On γ_5 schemes and the interplay of SMEFT operators (in the Higgs-gluon coupling and beyond)

(Based on Phys. Rev. D 109, 095024
with R. Gröber,G. Heinrich, J. Lang, M. Vitti)

Stefano Di Noi

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HEFT 2024, University of Bologna, 12/06/2024

Introduction

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- **Effective Field Theories** (**EFTs**): search for NP with minimal UV assumptions.

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- **Effective Field Theories** (**EFTs**): search for NP with minimal UV assumptions.

- This talk focuses on Standard Model Effective Field Theory (**SMEFT**) at dim 6 (**Warsaw basis**, ([Grzadkowski,Iskrzynski,Misiak,Rosiek,'10])).
- Operators built with SM fields, invariant under gauge group: $\mathrm{SU}(3)_\mathrm{C} \otimes \mathrm{SU}(2)_\mathrm{W} \otimes \mathrm{U}(1)_\mathrm{Y}$.

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\mathfrak{D}_i=6} \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_i,$$

Status of the Higgs-gluon coupling in the SMEFT

Several groups have studied the Higgs-gluon coupling with different subsets of the SMEFT operators:

- $\mathcal{O}_{tG}$ [Choudhury,Saha,'12].
- $\mathcal{O}_{tG}, \mathcal{O}_{t\phi}, \mathcal{O}_{\phi\Box/\phi D}$ [Degrande et al.,'12].
- $\mathcal{O}_{t\phi/b\phi}, \mathcal{O}_{\phi G}, \mathcal{O}_{tG}$ [Grazzini,Ilnicka,Spira,Wiesemann,'16], [Grazzini,Ilnicka,Spira,'18], [Battaglia,Grazzini,Spira,Wiesemann,'21].
- geoSMEFT approach: [Corbett,Martin,Trott,'21],[Martin,Trott,'23].
- $\mathcal{O}_{4t}$@2 loop in $pp \to h$ [Alasfar,de Blas,Gröber,'22] .

Four-top operators in Higgs-gluon coupling.

- We focus on four-top operators:

$$\mathcal{L}_{4t} = \frac{\mathcal{C}_{QQ}^{(1)}}{\Lambda^2}\left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{Q}_L\gamma^\mu Q_L\right) + \frac{\mathcal{C}_{QQ}^{(3)}}{\Lambda^2}\left(\bar{Q}_L\tau^I\gamma_\mu Q_L\right)\left(\bar{Q}_L\tau^I\gamma^\mu Q_L\right)$$
$$+ \frac{\mathcal{C}_{Qt}^{(1)}}{\Lambda^2}\left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{t}_R\gamma^\mu t_R\right) + \frac{\mathcal{C}_{Qt}^{(8)}}{\Lambda^2}\left(\bar{Q}_L T^A\gamma_\mu Q_L\right)\left(\bar{t}_R T^A\gamma^\mu t_R\right)$$
$$+ \frac{\mathcal{C}_{tt}}{\Lambda^2}\left(\bar{t}_R\gamma_\mu t_R\right)\left(\bar{t}_R\gamma^\mu t_R\right) .$$

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Istituto Nazionale di Fisica Nucleare

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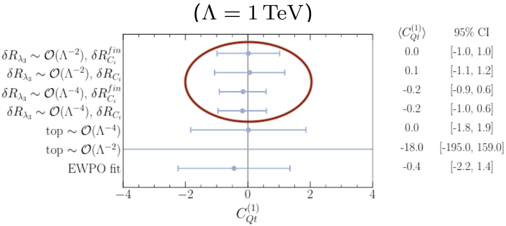
- Direct probes are difficult due to the small cross section.

- Alternative methods are possible.

State of the art

- Indirect bounds from single Higgs production are competitive with
  - Top quark data ([Ethier et. al.,'21]) (New bounds in [Celada et al.,'24]),
  - EWPO ([Dawson,Giardino,'22], [de Blas, Chala, Santiago,'15]).



[Alasfar,de Blas,Gröber,'22]

- Possible bounds also from flavour observables ([Silvestrini,Valli,'18]).

Dimensional regularisation and chiral couplings

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- γ_5 is a purely 4-dimensional object: **a continuation scheme must be chosen**.
- For the details, see [Di Noi et al.,'23].

Continuation to D dimensions schemes for γ_5

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- **Naive Dimensional Regularisation (NDR)**: assumes that the 4-dimensional relations hold also in D dimensions:

$$\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}\,, \qquad \{\gamma_\mu, \gamma_5\} = 0.$$

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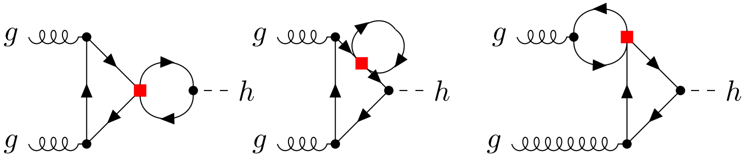
Algebraically consistent.

May break Ward identities (e.g., [Larin,'93]).

Computationally demanding.

Higgs-gluon coupling with four-top operators

- We compute the four-top contribution to $gg \to h$ using NDR and BMHV (reviewing the result in [Alasfar,de Blas,Gröber,'22]):



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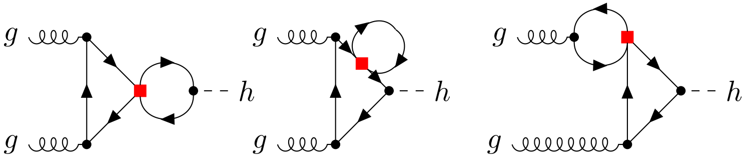

- Poles in $ht\bar{t}$, m_t corrections are **scheme-independent**.

Poles and Anomalous Dimension I

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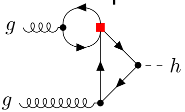

$$\Big|_{\mathrm{DIV}} = K_{tG} \times \left(\mathcal{C}^{(1)}_{Qt} - \frac{1}{6}\mathcal{C}^{(8)}_{Qt}\right) \frac{1}{\Lambda^2} g_s m_t \frac{1}{\epsilon} \frac{\sqrt{2}}{4\pi^2} \left(\frac{m_h^2}{2}\, g^{\mu_1\mu_2} - p_1^{\mu_2} p_2^{\mu_1}\right),$$

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

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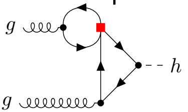

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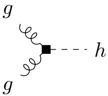
- **The anomalous dimension (AD) of $\mathcal{O}_{\phi G}$ depends on the scheme! $\rightarrow$ log terms scheme-dependent!**



$$= -4iv\frac{\mathcal{C}_{\phi G}}{\Lambda^2}\left(\frac{m_h^2}{2}\, g^{\mu_1\mu_2} - p_1^{\mu_2} p_2^{\mu_1}\right), \qquad \mathcal{O}_{\phi G} = \phi^\dagger \phi G_{\mu\nu} G^{\mu\nu},$$

$$16\pi^2 \mu \frac{d\mathcal{C}_{\phi G}}{d\mu} = -4\sqrt{2} g_{h\bar{t}t} g_s \Bigg(\underbrace{\mathcal{C}_{tG}}_{\text{1L}} + \underbrace{K_{tG}\left(\mathcal{C}_{Qt}^{(1)} - \frac{1}{6}\mathcal{C}_{Qt}^{(8)}\right)}_{\text{2L, new}} \Bigg).$$

Poles and Anomalous Dimension II

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- The scheme-dependence of the LO AD involving $(\bar{L}L)(\bar{R}R)$ is known (e.g., $b \to sg, s\gamma$, [M. Ciuchini et al.,'93]).

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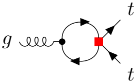
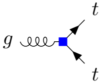


$$= \frac{\mathcal{C}^{(1)}_{Qt} - \frac{1}{6}\mathcal{C}^{(8)}_{Qt}}{\mathcal{C}_{tG}} K_{tG} \times$$



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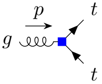

$$= -\frac{\mathcal{C}_{tG}}{\Lambda^2}\sqrt{2} v T^A \sigma^{\mu\nu} p_\nu.$$

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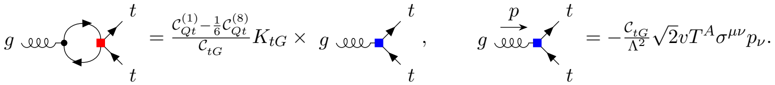

- $\mathcal{O}_{tG}, \mathcal{O}_{4t}$ **enter at the same order** [G. Buchalla et al.,'22].

Finite parts

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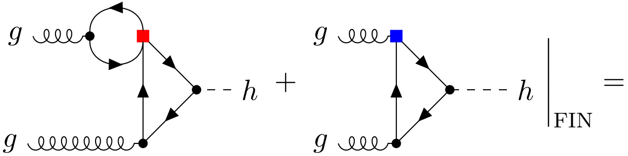

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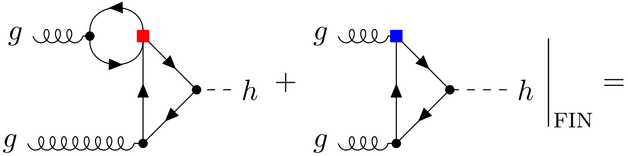

$$= \left[\mathcal{C}_{tG} + \left(\mathcal{C}^{(1)}_{Qt} - \frac{1}{6}\mathcal{C}^{(8)}_{Qt} \right) K_{tG} \right] \frac{1}{\Lambda^2} \mathcal{M}_{tG}|_{\text{FIN}} \equiv \frac{\tilde{\mathcal{C}}_{tG}}{\Lambda^2} \mathcal{M}_{tG}|_{\text{FIN}}$$

- … **Yes.**

SMEFT in NDR vs BMHV

- With this set of redefinitions, the two schemes give the same result (both for the finite parts and the AD).

$$\mathcal{C}_{tG}^{\text{NDR}} = \mathcal{C}_{tG}^{\text{BMHV}} - \left(\mathcal{C}_{Qt}^{(1)} - \frac{1}{6}\mathcal{C}_{Qt}^{(8)}\right) \frac{\sqrt{2} g_{h\bar{t}t} g_s}{16\pi^2},$$

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- Computed via one-loop diagrams.
- Validated by a matching with a UV model (top-down approach).

Conclusions

- Finite parts and AD are scheme-independent if $X^{\text{NDR}} = X^{\text{BMHV}} + \Delta X$, $X = \mathcal{C}_{tG}, g_{h\bar{t}t}, m_t$.

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- **In the bottom-up approach, a connection between NDR and BMHV is crucial for global fits.**
- Documentation of continuation and renormalisation scheme choices in EFT calculations and fits is recommended.
- Not only four-top: other operators show this interplay (e.g., $\mathcal{O}^{(1)}_{\phi Q} = \bar{Q}_L \gamma_\mu Q_L \left(\phi^\dagger i \overleftrightarrow{D}^\mu \phi \right)$).

Outlook

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Stay tuned!

Outlook

- Global map NDR vs BMHV in progress (with R. Gröber, P. Olgoso).
- Global fit and interpretation in the two schemes (with H. El Faham, R. Gröber, M. Vitti, E. Vryonidou)

Stay tuned!

Thank you for your attention!

S. Di Noi

Intro

4t in hgg

Conclusions

Backup

Backup

EFT notation

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$$\begin{aligned}
\mathcal{L}_{\mathcal{D}=6} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm 4t} + \mathcal{L}_{\rm 2t} + \mathcal{L}_{\rm s}, \\
\mathcal{L}_{\rm SM} &= -\frac{1}{4} G^{A}_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^{I}_{\mu\nu} W^{I\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \sum_{\psi} \bar{\psi} i \not{D} \psi \\
&\quad + (D_\mu \phi)^\dagger (D^\mu \phi) - \lambda \left(\phi^\dagger \phi - \frac{1}{2} v^2 \right)^2 - Y_u \tilde{\phi}^\dagger \bar{u}_R Q_L + \text{H.c.}, \\
\mathcal{L}_{\rm 2t} &= \left[\frac{\mathcal{C}_{t\phi}}{\Lambda^2} (\bar{Q}_L \tilde{\phi} t_R) \phi^\dagger \phi + \frac{\mathcal{C}_{tG}}{\Lambda^2} \bar{Q}_L \sigma^{\mu\nu} T^A t_R \tilde{\phi} G^{A}_{\mu\nu} + \text{H.c.} \right], \\
\mathcal{L}_{\rm s} &= \frac{\mathcal{C}_{\phi G}}{\Lambda^2} \phi^\dagger \phi G_{\mu\nu} G^{\mu\nu}.
\end{aligned} \tag{4.1}$$

- In unitary gauge $\phi = (1/\sqrt{2})(0, (v+h))^T$:

$$\mathcal{L}_{\mathcal{D}=6} \supset -m_t \bar{t} t - g_{h\bar{t}t} h \bar{t} t, \quad \begin{cases} m_t = \frac{v}{\sqrt{2}} \left(Y_t - \frac{v^2}{2} \frac{\mathcal{C}_{t\phi}}{\Lambda^2} \right), \\ g_{h\bar{t}t} = \frac{1}{\sqrt{2}} \left(Y_t - \frac{3v^2}{2} \frac{\mathcal{C}_{t\phi}}{\Lambda^2} \right) = \frac{m_t}{v} - \frac{v^2}{\sqrt{2}} \frac{\mathcal{C}_{t\phi}}{\Lambda^2}. \end{cases}$$

Renormalised matrix element

- The renormalised matrix element is:

$$\mathcal{M}^{\text{Ren}}_{\text{TOT}} = \left(\mathcal{C}^{(1)}_{Qt} + \frac{4}{3}\mathcal{C}^{(8)}_{Qt}\right)\frac{1}{\Lambda^2}\mathcal{M}^{\text{S.I.}}_{g_{h\bar{t}t}+m_t} + \left[\mathcal{C}_{tG} + \left(\mathcal{C}^{(1)}_{Qt} - \frac{1}{6}\mathcal{C}^{(8)}_{Qt}\right)K_{tG}\right]\frac{1}{\Lambda^2}\mathcal{M}_{tG}|_{\text{FIN}}$$
$$+\left[1 + \left(\mathcal{C}^{(1)}_{Qt} + \frac{4}{3}\mathcal{C}^{(8)}_{Qt}\right)\frac{1}{\Lambda^2}K_{h\bar{t}t}\right]\mathcal{M}_{\text{SM}}(g_{h\bar{t}t}, m_t) + \left(\mathcal{C}^{(1)}_{Qt} + \frac{4}{3}\mathcal{C}^{(8)}_{Qt}\right)\frac{1}{\Lambda^2}K_{m_t}\frac{\partial\mathcal{M}_{\text{SM}}}{\partial m_t} \times m_t + \mathcal{C}_{\phi G}\mathcal{M}_{\phi G}\frac{1}{\Lambda^2}.$$

- We define:

$$\tilde{\mathcal{C}}_{tG} = \mathcal{C}_{tG} + \left(\mathcal{C}^{(1)}_{Qt} - \frac{1}{6}\mathcal{C}^{(8)}_{Qt}\right)K_{tG},$$
$$\tilde{g}_{h\bar{t}t} = g_{h\bar{t}t}\left[1 + \left(\mathcal{C}^{(1)}_{Qt} + \frac{4}{3}\mathcal{C}^{(8)}_{Qt}\right)\frac{1}{\Lambda^2}K_{h\bar{t}t}\right],$$
$$\tilde{m}_t = m_t\left[1 + \left(\mathcal{C}^{(1)}_{Qt} + \frac{4}{3}\mathcal{C}^{(8)}_{Qt}\right)\frac{1}{\Lambda^2}K_{m_t}\right].$$

$$\mathcal{M}^{\text{Ren}}_{\text{TOT}} = \left(\mathcal{C}^{(1)}_{Qt} + \frac{4}{3}\mathcal{C}^{(8)}_{Qt}\right)\frac{1}{\Lambda^2}\mathcal{M}^{\text{S.I.}}_{g_{h\bar{t}t}+m_t}$$
$$+\frac{\tilde{\mathcal{C}}_{tG}}{\Lambda^2}\mathcal{M}_{tG}|_{\text{FIN}} + \mathcal{M}_{\text{SM}}(\tilde{g}_{h\bar{t}t}, \tilde{m}_t) + \frac{\mathcal{C}_{\phi G}}{\Lambda^2}\mathcal{M}_{\phi G}.$$

Matching with a UV model: $\Phi \sim (8,2)_{\frac{1}{2}}$

- We can test the relations between the parameters in NDR and BMHV matching the SMEFT with a UV toy model:

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger D^\mu \Phi - M_\Phi^2 \Phi^\dagger \Phi - Y_\Phi \left(\Phi^{A,\dagger} \varepsilon \bar{Q}_L^T T^A t_R + \text{H.c.} \right).$$

- Tree-level matching (in both schemes):

$$\frac{\mathcal{C}_{Qt}^{(1)}}{\Lambda^2} = -\frac{2}{9} \frac{Y_\Phi^2}{M_\Phi^2}, \qquad \frac{\mathcal{C}_{Qt}^{(8)}}{\Lambda^2} = \frac{1}{6} \frac{Y_\Phi^2}{M_\Phi^2}.$$

- One-loop matching + Fierz identities ([Fuentes-Martin et al.,'22]):

$$\frac{\mathcal{C}_{tG}^{\text{NDR}}}{\Lambda^2} = \frac{1}{16\pi^2} \frac{Y_\Phi^2}{M_\Phi^2} \frac{\sqrt{2} g_{h\bar{t}t} g_s}{4}, \qquad \frac{\mathcal{C}_{tG}^{\text{BMHV}}}{\Lambda^2} = 0.$$

- Using the tree-level matching for $\mathcal{C}_{Qt}^{(1,8)}$, we can verify:

$$\mathcal{C}_{tG}^{\text{NDR}} = \mathcal{C}_{tG}^{\text{BMHV}} - \left(\mathcal{C}_{Qt}^{(1)} - \frac{1}{6} \mathcal{C}_{Qt}^{(8)} \right) \frac{\sqrt{2} g_{h\bar{t}t} g_s}{16\pi^2}.$$

$h \to \bar{b}b$ rate in the SMEFT

$$\mathcal{L}_{\rm b} = \frac{\mathcal{C}^{(1)}_{Qb}}{\Lambda^2}\left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{b}_R\gamma^\mu b_R\right) + \frac{\mathcal{C}^{(8)}_{Qb}}{\Lambda^2}\left(\bar{Q}_L T^A\gamma_\mu Q_L\right)\left(\bar{b}_R T^A\gamma^\mu b_R\right) + \left[\frac{\mathcal{C}_{b\phi}}{\Lambda^2}(\phi^\dagger\phi)\bar{Q}_L\phi b_R + \text{H.c.}\right].$$

- The one-loop amplitude depends on the scheme:

$$\frac{\Gamma^{\rm NDR,1L}_{h\to b\bar{b}} - \Gamma^{\rm BMHV,1L}_{h\to b\bar{b}}}{\Gamma^{\rm SM}_{h\to b\bar{b}}} = \frac{\mathcal{C}^{(1)}_{Qb} + \frac{4}{3}\mathcal{C}^{(8)}_{Qb}}{8\pi^2\,\Lambda^2}(m_h^2 - 6m_b^2) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right).$$

- Using $\Gamma^{\rm X,TL}_{h\to b\bar{b}} \propto (g^{\rm X}_{h\bar{b}b})^2$, $\rm X = NDR, BMHV$.

$$g^{\rm NDR}_{h\bar{b}b} = g^{\rm BMHV}_{h\bar{b}b} - g_{h\bar{b}b}\left(\mathcal{C}^{(1)}_{Qb} + \frac{4}{3}\mathcal{C}^{(8)}_{Qb}\right)\frac{(m_h^2 - 6m_b^2)}{16\pi^2\Lambda^2},$$

$$\frac{\Gamma^{\rm NDR,TL}_{h\to b\bar{b}} - \Gamma^{\rm BMHV,TL}_{h\to b\bar{b}}}{\Gamma^{\rm SM}_{h\to b\bar{b}}} = -\frac{\mathcal{C}^{(1)}_{Qb} + \frac{4}{3}\mathcal{C}^{(8)}_{Qb}}{8\pi^2\,\Lambda^2}(m_h^2 - 6m_b^2) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right).$$

- $\Gamma^{\rm NDR,TL}_{h\to b\bar{b}} + \Gamma^{\rm NDR,1L}_{h\to b\bar{b}}$ is scheme-independent!

Are the log-enhanced terms enough?

- For every observable we can define ($R = \Gamma, \sigma$):

$$\delta R = \frac{R}{R_{\text{SM}}} - 1, \quad \delta R(\mathcal{C}_i) = \frac{\mathcal{C}_i}{\Lambda^2}\left(\delta R^{\text{fin}}(\mathcal{C}_i) + \delta R^{\log}(\mathcal{C}_i)\log\frac{\mu_R^2}{\Lambda^2}\right)$$

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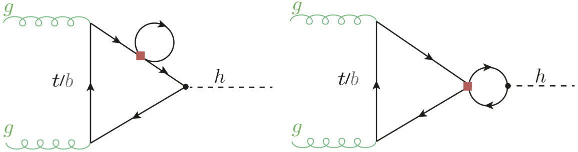
Operator	Process	μ_R	$\delta R^{fin}_{C_i}$ [TeV^2]	$\delta R^{log}_{C_i}$ [TeV^2]
$\mathcal{O}^{(1)}_{Qt}$	ggF	$\frac{m_h}{2}$	$9.91 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to gg$	m_h	$6.08 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to \gamma\gamma$	m_h	$-1.76 \cdot 10^{-3}$	$-0.80 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-4.20 \cdot 10^{-1}$	$-2.78 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV	$m_t + \frac{m_h}{2}$	$-4.30 \cdot 10^{-1}$	$-2.78 \cdot 10^{-3}$

[Alasfar,de Blas,Gröber,'22]



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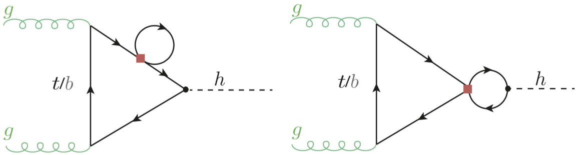

- **Finite terms are comparable with the log-enhanced ones if $\Lambda = \mathcal{O}(\text{TeV})$!**

Is the SMEFT general enough?

- The SMEFT assumes a SM-like Higgs boson:

$$(\tilde{\varphi}, \varphi) = \frac{v+h}{\sqrt{2}} \cdot U, \qquad U = \exp\left(i \frac{\pi^I \tau^I}{v} \right).$$

- The Higgs EFT (HEFT) instead assumes a more general scenario: U and h are treated separately.
- SM$\subset$SMEFT$\subset$HEFT.
- Less correlations between coefficients in HEFT: (e.g., in SMEFT $g_{5h} = v g_{6h}$ but not in HEFT).
- Measure correlation$\rightarrow$ insights about EW SSB.
- More about this topic in [Brivio,Trott,'17].

RGESolver

- A C++ library that performs RG evolution of SMEFT coefficients (dim6, 1 loop) ([S.D.N.,Silvestrini,'22]).
- General flavour structure (assuming L, B conservation).
- Numerical and approximate solutions of the RGEs with unprecedented efficiency.
- Back-rotation effects easily implemented.

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  - Luca Silvestrini.