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EFTs for HH production: tools and technical aspects

Gudrun Heinrich, **Karlsruhe Institute of Technology**

Higgs pairs mini-workshop

September 29, 2021

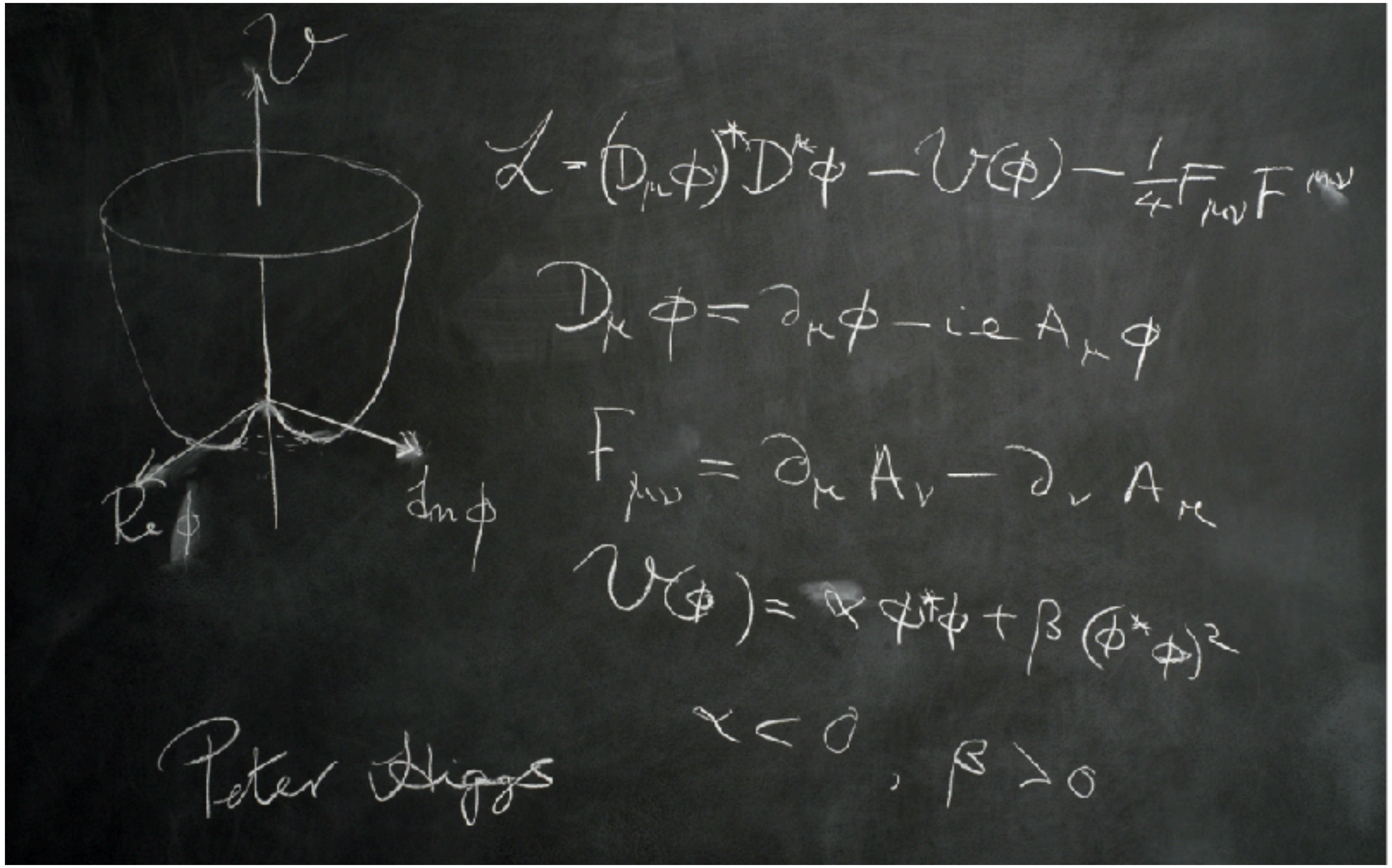
in collaboration with

*Daniel de Florian, Ignacio Fabre, Stephen Jones, Matthias Kerner,
Jannis Lang, Javier Mazzitelli, Ludovic Scyboz*

Outline

- Effective Field Theory parametrisation of BSM effects
- SMEFT and HEFT
  - counting schemes
  - truncation uncertainties
- HH production in gluon fusion (non-resonant)
  - public tools
  - beyond NLO
- Summary

Motivation



is there more than the SM α and β ?

EFT descriptions of BSM effects

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- parametrise ignorance about New Physics at scales (much) larger than the electroweak scale in a systematic way

- recipe: define
  - particle content
  - symmetries
  - counting scheme

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

  basically two schemes:

- SMEFT ("linear EFT") canonical dimension counting

- HEFT ("non-linear EFT") chiral dimension counting (also called "Electroweak Chiral Lagrangian")

SMEFT and HEFT

both respect the SM gauge symmetries

- **SMEFT:** Higgs field $\Phi(x)$ is complex doublet, transforms linearly under $SU(2) \times U(1)$

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

- **HEFT:** Higgs field is EW singlet

  Goldstone boson fields $\pi^a(x)$, represented as $U(x) = \exp(i\pi^a(x)\sigma^a/f)$

  linear transformations on $U(x)$ act non-linearly on $\pi^a(x)$

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

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)

- 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 expansion schemes

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SMEFT (Standard Model Effective Field Theory):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{\mathrm{dim6}} + \mathcal{O}(\frac{1}{\Lambda^3})$$

canonical dimension counting

HEFT (Higgs Effective Field Theory):

$$\mathcal{L}_{HEFT} = \mathcal{L}_0 + \sum_{L=1}^{\infty}\sum_i \left(\frac{1}{16\pi^2}\right)^L c_i^{(L)} O_i^{(L)}$$

counting of loop orders, expansion parameter: $f^2/\Lambda^2 \approx 1/(16\pi^2)$ $(\Lambda \sim 4\pi f)$

(similar to chiral perturbation theory)

E

new physics scale Λ

f : characteristic scale of Goldstone bosons

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

Naive comparison

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

Lagrangians relevant for HH production

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SMEFT:

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

(SILH basis/Warsaw)

Giudice et al. hep-ph/0703164

Grzadkowski et al. 1008.4884

Gröber et al. 1504.06577

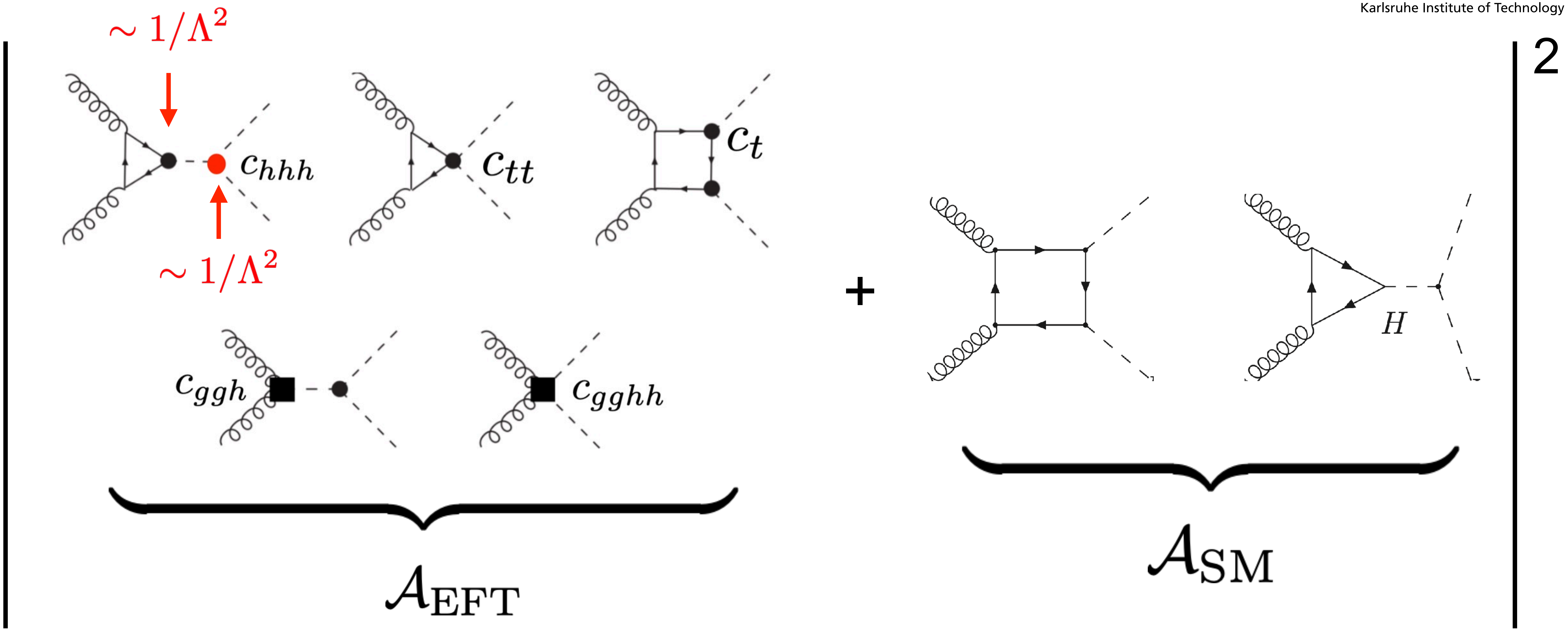
HEFT:

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

coupling relations: $c_t = 1 - \bar{c}_H/2 - \bar{c}_u$, $c_{tt} = -(\bar{c}_H + 3\bar{c}_u)/2$

$$c_{ggh} = 2\,c_{gghh} = 128\pi^2\bar{c}_g \;, \quad c_{hhh} = 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$$

SMEFT at amplitude squared level



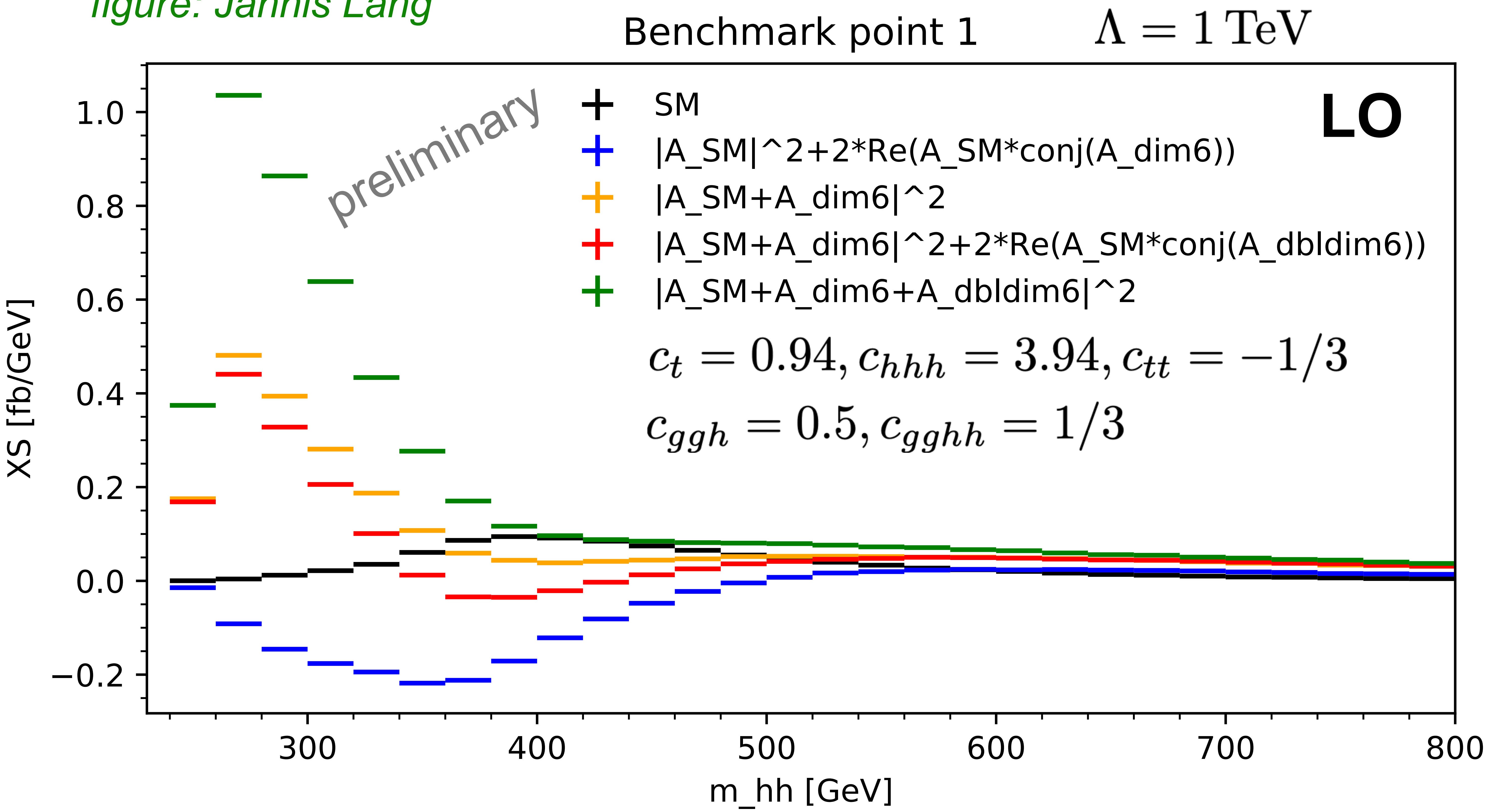
terms $\sim 1/\Lambda^4$ same order as dim 8 operators (which are not included)

SMEFT at amplitude squared level

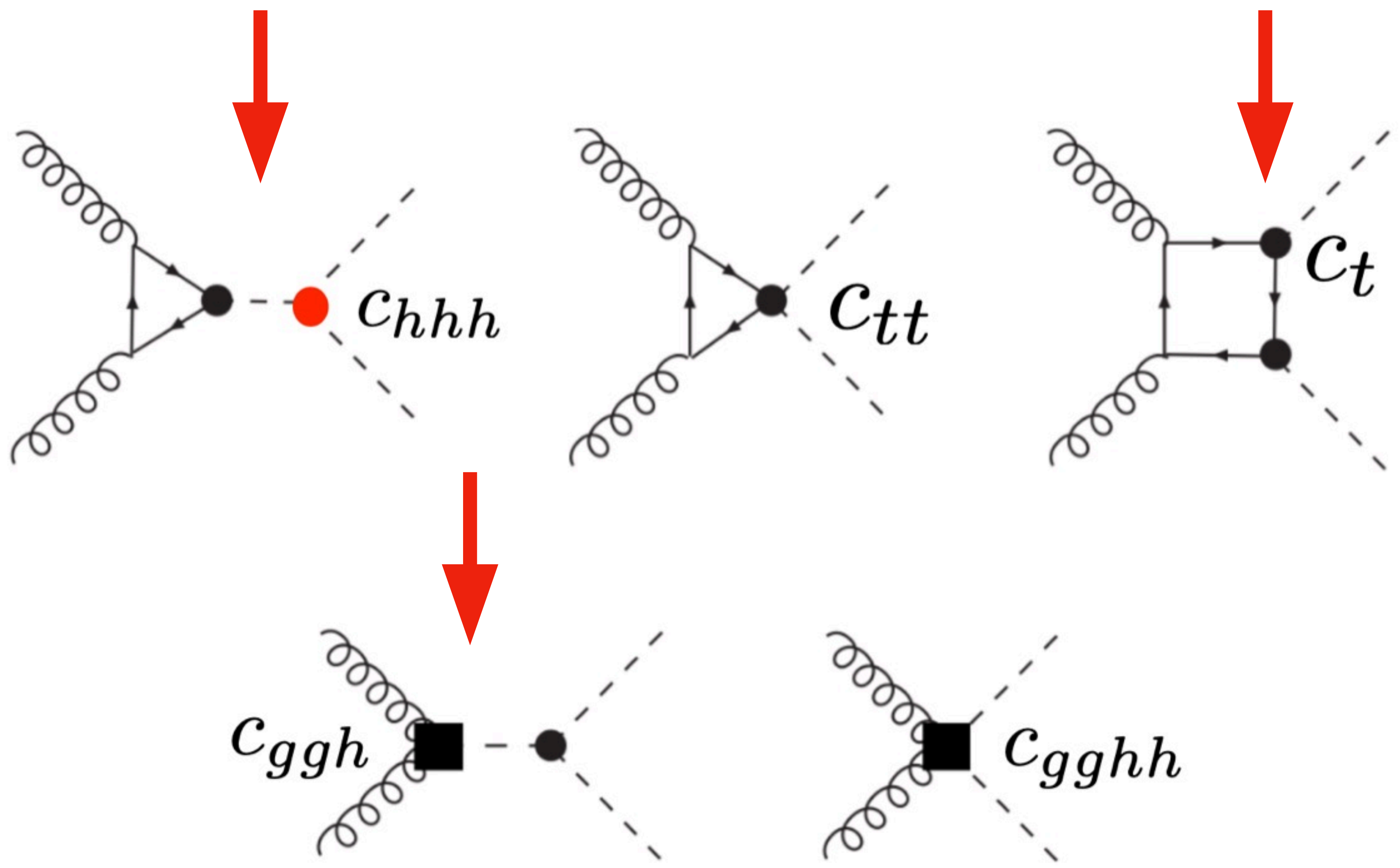
canonical dimension counting ⟶ how to treat |dim6|^2 versus dim8 ?

⟶ how to treat double operator insertions?

figure: Jannis Lang

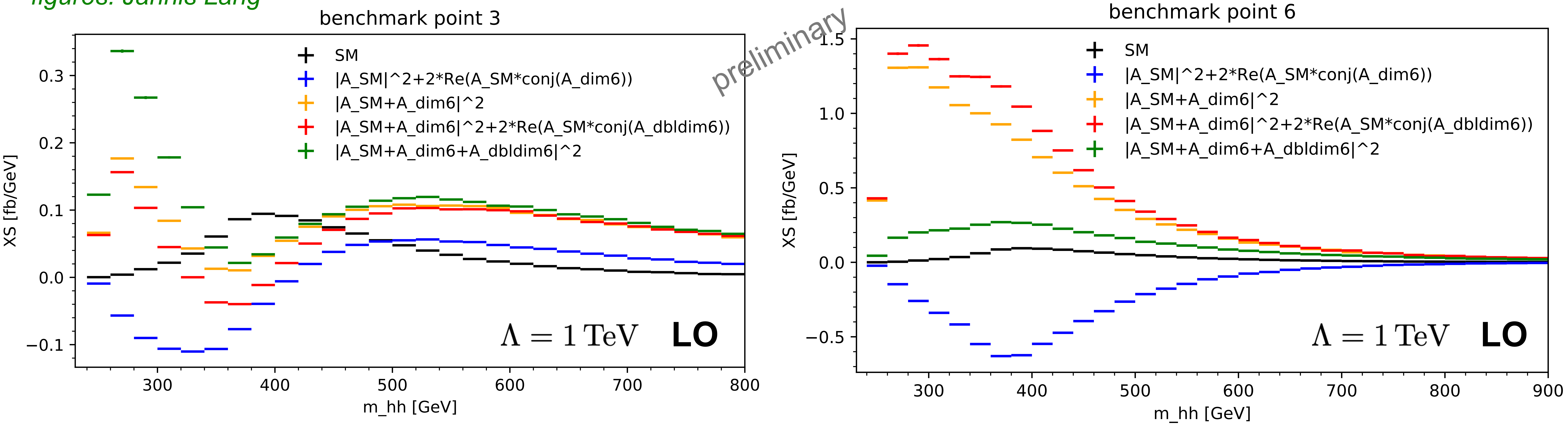


two operators in one diagram



SMEFT

figures: Jannis Lang



$c_t = 1.05, c_{hhh} = 2.21, c_{tt} = -1/3, c_{ggh} = c_{gghh} = 0.5$ $c_t = 0.83, c_{hhh} = 5.68, c_{tt} = 1/3, c_{ggh} = -0.5, c_{gghh} = 1/3$

current "recommendation" (?)

- default: |dim6|^2
- use double insertions/dim8 (if available) to estimate uncertainty

Tools (EFT, public)

efinger-consulting.de

Public Tools

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- **ggHH** GH, Jones, Kerner, Luisoni, Scyboz NLO with full top quark mass dependence

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

  5 anomalous couplings, specific to gg -> HH, HEFT: full NLO QCD

  SMEFT: linear and quadratic terms in the $1/\Lambda^2$ expansion, double operator insertions

- **MG5_aMC@NLO** HH: NLO_FTapprox (virtual part in heavy top limit)

  Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang

  linear and quadratic terms in the $1/\Lambda^2$ expansion , includes chromomagnetic operator

- **SMEFTsim** Brivio, Jiang, Trott leading order

  2 different EW input parameter schemes, different flavour symmetry assumptions, …

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  NLO in progress

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ggHH Powheg code

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table: Ludovic Scyboz

- `mtdep`: m_t approximations
  - `mtdep` $= 0$: pure HTL
  - `mtdep` $= 1$: Born-improved HTL
  - `mtdep` $= 2$: $\mathrm{FT}_{\mathrm{approx}}$
  - `mtdep` $= 3$: full theory

can be matched to Pythia 8 and Herwig 7 ($\tilde{q}$ and dipole showers)

- anomalous Higgs couplings
  - `ct` $= 1.0$: Higgs-top Yukawa coupling
  - `chhh` $= 1.0$: Higgs trilinear self-coupling
  - `ctt` $= 0.0$: $t\bar{t}HH$ effective coupling
  - `cggh` $= 0.0$: ggH effective coupling
  - `cgghh` $= 0.0$: $ggHH$ effective coupling

- $\rightarrow$ Example in `ggHH/testrun` folder
- Note: only `mtdep` $= 3$ for arbitrary coupling variations

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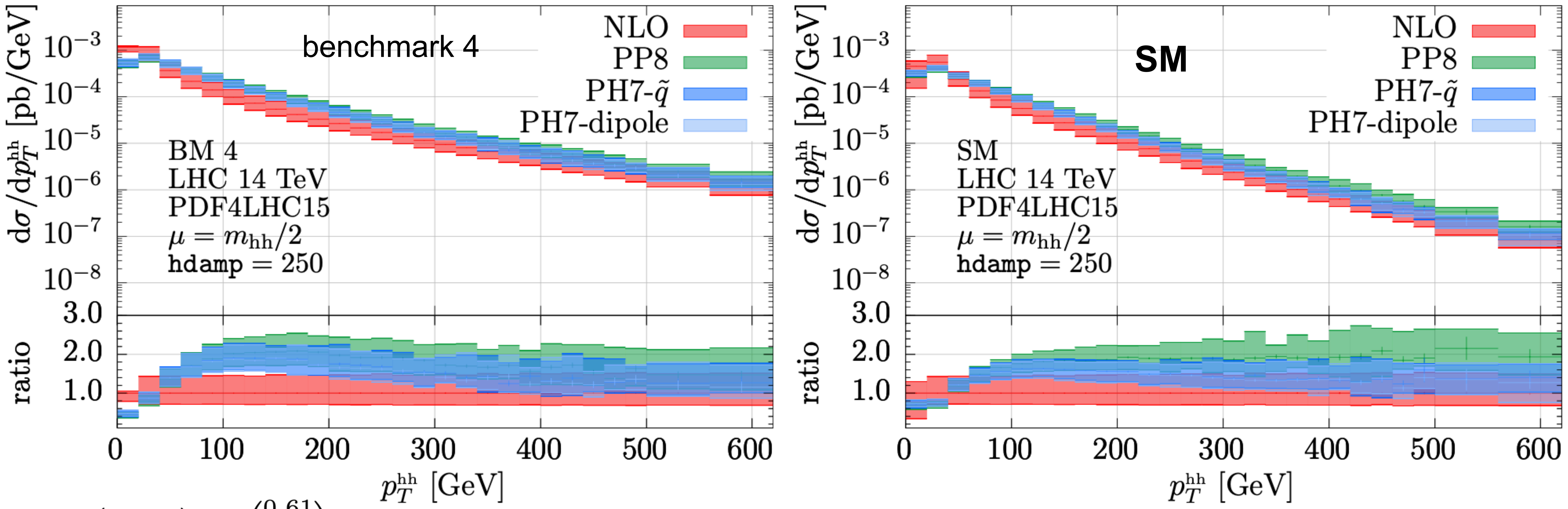


$$\text{BM 4:} \begin{pmatrix} c_t \\ c_{hhh} \\ c_{tt} \\ c_{ggh} \\ c_{gghh} \end{pmatrix} = \begin{pmatrix} 0.61 \\ 2.79 \\ \frac{1}{3} \\ -\frac{1}{2} \\ \frac{1}{6} \end{pmatrix}$$

effects of parton shower different in SM and BSM

Beyond NLO

De Florian, Fabre, GH, Mazzitelli, Scyboz

2106.14050

combination ggHH code + approxNNLO: NNLO’

higher order corrections for HH+EFT:

NLO in (BI) heavy top limit — Gröber, Mühlleitner, Spira, Streicher ’15

including CP-violating operators — Gröber, Mühlleitner, Spira ’17

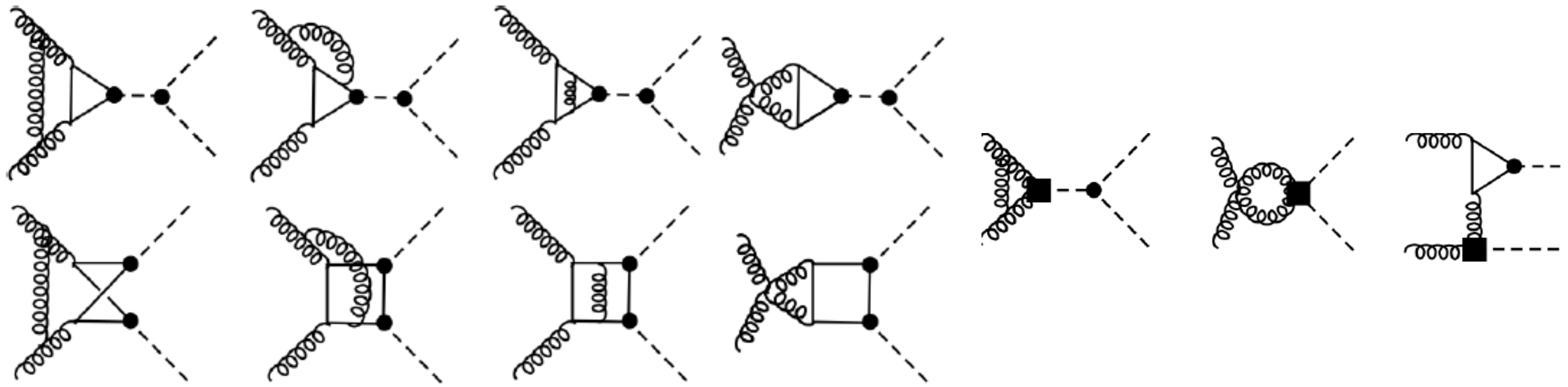
NLO in FTapprox (SMEFT) — Maltoni, Vryonidou, Zhang ’16

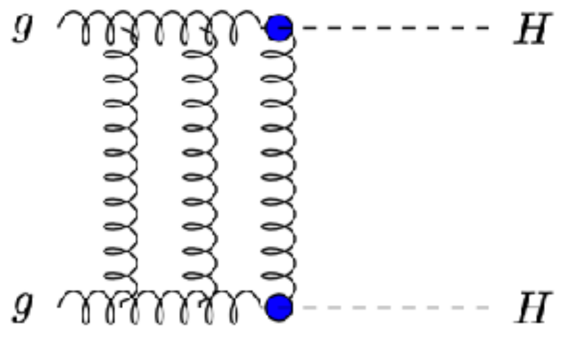
NNLO in (BI) heavy top limit — De Florian, Fabre, Mazzitelli ’16

full NLO — Buchalla, Capozi, Celis, GH, Scyboz ‘18

Capozi, GH ‘19

GH, Jones, Kerner, Scyboz ‘20





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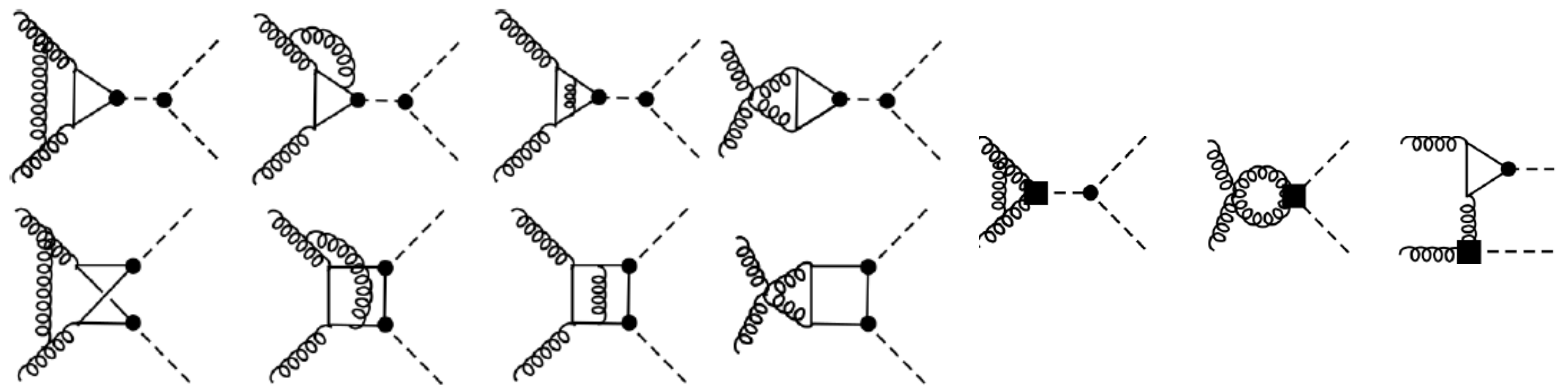

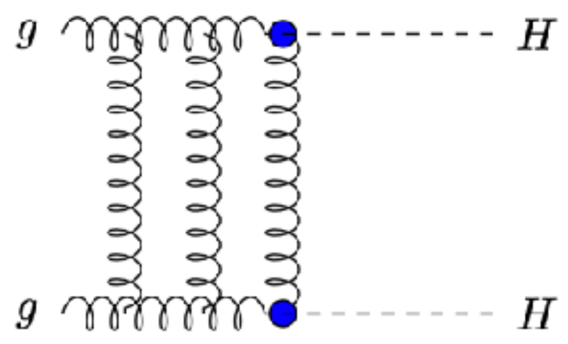

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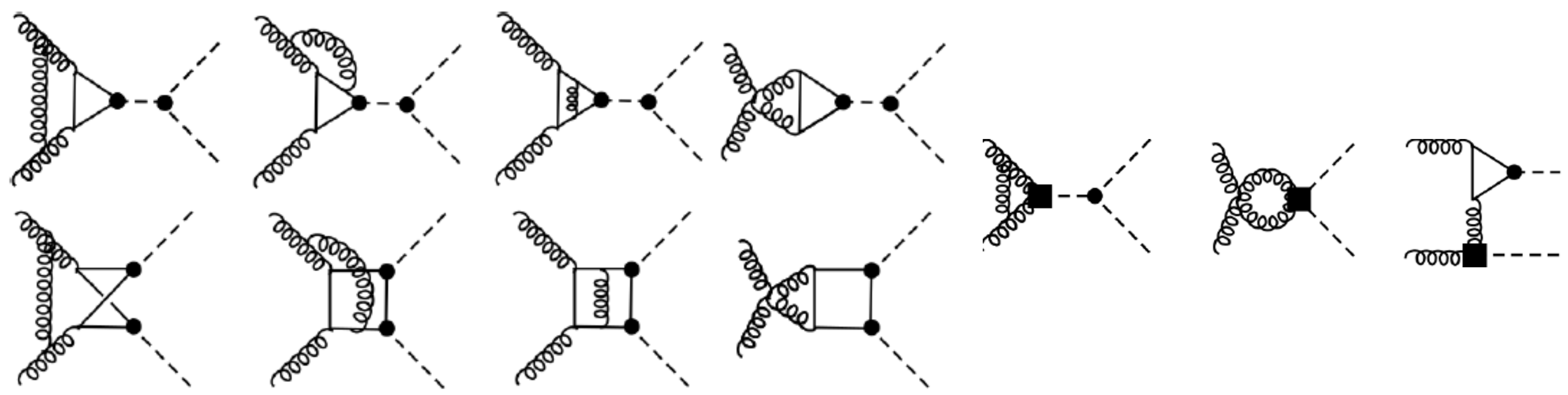
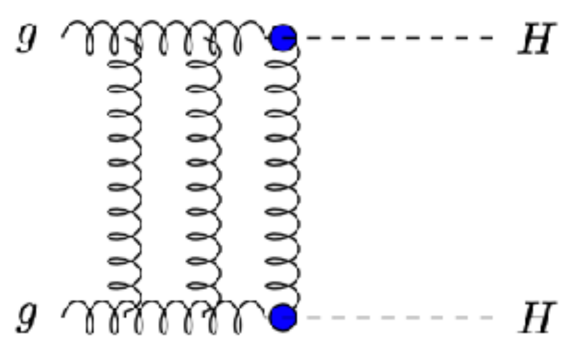


approximate NNLO (NNLO'):

De Florian, Fabre, GH, Mazzitelli, Scyboz '21



Approximate NNLO

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

parametrisation of cross section in terms of combinations of anomalous couplings

LO: 15, NLO: 23, NNLO: 25 combinations

$$\begin{aligned}
\sigma_{\rm BSM}/\sigma_{\rm SM} = {} & a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\
& + a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh} + a_{11}\, c_t^2 c_{ggh} c_{hhh} + a_{12}\, c_t^2 c_{gghh} \\
& + a_{13}\, c_t c_{hhh}^2 c_{ggh} + a_{14}\, c_t c_{hhh} c_{gghh} + a_{15}\, c_{ggh} c_{hhh} c_{gghh} + a_{16}\, c_t^3 c_{ggh} \\
& + a_{17}\, c_t c_{tt} c_{ggh} + a_{18}\, c_t c_{ggh}^2 c_{hhh} + a_{19}\, c_t c_{ggh} c_{gghh} + a_{20}\, c_t^2 c_{ggh}^2 \\
& + a_{21}\, c_{tt} c_{ggh}^2 + a_{22}\, c_{ggh}^3 c_{hhh} + a_{23}\, c_{ggh}^2 c_{gghh} + a_{24}\, c_{ggh}^4 + a_{25}\, c_{ggh}^3 c_t
\end{aligned}$$

Approximate NNLO

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

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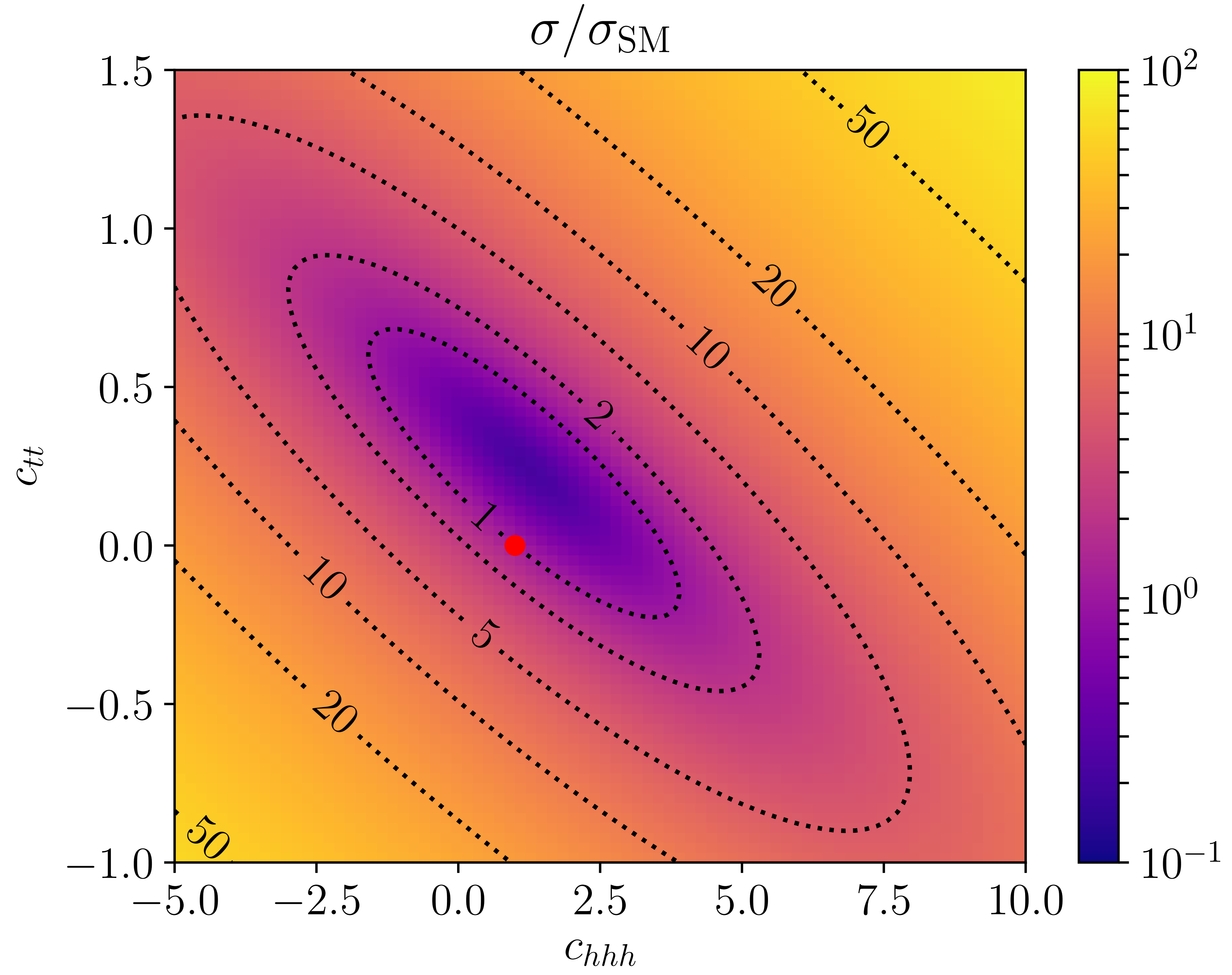
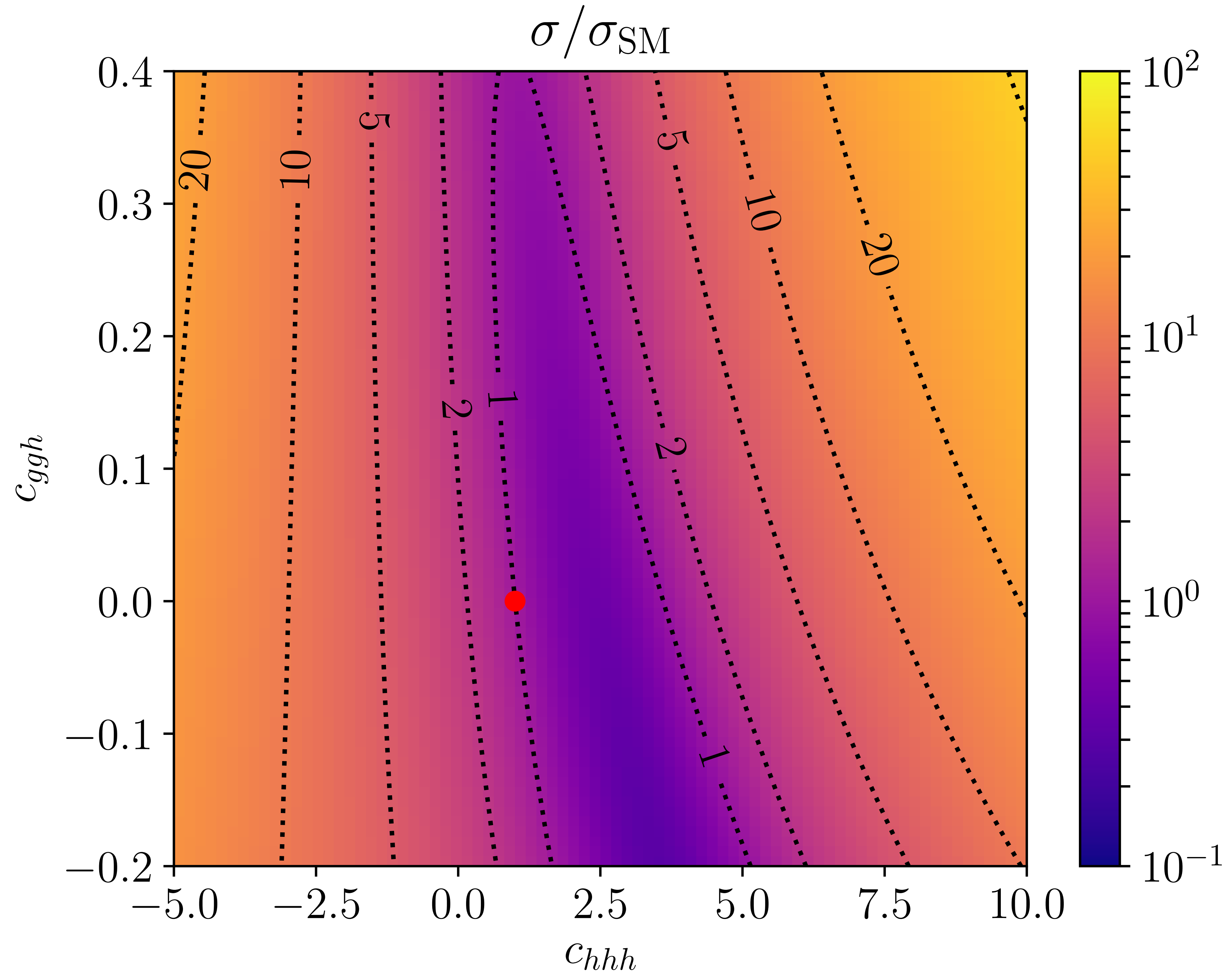
Total cross sections

- fit of coefficients based on 43 combinations of EFT parameter points
- scan over 10000 points in EFT parameter space

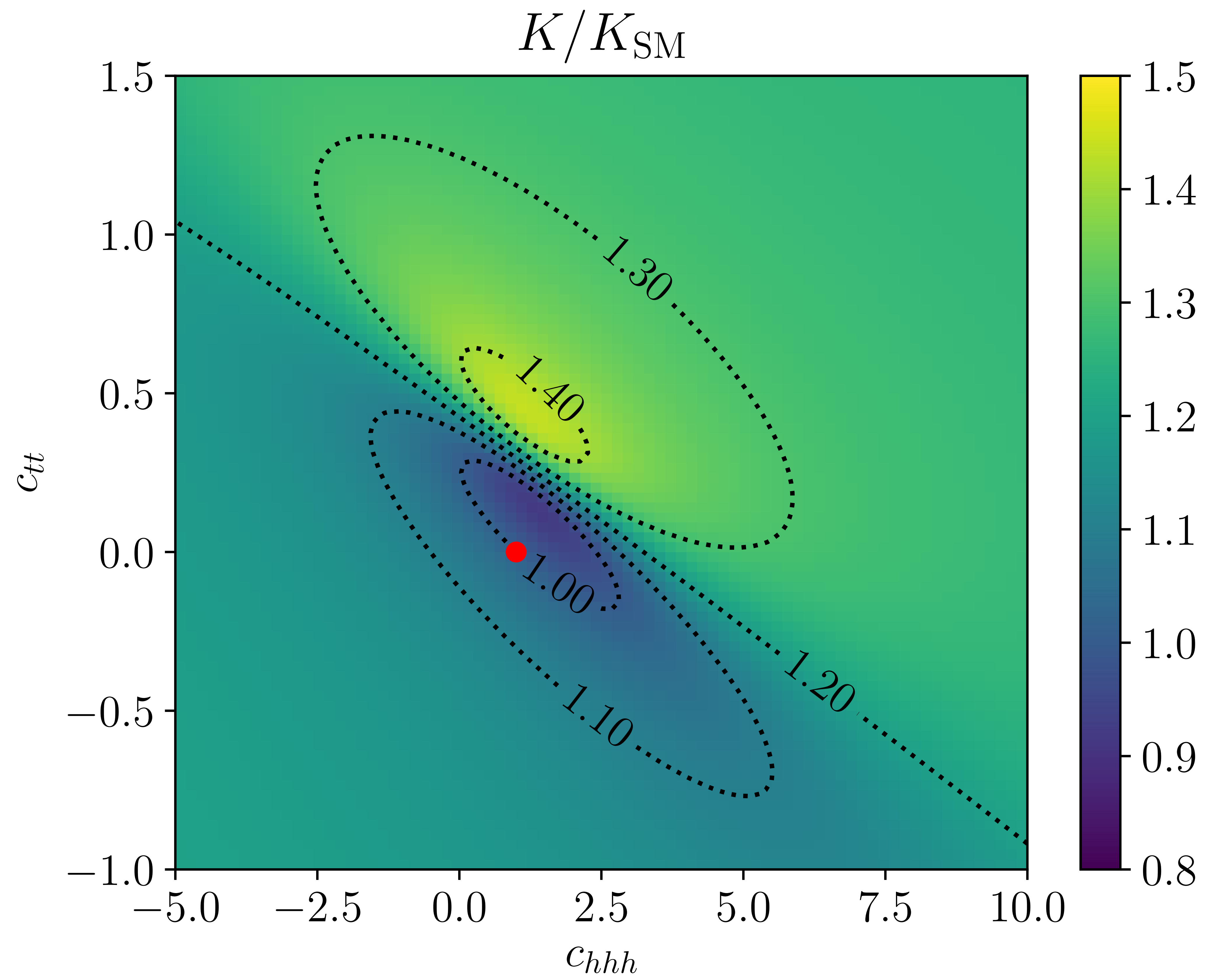
$c_{gghh} = c_{ggh} = 0,\ c_t = 1$

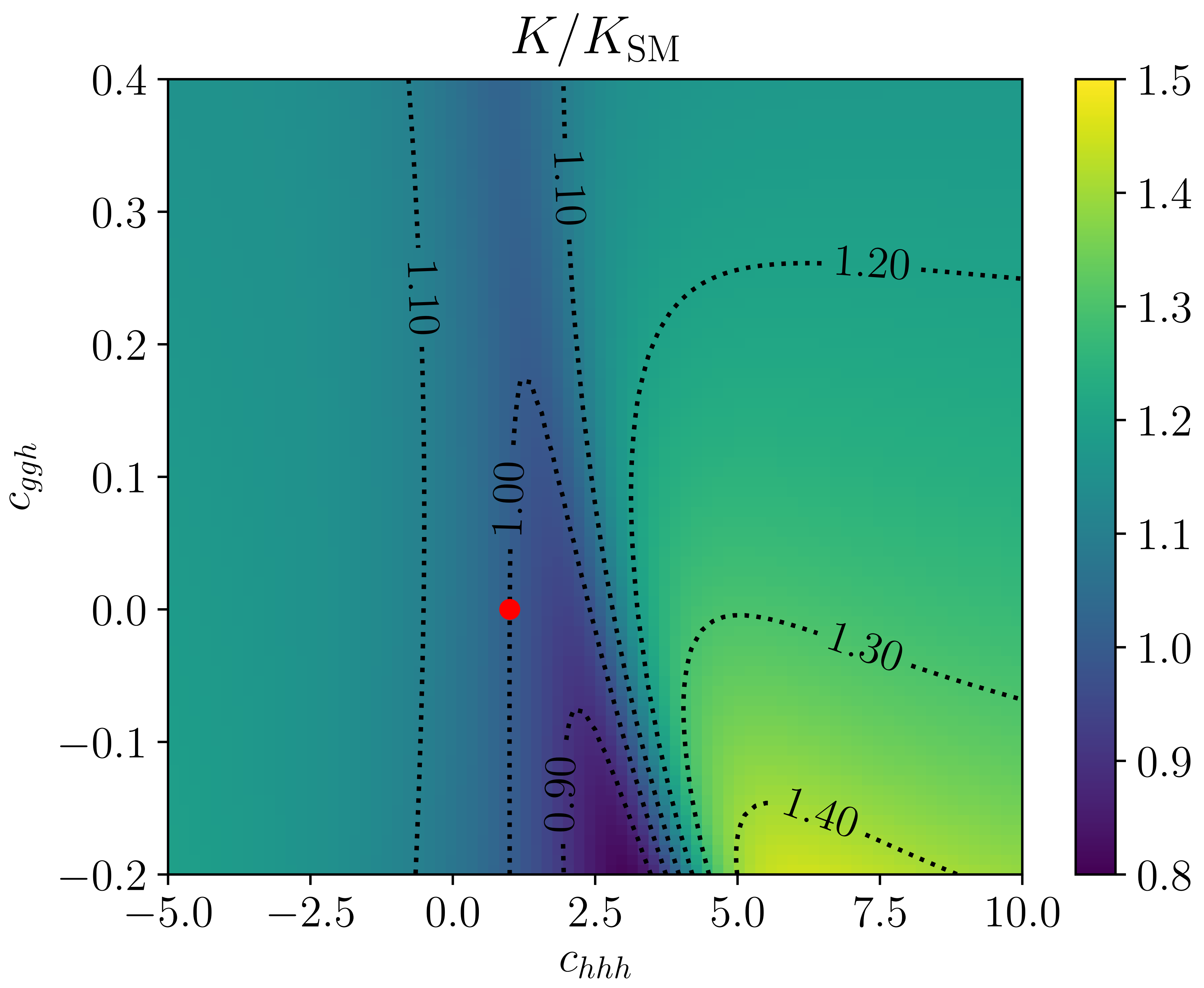


$c_{gghh} = c_{ggh}/2,\ c_{tt} = 0,\ c_t = 1$



K-factors





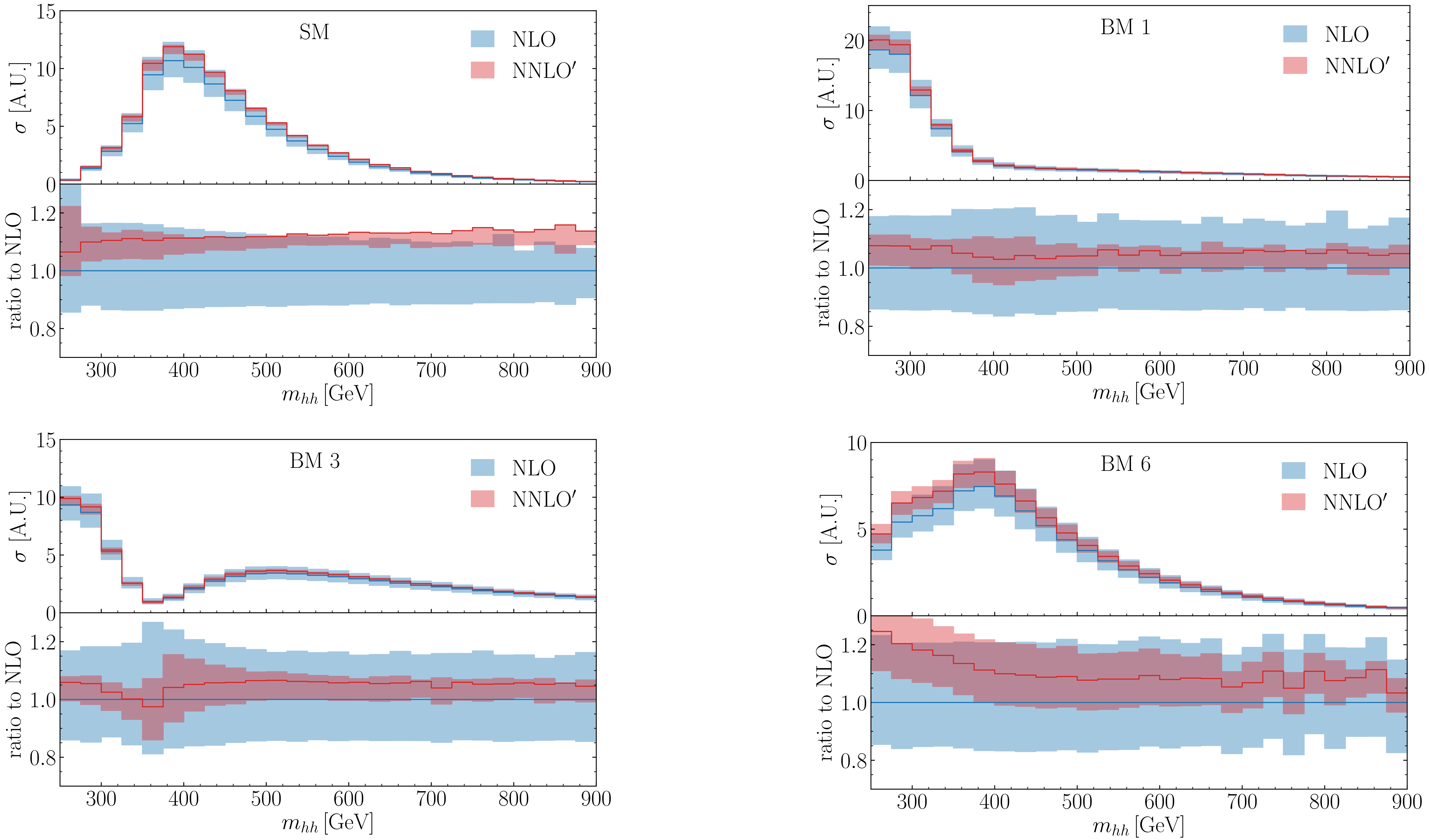
$\sigma^{NNLO'}/\sigma^{LO}$ normalised to SM K-factor (1.85)

Benchmark points

based on m_{hh} shape analysis at NLO [Capozi, GH '19]

benchmark	c_t	c_{hhh}	c_{tt}	c_{ggh}	c_{gghh}	σ_{NLO} [fb]	$\sigma_{NNLO'}$ [fb]	K_{NLO}	$K_{NNLO'}$	ratio to SM
SM	1	1	0	0	0	$32.90^{+14\%}_{-16\%}$	$36.69^{+0.0\%}_{-4.3\%}$	1.66	1.85	1.00
1	0.94	3.94	$-\frac{1}{3}$	0.5	$\frac{1}{3}$	$222.6^{+18\%}_{-14\%}$	$237.2^{+2.7\%}_{-5.4\%}$	1.90	2.03	6.47
2	0.61	6.84	$\frac{1}{3}$	0.0	$-\frac{1}{3}$	$168.1^{+20\%}_{-16\%}$	$191.1^{+7.1\%}_{-8.6\%}$	2.14	2.43	5.21
3	1.05	2.21	$-\frac{1}{3}$	0.5	0.5	$151.9^{+17\%}_{-14\%}$	$159.9^{+2.1\%}_{-5.2\%}$	1.84	1.92	4.36
4	0.61	2.79	$\frac{1}{3}$	-0.5	$\frac{1}{6}$	$63.14^{+20\%}_{-16\%}$	$69.57^{+8.9\%}_{-9.1\%}$	2.14	2.37	1.90
5	1.17	3.95	$-\frac{1}{3}$	$\frac{1}{6}$	-0.5	$154.8^{+14\%}_{-13\%}$	$166.7^{+0.0\%}_{-3.7\%}$	1.64	1.75	4.54
6	0.83	5.68	$\frac{1}{3}$	-0.5	$\frac{1}{3}$	$179.4^{+20\%}_{-16\%}$	$200.1^{+5.9\%}_{-9.3\%}$	2.16	2.41	5.45
7	0.94	-0.10	1	$\frac{1}{6}$	$-\frac{1}{6}$	$131.1^{+22\%}_{-17\%}$	$146.2^{+12\%}_{-11\%}$	2.26	2.54	3.98

Distributions



Summary

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- available public tools:
  - gg->HH specific Powheg code: 5 anomalous couplings, full NLO
  - MG5, SMEFTsim: more processes, partly heavy top limit or LO
- How to treat (dim6)^2 and double operator insertions in SMEFT is non-trivial
- uncertainty budget for gg->HH:
  - scale uncertainties ~3% at N^3LO HTL'
  - top mass scheme dependence [Baglio, Glaus, Mühlleitner, Spira, Ronca] ~18%
  - truncation of EFT series/double operator insertions xxx%

NNLO' coefficients of coupling combinations

	$\mu_R = \mu_F = \mu_0$	$\mu_R = \mu_F = \mu_0/2$	$\mu_R = \mu_F = 2\mu_0$
a_1	2.2359	2.2899	2.1062
a_2	12.465	13.191	11.469
a_3	0.34254	0.36853	0.31341
a_4	0.32832	0.27278	0.3225
a_5	12.035	12.139	11.435
a_6	-9.6736	-9.967	-9.0278
a_7	-1.5785	-1.6626	-1.4625
a_8	3.4554	3.621	3.2097
a_9	2.8013	2.5608	2.6905
a_{10}	16.173	16.712	15.144
a_{11}	-1.1806	-1.2201	-1.0647
a_{12}	-5.6581	-5.6718	-5.3808
a_{13}	0.63134	0.65511	0.59109
a_{14}	2.7664	2.9025	2.581
a_{15}	2.93	2.9659	2.7499
a_{16}	-0.10785	-0.14072	-0.12683
a_{17}	0.223	0.52954	0.098154
a_{18}	0.065656	0.032461	0.082079
a_{19}	0.18294	0.22852	0.1622
a_{20}	-0.048533	-0.056875	-0.02693
a_{21}	0.12436	0.33443	0.036752
a_{22}	0.027999	0.03496	0.022263
a_{23}	0.21161	0.21764	0.15791
a_{24}	0.00047051	0.00073051	0.00031311
a_{25}	0.00077149	0.00087966	-0.00040697

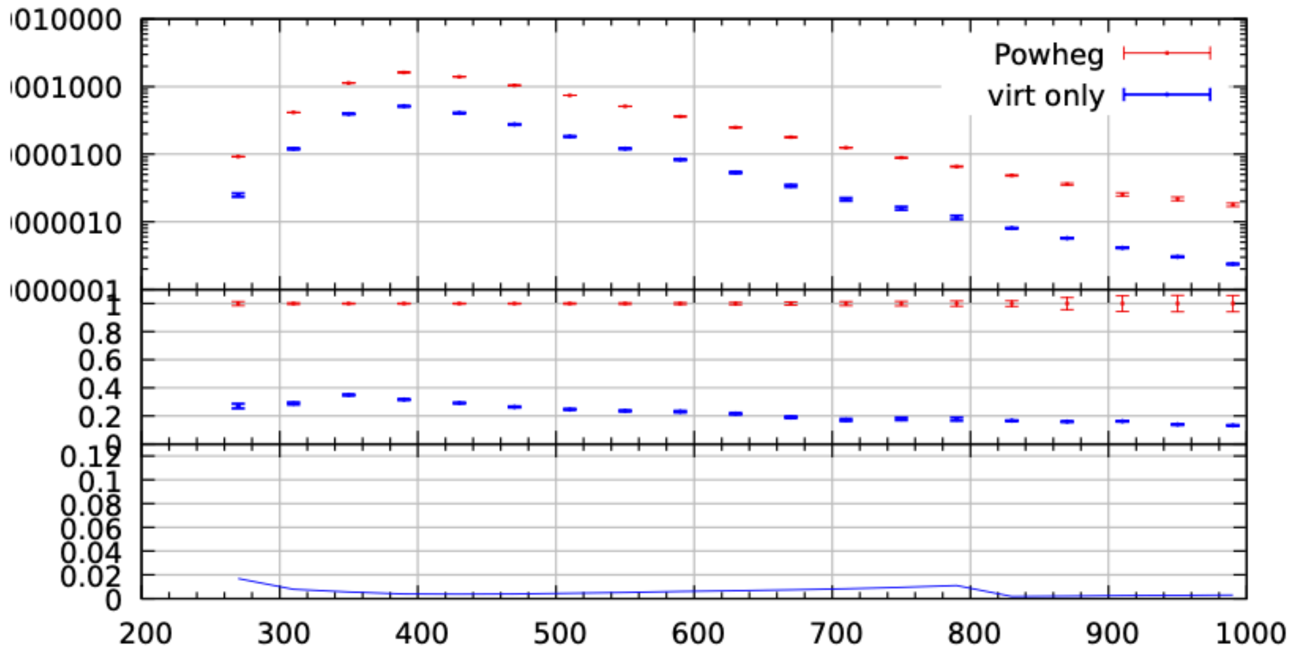
2106.14050

ggHH Powheg code

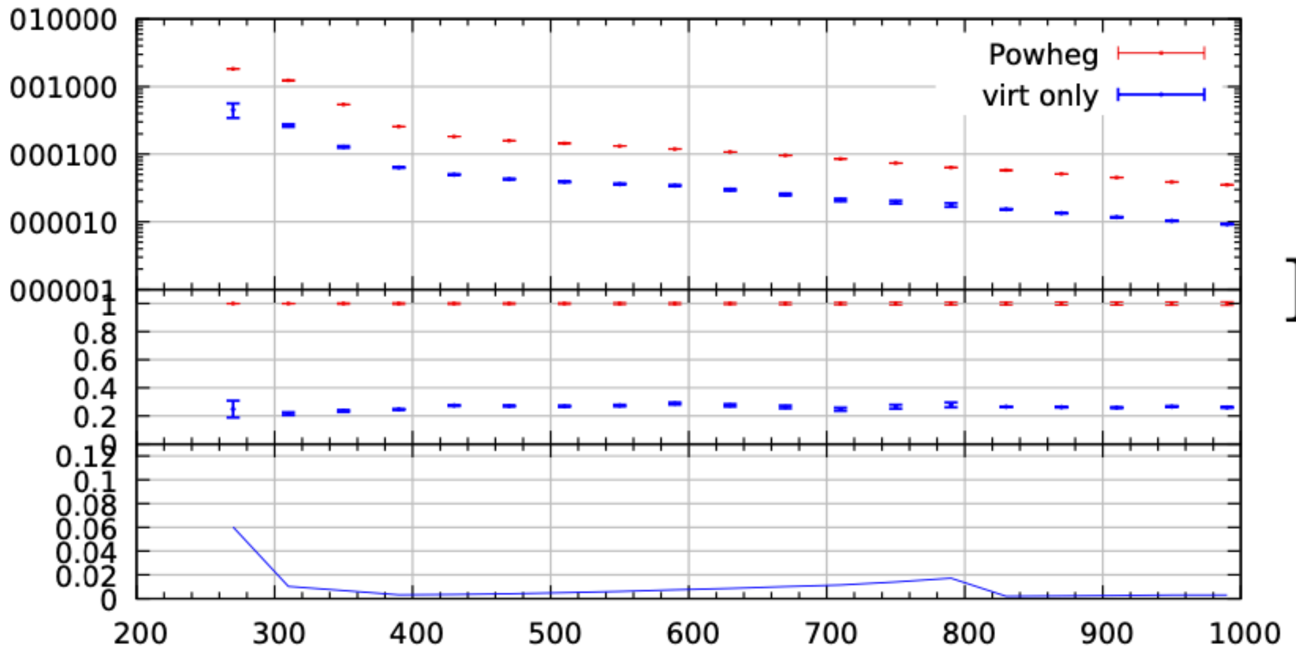
Stat. uncertainties from $\mathcal{M}_{B\times V}$

- Stat. uncertainty can become large in undersampled bins in BSM case

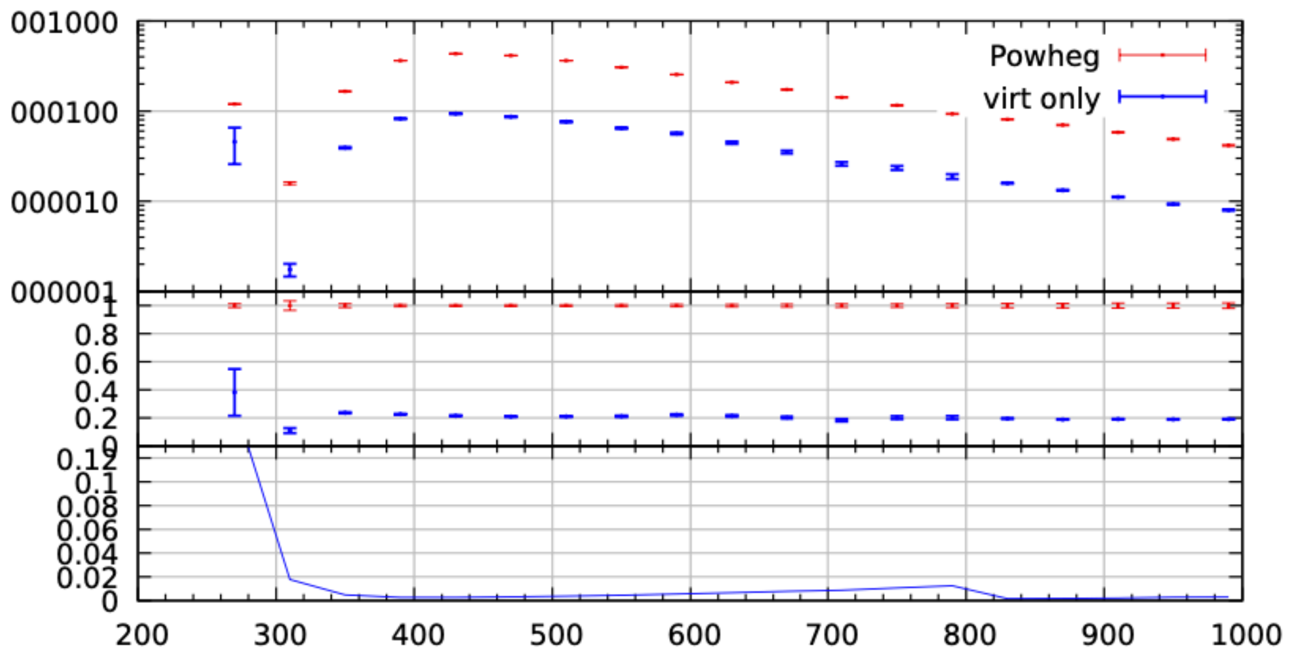
SM



BM 1



BM 5



slide: Ludovic Scyboz

Individual variations

yellow line:
current limit on total xs

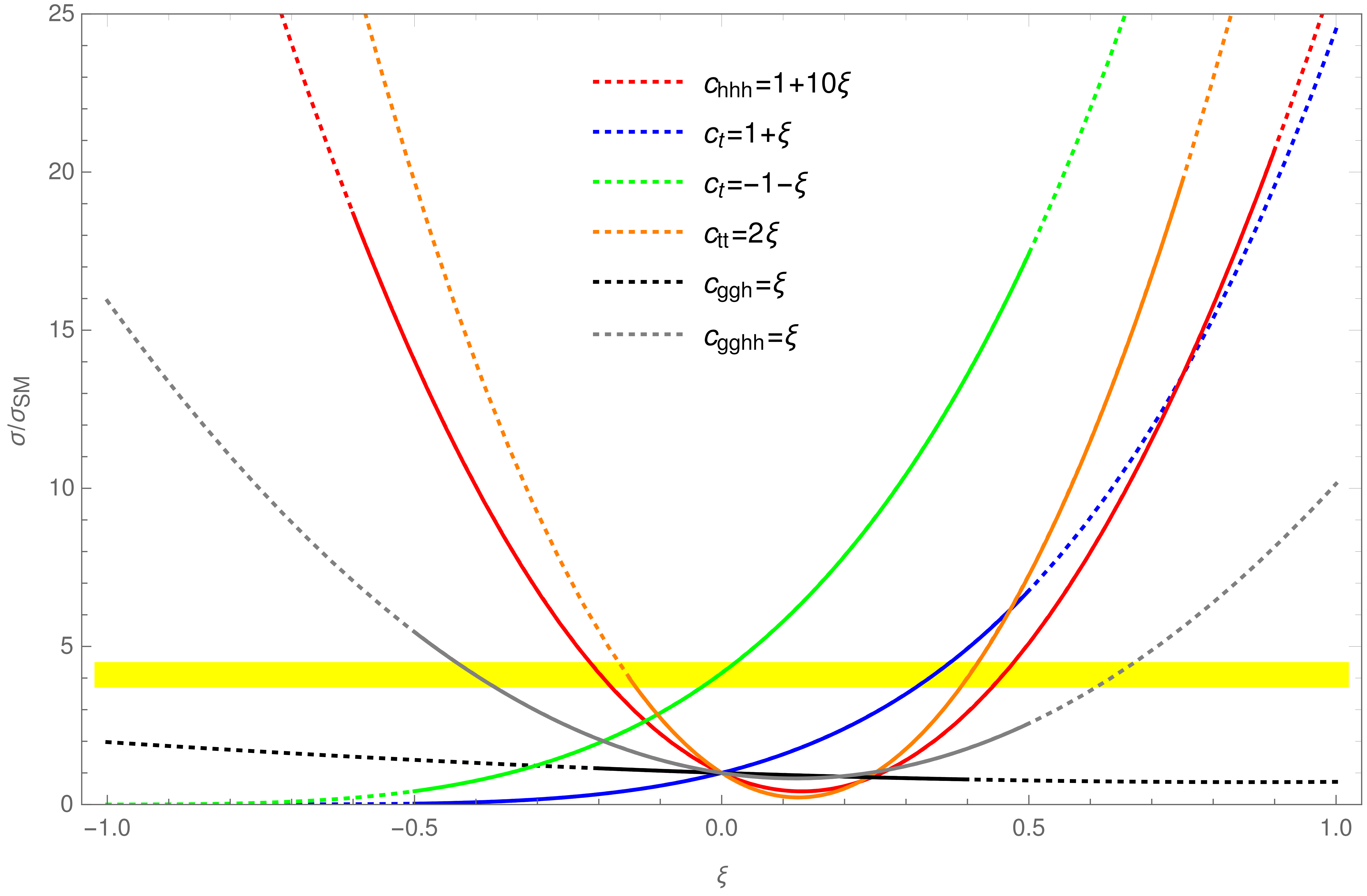
(ATLAS-CONF-2021-016)

solid: ~ experimental limits on couplings

all couplings except c_{ggh}

can generate variations of the cross section larger than the current limit from hh xs

➡ only simultaneous variations are meaningful



Counting schemes

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

$\xi = v^2/f^2$

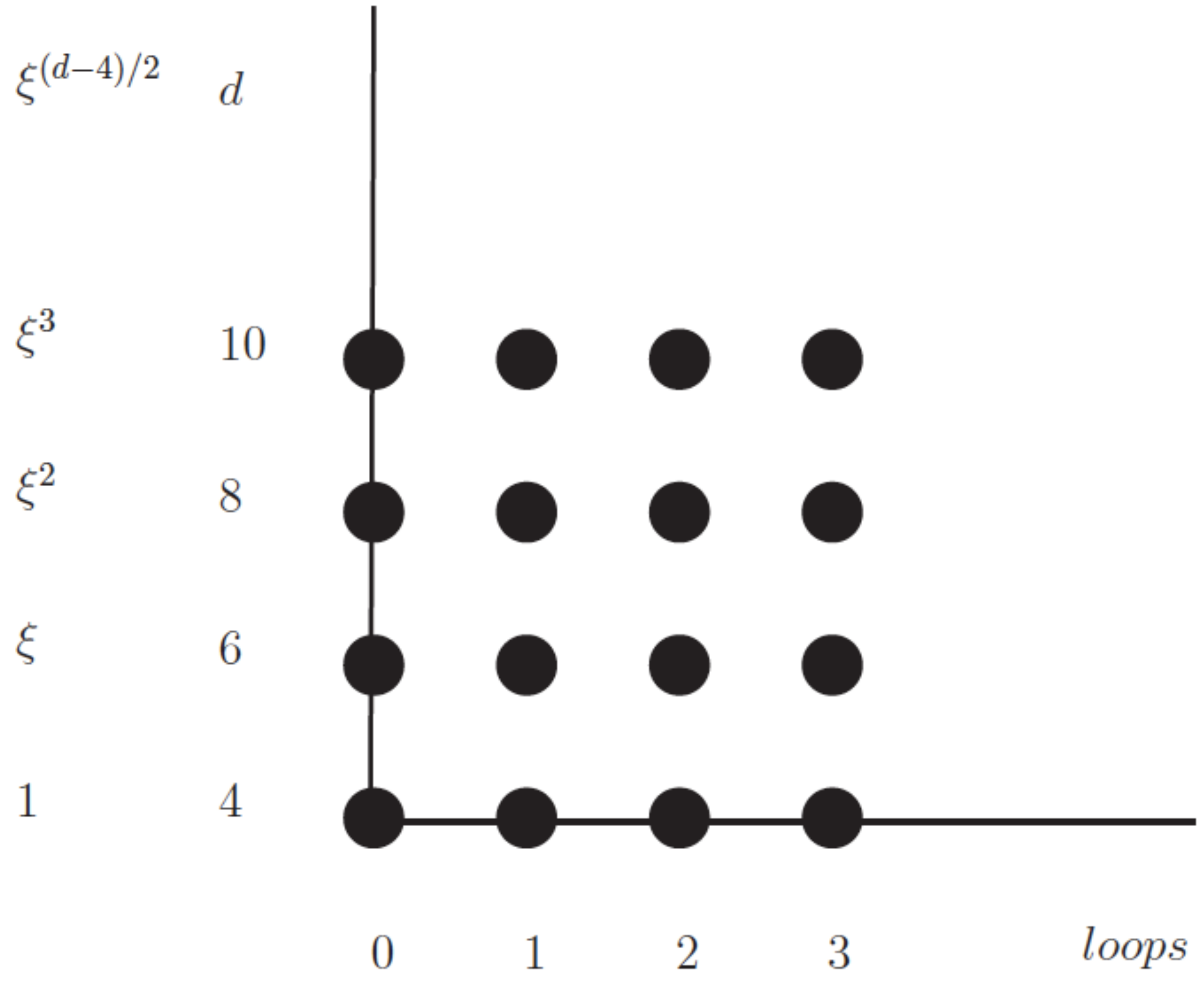


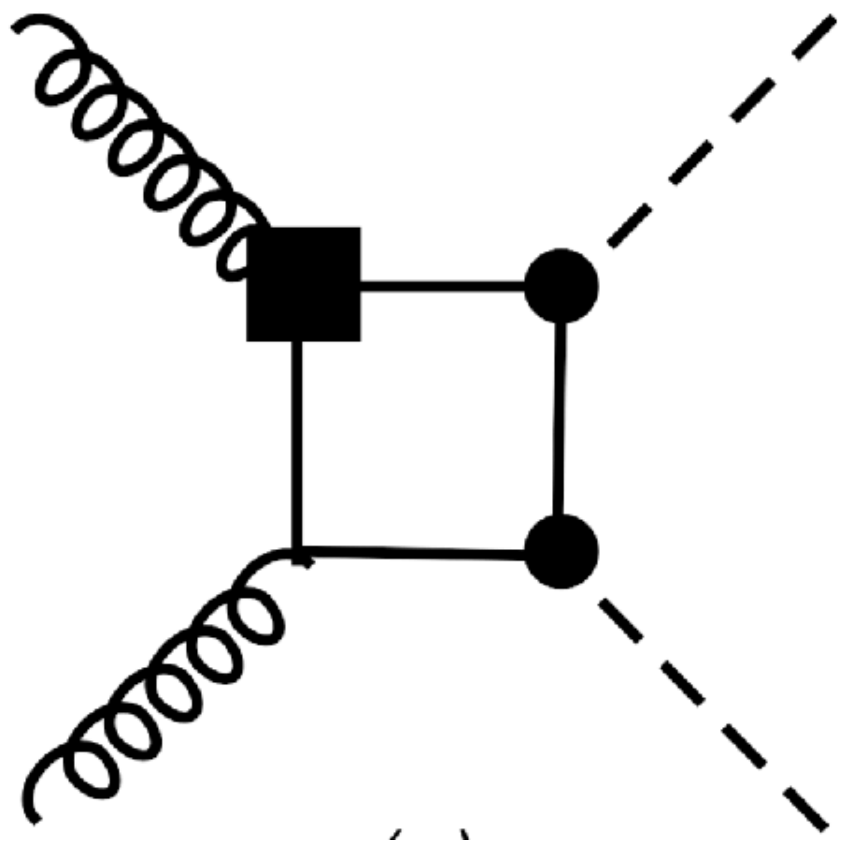
figure: G.Buchalla

loop expansion

HEFT

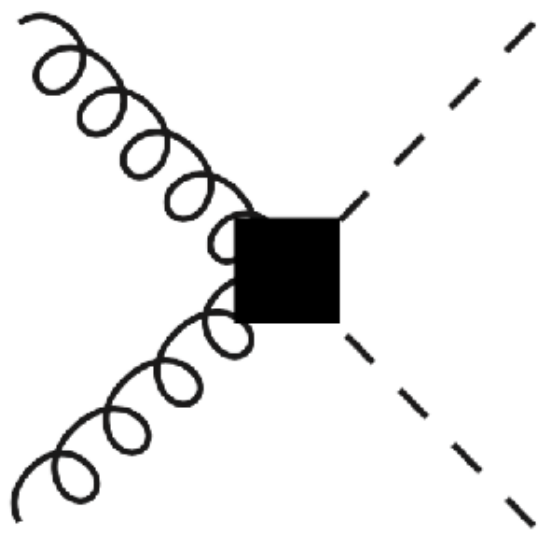
Chromomagnetic operator

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



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

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

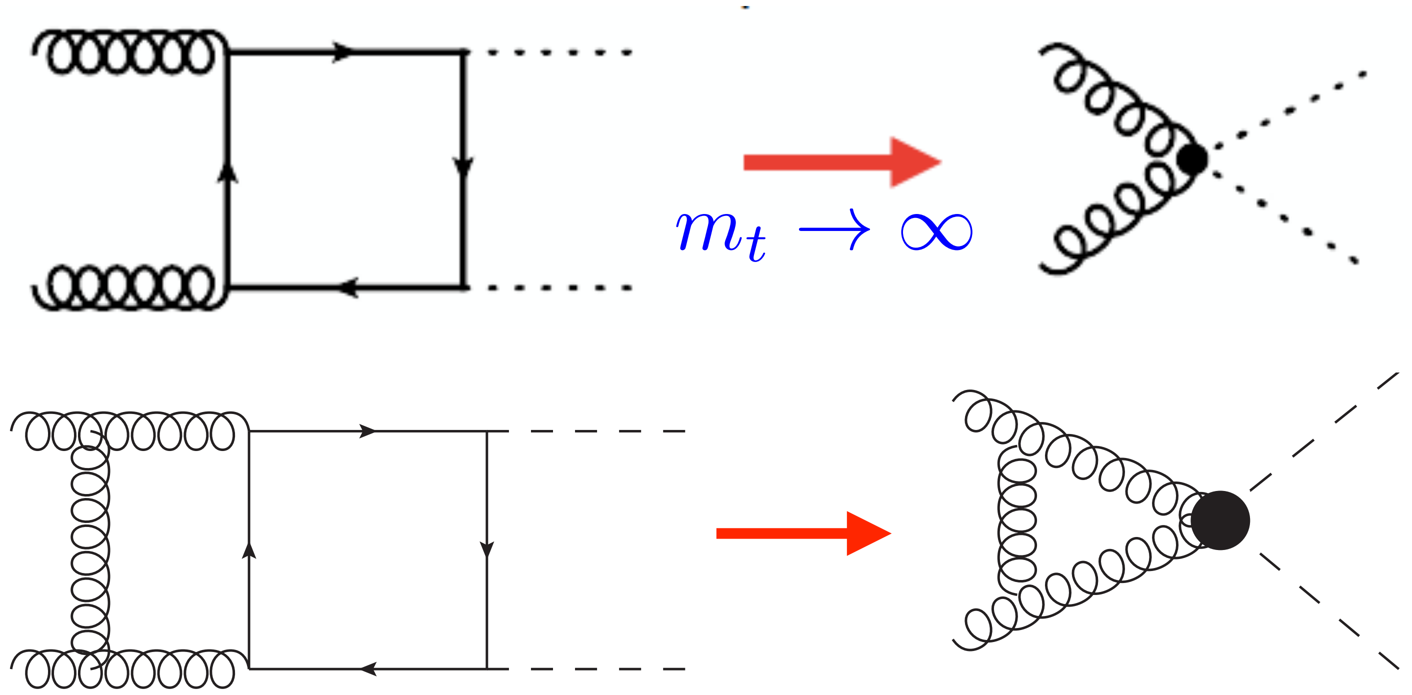


$ggh(h)$ interactions also come from contraction of a loop,
but they appear at tree level, while O_{tG} is inserted
into a loop diagram and therefore is suppressed

Approximations: NLO

Karlsruhe Institute of Technology

- $m_t \to \infty$ limit (HEFT):
  ("Higgs Effective Field Theory")

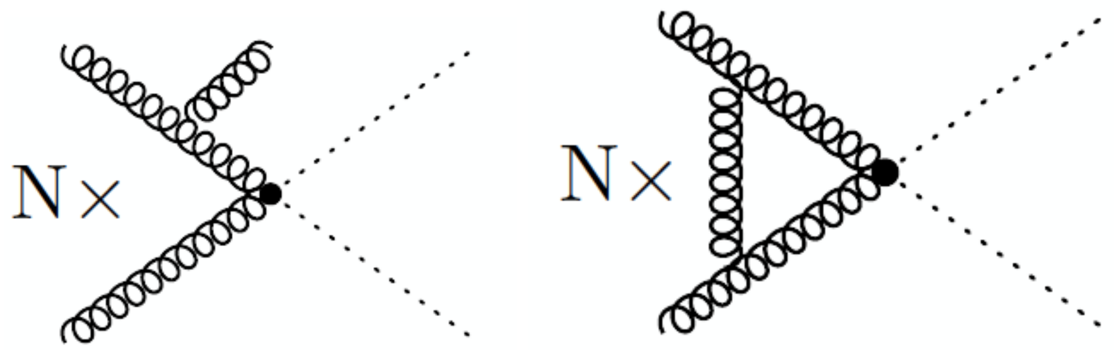


Leading Order (LO)

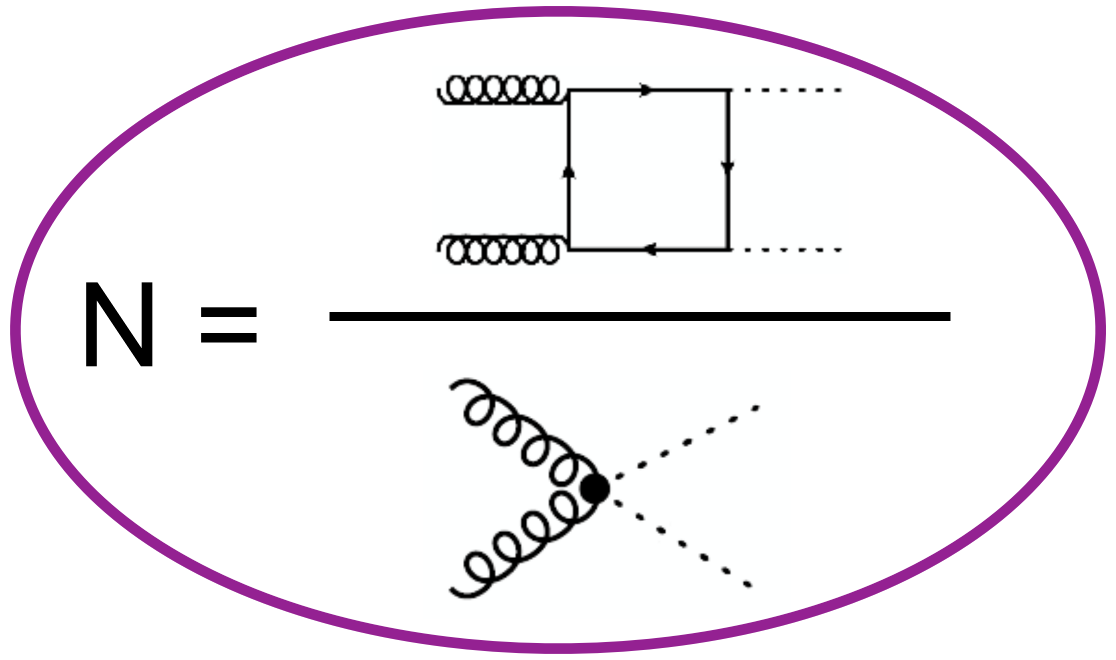
Next-to-Leading Order (NLO)

- Born-improved HEFT:

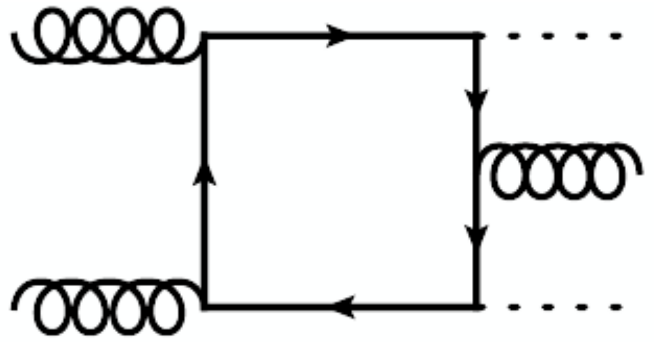
$$d\sigma^{\mathrm{NLO}}_{m_t\to\infty} \times \frac{d\sigma^{\mathrm{LO}}(m_t)}{d\sigma^{\mathrm{LO}}_{m_t\to\infty}}$$

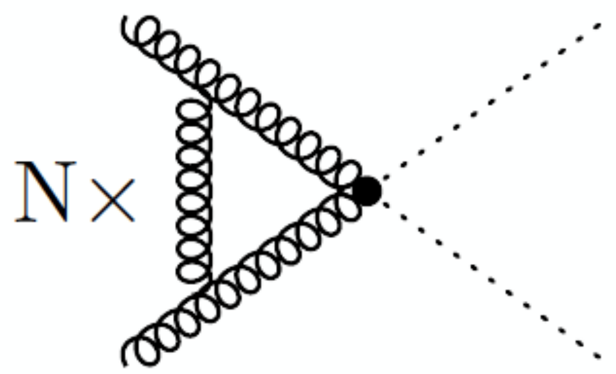


NLO real NLO virtual



- FTapprox:

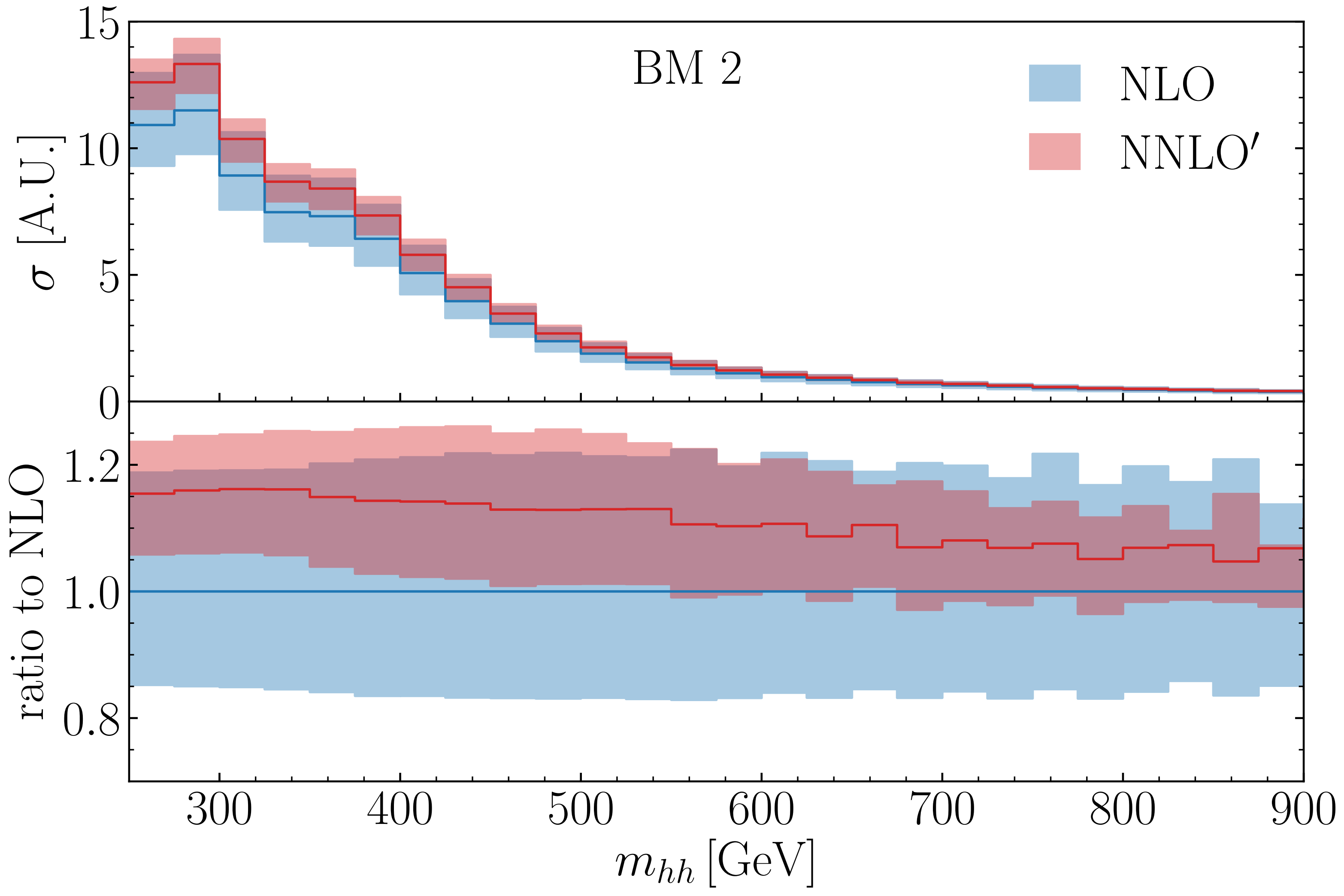


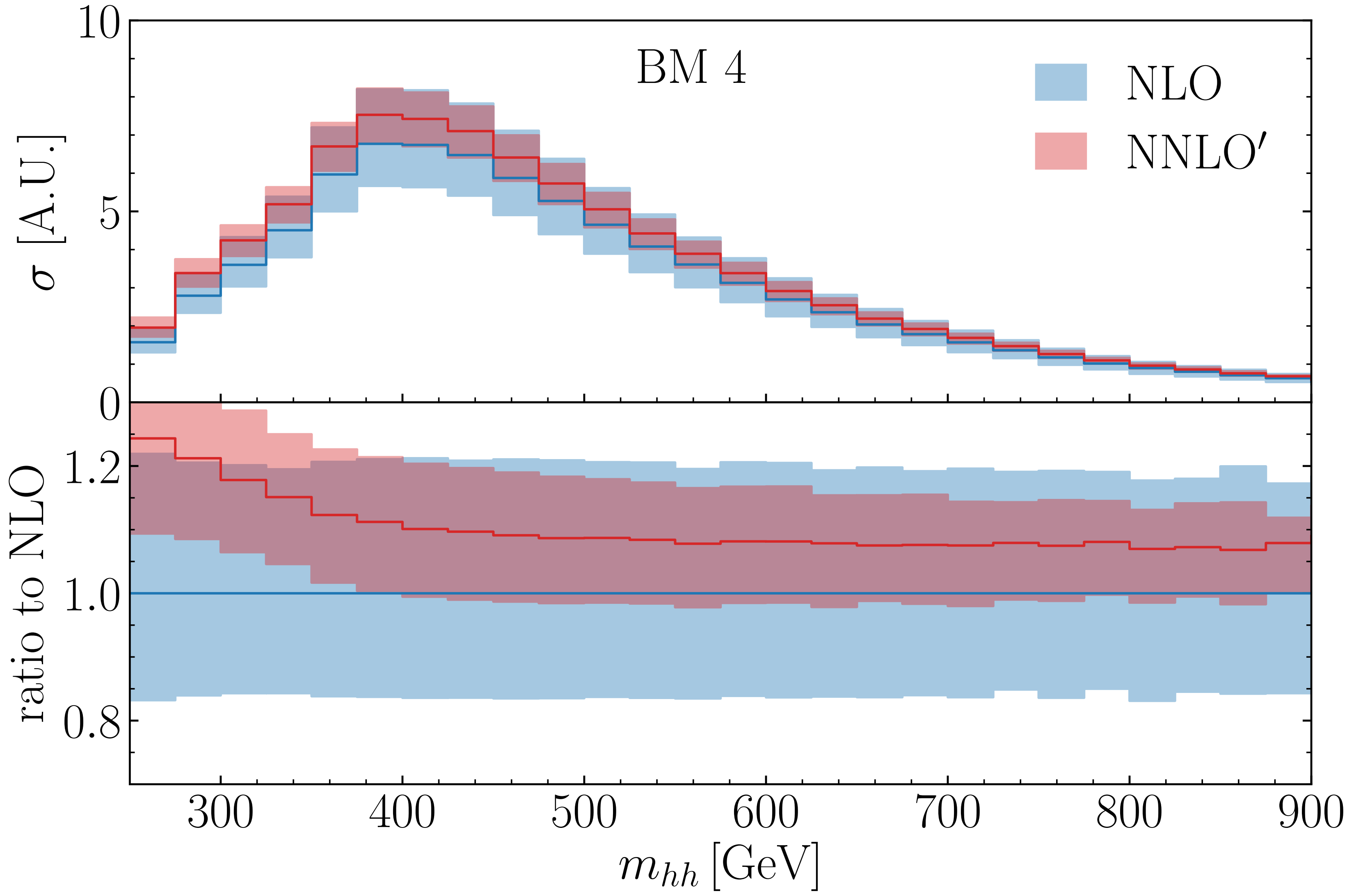


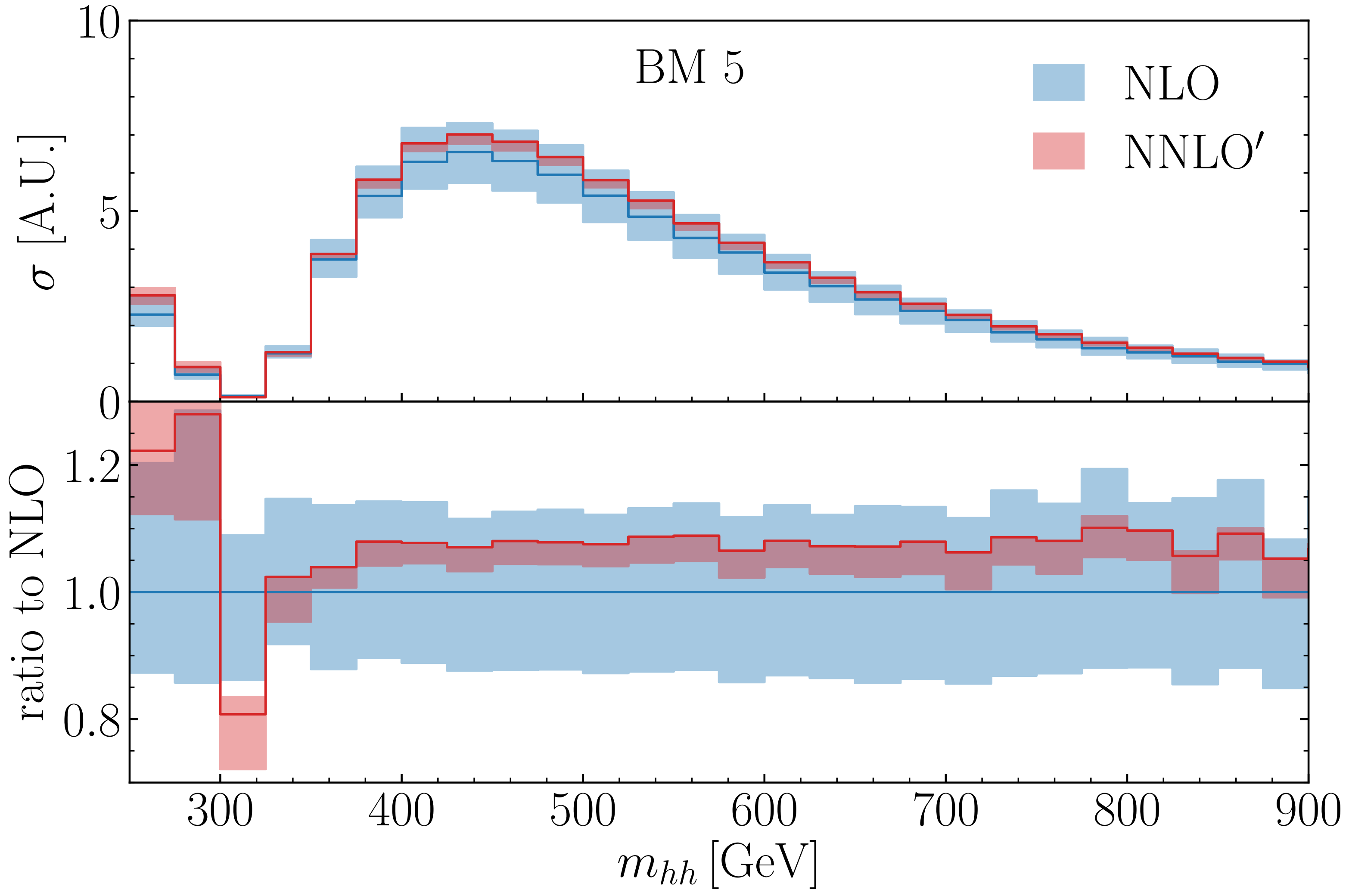
NLO real:
full m_t-dependence

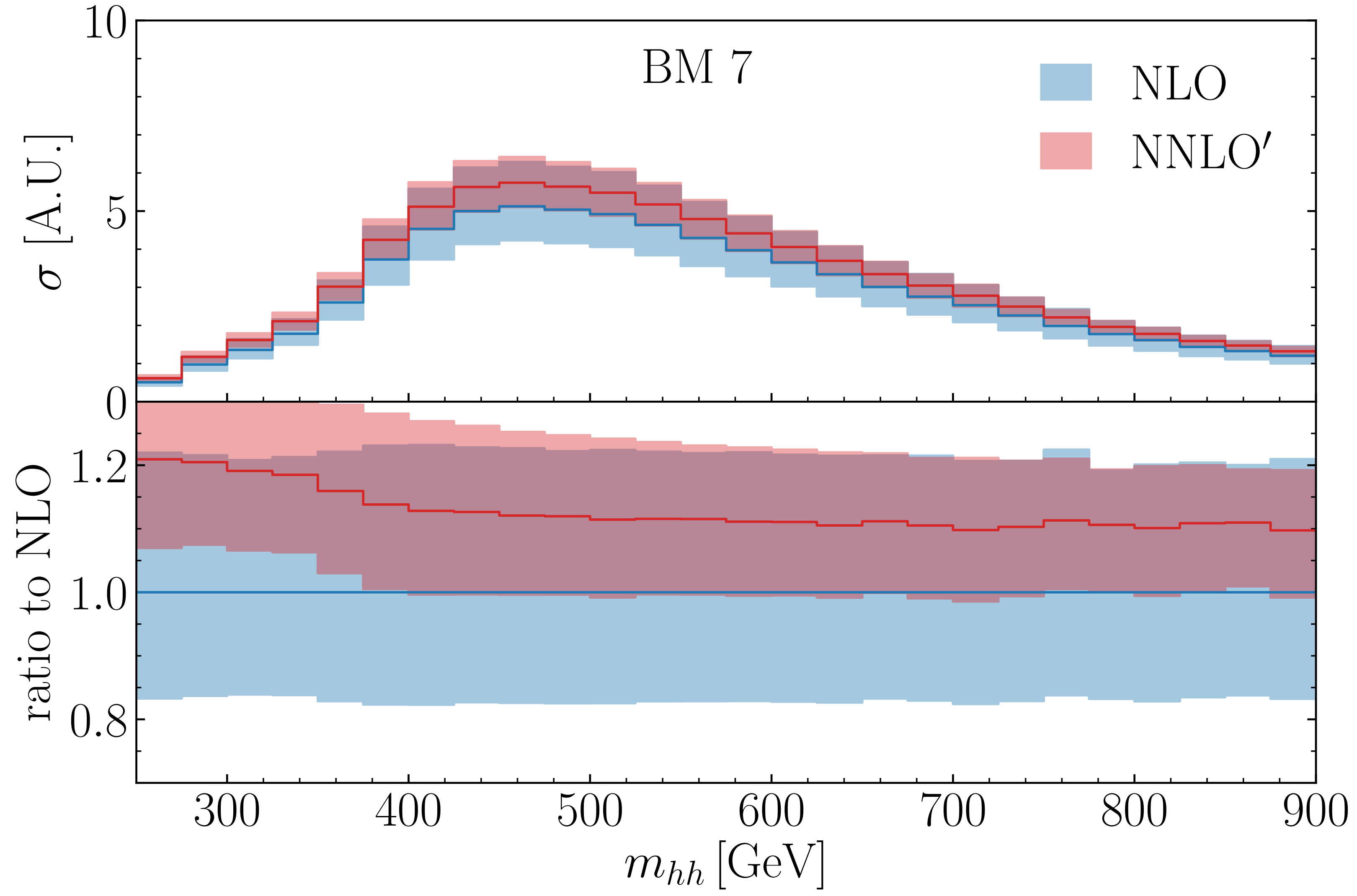
NLO virtual:
Born-improved HEFT

benchmark points 2,4,5,7









conventions

HEFT	SILH	Warsaw
c_{hhh}	$1-\frac{3}{2}\bar{c}_H+\bar{c}_6$	$1-2\frac{v^4}{m_h^2}C_H+3c_{H,kin}$
c_t	$1-\frac{\bar{c}_H}{2}-\bar{c}_u$	$1+c_{H,kin}-C_{uH}\frac{v^3}{\sqrt{2}m_t}$
c_{tt}	$-\frac{\bar{c}_H+3\bar{c}_u}{4}$	$-C_{uH}\frac{3v^3}{2\sqrt{2}m_t}+c_{H,kin}$
c_{ggh}	$128\pi^2\bar{c}_g$	$8\pi/\alpha_s v^2 C_{HG}$
c_{gghh}	$64\pi^2\bar{c}_g$	$4\pi/\alpha_s v^2 C_{HG}$

Buchalla et al. 1806.05162	Carvalho et al. 1507.02245	Gröber et al. 1504.06577
c_{hhh}	κ_λ	c_3
c_t	κ_t	c_t
c_{tt}	c_2	$c_{tt}/2$
c_{ggh}	$\frac{2}{3}c_g$	$8c_g$
c_{gghh}	$-\frac{1}{3}c_{2g}$	$4c_{gg}$