Operator basis construction and projection for Effective Field Theories with AutoEFT

Herbstschule HEP Bad Honnef 2026

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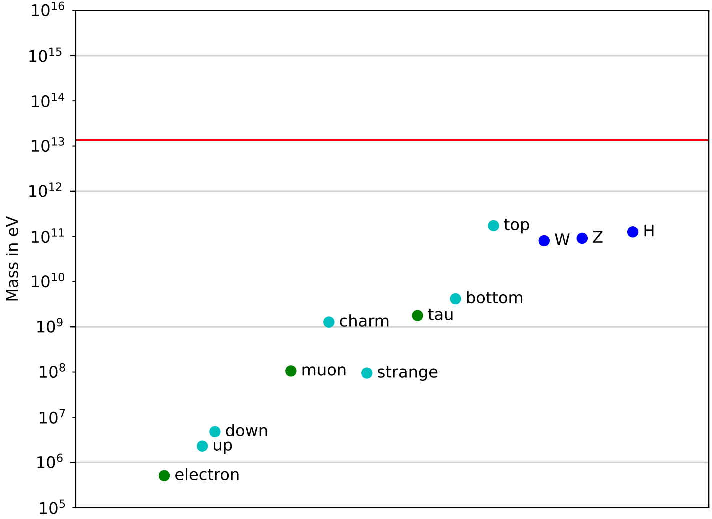
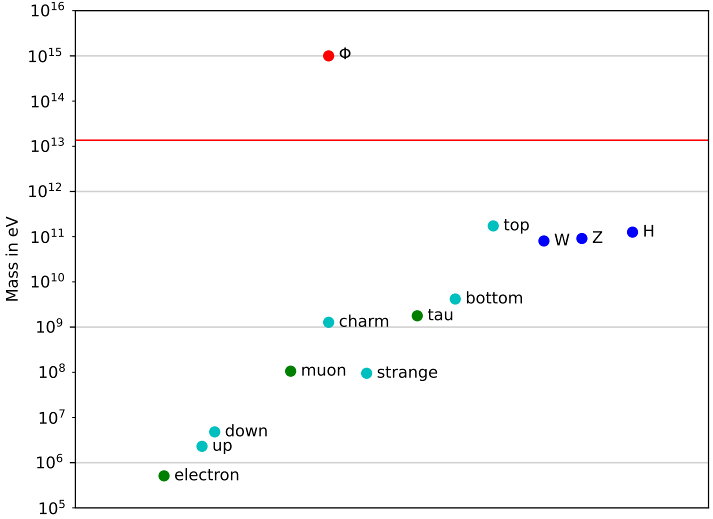
Effective field theories

Standard Model particles:



Effective field theories

BSM heavy scalar particle Φ:

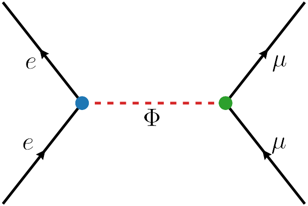


EFT interactions

$\mathcal{L}_{\text{BSM}}$ contains

$\bar{e}e\,\Phi$

$\bar{\mu}\mu\,\Phi$



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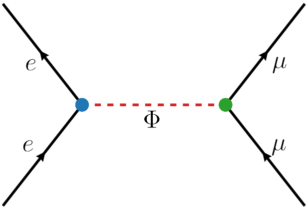
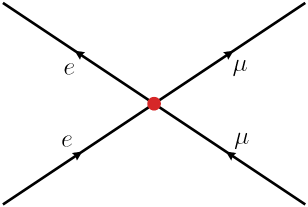


$\mathcal{L}_{\mathrm{SMEFT}}$ contains

$$\frac{\bar{e}e\,\bar{\mu}\mu}{M_\Phi^2}$$



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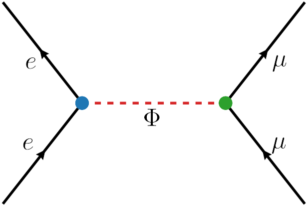
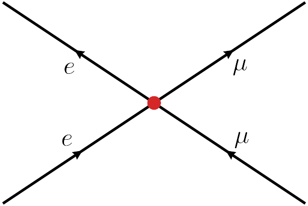


$\mathcal{L}_{\mathrm{SMEFT}}$ contains

$$\frac{\bar{e}e\,\bar{\mu}\mu}{M_\Phi^2}$$

$$\left(\frac{1}{p^2 - M_\Phi^2} \xrightarrow{p \ll M_\Phi} \frac{1}{M_\Phi^2}\right)$$



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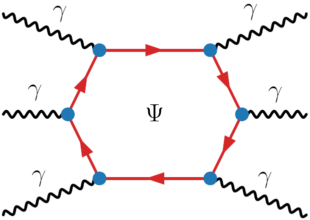

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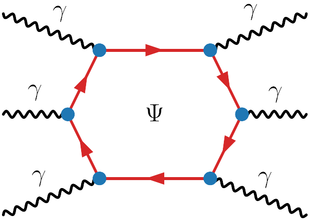
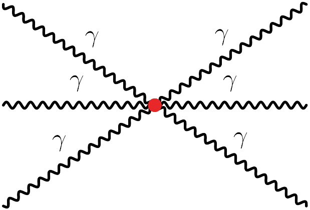


$\mathcal{L}_{\mathrm{SMEFT}}$ contains

$$\frac{A_{\mu}A^{\mu}A_{\nu}A^{\nu}A_{\rho}A^{\rho}}{M_{\Psi}^{2}}$$

$$+\ \ldots$$



The EFT Lagrangian

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- Vector Boson?
- Fermion?
- $U(1)$ charge?
- $SU(2), SU(3)$ representation?
- How many heavy particles?
- Heavy particle masses?

The EFT Lagrangian

$$\boxed{\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_i \mathcal{C}_i \mathcal{O}_i}$$

EFT operators $\mathcal{O}_i$ contain only SM fields.
Terms are sorted by Mass dimension d.

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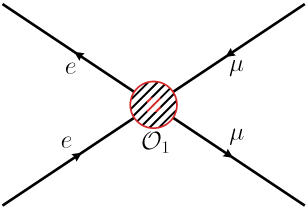

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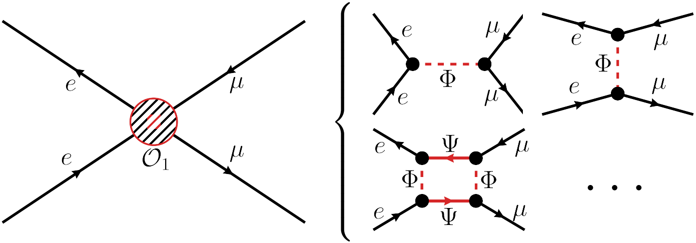

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For fixed mass dimension d:

$$\mathcal{L}_{\text{SMEFT}}^{(d)} \propto \sum_i \mathcal{C}_i \mathcal{O}_i$$

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For fixed mass dimension d:

$$\mathcal{L}^{(d)}_{\text{SMEFT}} \propto \sum_i \underbrace{\mathcal{C}_i}_{\text{Vector components}} \overbrace{\mathcal{O}_i}^{\text{Basis vectors}}$$

- The observed BSM effects are one vector in the space spanned by all EFT operators.
- Diagrams with $\mathcal{O}_i$ inserted depend on $\mathcal{C}_i$
- Need a set of operators with independent $\mathcal{C}_i$ (basis).

SMEFT operator bases

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

Some SMEFT Dimension 6 operators (Warsaw basis)

(Grzadkowski, Iskrzynski, Misiak, and Rosiek 2010)

SMEFT operator bases

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

More SMEFT Dimension 6 operators (Warsaw basis)

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SMEFT operator bases

Number of SMEFT operators by Mass dimension d

Mass dimension d (order $1/\Lambda^{d-4}$)	Onshell operators	Green's basis operators (offshell operators)
5	12	12
6	3045	3710
7	1542	2466
8	44 807	111 004
9	90 456	138 228
10	2 092 441	4 976 586

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Onshell basis: Used for $\mathcal{S}$-matrix-elements $\langle p|\mathcal{S}|k\rangle$, cross-sections σ
Offshell basis: Used for calculations on correlation functions $\langle 0|\phi \ldots |0\rangle$, e.g. renormalization: $\mathcal{C}_{i,\mathrm{bare}} = Z_{ji}\mathcal{C}_{j,\mathrm{R}}$.

AutoEFT

(Harlander and Schaaf 2024; Schaaf 2024)

EFT operator construction for many different models:

Supported fields

- Scalar fields
- Fermion fields (left/right Weyl spinors)
- Vector fields only as gauge fields
- Spin 2 Tensors (GRSMEFT)

Supported symmetries

- $U(1)$ symmetries
- $SU(n)$ symmetries

Symmetries can be either local (gauge) or global.

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Only Lorentz- and Gauge-invariant operators are constructed.
Added support for offshell basis (Green's basis) construction.

Operator redundancies

Naive idea: Write down every valid operator.

$\rightarrow$ **Overcomplete basis**: $\mathcal{C}_i$ cannot be fixed by experiments.

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Some examples of **redundancies**:

$$(\bar{\psi}\gamma^\mu P_L \psi)(\bar{\chi}\gamma_\mu P_L \chi) = (\bar{\psi}\gamma^\mu P_L \chi)(\bar{\chi}\gamma_\mu P_L \psi) \qquad \text{(Fierz Identity)}$$

$$D_\mu \bar{\psi}\gamma^\mu \psi \phi \simeq -\bar{\psi}\gamma^\mu D_\mu \psi \phi - \bar{\psi}\gamma^\mu \psi D_\mu \phi \qquad \text{(Integration by Parts)}$$

$$D_\mu D_\nu \phi - D_\nu D_\mu \phi = F_{\mu\nu}\phi \qquad \text{(Commutator of Covariant Derivatives)}$$

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Only for onshell bases:

$$\Box\phi \simeq 0, \quad D_\mu \gamma^\mu \psi \simeq 0, \quad D_\mu F^{\mu\nu} \simeq 0 \qquad \text{(Equation of Motion)}$$

Only for offshell bases:

$$\epsilon^{\alpha\beta} D_\alpha^{\dot{\alpha}} F_{L\beta\gamma} \simeq \epsilon_{\dot{\gamma}\dot{\alpha}} D_\gamma^{\dot{\gamma}} {F_R}^{\dot{\alpha}\dot{\beta}} \qquad \text{(Bianchi identity)}$$

Construction algorithm

Describe the field's representation in all symmetry groups:

- Lorentz group: $SO^+(3,1) \simeq SL(2,\mathbb{C}) \simeq SU(2) \times SU(2)$
  $\rightarrow$ A tuple of $SU(2)$-tableaux $\left(\mathcal{T}_L\,; \mathcal{T}_R\right)$.
- $SU(n)$ groups: One $SU(n)$-tableau $\mathcal{T}$.
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Example: SM Gluon field strength tensor $G^I_{\mu\nu}$:

$$G^I_{\mu\nu} \rightarrow \begin{cases} \text{Lorentz (Left):} & (G_L)_{\alpha\beta} = (\sigma^{\mu\nu})_{\alpha\beta} G_{\mu\nu} & \rightarrow & \left(\boxed{\alpha \mid \beta}\,;1\right) \\ \text{Lorentz (Right):} & (G_R)^{\dot\alpha\dot\beta} = (\bar\sigma^{\mu\nu})^{\dot\alpha\dot\beta} G_{\mu\nu} & \rightarrow & \left(1\,;\boxed{\dot\alpha \mid \dot\beta}\right) \\ SU(3): & G^{abc} = \epsilon^{adc}(T^I)^b_d G^I & \rightarrow & \begin{array}{|c|c|} \hline a & b \\ \hline c & \\ \cline{1-1} \end{array} \\ SU(2): & G \text{ (trivial)} & \rightarrow & 1 \\ U(1): & G \text{ (trivial)} & \rightarrow & 0 \end{cases}$$

Construction algorithm

Young Tableau product (*modified Littlewood-Richardson rule*):

$$
\begin{array}{ccccccccccccc}
G^I & \cdot & G^J & \rightarrow & G^{(I}G^{J)}, & & \delta^{IJ}G^IG^J, & & f^{IJK}G^IG^J, & & \ldots \\
\begin{ytableau} a & b \\ c \end{ytableau} & \otimes & \begin{ytableau} d & e \\ f \end{ytableau} & = & \begin{ytableau} a & b & d & e \\ c & f \end{ytableau} & \oplus & \begin{ytableau} a & b \\ c & d \\ e & f \end{ytableau} & \oplus & \begin{ytableau} a & b & d \\ c & e \\ f \end{ytableau} & \oplus & \ldots
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One $SU(3)$ invariant contraction.

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\end{array}
$$

One $SU(3)$ invariant contraction. Combine with fields G:

$$
\begin{array}{|c|c|}\hline a & b \\ \hline c & d \\ \hline e & f \\ \hline\end{array} \quad \to \quad
\begin{aligned}
\mathcal{O} &= \epsilon_{ace}\epsilon_{bdf}G^{abc}G^{def} \\
&= \epsilon_{ace}\epsilon_{bdf}\left(\epsilon^{agc}(T^I)^b_g G^I\right)\left(\epsilon^{dhf}(T^J)^e_h G^J\right)
\end{aligned}
$$

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Result is $\sigma(\mathcal{C}_1)$.

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Group B uses basis that does not contain $\mathcal{A}$:

$$\mathcal{A} = \sum_n a'_n \mathcal{O}'_n$$

Result is $\sigma(\mathcal{C}'_1, \ldots \mathcal{C}'_n)$.

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Result is $\sigma(\mathcal{C}'_1, \ldots \mathcal{C}'_n)$.

What are the expansion coefficients a'_n?
What are the Wilson coefficients $\mathcal{C}'_i(\mathcal{C}_1, \ldots \mathcal{C}_n)$?

Projection

$$
\begin{aligned}
\delta c_z &= \; - c_H - 3\delta v\,, \\
c_{gg} &= c_{GG}\,, \\
c_{ww} &= c_{WW}\,, \\
c_{zz} &= \frac{g^4 c_{WW} + 4 g^2 g'^2 c_{WB} + g'^4 c_{BB}}{(g^2+g'^2)^2}\,, \\
c_{z\gamma} &= \frac{g^2 c_{WW} - 2(g^2 - g'^2) c_{WB} - g'^2 c_{BB}}{g^2+g'^2}\,, \\
c_{\gamma\gamma} &= c_{WW} + c_{BB} - 4 c_{WB}\,, \\
c_{w\Box} &= \frac{2}{g^2 - g'^2}\left[g'^2 c_{WB} - c_T + \delta v\right], \\
c_{z\Box} &= \; - \frac{2}{g^2}\left[c_T - \delta v\right], \\
c_{\gamma\Box} &= \frac{2}{g^2 - g'^2}\left[(g^2 + g'^2) c_{WB} - 2 c_T + 2\delta v\right].
\end{aligned}
$$

Relations between redundant Wilson coefficients in SMEFT
(Falkowski, Fuks, Mawatari, Mimasu, Riva, and Sanz 2015)

Projection

Projection algorithm: Find a general function

$$P : \mathcal{A} \to a_n \quad \text{such that} \quad \mathcal{A} = \sum_n a_n \mathcal{O}_n$$

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Inner product $\langle \mathcal{A} | \mathcal{B} \rangle$:

$$\langle \mathcal{A} | \mathcal{B} \rangle = \sum_{n,m} a_n b_m \langle \mathcal{O}_n | \mathcal{O}_m \rangle = \sum_{n,m} a_n g_{nm} a_m$$

Define $g_{nm} = \langle \mathcal{O}_n | \mathcal{O}_m \rangle = \delta_{nm}$ for one special basis.

Summary

- **General EFT operators** can be used to describe high-energy effects without having to decide on a specific high-energy model.
- The **Number of operators** of an EFT increases with mass dimension, and for SMEFT past dimension 7 the basis can not be constructed by hand.
- **AutoEFT** generates EFT operator bases for SMEFT, and any other model with $U(1)$ and $SU(N)$ symmetries.
- Both **Onshell and Offshell** bases are supported. Mass dimension is limited only by computation time.
- **Operator projection** enables us to deal with EFT operators just like ordinary vectors, including easy change of basis.

Backup

Backup