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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Predictions for $gg \to hh$ at full NLO QCD comparing non-linear and linear EFT frameworks and truncation effects

Higgs Pairs Workshop 2022, Wildcard talk

Jannis Lang in collaboration with Gudrun Heinrich and Ludovic Scyboz [2204.13045] | June 3, 2022

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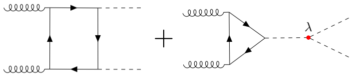
Outline

1. Motivation
2. HEFT and SMEFT
3. POWHEG code
4. NLO cross section
5. Truncation effects in invariant mass distribution
6. Summary and Outlook

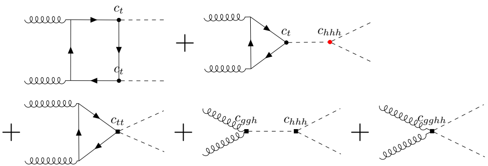
Why study *hh* production?

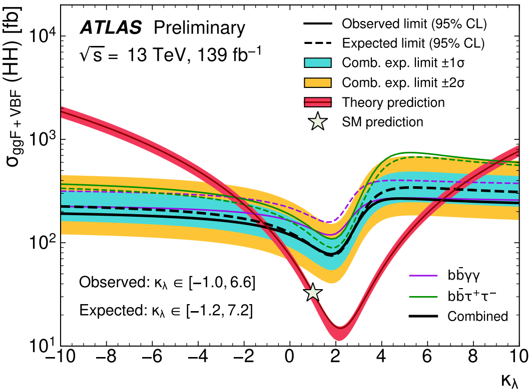
- Higgs potential largely unknown

$\Rightarrow$ Trilinear Higgs coupling accessible in *hh* production



- However, BSM deviations should enter in systematic way!





ATLAS-CONF-2021-052

Two distinct EFT systematics: HEFT vs. SMEFT

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HEFT:

- BSM: can be strongly coupling New Physics
- non-linear theory (EWχL), chiral counting of operators $d_\chi(\partial, \bar{\psi}\psi, g, y) = 1$
- light Higgs is EW gauge singlet $h(x)$, Goldstones have non-trivial transformation properties
- expansion in $\frac{f^2}{\Lambda^2} \sim \frac{1}{16\pi^2}$ ($\Rightarrow$ loop counting):

$$\mathcal{L}_{\text{HEFT}} \sim \mathcal{L}_{d_\chi=2} + \sum_{L=1} \sum_i \left(\frac{1}{16\pi^2}\right)^L c_i\, \mathcal{O}_i^{(d_\chi=2+2L)}$$

SMEFT:

- BSM: lightly coupling New Physics
- light Higgs contained in EW doublet field $\phi(x)$
- canonical counting (expansion in $\frac{1}{\Lambda}$):

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{n=1} \sum_i \frac{C_i}{\Lambda^{2n}} \mathcal{O}_i^{(4+2n)}$$

Relevant Lagrangian terms for hh

HEFT:

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

SMEFT:

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

Naive translation SMEFT $\leftrightarrow$ HEFT after field redefinition up to $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$ in Lagrangian ($C_{H,kin} = C_{H\Box} - 4C_{HD}$)

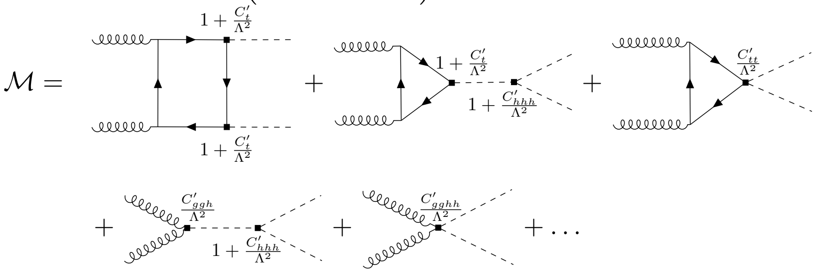
HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2} C_H + 3\frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}}$
c_t	$1 + \frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t} C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2}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

However, formally:

$c_i \sim \mathcal{O}(1)$ possible $\leftrightarrow$ $\frac{E^2}{\Lambda^2} C_i \ll 1$

SMEFT truncation

Dimension 6 operators in amplitude $\left(\frac{C_i'}{\Lambda^2} = c_i - c_{i,sm}\right)$:



$$= \mathcal{M}_{\mathrm{SM}} + \underbrace{\frac{1}{\Lambda^2}\mathcal{M}_{\mathrm{si}}}_{\mathrm{dim6}} + \underbrace{\frac{1}{\Lambda^4}\mathcal{M}_{\mathrm{di}}}_{\mathrm{dim6}^2}$$

$\Rightarrow$ Double operator insertion same order as (neglected) dimension 8 operators (and field redefinition)!

SMEFT truncation

Several possibilities for SMEFT truncation of final result:

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

(a) Truncation at leading order in $1/\Lambda$ of cross section (commonly used, if SM unsuppressed)

(b) Truncation at leading order in $1/\Lambda$ of amplitude (commonly used, if SM suppressed) $\Rightarrow$ investigate uncertainty

(c) Truncate cross section at $\mathcal{O}\left(1/\Lambda^4\right)$ from all dim6 operator insertions (ambiguous definition)

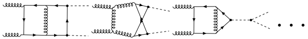
(d) Complete insertion, naive translation SMEFT $\leftrightarrow$ HEFT

POWHEG code ggHH_SMEFT

- built on NLO HEFT code with full m_t dependence ggHH
- available at http://powhegbox.mib.infn.it as User-Processes-V2/ggHH

[Borowka,Greiner,Heinrich,Jones,Kerner,et al. '16]
[Heinrich,Jones,Kerner,Luisoni,Vryonidou '17]
[Heinrich,Jones,Kerner,Luisoni,Scyboz '19]
[Heinrich,Jones,Kerner,Scyboz '20]

- modified for SMEFT Warsaw input and truncation options (a)-(d):
  - modified **GoSam** 1-loop files interfaced to POWHEG for reals
  - HEFT virtuals available as function of 23 grids a_i



$$
\begin{aligned}
|\mathcal{M}_{NLO}|^2 = & a_1 \cdot c_t^4 + a_2 \cdot c_{tt}^2 + a_3 \cdot c_t^2 c_{hhh}^2 + a_4 \cdot c_{ggh}^2 c_{hhh}^2 + a_5 \cdot c_{gghh}^2 + a_6 \cdot c_{tt} c_t^2 + a_7 \cdot c_t^3 c_{hhh} \\
& + a_8 \cdot c_{tt} c_t c_{hhh} + a_9 \cdot c_{tt} c_{ggh} c_{hhh} + a_{10} \cdot c_{tt} c_{gghh} + a_{11} \cdot c_t^2 c_{ggh} c_{hhh} + a_{12} \cdot c_t^2 c_{gghh} \\
& + a_{13} \cdot c_t c_{hhh}^2 c_{ggh} + a_{14} \cdot c_t c_{hhh} c_{gghh} + a_{15} \cdot c_{ggh} c_{hhh} c_{gghh} + a_{16} \cdot c_t^3 c_{ggh} \\
& + a_{17} \cdot c_t c_{tt} c_{ggh} + a_{18} \cdot c_t c_{ggh}^2 c_{hhh} + a_{19} \cdot c_t c_{ggh} c_{gghh} + a_{20} \cdot c_t^2 c_{ggh}^2 \\
& + a_{21} \cdot c_{tt} c_{ggh}^2 + a_{22} \cdot c_{ggh}^3 c_{hhh} + a_{23} \cdot c_{ggh}^2 c_{gghh}
\end{aligned}
$$

$\Rightarrow$ virtual grids can be directly reused for SMEFT except for truncation (b), where additional 1-loop contibutions are added analytically

POWHEG code ggHH_SMEFT

Usage of code (only new part of the input file is shown):

```
! Choose EFT parametrization
usesmeft     0        ! 0: use HEFT parametrization and ignore CHbox, CH, CuH, CHG (no truncation);
                      ! 1: use SMEFT (Warsaw) parametrization and ignore chhh, ct, ctt, cggh, cgghh (with truncation);
                      ! 2: use HEFT parametrization and ignore CHbox, CH, CuH, CHG (with truncation!, testing purpose/SILH-Lag. calculation)

! Values of the Higgs couplings w.r.t SM: HEFT parametrization
chhh       1.0       ! Trilinear Higgs self-coupling
ct         1.0       ! Top-Higgs Yukawa coupling
ctt        0.0       ! Two-top-two-Higgs (tthh) coupling
cggh       0.0       ! Effective gluon-gluon-Higgs coupling
cgghh      0.0       ! Effective two-gluon-two-Higgses coupling

! Values of the Higgs couplings using SMEFT (Warsaw) parametrization (Wilson coefficients enter as C/Lambda^2)
Lambda       1.0      ! EFT counting mass Scale (in TeV)
CHbox        0.0      ! Kinetic term of SU(2)_L singlet (with d'Alembert operator)
CHD          0.0      ! second Kinetic term
CH           0.0      ! Additional term to Higgs potential
CuH          0.0      ! Modified Yukawa term
CHG          0.0      ! Higgs-Glue-Glue operator

! Truncation options:
! 3: cross section based on |A_SM+A_dim6+A_dbldim6|^2
! 2: cross section based on |A_SM+A_dim6|^2+2*Re(A_SM x conj(A_dbldim6))
! 1: cross section based on |A_SM+A_dim6|^2
! 0: cross section based on |A_SM|^2+2*Re(A_SM*conj(A_dim6))
multiple-insertion  1
```

`multiple-insertion` $0, \ldots, 3 \quad \leftrightarrow \quad$ truncation option (a), …, (d)

$\Rightarrow$ now available at http://powhegbox.mib.infn.it as /User-Processes-V2/ggHH_SMEFT [Heinrich,JL,Scyboz '22]

NLO cross section

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NLO HEFT cross section parametrised as function of coefficients A_i (similar to $|\mathcal{M}_{NLO}|^2$)

$$
\begin{aligned}
\frac{\sigma_{BSM}}{\sigma_{SM}} =& A_1 \cdot c_t^4 + A_2 \cdot c_{tt}^2 + A_3 \cdot c_t^2 c_{hhh}^2 + A_4 \cdot c_{ggh}^2 c_{hhh}^2 + A_5 \cdot c_{gghh}^2 + A_6 \cdot c_{tt} c_t^2 + A_7 \cdot c_t^3 c_{hhh} \\
&+ A_8 \cdot c_{tt} c_t c_{hhh} + A_9 \cdot c_{tt} c_{ggh} c_{hhh} + A_{10} \cdot c_{tt} c_{gghh} + A_{11} \cdot c_t^2 c_{ggh} c_{hhh} + A_{12} \cdot c_t^2 c_{gghh} \\
&+ A_{13} \cdot c_t c_{hhh}^2 c_{ggh} + A_{14} \cdot c_t c_{hhh} c_{gghh} + A_{15} \cdot c_{ggh} c_{hhh} c_{gghh} + A_{16} \cdot c_t^3 c_{ggh} \\
&+ A_{17} \cdot c_t c_{tt} c_{ggh} + A_{18} \cdot c_t c_{ggh}^2 c_{hhh} + A_{19} \cdot c_t c_{ggh} c_{gghh} + A_{20} \cdot c_t^2 c_{ggh}^2 \\
&+ A_{21} \cdot c_{tt} c_{ggh}^2 + A_{22} \cdot c_{ggh}^3 c_{hhh} + A_{23} \cdot c_{ggh}^2 c_{gghh}
\end{aligned}
$$

- Translation:

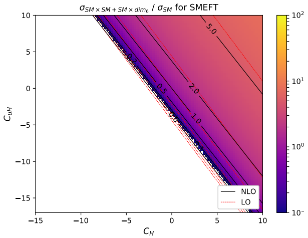
HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2} C_H + 3\frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}}$
c_t	$1 + \frac{v^2}{\Lambda^2} C_{H,\mathrm{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t} C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2}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

- Truncation:

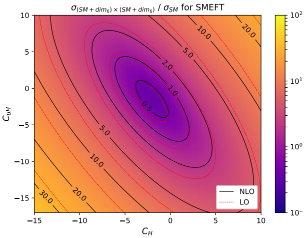
$$
\sigma \simeq \begin{cases}
\sigma_{\text{SM}} + \sigma_{\text{SM}\times\text{dim6}} & \text{(a)} \\
\sigma_{(\text{SM}+\text{dim6})\times(\text{SM}+\text{dim6})} & \text{(b)} \\
\sigma_{(\text{SM}+\text{dim6})\times(\text{SM}+\text{dim6})} + \sigma_{\text{SM}\times\text{dim6}^2} & \text{(c)} \\
\sigma_{\left(\text{SM}+\text{dim6}+\text{dim6}^2\right)\times\l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

NLO cross section

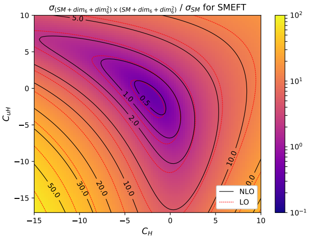
Generated at $\sqrt{s} = 13$ TeV with $\Lambda = 1$ TeV



option (a)



option (b)



option (d)

- large area of negative cross section for truncation (a)
- non-trivial shape for HEFT-like option (d)
- flat directions differ substantially

NLO cross section

Consider benchmark points for characteristic m_{hh} shapes in HEFT

- benchmark 1: enhanced low m_{hh} region
- benchmark 3: enhanced low m_{hh} and second local maximum above $m_{hh} \simeq 2m_t$
- benchmark 6: close-by double peaks or shoulder left

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

(compare [Capozi, Heinrich '19], new benchmarks fulfilling current constraints by Ludovic Scyboz)

$\Rightarrow$ SMEFT expansion based on $E^2 \frac{C_i}{\Lambda^2} \ll 1$ justified?

NLO cross section

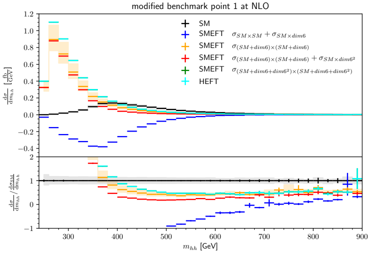
Generated at $\sqrt{s} = 13$ TeV

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	-	-
$\Lambda = 1$ 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
$\Lambda = 2$ 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	-

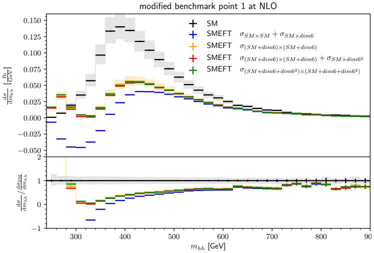
Invariant mass distributions at NLO QCD ($\sqrt{s} = 13$ TeV)

- HEFT benchmark 1:

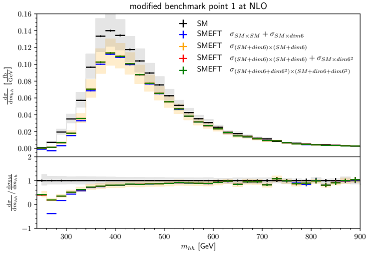
c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\text{kin}}$	C_H	C_{uH}	C_{HG}
5.105	1.1	0	0	0	4.95	-6.81	3.28	0



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV



$\Lambda = 4$ TeV

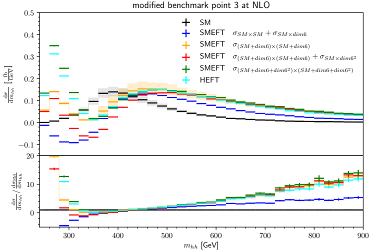
- truncation (a): negative cross sections
- shape approaches SM for increasing Λ

$\Rightarrow$ valid HEFT point invalid in SMEFT after direct translation

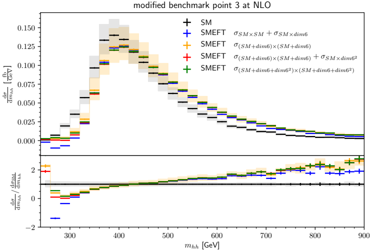
Invariant mass distributions at NLO QCD ($\sqrt{s} = 13$ TeV)

- HEFT benchmark 3:

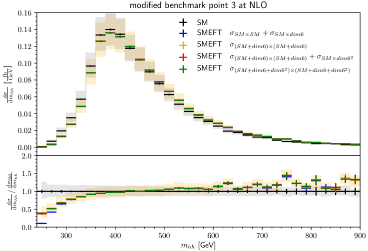
c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\text{kin}}$	C_H	C_{uH}	C_{HG}
2.21	1.05	$-\frac{1}{3}$	0.5	0.25*	13.5	2.64	12.6	0.0387



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV



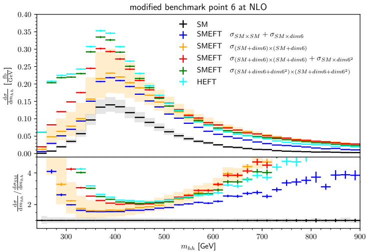
$\Lambda = 4$ TeV

- truncation (c): double operator insertion quite substantial
- shape close but distinguishable from SM for increasing Λ

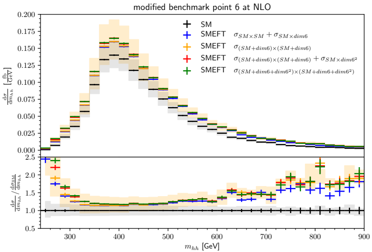
Invariant mass distributions at NLO QCD ($\sqrt{s} = 13$ TeV)

- HEFT benchmark 6:

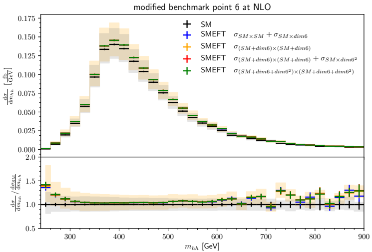
c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}
-0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387



$\Lambda = 1$ TeV



$\Lambda = 2$ TeV



$\Lambda = 4$ TeV

- no negative cross section
- shape indistinguishable from SM for $\Lambda = 4$ TeV within scale uncertainties

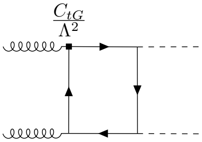
Summary

- NLO QCD code `ggHH_SMEFT` for SMEFT (and HEFT)
- comparison of HEFT and SMEFT and of different SMEFT truncation options
- naive translation from HEFT $\rightarrow$ SMEFT can lead out of validity of $\frac{1}{\Lambda^2}$ expansion
- valid SMEFT points close to SM, often hardly distinguishable from SM within scale uncertainties
- Outlook: running Wilson coefficients and inclusion of loop-suppressed chromo-magnetic operator O_{tG}, 4-fermion operators, . . .

Loop counting in SMEFT and chromo-magnetic operator

Following the procedure of *Loop counting matters in SMEFT* [Buchalla, Heinrich, Müller-Salditt, Pandler '22]

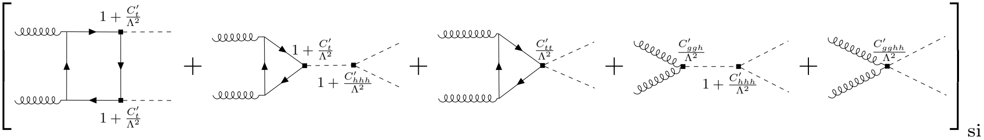
$\mathcal{O}_{tG} \sim [\kappa^4]\,(\bar{q}_L \sigma^{\mu\nu} T^a t_R)\,\tilde{\phi}\, G^a_{\mu\nu}$ with $d_\chi = 6$ $\Rightarrow$



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

with $C\,(6, d_\chi) = \frac{1}{\Lambda^2}\left(\frac{1}{16\pi^2}\right)^{(d_\chi - 4)/2}$

$\Rightarrow$ Enters with overall loop factor suppression $\frac{1}{16\pi^2}$ compared to



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