SMEFT Hands-on

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What you need to have installed

follow instructions on the **TWiki**

- Mathematica
- FeynRules
- VirtualBox with `Delphes2020.vdi`
- material in the TWiki:
  - download on your laptop: `SMEFT_HandsOn_pt1.tar`
  - for the second part, on the VM: `SMEFT_HandsOn_pt2.tar`

Part I – theory

The SMEFT

theory valid if:

- new physics nearly decoupled: $\Lambda \gg (v, E)$
- at the accessible scale: **SM** fields + symmetries

☛ a Taylor expansion in canonical dimensions ($\delta = v/\Lambda$ or E/Λ):

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

$\mathcal{O}_i$ invariant operators that form a complete, non redundant **basis**

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- new physics nearly decoupled: $\Lambda \gg (v, E)$
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$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{L}_6$$

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

$\mathcal{O}_i$ invariant operators that form a complete, non redundant **basis**

The Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

1 X^3		2 φ^6 and $\varphi^4 D^2$ 3		$\psi^2\varphi^3$ 5	
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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
4 $X^2\varphi^2$		6 $\psi^2 X\varphi$		$\psi^2\varphi^2 D$ 7	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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8a $(\bar{L}L)(\bar{L}L)$

Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

8b $(\bar{R}R)(\bar{R}R)$

Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}L)(\bar{R}R)$ **8c**

Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

8d $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$

Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

B-violating

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_{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_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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8a	$(\bar{L}L)(\bar{L}L)$	8b	$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$ 8c
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}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
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8d	$(\bar{L}R)(\bar{R}L)$ 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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u^\beta\right.$ [illegible]
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(\right.$ [illegible] $\left.C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}$ [illegible] $\left] \left[(q_s^{\gamma m})^T C l_t^n\right]\right.$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	[illegible] $C u_r^\beta\right] \left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

omitted

A code for LO SMEFT: SMEFTsim

today we will be using `SMEFTsim` Brivio,Jiang,Trott 1709.06492

- website: `http://feynrules.irmp.ucl.ac.be/wiki/SMEFT`
- a `FeynRules` model with the complete Warsaw basis
- it comes also in pre-exported UFO models
- implements **3** flavor assumptions × **2** input parameter schemes

  `general`
  `MFV`
  `U35`

  $\{\alpha_{\rm em}, m_Z, G_F\}$
  $\{m_W, m_Z, G_F\}$

- works in Mathematica and MC generators (MadGraph)
- allows MC generation at **LO** → for NLO use `SMEFT@NLO`
- SM $hgg, h\gamma\gamma, hZ\gamma$ vertices implemented in the $m_t \to \infty$ limit

A closer look at some operators

In the SMEFT_HandsOn.nb notebook in Mathematica:

- load FeynRules
- define the variables

```
Flavor = U35
Scheme = MwScheme
```

- load the model SMEFTsim_A_main.fr
- output the Feynman rules for some operators, e.g.:

```
OH13
OdH
OHd
OHB
...
```

Flavor assumptions

The SMEFT Lagrangian is defined with free flavor indices

→ this means **2499 real parameters**

e.g. $\mathcal{L} \supset (C_{He})_{pr}\,(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_{R,p}\gamma^\mu e_{R,r})$

→ hermitian: $(C_{He})_{pr} = (C_{He})^*_{rp} \to 3\,\mathbb{R} + 3\,\mathbb{C} \equiv$ **9** real. par.

e.g. $\mathcal{L} \supset (C_{le})_{prst}\,(\bar{l}_{L,p}\gamma_\mu l_{L,r})(\bar{e}_{R,s}\gamma^\mu e_{R,t})$

→ hermitian: $(C_{le})_{prst} = (C_{le})^*_{rpst} = (C_{le})^*_{prts} = (C_{le})_{rpts}$

→ $9\,\mathbb{R} + 36\,\mathbb{C} \equiv$ **45** real par.

e.g. $\mathcal{L} \supset (C_{ledq})_{prst}\,(\bar{l}^j_{L,p}\gamma_\mu e_{R,r})(\bar{d}_{R,s}\gamma^\mu q^j_{R,t})$

→ **not** hermitian: → $81\,\mathbb{C} \equiv$ **162** real par.

Flavor assumptions

one can assume a flavor symmetry $\rightarrow$ **only invariant contractions allowed**

$U(3)^5$

maximal: for each SM field $\psi = \{q_L, u_R, d_R, l_L, e_R\}$:

$$\psi_p \mapsto \Omega_{\psi,pr}\,\psi_r \text{ with } \Omega_\psi \text{ a } 3\times 3 \text{ unitary matrix}$$

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invariants:

eg. $\bar{u}_R\gamma^\mu u_R \to \bar{u}_{Rp}\gamma^\mu\,(\Omega_u^\dagger)_{ps}(\Omega_u)_{sr}\,u_{Rr} = \bar{u}_{Rp}\gamma^\mu\,\delta_{pr}\,u_{Rr}$ diagonal

$\bar{q}_L\,u_R? \to \bar{q}_{Lp}\,(\Omega_q^\dagger)_{ps}(\Omega_u)_{sr}\,u_{Rr}$ not invariant!

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Yukawas inserted as spurions: constants transforming under the sym.:

$$Y_u \mapsto \Omega_u\,Y_u\,\Omega_q^\dagger, \quad Y_d \mapsto \Omega_d\,Y_d\,\Omega_q^\dagger, \quad Y_e \mapsto \Omega_e\,Y_e\,\Omega_l^\dagger$$

in this way $(\bar{u}_R Y_u q_L)$, $(\bar{d}_R Y_d q_L)$, $(\bar{e}_R Y_e l_L)$ are allowed

→ all **chirality-changing** currents require inserting a Yukawa!

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→ all **chirality-changing** currents require inserting a Yukawa!

→ **81 real parameters**

Predictions in the SMEFT

From $\mathcal{L}_{\text{SMEFT}}$ to observables

so, we have chosen a flavor assumption and written down the Lagrangian. Are we ready to calculate?

Nope. Not yet.

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Some Lagrangian manipulations are needed first:

- normalize and diagonalize all **kinetic terms**
- define a **input** parameter scheme ("tree-level renormalization scheme")

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- define a **input** parameter scheme ("tree-level renormalization scheme")

corrections stemming from these operations are induced by $\mathcal{L}_6$: $\propto C_i$

$\rightarrow$ when applied to $\mathcal{L}_6$ itself: $\mathcal{O}(C_i^2)$ effects $\rightarrow$ neglected

$\rightarrow$ only need to be evaluated on $\mathcal{L}_{SM}$

Kinetic term normalization and field redefinitions

Some $d = 6$ operators give corrections to kinetic terms

e.g. $$C_{HB}\,(H^\dagger H)B_{\mu\nu}B^{\mu\nu} \xrightarrow{\text{unitary g.}} C_{HB}\frac{v^2}{2}B_{\mu\nu}B^{\mu\nu} + C_{HB}\frac{2vh+h^2}{2}B_{\mu\nu}B^{\mu\nu}$$

$$C_{HD}\,(H^\dagger D_\mu H)(D^\mu H^\dagger H) \xrightarrow{\text{unitary g.}} C_{HD}\frac{v^2}{4}\partial_\mu h\partial^\mu h + \dots$$

$$C_{H\square}\,(H^\dagger H)D_\mu D^\mu(H^\dagger H) \xrightarrow{\text{unitary g.}} C_{H\square}\left[\frac{v^2}{2}\partial_\mu h\partial^\mu h + \frac{3}{2}v^2 h\partial_\mu\partial^\mu h\right] + \dots$$
$$= -C_{H\square}\,\partial_\mu h\partial^\mu h + \dots$$

Calculating with non-canonically normalized kinetic terms is complicated
$\to$ requires modifying LSZ formula

Kinetic term normalization and field redefinition: B_μ

an easier solution: redefine the fields

eg. B_μ $\mathcal{L}_{\rm SMEFT} \supset -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} \Big[1 - 2v^2 C_{HB} \Big]$

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replace everywhere $\begin{cases} B_\mu \to B_\mu \left[1 + v^2 C_{HB}\right] \\ g' \to g' \left[1 - v^2 C_{HB}\right] \end{cases}$ and expand linearly in C_{HB}

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$$\to -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} \left[1 - 2v^2 C_{HB}\right] \left[1 + 2v^2 C_{HB}\right] = -\frac{\mathbf{1}}{\mathbf{4}} B_{\mu\nu} B^{\mu\nu} + \mathcal{O}(C_{HB}^2)$$

$\to D_\mu \sim g' B_\mu$ unchanged up to $\mathcal{O}(C_{HB}^2)$

$\to \mathcal{L}_6$ unchanged up to $\mathcal{O}(C_{HB}^2)$

$\to C_{HB}$ only remains in $C_{HB} \dfrac{2vh + h^2}{2} B_{\mu\nu} B^{\mu\nu}$

Kinetic term normalization and field redefinitions: h

an easier solution: redefine the fields

eg. h $\mathcal{L}_{\rm SMEFT} \supset \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \frac{v^2}{2} C_{HD} - 2v^2 C_{H\Box}\right] = \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \Delta_h\right]$

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replace everywhere $h \to h\left[1 - \frac{v^2}{4} C_{HD} + v^2 C_{H\Box}\right]$, expand linearly in $C_{HD},\ C_{H\Box}$

Kinetic term normalization and field redefinitions: h

an easier solution: **redefine the fields**

eg. h $\quad \mathcal{L}_{\rm SMEFT} \supset \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \frac{v^2}{2}C_{HD} - 2v^2 C_{H\Box}\right] = \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \Delta_h\right]$

replace everywhere $h \to h\left[1 - \frac{v^2}{4}C_{HD} + v^2 C_{H\Box}\right]$, expand linearly in C_{HD}, $C_{H\Box}$

$$\to \frac{1}{2}\partial_\mu h \partial^\mu h \left[1 + \Delta_h\right]\left[1 - \Delta_h\right] \quad = \quad \mathbf{\frac{1}{2}}\partial_\mu h \partial^\mu h + \mathcal{O}(\Delta_h^2)$$

$\to \mathcal{L}_6$ unchanged up to $\mathcal{O}(\Delta_h^2)$

$\to$ **SM Higgs couplings**: $h^3, h^4, hVV, hhVV, h\bar\psi\psi$

with n h-legs are rescaled by $[1 - n\,\Delta_h]$

A special kinetic term correction: $\mathcal{O}_{HWB}$

$$C_{HWB}\,(H^\dagger W_{\mu\nu} H) B^{\mu\nu} \quad \xrightarrow{\text{unitary g.}} \quad -C_{HWB}\frac{v^2}{2} W^3_{\mu\nu} B^{\mu\nu} + \dots$$

introduces a **kinetic mixing** between $W^3, B \longrightarrow$ needs to be diagonalized!

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introduces a **kinetic mixing** between $W^3, B \longrightarrow$ needs to be diagonalized!

3 subsequent operations:

(1) normalize kin. term for B C_{HB} and W^i C_{HW}

(2) rotate to diagonalize kin. term in (W^3, B) C_{HWB}

(3) rotate to diagonalize mass term $\to (Z, A)$

doing **(2)**, **(3)** it at once:

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} 1 & -v^2 C_{HWB}/2 \\ -v^2 C_{HWB}/2 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

A special kinetic term correction: $\mathcal{O}_{HWB}$

$$C_{HWB}\,(H^\dagger W_{\mu\nu} H) B^{\mu\nu} \quad \xrightarrow{\text{unitary g.}} \quad -C_{HWB}\frac{v^2}{2} W^3_{\mu\nu} B^{\mu\nu} + \dots$$

introduces a **kinetic mixing** between $W^3, B \longrightarrow$ needs to be diagonalized!

3 subsequent operations:

(1) normalize kin. term for B C_{HB} and W^i C_{HW}

(2) rotate to diagonalize kin. term in (W^3, B) C_{HWB}

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$\to$ correction to the **Weinberg angle** $\to$ enters **SM γ, Z couplings**

Input parameters

In order to make numerical predictions we need to assign numerical values to the Lagrangian parameters

SM

$\mathcal{L}_{SM}$ parameters

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$

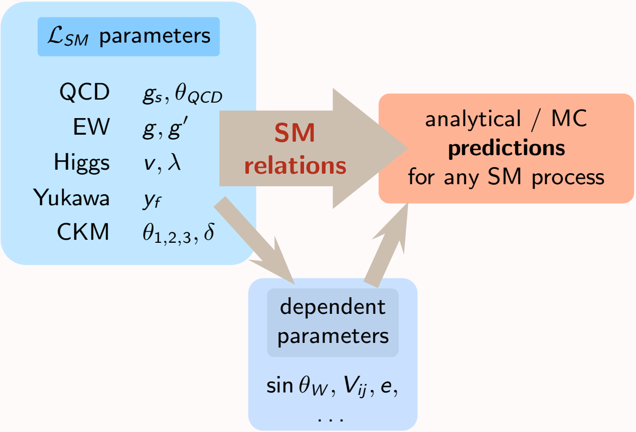
SM relations →

analytical / MC
predictions
for any SM process

Input parameters

In order to make numerical predictions we need to assign numerical values to the Lagrangian parameters

SM



Input parameters

In order to make numerical predictions we need to assign numerical values to the Lagrangian parameters

SM

input measurements

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

$\mathcal{L}_{SM}$ parameters

QCD	g_s, θ_{QCD}
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Higgs	v, λ
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α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
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meson decay/osc

$\mathcal{L}_{SM}$ parameters

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$

SM relations

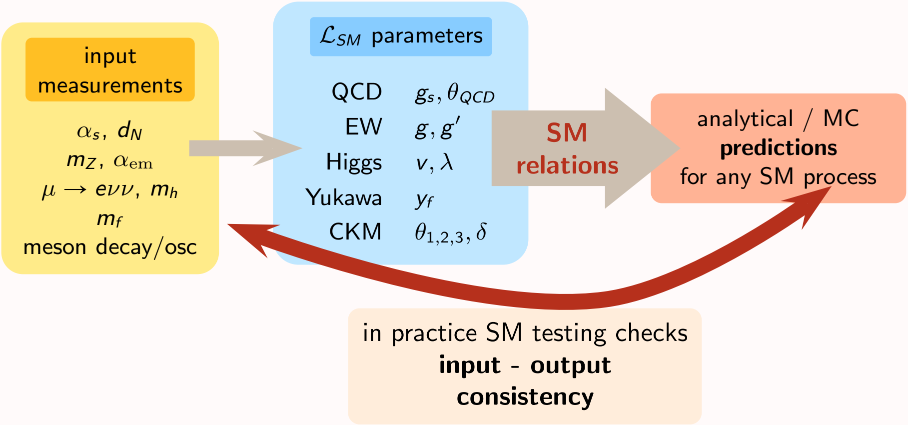
analytical / MC **predictions** for any SM process

- calculate [input process](param)
- invert [param](input process)
- measure input process and assign param the corresponding **value**
- use this number in $\mathcal{L}_{SM}$

Input parameters

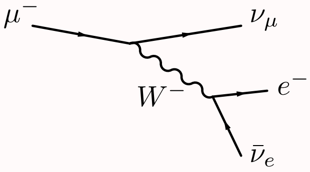
In order to make numerical predictions we need to assign numerical values to the Lagrangian parameters

SM



Input parameters example: G_F

The Fermi constant is precisely measured from muon decay



$$\Gamma_{SM}(\mu^- \to e^- \bar{\nu}_e \nu_\mu) = \frac{G_F^2\, m_\mu^5}{192\pi^3}$$

Input parameters

In order to make numerical predictions we need to assign numerical values to the Lagrangian parameters

SMEFT

input measurements

α_s, d_N

m_Z, $\alpha_{\rm em}$

$\mu \to e\nu\nu$, m_h

m_f

meson decay/osc

→

$\mathcal{L}_{\rm SMEFT}$ parameters

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$
EFT	C_i

→ **SMEFT relations** →

analytical / MC **predictions** for any process

Input parameters

In order to make numerical predictions we need to assign numerical values to the Lagrangian parameters

SMEFT

input measurements

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

$\mathcal{L}_{\rm SMEFT}$ parameters

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$
EFT	C_i

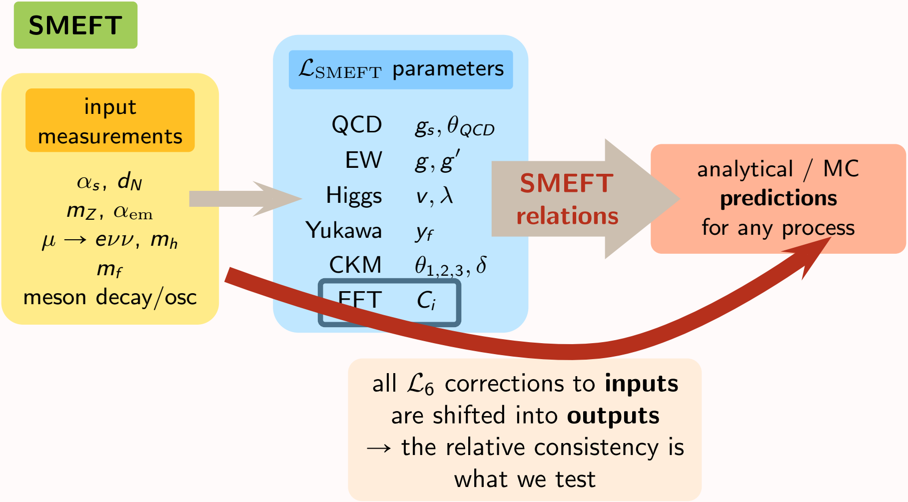
SMEFT relations

analytical / MC **predictions** for any process

- calculate [input process](param, $\mathbf{C_i}$)
- invert [param](input process, $\mathbf{C_i}$)
- assign param measured value + shift in $\mathbf{C_i}$
- replace this everywhere in $\mathcal{L}_{\rm SM(EFT)}$

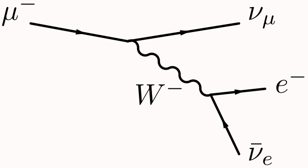
Input parameters

In order to make numerical predictions we need to assign numerical values to the Lagrangian parameters

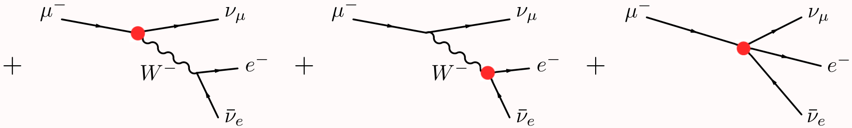


Input parameters example: G_F

The Fermi constant is precisely measured from muon decay



$$\Gamma_{SM}(\mu^- \to e^- \bar{\nu}_e \nu_\mu) = \frac{G_F^2\, m_\mu^5}{192\pi^3}$$



$$\Gamma_{\mathrm{SMEFT}}(\mu^- \to e^- \bar{\nu}_e \nu_\mu) = \Gamma_{SM}\left[1 + 2v^2\left((C_{Hl}^{(3)})_{22} + (C_{Hl}^{(3)})_{11} - (C_{ll})_{1221}\right)\right]$$
$$\overset{U(3)^5}{=} \Gamma_{SM}\left[1 + 4v^2\left(C_{Hl}^{(3)} - \frac{1}{2}C'_{ll}\right)\right]$$

Input parameters example: G_F

$$\Gamma_{\rm SMEFT}(\mu^- \to e^-\bar{\nu}_e\nu_\mu) = \Gamma_{SM}\left[1 + 2v^2\left((C_{Hl}^{(3)})_{22} + (C_{Hl}^{(3)})_{11} - (C_{ll})_{1221}\right)\right]$$

$$\overset{U(3)^5}{=} \Gamma_{SM}\left[1 + 4v^2\left(C_{Hl}^{(3)} - \frac{1}{2}C'_{ll}\right)\right]$$

$$\to 1.1663787(6)\times 10^{-5}\ \text{GeV}^{-2} = G_F\left[1 + 2v^2\left(C_{Hl}^{(3)} - \frac{1}{2}C'_{ll}\right)\right]$$

$$= G_F\left[1 + \sqrt{2}\,\Delta G_F\right]$$

$$\to \bar{v} = \frac{1}{2^{1/4}\sqrt{G_F}} = \hat{v}\left[1 + \frac{\Delta G_F}{\sqrt{2}}\right]$$

$\hat{v} \equiv 246.22$ GeV

$\bar{v} \equiv$ parameter in $\mathcal{L} \to \Delta G_F$ enters all **vertices with v** in $\mathcal{L}_{SM}$

Input parameters for the EW sector

a more correct analysis: the **EW sector** has 3 independent parameters

$$\{v,\, g,\, g'\}$$

that are fixed by **3** input measurements, usually chosen among

$$\{m_Z,\, m_W,\, G_F,\, \alpha_{\rm em}\}$$

Input parameters for the EW sector

a more correct analysis: the **EW sector** has 3 independent parameters

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that are fixed by **3** input measurements, usually chosen among

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ie. one chooses **3** equations among

$$\hat{m}_Z^2 = [91.1876\ \text{GeV}]^2 = \frac{\bar{v}^2}{4}(\bar{g}^2+\bar{g}'^2)\left[1+\frac{v^2 C_{HD}}{2}+\frac{2v^2\bar{g}\bar{g}'}{\bar{g}^2+\bar{g}'^2}C_{HWB}\right]$$

$$\hat{m}_W^2 = [80.387\ \text{GeV}]^2 = \frac{\bar{v}^2\bar{g}^2}{4}$$

$$\hat{G}_F^2 = 1.1663787\times 10^{-5}\ \text{GeV}^{-2} = \frac{1}{\sqrt{2}\bar{v}^2}\left[1+2v^2 C_{Hl}^{(3)} - v^2 C'_{ll}\right]$$

$$\hat{\alpha_{\rm em}}(m_Z) = 1/127.95 = \frac{1}{4\pi}\frac{\bar{g}^2\bar{g}'^2}{\bar{g}^2+\bar{g}'^2}\left[1-\frac{v^2\bar{g}\bar{g}'}{\bar{g}^2+\bar{g}'^2}C_{HWB}\right]$$

solves in $\{\bar{v},\bar{g},\bar{g}'\}$ and **replaces** the solution $\bar{x}\to\hat{x}(1+\delta x/x)$ in $\mathcal{L}_{SM}$

Input parameters for the EW sector

example: $\{m_Z, G_F, \alpha_{\rm em}\}$ scheme

$$\bar{v}^2 = \hat{v}^2\left[1+\sqrt{2}\Delta G_F\right], \qquad \hat{v}^2 = \frac{1}{\sqrt{2}\hat{G}_F}$$

$$\bar{g}^2 = \hat{g}^2\left[1-\frac{c_\theta^2}{c_{2\theta}}\left(\frac{\Delta m_Z^2}{m_Z^2}+\frac{\Delta G_F}{\sqrt{2}}\right)-\frac{s_\theta^2}{c_{2\theta}}\frac{\Delta\alpha_{\rm em}}{\alpha_{\rm em}}\right], \qquad \hat{g}^2 = \frac{4\pi\hat{\alpha_{\rm em}}}{s_\theta^2}$$

$$\bar{g}'^2 = \hat{g}'^2\left[1+\frac{s_\theta^2}{c_{2\theta}}\left(\frac{\Delta m_Z^2}{m_Z^2}+\frac{\Delta G_F}{\sqrt{2}}\right)+\frac{c_\theta^2}{c_{2\theta}}\frac{\Delta\alpha_{\rm em}}{\alpha_{\rm em}}\right], \qquad \hat{g}'^2 = \frac{4\pi\hat{\alpha_{\rm em}}}{c_\theta^2}$$

with

$$\frac{\Delta m_Z^2}{m_Z^2} = v^2\left(\frac{C_{HD}}{2}+s_{2\theta}C_{HWB}\right)$$

$$\frac{\Delta\alpha_{\rm em}}{\alpha_{\rm em}^2} = -\frac{v^2 s_{2\theta}}{2}C_{HWB}$$

$$\sqrt{2}\Delta G_F = v^2\left(2C_{Hl}^{(3)}-C'_{ll}\right)$$

and $s_\theta^2 = \frac{1}{2}\left[1-\sqrt{1-\frac{2\sqrt{2}\pi\hat{\alpha_{\rm em}}}{\hat{G}_F\hat{m}_Z^2}}\right]$

Input parameters for the EW sector

example: $\{m_Z, G_F, \alpha_{\rm em}\}$ scheme

$$\bar{v}^2 = \hat{v}^2\left[1+\sqrt{2}\Delta G_F\right], \qquad \hat{v}^2 = \frac{1}{\sqrt{2}\hat{G}_F}$$

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→ **corrections** to m_W^2

$Z\bar{f}f$

$W\bar{f}f$

TGC

QGC

...

Input parameters for the EW sector

example: $\{m_Z, G_F, m_W\}$ scheme

$$\bar{v}^2 = \hat{v}^2\left[1+\sqrt{2}\Delta G_F\right], \qquad \hat{v}^2 = \frac{1}{\sqrt{2}\hat{G}_F}$$

$$\bar{g}^2 = \hat{g}^2\left[1-\frac{\Delta G_F}{\sqrt{2}}\right], \qquad \hat{g}^2 = 4\sqrt{2}G_F m_Z^2 c_\theta^2$$

$$\bar{g}'^2 = \hat{g}'^2\left[1-\frac{\Delta G_F}{\sqrt{2}}-\frac{1}{s_\theta^2}\frac{\Delta m_Z^2}{m_Z^2}\right], \qquad \hat{g}'^2 = 4\sqrt{2}G_F m_Z^2 s_\theta^2$$

with

$$\frac{\Delta m_Z^2}{m_Z^2} = v^2\left(\frac{C_{HD}}{2}+s_{2\theta}C_{HWB}\right)$$

$$\sqrt{2}\Delta G_F = v^2\left(2C_{Hl}^{(3)}-C'_{ll}\right)$$

and $s_\theta^2 = 1-\dfrac{\hat{m}_W^2}{\hat{m}_Z^2}$

Input parameters for the EW sector

example: $\{m_Z, G_F, m_W\}$ scheme

$$\bar{v}^2 = \hat{v}^2\left[1+\sqrt{2}\Delta G_F\right], \qquad \hat{v}^2 = \frac{1}{\sqrt{2}\hat{G}_F}$$

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→ **corrections** to $\gamma\bar{f}f$

$Z\bar{f}f$

$W\bar{f}f$

TGC

QGC

...

Input parameter example: m_b

assuming $U(3)^5 \to$ $\mathcal{O}_{dH}$ $= (H^\dagger H)(\bar{q}_L Y_D^\dagger H^\dagger d_R) \quad \to \quad$ take the b terms:

$$\mathcal{L}_{\rm SMEFT} \supset -\frac{\bar{y}_b \bar{v}}{\sqrt{2}}\left[1-\frac{v^2}{2}C_{dH}\right]\bar{b}_L b_R - \frac{\bar{y}_b}{\sqrt{2}}\left[1-\frac{3v^2}{2}C_{dH}\right]h\bar{b}_L b_R + \text{h.c.}$$

$$= -\frac{\bar{y}_b \hat{v}}{\sqrt{2}}\left[1-\frac{v^2}{2}C_{dH}+\frac{\Delta G_F}{\sqrt{2}}\right]\bar{b}_L b_R - \frac{\bar{y}_b}{\sqrt{2}}\left[1-\frac{3v^2}{2}C_{dH}\right]h\bar{b}_L b_R + \text{h.c.}$$

Input parameter example: m_b

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$$= \underbrace{-\frac{\bar{y}_b \hat{v}}{\sqrt{2}}\left[1 - \frac{v^2}{2}C_{dH} + \frac{\Delta G_F}{\sqrt{2}}\right]}_{\text{measured as } \hat{m}_b}\bar{b}_L b_R - \frac{\bar{y}_b}{\sqrt{2}}\left[1 - \frac{3v^2}{2}C_{dH}\right] h\bar{b}_L b_R + \text{h.c.}$$

$$\to \bar{y}_b = \hat{m}_b \frac{\sqrt{2}}{\hat{v}}\left[1 + \frac{v^2}{2}C_{dH} - \frac{\Delta G_F}{\sqrt{2}}\right]$$

Input parameter example: m_b

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$$\to \bar{y}_b = \hat{m}_b \frac{\sqrt{2}}{\hat{v}}\left[1+\frac{v^2}{2}C_{dH}-\frac{\Delta G_F}{\sqrt{2}}\right]$$

replacing $\bar{y}_b$ back in $\mathcal{L}$:

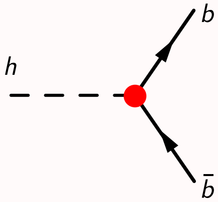
$$\mathcal{L}_{\rm SMEFT} \supset -\hat{m}_b \bar{b}_L b_R - \frac{\hat{m}_b}{\hat{v}}\left[1 - v^2 C_{dH} - \frac{\Delta G_F}{\sqrt{2}}\right] h\bar{b}_L b_R + \text{h.c.}$$

correction to Yukawa coupling

$$h \to b\bar{b}$$

LO SMEFT corrections to $h \to b\bar{b}$

for NLO check Cullen,Gauld,Pecjak,Scott 1512.02508, 1607.06354, 1904.06358



LO SMEFT contributions are all SM-like:

$$\Gamma_{\rm SMEFT}(h \to b\bar{b}) = \Gamma_{SM}(h \to b\bar{b})\left[1 + 2\,\mathrm{Re}\;\delta g_{hbb}\right]$$

direct $\mathcal{O}_{dH}$ contribution	$-\frac{3v^2}{2}C_{dH}$
input shifts	$+\frac{v^2}{2}C_{dH} - \frac{\Delta G_F}{\sqrt{2}}$
Higgs kinetic term redefinition	$-\frac{v^2}{4}C_{HD} + v^2 C_{H\Box}$
$\frac{\delta g_{hbb}}{v^2}$	$-\frac{C_{HD}}{4} + C_{H\Box} - C_{dH} - C^{(3)}_{Hl} + \frac{C'_{ll}}{2}$