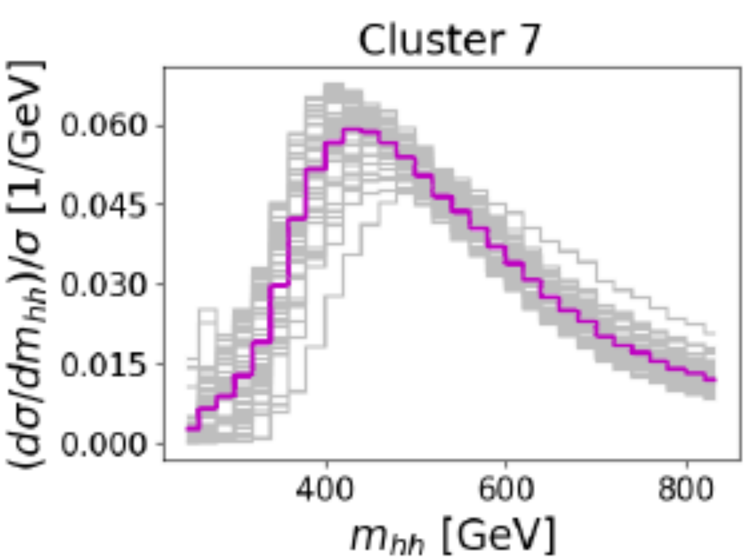


dip destroyed by large values of c_{ggh}, c_{gghh}

Shape analysis

M.Capozi, GH; 1908.08923

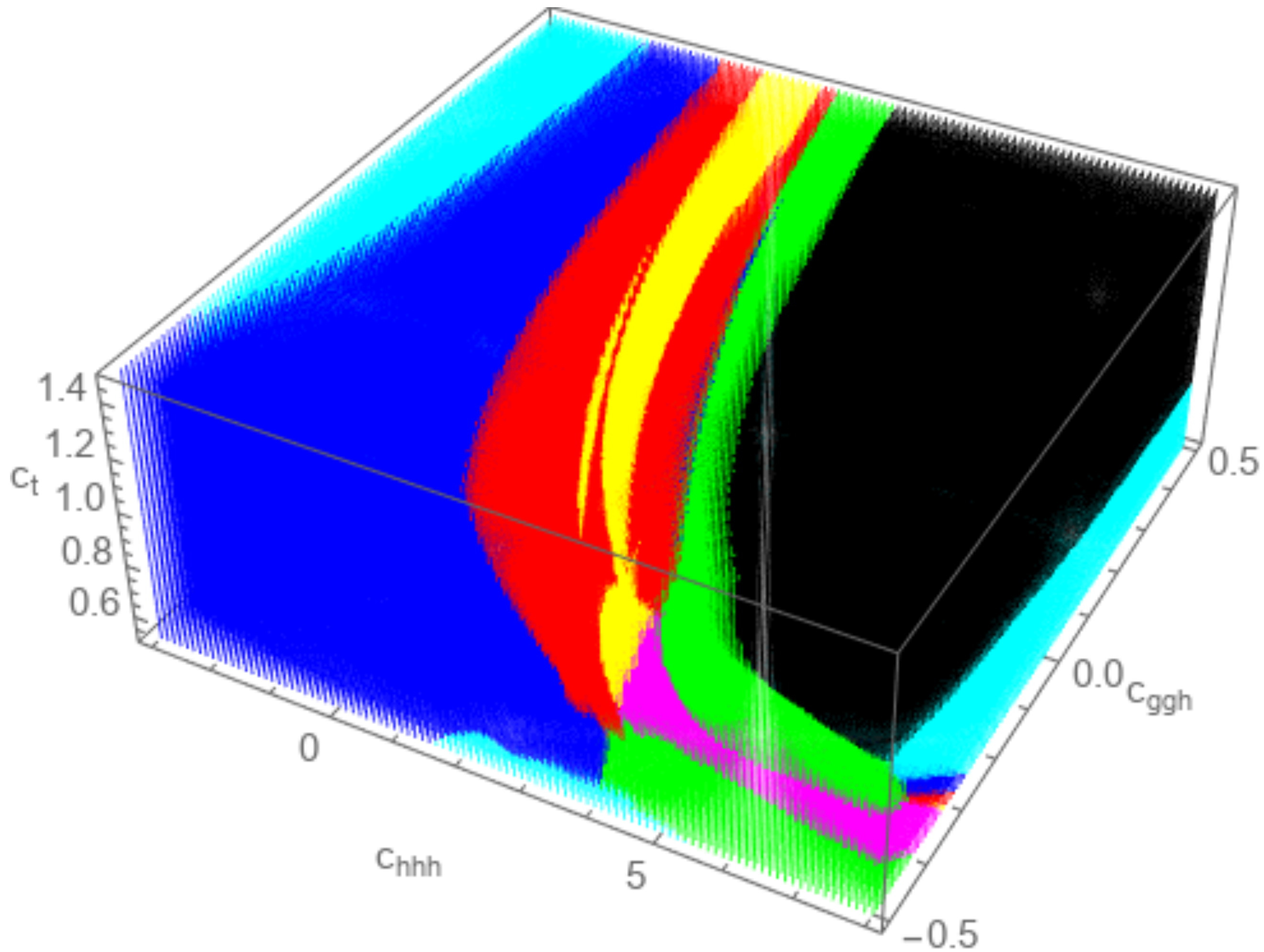




used unsupervised learning tools to identify shape clusters

how likely is it to find a dip even though $c_{hhh} = 1$?

Shape analysis



red: SM-like shape

yellow: SM-like with shoulder left of peak

dip: blue or green

used $c_{gghh} = 0.5 c_{ggh}$ and $c_{tt} = 0.05 c_t$

(simulation of SMEFT situation)

Summary & Outlook

- HH production in gluon fusion at full NLO including variations of trilinear coupling and top-Yukawa coupling available at

http://powhegbox.mib.infn.it/User-Process-V2/ggHH

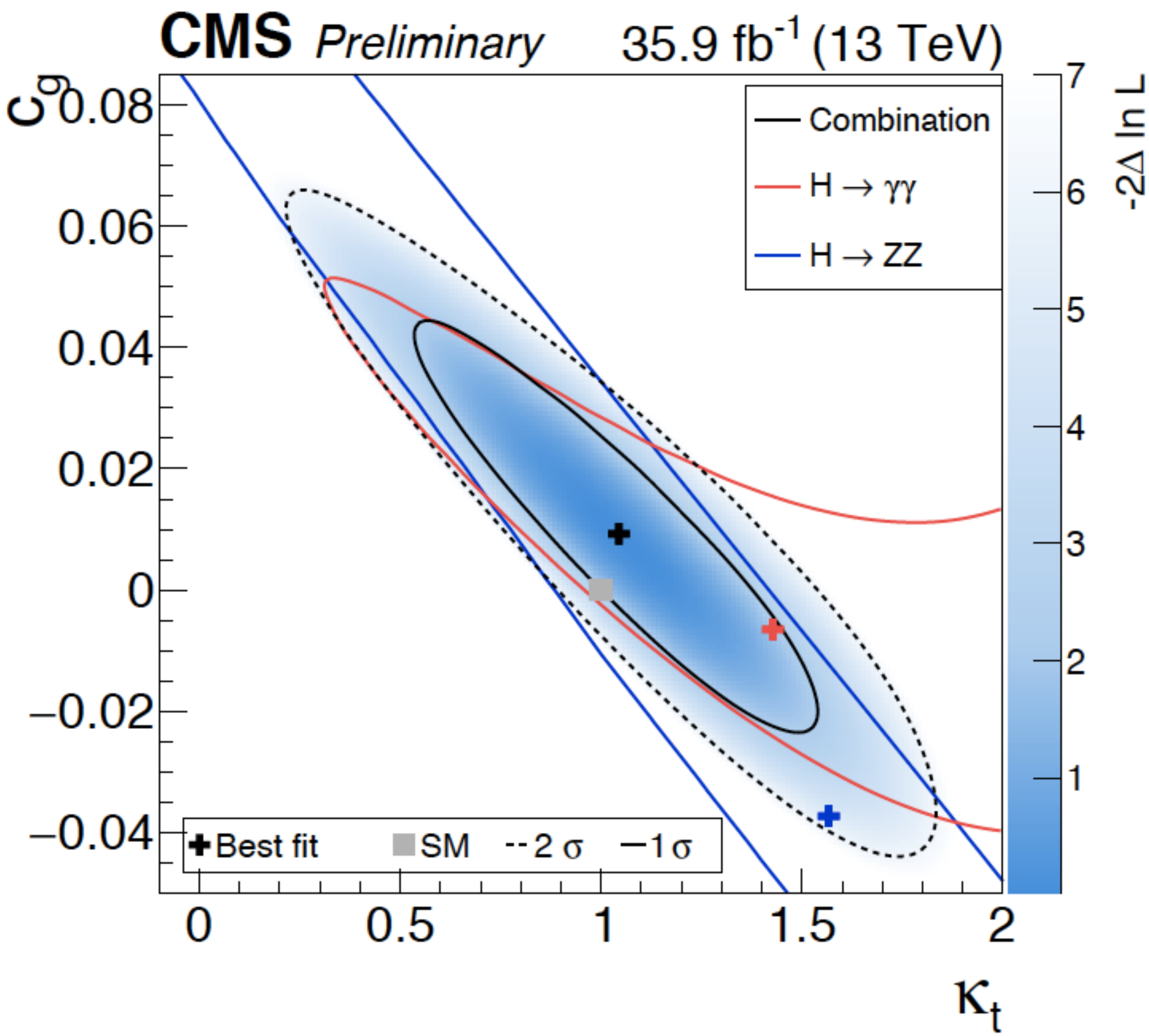
- 5 anomalous couplings within non-linear EFT framework in Higgs sector, $c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}$ at order $d_\chi = 6, \alpha_s^3$

- full NLO QCD corrections lead to sizeable and non-homogeneous K-Factors, varying also with the values of the couplings

- shape analysis in combination with limits on total xs important

- variations of 5 couplings in POWHEG: work in progress

constraints on ggH and top Yukawa couplings

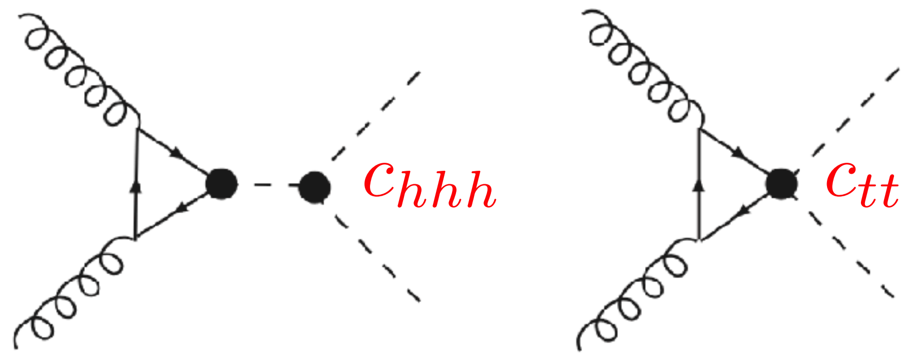


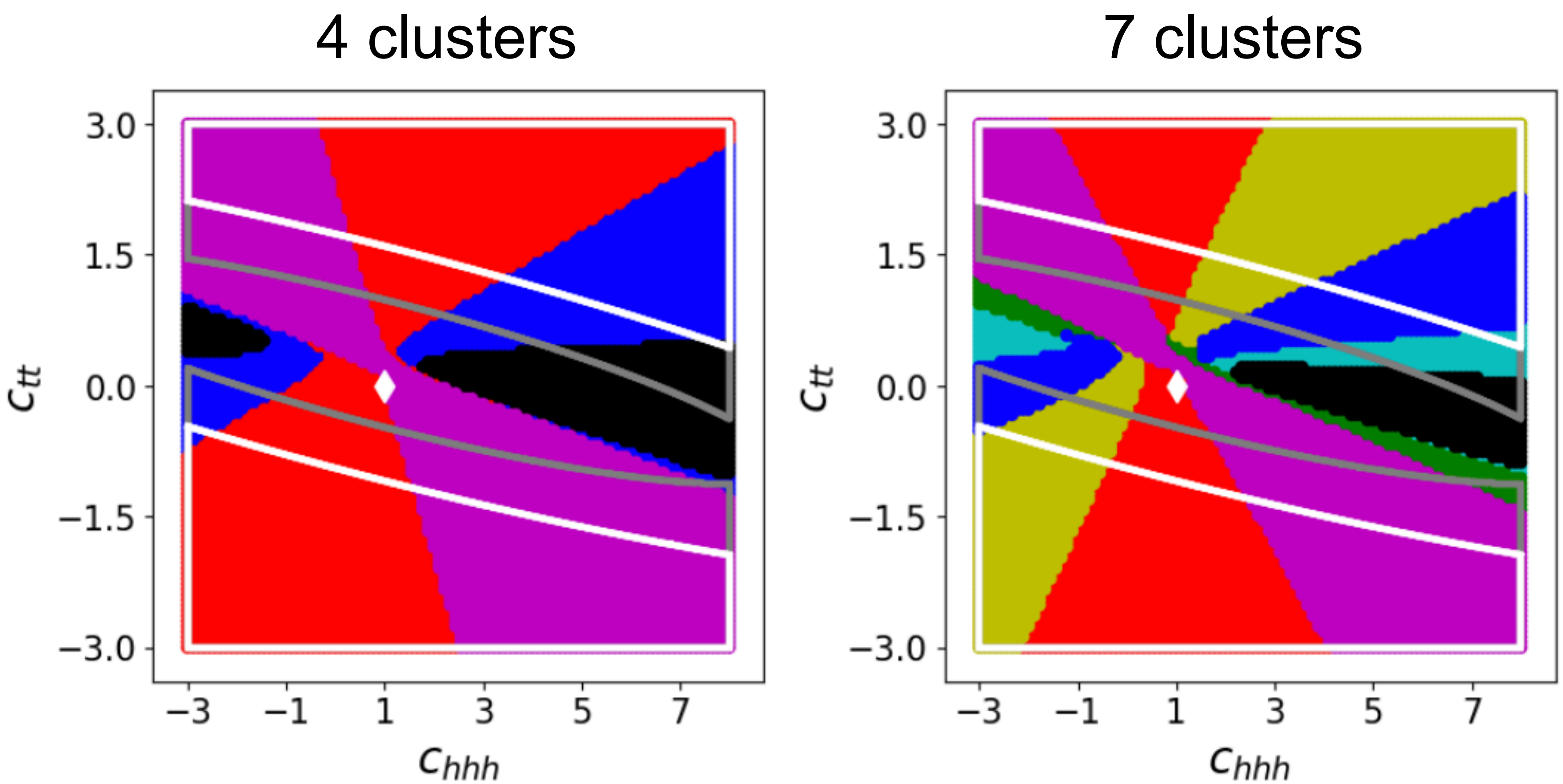
1812.06504

c_{ggh} and c_t
are already quite well constrained from other processes (single Higgs, ttH)

note: $c_{ggh} = 8\, c_g$

Shape analysis





c_{tt} also has strong influence on shape

- region where SM shape is produced is rather small
- shape combined with bounds on total cross section puts constraints on c_{tt}

Parametrisation of the NLO cross section

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

$$A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh}$$

$$+ A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh}$$

$$+ A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh}$$

$$+ A_{16}\, c_t^3 c_{ggh} + A_{17}\, c_t c_{tt} c_{ggh} + A_{18}\, c_t c_{ggh}^2 c_{hhh} + A_{19}\, c_t c_{ggh} c_{gghh}$$

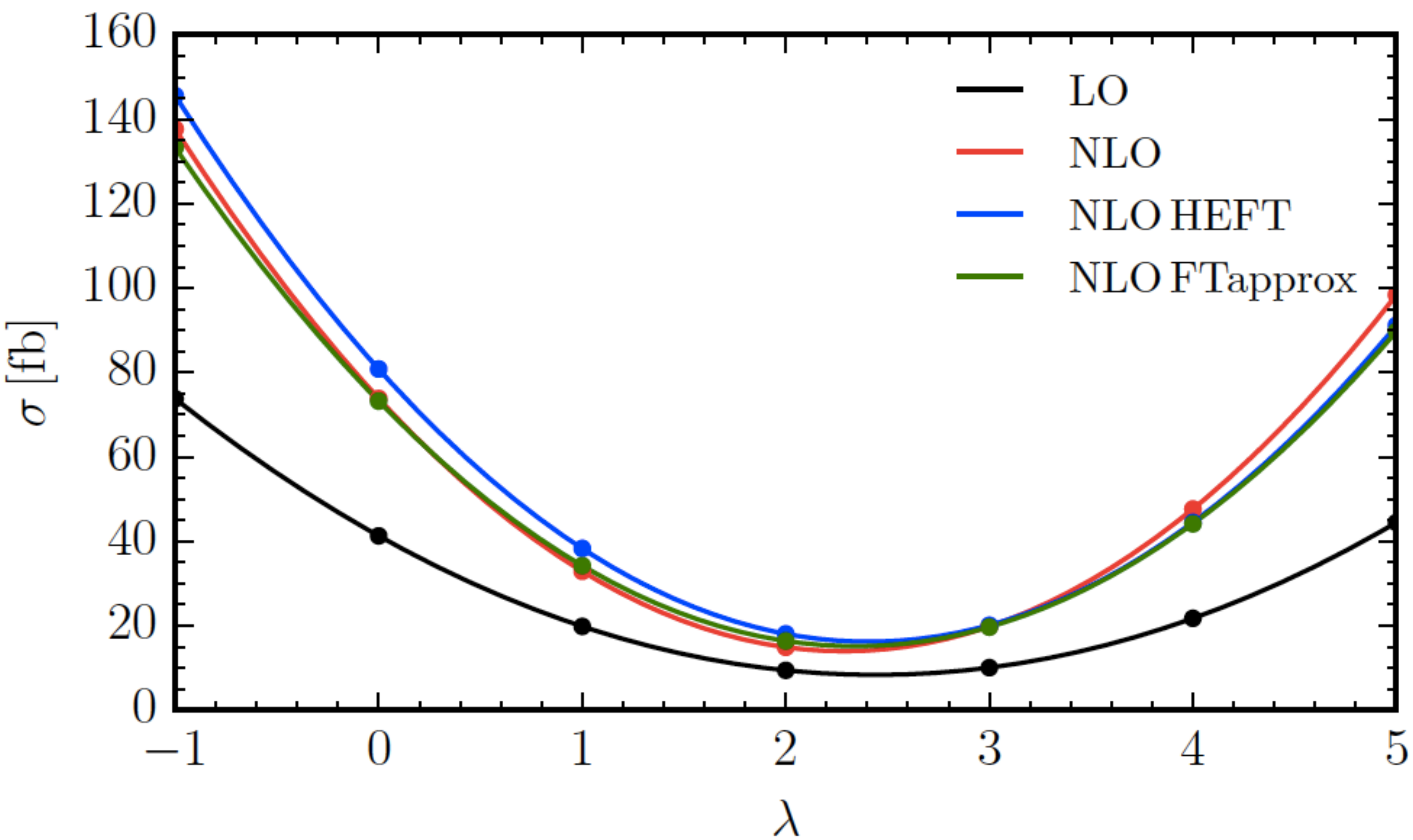
$$+ A_{20}\, c_t^2 c_{ggh}^2 + A_{21}\, c_{tt} c_{ggh}^2 + A_{22}\, c_{ggh}^3 c_{hhh} + A_{23}\, c_{ggh}^2 c_{gghh}\,.$$

only present at NLO

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

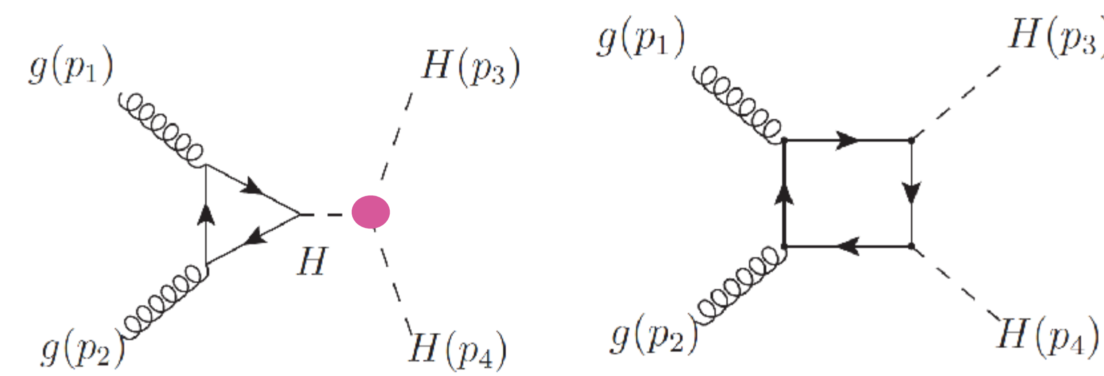
- also available in differential form for m_{hh} distribution
- for 14 TeV on https://arxiv.org/abs/1806.05162v1 as .csv tables
- for 13 and 27 TeV available on request

Variations of the trilinear Higgs coupling



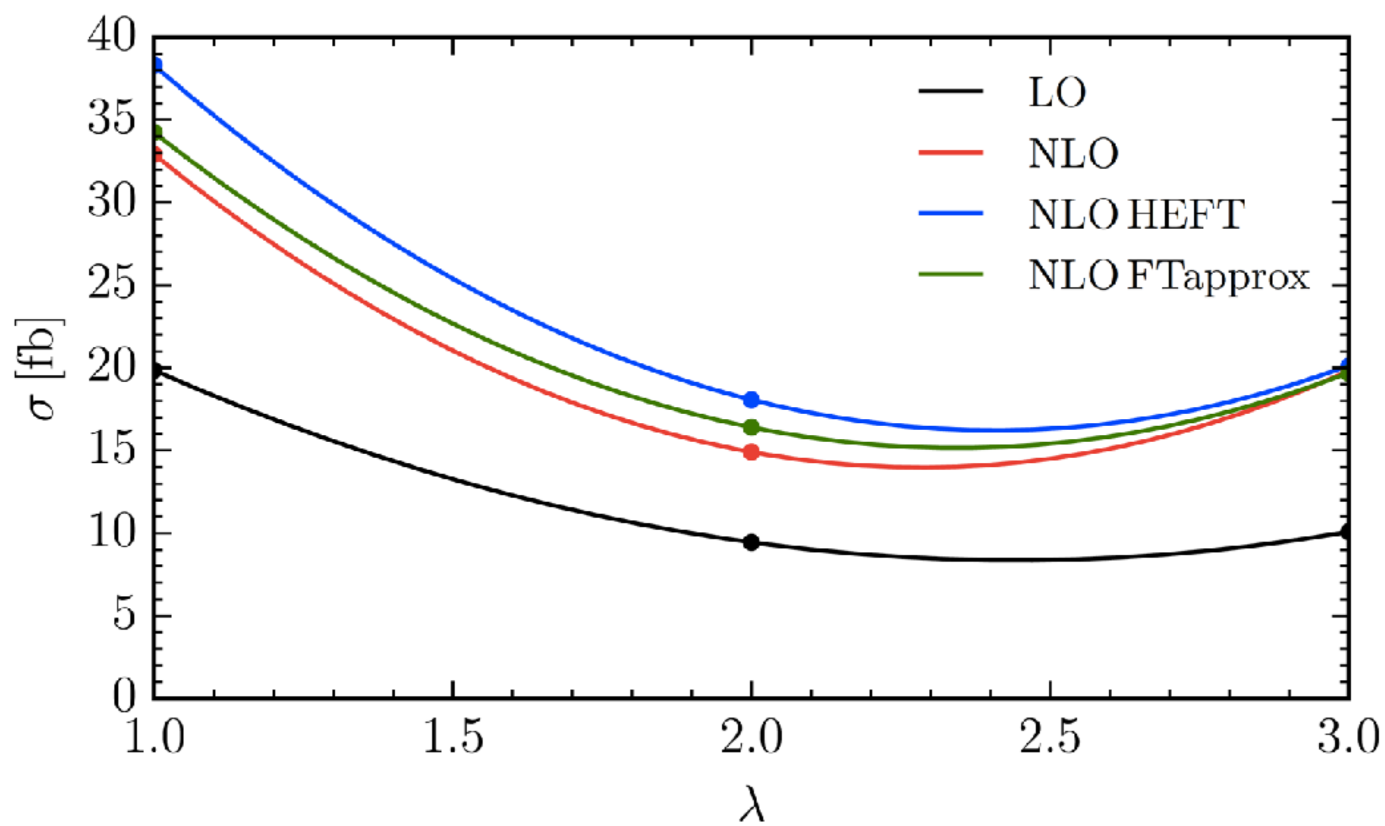
cross section is quadratic polynomial in λ

(ignoring EW corrections)

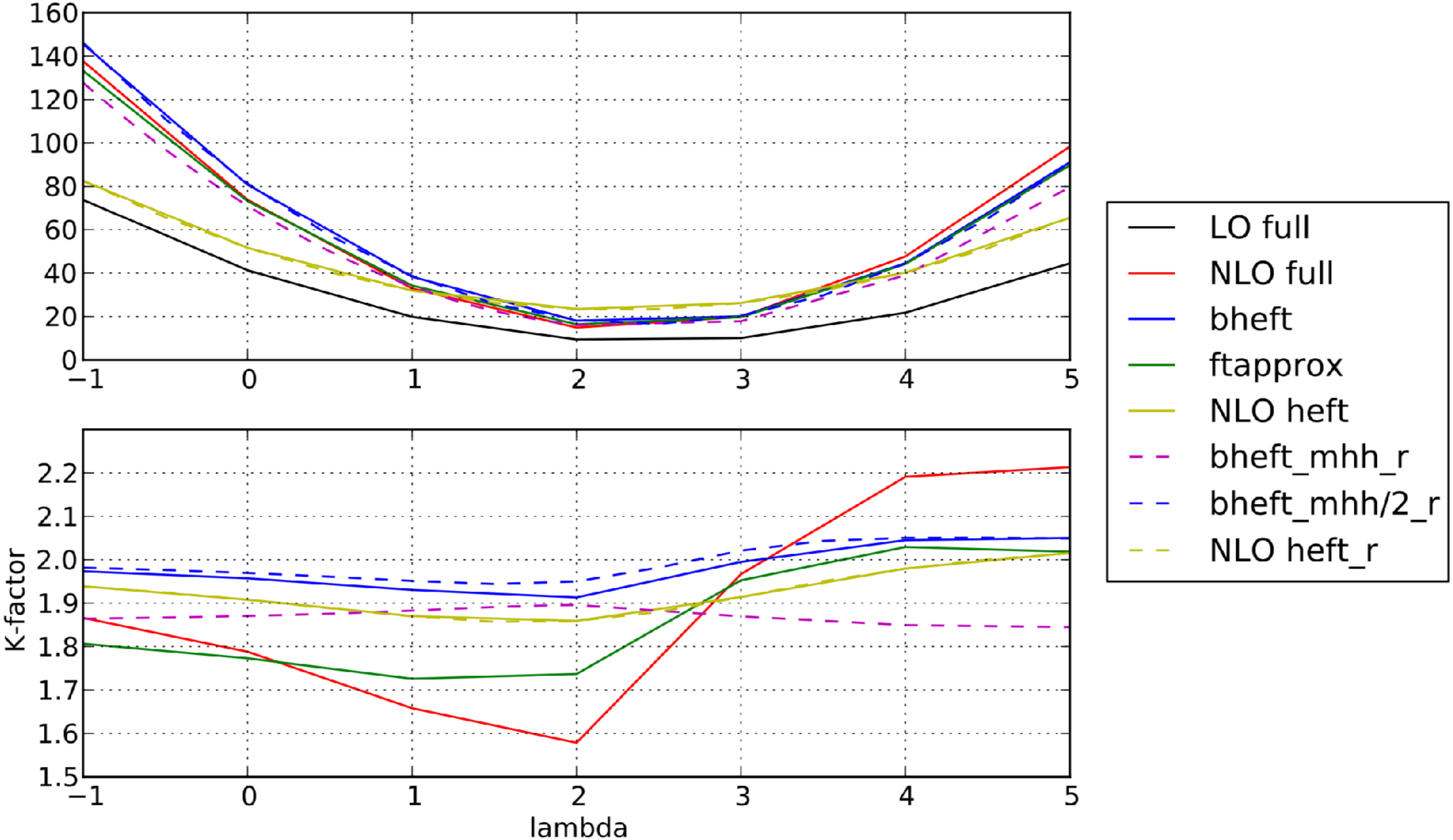


maximal destructive interference between box- and triangle-type diagrams at

$c_{hhh} = \lambda_{\mathrm{BSM}}/\lambda_{\mathrm{SM}} \approx 2.4$



Lambda- and mt-dependence of K-factors



plot by Johannes Schlenk; _r: data from Ramona Gröber

EWChL Lagrangian

$$\mathcal{L}_2 = -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{\psi=q_L,l_L,u_R,d_R,e_R} \bar{\psi} i \not{D} \psi$$

$$+\frac{v^2}{4}\left\langle D_\mu U^\dagger D^\mu U\right\rangle\left(1+F_U(h)\right) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

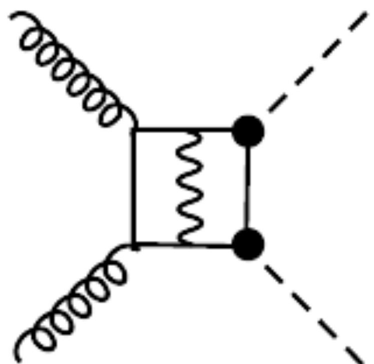
$$-v\left[\bar{q}_L\left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)}\left(\frac{h}{v}\right)^n\right) U P_+ q_R + \bar{q}_L\left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- q_R\right.$$

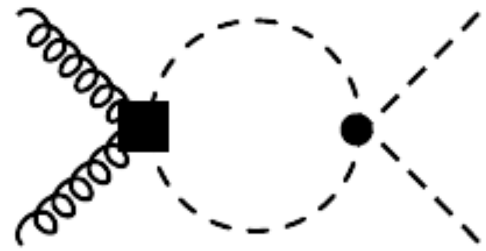
$$\left. + \bar{l}_L\left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- l_R + \text{h.c.}\right] \qquad \text{(II}$$

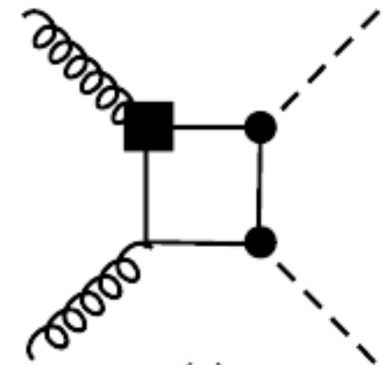
Diagrams of higher order

not contributing diagram types:

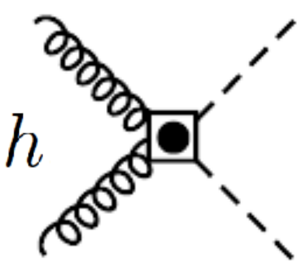
$y_t g_s \bar{t}_L \sigma_{\mu\nu} G^{\mu\nu} t_R$

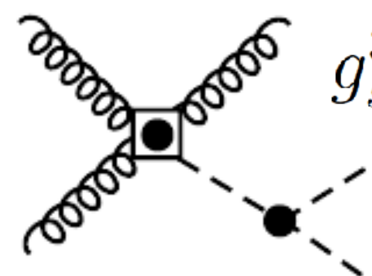

(a)


(b)


(c)

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


(d)


(e)

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

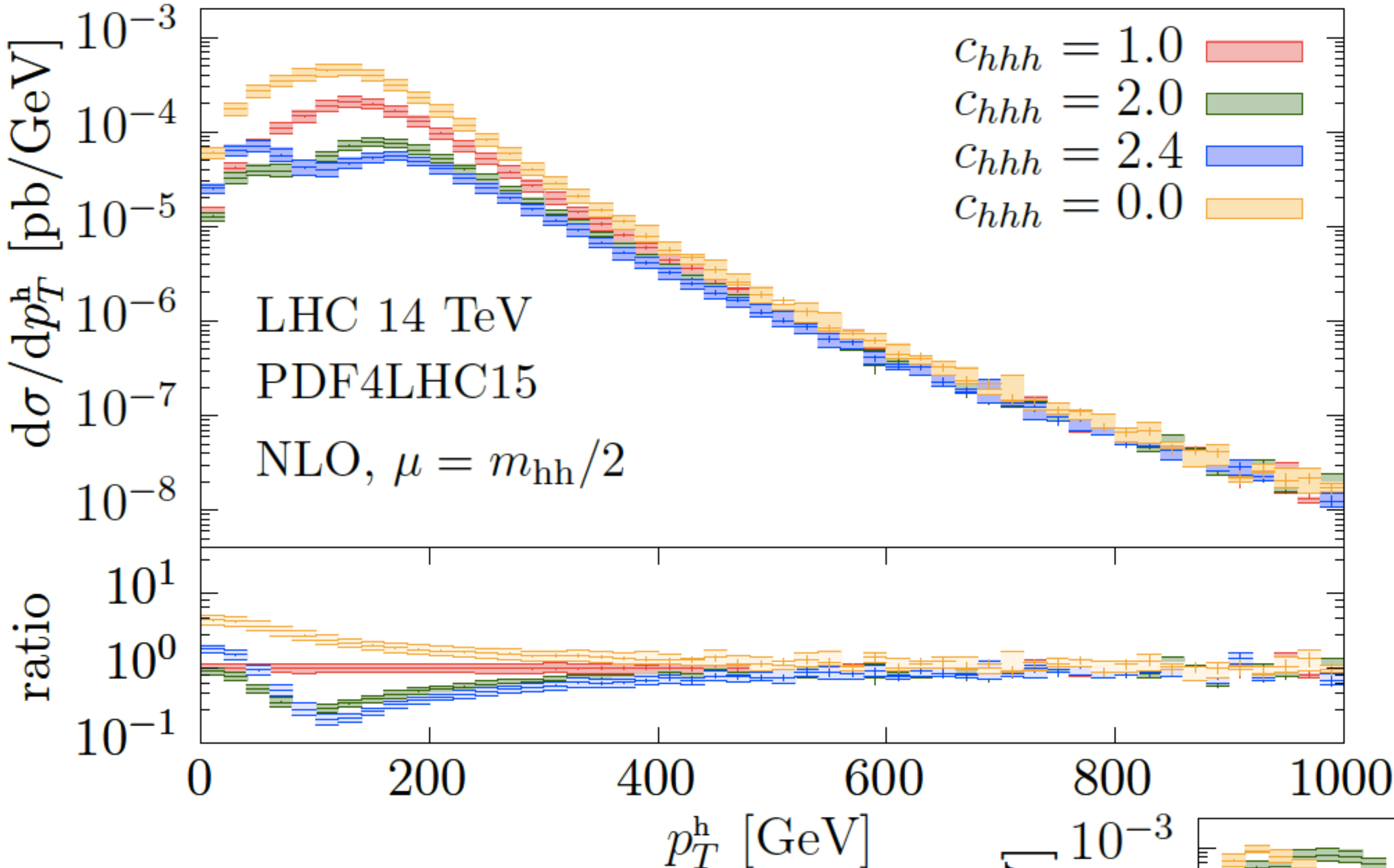
(a),(b): $d\chi = 6$ but of order $g_s^2 g_w^2$ (a), $g_s^2 c_{4h}$ (b)

(c),(d): not of order g_s^4, suppressed by $1/16\pi^2$

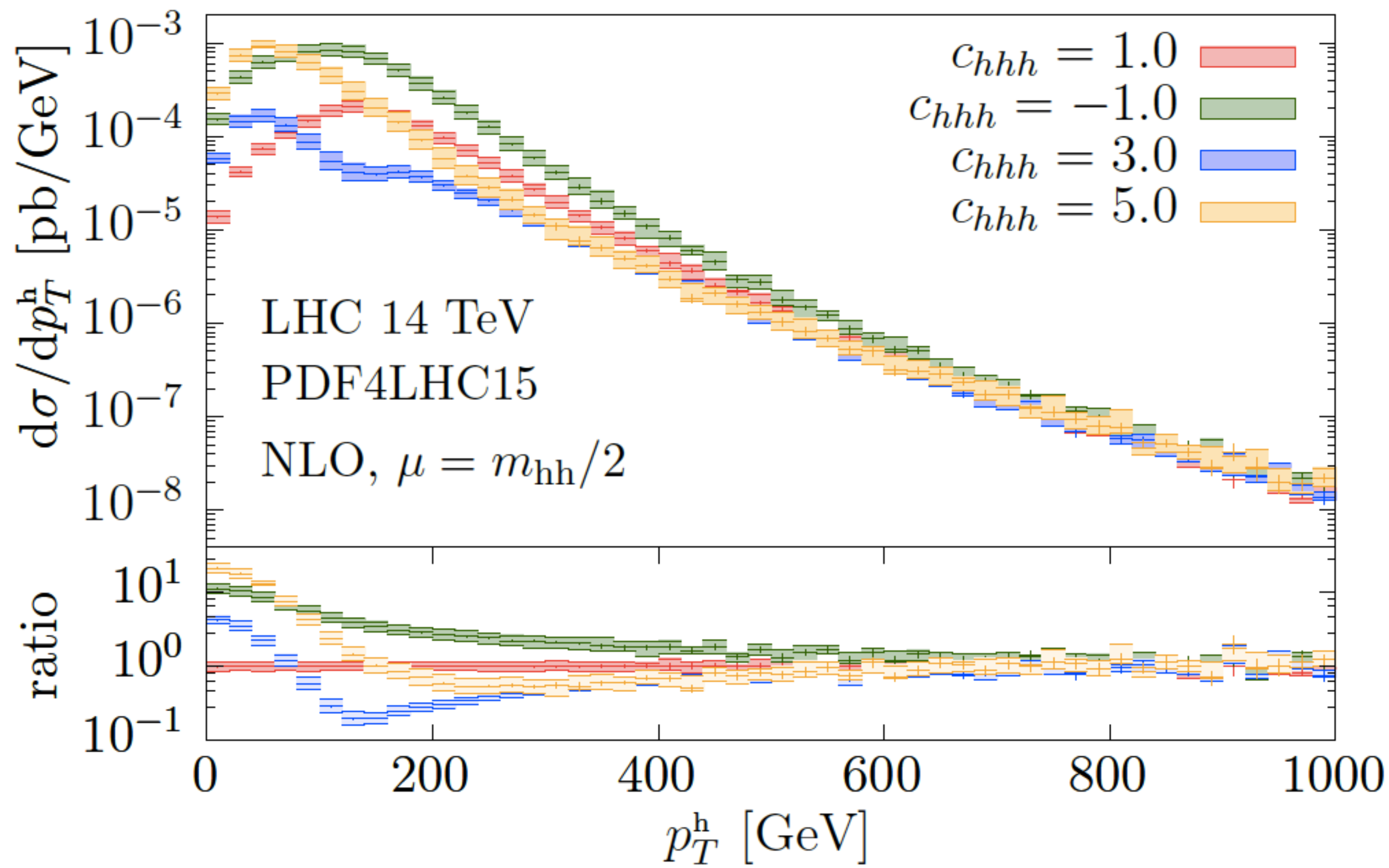
(operator must come from contracted loop, see hep-ph/9405214)

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

H transverse momentum distributions



dip visible, but much less pronounced



Two EFT frameworks

	PRO	CON
SMEFT	practical: in gg to HH less parameters to constrain e.g. $c_{ggh} = 2c_{gghh}$	relations between couplings rely on assumption on Higgs field (EW doublet)
HEFT	more general regarding relations between coupling parameters dominant new physics effects are in Higgs sector	a priori deviations from SM in Higgs sector can be large; however no observation of large effects