Higgs probes of top contact interactions and their interplay with Higgs self-coupling

(Mainly based on 2202.02333)

LHCP 2023 - Belgrade

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in collaboration with Ramona Gröber and Marco Vitti

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Introduction

- The **Standard Model** (**SM**) is one of the biggest scientific successes of our time, but leaves some phenomena unexplained (massive neutrinos, dark matter. . .)

- None of the proposed **New Physics** models has empirical support to date.

- We don't expect "smoking guns" in the near future from collider experiments.

Effective field theories

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- **Idea**: use only the relevant DOFs (at a given energy scale) and develop an expansion series.
- The details of the underlying theory at all scales are not required.
- A general parametrization of our ignorance (bottom-up).
- More details in S. Banerjee's talk.

The Standard Model Effective Field Theory (SMEFT)

- New Physics is parametrized by higher dimensional operators.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{\mathfrak{D}_i > 4} \frac{C_i}{\Lambda^{\mathfrak{D}_i - 4}} \mathcal{O}_i,$$

$$O_i \sim \partial^{n^i_d} \, \phi^{n^i_\phi} \, A^{n^i_A} \, \psi^{n^i_\psi}, \qquad \mathfrak{D}_i = n^i_d + n^i_\phi + n^i_A + \frac{3}{2} n^i_\psi,$$

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- Gauge group: $\text{SU}(3)_\text{C} \otimes \text{SU}(2)_\text{L} \otimes \text{U}(1)_\text{Y}$.

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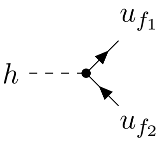
- **Assumption:** New Physics is heavy ($\Lambda \gtrsim v$).

Impact of SMEFT operators

- Interaction vertices: SM+$\mathcal{O}\left(Q^2/\Lambda^2\right)$ corrections ([Dedes,Materkowska,Paraskevas,Rosiek,Suxho,'17]).



$$= \overbrace{-i\frac{i}{v} m_{u_{f_1}} \delta_{f_1 f_2}}^{\text{S.M.}} - i v m_{u_{f_1}} \delta_{f_1 f_2} \frac{C_{\phi\Box}}{\Lambda^2} - i\frac{v}{4}\delta_{f_1 f_2}\frac{C_{\phi D}}{\Lambda^2} + \frac{iv^2}{\sqrt{2}}\left(\mathbb{P}_L C_{u\phi}^{f_2 f_1 *} + \mathbb{P}_R C_{u\phi}^{f_1 f_2}\right)$$

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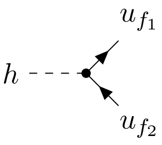

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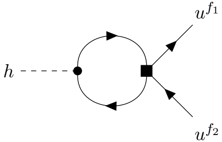
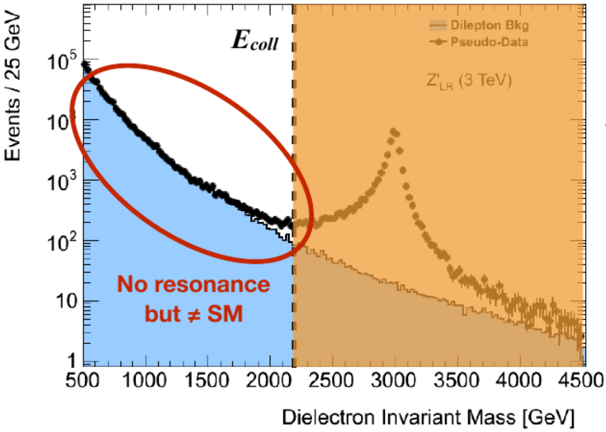
- Effects on running of SM parameters ([Jenkins,Manohar,Trott,'13]).



SMEFT: how should we use it?



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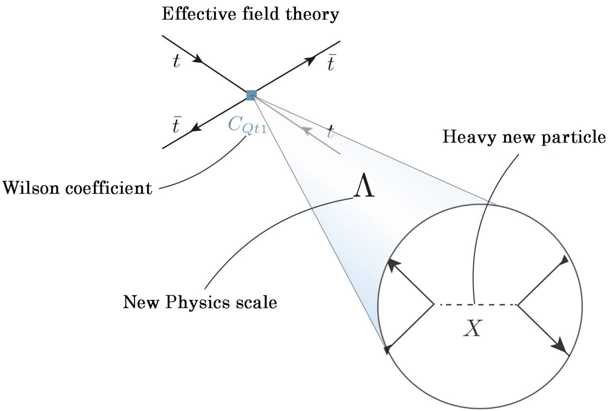

Figure: courtesy of L. Alasfar

- Information on UV mediator from IR dynamics: see [Altmannshofer, Gori, Lehmann, Zuo,'23]

The SMEFT in practice

- $\mathfrak{D} = 5$: 1 L-violating operator.
- $\mathfrak{D} = 6$: 2499 L, B-conserving independent operators (general flavour scenario, $n_f = 3$), **Warsaw basis** ([Grzadkowski,Iskrzynski,Misiak,Rosiek,'10]).

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- How can we constrain them?
- The obvious answer is top quark data (see A. Trapote (poster), H. El Faham,D. Valsecchi, E. Rossi (talks) and others).

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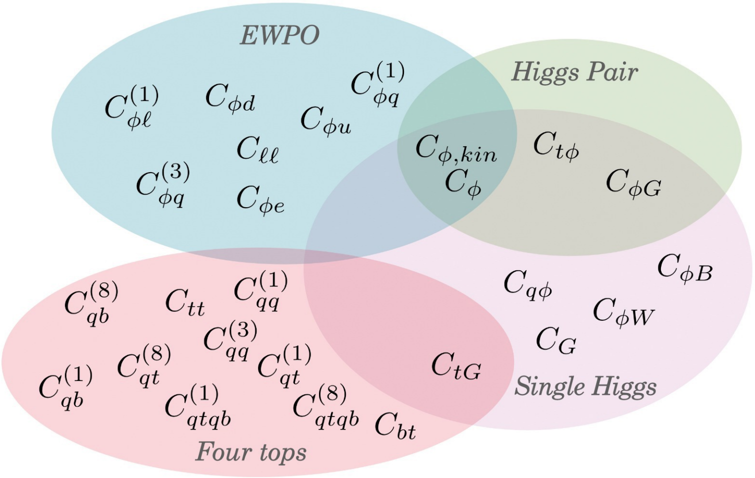

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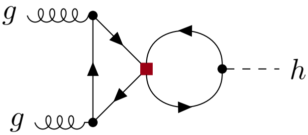
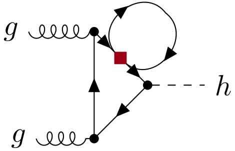
Interplay between $4t$ and λ_3.

- $4t$ operators affect Higgs production @2loop:





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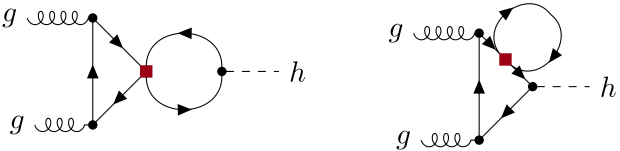

- In the SMEFT $\mathcal{L} \supset \frac{C_\phi}{\Lambda^2} \left(\phi^\dagger \phi\right)^3$.
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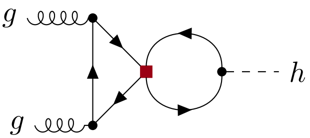

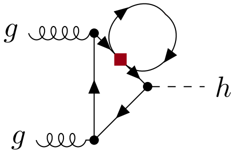

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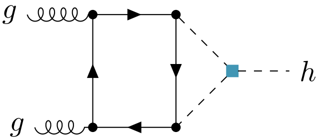
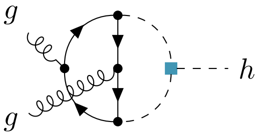
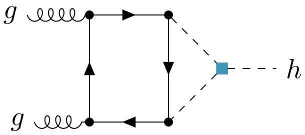




λ_3-induced corrections



- Process specific contribution.

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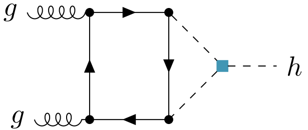

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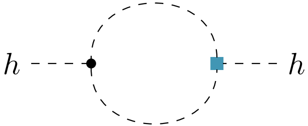

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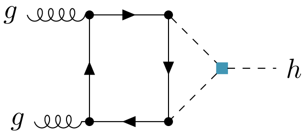

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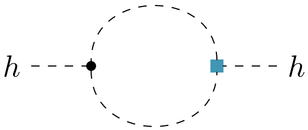

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- Details in [Degrassi, Giardino, Maltoni, Pagani,'16], [Gorbahn, Haisch,'16].

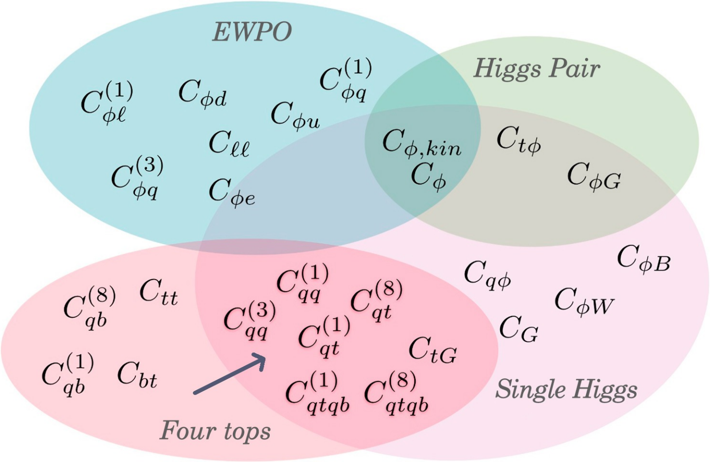

Figure: courtesy of L. Alasfar.

Are the log-enhanced terms enough?

- The bare matrix element in our case is (using D.R. with $D = 4 - 2\epsilon$):

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- A: obtained from the RGEs ([Jenkins,Manohar,Trott,'13], [Jenkins,Manohar,Trott,'13], [Alonso,Jenkins,Manohar,Trott,'13]): **no computation is required**.

- B: **requires the full computation**.

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

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

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$\mathcal{O}_{Qt}^{(1)}$	ggF	$\frac{m_h}{2}$	$9.91 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to gg$	m_h	$6.08 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-1.76 \cdot 10^{-3}$	$-0.80 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-4.20 \cdot 10^{-1}$	$-2.78 \cdot 10^{-3}$
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[Alasfar,de Blas,Gröber,'22]

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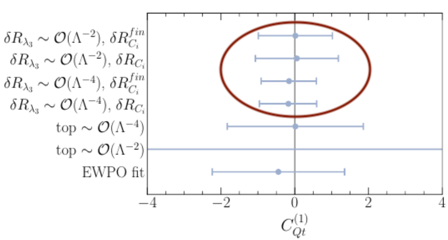
[Alasfar,de Blas,Gröber,'22]

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

State of the art

- Indirect bounds from single Higgs production $(gg \to h, gg \to \bar{t}th)$ and decay $(h \to gg,\ h \to gg)$ are competitive with:
  - Top quark data ([Ethier et. al.,'21]),
  - EWPO ([Dawson,Giardino,'22], [de Blas, Chala, Santiago,'15]).



$\langle C^{(1)}_{Qt} \rangle$	95% CI
0.0	[-1.0, 1.0]
0.1	[-1.1, 1.2]
-0.2	[-0.9, 0.6]
-0.2	[-1.0, 0.6]
0.0	[-1.8, 1.9]
-18.0	[-195.0, 159.0]
-0.4	[-2.2, 1.4]

($\Lambda = 1\,\mathrm{TeV}$, marginalized w.r.t. C_ϕ) [Alasfar,de Blas,Gröber,'22]

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

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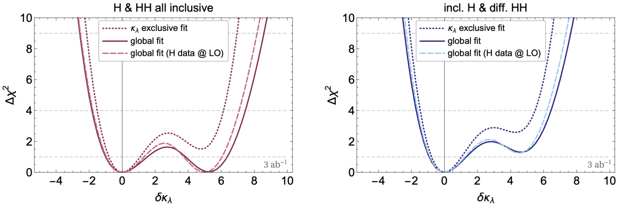

([Di Vita, Grojean, Panico, Riembau, Vantaloni,'17])

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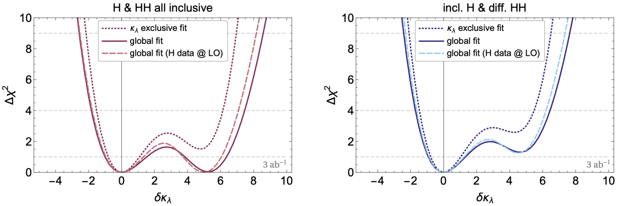

([Di Vita, Grojean, Panico, Riembau, Vantaloni,'17])

- $pp \to hh$: another viable strategy (see J. Lang's talk).

$\bar{q}q \to gh$

- Partonic channels: $\bar{q}q \to gh$, $qg \to qh$, $\bar{q}g \to \bar{q}h$, $gg \to gh$.

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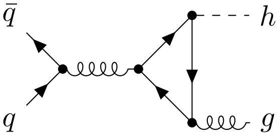
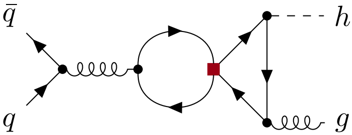


- **LO=SM** (2 diagrams).



- **NLO** (12 diagrams).

■ : SMEFT 4t vertex, • : SM vertex.

Running effects

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- 4 top operators at $\mu = \Lambda$ generate via operator mixing $\bar{q}q\bar{t}t$ operators at $\mu = \mu_{\mathrm{Low}} = \frac{\sqrt{p_T^2 + m_h^2}}{2}$.
- Operator mixing generates also $C_{t\phi}(\mu_{\mathrm{Low}}) \neq 0$ (rescaling of Y_t).

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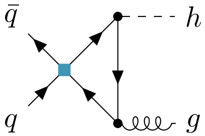
- 4t operators modify the $h + j$ production via their matrix element $\mathcal{M}_{4\text{t}}$.
- 4 top operators at $\mu = \Lambda$ generate via operator mixing $\bar{q}q\bar{t}t$ operators at $\mu = \mu_{\text{Low}} = \frac{\sqrt{p_T^2 + m_h^2}}{2}$.
- Operator mixing generates also $C_{t\phi}(\mu_{\text{Low}}) \neq 0$ (rescaling of Y_t).

$$\mathcal{M}_{\text{NLO}} = \mathcal{M}_{\text{LO}}(1 + \underbrace{\Delta Y_t}_{\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)}) + \underbrace{\mathcal{M}_{4\text{t}}}_{\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)} + \underbrace{\mathcal{M}_{\bar{q}q\bar{t}t}}_{\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)}$$

$\mathcal{M}_{\bar{q}q\bar{t}t} =$



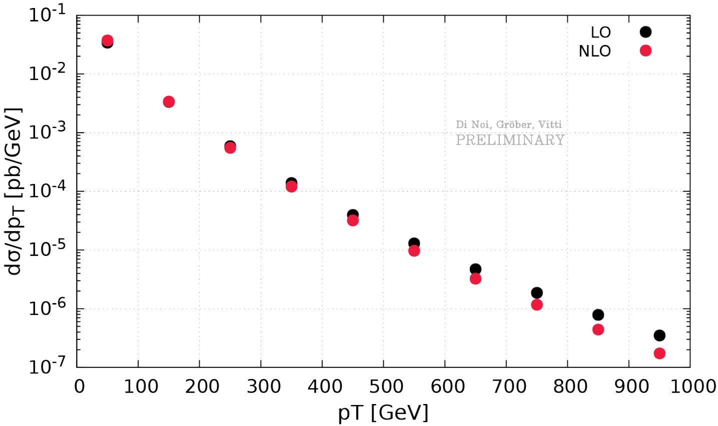
RGESolver

- A C++ library that performs RG evolution of SMEFT coefficients ([S.D.N.,Silvestrini,'22]).
- General flavour structure (assuming L, B conservation).
- Numerical solution of the RGEs (tested against the Mathematica package DsixTools, [Fuentes-Martin,Ruiz-Femenia,Vicente,Virto,'20])
- Numerical running: $\mathcal{O}(0.1\,s)$ vs $\mathcal{O}(10\,s)$ (DsixTools).
- Back-rotation effects can be included easily ([Aebischer,Kumar,'20]).

- Authors:
  - Stefano Di Noi,
  - Luca Silvestrini.

Transverse momentum distribution (preliminary)

$$C_X(\Lambda) = \frac{1}{\Lambda^2},\ \Lambda = 1\,\mathrm{TeV} \quad (X = tt, QQ1, QQ3, Qt1, Qt8),\ E_{\mathrm{coll}} = 13\,\mathrm{TeV}.$$



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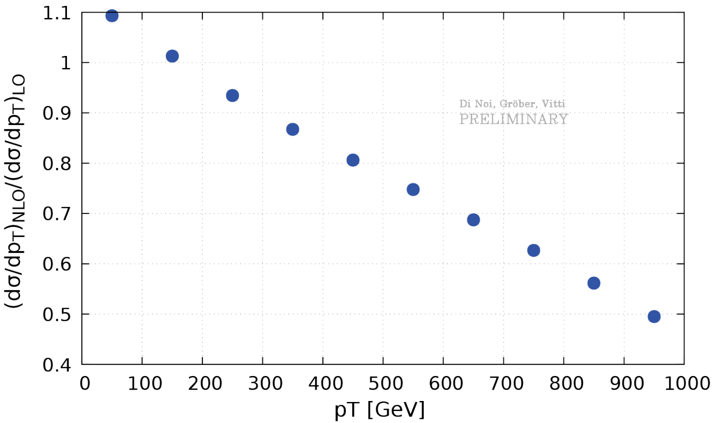

Outlook and challenges

- **What's next?**
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Stay tuned!

Thank you for your attention!

Backup

2-parameters fit results

S. Di Noi

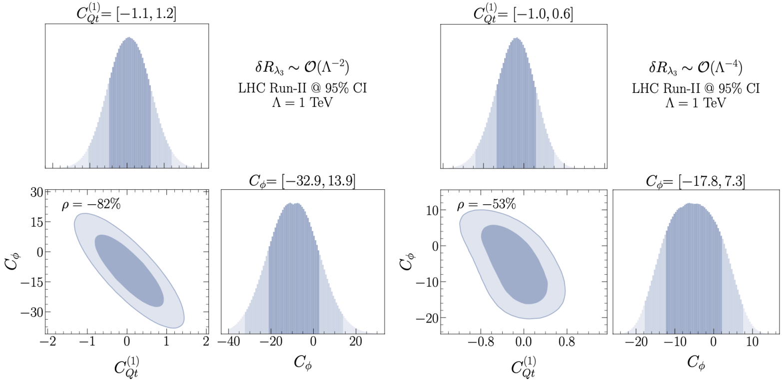


Figure: from [Alasfar,de Blas,Gröber,'22]

4-parameters fit results

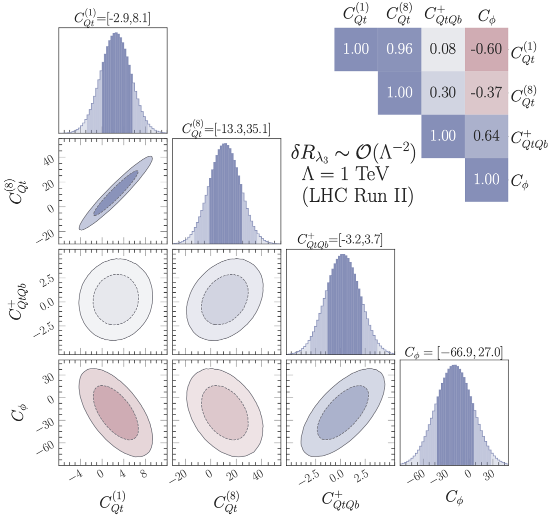


Figure: from [Alasfar,de Blas,Gröber,'22]

$\mathfrak{D} = 5$

- 1 gauge-invariant, $\not{L}$-violating operator (Weinberg operator):

$$\mathcal{O}_5^{pr} = (\tilde{\varphi}^\dagger l^p)(\tilde{\varphi}^\dagger l^r).$$

- After S.S.B. $\mathcal{O}_5^{pr}$ gives a (Majorana) mass term to neutrinos:

$$m_\nu^{pr} = C_5^{pr} v^2.$$

- assuming $c_5 = \mathcal{O}(1)$:

$$m_\nu = \mathcal{O}(\mathrm{eV}) \to \Lambda_{\not{L}} = \mathcal{O}\left(10^{10}\ \mathrm{TeV}\right).$$

- We assume: $\Lambda_{\not{L}}, \Lambda_{\not{B}} \gg \Lambda$.

$\mathfrak{D} = 6$

- A huge number of field combinations: need a complete set of operators.
- Independent operators: no linear combination vanishes due to EOMs (up to total derivatives).
- A complete $\mathfrak{D} = 6$ basis is the **Warsaw basis** ([Grzadkowski,Iskrzynski,Misiak,Rosiek,'10]).
- 59 independent operators (barring flavour structure), 2499 (general flavour scenario, $n_f = 3$).

The Warsaw Basis I

S. Di Noi

([Grzadkowski,Iskrzynski,Misiak,Rosiek,'10])

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

The Warsaw Basis II

([Grzadkowski,Iskrzynski,Misiak,Rosiek,'10])

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

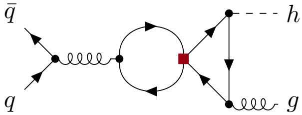
Is the SMEFT general enough?

- 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$\to$ insights about EW SSB.
- More about this topic in [Brivio,Trott,'17].

Master Integrals



- MIs=1 loop $\times$ 1 loop.
- Example: $B_0 \times C_0$.

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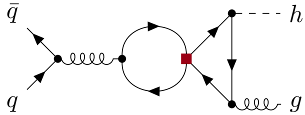

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$$B_0(p, m_t) = \int \frac{d^D l}{(2\pi)^D} \frac{1}{l^2 - m_t^2} \frac{1}{(l+p)^2 - m_t^2} = \frac{B_0^{(-1)}}{\epsilon} + B_0^{(0)} + \epsilon B_0^{(1)} + \mathcal{O}\left(\epsilon^2\right),$$

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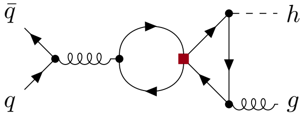

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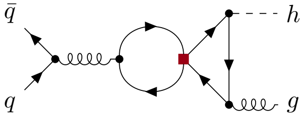

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- $C_0^{(1)}$ computed by G. Crisanti, P. Mastrolia (Padova Amplitudes group).
- $D_0^{(1)}$: **To be done!**

Renormalization and γ_5

- Diagrams are $(1\ \mathrm{Loop})^2$: only1 loop counterterms expected.

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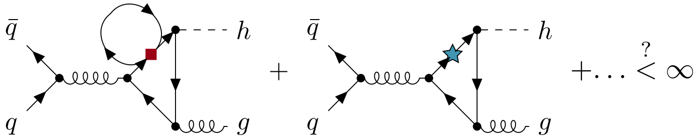

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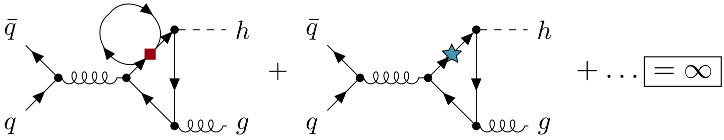

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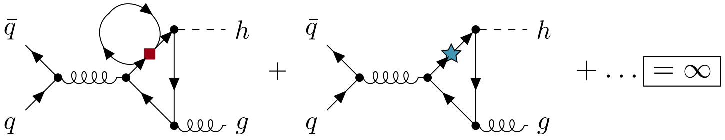

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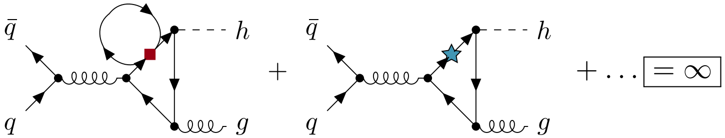

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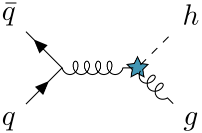

- The divergence could be eliminated using $\mathcal{O}_{\phi G}$:

$$\delta_{\phi G} = \left(C_{Qt8} - 6C_{Qt1}\right)\frac{g_s^2 m_t^2}{3\,(16\pi^2)^2 \epsilon v^2}.$$

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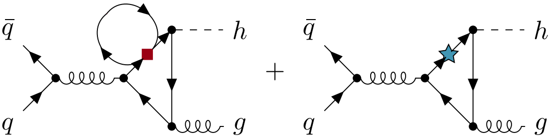

$+ \dots \boxed{= \infty}$

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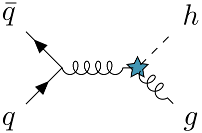

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- This result holds in **NDR**. What about **BMHV**?