Karlsruhe Institute of Technology

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Institute for Theoretical Physics

Subleading operators and gamma5-scheme dependence in SMEFT for Higgs boson pair production

John Manders

Loops & Legs in Quantum Field Theory

Wittenberg, April 16, 2024

Gudrun Heinrich

Institute for Theoretical Physics, Karlsruhe Institute of Technology

based on work in collaboration with

Ramona Gröber, Stephen Jones, Matthias Kerner, Jannis Lang,

Stefano Di Noi, Ludovic Scyboz, Marco Vitti

https://arxiv.org/abs/2311.15004	GH, Jannis Lang
https://arxiv.org/abs/2310.18221	Stefano Di Noi, Ramona Gröber, GH, Jannis Lang, Marco Vitti
https://arxiv.org/abs/2204.13045	GH, Jannis Lang, Ludovic Scyboz

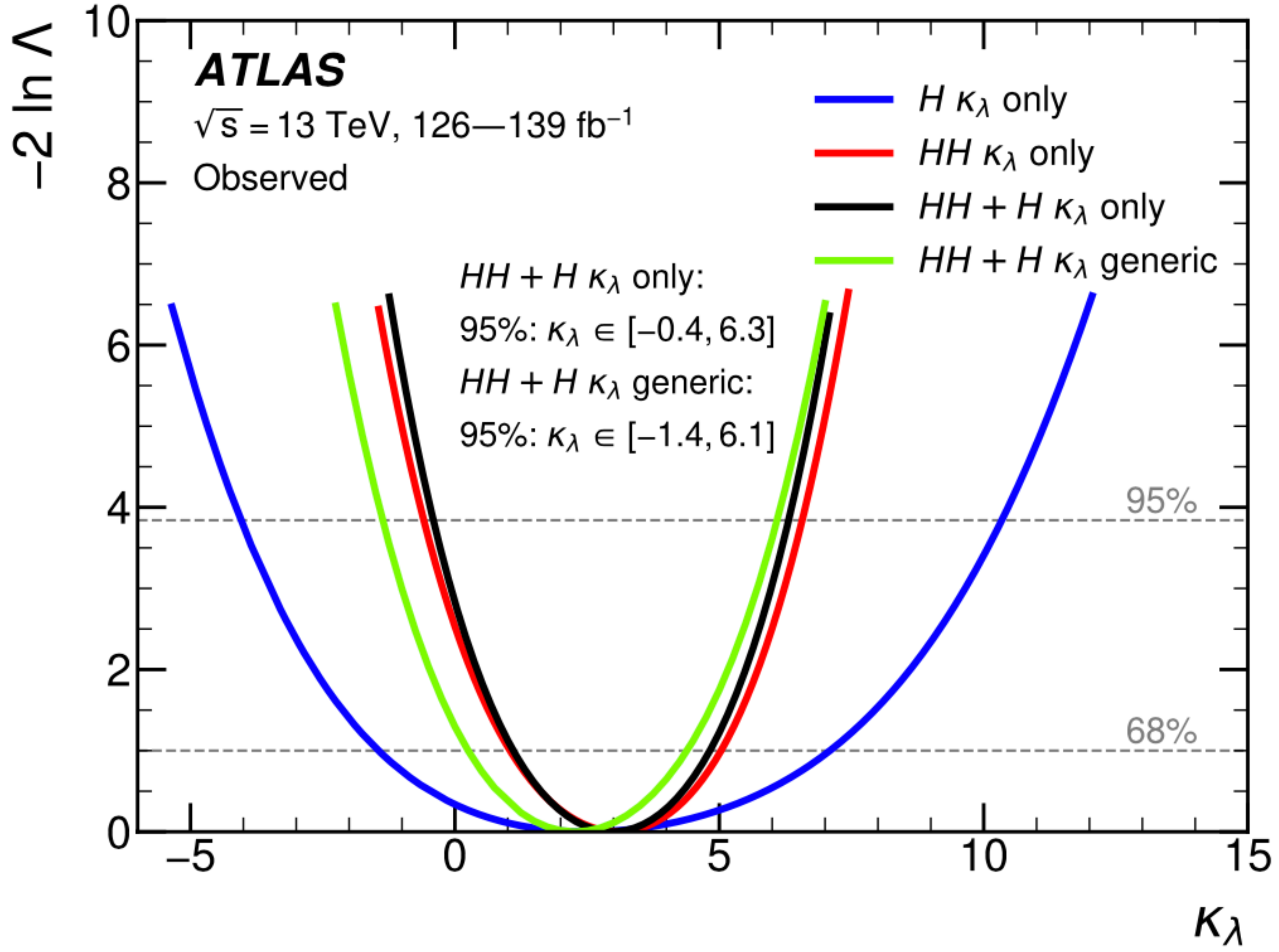
Higgs boson pair production

prime process to explore the Higgs potential

$$V(h) \sim \frac{1}{2}\underbrace{(2v^2\lambda)}_{m_h^2}\, h^2 + v\lambda\, h^3 + \frac{\lambda}{8}\, h^4$$

Standard Model: $\lambda = \frac{m_h^2}{2v^2} \approx 0.125$

$$\kappa_\lambda = \lambda/\lambda_{\mathrm{SM}}$$



[2211.01216]

experimentally established deviations from

$\kappa_\lambda = 1$ are a clear sign of New Physics!

ggHH: higher order QCD corrections in the SM

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

N3LO(HTL)+N3LL: Ajjath, Shao '22

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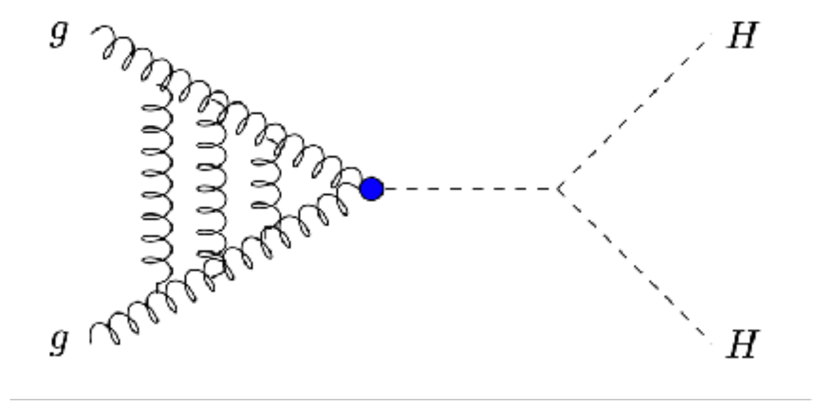

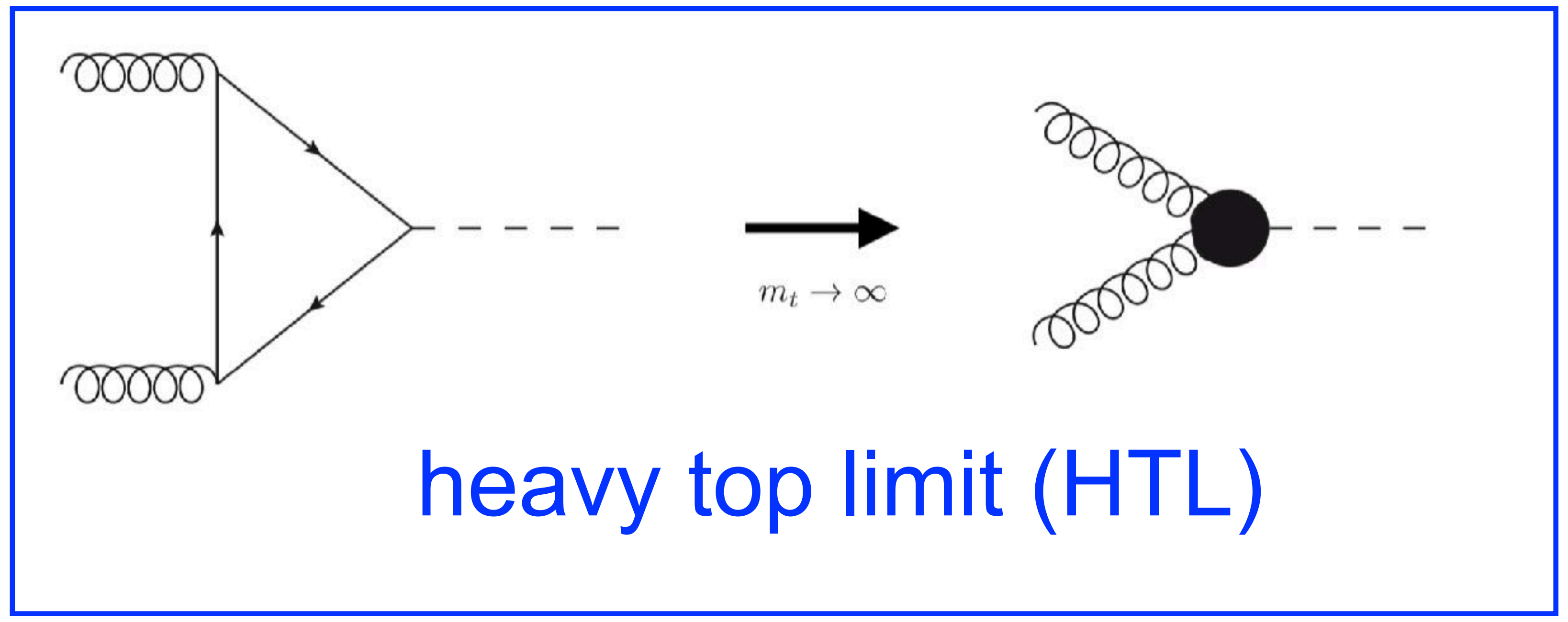

$\mathrm{NNLO}_{\mathrm{FTapprox}}$ Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18

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

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

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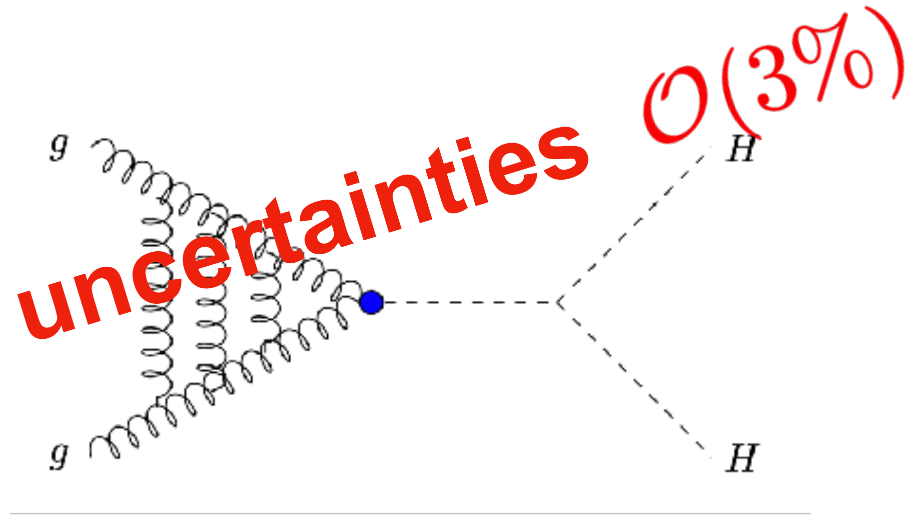

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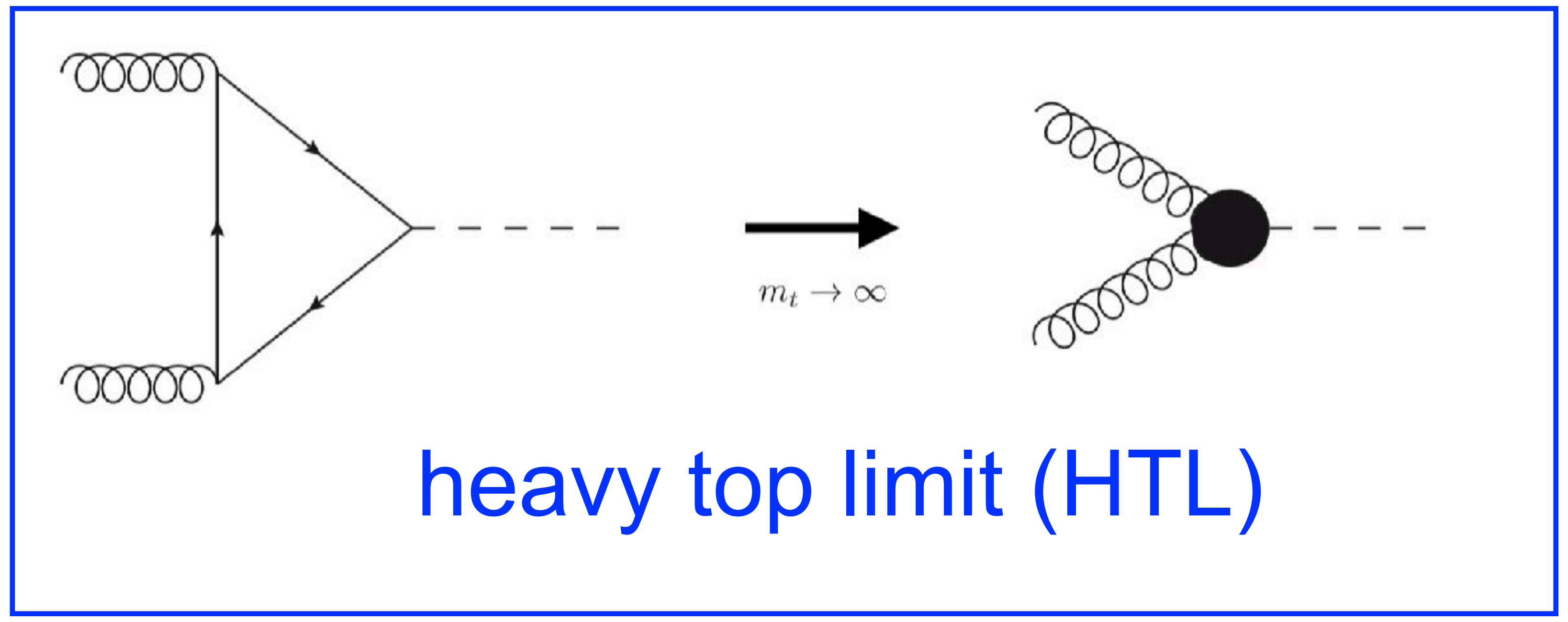

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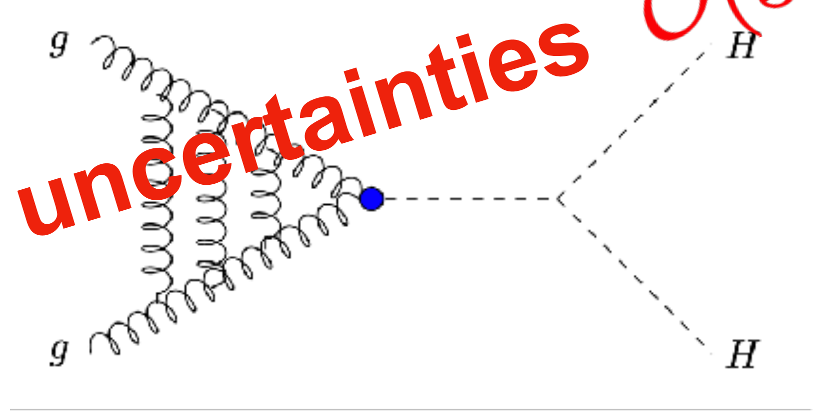
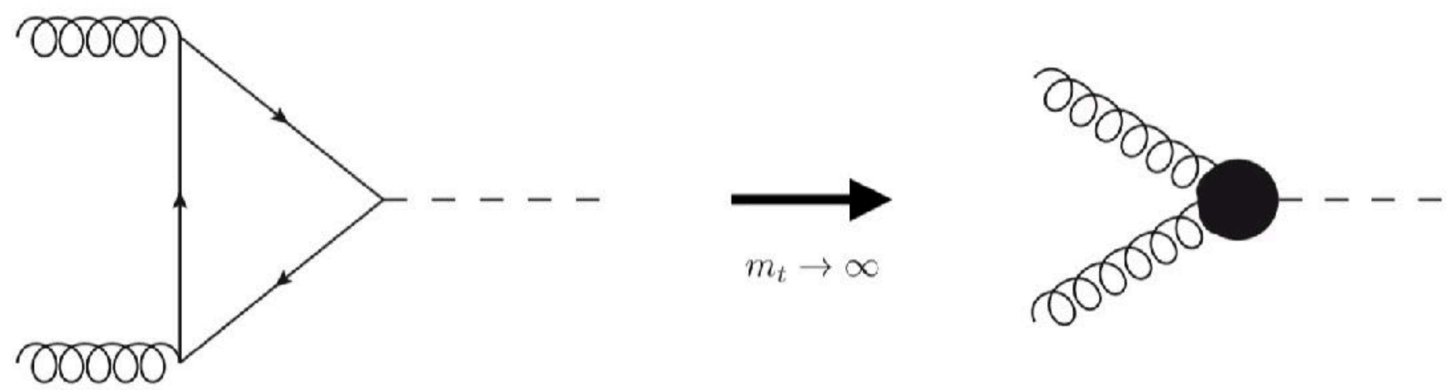


scale uncertainties $\mathcal{O}(3\%)$



heavy top limit (HTL)

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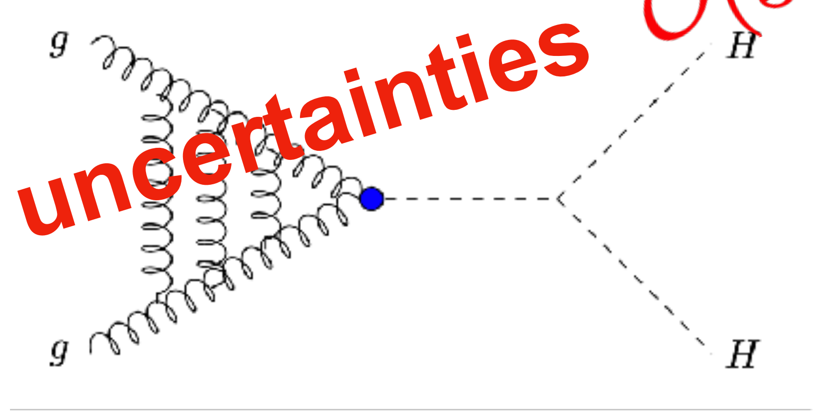

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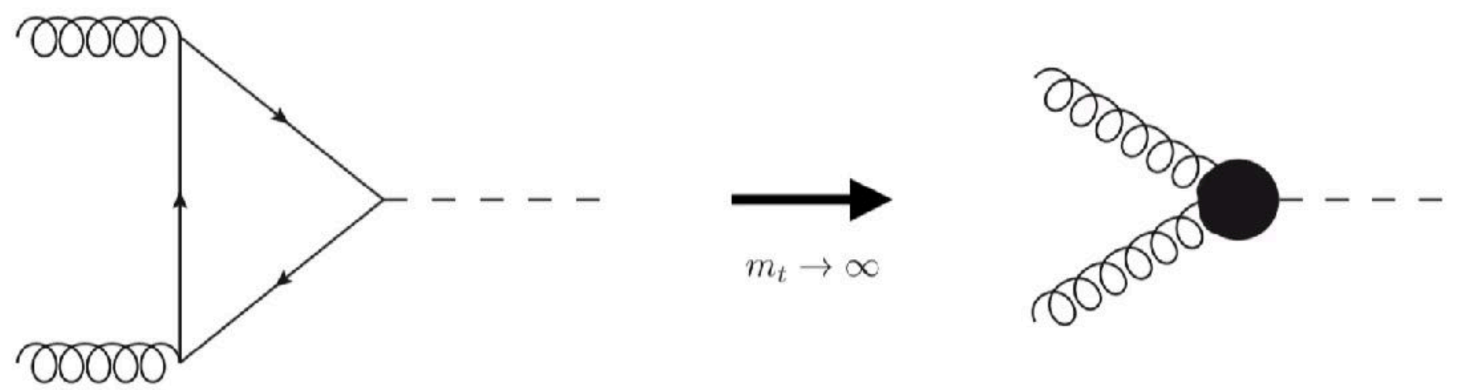

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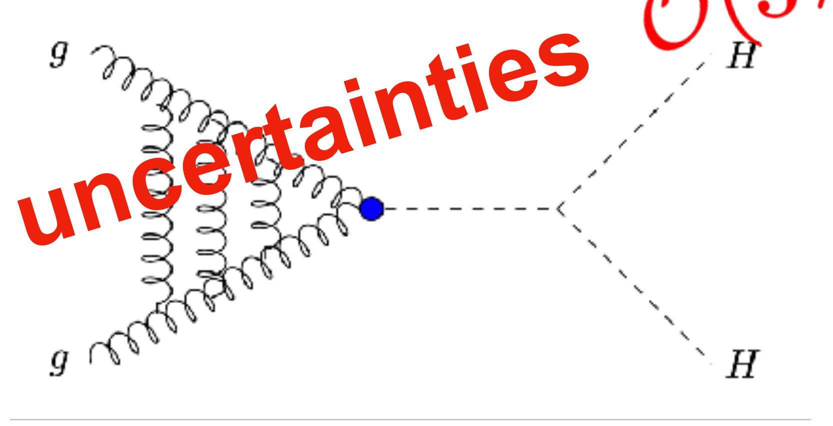

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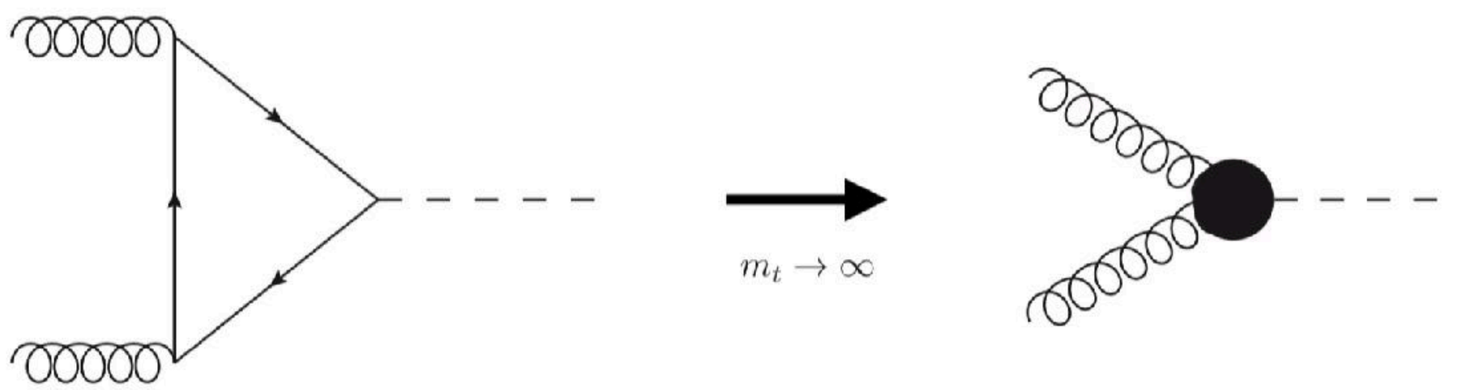

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top quark mass scheme uncertainties: pole mass versus $\overline{\mathrm{MS}}$ mass → towards NNLO with full m_t

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see talk by Joshua Davies (Monday)

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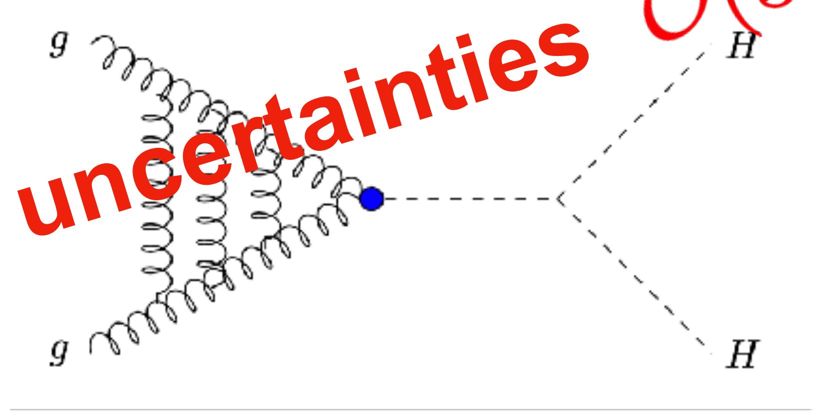

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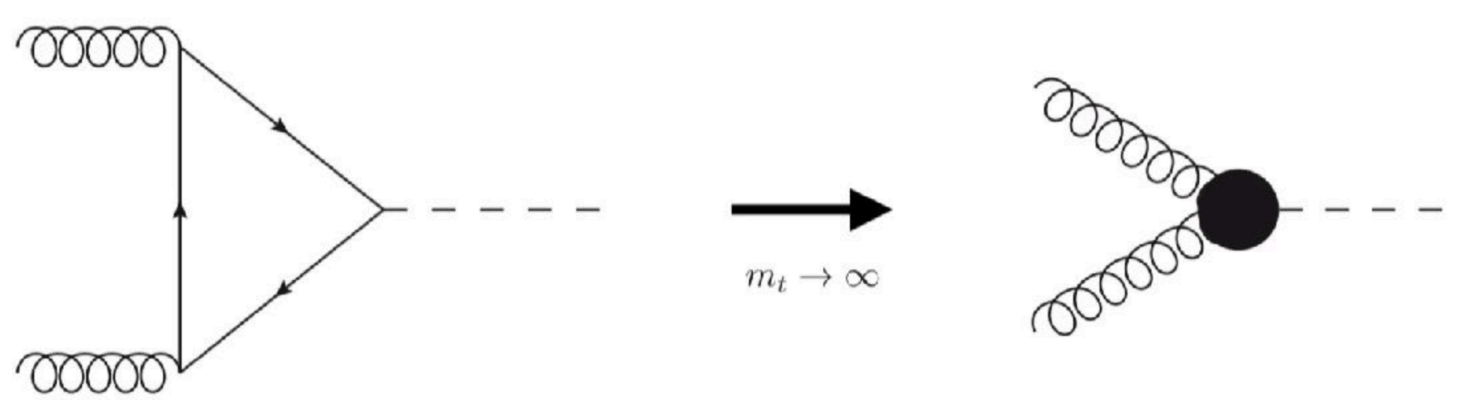

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see also NLO corrections to HH decay to $b\bar{b}\gamma\gamma$

Li, Si, Wang, Zhang, Zhao 2402.00401

QCD corrections to the decay decrease LO result by 19%

→ towards NNLO with full m_t

see talk by Joshua Davies (Monday)

ggHH: higher order EW corrections in the SM

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Full NLO EW corrections: **- 4%** (total cross section, larger for distributions)

Bi, Huang, Huang, Ma ’23

Davies, Schönwald, Steinhauser, Zhang ’23 (large mt-expansion)

see also

Davies, Mishima, Schönwald, Steinhauser, Zhang ’22

Mühlleitner, Schlenk, Spira ‘22

Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao ‘19

Bizon, Haisch, Rottoli [Gillis, Moser, Windischhofer] ’18, ‘24

talks by
Matthias Kerner, Hantian Zhang
Monday afternoon

Anomalous couplings in Higgs boson pair production

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if trilinear coupling is different from the SM, other couplings are likely to be non-SM as well

→ **need full Effective Field Theory parametrisation**

$$\mathcal{M}^{\mathrm{LO}}_{\mathrm{SMEFT}} =$$

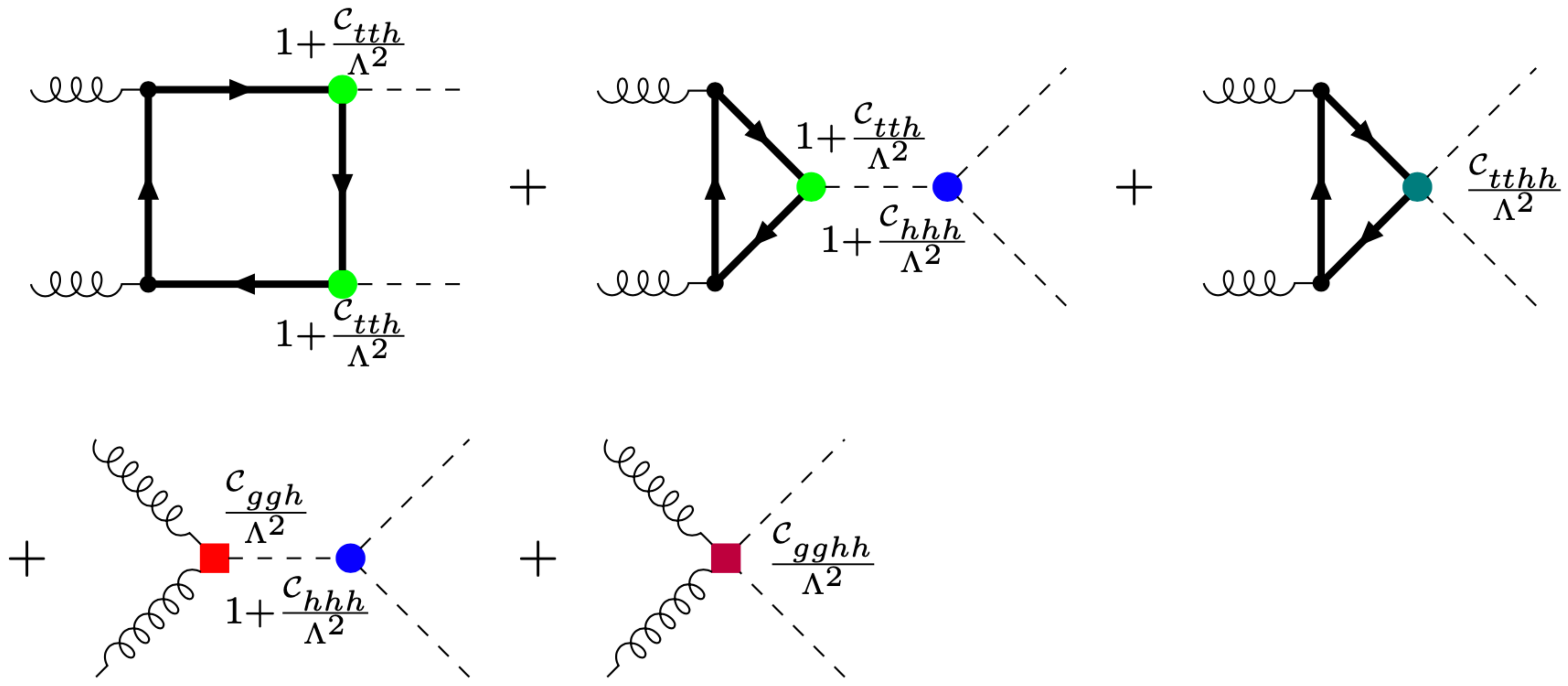


figure: Jannis Lang

Effective Field Theory

Karlsruhe Institute of Technology

E

new physics scale Λ

f : characteristic scale of Goldstone bosons

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

- need a scale separation
- expansion parameter small through suppression by a large scale

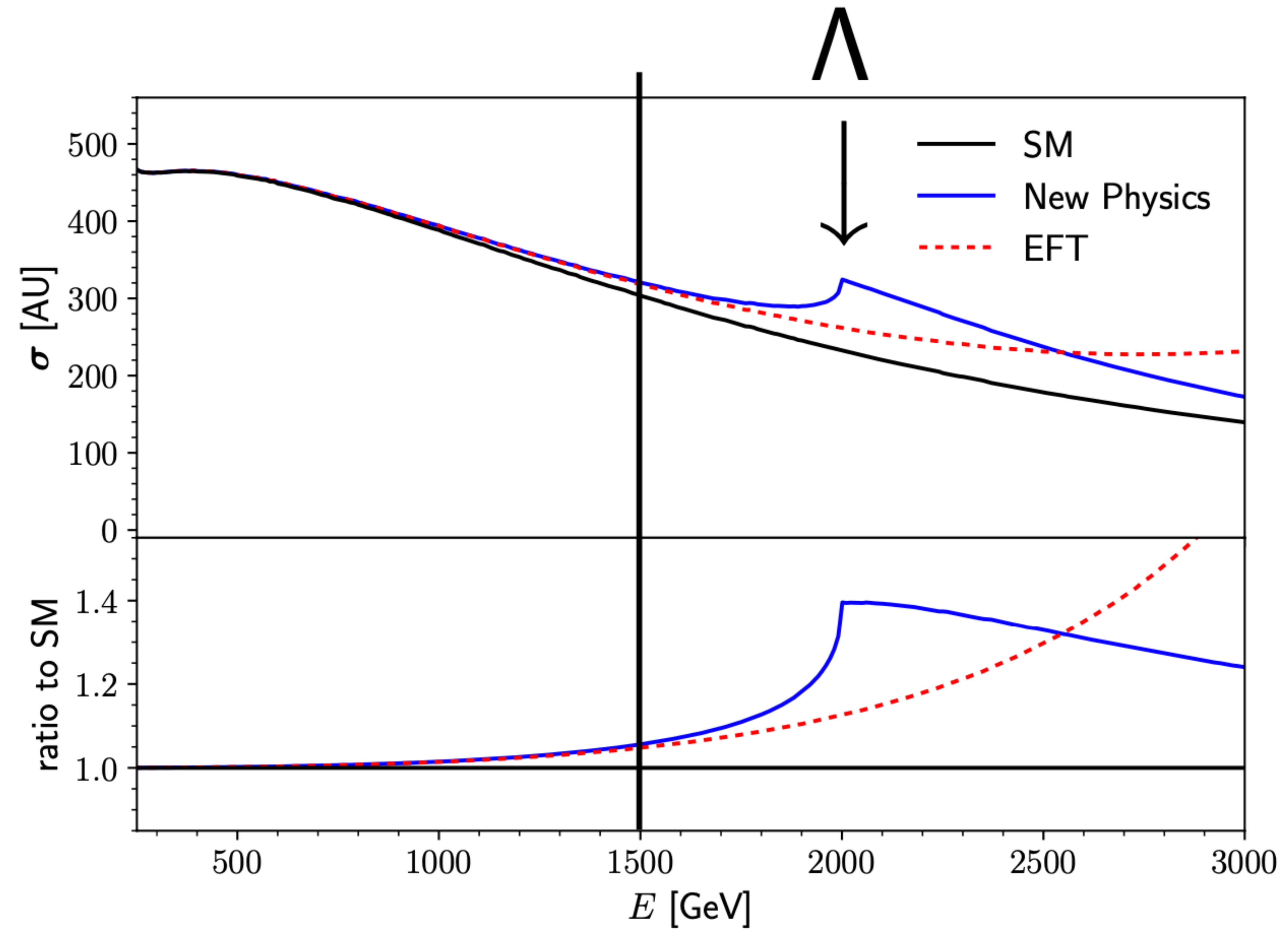
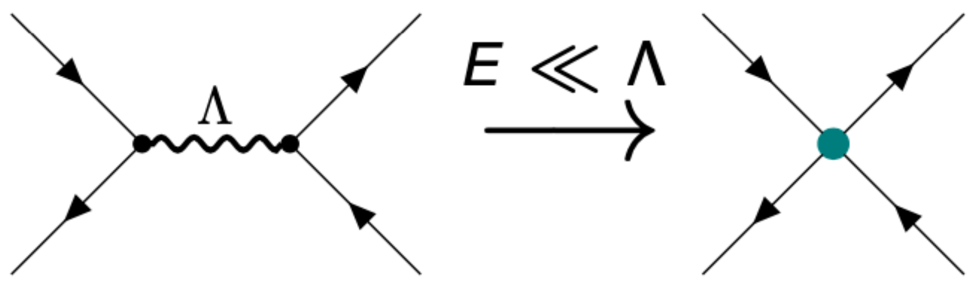
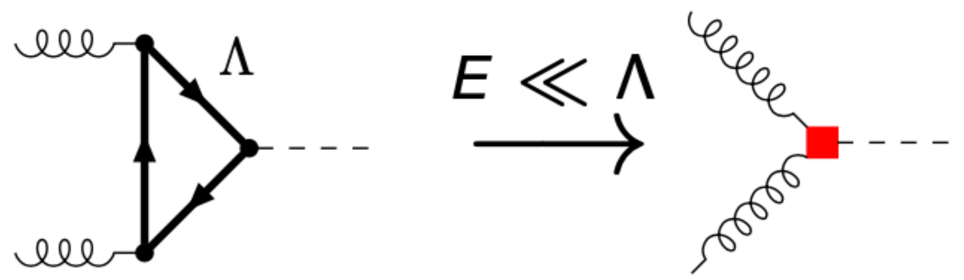


figure: Jannis Lang



$$\longrightarrow \Delta\mathcal{L} = \frac{C}{\Lambda^2}\bar{\psi}_i\gamma^\mu\psi_j\,\bar{\psi}_k\gamma_\mu\psi_l + \mathcal{O}\left(\Lambda^{-4}\right)$$



$$\longrightarrow \Delta\mathcal{L} = \frac{g_s^2 C'}{(16\pi^2)\Lambda^2}(\phi^\dagger\phi)\,G^a_{\mu\nu}G^{a\,\mu\nu} + \mathcal{O}\left(\Lambda^{-4}\right)$$

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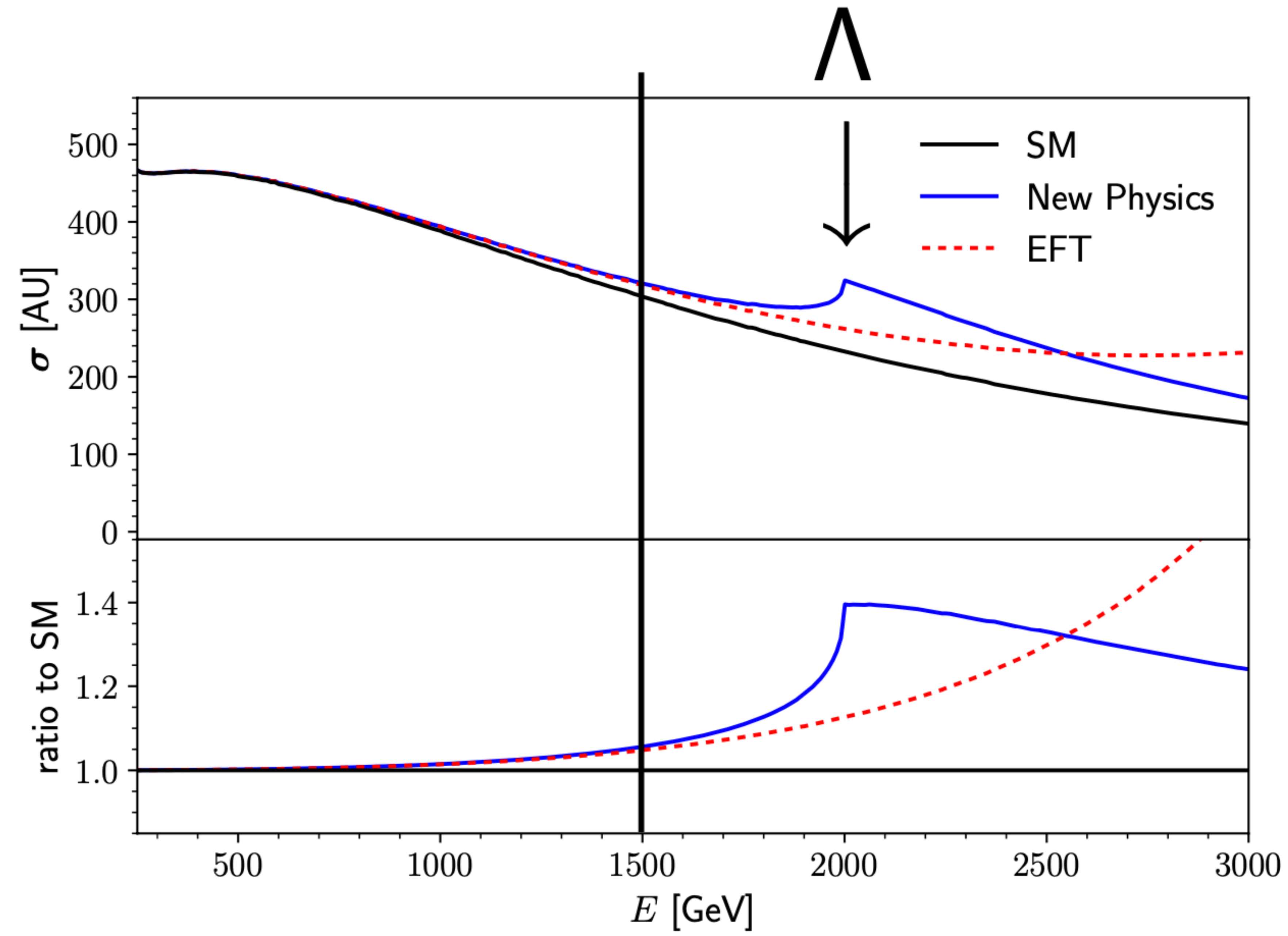

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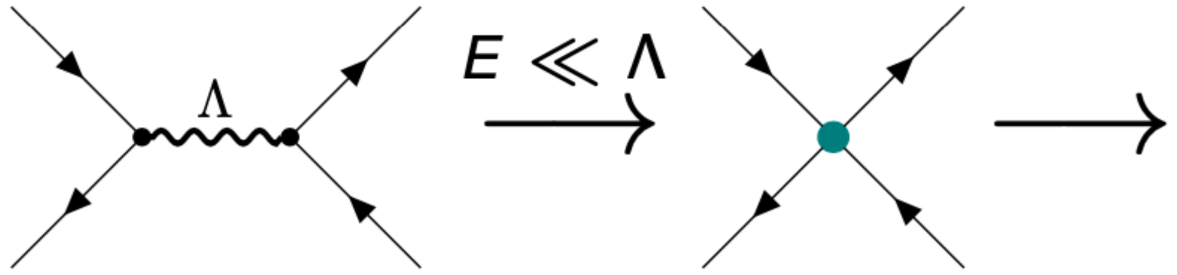

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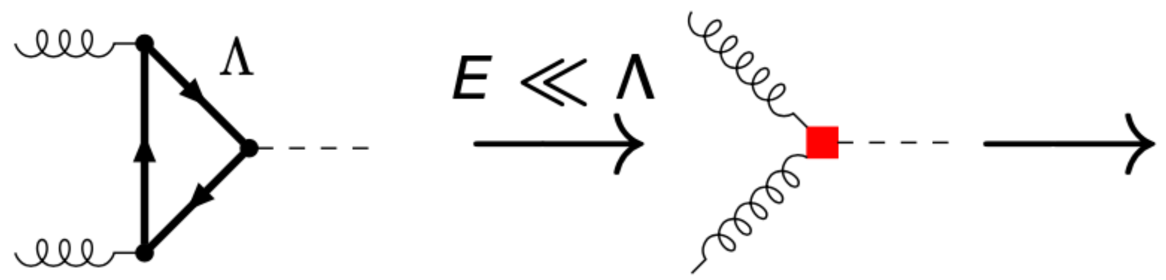

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Effective Field Theory expansion schemes

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SMEFT (Standard Model Effective Field Theory):

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

- assumes that Higgs field transforms linearly as a doublet under SU(2)_L
- canonical (mass) dimension counting
- weakly coupled UV completion

Leading SMEFT operators relevant for HH production

Karlsruhe Institute of Technology

SMEFT: Warsaw basis Grzadkowski et al. 1008.4884

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

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? $$+\frac{C_{uG}}{\Lambda^2}\left(\bar{q}_L\sigma^{\mu\nu}T^a G^a_{\mu\nu}\phi^c\, t_R + \text{h.c.}\right)$$

(chromomagnetic operator)

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(chromomagnetic operator)

sub-leading here if UV completion is a weakly coupled, renormalisable gauge theory

EFT expansion + higher orders in QCD

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(SM)EFT expansion parameters:

$$\Lambda^{-d_c}(g_s^2\,L)^{l_{\rm QCD}}\,\mathbf{L}^{l_{\rm not\_QCD}}$$

d_c : canonical dimension

This is an expansion in several parameters

g_s : strong coupling

$L=(16\pi)^{-1}$: loop factor (QCD)

$\mathbf{L}=(16\pi)^{-1}$: loop factor (new physics)

$l_{\rm QCD}$: number of QCD loops

$l_{\rm not\_QCD}$: number of loops involving new particles or new interactions or EW corrections

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In renormalisable, weakly coupled UV completions:

Operators containing field strength tensors are loop-generated $\Rightarrow$ get a loop suppression factor

Arzt, Einhorn Wudka ’94; Buchalla, GH, Müller-Salditt, Pandler 2204.11808

Loop-generated operators

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Isidori, Wilsch, Wyler, Review Mod. Phys. 2303.16922

PTG: Potentially Tree Generated

LG: Loop Generated

5–7: Fermion Bilinears (ψ^2)

non-hermitian ($\bar{L}R$)			
5: $\psi^2 H^3$ + h.c. [PTG]	6: $\psi^2 XH$ + h.c. [LG]		
Q_{eH} $(H^\dagger H)(\bar{\ell}_p e_r H)$	Q_{eW} $(\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	Q_{uG} $(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H} G^A_{\mu\nu}$	Q_{dG} $(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
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Q_{dH} $(H^\dagger H)(\bar{q}_p d_r H)$		Q_{uB} $(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H} B_{\mu\nu}$	Q_{dB} $(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$

7: $\psi^2 H^2 D$ – hermitian + Q_{Hud} [PTG]		
$(\bar{L}L)$	$(\bar{R}R)$	$(\bar{R}R')$ + h.c.
$Q^{(1)}_{H\ell}$ $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}_p \gamma^\mu \ell_r)$	Q_{He} $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	Q_{Hud} $i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$
$Q^{(3)}_{H\ell}$ $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$	Q_{Hu} $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
$Q^{(1)}_{Hq}$ $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	Q_{Hd} $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	
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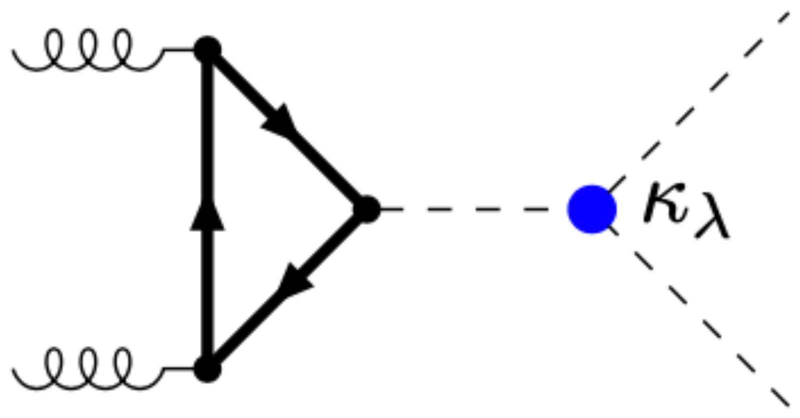
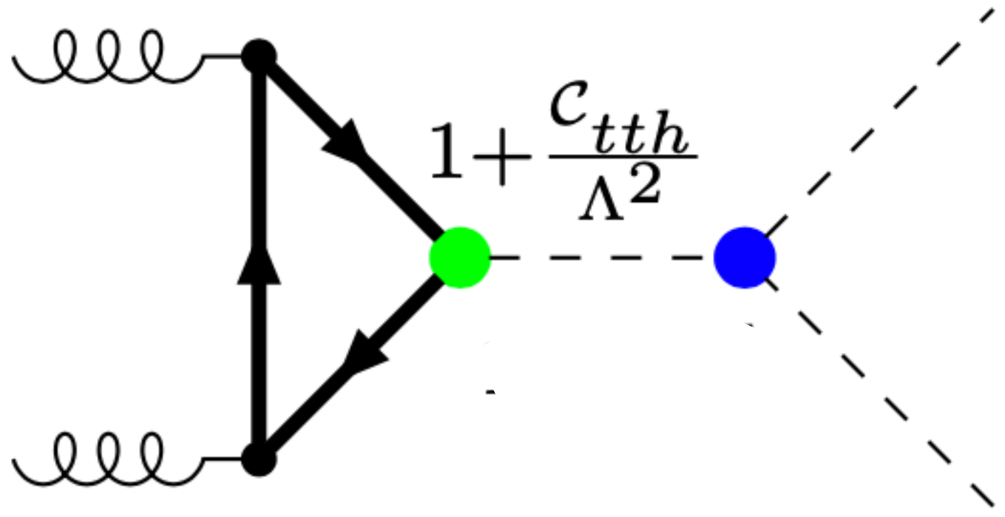
$Q^{(3)}_{H\ell}$ $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$	Q_{Hu} $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
$Q^{(1)}_{Hq}$ $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	Q_{Hd} $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	
$Q^{(3)}_{Hq}$ $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$		

Loop counting in SMEFT



$$\frac{1}{16\pi^2} \quad l_{\rm QCD} = 1$$



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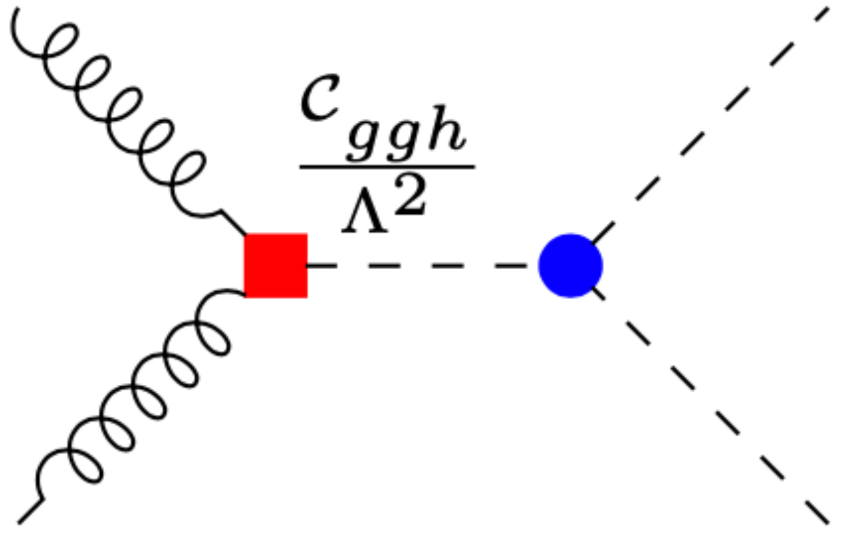
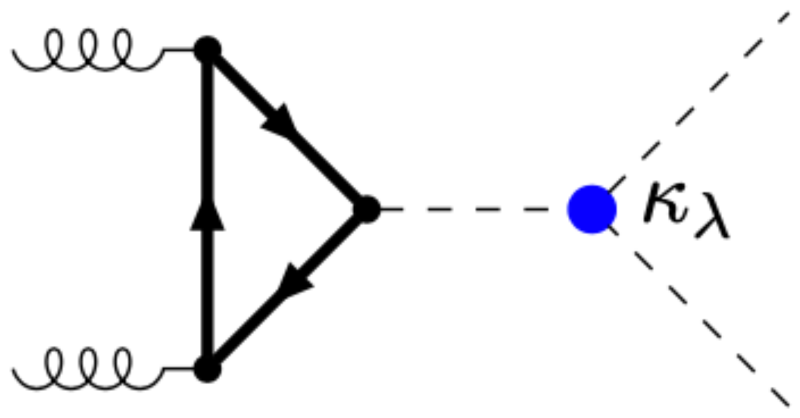


$$\frac{1}{\Lambda^2}\frac{1}{16\pi^2} \quad l_{\rm not\_QCD} = 1$$

Loop counting in SMEFT



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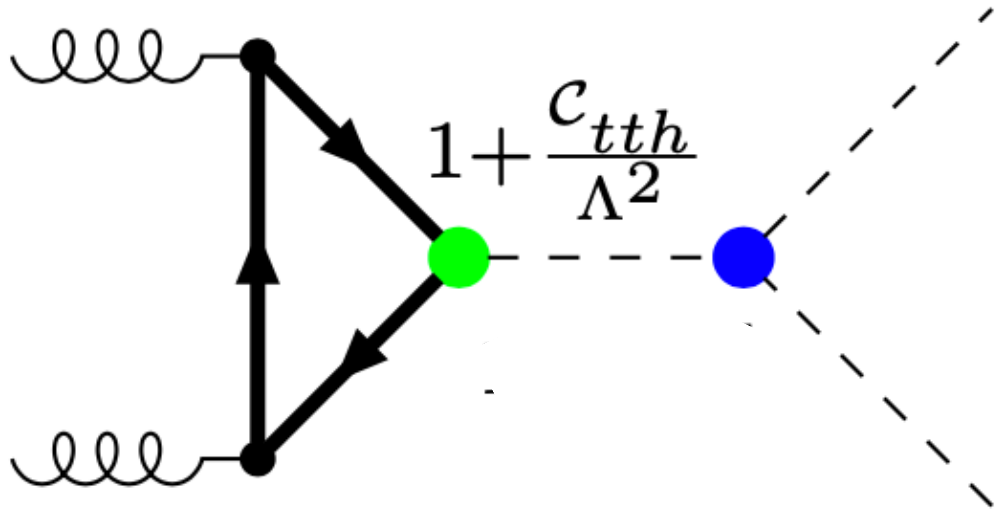

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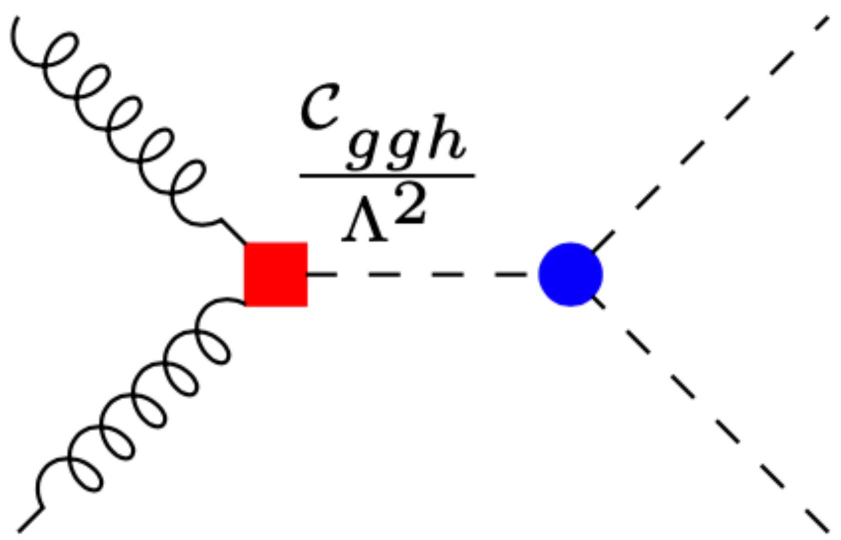

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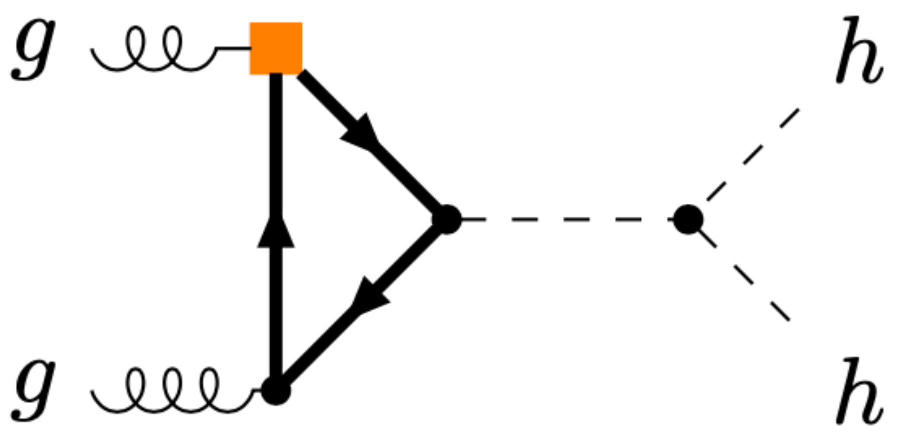
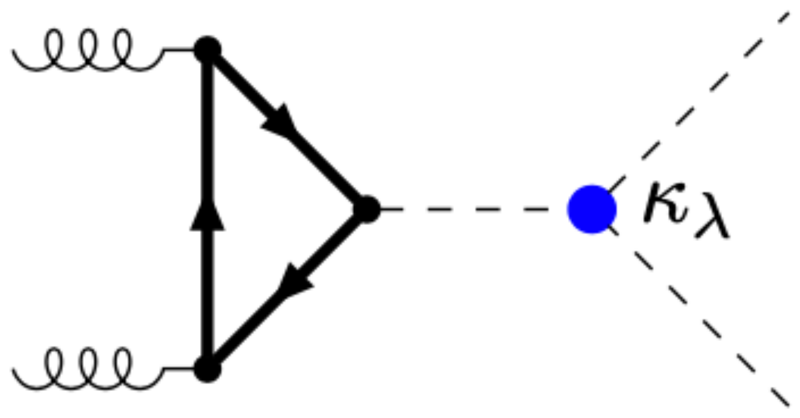


chromomagnetic operator

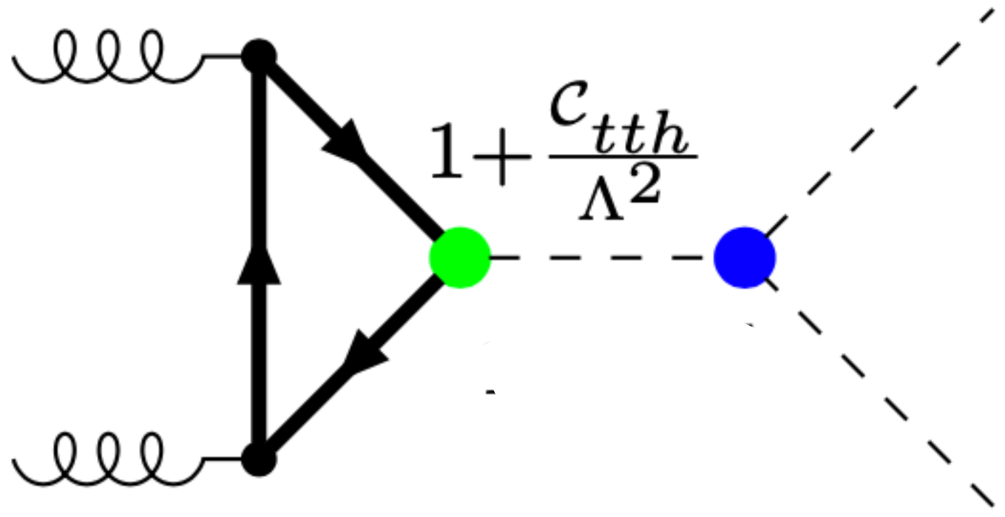
$$\frac{1}{\Lambda^2}\frac{1}{(16\pi^2)^2} \quad l_{\rm QCD} = 1, l_{\rm not\_QCD} = 1$$

explicit implicit

Loop counting in SMEFT



$\frac{1}{16\pi^2}$ $\quad l_{\rm QCD} = 1$



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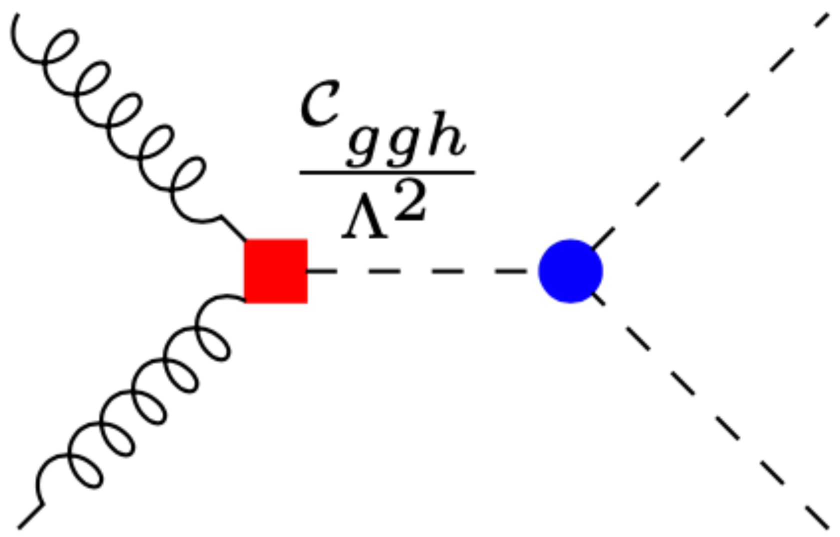

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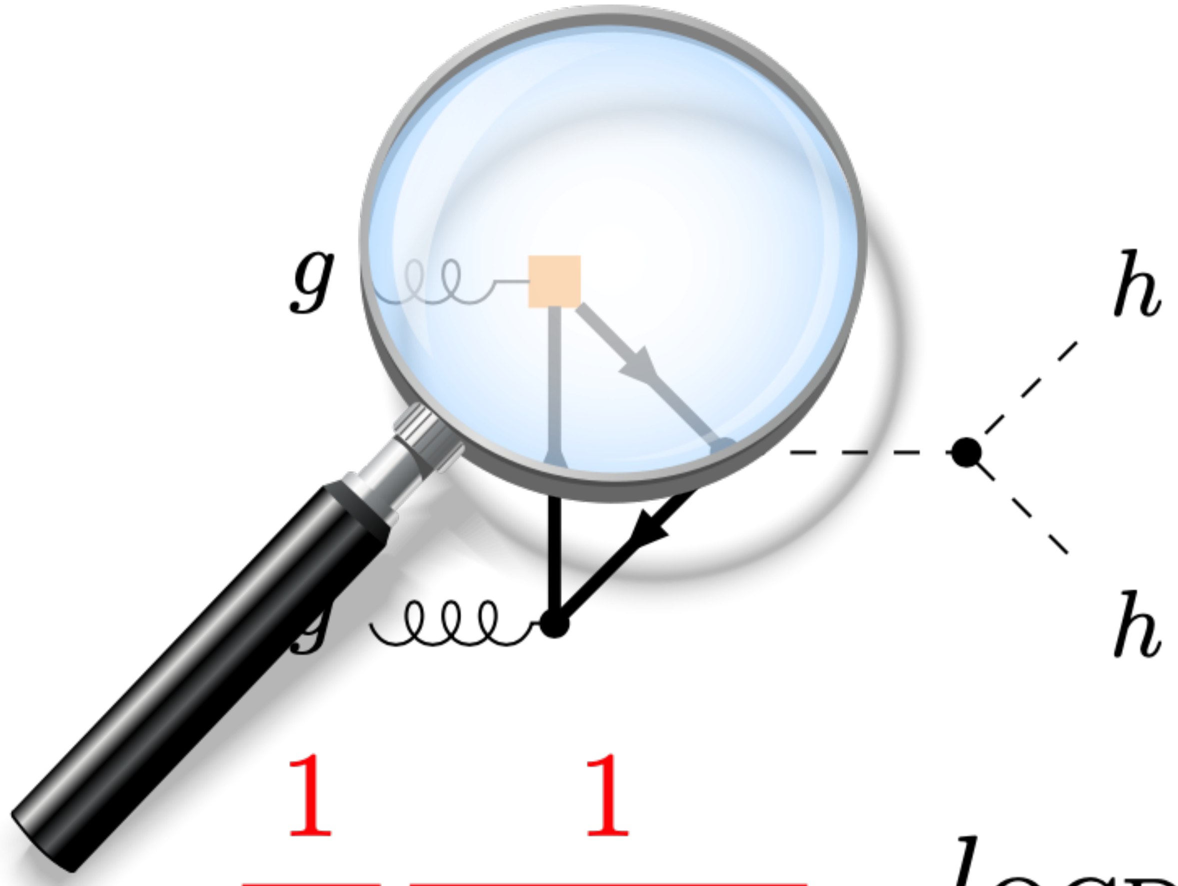

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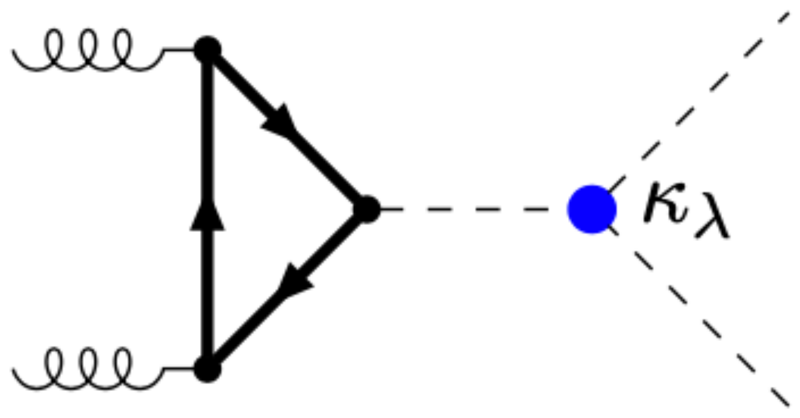
Loop counting in SMEFT



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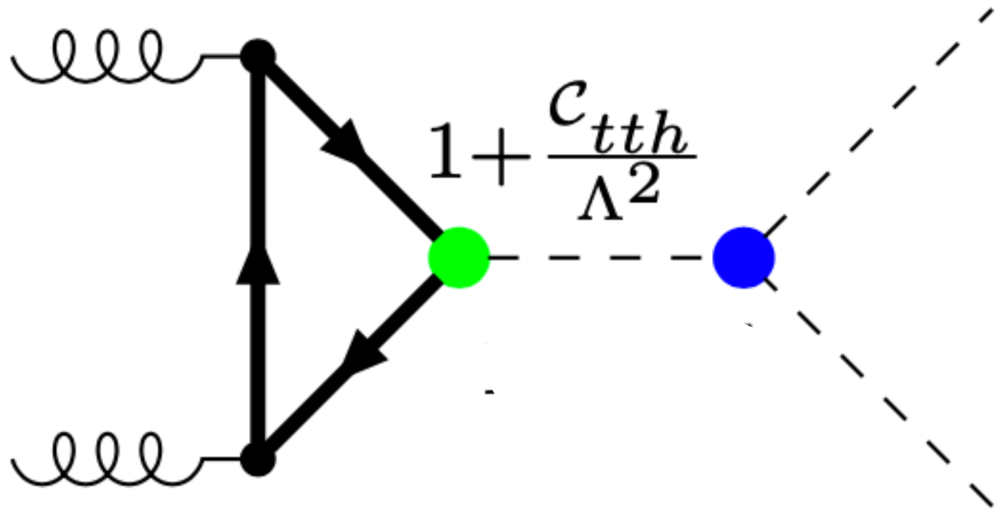

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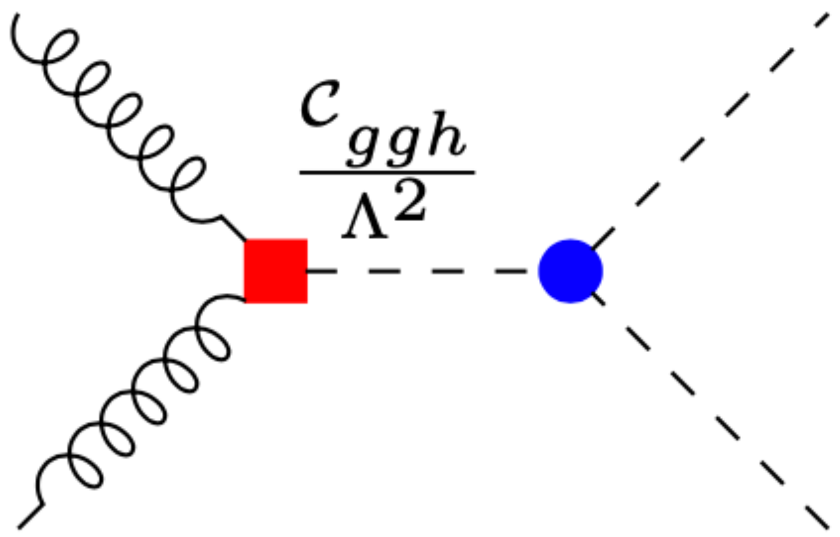

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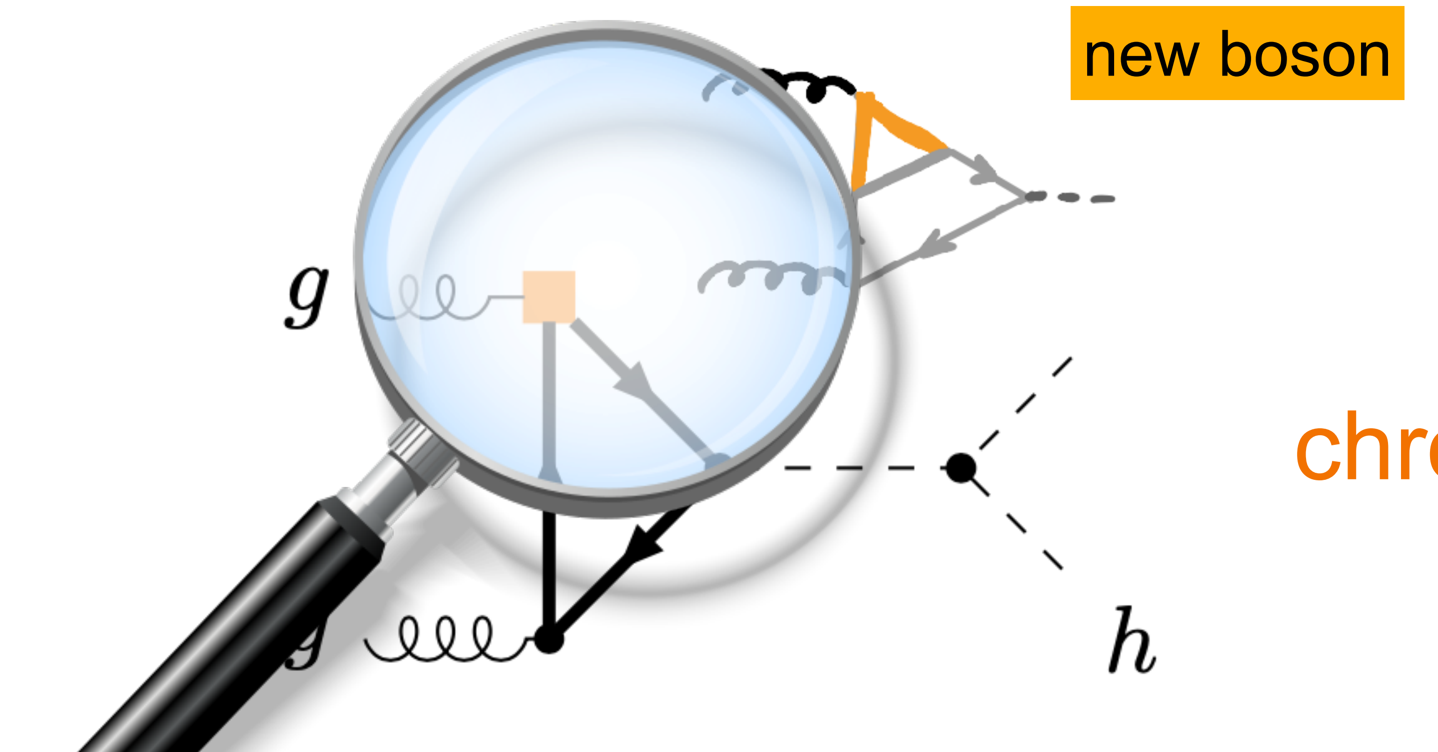

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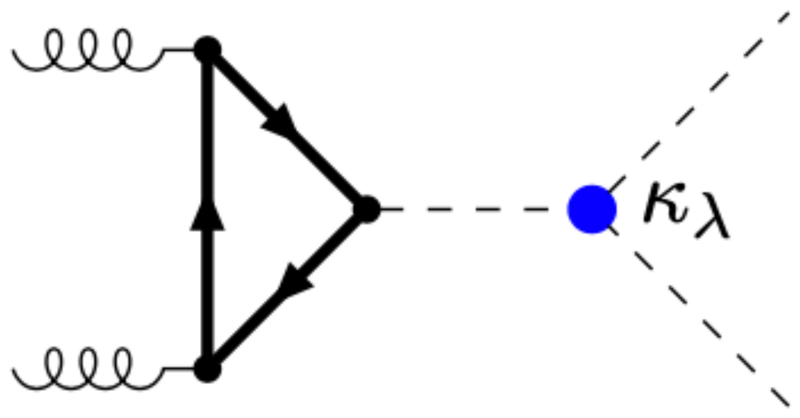

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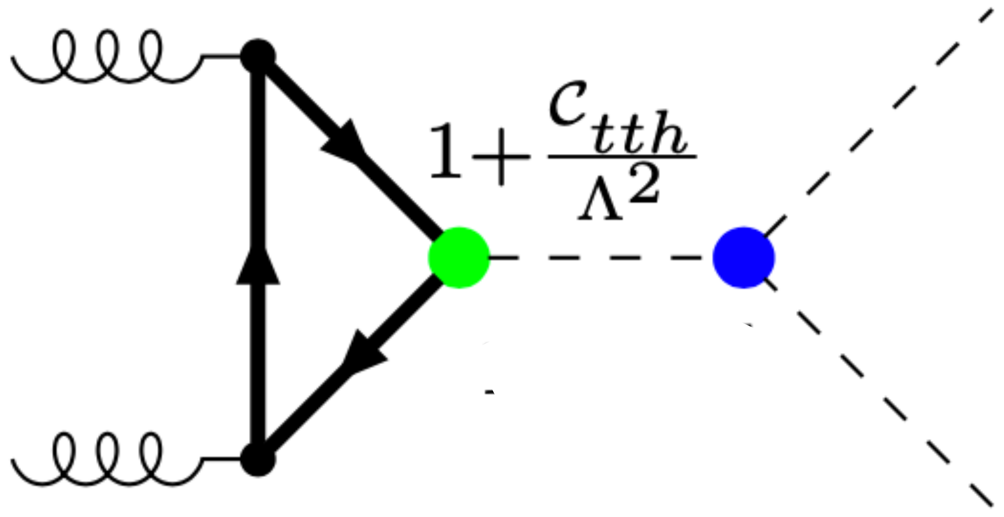

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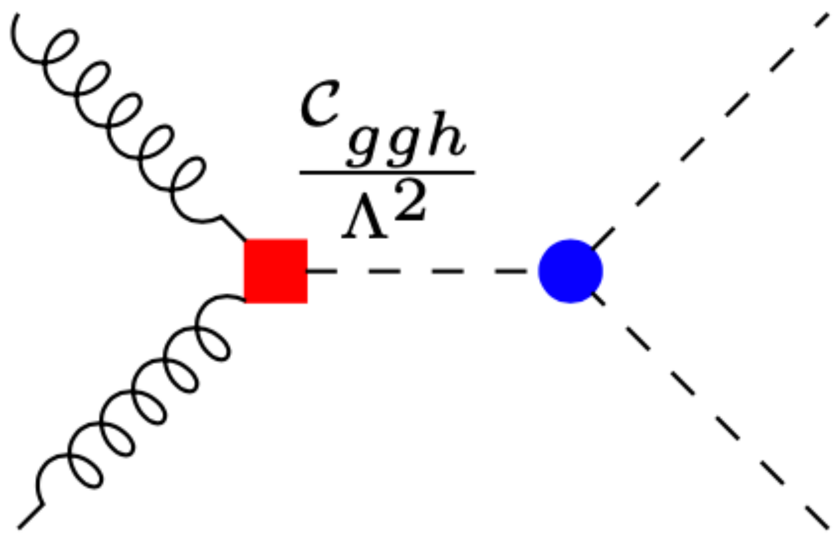

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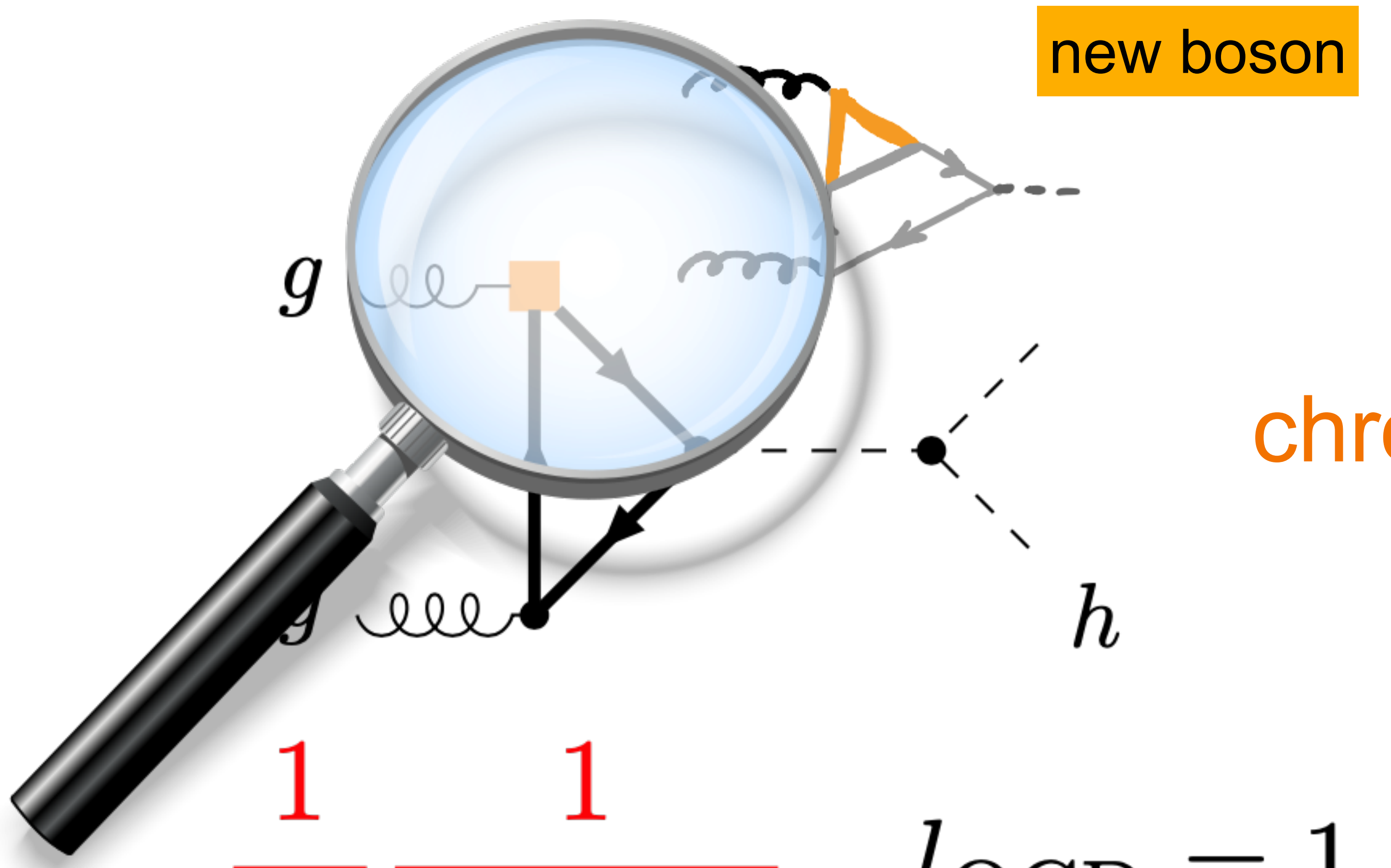

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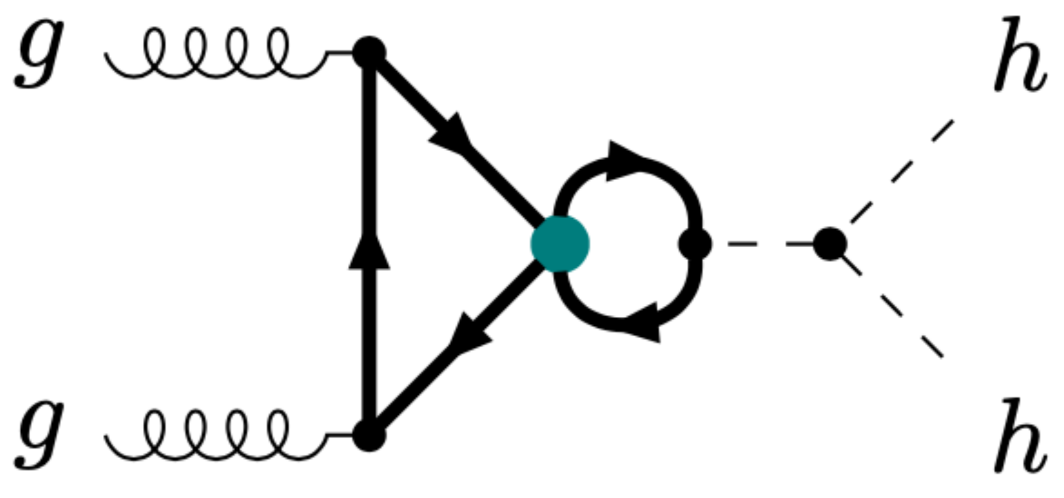


4-top operators enter at the same order!

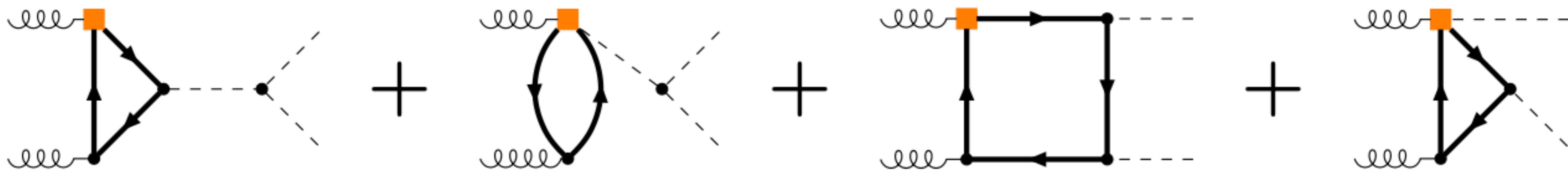
$$\frac{1}{\Lambda^2}\frac{1}{(16\pi^2)^2} \quad l_{\text{QCD}} = 1, l_{\text{not\_QCD}} = 1$$

explicit explicit

Subleading operators in SMEFT

in a renormalisable, weakly coupling UV completion

$$\mathcal{L}_{tG} = \frac{C_{tG}}{\Lambda^2}\left(\bar{Q}_L \sigma^{\mu\nu} T^a G^a_{\mu\nu} \tilde{\phi} t_R + \text{h.c.}\right)$$

$\mathcal{M}_{\text{tG}} =$ 

$$\mathcal{L}_{4t} = \frac{C^{(1)}_{Qt}}{\Lambda^2} \bar{Q}_L \gamma^\mu Q_L \bar{t}_R \gamma_\mu t_R + \frac{C^{(8)}_{Qt}}{\Lambda^2} \bar{Q}_L \gamma^\mu T^a Q_L \bar{t}_R \gamma_\mu T^a t_R$$
$$+ \frac{C^{(1)}_{QQ}}{\Lambda^2} \bar{Q}_L \gamma^\mu Q_L \bar{Q}_L \gamma_\mu Q_L + \frac{C^{(8)}_{QQ}}{\Lambda^2} \bar{Q}_L \gamma^\mu T^a Q_L \bar{Q}_L \gamma_\mu T^a Q_L$$
$$+ \frac{C_{tt}}{\Lambda^2} \bar{t}_R \gamma^\mu t_R \bar{t}_R \gamma_\mu t_R$$

Subleading operators in SMEFT

in a renormalisable, weakly coupling UV completion

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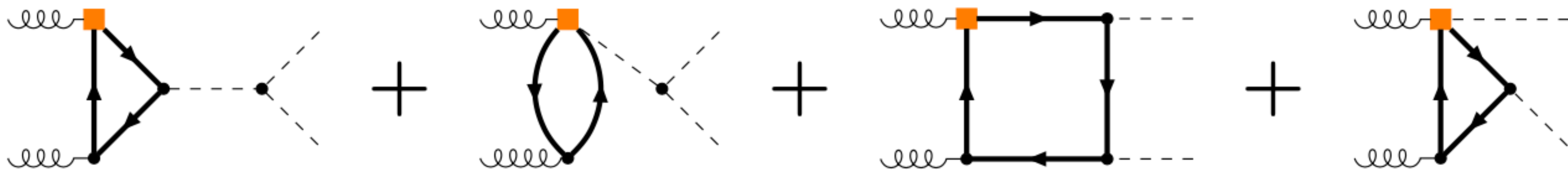
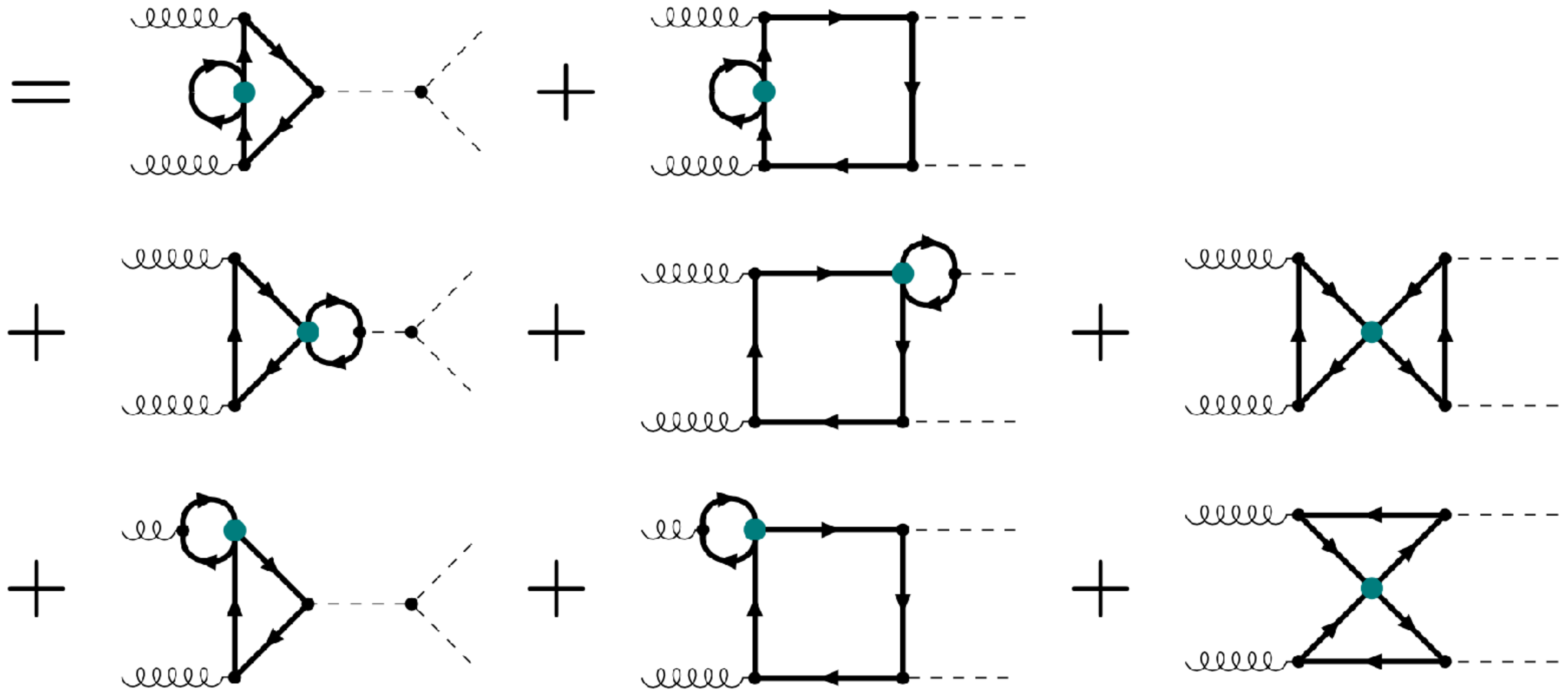
$\mathcal{M}_{\rm tG} =$



$$\mathcal{L}_{4t} = \frac{C^{(1)}_{Qt}}{\Lambda^2}\bar{Q}_L\gamma^\mu Q_L \bar{t}_R\gamma_\mu t_R + \frac{C^{(8)}_{Qt}}{\Lambda^2}\bar{Q}_L\gamma^\mu T^a Q_L \bar{t}_R\gamma_\mu T^a t_R$$
$$+ \frac{C^{(1)}_{QQ}}{\Lambda^2}\bar{Q}_L\gamma^\mu Q_L \bar{Q}_L\gamma_\mu Q_L + \frac{C^{(8)}_{QQ}}{\Lambda^2}\bar{Q}_L\gamma^\mu T^a Q_L \bar{Q}_L\gamma_\mu T^a Q_L$$
$$+ \frac{C_{tt}}{\Lambda^2}\bar{t}_R\gamma^\mu t_R \bar{t}_R\gamma_\mu t_R$$

$\mathcal{M}_{\rm 4t} =$



Four-top operators

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$$\mathcal{L}_{4t} = \frac{C_{Qt}^{(1)}}{\Lambda^2} \underbrace{\bar{t}_L \gamma^\mu t_L \, \bar{t}_R \gamma_\mu t_R}_{\bar{t}\mathbb{P}_R \gamma^\mu \mathbb{P}_L t \, \bar{t}\mathbb{P}_L \gamma_\mu \mathbb{P}_R t} + \frac{C_{Qt}^{(8)}}{\Lambda^2} \bar{t}_L \gamma^\mu T^a t_L \, \bar{t}_R \gamma_\mu T^a t_R + \ldots$$

$$; \quad \mathbb{P}_{L/R} = (\mathbb{I} \mp \gamma_5)/2$$

- 4-top operators occur in 2-loop diagrams
- treatment of γ_5 matters!
- translation between schemes also affects other operators and parameters

3 theses about gamma5 in 4 dimensions

$$\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$$

definition in 4 space-time dimensions

3 theses about gamma5 in 4 dimensions

Karlsruhe Institute of Technology

$$\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$$ definition in 4 space-time dimensions

in 4 dimensions:

$\{\gamma_5, \gamma^\mu\} = 0$ (1) ; $\mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma_5] = -4i\epsilon^{\mu\nu\rho\sigma}$ (2) ; $\mathrm{Tr}[\Gamma_1\Gamma_2\gamma_5] = \mathrm{Tr}[\gamma_5\Gamma_1\Gamma_2]$ (3)

cyclicity of Traces

3 theses about gamma5 in 4 dimensions

$$\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$$

definition in 4 space-time dimensions

in 4 dimensions:

$\{\gamma_5, \gamma^\mu\} = 0$ (1) ; $\mathrm{Tr}[\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma_5] = -4i\epsilon^{\mu\nu\rho\sigma}$ (2) ; $\mathrm{Tr}[\Gamma_1\Gamma_2\gamma_5] = \mathrm{Tr}[\gamma_5\Gamma_1\Gamma_2]$ (3)

cyclicity of Traces

in $D = 4 - 2\epsilon$ dimensions: (1), (2) and (3) cannot be maintained simultaneously

gamma5 in D dimensions

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different schemes to extend γ_5 to D dimensions:

"naive dimensional regularisation" (**NDR**):	Breitenlohner, Maison; ‘t Hooft, Veltman (**BMHV**):
keep $\{\gamma_5, \gamma^\mu\} = 0$	$\gamma^\mu = \underbrace{\bar{\gamma}^\mu}_{\text{4-dim.}} + \underbrace{\hat{\gamma}^\mu}_{\text{(D-4) dim.}}$; $\{\gamma_5, \bar{\gamma}^\mu\} = 0$; $[\gamma_5, \hat{\gamma}^\mu] = 0$
abandon cyclicity of trace (or fix inconsistencies by hand)	• spurious breaking of gauge invariance
reading point for traces: "Kreimer scheme"	• needs symmetry restoring counterterms
but: ambiguities observed at high loop orders L. Chen, 2304.13814, J. Davies et al 2110.05496, …	• the latter can be derived algorithmically

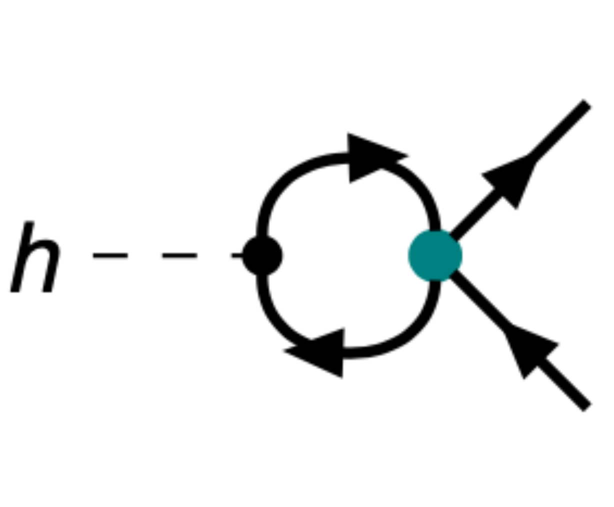
see talks by Matthias Weisswange,
Paul Kühler, Dominik Stöckinger

Scheme dependence induced by 4t operators

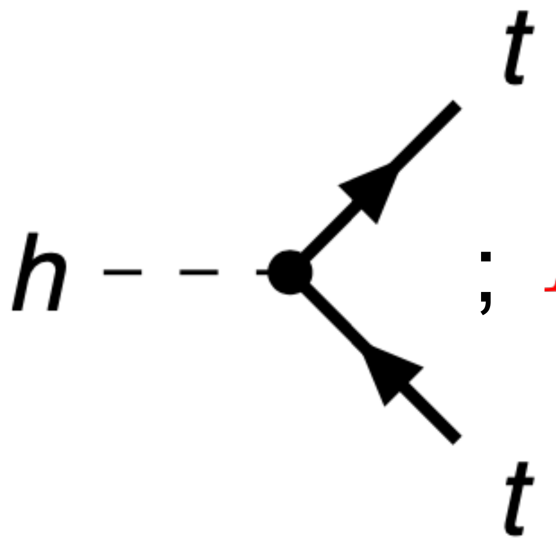
scheme dependent part

$$= \frac{C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}}{\Lambda^2} \left(B_{m_t} + K_{m_t}\right) \times$$

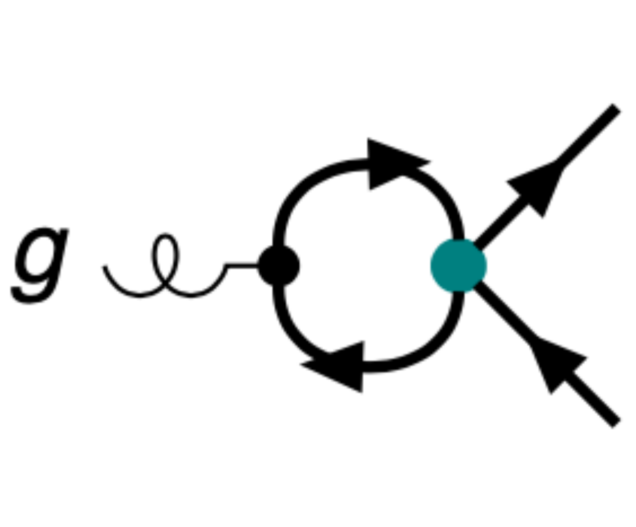
$$; \quad K_{m_t} = \begin{cases} -\frac{m_t^2}{8\pi^2} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$



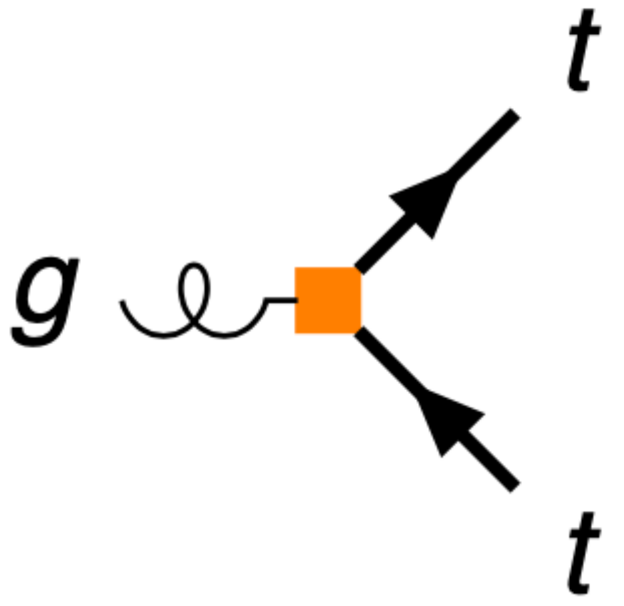
$$= \frac{C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}}{\Lambda^2} \left(B_{ht\bar{t}} + K_{m_t} - \frac{v^3}{\sqrt{2}m_t} K_{tH}\right) \times$$



$$; \quad K_{tH} = \begin{cases} \frac{\sqrt{2}m_t(4m_t^2 - m_h^2)}{16\pi^2 v^3} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$



$$= \frac{C_{Qt}^{(1)} + \left(c_F - \frac{c_A}{2}\right) C_{Qt}^{(8)}}{C_{tG}} K_{tG} \times$$



$$; \quad K_{tG} = \begin{cases} -\frac{\sqrt{2}m_t g_s}{16\pi^2 v} & \text{(NDR)} \\ 0 & \text{(BMHV)} \end{cases}$$

Scheme (in)dependence

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The renormalised physical amplitude must be scheme-independent

$$
\begin{aligned}
\mathcal{M}^{\text{ren}} &= \mathcal{M}^{\text{scheme indep.}} \\
&+ \left(C_{Qt}^{(1)} + c_F\, C_{Qt}^{(8)}\right) \frac{1}{\Lambda^2} K_{m_t} \frac{\partial \mathcal{M}_{\text{SM}}}{\partial m_t} \times m_t \\
&+ \left[1 - \frac{v^3}{\sqrt{2} m_t} \left(\frac{C_{tH}}{\Lambda^2} + K_{tH} \frac{C_{Qt}^{(1)} + c_F\, C_{Qt}^{(8)}}{\Lambda^2} \right)\right] \mathcal{M}_{\text{SM}} \\
&+ \left[C_{tG} + \left(C_{Qt}^{(1)} + (c_F - \frac{c_A}{2}) C_{Qt}^{(8)}\right) K_{tG}\right] \frac{1}{\Lambda^2} \mathcal{M}_{tG}\big|_{\text{FIN}}
\end{aligned}
$$

Scheme (in)dependence

Karlsruhe Institute of Technology

The renormalised physical amplitude must be scheme-independent

$$\mathcal{M}^{\text{ren}} = \mathcal{M}^{\text{scheme indep.}}$$
$$+ \left(C_{Qt}^{(1)} + c_F\, C_{Qt}^{(8)}\right) \frac{1}{\Lambda^2} K_{m_t} \frac{\partial \mathcal{M}_{\text{SM}}}{\partial m_t} \times m_t$$
$$+ \left[1 - \frac{v^3}{\sqrt{2} m_t} \left(\frac{C_{tH}}{\Lambda^2} + K_{tH} \frac{C_{Qt}^{(1)} + c_F\, C_{Qt}^{(8)}}{\Lambda^2} \right)\right] \mathcal{M}_{\text{SM}}$$
$$+ \left[C_{tG} + \left(C_{Qt}^{(1)} + (c_F - \frac{c_A}{2}) C_{Qt}^{(8)}\right) K_{tG}\right] \frac{1}{\Lambda^2} \mathcal{M}_{tG}\big|_{\text{FIN}}$$

$\Rightarrow$ scheme dependence of K-terms must be cancelled by scheme dependence of Wilson coefficients and parameters

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$$+ \left[1 - \frac{v^3}{\sqrt{2} m_t} \left(\frac{C_{tH}}{\Lambda^2} + K_{tH} \frac{C_{Qt}^{(1)} + c_F\, C_{Qt}^{(8)}}{\Lambda^2} \right)\right] \mathcal{M}_{\text{SM}}$$
$$+ \underbrace{\left[C_{tG} + \left(C_{Qt}^{(1)} + (c_F - \frac{c_A}{2}) C_{Qt}^{(8)}\right) K_{tG}\right]}_{\tilde{C}_{tG}} \frac{1}{\Lambda^2} \mathcal{M}_{tG}|_{\text{FIN}}$$

$\Rightarrow$ scheme dependence of K-terms must be cancelled by scheme dependence of Wilson coefficients and parameters

Scheme (in)dependence

possible solution: redefine parameters, absorbing scheme dependent parts

$$\tilde{C}_{tG} = C_{tG} + \left(C_{Qt}^{(1)} + (c_F - \frac{c_A}{2}) C_{Qt}^{(8)} \right) K_{tG}$$

$$\tilde{C}_{tH} = C_{tH} + \left(C_{Qt}^{(1)} + c_F C_{Qt}^{(8)} \right) K_{tH}$$

$$\tilde{m}_t = m_t \left(1 + \frac{C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}}{\Lambda^2} K_{m_t} \right)$$

known e.g. in flavour physics
Ciuchini et al. '93
Herrlich, Nierste '94

S. Di Noi et al, 2310.18221

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S. Di Noi et al, 2310.18221

more flexible: derive a **translation dictionary** by requiring $\tilde{X}^{\mathrm{NDR}} \stackrel{!}{=} \tilde{X}^{\mathrm{BMHV}}$

Translation between BMHV and NDR

4-top operators are linked to other operators through a scheme translation

$$m_t^{\mathrm{BMHV}} = m_t^{\mathrm{NDR}} - \frac{m_t^3}{8\pi^2\Lambda^2}\left(C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}\right)$$

$$C_{tH}^{\mathrm{BMHV}} = C_{tH}^{\mathrm{NDR}} + \frac{\sqrt{2}m_t(4m_t^2 - m_h^2)}{16\pi^2 v^3}\left(C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}\right)$$

$$C_{tG}^{\mathrm{BMHV}} = C_{tG}^{\mathrm{NDR}} + \frac{\sqrt{2}m_t g_s}{16\pi^2 v}\left(C_{Qt}^{(1)} + (c_F - \frac{c_A}{2})C_{Qt}^{(8)}\right)$$

S. Di Noi et al, 2310.18221

note: loop suppression factor for C_{tG} not included here (Warsaw basis conventions)

Translation between BMHV and NDR

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$$C_{tH}^{\mathrm{BMHV}} = C_{tH}^{\mathrm{NDR}} + \frac{\sqrt{2}m_t(4m_t^2 - m_h^2)}{16\pi^2 v^3}\left(C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}\right)$$

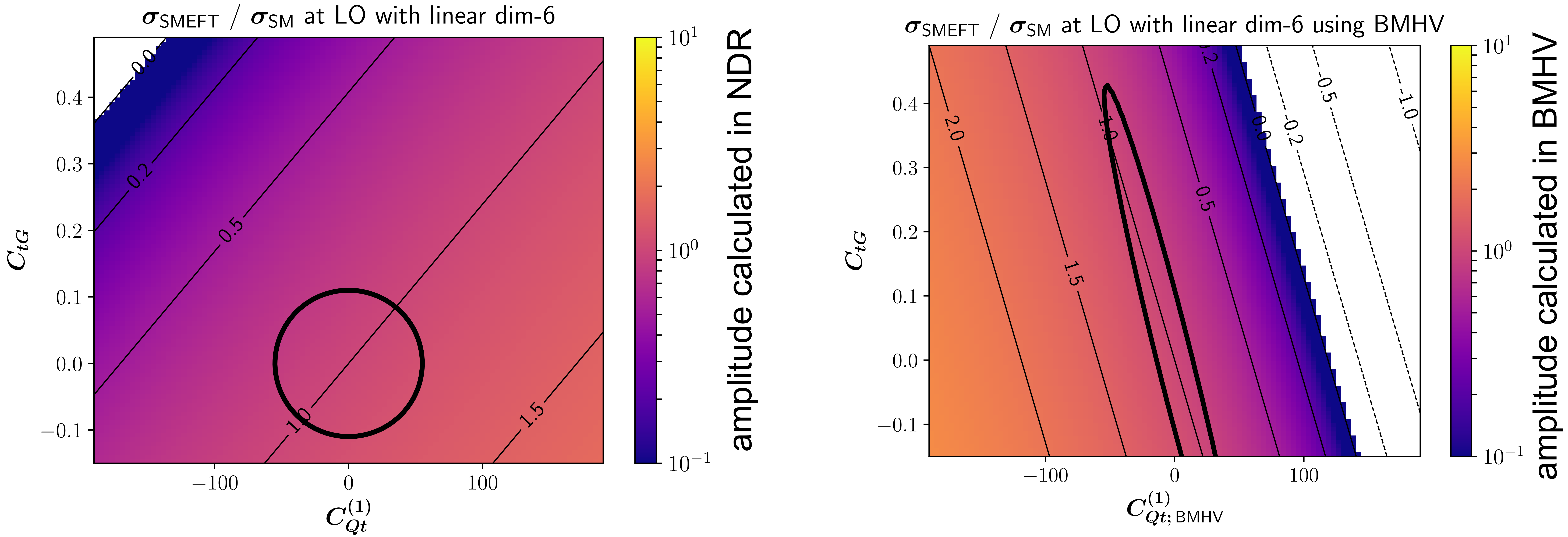
$$\frac{C_{tG}^{\mathrm{BMHV}}}{16\pi^2} = \frac{C_{tG}^{\mathrm{NDR}}}{16\pi^2} + \frac{\sqrt{2}m_t g_s}{16\pi^2 v}\left(C_{Qt}^{(1)} + (c_F - \frac{c_A}{2})C_{Qt}^{(8)}\right)$$

note: loop suppression factor for C_{tG} not included here (Warsaw basis conventions)

shift can be of same order as Wilson coefficient itself

S. Di Noi et al, 2310.18221

Effect of different gamma5-schemes

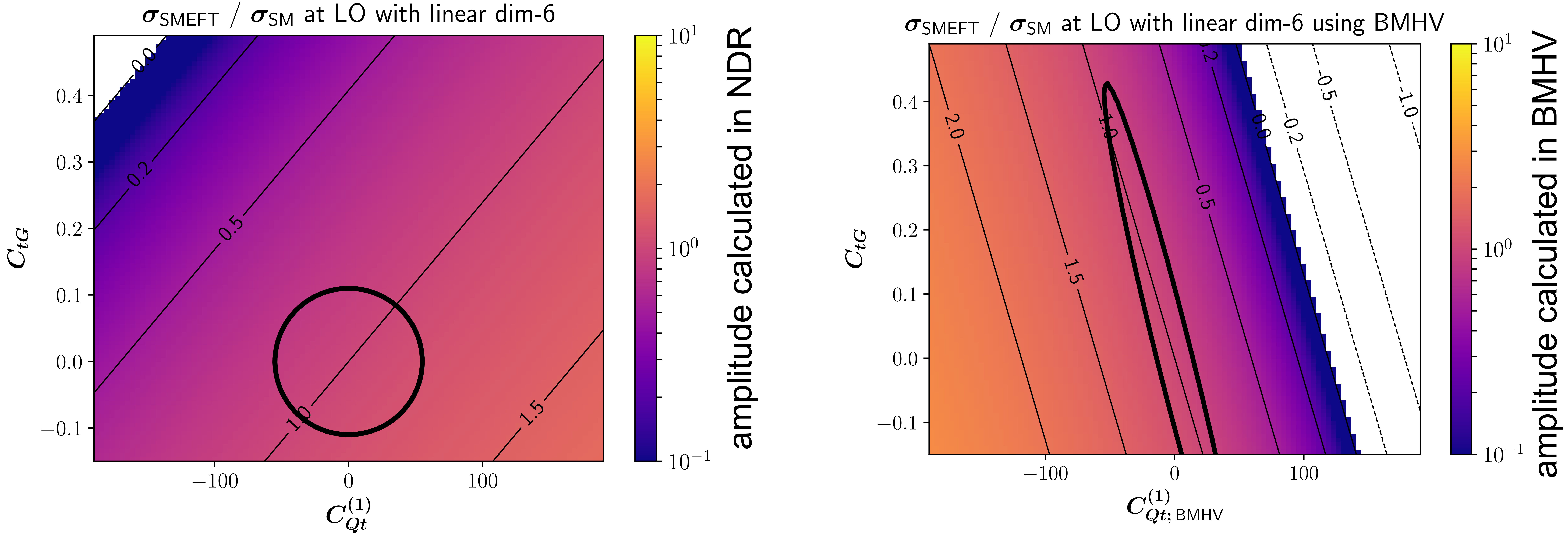


GH, J. Lang, 2311.15004

value pairs of $(C_{Qt}^{(1)}, C_{tG}^{\rm NDR})$ within the circle are mapped to value pairs of $(C_{Qt}^{(1)}, C_{tG}^{\rm BMHV})$ within the ellipse

$$C_{tG}^{\rm BMHV} = C_{tG}^{\rm NDR} - \frac{\sqrt{2} m_t g_s}{16\pi^2 v}\left(C_{Qt}^{(1)} + \left(c_F - \frac{c_A}{2}\right) C_{Qt}^{(8)}\right)$$

Effect of different gamma5-schemes



GH, J. Lang, 2311.15004

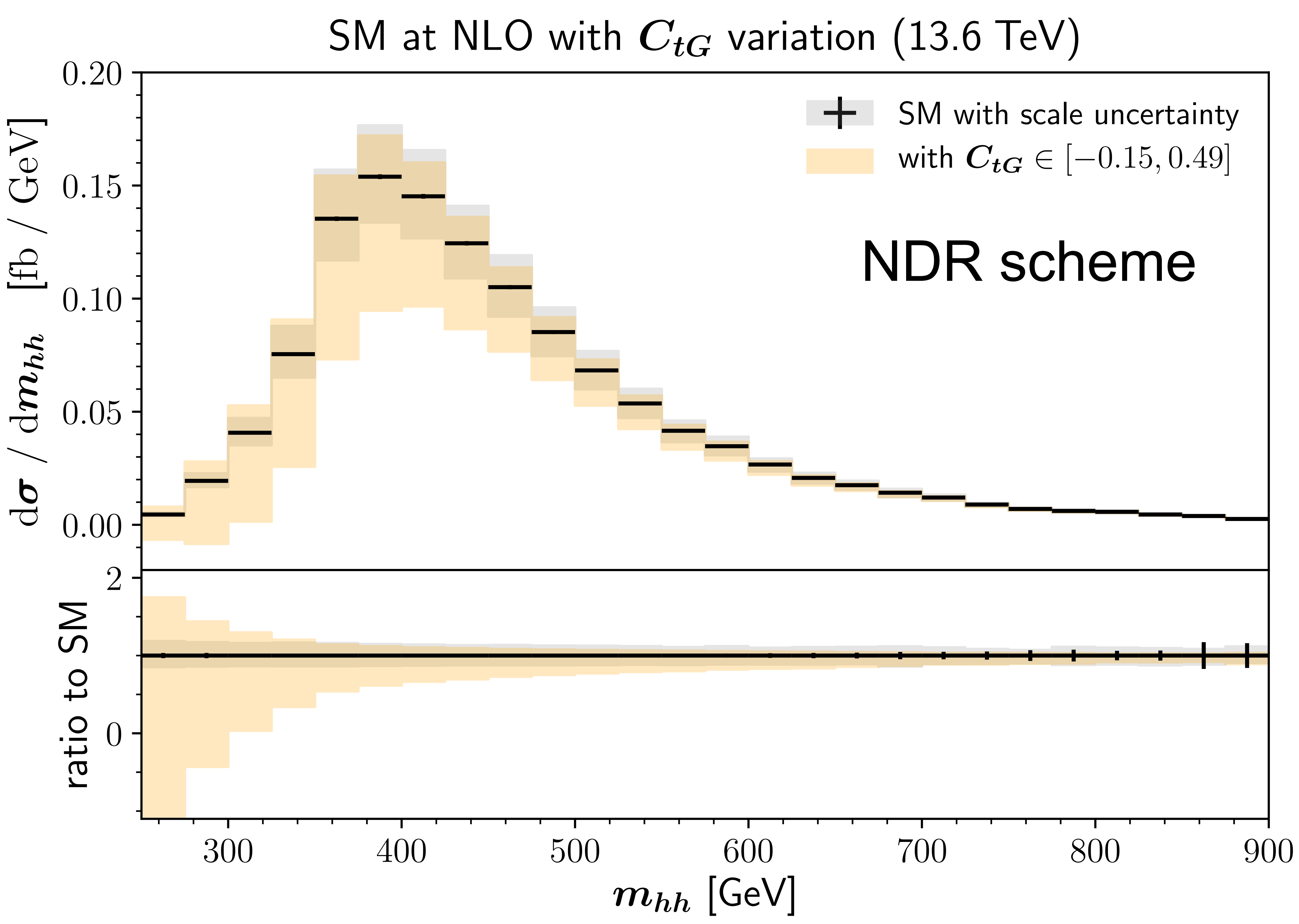
value pairs of $(C^{(1)}_{Qt}, C^{\text{NDR}}_{tG})$ within the circle are mapped to value pairs of $(C^{(1)}_{Qt}, C^{\text{BMHV}}_{tG})$ within the ellipse

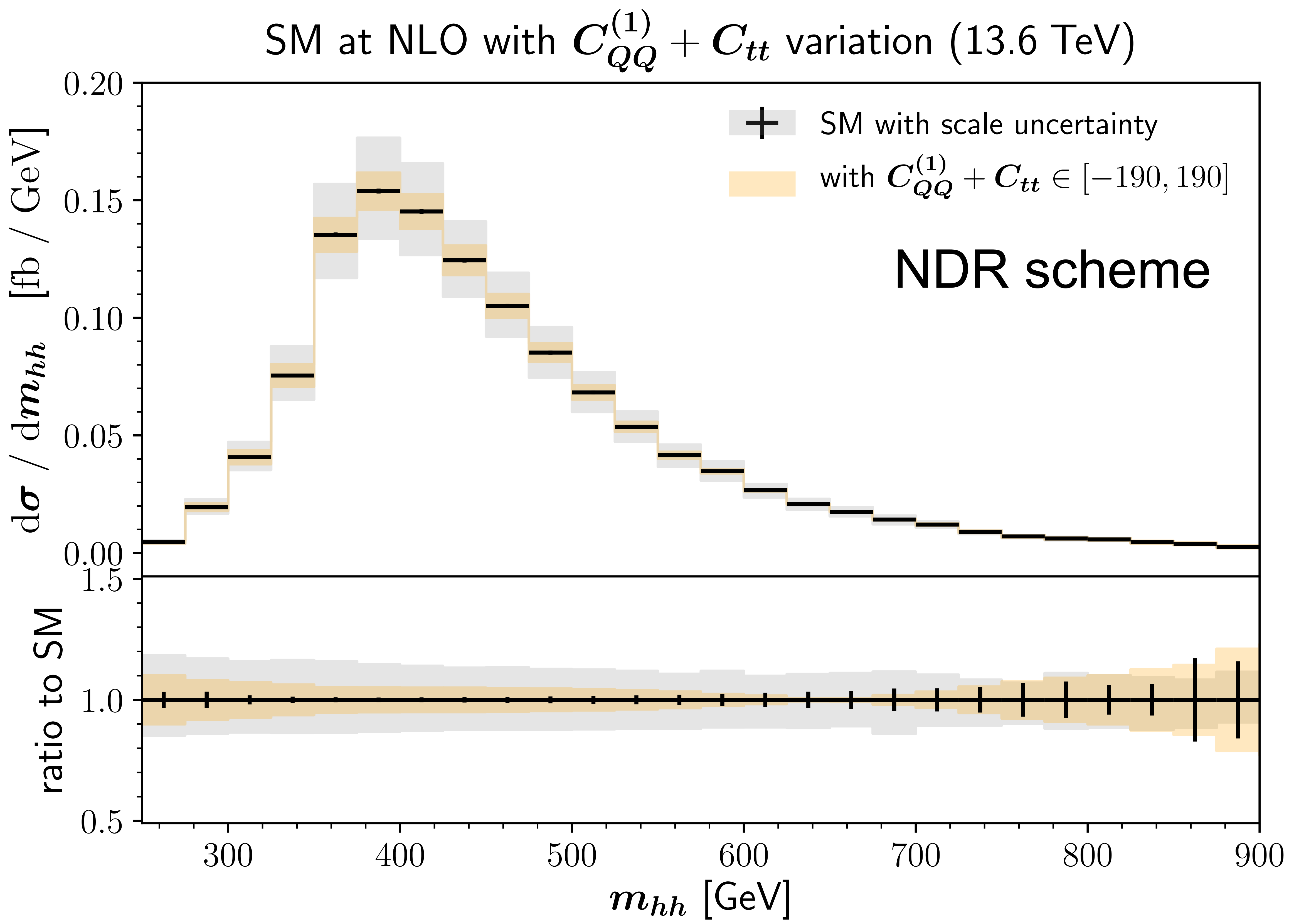
$$C^{\text{BMHV}}_{tG} = C^{\text{NDR}}_{tG} - \frac{\sqrt{2} m_t g_s}{16\pi^2 v} \left(C^{(1)}_{Qt} + \left(c_F - \frac{c_A}{2} \right) C^{(8)}_{Qt} \right)$$

total cross section is the same in both schemes, a single Wilson coefficient is not an observable

Effect of chromomagnetic and $C_{QQ}^{(1)} + C_{tt}$ operators

variation ranges: from global fit (marginalised) , Ethier et al, 2105.00006 [SMEFiT coll.]





GH, J. Lang, 2311.15004

Effect of C_{tG} in this variation range larger than SM scale uncertainties

Effect of $C_{Qt}^{(1)}$ in different gamma5 schemes

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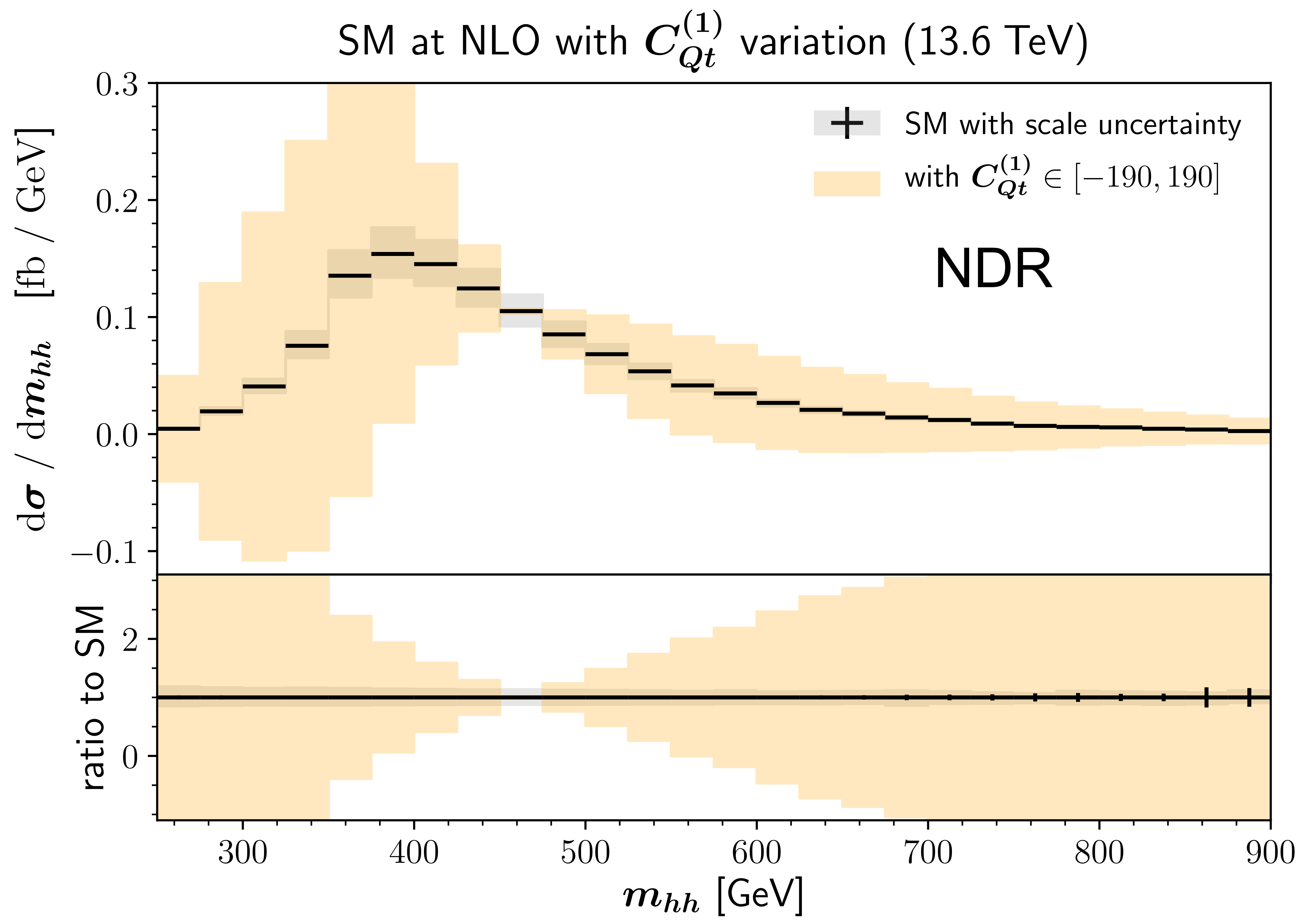
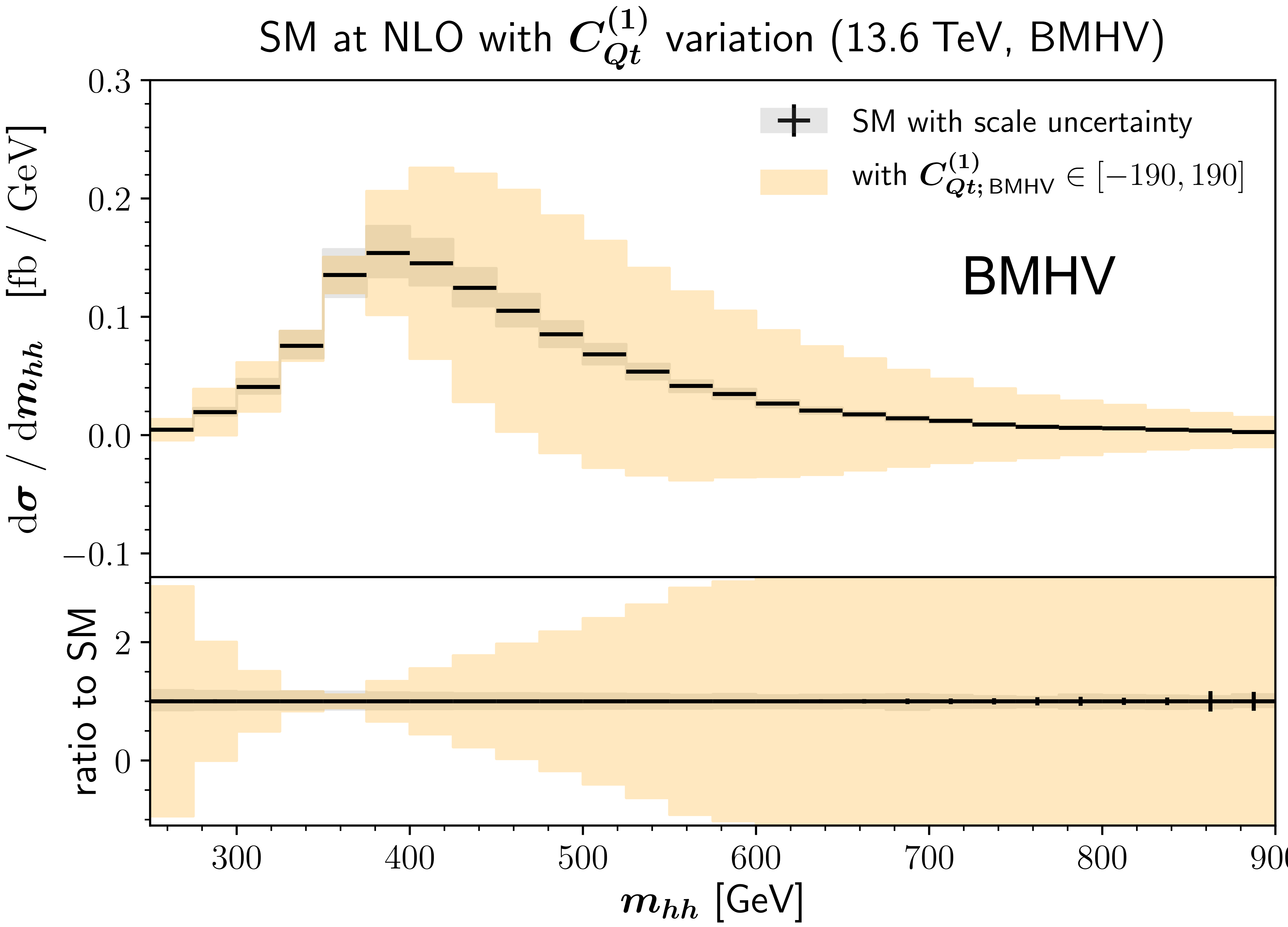
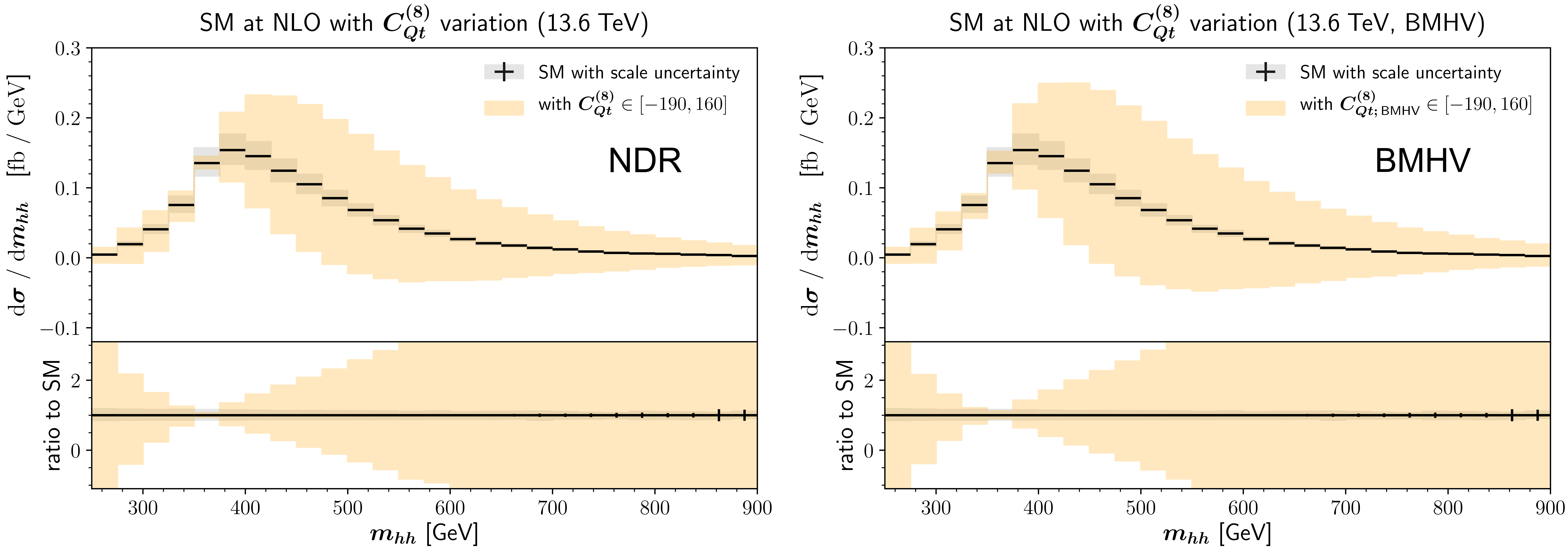




GH, J. Lang, 2311.15004

large effect and very different behaviour in the two schemes

Effect of $C_{Qt}^{(8)}$ in different gamma5 schemes



GH, J. Lang, 2311.15004

large effect, scheme difference less pronounced; H(H) production to constrain 4top-operators?

Summary & outlook

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- Increasing the precision in modelling potential new physics effects by Effective Field Theory has several aspects:
  - combination with higher orders in perturbation theory
  - inclusion of subleading operators
  - control of truncation effects, inclusion of operators beyond dimension 6, running Wilson coefficients, …
- SMEFT description of Higgs boson (pair) production beyond leading O's:
  - 4-fermion operators enter at two loops, introduce a dependence on gamma5
  - gamma5 scheme dependence **also affects other operators**
  - scheme translation "dictionary" provided for operators entering H(H) production
  - constraints on individual Wilson coefficients can be scheme dependent!

if we lead a careless life
all our money cannot
buy a place in heaven
(free interpretation of Luther)

if we lead a careless life
all our money cannot
buy a place in heaven
(free interpretation of Luther)

if we treat gamma5 carelessly
all our fits of Wilson coefficients
may not lead us to a BSM theory

backup slides

Translation between BMHV and NDR

similarly: operators of type $\psi^2\phi^2 D$, e.g. $\mathcal{L}_{2t2\phi} = \frac{\mathcal{C}^{(1)}_{\phi Q}}{\Lambda^2}\bar{Q}_L\gamma_\mu Q_L\left(\phi^\dagger i\overleftrightarrow{D}^\mu\phi\right) + \frac{\mathcal{C}_{\phi t}}{\Lambda^2}\bar{t}_R\gamma_\mu t_R\left(\phi^\dagger i\overleftrightarrow{D}^\mu\phi\right)$

$$y_t^{\mathrm{BMHV}} = y_t^{\mathrm{NDR}}\left(1 - \frac{\lambda v^2}{32\pi^2}\frac{\mathcal{C}^{(1)}_{HQ} - \mathcal{C}_{Ht}}{\Lambda^2}\right)$$

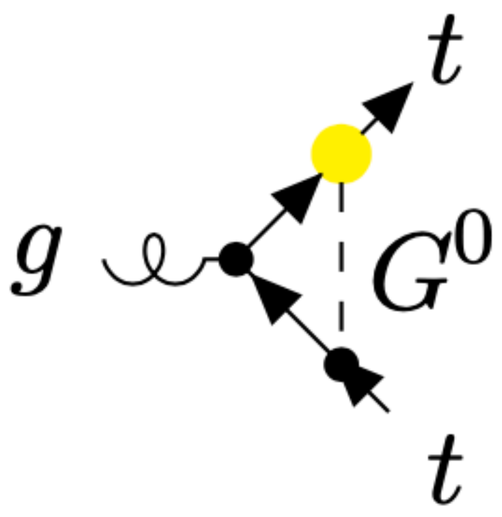
$$\mathcal{C}_{tH}^{\mathrm{BMHV}} = \mathcal{C}_{tH}^{\mathrm{NDR}} - \frac{y_t(y_t^2 + 3\lambda)}{48\pi^2}\left(\mathcal{C}^{(1)}_{HQ} - \mathcal{C}_{Ht}\right)$$

$$\mathcal{C}_{tG}^{\mathrm{BMHV}} = \mathcal{C}_{tG}^{\mathrm{NDR}} + \frac{g_s y_t}{48\pi^2}\left(\mathcal{C}^{(1)}_{HQ} - \mathcal{C}_{Ht}\right)$$

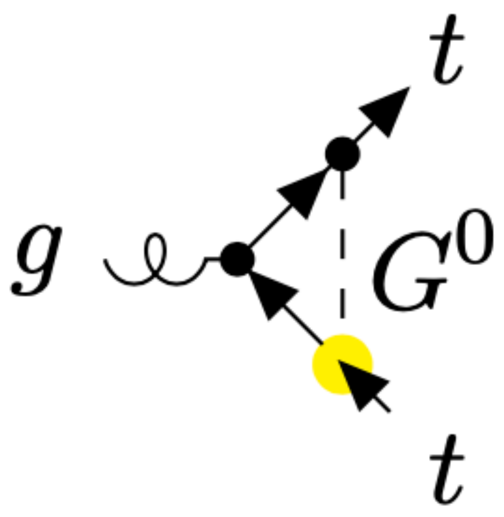
modification of EW-type couplings

note: $m_t = \frac{v}{\sqrt{2}}\left(y_t - \frac{v^2}{2}\frac{C_{tH}}{\Lambda^2}\right)$

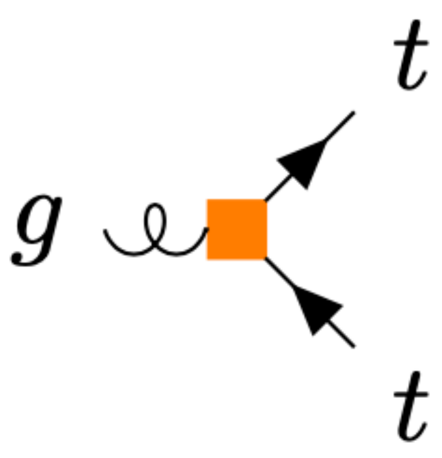
example



$+$



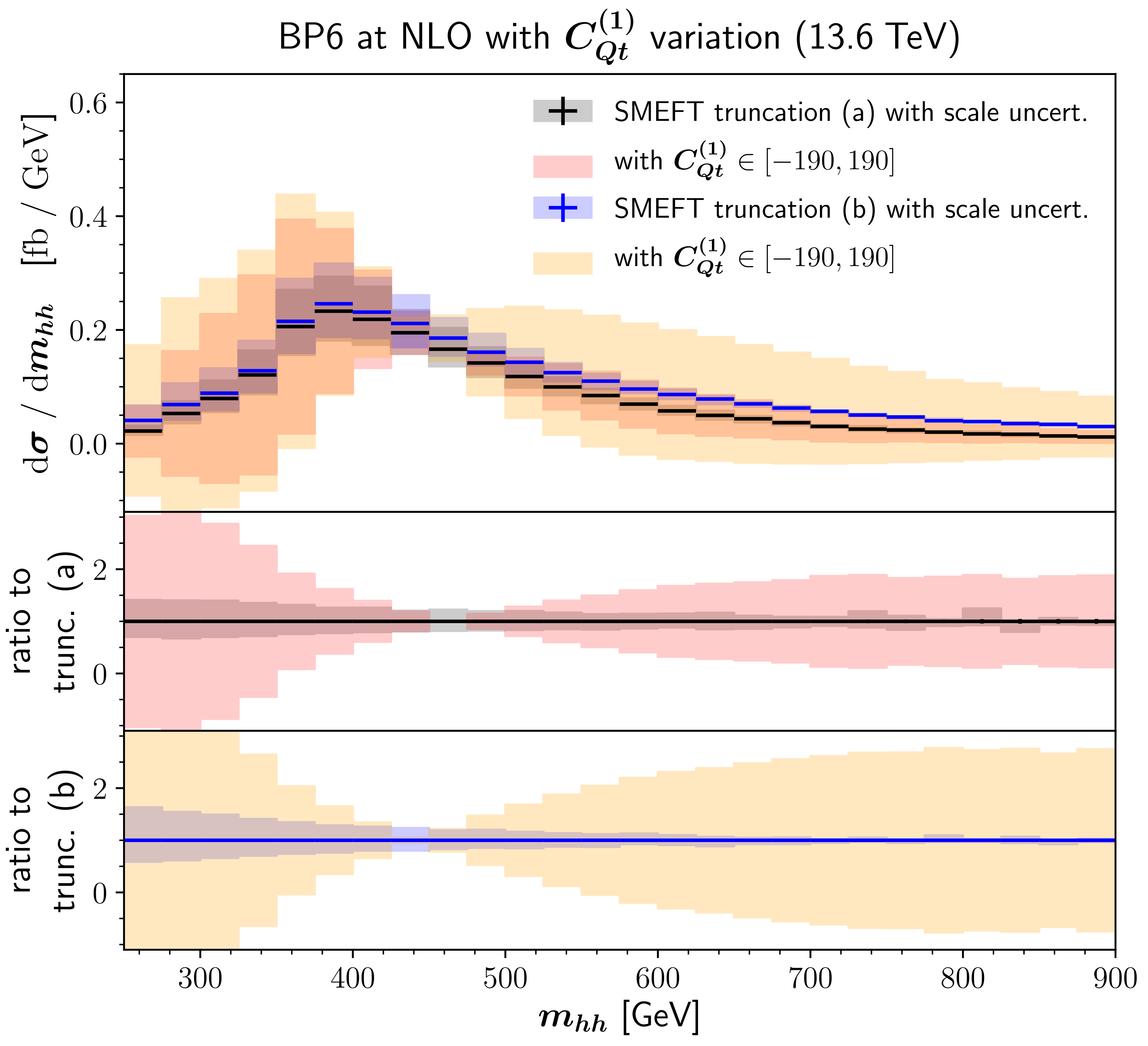
$= \frac{\mathcal{C}^{(1)}_{HQ} - \mathcal{C}_{Ht}}{\mathcal{C}_{tG}} K^{2t2\phi}_{tG} \times$

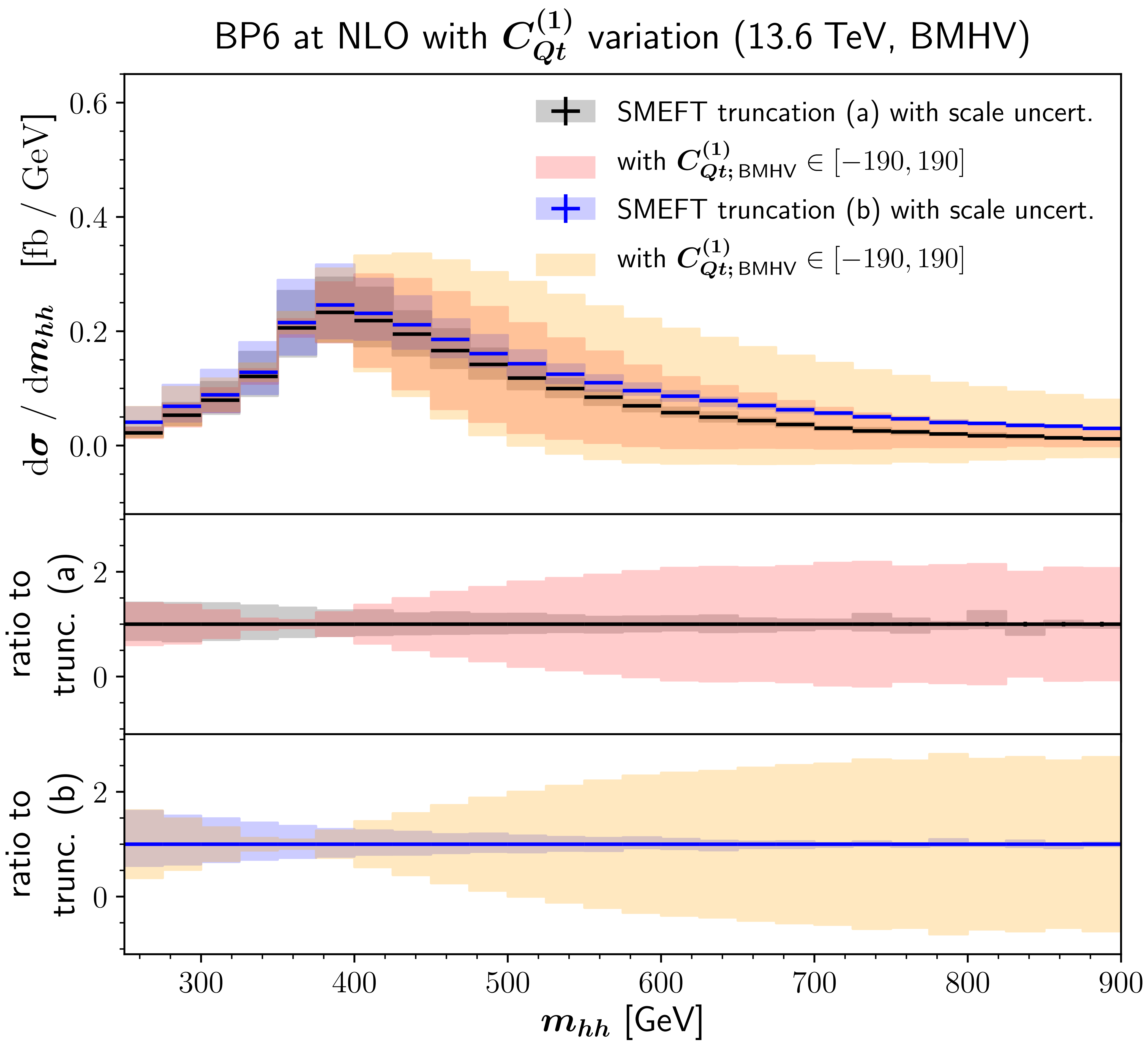


$+ \ldots$

Effect of different gamma5 schemes

benchmark point 6





Tools for ggHH production with QCD corr. + EFT

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HEFT

- LO + NLO in heavy top limit: HPAIR   Gröber Mühlleitner, Spira, Streicher ’15, ‘17
- NLO QCD with full top quark mass dependence implemented in **ggHH** code available at

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

  κ_λ variations only: GH, Jones, Kerner, Luisoni, Scyboz 1903.08137

  5 anomalous couplings: GH, Jones, Kerner, Scyboz 2006.16877

- approximate NNLO (HTL NNLO, full NLO):   De Florian, Fabre, GH, Mazzitelli, Scyboz 2106.14050

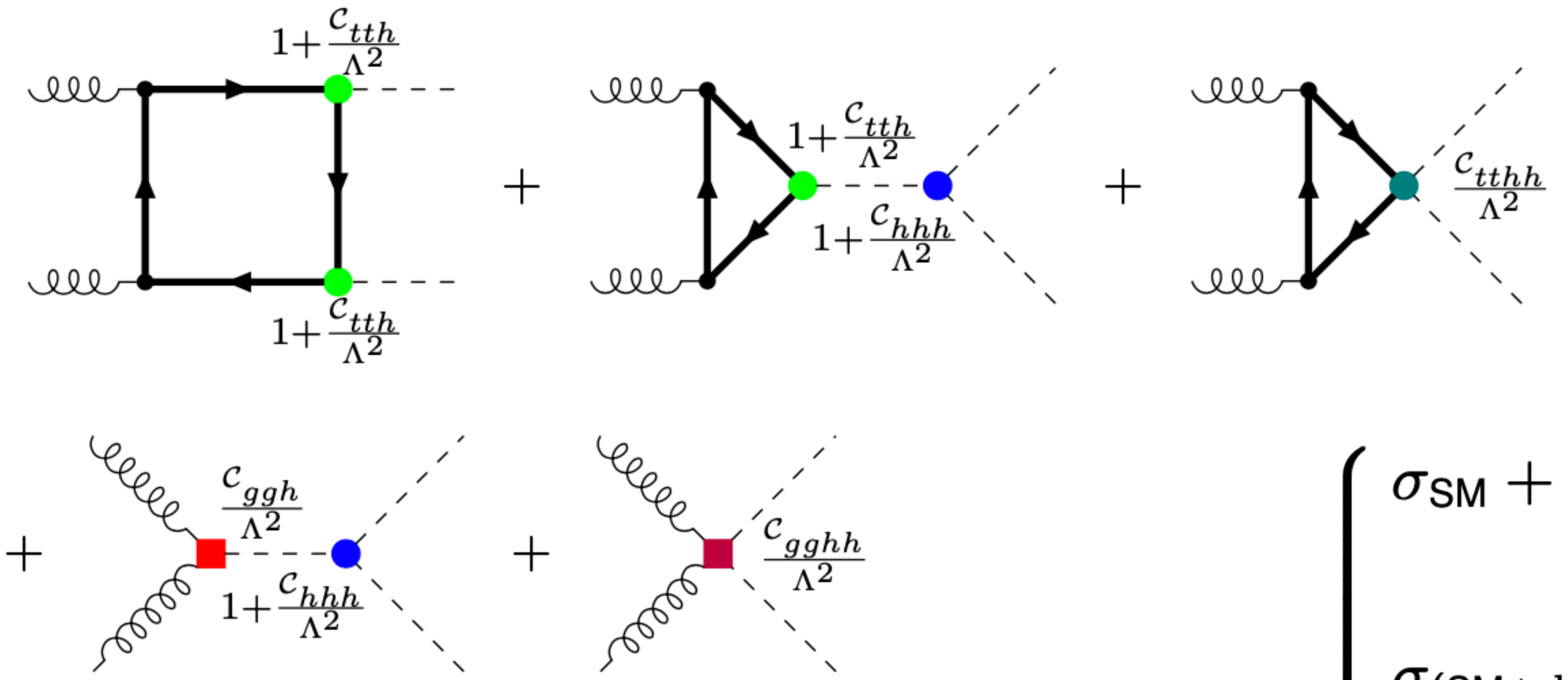
SMEFT

leading + subleading operators: **ggHH_SMEFT** (NLO QCD)   **GH, Lang, Scyboz ’22, ‘23**

also: LO / HTL tools, MG5_aMC@NLO   Brivio et al., Degrande et al.

SMEFT truncation

$$\mathcal{M}^{\rm LO}_{\rm SMEFT} =$$



$$= \mathcal{M}_{\rm SM} + \mathcal{M}_{\rm dim6} + \mathcal{M}_{\rm (dim6)^2}$$

$$\sigma \simeq \begin{cases} \sigma_{\rm SM} + \sigma_{\rm SM\times dim6} & \text{“linear”} \quad \text{(a)} \\ \sigma_{\rm (SM+dim6)\times(SM+dim6)} & \text{“quadratic”} \quad \text{(b)} \\ \sigma_{\rm (SM+dim6)\times(SM+dim6)} + \sigma_{\rm SM\times dim6^2} & \text{(c)} \\ \sigma_{\rm (SM+dim6+dim6^2)\times(SM+dim6+dim6^2)} & \text{(d)} \end{cases}$$

Naive translation HEFT to SMEFT

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\text{kin}}$	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}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
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}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$

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

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

$h \to h + v^2\frac{C_{H;\text{kin}}}{\Lambda^2}\left(h + \frac{h^2}{v} + \frac{h^3}{3v^2}\right)$ to achieve canonical kinetic term

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

Truncation effects on Higgs boson pair invariant mass

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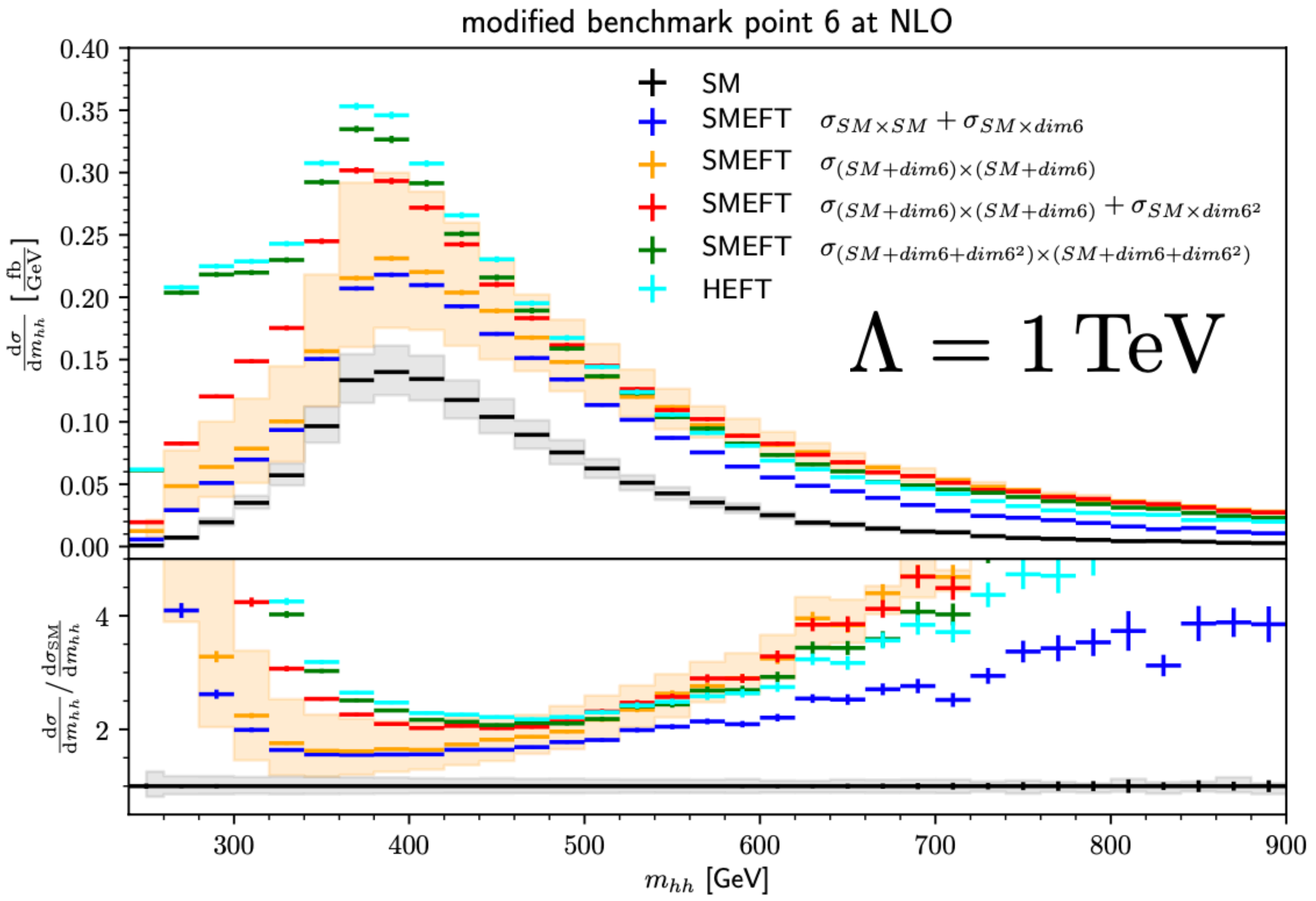
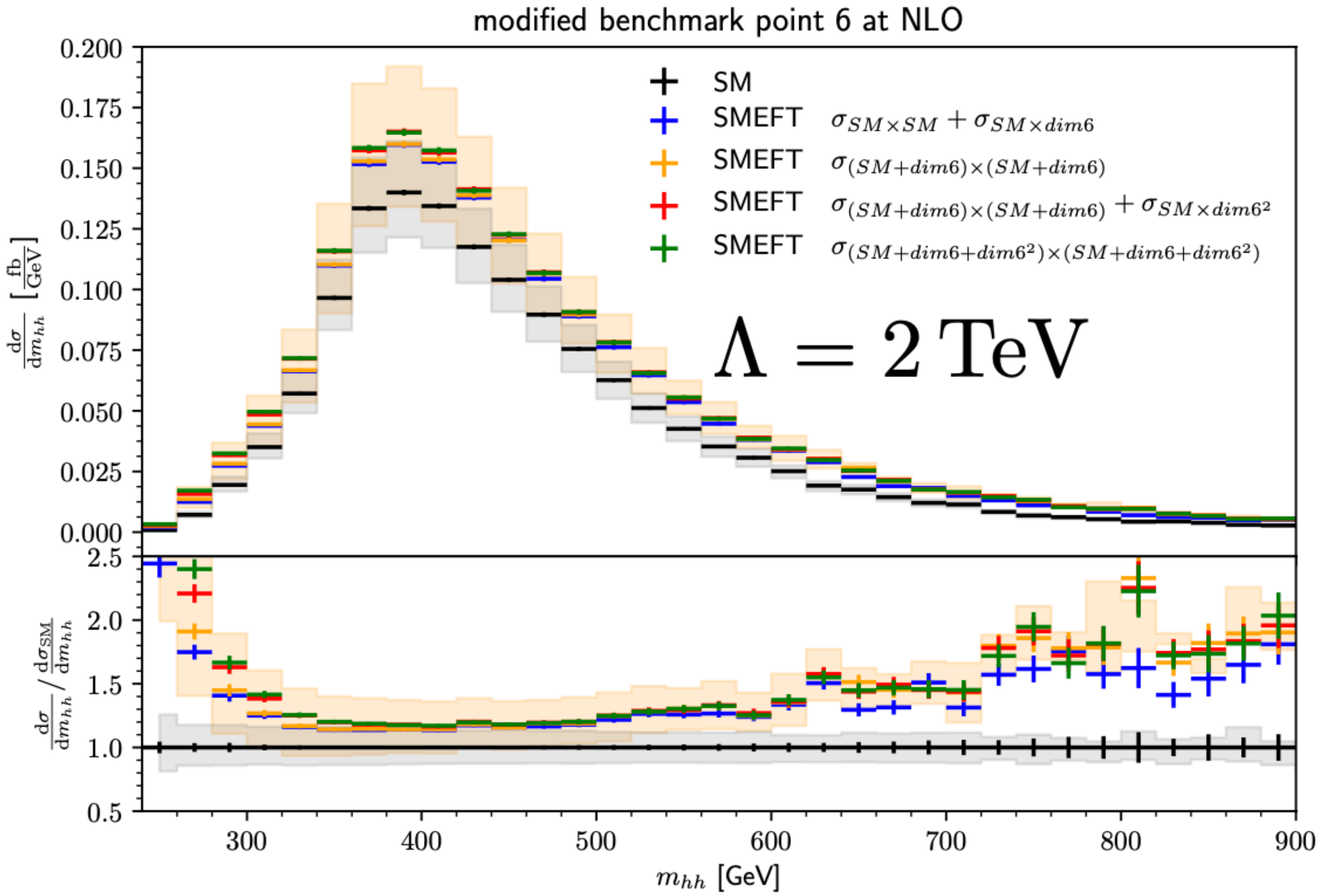
benchmark point 6*

figures: Jannis Lang



large differences between different truncation options and HEFT/SMEFT



differences between truncation options smaller, but

can hardly be distinguished from SM within NLO scale uncertainties

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 $SU(2) \times U(1)$

Loop counting matters in SMEFT

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

general term in EFT Lagrangian: $C \cdot \partial^{N_p} \phi^{N_\phi} A^{N_A} \psi^{N_\psi} \kappa^{N_\kappa}$

EFT power counting: estimate size of coefficient C

size depends on both, canonical dimension d_c and loop order L

loop order L can also be expressed by chiral dimension d_χ : $L = \frac{1}{2}(d_\chi - 2)$

$$\Rightarrow \quad C = C(d_c, d_\chi)$$

$$d_c = N_p + \frac{3}{2} N_\psi + N_\phi + N_A \quad , \quad d_\chi = N_p + \frac{1}{2} N_\psi + N_\kappa$$

Loop counting matters in SMEFT

define reference scale $f = \Lambda/4\pi$ where EFT expansion is valid

Lagrangian has canonical dimension 4, loop factors $1/16\pi^2$ are counted by L

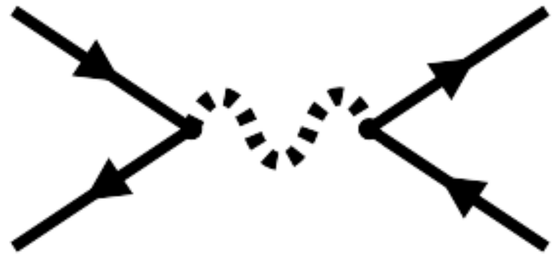
$$\Rightarrow C(d_c, d_\chi) = \frac{f^{4-d_c}}{(4\pi)^{d_\chi - 2}} = \frac{1}{\Lambda^{d_c - 4}} \left(\frac{1}{4\pi}\right)^{d_\chi - d_c + 2}$$

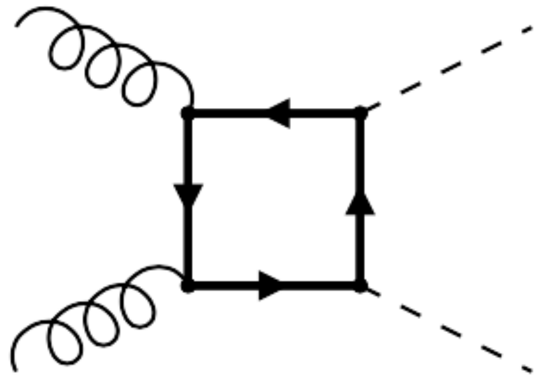
therefore, at canonical dimension $d_c = 6 : C(d_c, d_\chi) = \frac{1}{\Lambda^2} \left(\frac{1}{16\pi^2}\right)^{\frac{d_\chi - 4}{2}}$

$d_\chi = N_p + \frac{1}{2} N_\psi + N_\kappa \Rightarrow$ need to know scaling with number of weak couplings N_κ

Loop counting matters in SMEFT

result for **renormalisable** interactions:

terms with 4 fermions:  $\kappa^2(\bar{\psi}\psi)^2$ $\quad d_\chi = 4$

terms with field strength tensors:  generally loop-induced operators $\sim \kappa^4$

$$\kappa^4 \bar{\psi}\,\sigma_{\mu\nu} F^{\mu\nu}\,\phi\,\psi\,,\ \kappa^4 \phi^\dagger \phi\, F_{\mu\nu} F^{\mu\nu} \qquad d_\chi = 6$$

chromomagnetic operator

$$C(d_c = 6, d_\chi) = \frac{1}{\Lambda^2}\left(\frac{1}{16\pi^2}\right)^{\frac{d_\chi - 4}{2}} \Rightarrow C_{\text{chromo}} = \frac{1}{\Lambda^2}\left(\frac{1}{16\pi^2}\right)$$