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Anomalous couplings and higher order corrections in Higgs boson pair production

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in collaboration with

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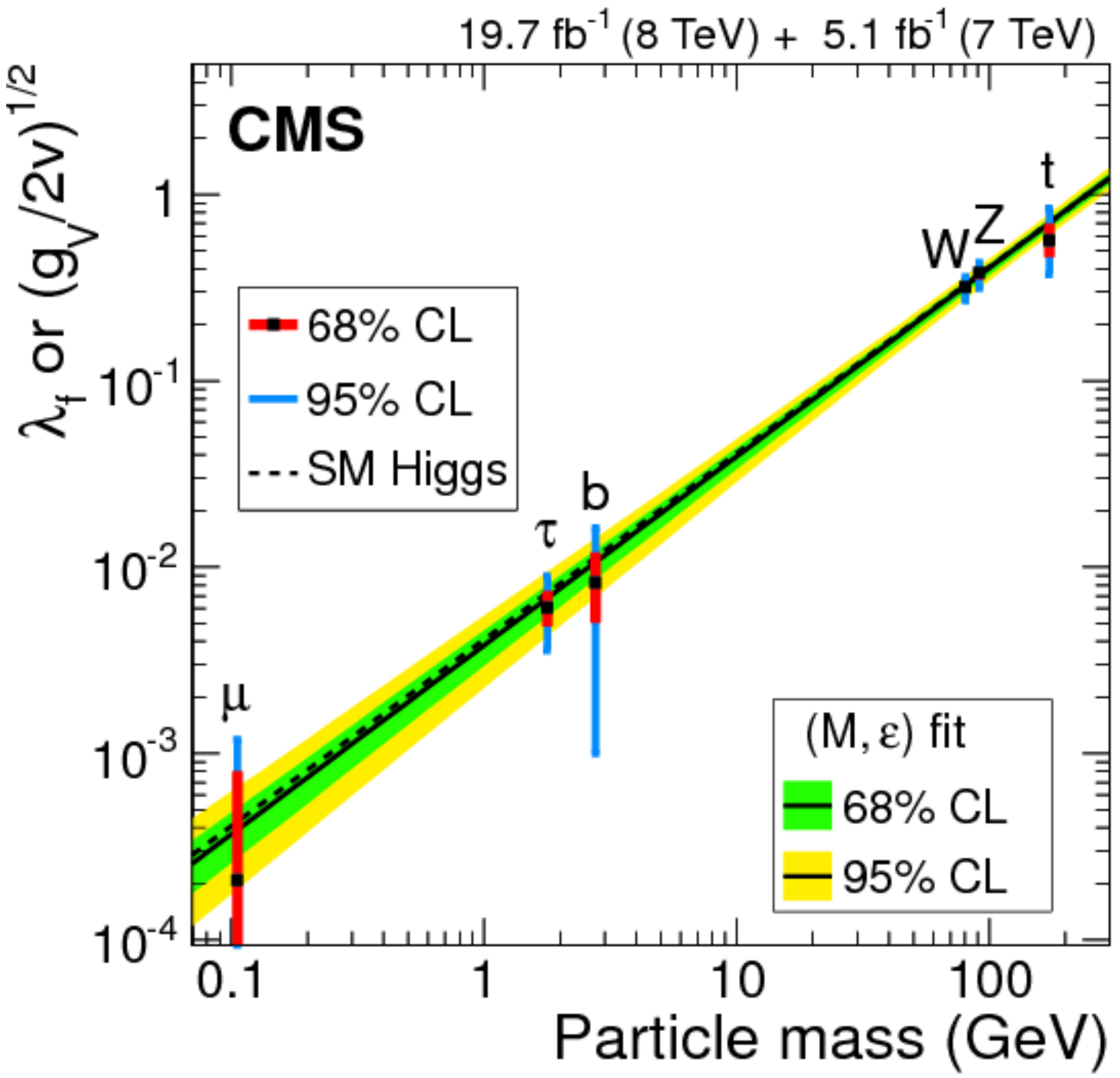
Foto: Konrad Adenauer Stiftung

A Loop Summit

Cadenabbia, July 26, 2021

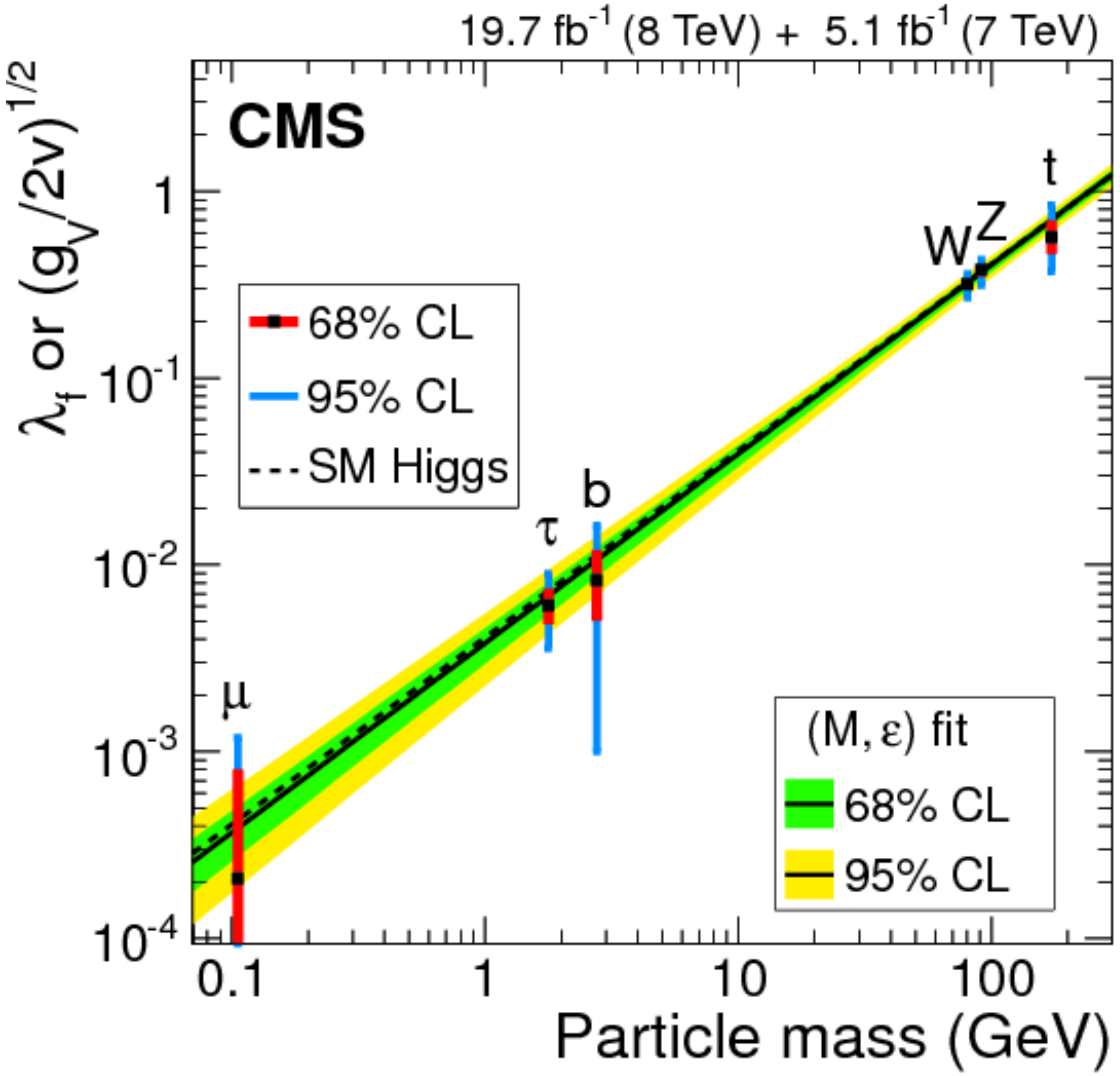
Motivation

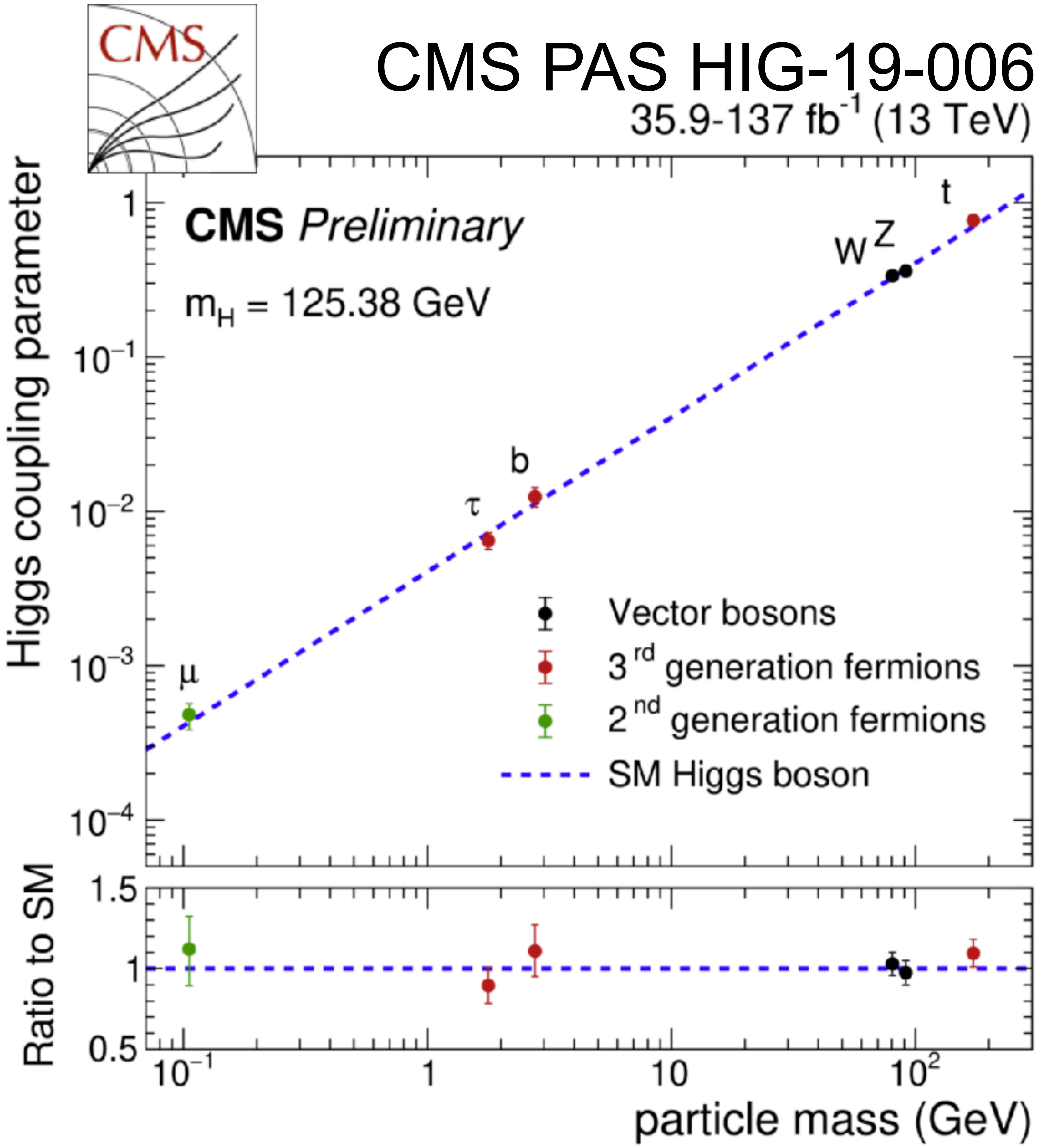
Run I



Motivation

Run I



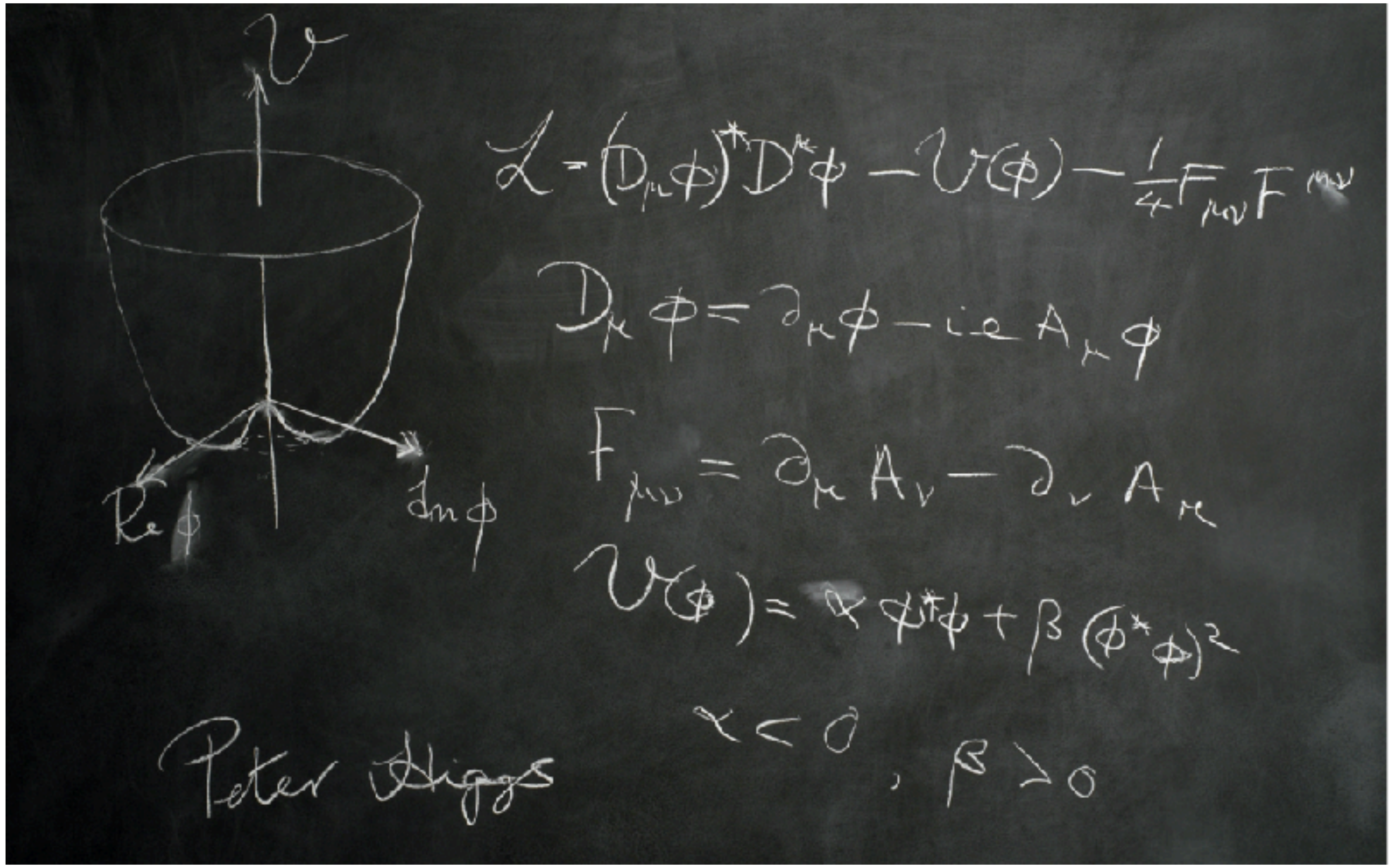


H?

enormous experimental progress

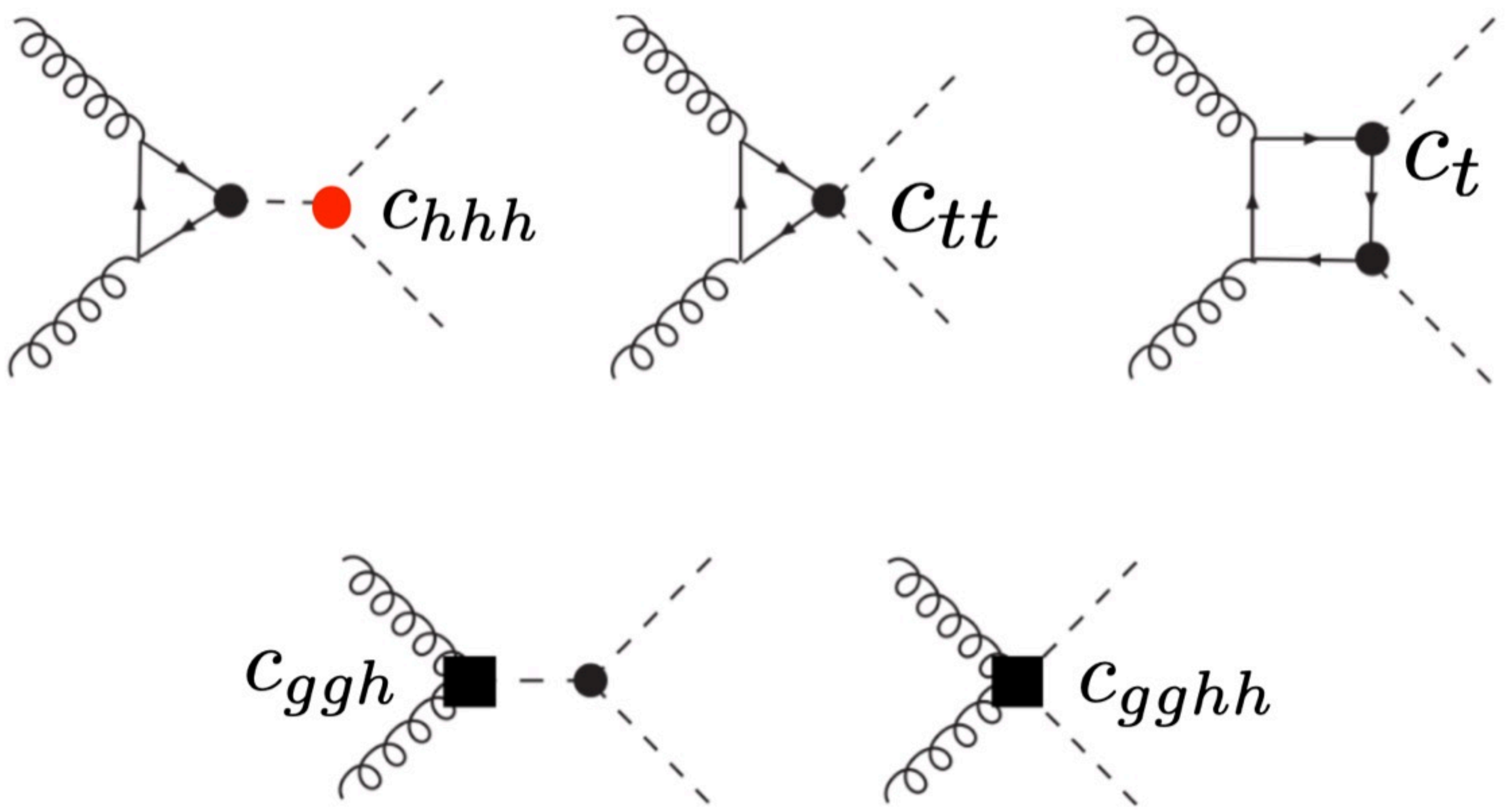
Progress on the theory side

Progress on the theory side



Exploring the Higgs potential

through Higgs boson pair production in gluon fusion



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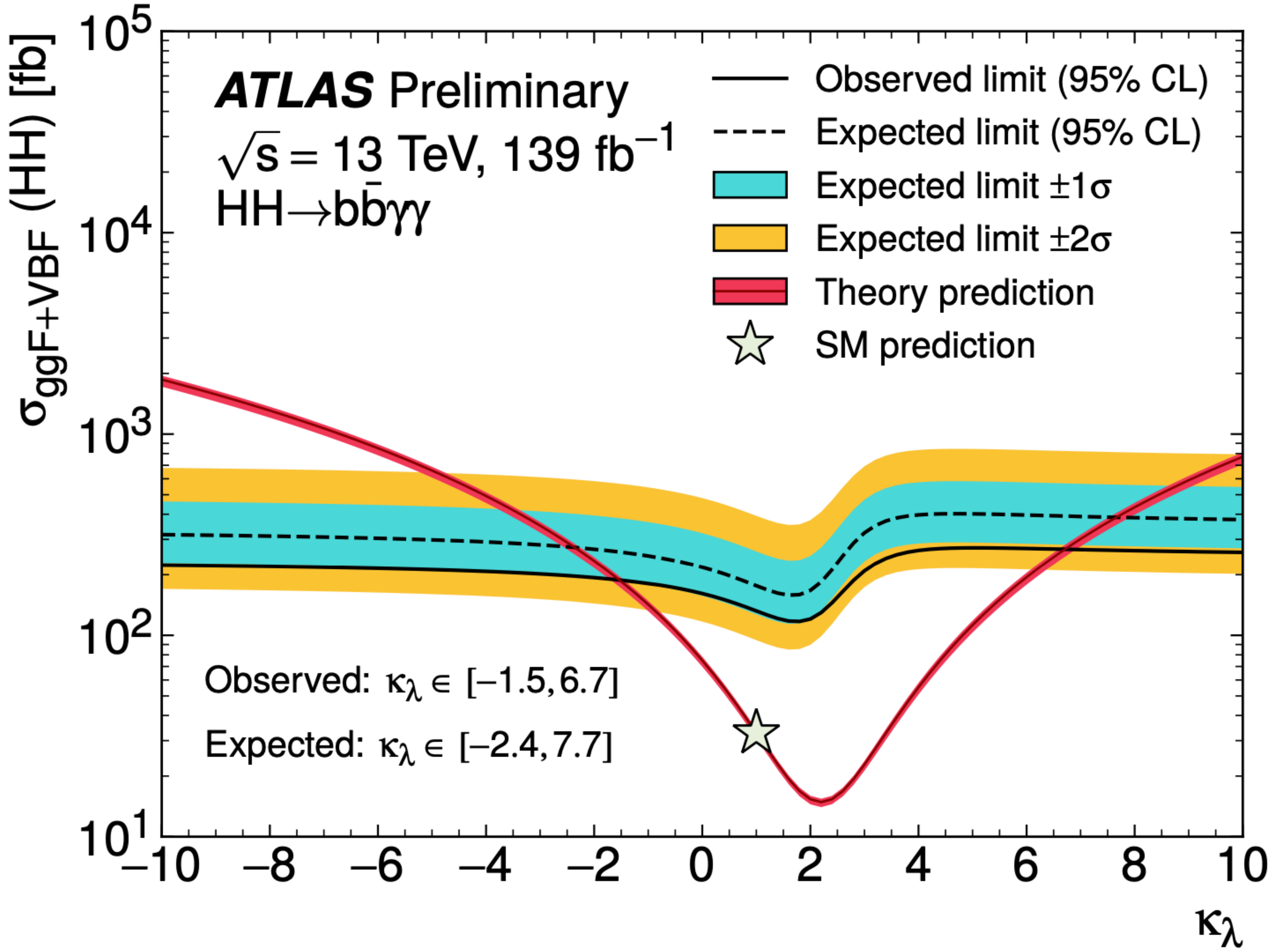

$$\kappa_\lambda \equiv c_{hhh}$$

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

Higher order corrections: SM

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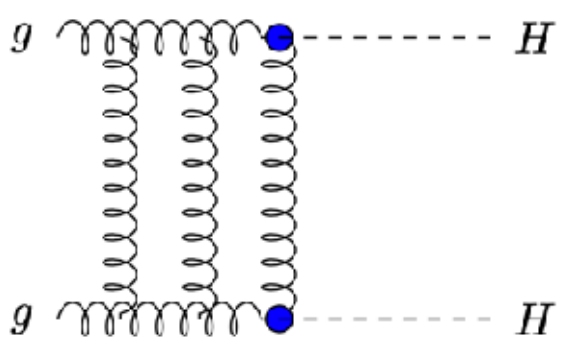
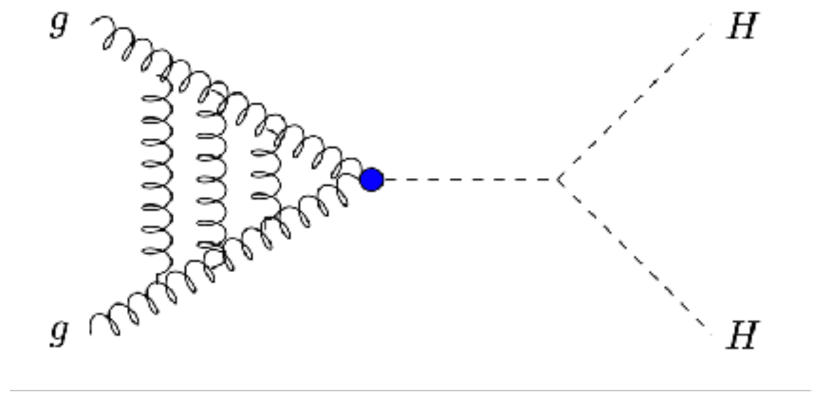
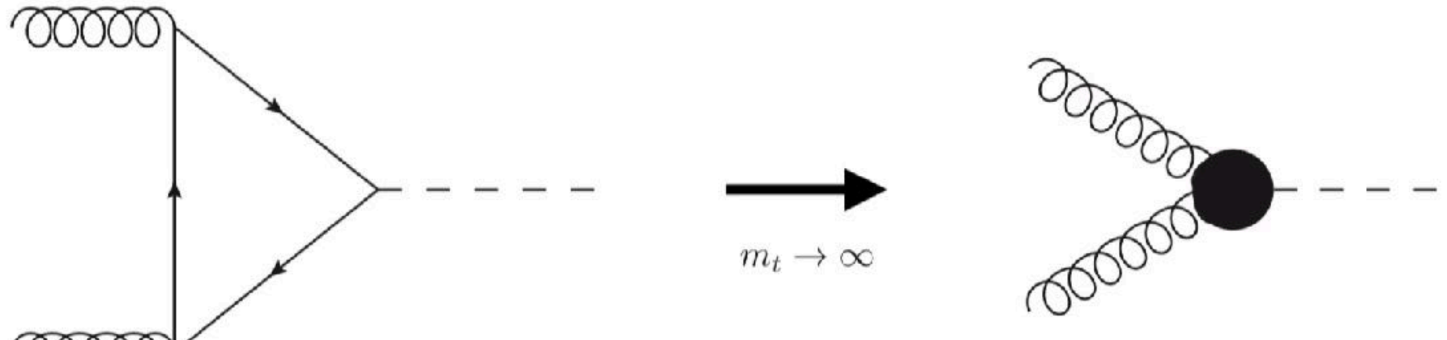
N3LO: Chen, Li, Shao, Wang '19 (HTL with top mass effects)





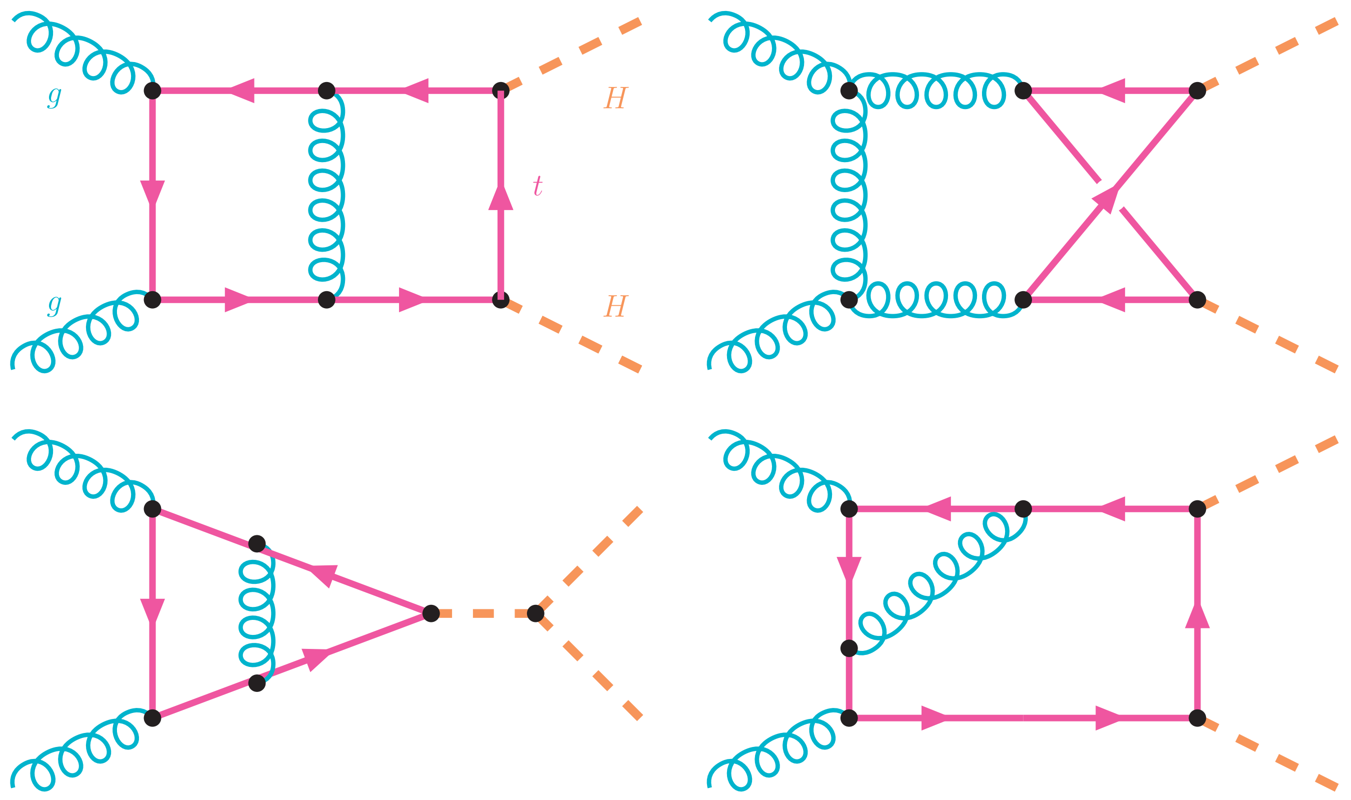


heavy top limit (HTL)

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 $\mathcal{O}(\alpha_s^3)$



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: EFT

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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

Higher order corrections: EFT

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

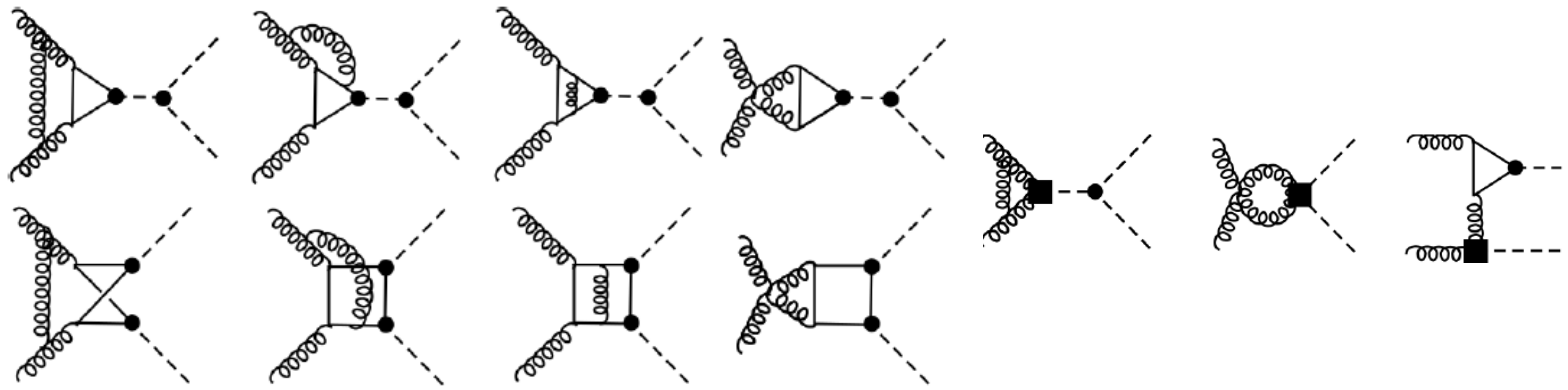
including CP-violating operators — Gröber, Mühlleitner, Spira ’17

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



approximate NNLO (NNLO’):

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

Approximate NNLO

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

parametrisation of cross section in terms of combinations of anomalous couplings

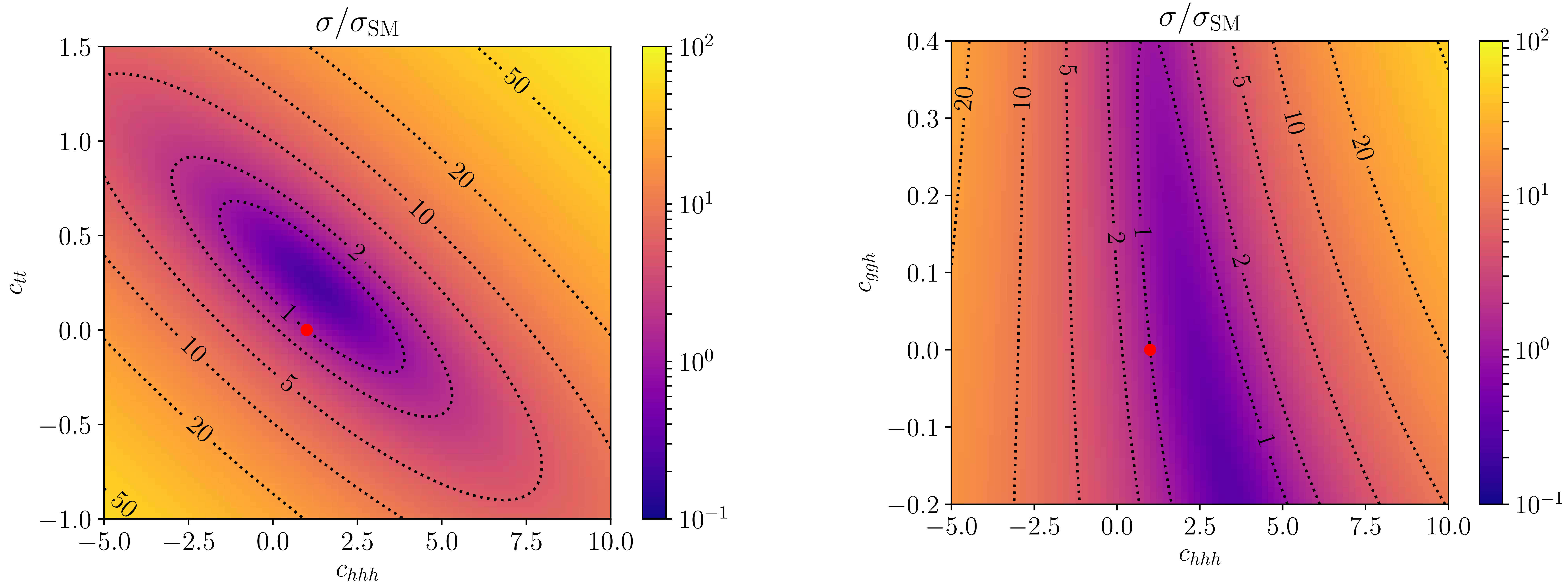
LO: 15, NLO: 23, NNLO: 25 combinations

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

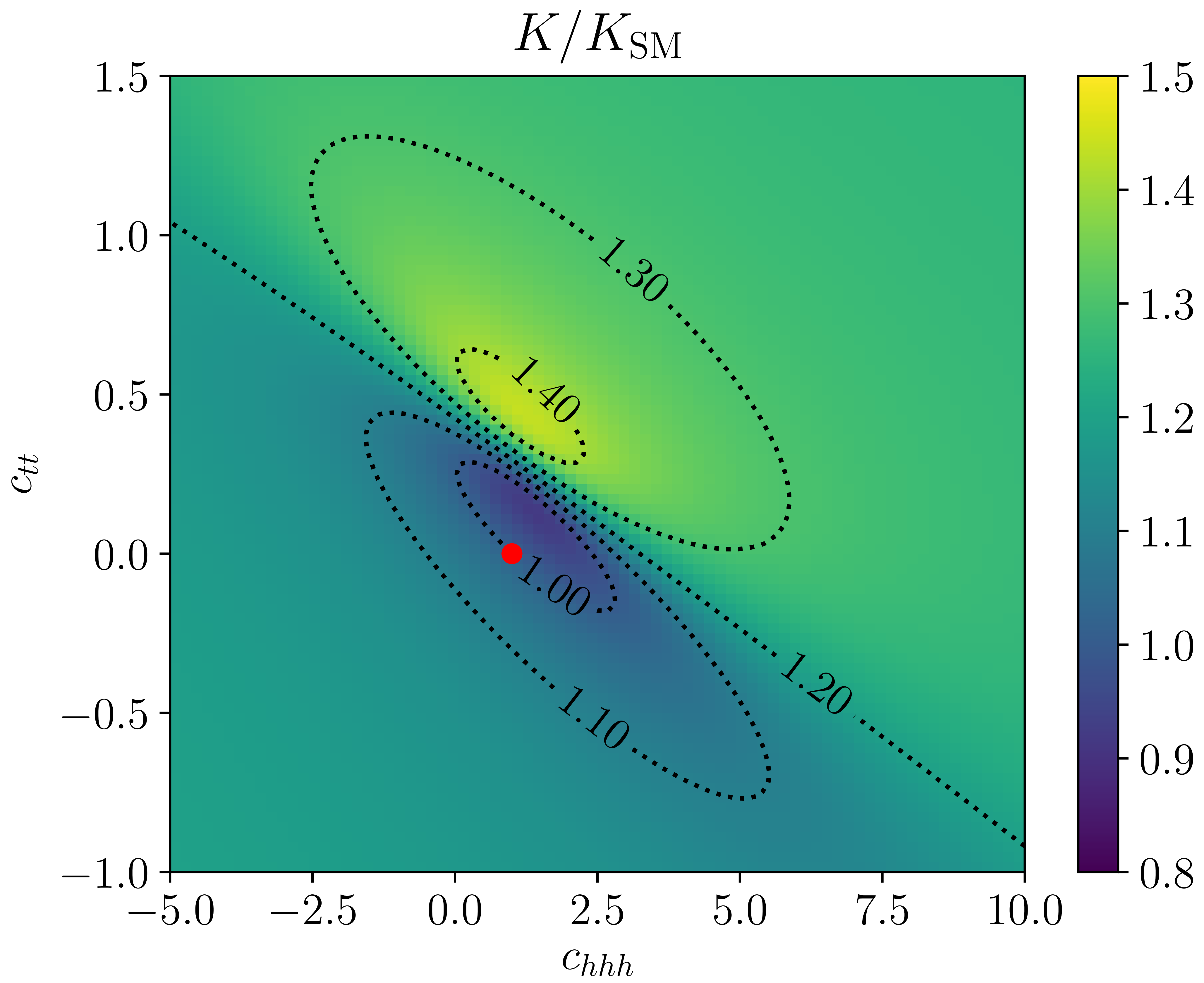
Total cross sections

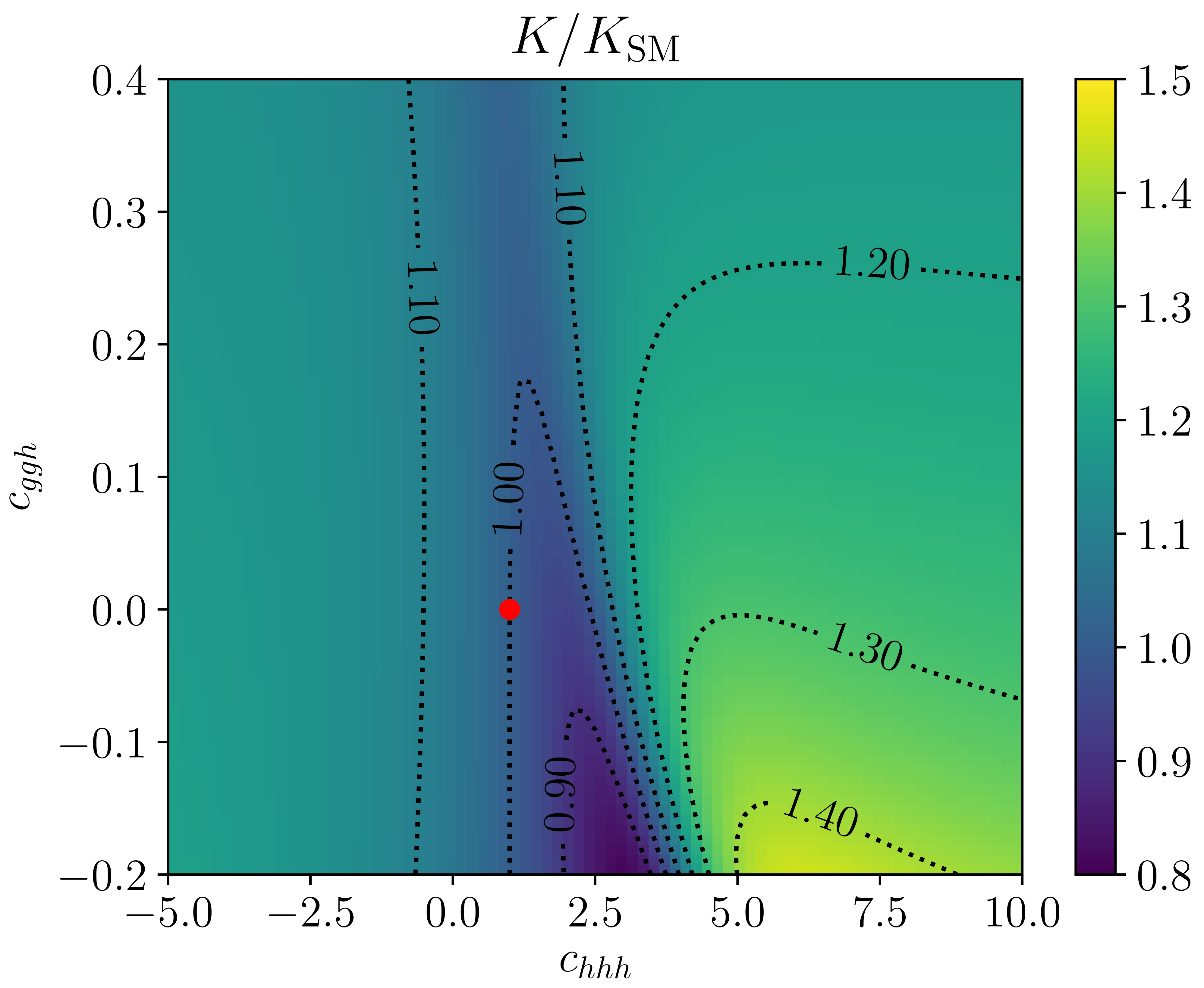
- fit of coefficients based on 43 combinations of EFT parameter points
- scan over 10000 points in EFT parameter space

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



K-factors





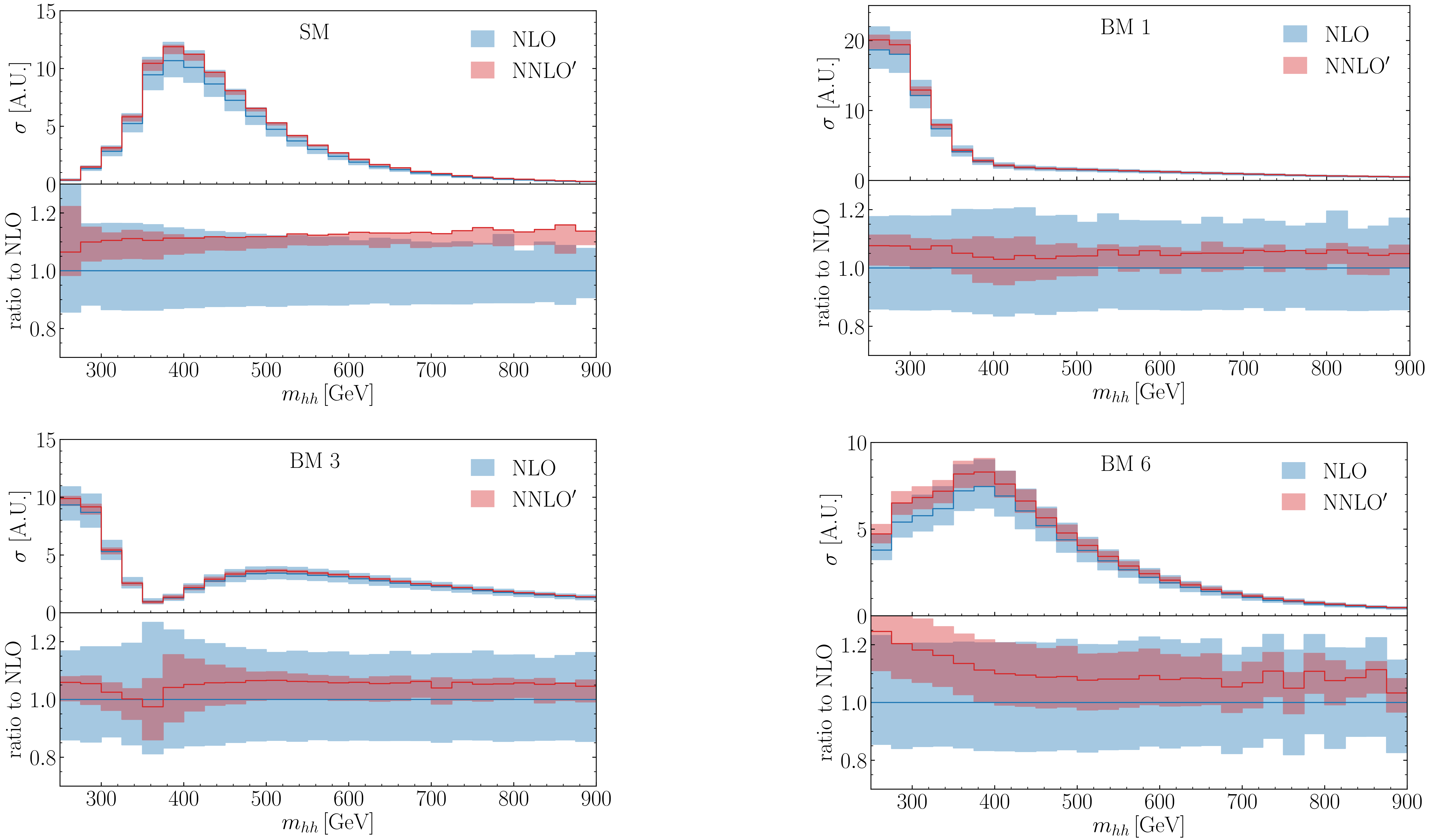
$\sigma^{NNLO'}/\sigma^{LO}$ normalised to SM K-factor (1.85)

Benchmark points

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

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

Distributions



Current experimental constraints

yellow line:
current limit on total xs

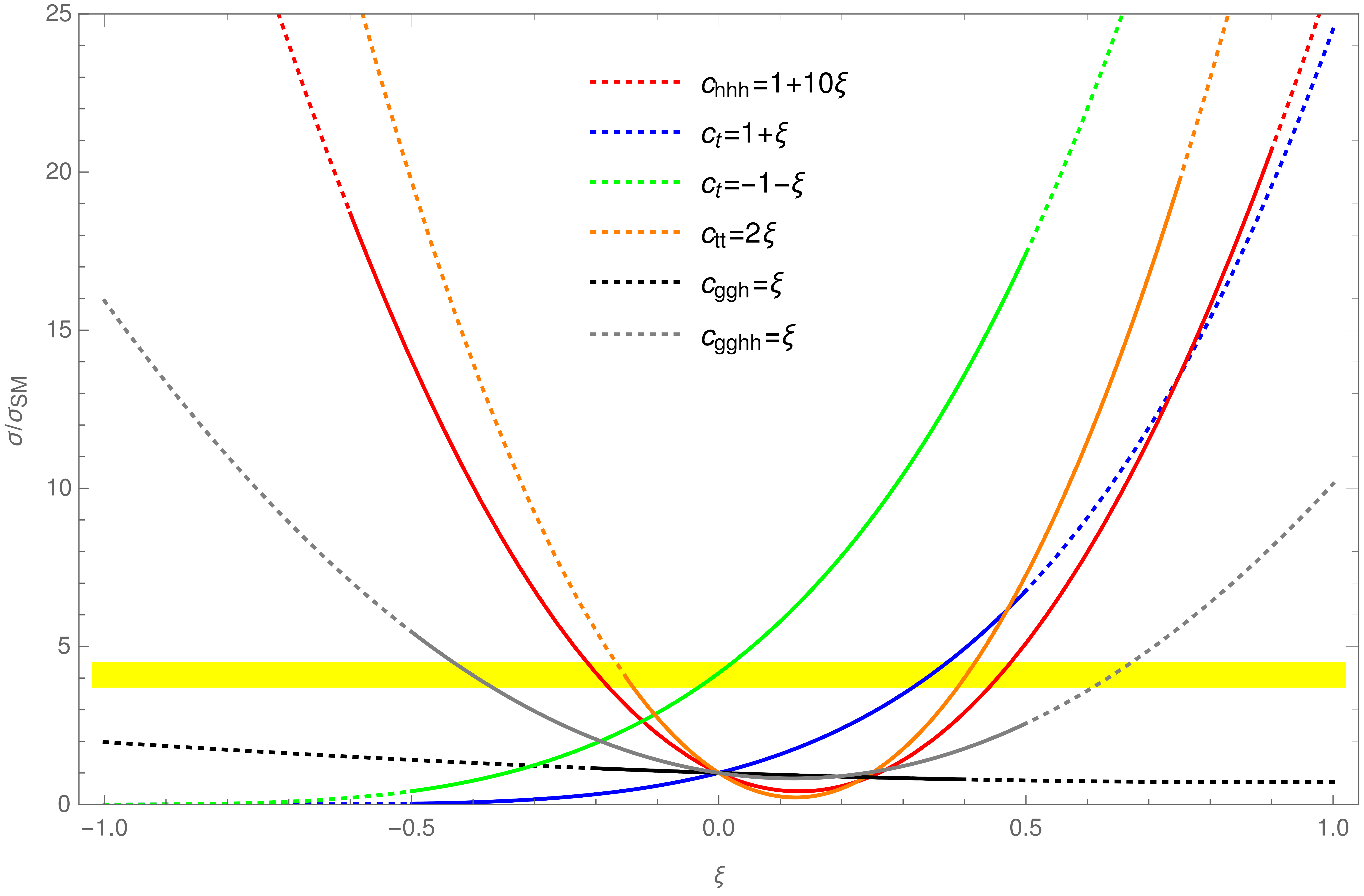
(ATLAS-CONF-2021-016)

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



What about SMEFT?

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HEFT (EW Chiral Lagrangian):

$$\mathcal{L}_{\mathrm{ew}\chi} = \mathcal{L}_{\mathrm{LO}} + \sum_{L=1}^{\infty} \sum_i \left(\frac{1}{16\pi^2} \right)^L c_i^{(L)} \mathcal{O}_i^{(L)}$$

SMEFT:

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

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

coupling relations:

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

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

SMEFT

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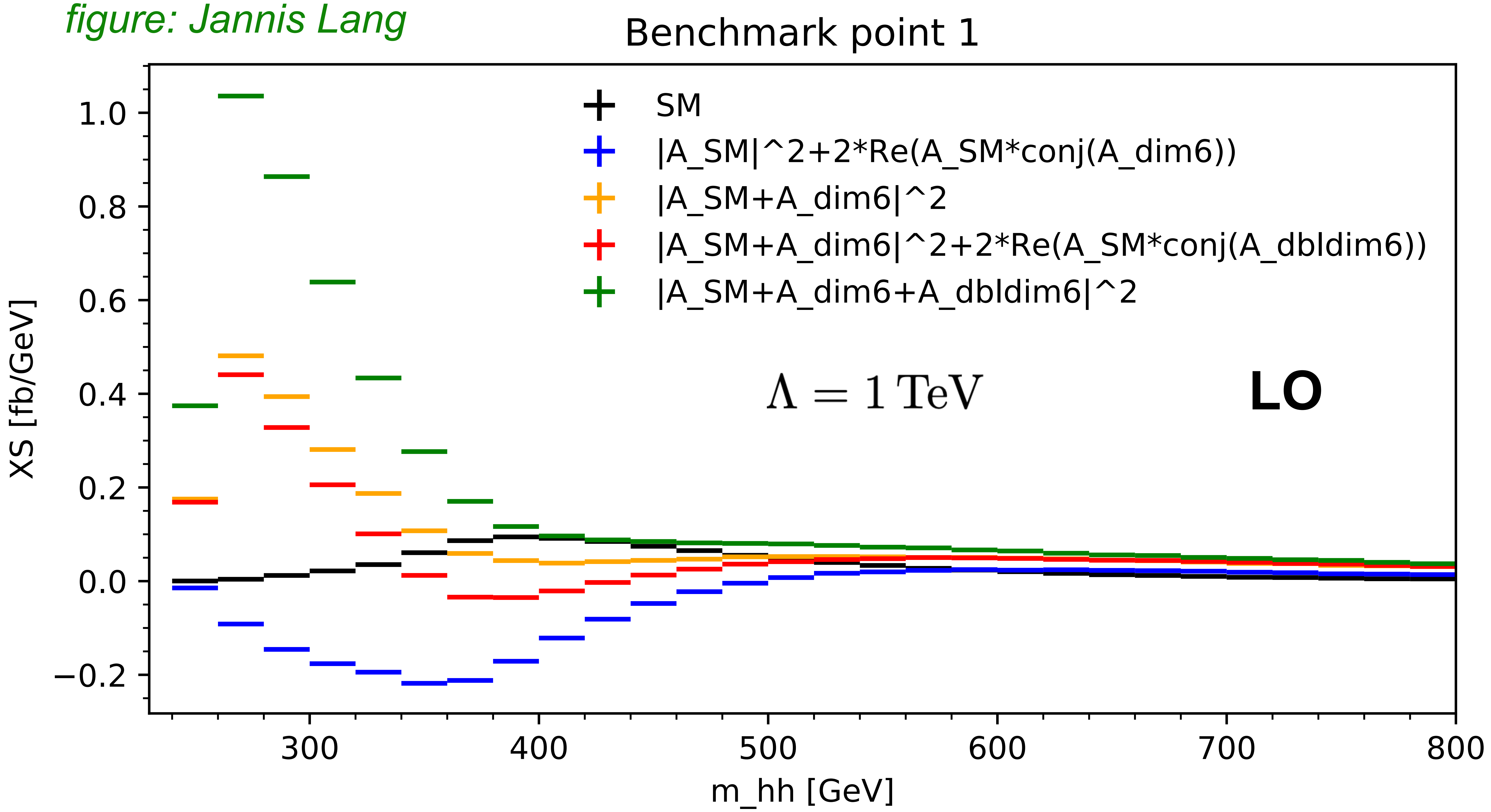
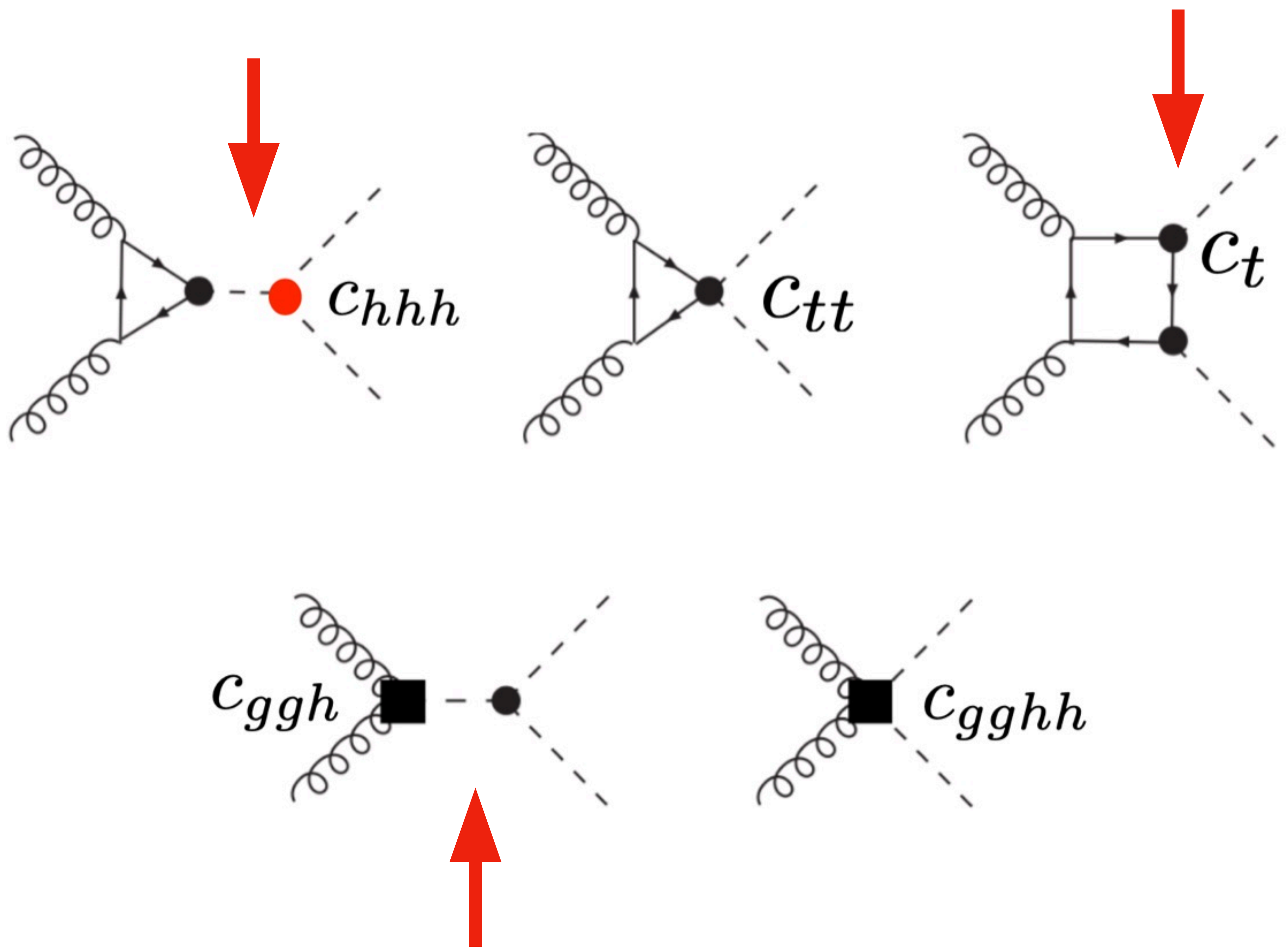
canonical dimension counting ⟶ how to treat |dim6|^2 versus dim8 ?

⟶ how to treat double operator insertions?

figure: Jannis Lang

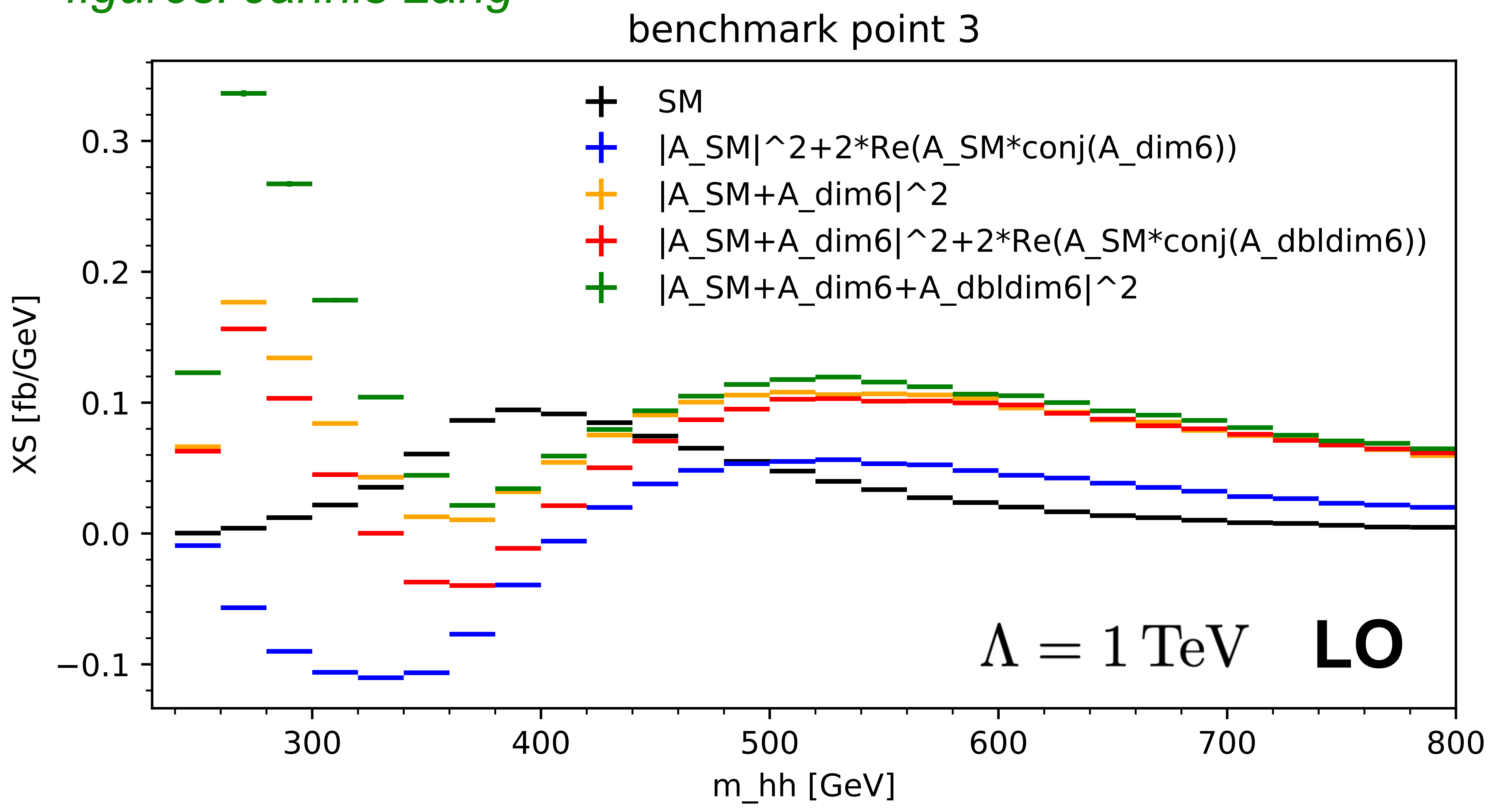


two operators in one diagram

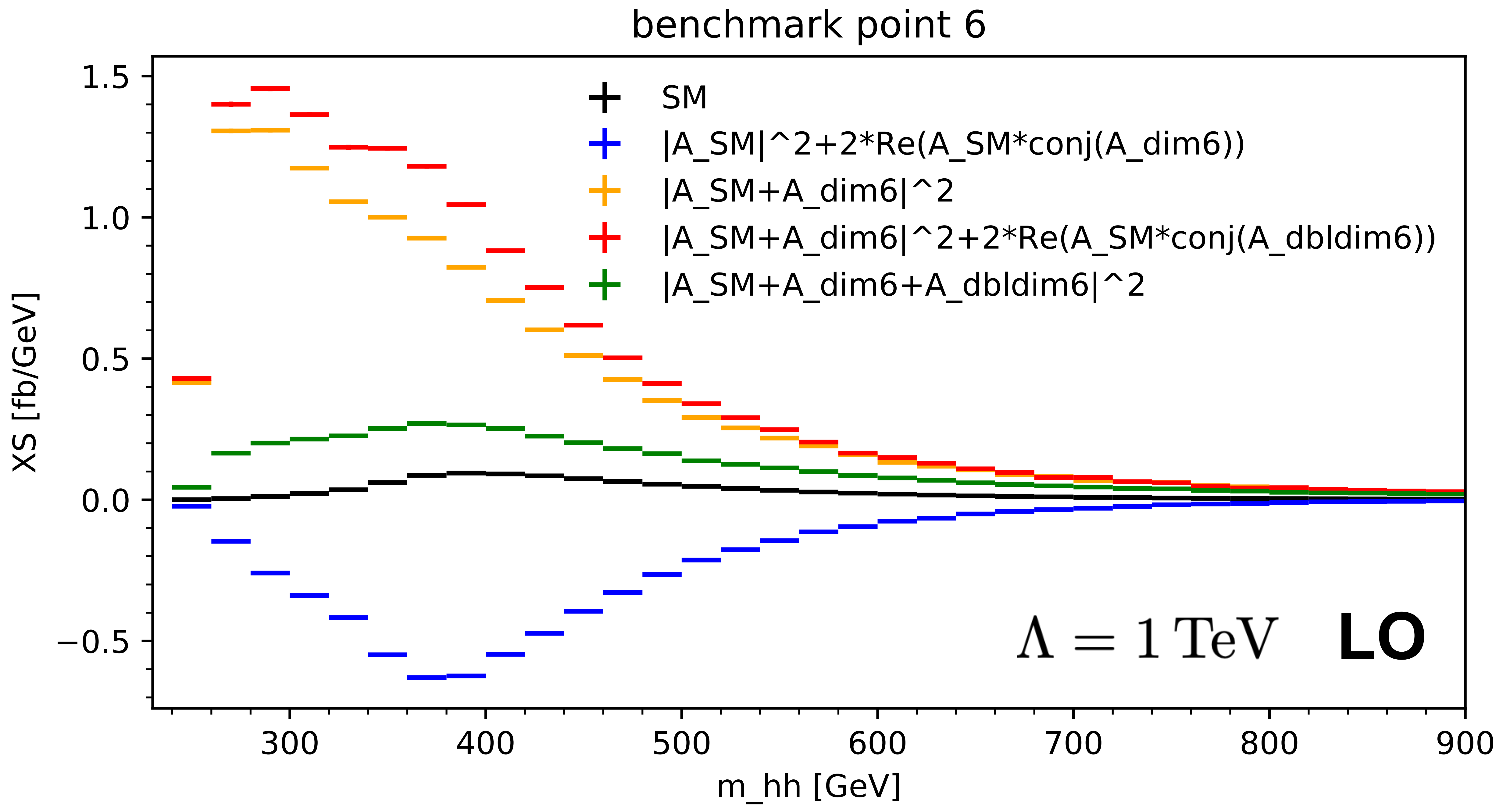


SMEFT

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” of CERN LHC Higgs WG2:

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

Summary & Outlook

- The Higgs sector might be a window to New Physics
- Precision is the key at current collider energies
- Increasing the precision in the Higgs sector has many facets

  example EFT parametrisation of New Physics effects for $pp \rightarrow HH$:

  higher orders in QCD, mass effects, scheme dependence,

  truncation of EFT series …

A loop summit

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

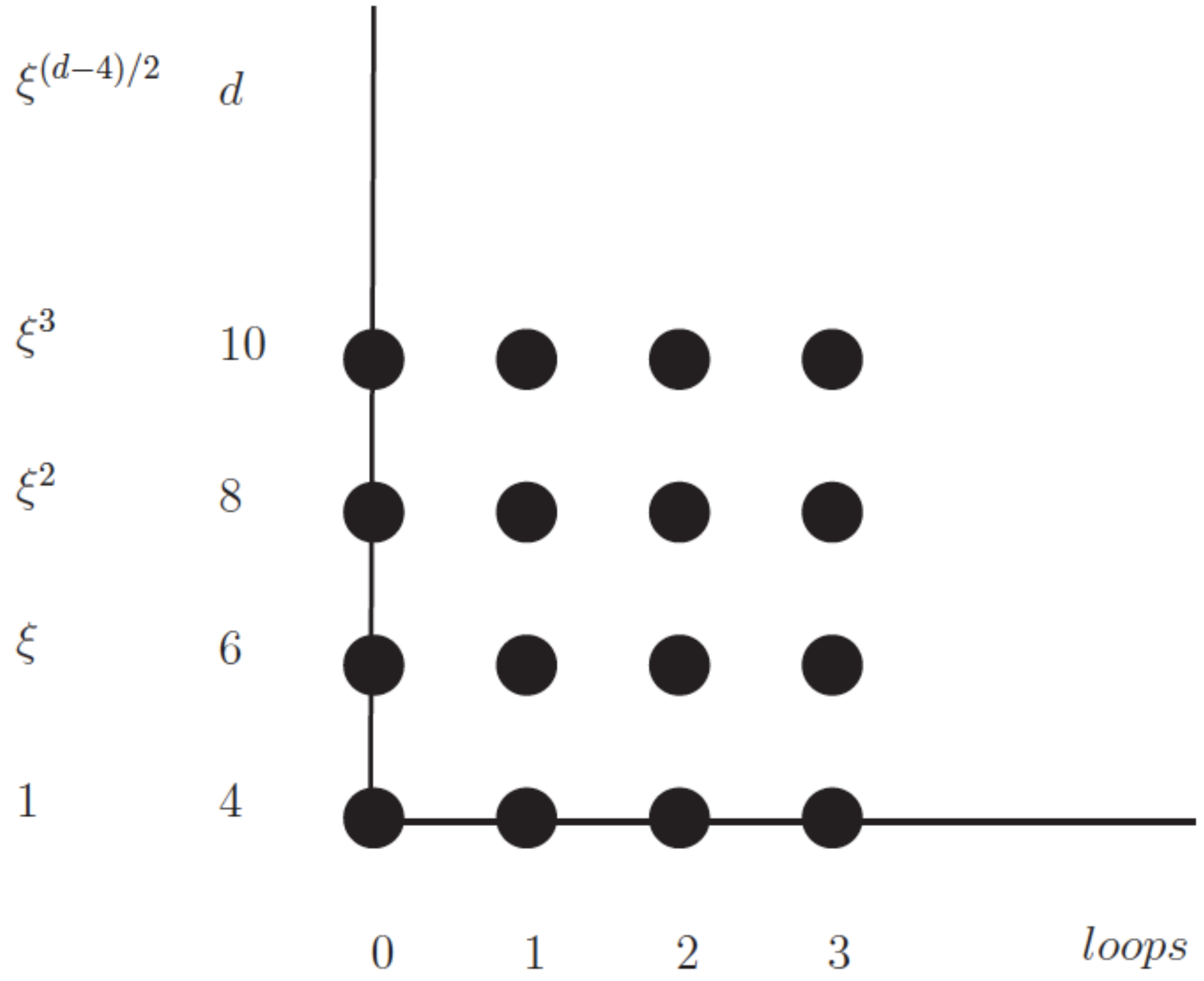


figure: G.Buchalla

loop expansion

HEFT

Effective Field Theory descriptions

scale hierarchies

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E

new physics scale Λ

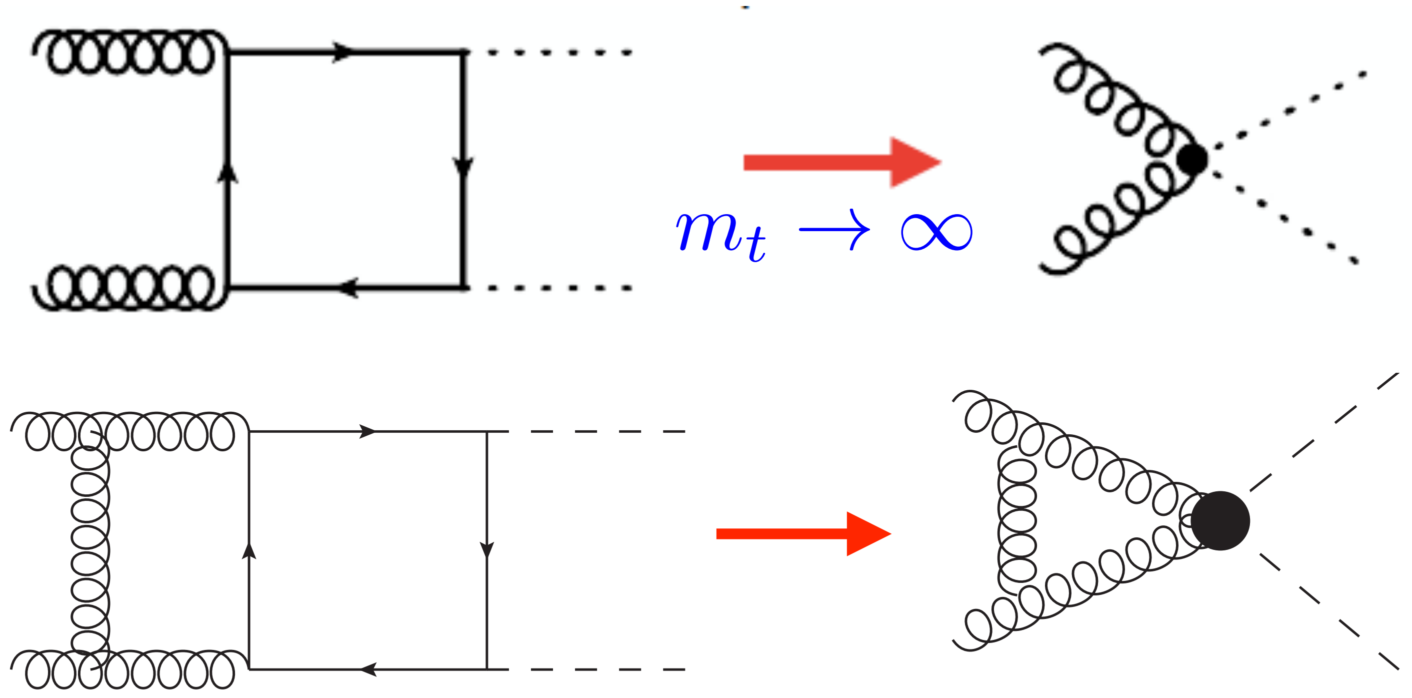
f : characteristic scale of Goldstone bosons

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

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

Approximations: NLO

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

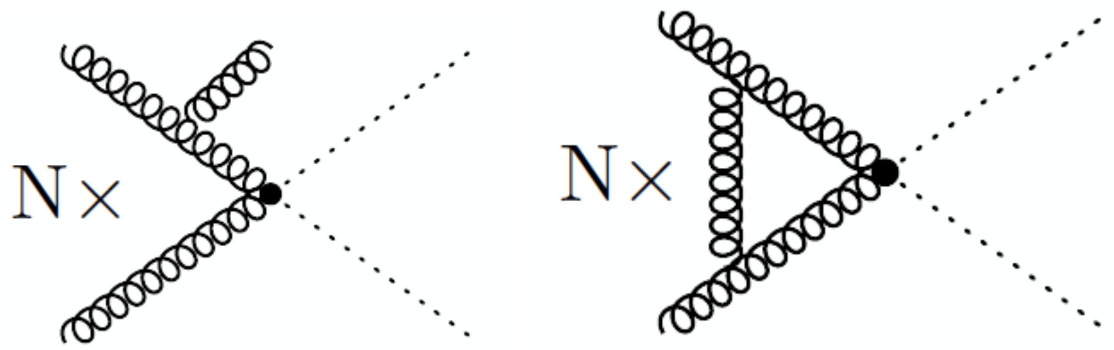


Leading Order (LO)

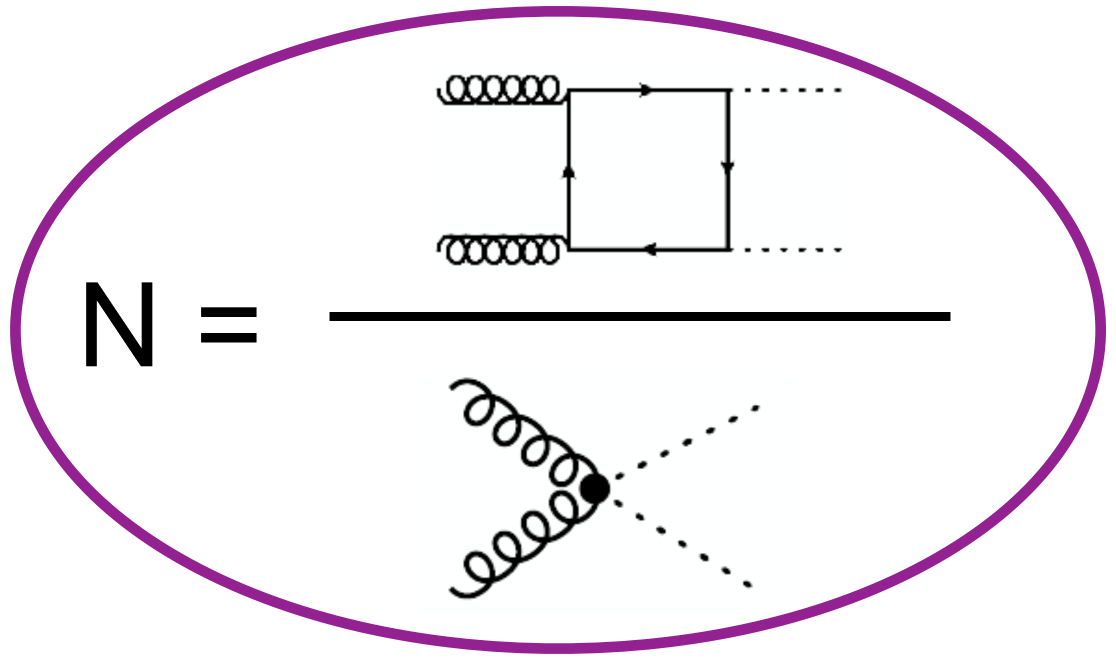
Next-to-Leading Order (NLO)

- Born-improved HEFT:

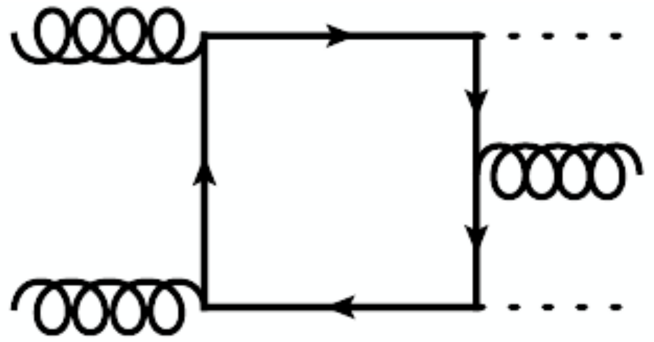
$$d\sigma^{\mathrm{NLO}}_{m_t\to\infty} \times \frac{d\sigma^{\mathrm{LO}}(m_t)}{d\sigma^{\mathrm{LO}}_{m_t\to\infty}}$$

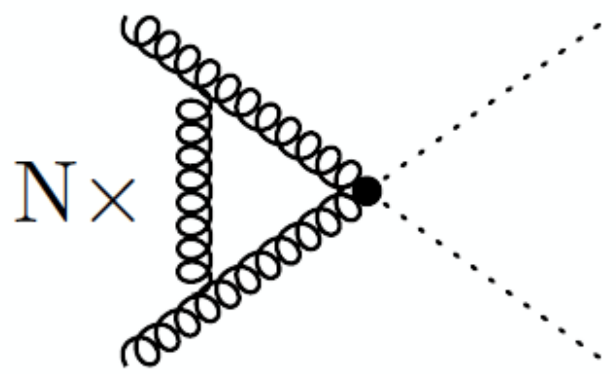


NLO real NLO virtual



- FTapprox:



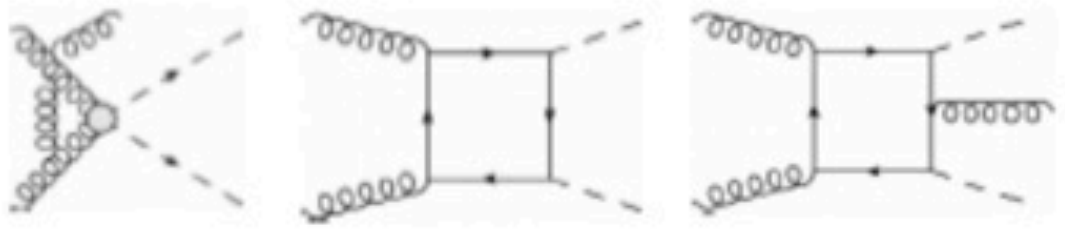


NLO real:
full m_t-dependence

NLO virtual:
Born-improved HEFT

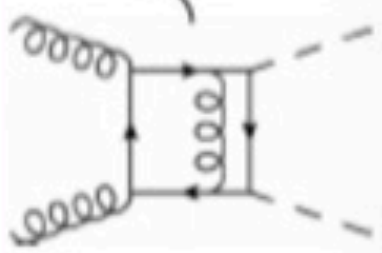
Approximations: NNLO approx

Technical ingredients

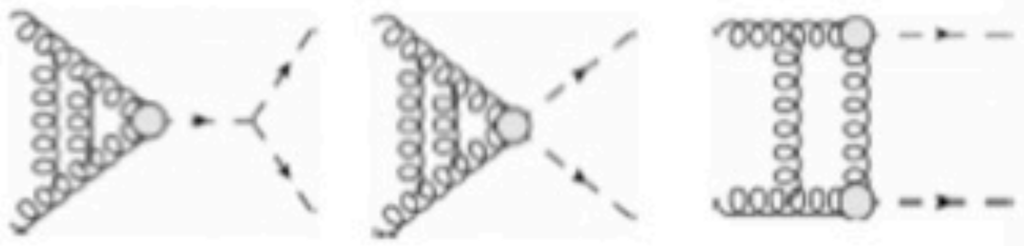


Tree-level and one-loop amplitudes (HEFT and full-M_t) → OpenLoops
[Cascioli, Lindert, Maierhofer, Pozzorini]

Full NLO (two-loop) virtual corrections → two dimensional grid + interpolation
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke, '16]



Analytical results for NNLO two-loop corrections in the HEFT
[de Florian, JM, '13]

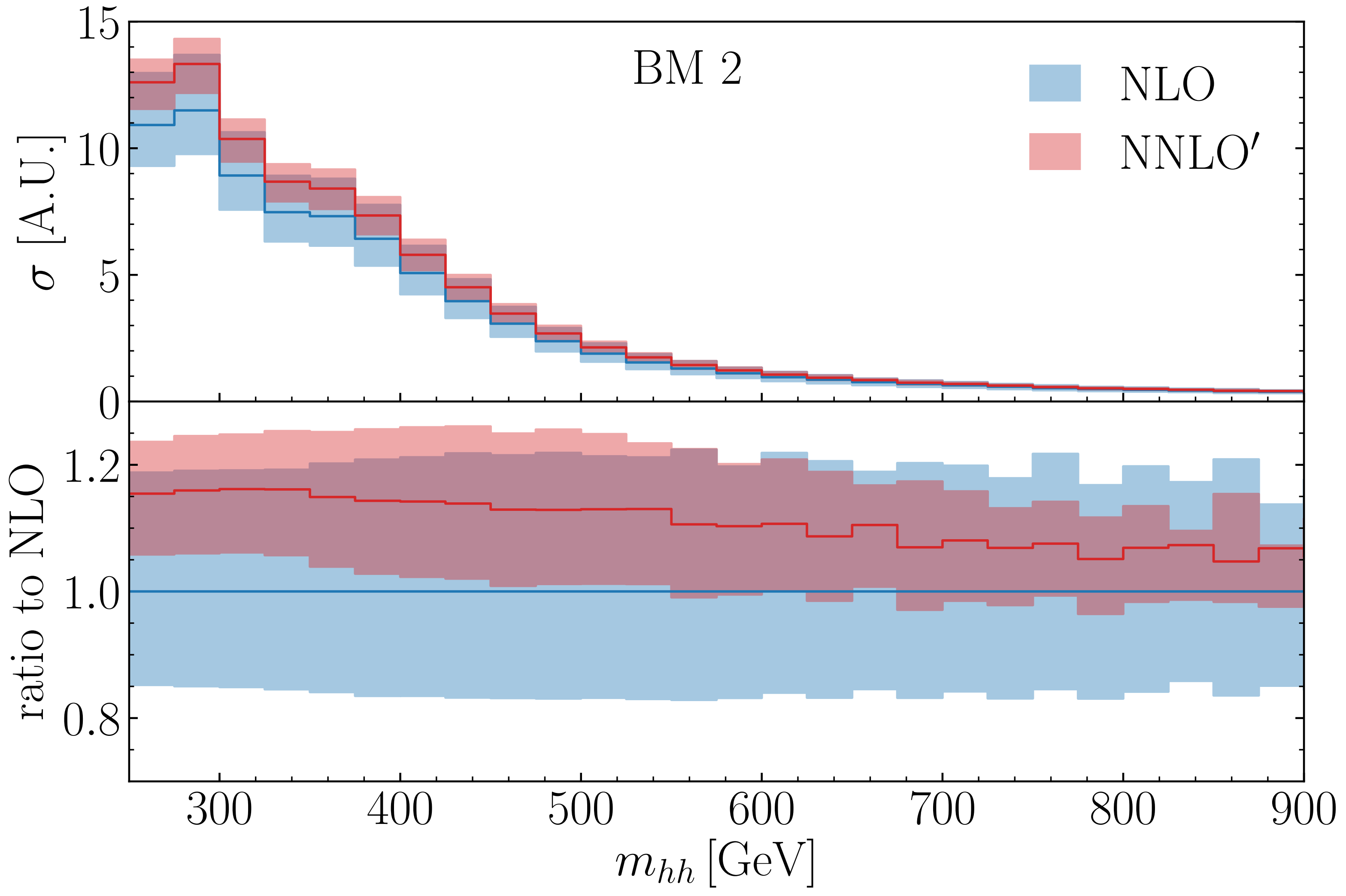


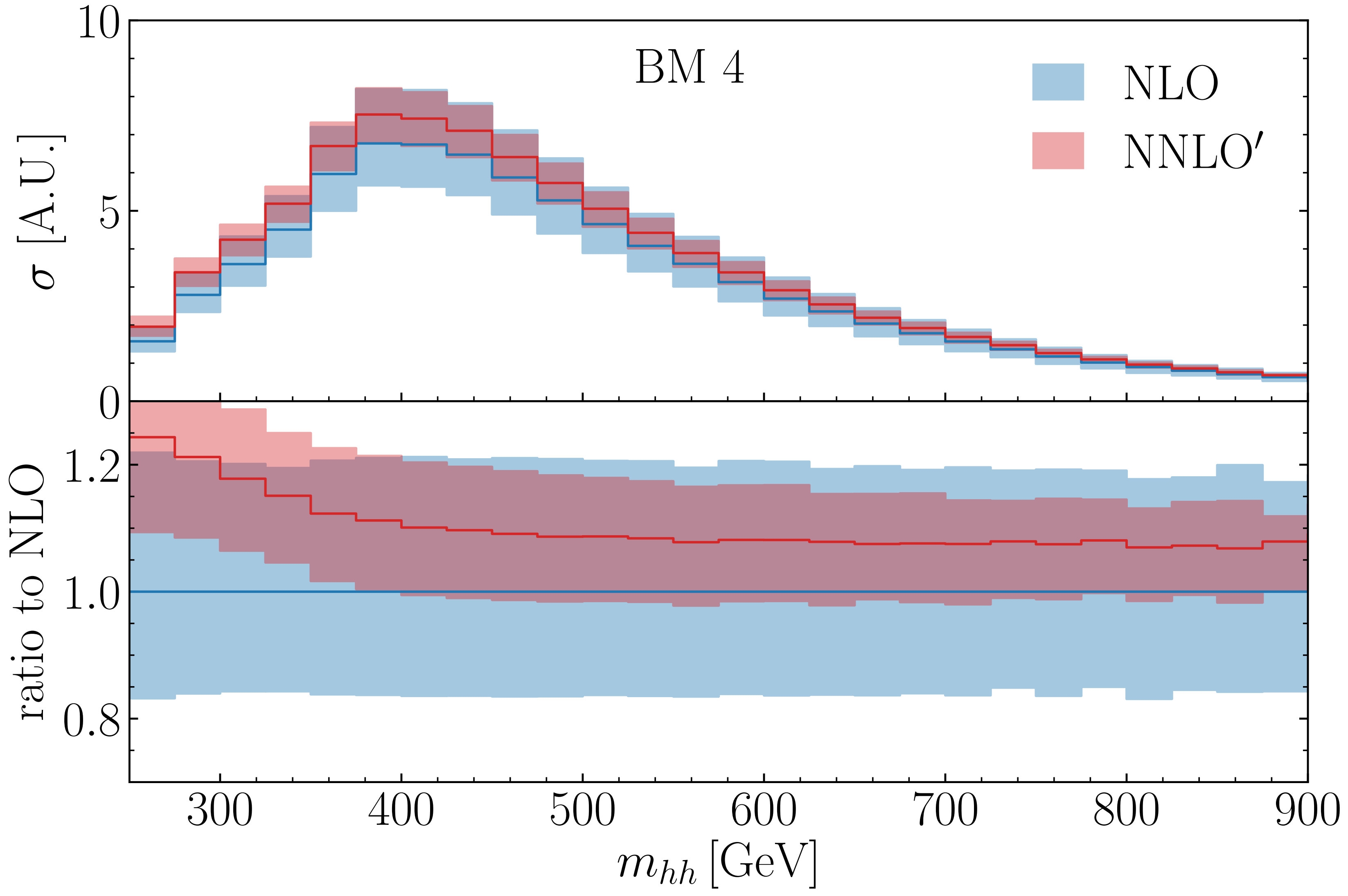
NNLO subtraction formalism: q_T-subtraction
[Catani, Grazzini, '07]

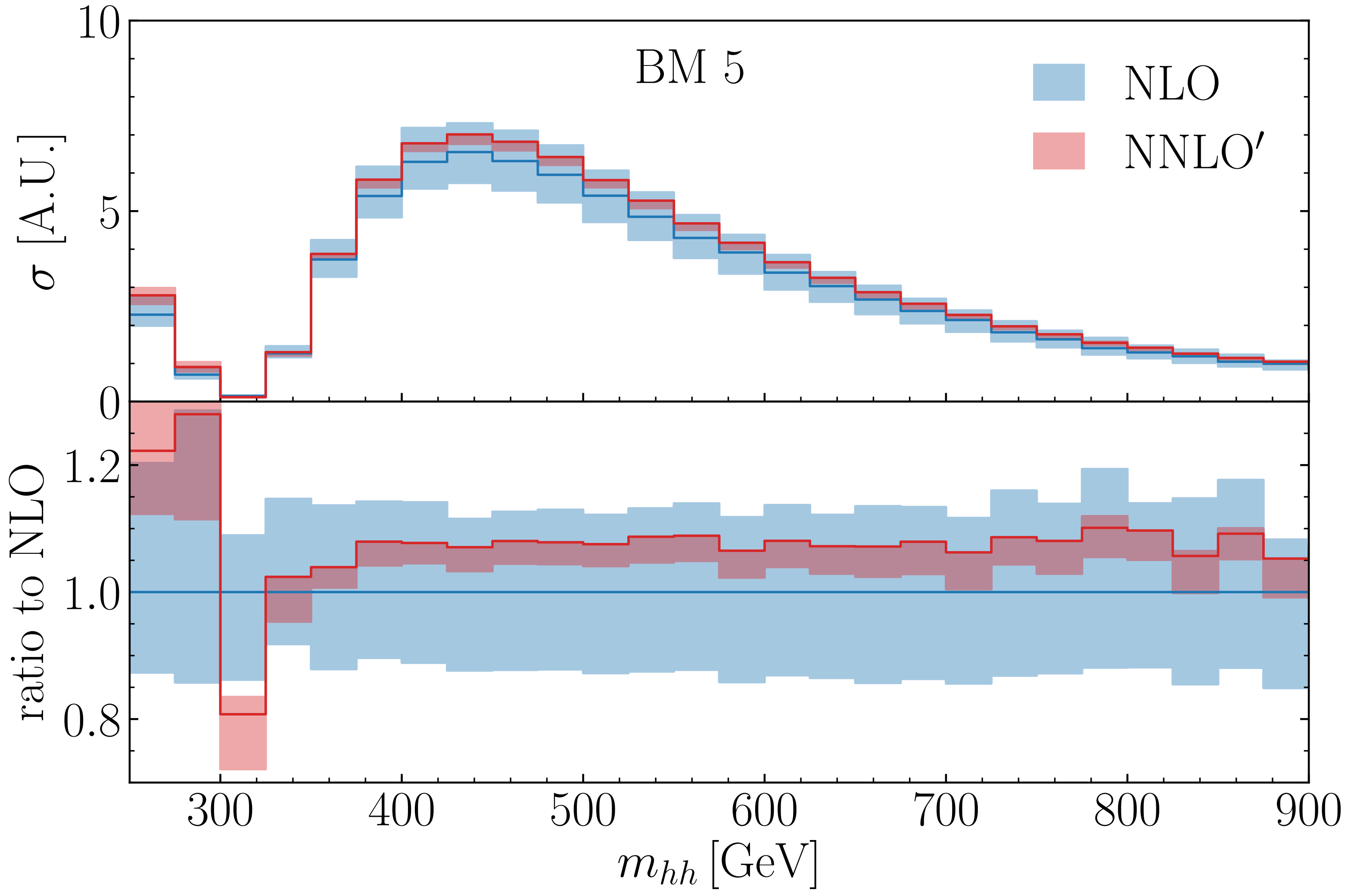
Implementation based on public code MATRIX
[Kallweit, Grazzini, Wiesemann, '17]

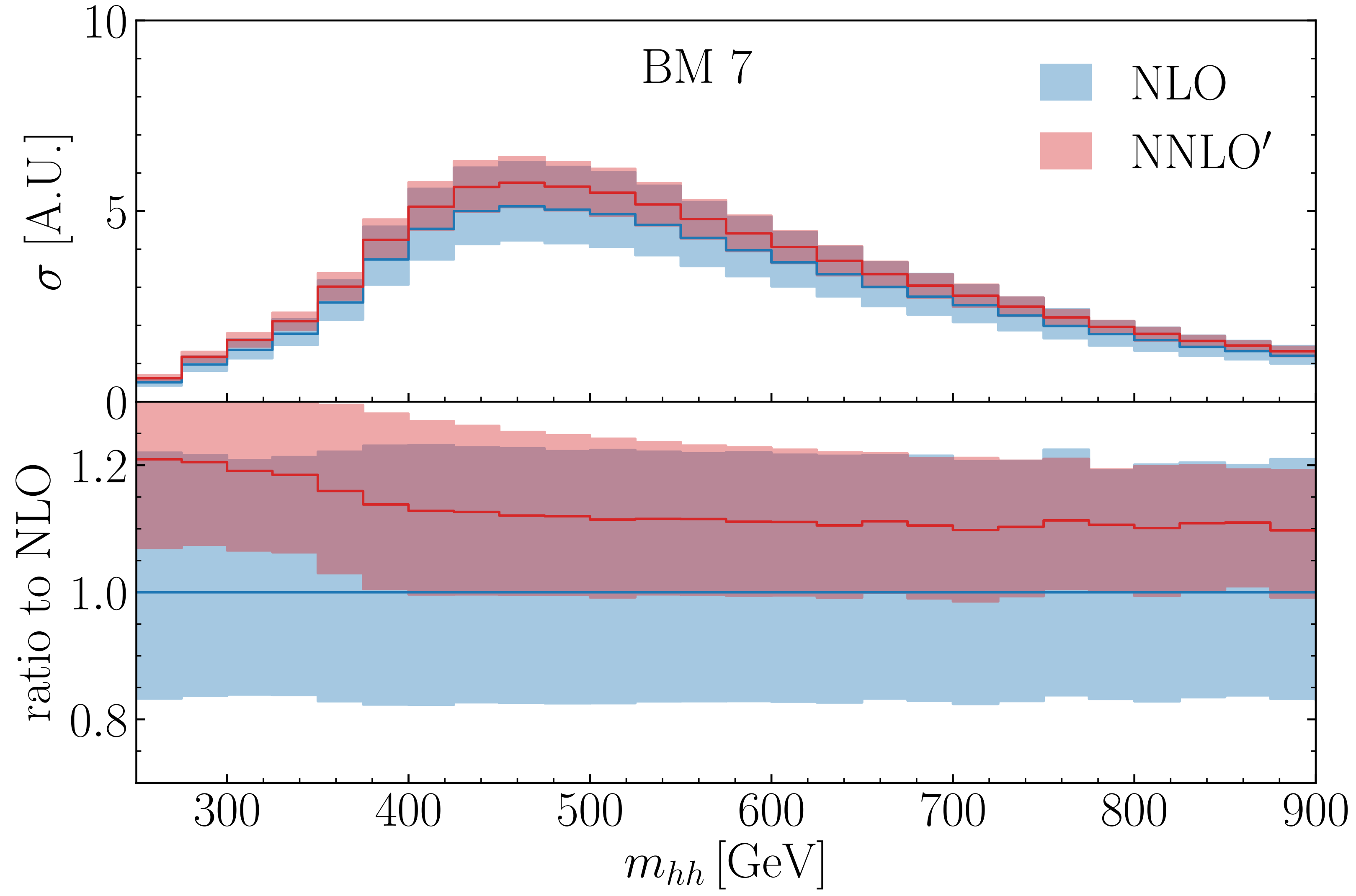
Javier Mazzitelli

benchmark points 2,4,5,7



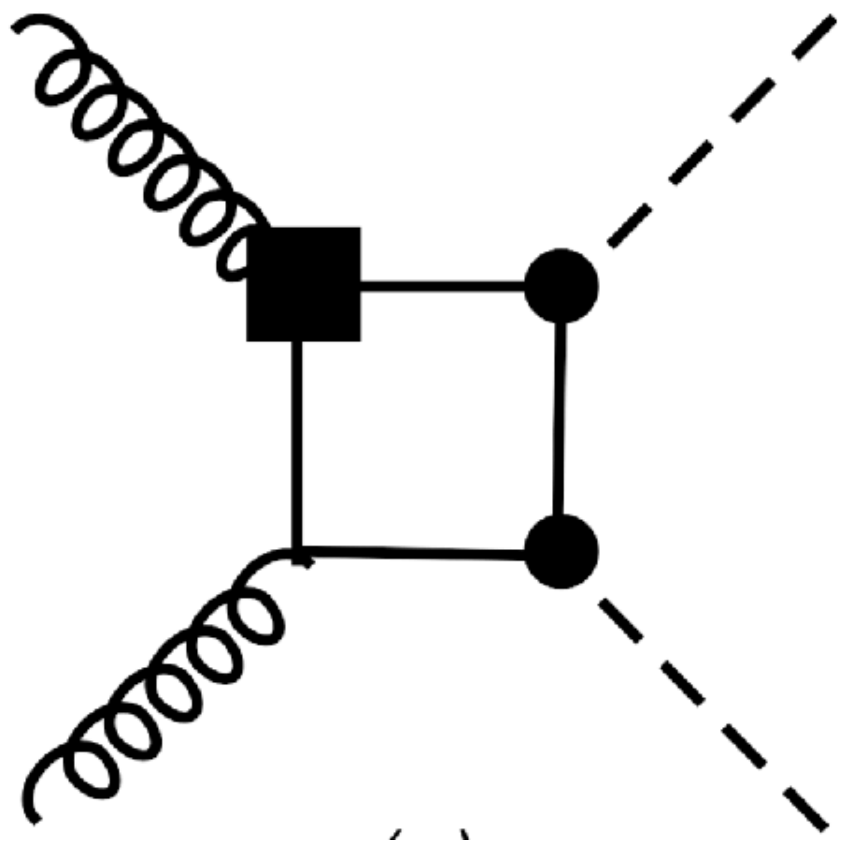






Chromomagnetic operator

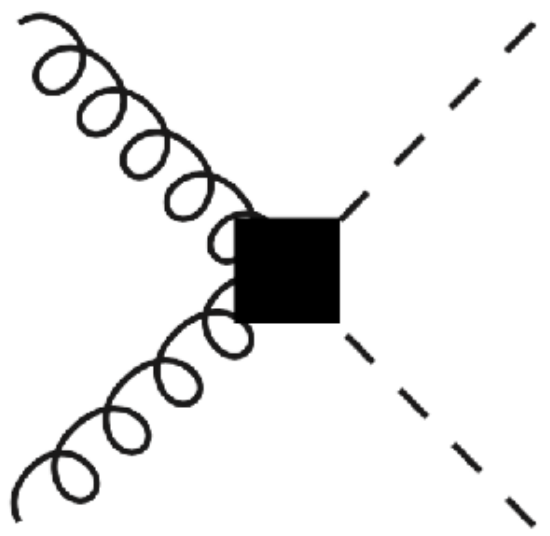
$$O_{tG} = y_t g_s \bar{t}_L \sigma_{\mu\nu} G^{\mu\nu} t_R$$



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