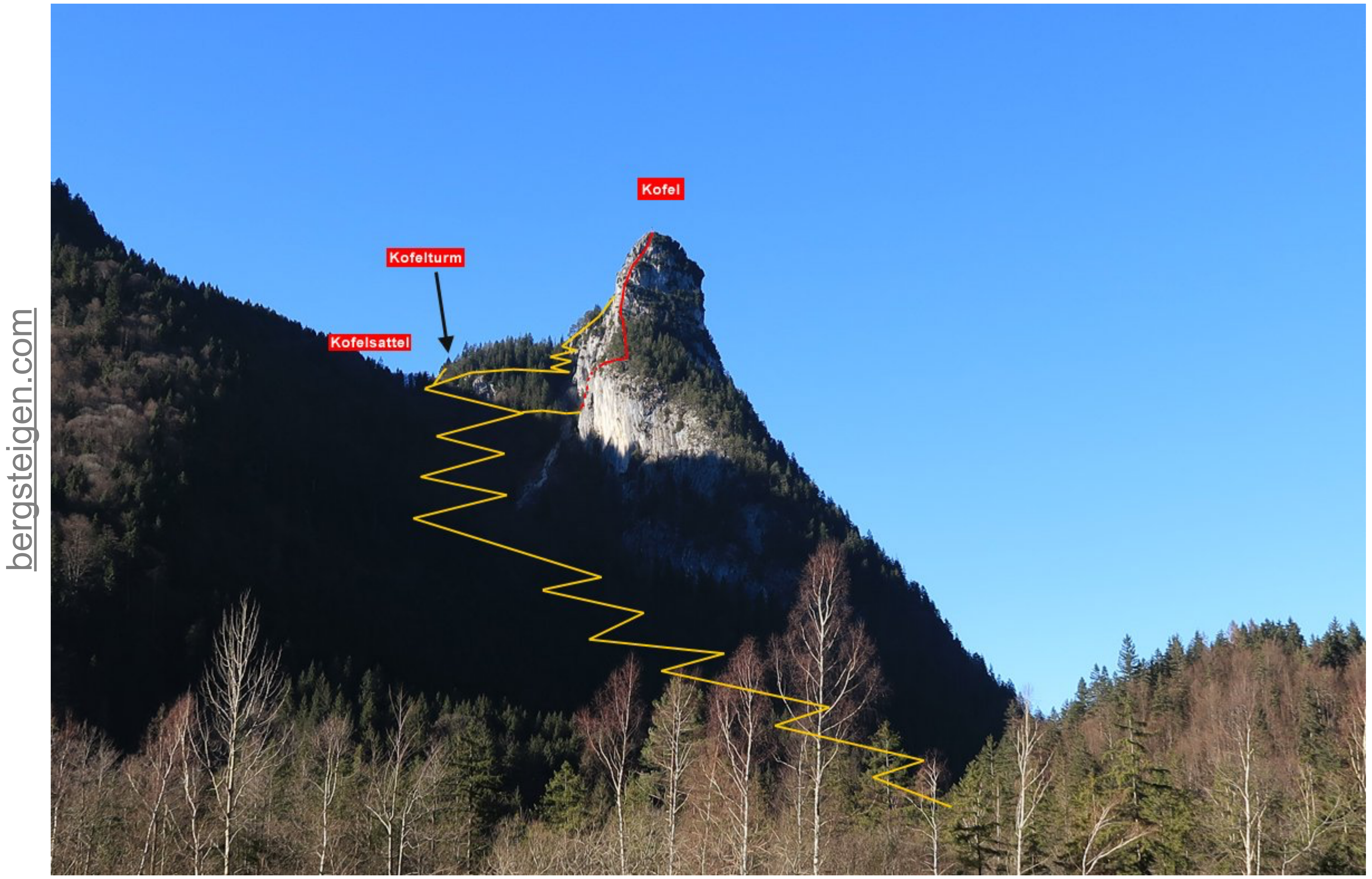
Higgs pair production in SMEFT at NLO QCD:

truncation uncertainties



Gudrun Heinrich

Institute for Theoretical Physics, Karlsruhe Institute of Technology

in collaboration with
Jannis Lang, Ludovic Scyboz
2204.13045

builds on work with
Stephen Jones, Matthias Kerner et al.

Loops & Legs 2022, Ettal

April 28, 2022

Motivation

Karlsruhe Institute of Technology

How to identify imprints of New Physics?

need:

- precise SM predictions

→ increase number of loops, legs, scales

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this talk:
loops: up to 2
legs: up to 5 at 1-loop
scales: up to 4 at 2-loop (s, t, mt, mH)

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  → - investigate concrete BSM models, or

  - parametrise effects of heavy New Physics by Effective Field Theory (EFT)

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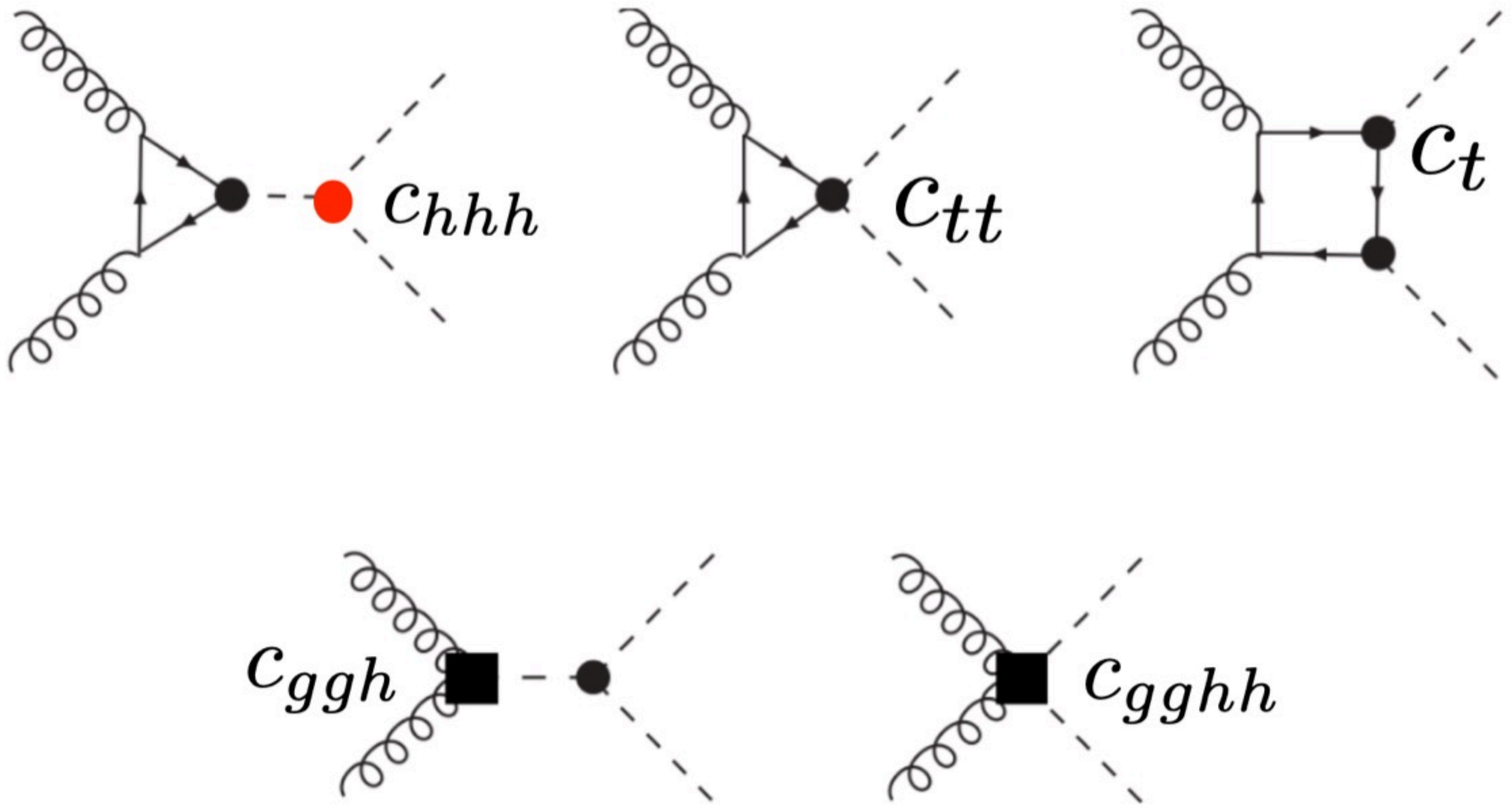
- parametrise effects of heavy New Physics by Effective Field Theory (EFT)

Wilson coefficients: up to five!

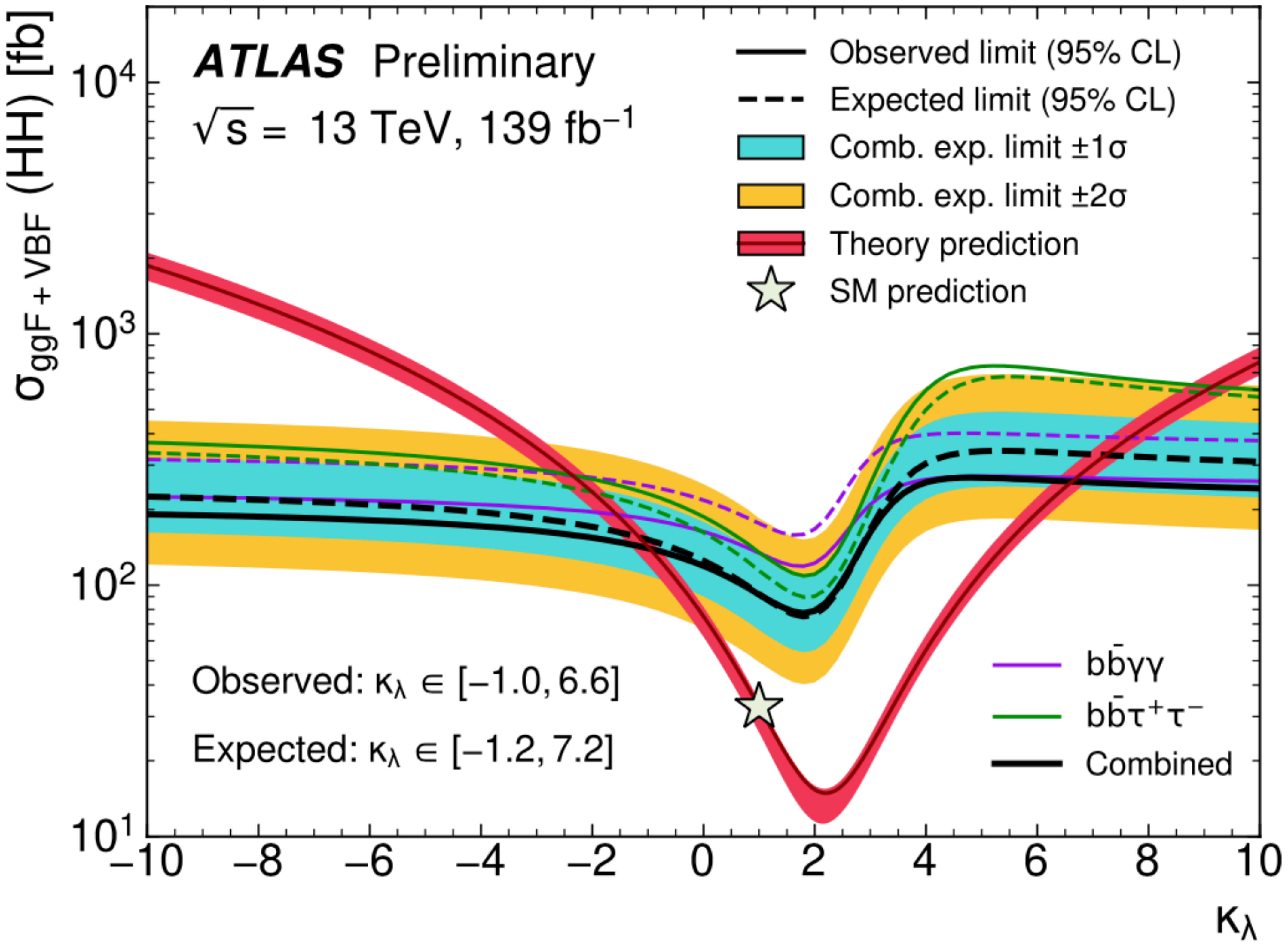
Higgs boson pair production

- prime process to explore the Higgs potential (Higgs boson trilinear coupling)
- if trilinear coupling different from SM, other couplings are likely to be non-SM as well

→ EFT parametrisation by extra operators



ATLAS-CONF-2021-052



$$\kappa_\lambda \equiv c_{hhh} = \lambda/\lambda_{SM}$$

Effective Field Theory expansion schemes

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):

$$\mathcal{L}_{\mathrm{HEFT}} = \mathcal{L}_2 + \sum_{L=1}^{\infty} \sum_i \left(\frac{1}{16\pi^2}\right)^L c_i^{(L)} O_i^{(L)}$$

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

(similar to chiral perturbation theory)

E

new physics scale Λ

f : characteristic scale of Goldstone bosons

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

HEFT and SMEFT

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- 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 (cf. non-linear sigma-model)

    → 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

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

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

Lagrangians relevant for HH production

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SMEFT:

$$\Delta\mathcal{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 + \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\phi^c t_R + h.c.\right) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a}$$

(Warsaw basis)

Grzadkowski et al. 1008.4884

HEFT:

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

Feruglio ’93, Buchalla et al. ’13, ‘18

NLO with full top quark mass dependence implemented in

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

GH, Jones, Kerner, Luisoni, Scyboz 2006.16877

NNLO’: De Florian, Fabre, GH, Mazzitelli, Scyboz 2106.14050

Lagrangians relevant for HH production

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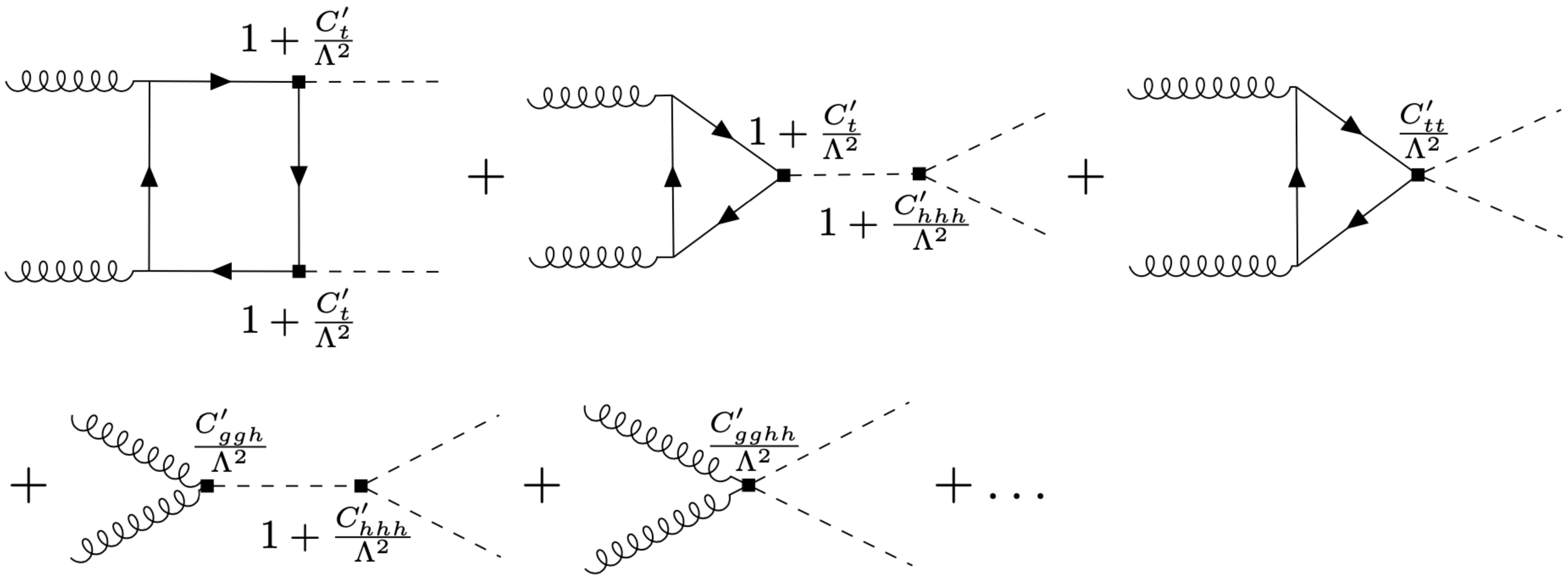
naive translation (comparing coefficients at Lagrangian level):

HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_t	$1 + \frac{v^2}{\Lambda^2}C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH} + \frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$

$$C_{H,\text{kin}} = C_{H,\Box} - \frac{1}{4}C_{HD}$$

SMEFT truncation

$\mathcal{M} =$

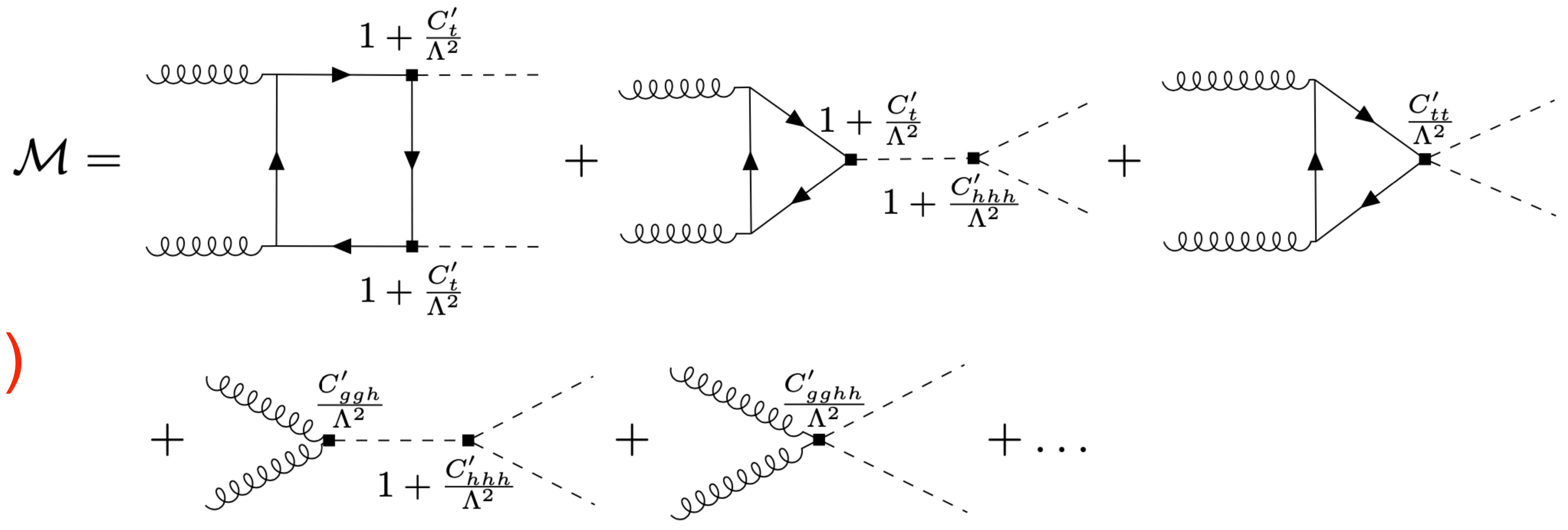


$$= \mathcal{M}_{\mathrm{SM}} + \mathcal{M}_{\text{single ins.}} + \mathcal{M}_{\text{double ins.}}$$

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

SMEFT at amplitude squared level

truncation options:



$$\sigma = \sigma_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sigma_{\mathrm{SM}\times\mathrm{single\,ins.}} \qquad \text{(a)}$$

$$+ \frac{1}{\Lambda^4}\sigma_{\mathrm{single\,ins.}\times\mathrm{single\,ins.}} \qquad \text{(b)}$$

$$+ \frac{1}{\Lambda^4}\sigma_{\mathrm{SM}\times\mathrm{double\,ins.}} \qquad \text{(c)}$$

$$+ \frac{1}{\Lambda^6}\sigma_{\mathrm{single\,ins.}\times\mathrm{double\,ins.}} + \frac{1}{\Lambda^8}\sigma_{\mathrm{double\,ins.}\times\mathrm{double\,ins.}} \qquad \text{(d)}$$

SMEFT at amplitude squared level

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4 options:

$$\sigma \simeq \begin{cases} \sigma_{\mathrm{SM}} + \sigma_{\mathrm{SM}\times\mathrm{dim6}} & \text{(a)} \\ \sigma_{(\mathrm{SM}+\mathrm{dim6})\times(\mathrm{SM}+\mathrm{dim6})} & \text{(b)} \\ \sigma_{(\mathrm{SM}+\mathrm{dim6})\times(\mathrm{SM}+\mathrm{dim6})} + \sigma_{\mathrm{SM}\times\mathrm{dim6}^2} & \text{(c)} \\ \sigma_{\left(\mathrm{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)\times\left(\mathrm{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)} & \text{(d)} \end{cases}$$

(a): “linearised dim 6” (first order of expansion in $1/\Lambda^2$ at cross section level)

(b): “quadratic dim 6” (first order of expansion in $1/\Lambda^2$ at amplitude level, then squared)

(c): include all terms $\mathcal{O}(1/\Lambda^4)$ coming from dim6^2 and double operator insertions

(d): would correspond to HEFT except for treatment of α_s

Results: total HH cross section

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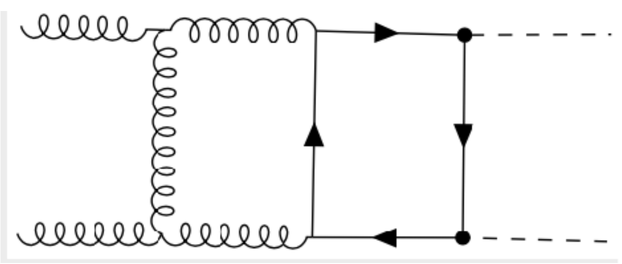
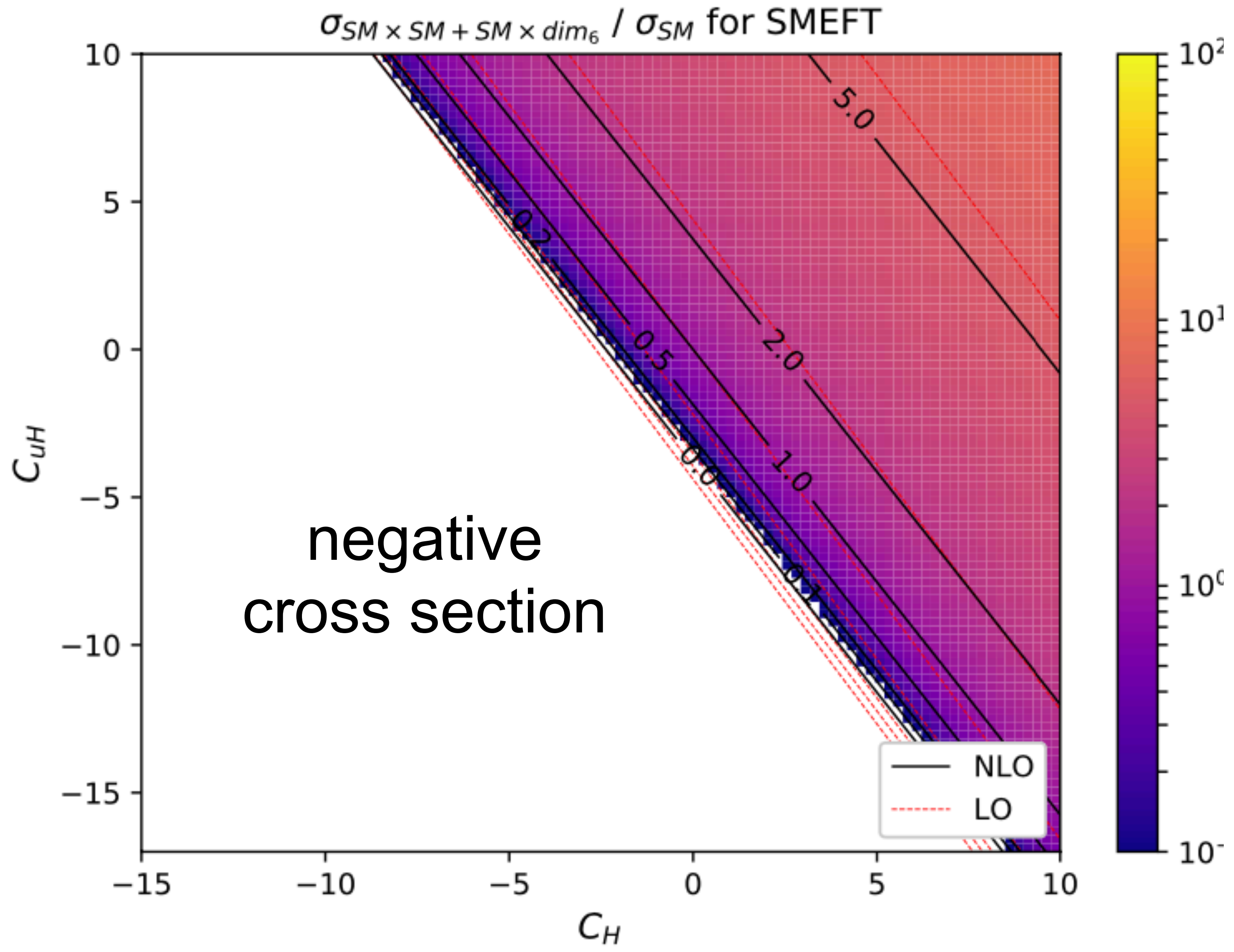
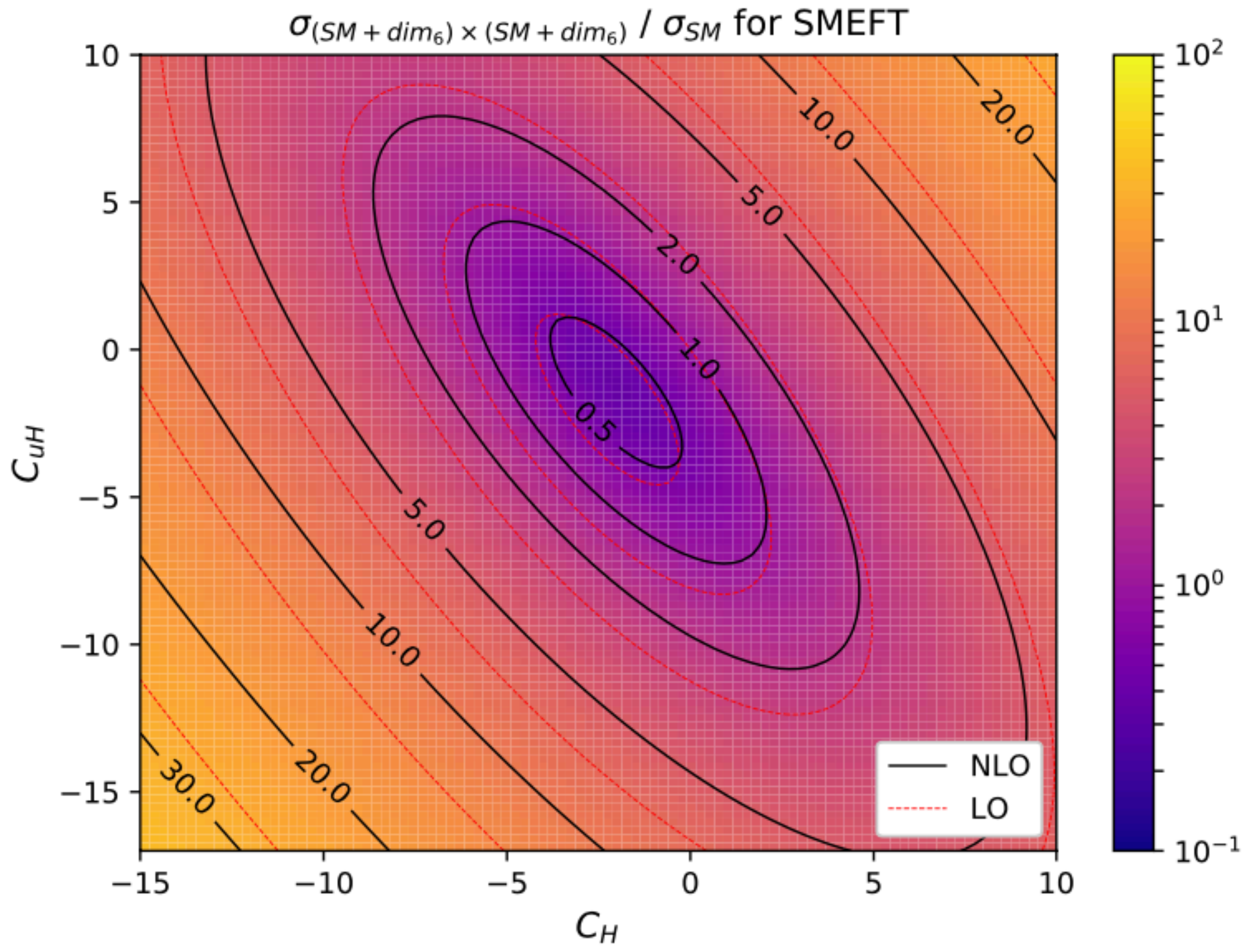
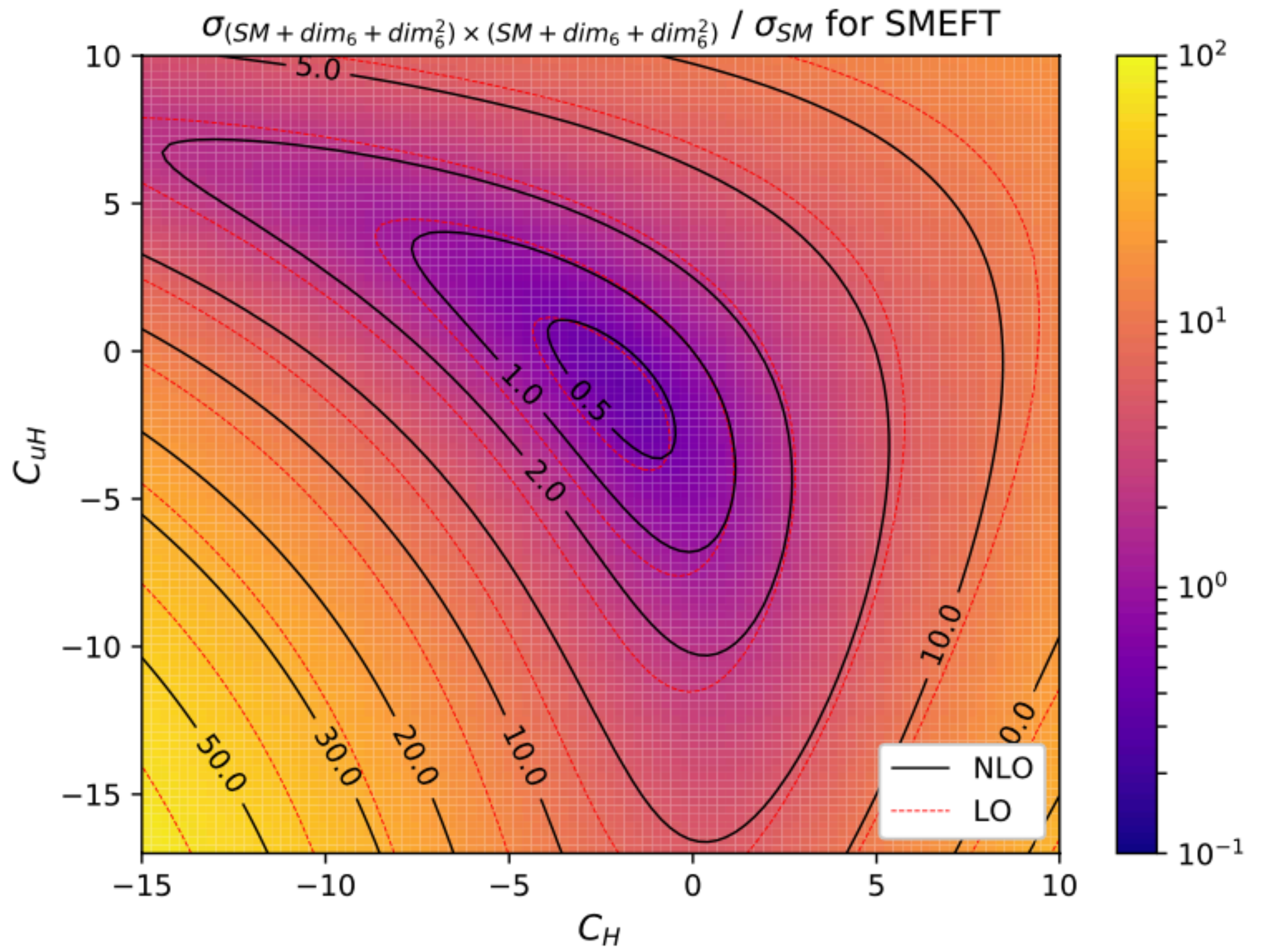
note: full NLO QCD corrections   building on Borowka, Greiner, GH, Jones, Kerner, et al. '16









linear
option (a)

quadratic
option (b)

all squared
option (d)

flat directions very different for different truncation options

figures: Jannis Lang

Results at benchmark points

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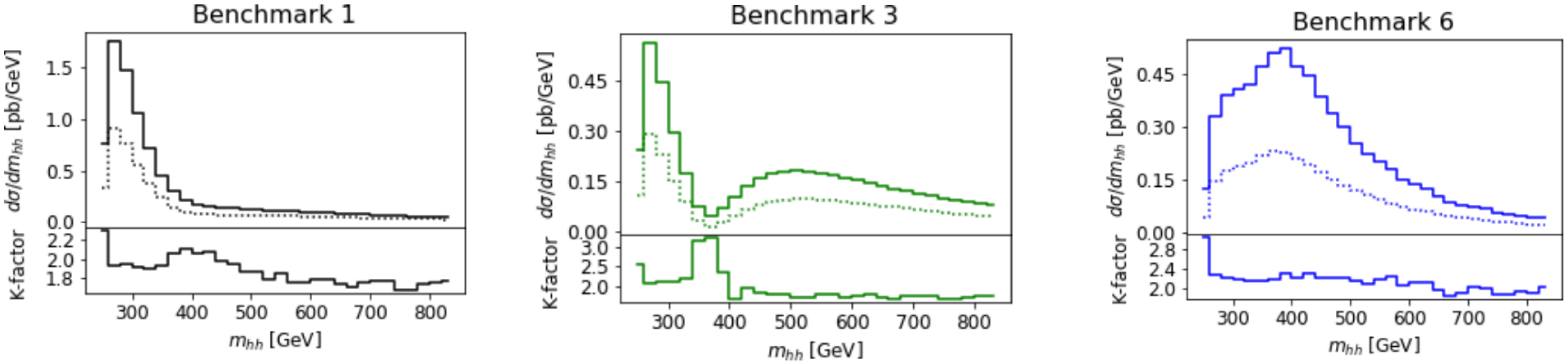
consider benchmark points characteristic for a certain mHH **shape**



Capozi, GH, 1908.08923

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	5.105	1.1	0	0	0
3*	2.21	1.05	$-\frac{1}{3}$	0.5	0.25*
6*	-0.684	0.9	$-\frac{1}{6}$	0.5	0.25

- benchmark **1**: enhanced low mHH
- benchmark **3**: dip
- benchmark **6**: SM-like except for shoulder left of peak

new benchmarks fulfilling current constraints: Ludovic Scyboz

modified: to fulfil SMEFT relation $c_{ggh} = 2c_{gghh}$

Results: total HH cross sections

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quadratic dim-6   linearised dim-6

benchmark	σ_{NLO}[fb] option (b)	K-factor option (b)	ratio to SM option (b)	σ_{NLO}[fb] option (a)	σ_{NLO}[fb] HEFT
SM	$27.94^{+13.7\%}_{-12.8\%}$	1.67	1	-	-
$\Lambda = 1\,\mathrm{TeV}$					
1	$74.29^{+19.8\%}_{-15.6\%}$	2.13	2.66	-61.17	94.32
3	$69.20^{+11.7\%}_{-10.3\%}$	1.82	2.47	29.64	72.43
6	$72.51^{+20.6\%}_{-16.4\%}$	1.90	2.60	52.89	91.40
$\Lambda = 2\,\mathrm{TeV}$					
1	$14.03^{+12.0\%}_{-11.9\%}$	1.56	0.502	5.58	-
3	$30.81^{+16.0\%}_{-14.4\%}$	1.71	1.10	28.35	-
6	$35.39^{+17.5\%}_{-15.2\%}$	1.76	1.27	34.18	-

Naive translation at Lagrangian level:

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}	Λ
SM	1	1	0	0	0	0	0	0	0	1 TeV
1*	5.105	1.1	0	0	0	4.95	-6.81	3.28	0	1 TeV
3*	2.21	1.05	$-\frac{1}{3}$	0.5	0.25*	13.5	2.64	12.6	0.0387	1 TeV
6*	-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387	1 TeV

HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2} C_H + 3\frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}}$
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c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s} C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s} C_{HG}$

$E^2 \frac{|C_i|}{\Lambda^2} \ll 1$ not fulfilled for $\Lambda \simeq 1\,\mathrm{TeV}$

and $E \simeq m_{hh}$ up to ~1 TeV

Higgs boson pair invariant mass spectrum

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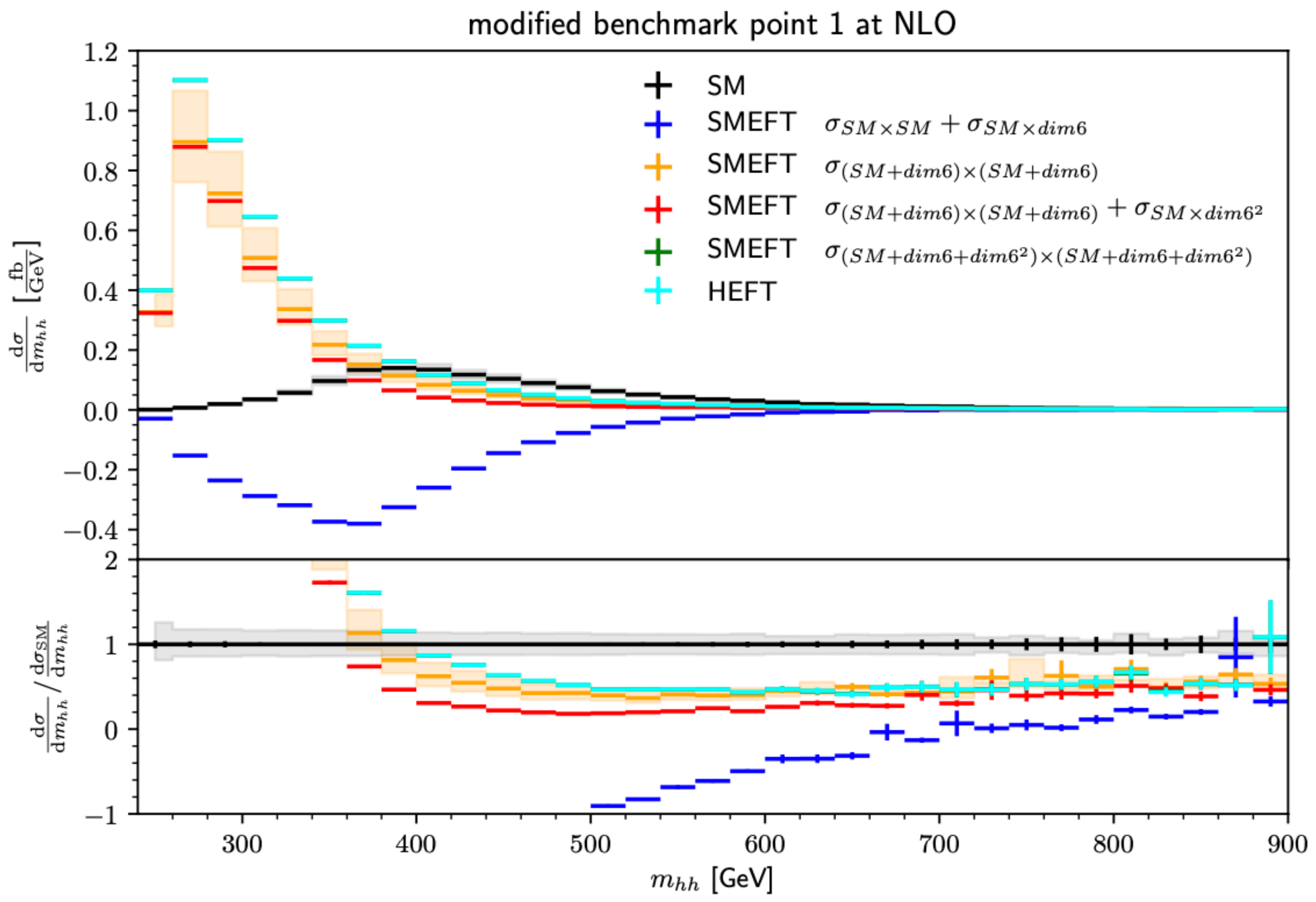
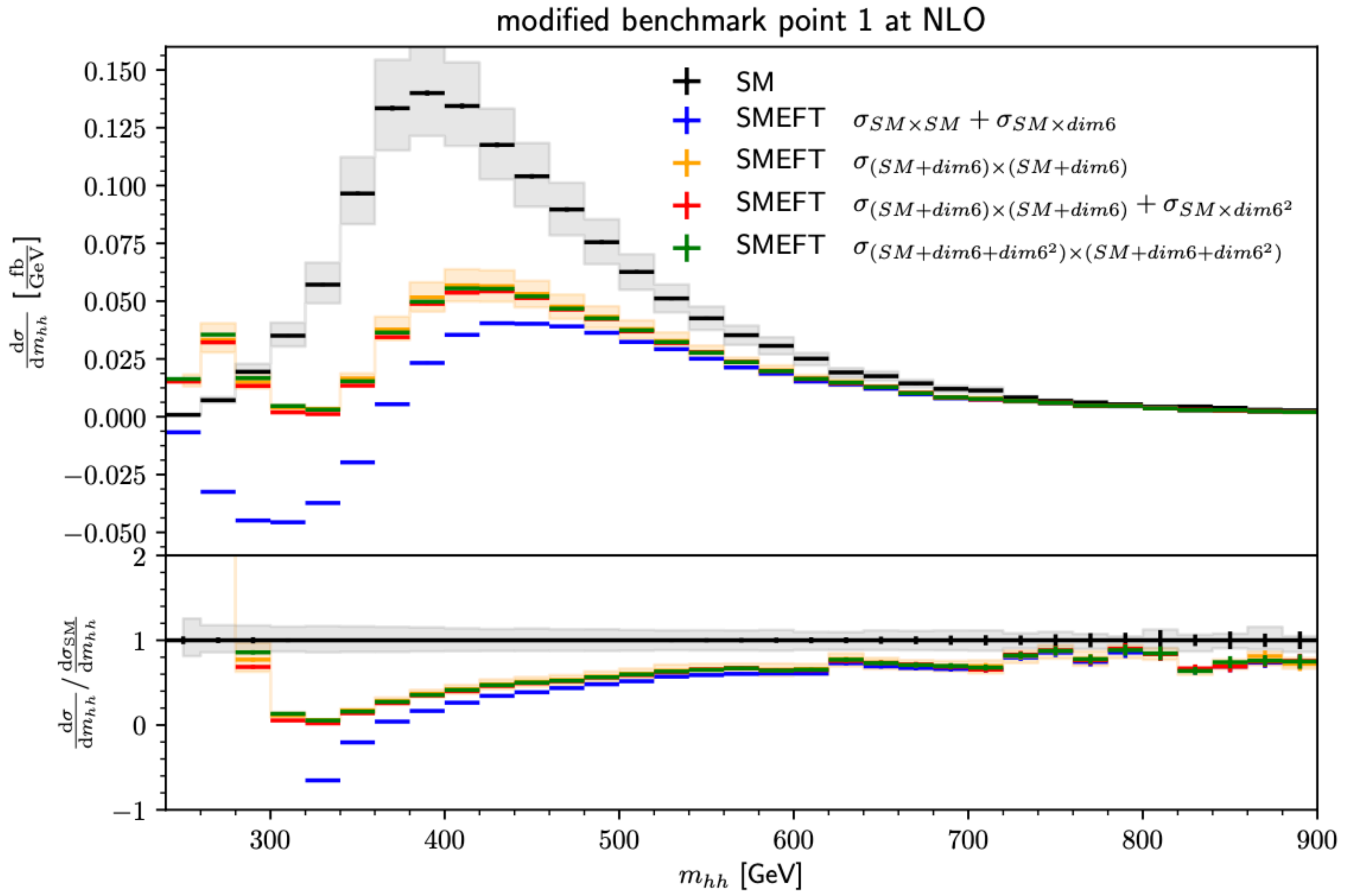
benchmark point 1

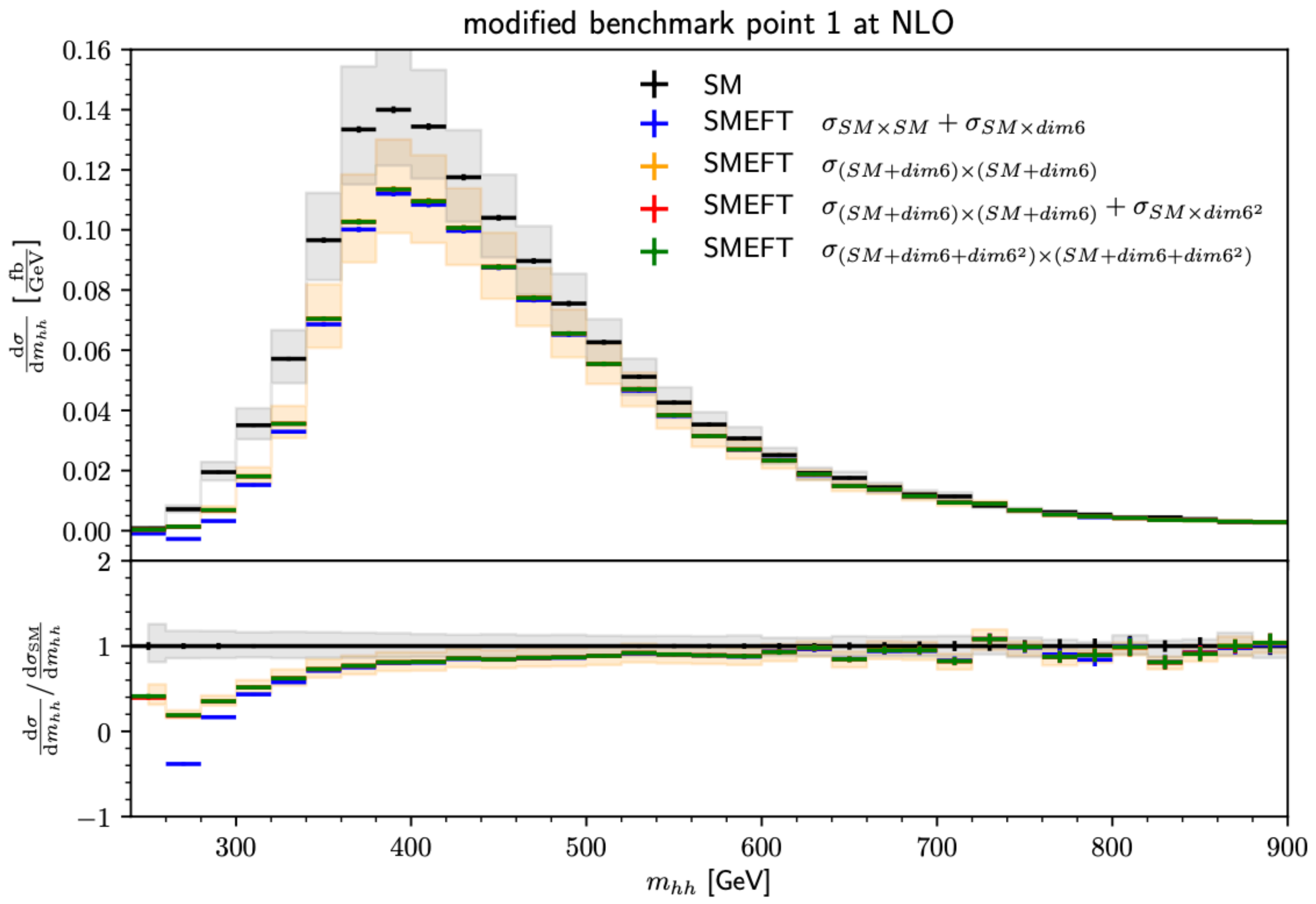
figures: Jannis Lang



$\Lambda = 1\,\mathrm{TeV}$



$\Lambda = 2\,\mathrm{TeV}$



$\Lambda = 4\,\mathrm{TeV}$

linear dim6: negative cross sections

shape changes as Λ is increased (obviously, approaching SM shape)

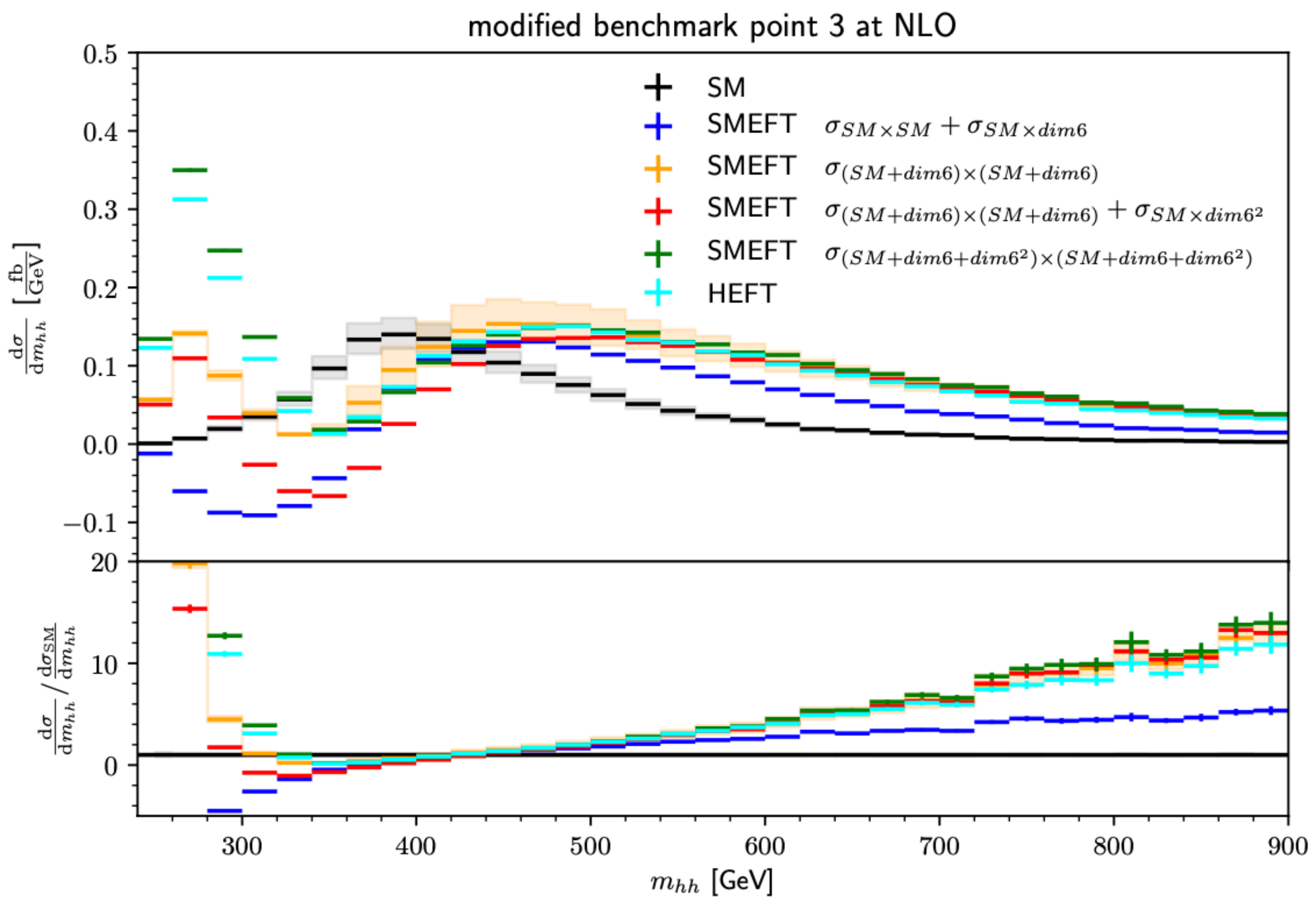
→ for low values of Λ: parameter point valid in HEFT can be invalid in SMEFT

Higgs boson pair invariant mass spectrum

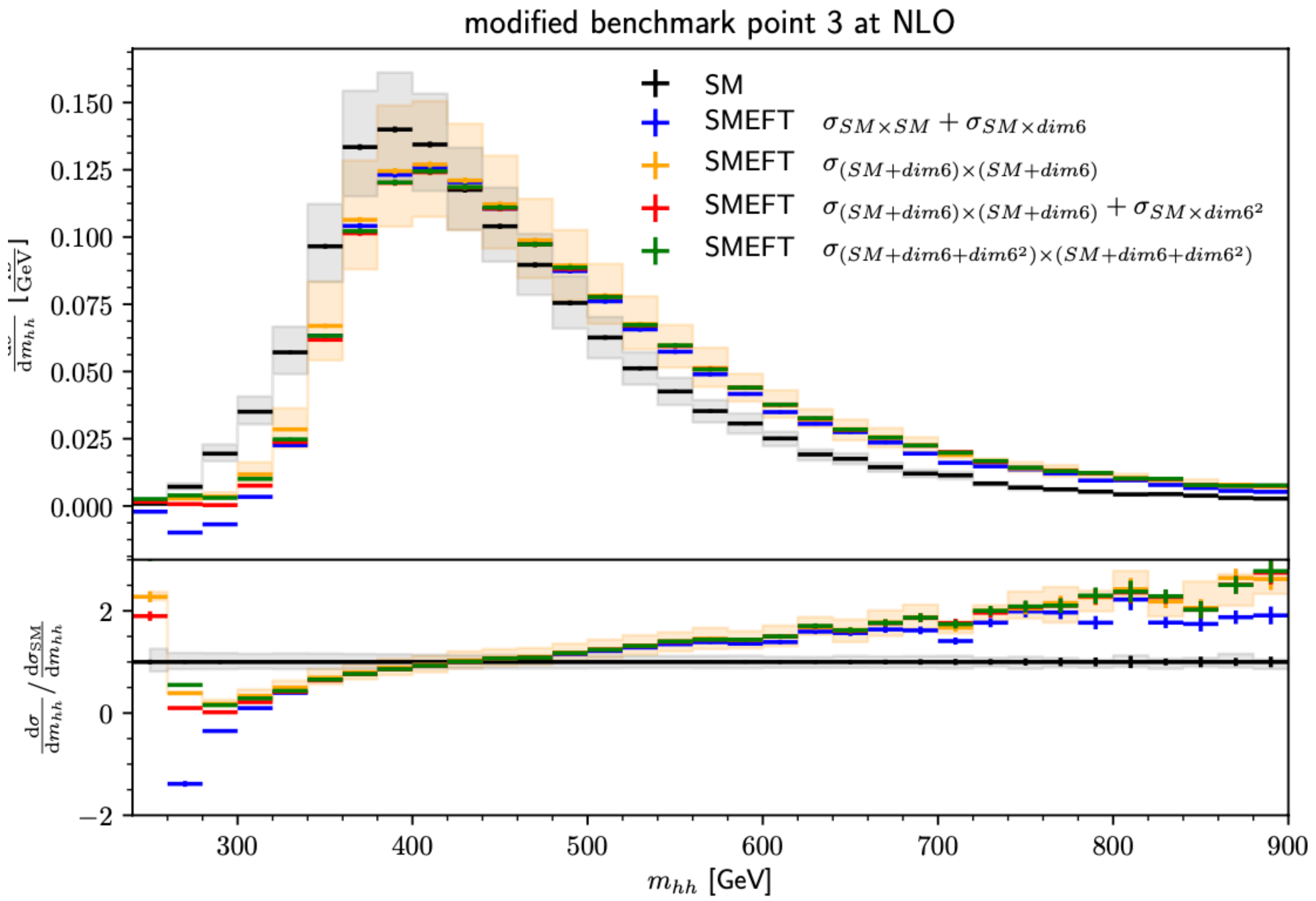
Karlsruhe Institute of Technology

figures: Jannis Lang

benchmark point 3



$\Lambda = 1\,\text{TeV}$



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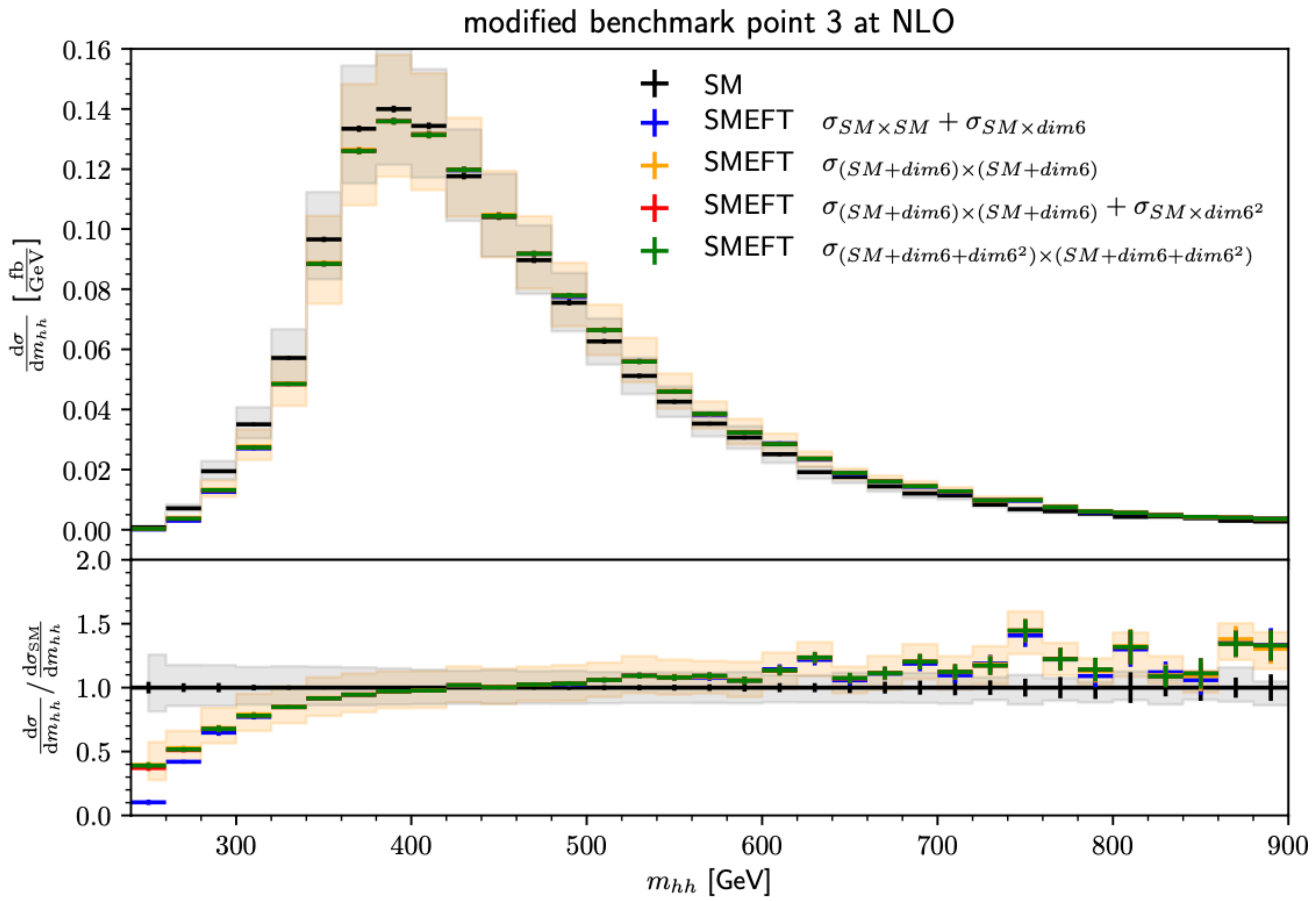


$\Lambda = 4\,\text{TeV}$

double operator insertions have large effect

distinguishable from SM within NLO uncertainties

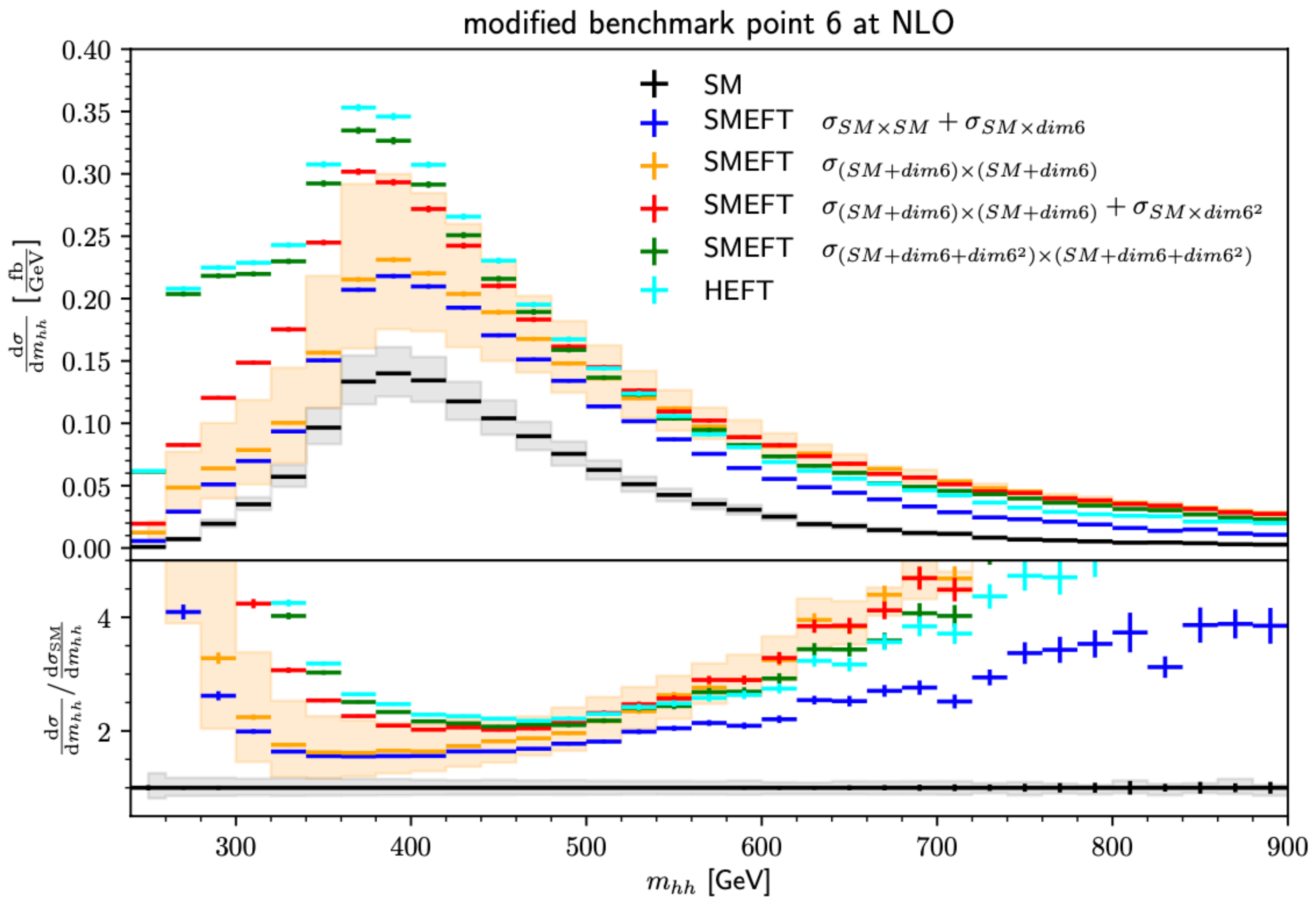
can be distinguished from SM in low mHH region

Higgs boson pair invariant mass spectrum

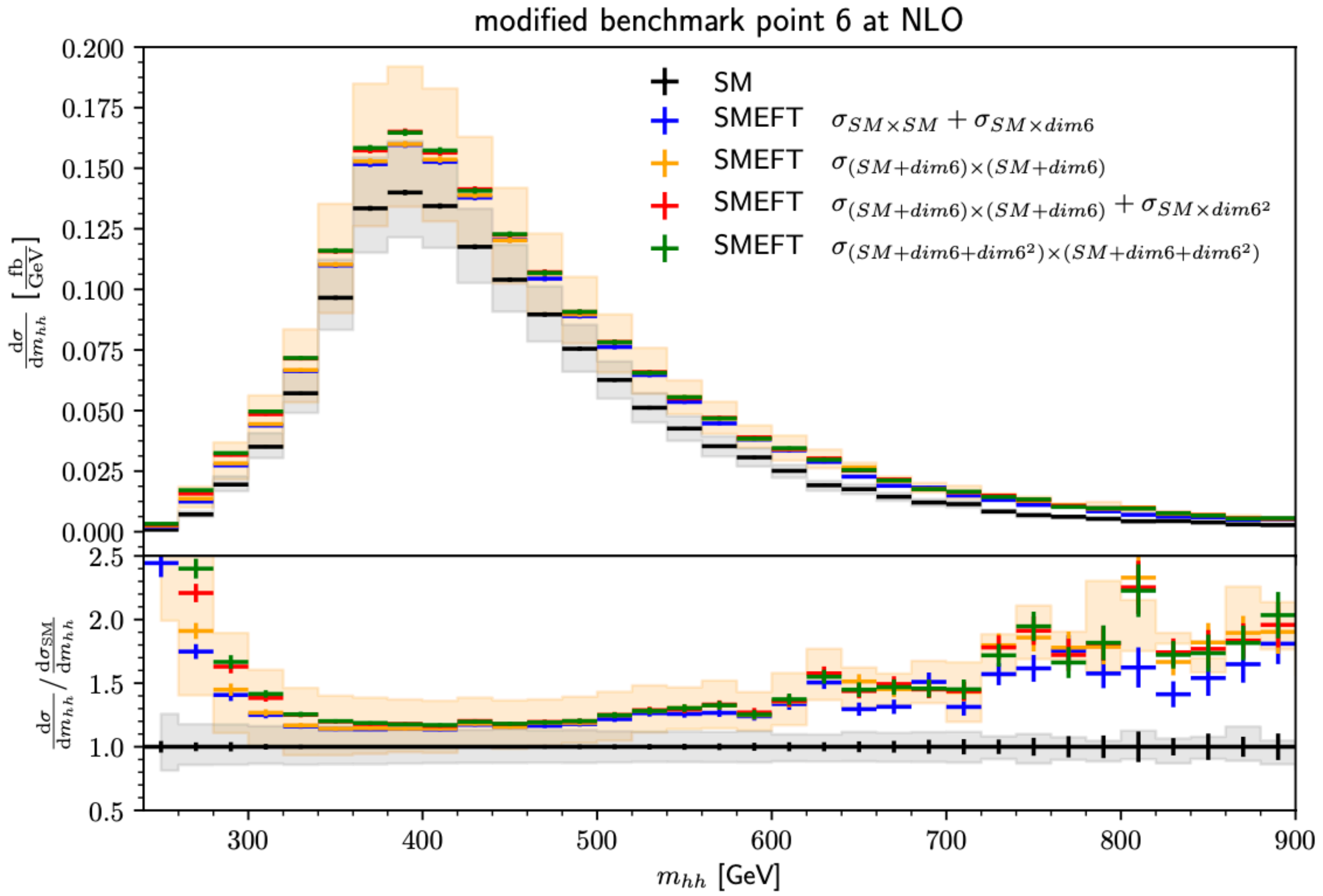
Karlsruhe Institute of Technology

figures: Jannis Lang

benchmark point 6



$$\Lambda = 1\,\mathrm{TeV}$$



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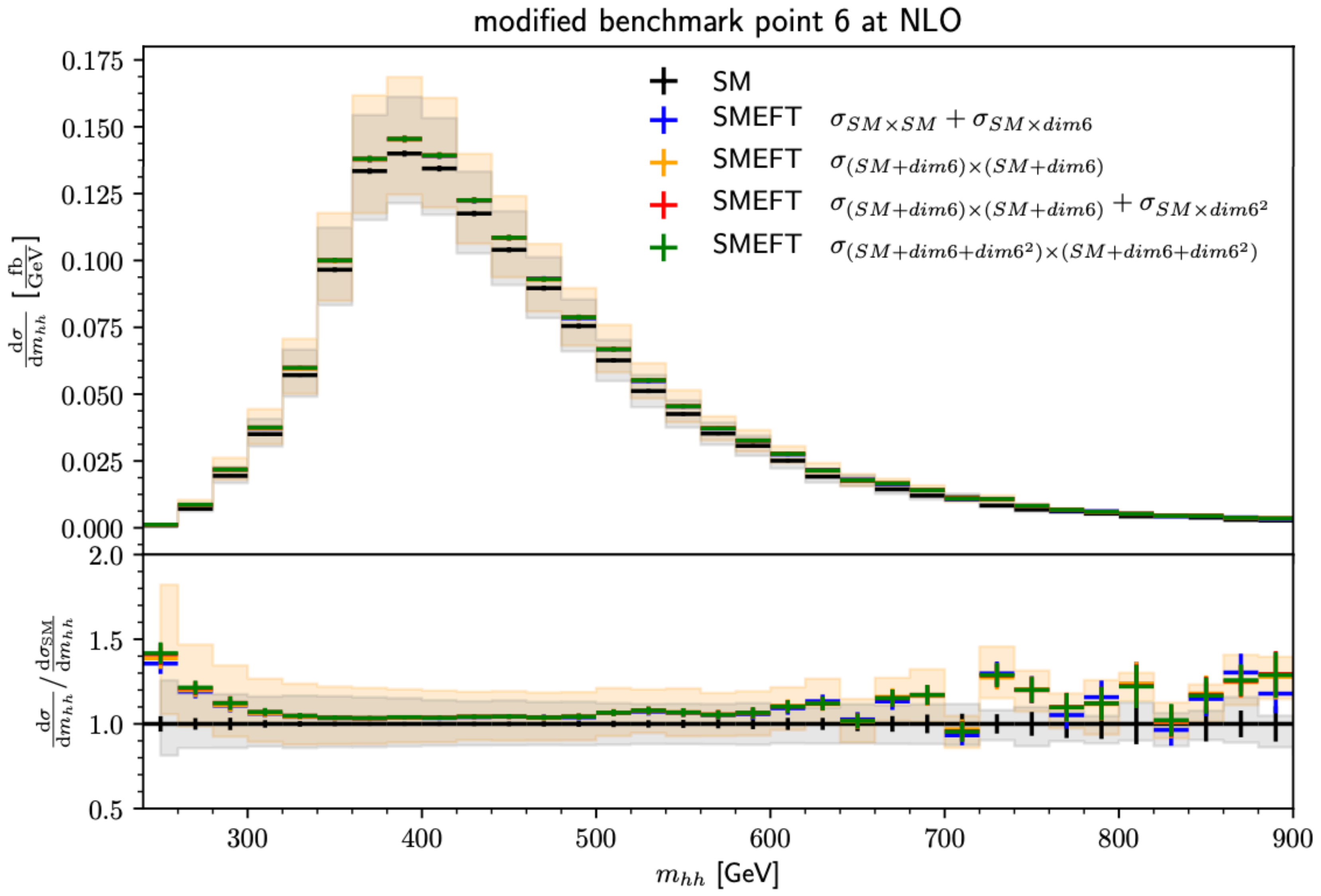

$$\Lambda = 4\,\mathrm{TeV}$$

difference between green and cyan only running of α_s

shoulder left gone

can hardly be distinguished from SM within NLO scale uncertainties

Summary & Outlook

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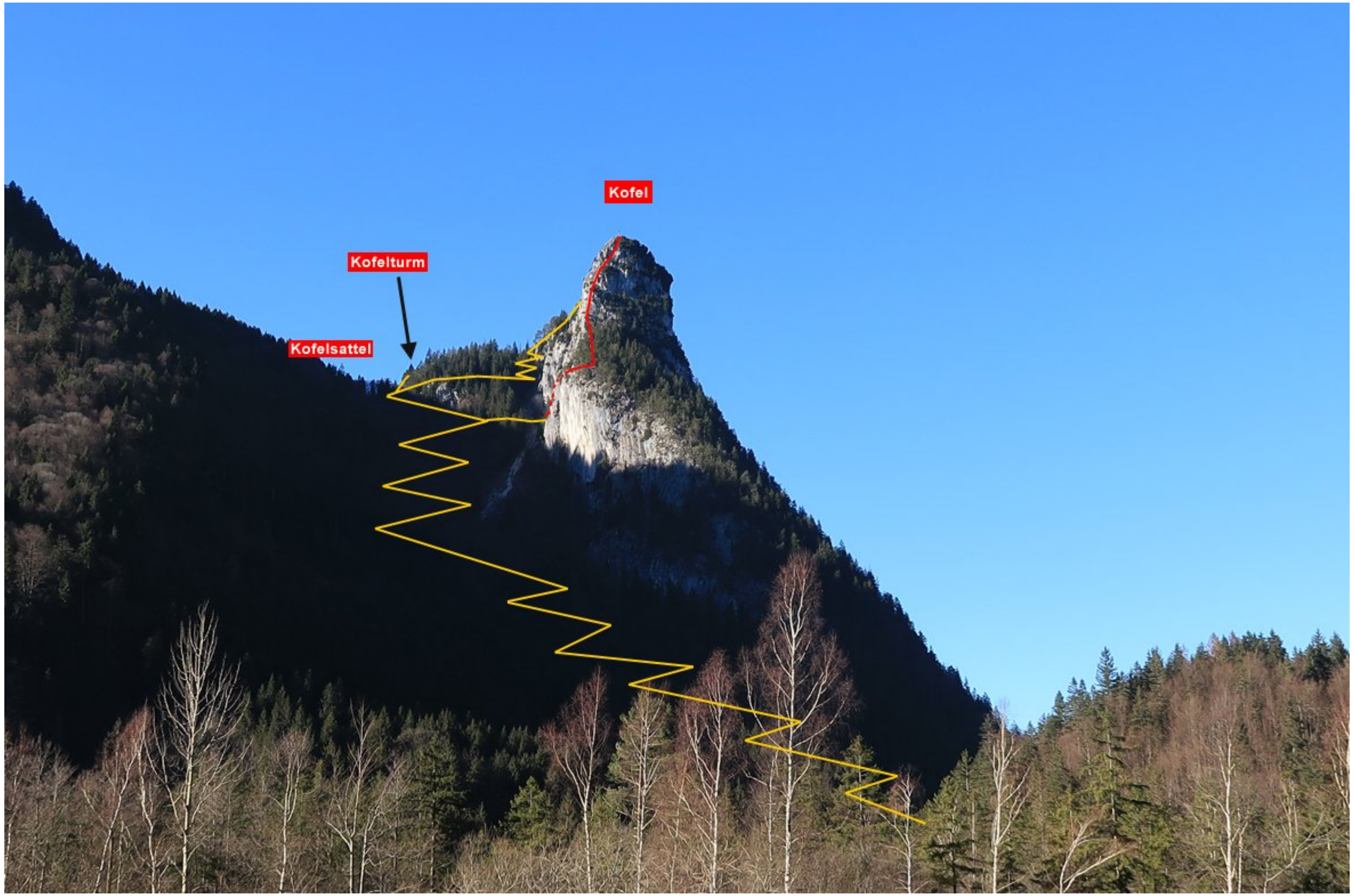
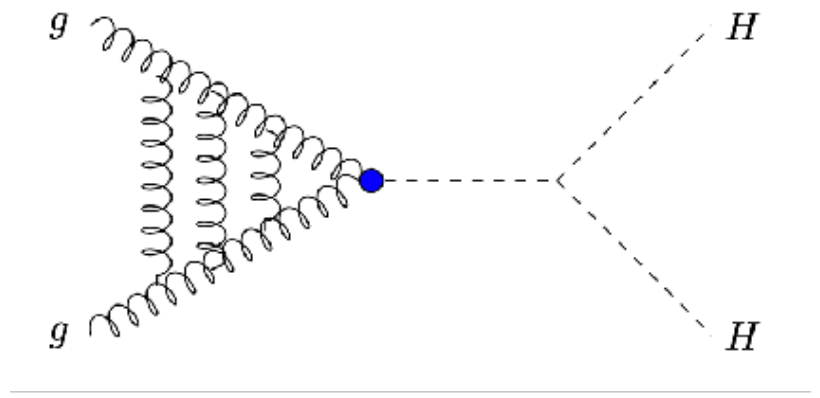
- full NLO corrections for $gg \to HH$ available within SMEFT (and HEFT)
- comparison between HEFT and SMEFT parametrisations
- studied truncation effects: including dim-6 operators squared, double operator insertions
- naive translation from HEFT to SMEFT can lead out of SMEFT validity range
- delicate cancellations -> small changes in treatment of anomalous couplings can have large effects
- small distortions from SM values described well by SMEFT often not distinguishable from SM within scale uncertaities

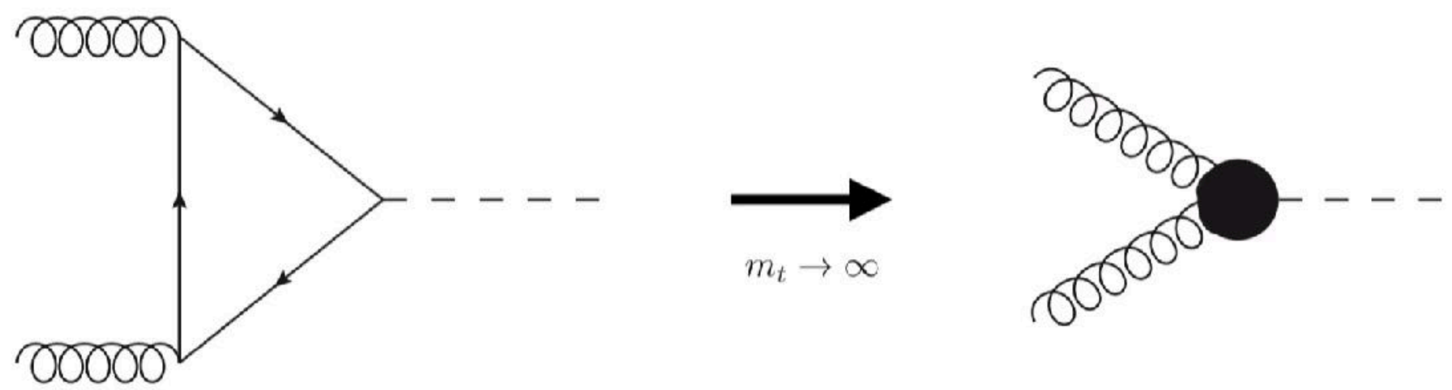

Kofel
Kofelturm
Kofelsattel


Kofel

Higher order corrections: SM

N3LO: Chen, Li, Shao, Wang '19 (HTL with top mass effects)

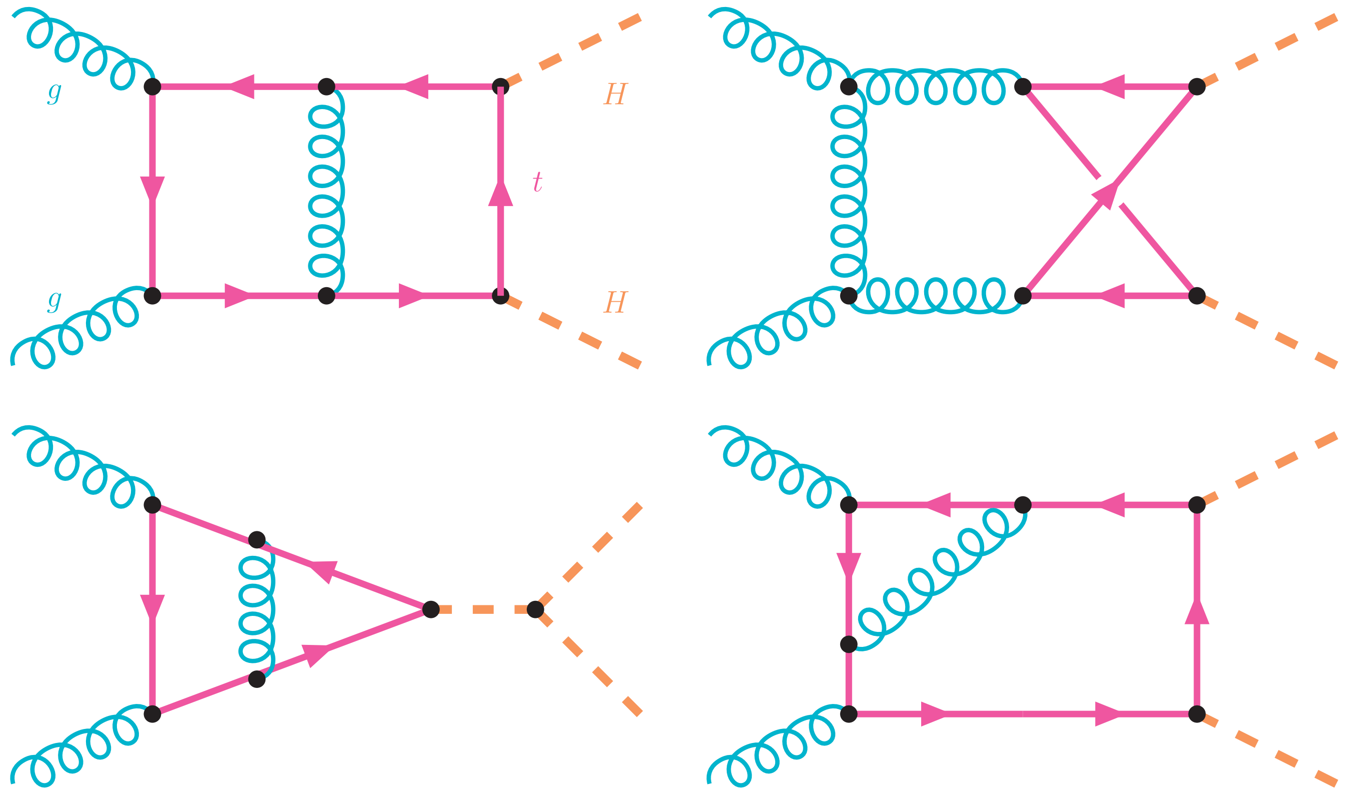




NNLO: De Florian, Mazzitelli '13
Grigo, Melnikov, Steinhauser '14

$\mathrm{NNLO}_{\mathrm{FTapprox}}$ Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18

inclusion of top quark mass dependence except in virtual $\mathcal{O}(\alpha_s^3)$



NLO full m_t

Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16

Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18

Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19

top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '18, '20

Higher order corrections: SM

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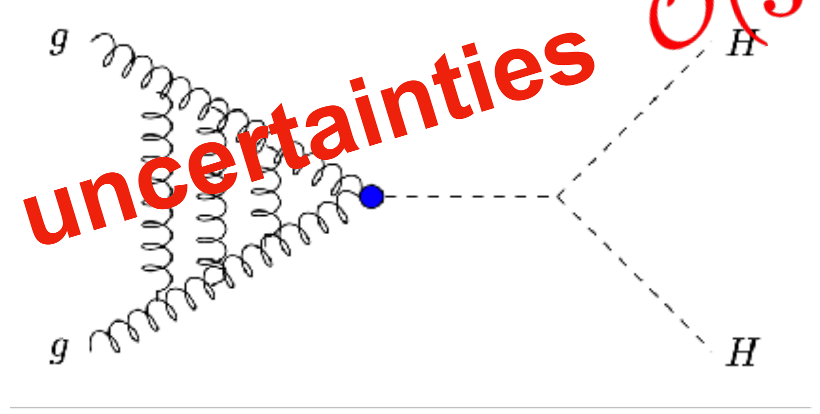
N3LO: Chen, Li, Shao, Wang ’19
(HTL with top mass effects)



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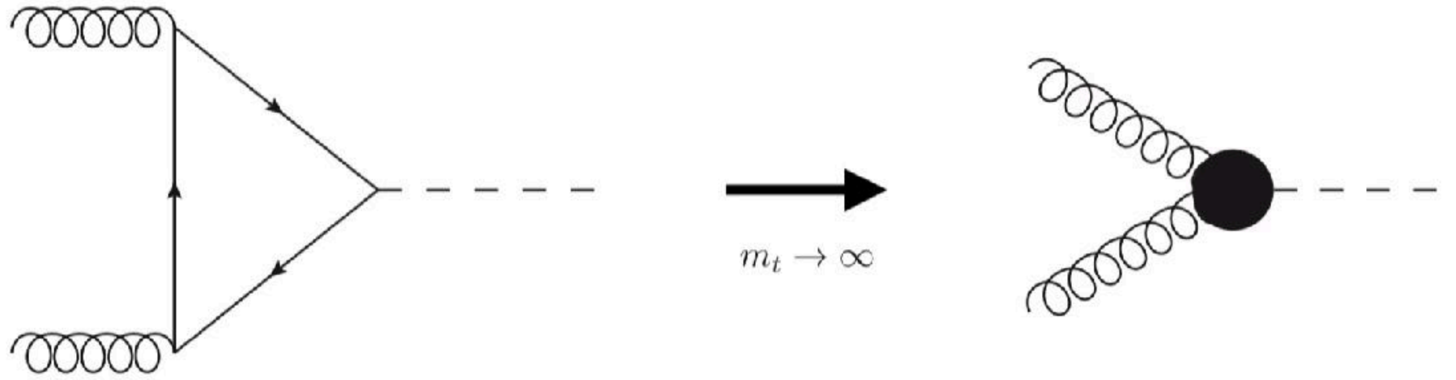
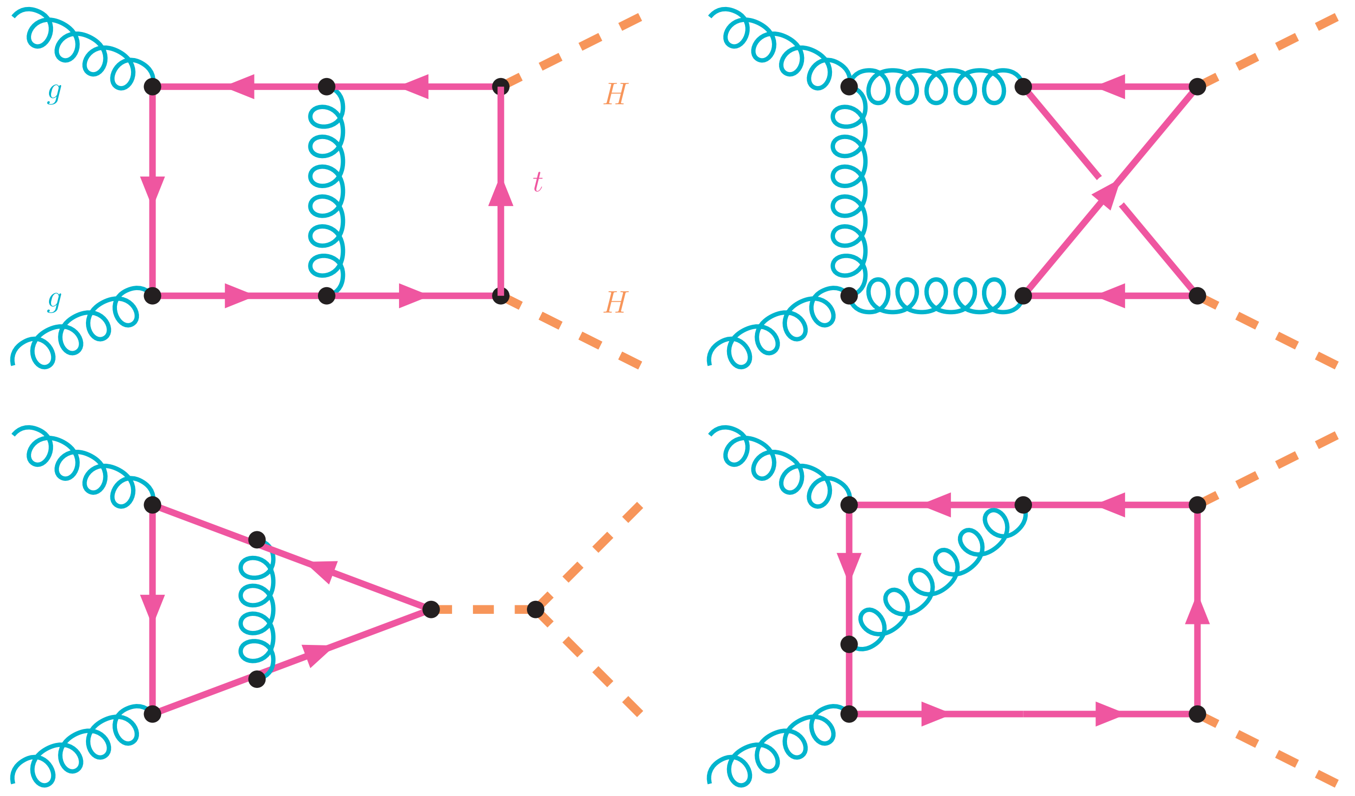


heavy top limit (HTL)

$\mathrm{NNLO_{FTapprox}}$ Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli ‘18

inclusion of top quark mass dependence except in virtual $\mathcal{O}(\alpha_s^3)$



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top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ‘20

Higher order corrections: SM

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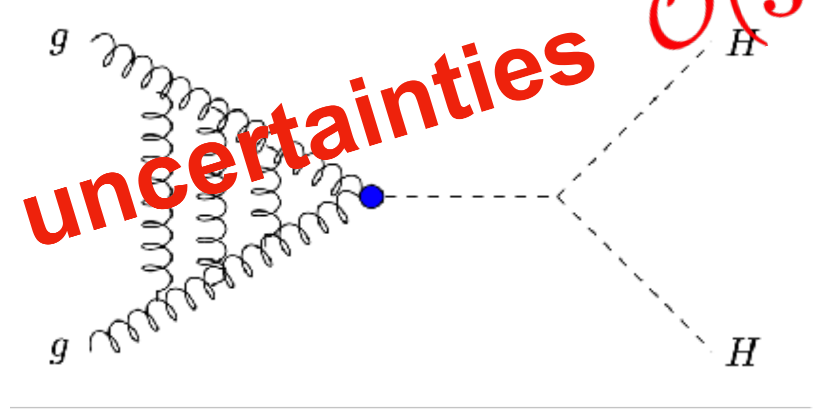
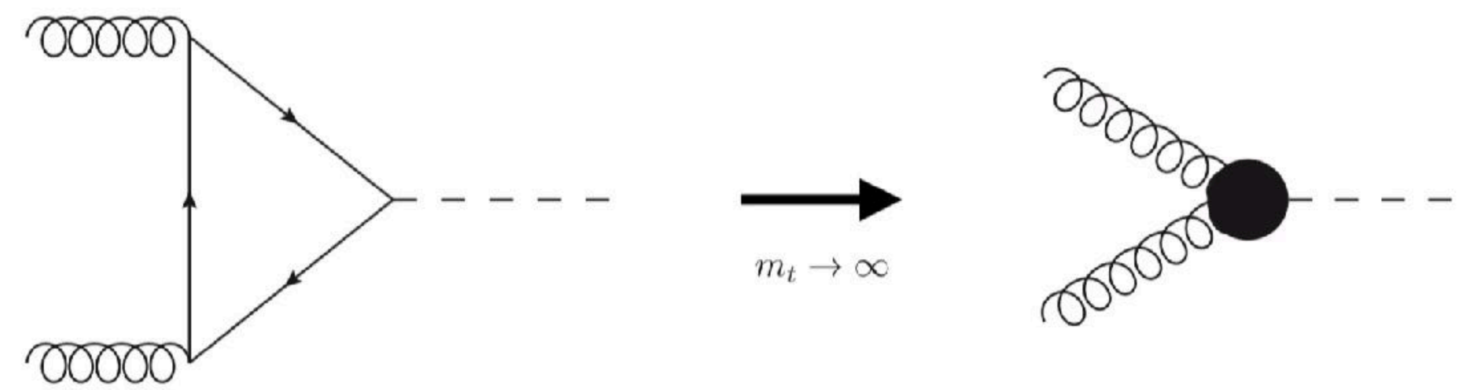


scale uncertainties $\mathcal{O}(3\%)$



$\mathrm{NNLO}_{\mathrm{FTapprox}}$ Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18

inclusion of top quark mass dependence except in virtual $\mathcal{O}(\alpha_s^3)$

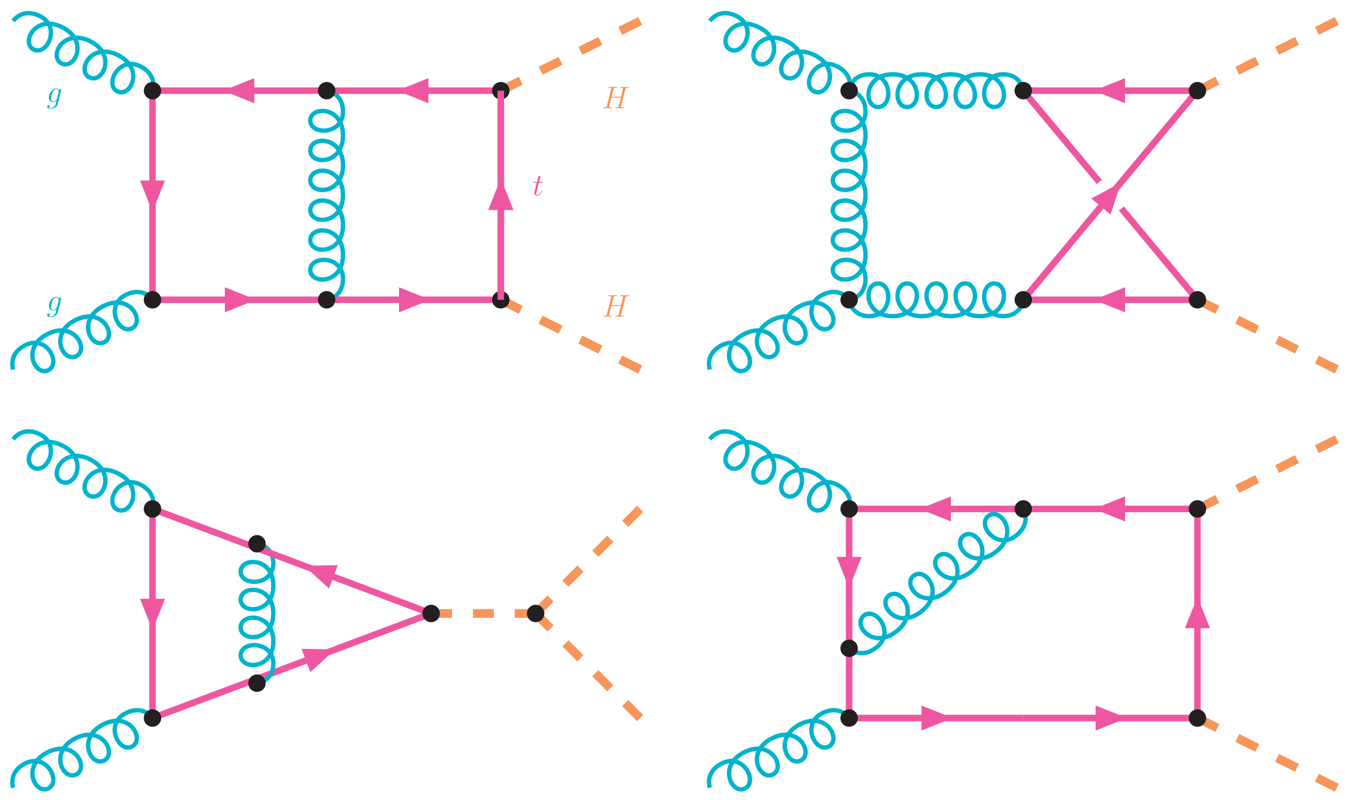
residual missing top mass effects estimated to $\mathcal{O}(5\%)$

NLO full m_t

Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16

Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18

Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19



top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

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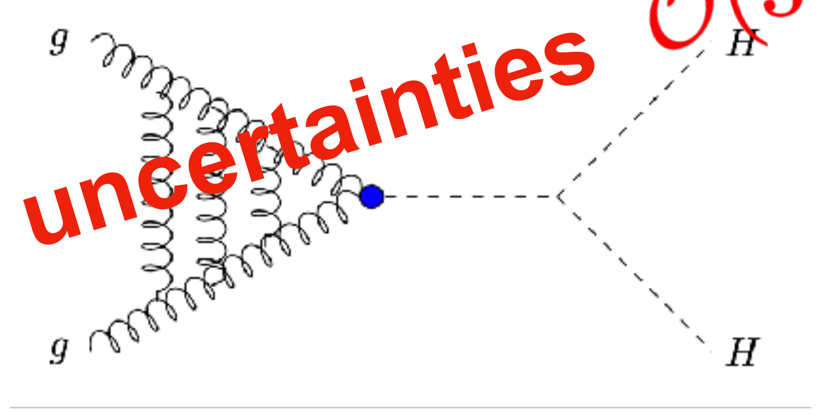
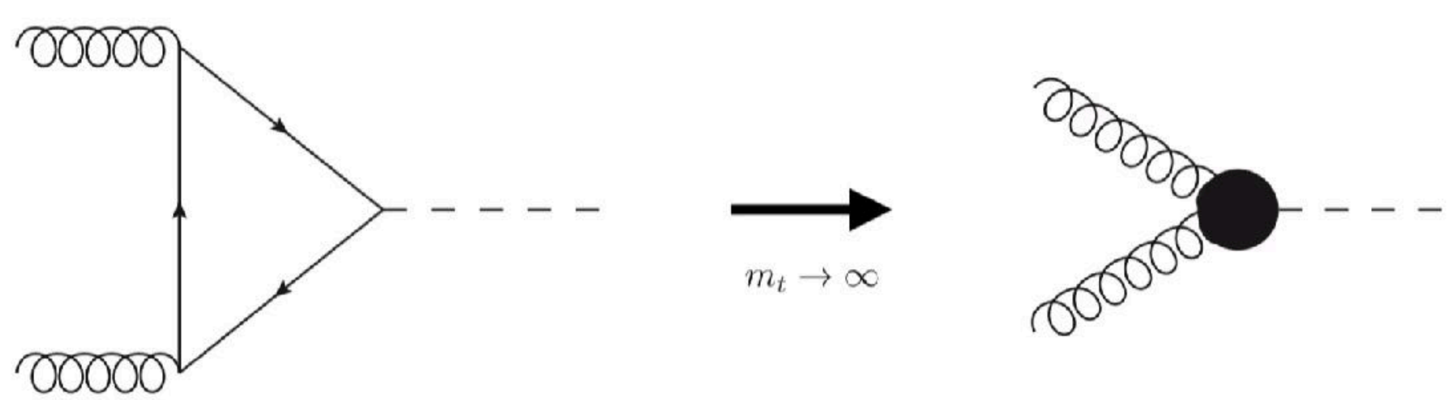


scale uncertainties $\mathcal{O}(3\%)$



heavy top limit (HTL)

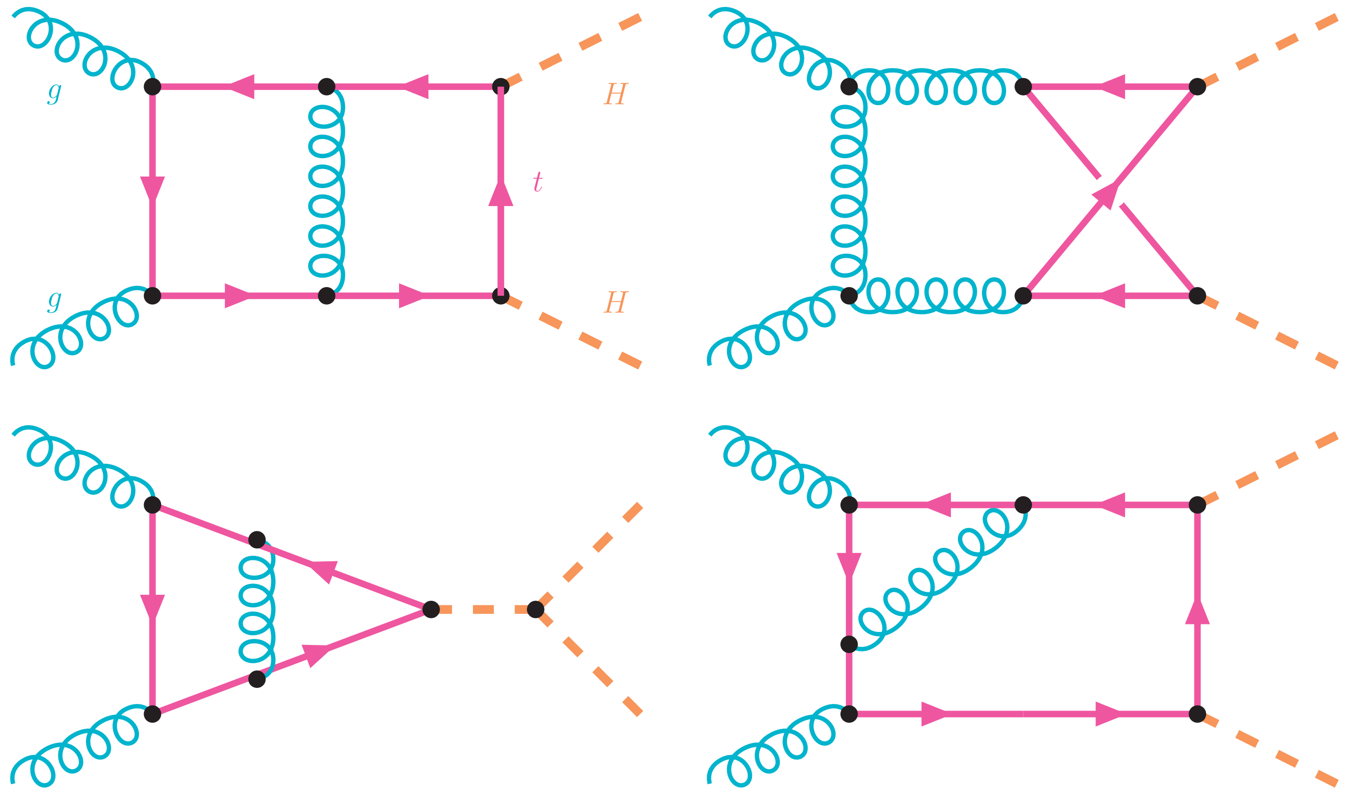
NNLO: De Florian, Mazzitelli '13
Grigo, Melnikov, Steinhauser '14

$\mathrm{NNLO}_{\mathrm{FTapprox}}$ Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18

inclusion of top quark mass dependence except in virtual $\mathcal{O}(\alpha_s^3)$

residual missing top mass effects estimated to $\mathcal{O}(5\%)$

NLO full m_t



Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16

Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18

Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19

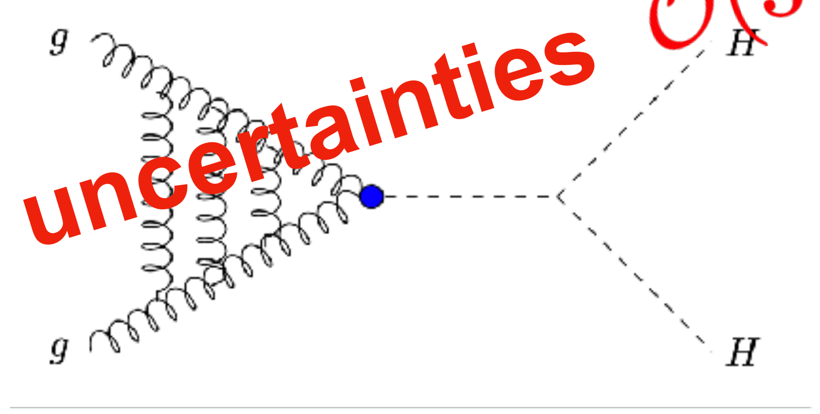
top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass

Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '18, '20

uncertainty due to top mass scheme $\mathcal{O}(20\%)$

Higher order corrections: SM

N3LO: Chen, Li, Shao, Wang '19 (HTL with top mass effects)



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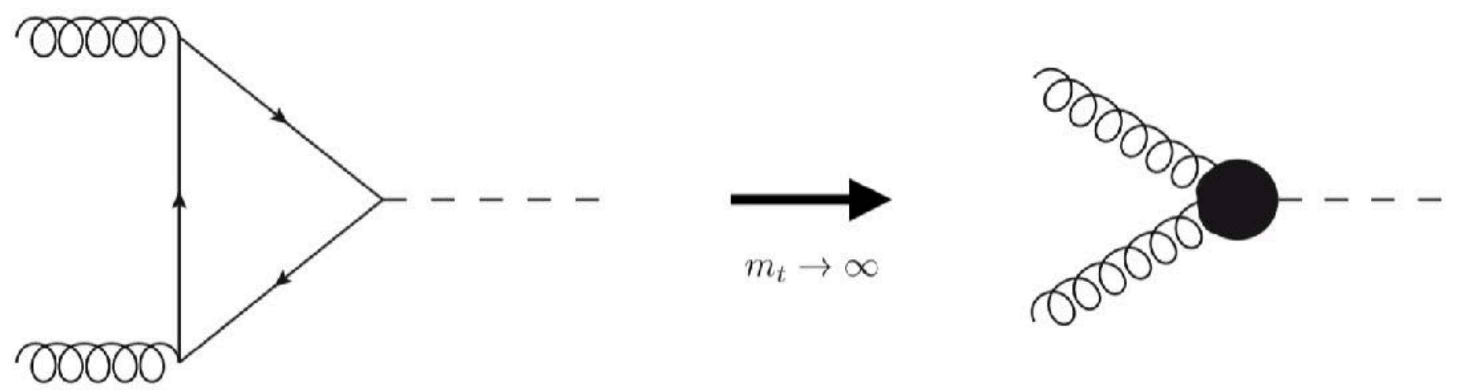

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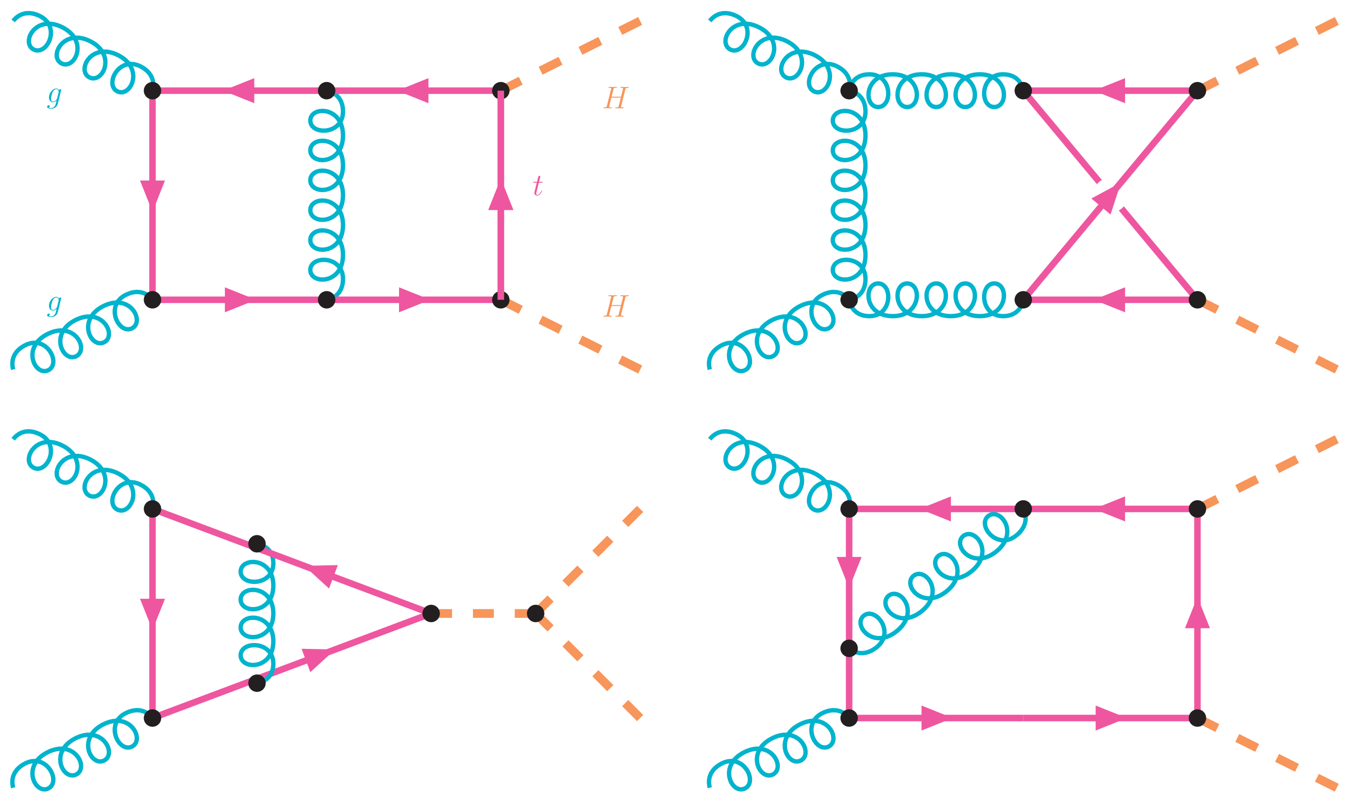
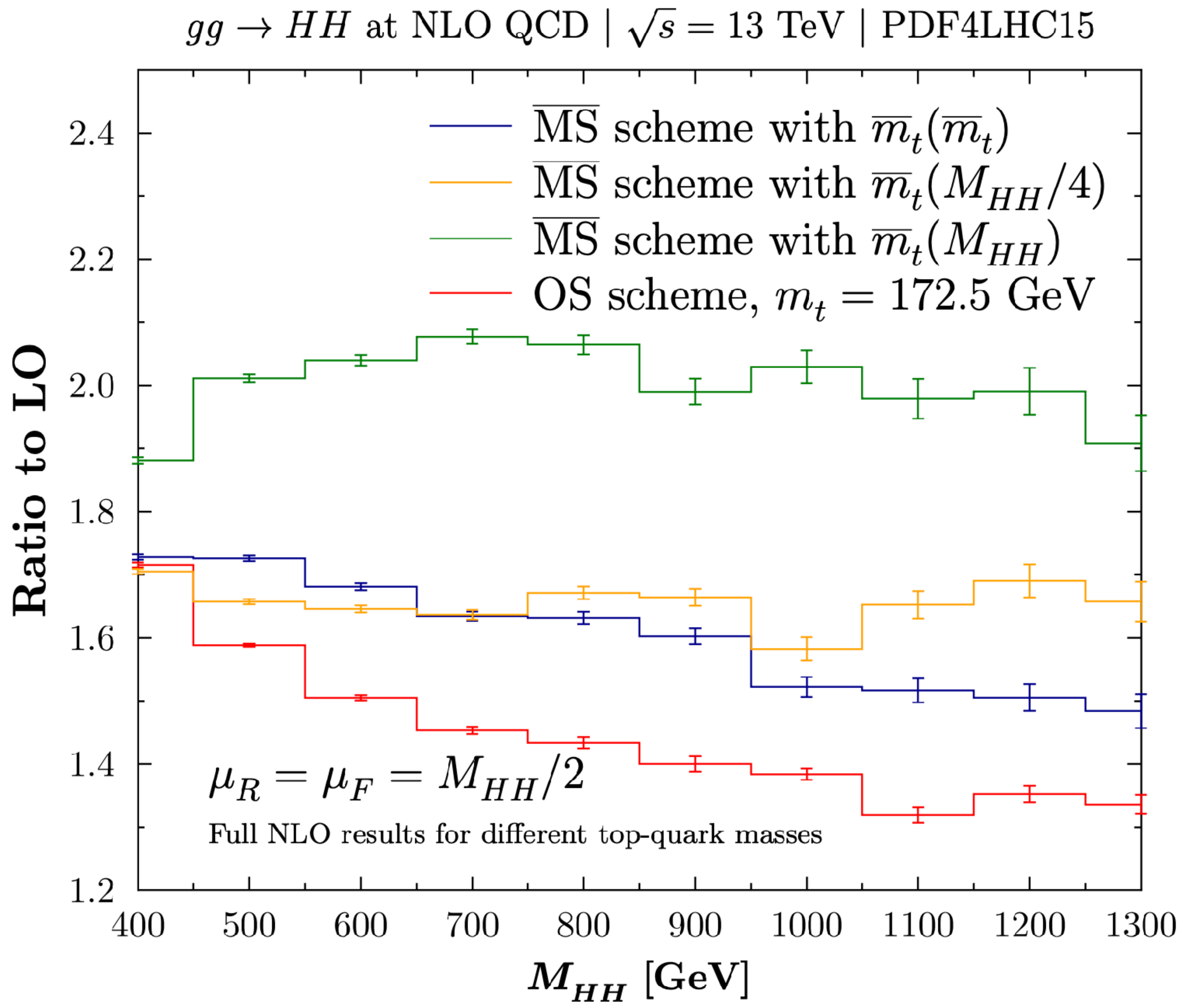


for top mass scheme uncertainties see also talk of Stephen Jones

Top quark mass renormalisation scheme uncertainties

$$\overline{m}_t(m_t) = \frac{m_t}{1 + \frac{4}{3}\frac{\alpha_s(m_t)}{\pi} + K_2\left(\frac{\alpha_s(m_t)}{\pi}\right)^2 + K_3\left(\frac{\alpha_s(m_t)}{\pi}\right)^3 + \ldots}$$

relation between pole mass and $\overline{\text{MS}}$ mass

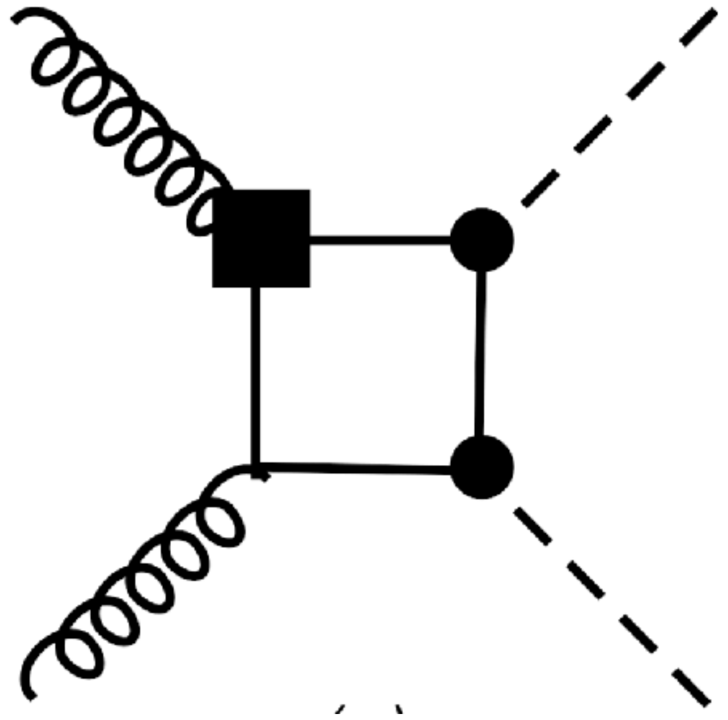


Baglio, Campanario, Glaus Mühlleitner, Ronca, Spira 2003.03227, 2008.11626

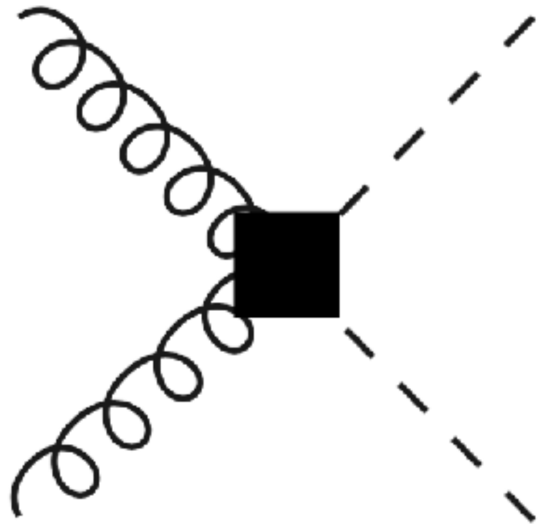
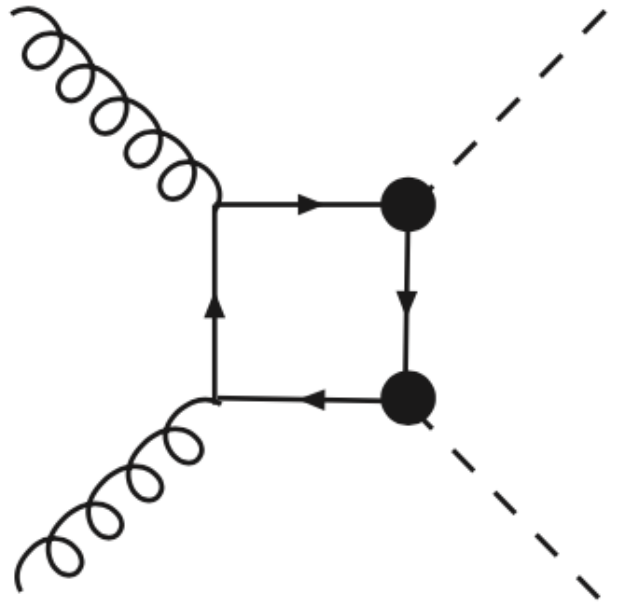
also present in other heavy quark loop induced processes

Chromagnetic operator

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



suppressed by loop factor $1/(16\pi^2)$

relative to  or 

Buchalla, GH, Müller-Salditt, Pandler
arXiv:2204.11808

in weakly coupled UV theories operators coupling to field strength tensors must come from a contracted loop

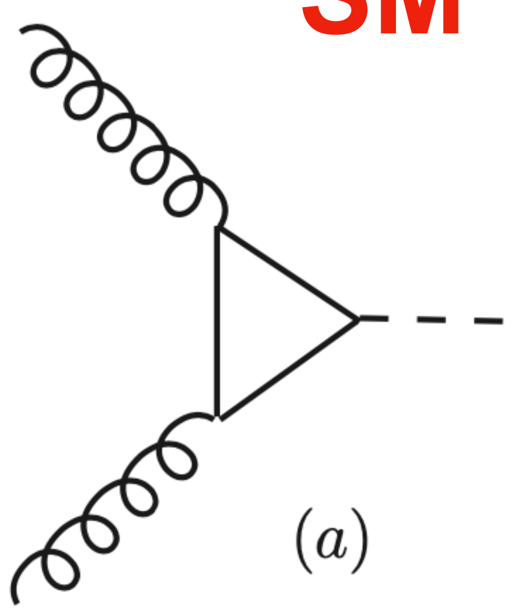
see also Buchalla et al 1806.05162;
Arzt, Einhorn, Wudka, hep-ph/9405214

Loop counting matters in SMEFT

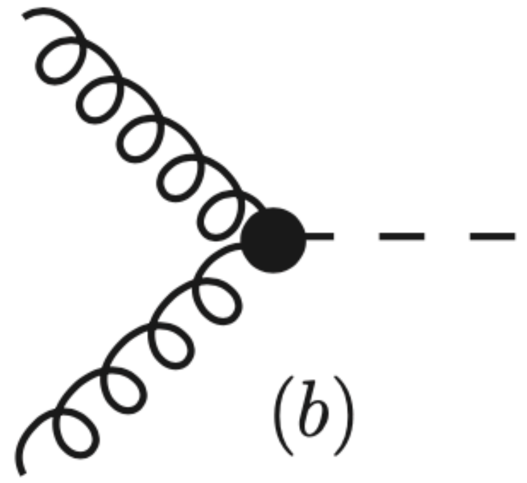
Karlsruhe Institute of Technology

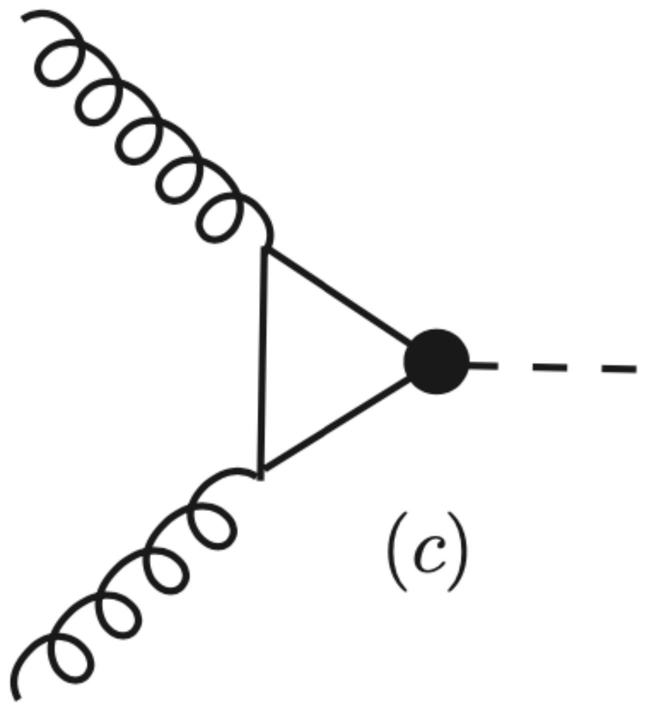
example single Higgs production   Buchalla, GH, Müller-Salditt, Pandler, arXiv:2204.11808

SM

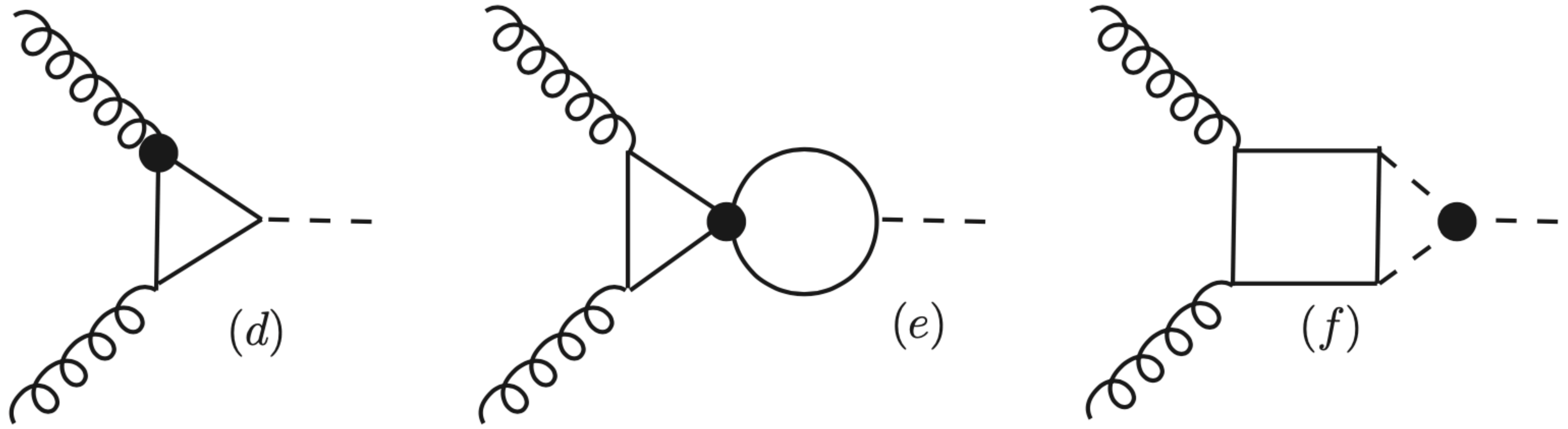


$$\frac{1}{16\pi^2}$$

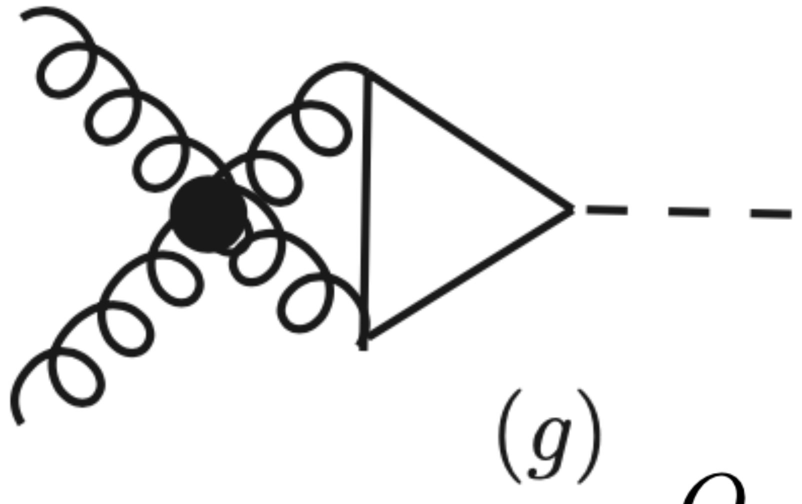




$$\frac{1}{\Lambda^2}\,\frac{1}{16\pi^2}$$



$$\frac{1}{\Lambda^2}\,\frac{1}{(16\pi^2)^2}$$



$$\frac{1}{\Lambda^2}\,\frac{1}{(16\pi^2)^3}$$

$$Q_{uG} = \bar{q}\sigma^{\mu\nu}T^A u\,\tilde{\phi}G^A_{\mu\nu}$$

$$Q_G = f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$$

if only canonical dimension is counted, (b) - (g) would all contribute at the same order (dim 6) !

Counting schemes

Karlsruhe Institute of Technology

HEFT (EWChL): “loop expansion”

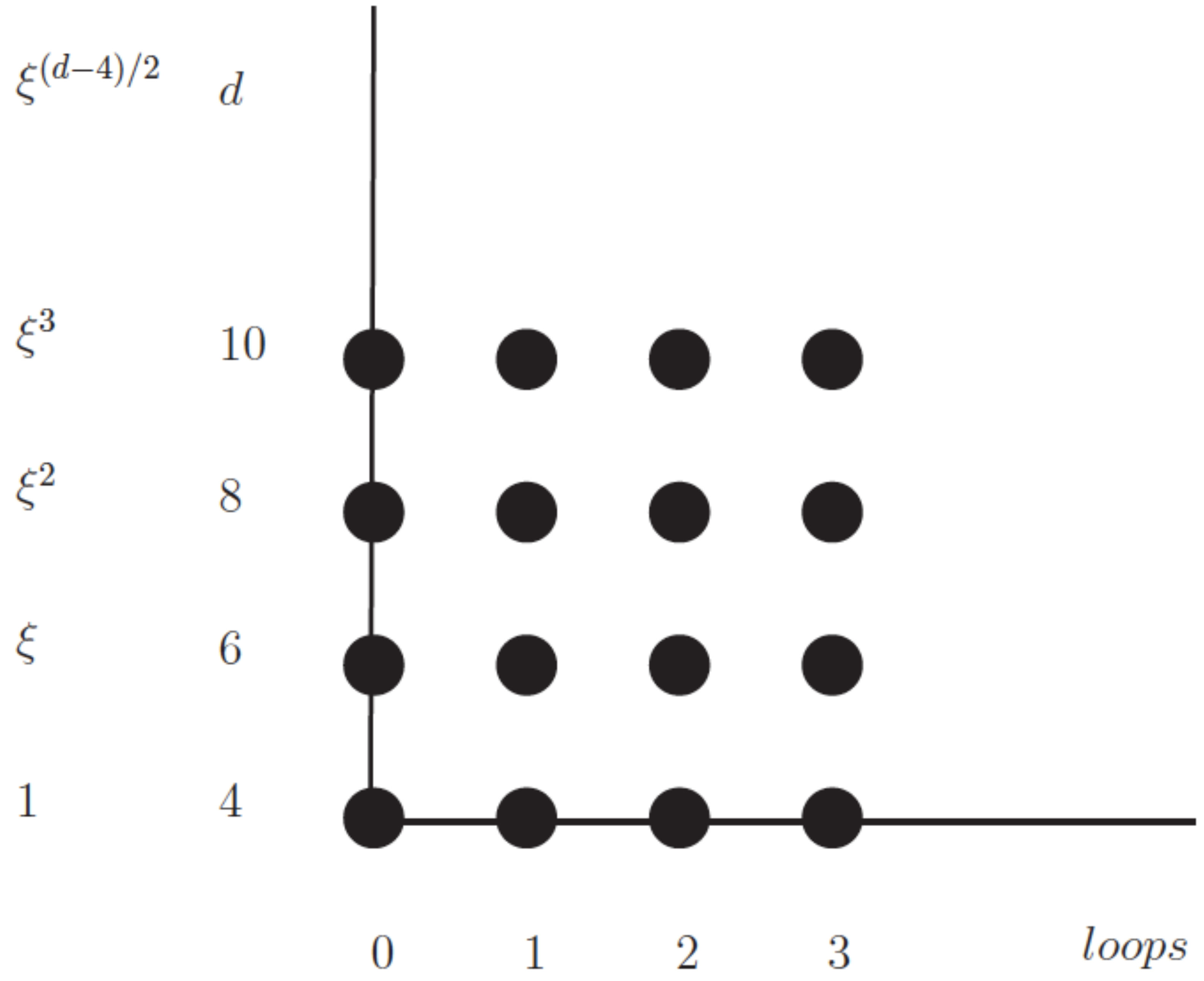
based on chiral dimension $d_\chi = 2L + 2$ $\quad L$: “Loop”

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

$\xi \sim E^2/\Lambda^2$



loop expansion

HEFT

figure: G.Buchalla

SMEFT and HEFT

Karlsruhe Institute of Technology

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 $\pi^a(x)$

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