Effective Field Theories Across the Universe

The Standard Model Effective Field Theory

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Outline

Introduction to EFT in particle physics

- Main ideas.
- Main strategies.
- Some examples: from Fermi theory to the SM to the SMEFT.

Constructing the SMEFT

- The SM: brief review, strengths and weaknesses.
- Adding SMEFT interactions, how and why.

The SMEFT hands on

- SMEFT effects on SM parameters and SM interactions.
- Calculating observables in the SMEFT.

Constraining SMEFT interactions

- Global fits of collider observables (EW, Higgs, top), flavor observables, low energy observables.
- Matching to UV models.

Constructing the SMEFT

- The SM: brief review, strengths and weaknesses.
- Adding dim=6 SMEFT interactions.

Adding SMEFT interations

- How to build the SMEFT Lagrangian order by order in the EFT expansion
- Explicit examples: $\mathcal{L}_{SMEFT}^{(d=5)}$ and $\mathcal{L}_{SMEFT}^{(d=6)}$

The SMEFT framework

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \frac{C^{(5)}}{\Lambda} Q^{(5)} \sum_{i=1}^{n_6} \frac{C_i^{(6)}}{\Lambda^2} Q_i^{(6)} + \cdots$$

dim=5: only 1 operator

dim=6: "Warsaw" basis

$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4} G_{\mu\nu}^A G^{A,\mu\nu} - \frac{1}{4} W_{\mu\nu}^I W^{I,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + (D_\mu\varphi)^\dagger (D^\mu \varphi) + m^2 \varphi^\dagger\varphi - \frac{1}{2}\lambda(\varphi^\dagger\varphi)^2 + i\,(\bar{l}'_L \not{D} l'_L + \bar{e}'_R \not{D} e'_R + \bar{q}'_L \not{D} q'_L + \bar{d}'_R \not{D} d'_R) - (\bar{l}'_L \Gamma_e e'_R \varphi + \bar{q}'_L \Gamma_u u'_R \tilde{\varphi} + \bar{q}'_L \Gamma_d d'_R \varphi) + h.c.$$

with covariant derivative:

$$D_\mu = \partial_\mu + i g_s G_\mu^A T^A + i g_W W_\mu^I T^I + i g_1 B_\mu Y$$

gauge fields and masses, HVV, VVV

Higgs field and Mh

Yukawa couplings

Vff, HFF

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\star (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

hermitian						non-hermitian	
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)$ + h.c.	
$Q_{\ell\ell}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$Q_{\ell e}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{e}_s \gamma^\mu e_t)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^i u_r)\varepsilon_{ij}(\bar{q}_s^j d_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$Q_{\ell u}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{u}_s \gamma^\mu u_t)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^i T^A u_r)\varepsilon_{ij}(\bar{q}_s^j T^A d_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{\ell d}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{\ell equ}^{(1)}$	$(\bar{\ell}_p^i e_r)\varepsilon_{ij}(\bar{q}_s^j u_t)$
$Q_{\ell q}^{(1)}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$	$Q_{\ell equ}^{(3)}$	$(\bar{\ell}_p^i \sigma_{\mu\nu} e_r)\varepsilon_{ij}(\bar{q}_s^j \sigma^{\mu\nu} u_t)$
$Q_{\ell q}^{(3)}$	$(\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$		
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$		
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$	$(\bar{L}R)(\bar{R}L)$ + h.c.	
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{\ell edq}$	$(\bar{\ell}_p^i e_r)(\bar{d}_s q_{ti})$

4-fermion interactions: tt, ttH, Drell-Yan

- Obeying SM symmetries,.
- One Higgs doublet of $SU(2)_L$, SSB linearly realized.
- L and B conserving
- Assuming various flavor symmetries, of incremental complexity

Constructing SMEFT operators

Not having any information on the UV theory, **use purely symmetry arguments dictated by phenomenological evidence**

Main requirements

- Dimensionality (dim=5,6,…)
- Lorentz invariance
- SM gauge symmetry

Additional optional requirements

- Global symmetry of the SM, exact or approximate: L, B, flavor, …
- No additional CP violation

We'll follow these principles in building the SMEFT dim=5,6 operators

Build a basis of operators, i.e. reduce them to the minimal number required to generate all dim=6 interactions

Various techniques to eliminate redundant operators

- Integration by parts
- Field redefinition
- Fierz identities
- Dirac structure reduction

We will discuss them in the following.

SMEFT: dim=5

Due to both Lorentz and gauge invariance:

- Scalars can only come as $\varphi^\dagger\varphi \to [\varphi^\dagger\varphi] = 2$
- Fermions can only come as bilinears $\to [\bar{\psi}(\dots)\psi] = 3$
  But SM fermions are chiral: $\bar{\psi}\psi = \bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L$ and
  $\bar{\psi}\gamma^\mu\gamma^\nu D_\mu D_\nu\psi = \bar{\psi}D^2\psi \to$ not gauge invariant
- Vectors can only come via the $X^{\mu\nu}$ tensor $\to [X^{\mu\nu}] = 2$
  and Lorentz indices have to be saturated:
  $[X^{\mu\nu}\partial_\mu\partial_\nu] = [X^{\mu\nu}X_{\mu\nu}] = 4$

A dim=5 operator cannot be made of only scalars, only fermions, or only vectors

Dimensionality of elementary building blocks:

$$[\psi] = \frac{3}{2}\,,\ [A^\mu] = 1\,,\ [\partial^\mu] = 1\,,\ [X^{\mu\nu}] = 2\,,\ [\phi] = 1$$

Gauge group transformation properties of SM fields:

	ℓ	e	q	u	d	H	G	W	B
$\mathrm{SU}(3)_c$ representation	**1**	**1**	**3**	**3**	**3**	**1**	**8**	**1**	**1**
$\mathrm{SU}(2)_L$ representation	**2**	**1**	**2**	**1**	**1**	**2**	**1**	**3**	**1**
$\mathrm{U}(1)_Y$ charge	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	0	0	0

Notice: work in the unbroken phase to easily use the SM gauge symmetry constraint.

- Scalars + Vectors
- Fermion + Vectors

} dimensionally not allowed, given above building blocks

- Scalars + Fermions → dimensionally allowed, need to examine gauge properties

SMEFT: dim=5

Three main further steps:

- φ and $\varphi^\dagger$ have total $Y = 0$, but this would require to match with $\bar{\psi}\psi$ which is forbidden by gauge invariance. Need to use $\varphi\ \varphi\ \rightarrow$ need two fermion doublets to obtain $Y = 0\ \rightarrow$ to match Y_φ they need to be leptons
- To obtain an $SU(2)_L \times U(1)_Y$ invariant object we need to combine them as $(l^T\epsilon\varphi)(\varphi^T\epsilon l)$ since $(\varphi^T\epsilon\varphi) = 0$ [where $\epsilon = i\sigma_2$]
- Make it a Lorentz scalar using the charge conjugate operator $C = i\gamma^2\gamma^0$:

$$Q^{(5)} = (l^T C\epsilon\varphi)(\varphi^T\epsilon l)$$

a.k.a. "Weinberg operator"

S. Weinberg, "Baryon and Lepton Nonconserving Processes," Phys. Rev. Lett. 43, 1566–1570

Important consequences for beyond SM physics:

- It **violates lepton number** $(l \rightarrow e^{i\gamma}l)$ by two units
- Upon SSB it **generates a Majorana mass for left-handed neutrinos**

$$\frac{1}{\Lambda}Q^{(5)} \xrightarrow{\langle\varphi\rangle=(0,v)^T} = \frac{v^2}{\Lambda}\nu_L^T C\nu_L$$

Set lower bound on scale of L violation

$$m_\nu \sim 1\,\mathrm{eV} \rightarrow \Lambda \sim 10^{13}\,\mathrm{GeV}$$

SMEFT: dim 6

Very similar considerations leads to identify a basis of dim=6 SMEFT operators.

"Warsaw" or GIMR basis: most commonly used

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

With respect to the dim=5 case, the problem arises of identifying a minimal set of independent operators.

(59 operators excluding L- and B-violating ones and suppressing flavor indices).

Considering the flavor structure of the operators: 2499 couplings out of which 1350 are CP-even and 1149 are CP-odd.

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

hermitian						non-hermitian	
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$		$(\bar LR)(\bar LR)$ + h.c.	
$Q_{\ell\ell}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar\ell_s\gamma^\mu\ell_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$Q_{\ell e}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar e_s\gamma^\mu e_t)$	$Q_{quqd}^{(1)}$	$(\bar q_p^i u_r)\varepsilon_{ij}(\bar q_s^j d_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$Q_{\ell u}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar u_s\gamma^\mu u_t)$	$Q_{quqd}^{(8)}$	$(\bar q_p^i T^A u_r)\varepsilon_{ij}(\bar q_s^j T^A d_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$Q_{\ell d}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar d_s\gamma^\mu d_t)$	$Q_{\ell equ}^{(1)}$	$(\bar\ell_p^i e_r)\varepsilon_{ij}(\bar q_s^j u_t)$
$Q_{\ell q}^{(1)}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$	$Q_{\ell equ}^{(3)}$	$(\bar\ell_p^i\sigma_{\mu\nu} e_r)\varepsilon_{ij}(\bar q_s^j\sigma^{\mu\nu} u_t)$
$Q_{\ell q}^{(3)}$	$(\bar\ell_p\gamma_\mu\tau^I\ell_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$		
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$		
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$	$(\bar LR)(\bar RL)$ + h.c.	
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{\ell edq}$	$(\bar\ell_p^i e_r)(\bar d_s q_{ti})$

Reducing to GIMR basis

Integration by parts: in QFT we assume that total derivatives in the action *S* vanish

For instance: scalar kinetic term can be written in two ways

$$\int d^4x D^\mu(\varphi^\dagger D_\mu \varphi) = 0 \quad \longrightarrow \quad \text{can trade } D^\mu \varphi^\dagger D_\mu \varphi \longleftrightarrow \varphi^\dagger D^2 \varphi$$

Equation of motions (e.o.m.) relate different operators

For dim=6 operators, we can use SM e.o.m., derived from $\mathcal{L}_{SM}^{(4)}$, since we are cutting the EFT expansion at $O(1/\Lambda^2)$

$$\begin{aligned}
(D^\mu D_\mu \varphi)^j &= m^2 \varphi^j - \lambda (\varphi^\dagger \varphi) \varphi^j - \bar{e}\,\Gamma_e^\dagger l^j + \varepsilon_{jk} \bar{q}^k\, \Gamma_u u - \bar{d}\,\Gamma_d^\dagger q^j, \\
(D^\rho G_{\rho\mu})^A &= g_s \left(\bar{q}\gamma_\mu T^A q + \bar{u}\gamma_\mu T^A u + \bar{d}\gamma_\mu T^A d\right), \\
(D^\rho W_{\rho\mu})^I &= \frac{g}{2}\left(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi + \bar{l}\gamma_\mu \tau^I l + \bar{q}\gamma_\mu \tau^I q\right), \\
\partial^\rho B_{\rho\mu} &= g' Y_\varphi\, \varphi^\dagger i \overleftrightarrow{D}_\mu \varphi + g' \sum_{\psi \in \{l,e,q,u,d\}} Y_\psi\, \bar{\psi}\gamma_\mu \psi.
\end{aligned}$$

- The same result can be achieved via field redefinition
- Care must be taken in extending it beyond dim=6: need to take into account EFT effects in either the e.o.m. or field redefinitions.

Used to reduce the number of derivative → Example: there are no $\varphi^2 D^4, \varphi^2 X D^2, X^2 D^2$ type of operators in the GIMR basis

Reducing to GIMR basis, ctd.

Fierz identities for spinor indices and Dirac structure reduction

C_n coeffs: determined by contracting with elements of $\{\Gamma^n\}$

$$X \otimes Y = \sum_n C_n(X,Y)\,\Gamma^n \otimes \tilde{\Gamma}_n + E(X,Y)$$

"Evanescent operators": extra structures arising when using Dimensional Regularization $(d = 4 - \epsilon)$ defined by this equation. Relevant at loop level.

$X, Y \rightarrow$ generic Dirac structures

Basis in d=4, and its dual

$$\{\Gamma^n\} = \{P_L, P_R, \gamma^\mu P_L, \gamma^\mu P_R, \sigma^{\mu\nu}\}$$
$$\{\tilde{\Gamma}_n\} = \{P_L, P_R, \gamma_\mu P_L, \gamma_m u P_R, \sigma_{\mu\nu}/2\}$$

$$\mathrm{tr}\{\Gamma^n, \tilde{\Gamma}_m\} = 2\delta^n_m$$

$$P_{L,R} = \frac{1 - \gamma^5}{2}$$
$$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

Used to separate lepton and quark fields in different fermion currents

Fierz identities for $SU(3)_c$ indices [T^agenerators of the fundamental representation of $SU(3)_c$]

$$(T^a)_{ij}(T^a)_{kl} = \frac{1}{2}\left(\delta_{il}\delta_{kj} - \frac{1}{N}\delta_{ij}\delta_{kl}\right)$$

Global symmetries

"Accidental" symmetries:
symmetries arising in the lowest-dimensional theory as an indirect consequence of the symmetries explicitly imposed on the theory (ex.: in the SM B and L conservation is a consequence of the gauge symmetry)

- Lepton number L, together with $L_{e-\mu}$ and $L_{\mu-\tau}$ (or individual L_e, L_μ, L_τ)
  Strong bound from m_ν $\rightarrow$ $\Lambda > 10^{13}$ GeV
- Baryon number B
  Strong bound from proton decay $\rightarrow$ $\Lambda > 10^{16}$GeV

see discussion about dim=5 operator

If allowed, SMEFT effects would be tiny. Retain both symmetries in the SMEFT and **envision a multi-scale EFT**

"Approximate" symmetries:
Symmetries that are only mildly violated by tiny parameters in the Lagrangian of the lowest-dimensional theory

- Flavor symmetry, mildly broken in the SM by Yukawa coupling for the light generations and off-diagonal CKM matrix elements
  Strong bounds from FCNC processes (such as $B-\overline{B},\ K-\overline{K}$ mixing)$\rightarrow$ $\Lambda > \ 10^{8}$ GeV

Two commonly considered scenarios: $U(3)^5$and $U(2)^5$

The SMEFT hands on

- Effects of SMEFT interactions on SM parameters and SM interactions.
- Calculating observables in the SMEFT.

Effects of SMEFT interactions

- Effective operators at Λ_{EW} induce "direct" and "indirect" contributions of their Wilson coefficients in physical observables.

Modify existent interactions
+
New EFT interactions

Shift fields and parameters from the SM ones

EFT effects in **Lagrangian**

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \frac{C_i}{\Lambda^2} Q_i$$

→ EFT effects in **fields and parameters** → EFT effects in **interactions** → EFT effects in **probability amplitudes** → EFT effects in **physical observables**

Lagrangian: $\frac{C_i}{\Lambda^2}$

Fields and parameters through physical observables: $\frac{C_i}{\Lambda^2}, \frac{C_i^2}{\Lambda^4}, \ldots$

EFT effects in **Lagrangian**

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \frac{C_i}{\Lambda^2} Q_i$$

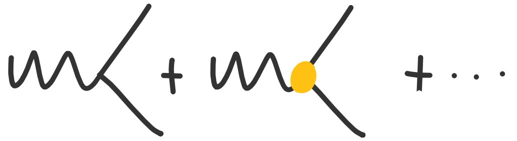
→ EFT effects in **fields and parameters** → EFT effects in **interactions** → EFT effects in **probability amplitudes** → EFT effects in **physical observables**

EFT effects in Lagrangian: $\frac{C_i}{\Lambda^2}$

EFT effects in fields and parameters, and in interactions: $\frac{C_i}{\Lambda^2}$

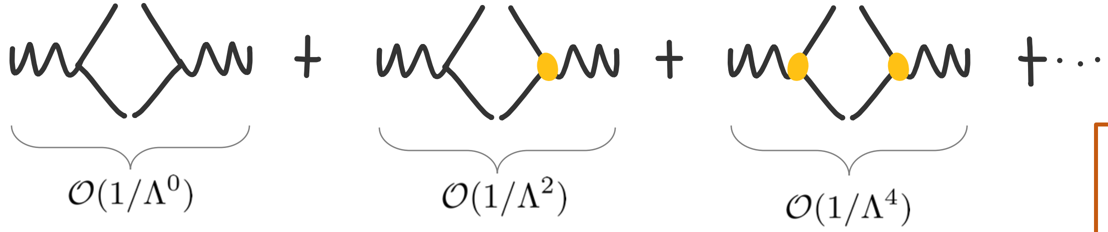
EFT effects in probability amplitudes, and in physical observables: $\frac{C_i}{\Lambda^2}, \frac{C_i^2}{\Lambda^4}, \ldots$

interaction-level :



Often computed up to quadratic order to assure positivity

amplitude-level :



Careful: quadratic terms may also arise from the expansion of indirect SMEFT effects.

observable-level :

$$O_{SMEFT} = O_{SM} + \Delta O^{(1)} + \Delta O^{(2)} + \ldots$$

EFT effects in **Lagrangian**

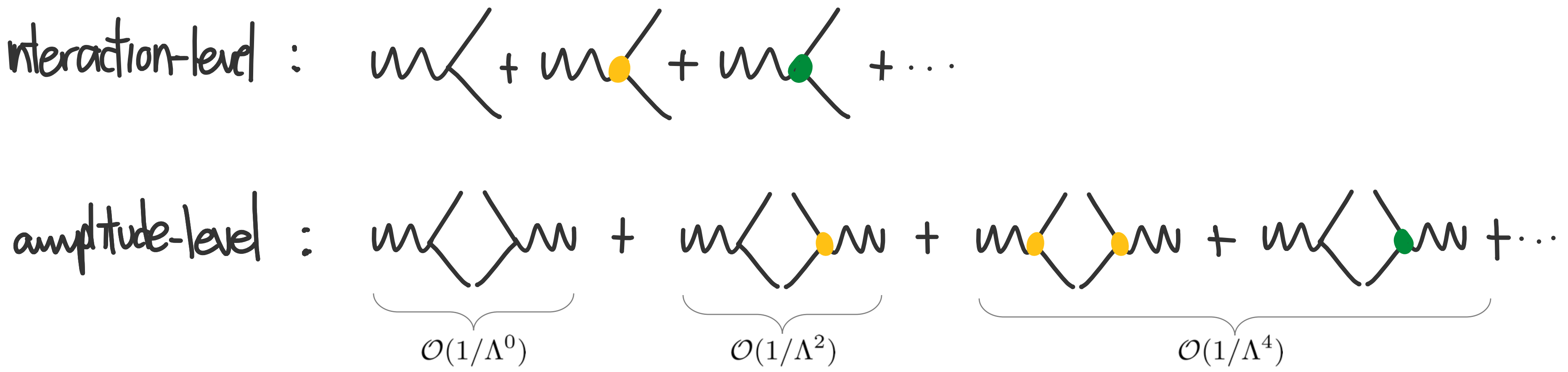
$$\mathcal{L}_{SMEFT} = \mathcal{L}^{(4)}_{SM} + \frac{C_i}{\Lambda^2} Q_i$$

→ EFT effects in **fields and parameters** → EFT effects in **interactions** → EFT effects in **probability amplitudes** → EFT effects in **physical observables**

$\frac{C_i}{\Lambda^2}$ (Lagrangian)

$\frac{C_i}{\Lambda^2}, \frac{C_i^2}{\Lambda^4}$ (fields and parameters, interactions)

$\frac{C_i}{\Lambda^2}, \frac{C_i^2}{\Lambda^4}, \ldots$ (probability amplitudes, physical observables)



observable-level :

$$O_{SMEFT} = O_{SM} + \Delta O^{(1)} + \Delta O^{(2)} + \ldots$$

EFT effects in fields and parameters: Higgs sector

$$\mathcal{L}_\varphi = (D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{2}(\varphi^\dagger\varphi)^2 + \hat{C}_\varphi(\varphi^\dagger\varphi)^3 + \hat{C}_{\varphi\Box}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + \hat{C}_{\varphi D}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$$

VEV identified from the minimization of V(φ):

$$\bar{v} = \sqrt{\frac{2m^2}{\lambda}}\left(1 + \frac{3m^2\hat{C}_\varphi}{2\lambda^2} + \frac{63m^4\hat{C}_\varphi^2}{8\lambda^4} + \ldots\right)$$

$$\varphi = \begin{pmatrix} 0 \\ \frac{\bar{v}+h}{\sqrt{2}} \end{pmatrix} \longleftrightarrow$$

Expansion of SU(2) scalar doublet around the VEV and Higgs field (unitary gauge)

Shift on the Higgs field identified from the normalization of its kinetic-term:

$$\bar{h} \equiv Z_h h = \left(1 + \frac{\bar{v}^2}{4}\left(\hat{C}_{\varphi D} - 4\hat{C}_{\varphi\Box}\right) - \frac{\bar{v}^4}{32}\left(\hat{C}_{\varphi D} - 4\hat{C}_{\varphi\Box}\right)^2 + \ldots\right) h$$

Shift on the physical mass of the Higgs field identified from the normalization of its mass-term:

$$M_h^2 = \lambda\bar{v}^2 - \bar{v}^4\left(3\hat{C}_\varphi - 2\hat{C}_{\varphi\Box}\lambda + \frac{1}{2}\hat{C}_{\varphi D}\lambda\right) - \frac{\bar{v}^6}{2}(4\hat{C}_{\varphi\Box} - \hat{C}_{\varphi D})\left(3\hat{C}_\varphi - 2\hat{C}_{\varphi\Box}\lambda + \frac{1}{2}\hat{C}_{\varphi D}\lambda\right) + \ldots$$

EFT effects in fields and parameters: Gauge sector

$$\mathcal{L}_{Gauge} \supset -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} + \hat{C}_{\varphi G}(\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} + \hat{C}_{\varphi W}(\varphi^\dagger\varphi)W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \hat{C}_{\varphi B}(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu}$$
$$+ \hat{C}_{\varphi WB}(\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu} + (D_\mu\varphi)^\dagger(D^\mu\varphi) + \hat{C}_{\varphi D}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$$

Shift of gauge fields identified from the normalization of their kinetic-terms:

$$\bar{W}^I_\mu \equiv Z_g W^I_\mu = \left(1 - \hat{C}_{\varphi W}\bar{v}^2 - \tfrac{1}{2}\hat{C}^2_{\varphi W}\bar{v}^4 + \ldots\right) W^I_\mu$$
$$\bar{B}_\mu \equiv Z_{g'} B_\mu = \left(1 - \hat{C}_{\varphi B}\bar{v}^2 - \tfrac{1}{2}\hat{C}^2_{\varphi B}\bar{v}^4 + \ldots\right) B_\mu$$
$$\bar{G}^A_\mu \equiv Z_{g_s} G^A_\mu = \left(1 - \hat{C}_{\varphi G}\bar{v}^2 - \tfrac{1}{2}\hat{C}^2_{\varphi G}\bar{v}^4 + \ldots\right) G^A_\mu$$

→

Shift of gauge couplings by requiring invariance of the covariant derivative:

$$\bar{g} = Z_g^{-1} g \qquad \bar{g}' = Z_{g'}^{-1} g' \qquad \bar{g}_s = Z_{g_s}^{-1} g_s$$

$$\left(D_\mu = \partial_\mu + i g_s G^A_\mu \mathcal{T}^A + i g W^I_\mu T^I + i g' B_\mu Y\right)$$

Charged gauge fields defined as in d=4 SM:

$$\bar{W}^\pm_\mu = \frac{1}{\sqrt{2}}(\bar{W}^1_\mu \mp i\bar{W}^2_\mu)$$

EFT effects in fields and parameters: Gauge sector

$$\mathcal{L}_{EW} \supset -\frac{1}{2}\bar{W}^+_{\mu\nu}\bar{W}^{-\mu\nu} - \frac{1}{4}\bar{W}^3_{\mu\nu}\bar{W}^{3\mu\nu} - \frac{1}{4}\bar{B}_{\mu\nu}\bar{B}^{\mu\nu} - \frac{1}{2}\hat{C}_{\varphi WB}\bar{v}^2(1+\hat{C}_{\varphi W}\bar{v}^2+\hat{C}_{\varphi B}\bar{v}^2)\bar{W}^3_{\mu\nu}\bar{B}^{\mu\nu}$$
$$-\frac{\bar{g}^2\bar{v}^2}{8}\bar{W}^+_\mu\bar{W}^{-\mu} + \frac{\bar{g}^2\bar{v}^2}{8}\left(1+\frac{1}{2}\hat{C}_{\varphi D}\bar{v}^2\right)\bar{W}^3_\mu\bar{W}^{3\mu} + \frac{\bar{g}'^2\bar{v}^2}{8}\left(1+\frac{1}{2}\hat{C}_{\varphi D}\bar{v}^2\right)\bar{B}_\mu\bar{B}^\mu - \frac{\bar{g}\bar{g}'\bar{v}^2}{4}\left(1+\frac{1}{2}\hat{C}_{\varphi D}\bar{v}^2\right)\bar{W}^3_\mu\bar{B}^\mu$$

Physical mass of the charged gauge bosons identified from its mass-term:

$$M_W^2 = \frac{\bar{g}^2\bar{v}^2}{4}$$

Transformation of basis:

$$\begin{pmatrix}\bar{W}^3_\mu \\ \bar{B}_\mu\end{pmatrix} = \mathbb{X}\begin{pmatrix}\bar{Z}_\mu \\ \bar{A}_\mu\end{pmatrix} = \begin{pmatrix}1+3S^2/8 & -S/2 \\ -S/2 & 1+3S^2/8\end{pmatrix}\begin{pmatrix}\bar{c}_W & \bar{s}_W \\ -\bar{s}_W & \bar{c}_W\end{pmatrix}\begin{pmatrix}\bar{Z}_\mu \\ \bar{A}_\mu\end{pmatrix}$$

with,

$$S = \hat{C}_{\varphi WB}\bar{v}^2(1+\hat{C}_{\varphi W}\bar{v}^2+\hat{C}_{\varphi B}\bar{v}^2)$$

$$\tan\theta_W = \frac{\bar{g}'}{\bar{g}} + \frac{\hat{C}_{\varphi WB}(\bar{g}^2-\bar{g}'^2)\bar{v}^2}{2\bar{g}^2} + \frac{\hat{C}_{\varphi WB}[2(\hat{C}_{\varphi B}+\hat{C}_{\varphi W})\bar{g}-\hat{C}_{\varphi WB}\bar{g}'](\bar{g}^2-\bar{g}'^2)\bar{v}^4}{4\bar{g}^3} + \ldots$$

EFT effects in fields and parameters: Gauge sector

The photon field $\bar{A}_\mu$ **remains massless**, while the neutral boson $\bar{Z}_\mu$ **acquires mass**:

$$M_Z^2 = \frac{(\bar{g}^2 + \bar{g}'^2)\bar{v}^2}{4} + \frac{\bar{v}^4}{8}\left(\hat{C}_{\varphi D}(\bar{g}^2 + \bar{g}'^2) + 4\hat{C}_{\varphi WB}\bar{g}\bar{g}'\right) + \frac{\bar{v}^6}{4}\left(\hat{C}_{\varphi WB}^2(\bar{g}^2 + \bar{g}'^2) + \hat{C}_{\varphi WB}(2\hat{C}_{\varphi W} + 2\hat{C}_{\varphi B} + \hat{C}_{\varphi D})\bar{g}\bar{g}'\right) + \ldots$$

The **physical electromagnetic charge** can be identified from the covariant derivative:

$$\bar{D}_\mu = \partial_\mu + i\frac{\bar{g}'}{\sqrt{2}}\left(T^+W^+ + T^-W^-\right) + i\left(\bar{g}'\mathbb{X}_{21}Y + \bar{g}\mathbb{X}_{11}T^3\right)\bar{Z}_\mu + i\underbrace{\left(\bar{g}'\mathbb{X}_{22}Y + \bar{g}\mathbb{X}_{12}T^3\right)}_{eQ,\ Q = T^3 + Y}\bar{A}_\mu\,.$$

$$e = \frac{\bar{g}\bar{g}'}{(\bar{g}^2 + \bar{g}'^2)^{1/2}} - \frac{\hat{C}_{\varphi WB}\bar{g}^2\bar{g}'^2\bar{v}^2}{(\bar{g}^2 + \bar{g}'^2)^{3/2}} + \frac{\hat{C}_{\varphi WB}\bar{g}^2\bar{g}'^2\bar{v}^4}{2(\bar{g}^2 + \bar{g}'^2)^{5/2}}\left(3\hat{C}_{\varphi WB}\bar{g}\bar{g}' - 2(\hat{C}_{\varphi W} + \hat{C}_{\varphi B})(\bar{g}^2 + \bar{g}'^2)\right) + \ldots$$

EFT effects in fields and parameters: Fermion sector

$$\mathcal{L}_f \supset i\left(\bar{l}'_L \not{D} l'_L + \bar{e}'_R \not{D} e'_R + \bar{q}'_L \not{D} q'_L + \bar{u}'_R \not{D} u'_R + \bar{d}'_R \not{D} d'_R\right)$$

$$- \bar{l}'_L \Gamma_e e'_R \varphi + (\varphi^\dagger\varphi)(\bar{l}'_L \hat{C}'_{e\varphi} e'_R \varphi) - \bar{q}'_L \Gamma_u u'_R \tilde{\varphi} + (\varphi^\dagger\varphi)(\bar{q}'_L \hat{C}'_{u\varphi} u'_R \tilde{\varphi}) - \bar{q}'_L \Gamma_d d'_R \varphi + (\varphi^\dagger\varphi)(\bar{l}'_L \hat{C}'_{d\varphi} d'_R \varphi) + h.c.$$

Shift of the fermion mass-matrices (gauge-basis) identified from the mass-terms of fermion fields:

$$\mathcal{M}'_\psi \equiv \frac{\bar{v}}{\sqrt{2}}\left(\Gamma_\psi - \frac{\bar{v}^2}{2}\hat{C}'_{\psi\varphi}\right)$$

for,

$$\psi = \{e, u, d\}$$

Transformation to the mass-basis:

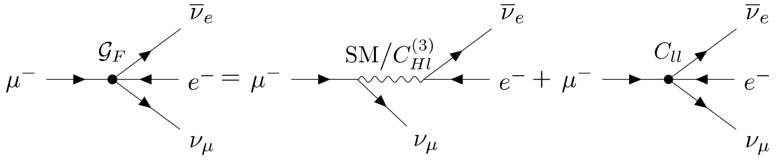
$$\psi'_L = \mathbb{U}_{\psi L}\psi_L \qquad \psi'_R = \mathbb{U}_{\psi R}\psi_R$$

$$\mathcal{M}_\psi = \mathbb{U}^\dagger_{\psi L}\mathcal{M}'_\psi \mathbb{U}_{\psi R}$$

$$\hat{C}_{\psi\varphi} = \mathbb{U}^\dagger_{\psi L}\hat{C}'_{\psi\varphi}\mathbb{U}_{\psi R}$$

$$\mathcal{L}_{Fermi} = -\frac{4G_F}{\sqrt{2}}\left(\bar{\nu}'_{\mu,L}\gamma_\mu \mu'_L\right)\left(\bar{e}'_L\gamma^\mu \bar{\nu}'_{e,L}\right) + h.c. \Longrightarrow G_F = \frac{1}{\sqrt{2}\bar{v}^2}\left(1 + \left(\hat{C}^{(3)22}_{\varphi l} + \hat{C}^{(3)11}_{\varphi l} - \frac{\hat{C}^{1221}_{ll} + \hat{C}^{2112}_{ll}}{2}\right)\bar{v}^2 + \hat{C}^{(3)11}_{\varphi l}\hat{C}^{(3)22}_{\varphi l}\bar{v}^4\right) + \ldots$$

$\hookrightarrow \frac{2}{v^2}$



EFT effects in interactions:

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}'_p d'_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar{q}'_p \sigma^{\mu\nu} d'_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}'_p \gamma^\mu d'_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}'_p \sigma^{\mu\nu} d'_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}'_p \gamma^\mu d'_r)$

Higgs-fermion interactions:

$$"\bar{\psi}'\Gamma_\psi\psi' h"$$

Direct $\longrightarrow \psi^2\varphi^3$

Indirect $\longrightarrow \varphi^4 D^2$

Gauge-gauge interactions:

$$"X_{\mu\nu}X^{\mu\nu}"$$

Direct $\longrightarrow X^3$

Indirect $\longrightarrow X^2\varphi^2$

EFT effects in interactions: Charged/Neutral Current Interactions

$$"i\bar{\psi}'\not{D}\psi'"$$

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^*\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}'_p d'_r\varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}'_p\sigma^{\mu\nu}d'_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}'_p\gamma^\mu d'_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}'_p\sigma^{\mu\nu}d'_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}'_p\gamma^\mu d'_r)$

Gauge fields arising from covariant derivatives does not introduce indirect contributions!

Both neutral and charged current interactions only have **direct contributions** of effective operators.

$$\mathcal{L}_{c.c} = -\frac{\bar{g}}{\sqrt{2}}\left(\bar{\nu}'_L\gamma^\mu W_\mu^+ e'_R + \bar{u}'_L\gamma^\mu W_\mu^+ d'_R + h.c\right)$$

$$+\hat{C}_{\varphi l(3)}\left(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi\right)\left(\bar{l}'_L\tau^I\gamma^\mu l'_L\right) + \hat{C}_{\varphi q(3)}\left(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi\right)\left(\bar{q}'_L\tau^I\gamma^\mu q'_L\right)$$

$$+\hat{C}_{\varphi ud}\, i\left(\varphi^\dagger D_\mu\varphi\right)\left(\bar{u}'_L\gamma^\mu d'_L\right)$$

$$= -\frac{\bar{g}}{\sqrt{2}}\bar{\nu}_L\gamma^\mu W_\mu^+ U^\dagger\left(1+\bar{v}^2\hat{C}_{\varphi l(3)}\right)e_L - \frac{\bar{g}}{\sqrt{2}}\bar{u}_L\gamma^\mu W_\mu^+ K\left(1+\bar{v}^2\hat{C}_{\varphi q(3)}\right)d_L$$

$$-\frac{\bar{g}}{2\sqrt{2}}\bar{u}_R\gamma^\mu W_\mu^+\bar{v}^2\left(\hat{C}_{\varphi ud}\right)d_L + h.c.$$

with,

$K \equiv U_{uL}^\dagger U_{dL} \longrightarrow$ CKM-matrix

$U \equiv U_{eL}^\dagger U_{\nu L} \longrightarrow$ PMNS-matrix

Change of input-scheme:

$$\{\bar{g}, \bar{g}', \bar{v}, \lambda\} \rightarrow \{\widetilde{\alpha}, \widetilde{M}_Z, \widetilde{G}_F, \widetilde{M}_h\}$$

1

Write "barred" initial parameters in terms of "barred" final parameters:

$$\bar{g} = \sqrt{8\pi\bar{\alpha}}\left[1 - \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{g}' = \sqrt{8\pi\bar{\alpha}}\left[1 + \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{v} = \frac{1}{\sqrt{\sqrt{2}\bar{G}_F}}$$

$$\lambda = \frac{\bar{M}_h{}^2}{\bar{v}^2}$$

2

Write final input parameters ("tilded") in terms of their "barred" and shifts:

$$\widetilde{\alpha} \equiv \bar{\alpha}\left(1 + \delta_\alpha\right)$$

$$\widetilde{M}_Z^2 \equiv \bar{M}_Z^2\left(1 + \delta_{M_Z^2}\right)$$

$$\widetilde{G}_F \equiv \bar{G}_F\left(1 + \delta_{G_F}\right)$$

$$\widetilde{M}_h^2 \equiv \bar{M}_h{}^2\left(1 + \delta_{M_h^2}\right)$$

Change of input-scheme:

1 & 2

$$\bar{g} = \frac{\sqrt{4\pi\tilde{\alpha}}}{\tilde{s}_W}\left(1 - \frac{\delta_\alpha}{2} + \frac{3\delta_\alpha^2}{8} + \frac{\left((-\delta_\alpha + \delta_{G_F} + \delta_{M_Z^2})(2 - 3\delta_\alpha) + 2\delta_{G_F}\delta_{M_Z^2}\right)\tilde{c}_W^2}{4(2\tilde{s}_W^2 - 1)} + \frac{(-\delta_\alpha + \delta_{G_F} + \delta_{M_Z^2})^2(10\widetilde{s_W}^2 - 3)\tilde{c}_W^4}{8(2\tilde{s}_W^2 - 1)^3}\right) + \dots$$

$$\bar{g}' = \frac{\sqrt{4\pi\tilde{\alpha}}}{\tilde{c}_W}\left(1 - \frac{\delta_\alpha}{2} + \frac{3\delta_\alpha^2}{8} + \frac{\left((-\delta_\alpha + \delta_{G_F} + \delta_{M_Z^2})(-2 + \delta_\alpha) - 2\delta_{G_F}\delta_{M_Z^2}\right)\tilde{s}_W^2}{4(2\tilde{s}_W^2 - 1)} + \frac{(-\delta_\alpha + \delta_{G_F} + \delta_{M_Z^2})^2(10\tilde{s}_W^2 - 7)\tilde{s}_W^4}{8(2\tilde{s}_W^2 - 1)^3}\right) + \dots$$

$$\bar{v} = \frac{1}{2^{1/4}\tilde{G}_F^{1/2}}\left(1 + \frac{1}{2}\delta_{G_F} - \frac{1}{8}\delta_{G_F}^2 + \dots\right)$$

$$\lambda = \sqrt{2}\tilde{G}_F\widetilde{M}_h^2\left(1 - \delta_{G_F} + \delta_{M_h^2} + \delta_{G_F}^2 - \delta_{G_F}\delta_{M_h^2} + \dots\right)$$

with,

$$\tilde{c}_W \equiv \frac{1}{\sqrt{2}}\left[1 + \sqrt{1 - \frac{2\sqrt{2}\pi\tilde{\alpha}}{\tilde{G}_F\widetilde{M}_Z^2}}\right]^{1/2} \qquad \tilde{s}_W \equiv \frac{1}{\sqrt{2}}\left[1 - \sqrt{1 - \frac{2\sqrt{2}\pi\tilde{\alpha}}{\tilde{G}_F\widetilde{M}_Z^2}}\right]^{1/2}$$

Change of input-scheme:

$$\{\bar{g}, \bar{g}', \bar{v}, \lambda\} \to \{\widetilde{\alpha}, \widetilde{M}_Z, \widetilde{G}_F, \widetilde{M}_h\}$$

1

Write "barred" initial parameters in terms of "barred" final parameters:

$$\bar{g} = \sqrt{8\pi\bar{\alpha}}\left[1 - \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{g}' = \sqrt{8\pi\bar{\alpha}}\left[1 + \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{v} = \frac{1}{\sqrt{\sqrt{2}\bar{G}_F}}$$

$$\lambda = \frac{\bar{M}_h{}^2}{\bar{v}^2}$$

2

Write final input parameters ("tilded") in terms of their "barred" and shifts:

$$\widetilde{\alpha} \equiv \bar{\alpha}\,(1 + \delta_\alpha)$$

$$\widetilde{M}_Z^2 \equiv \bar{M}_Z^2\left(1 + \delta_{M_Z^2}\right)$$

$$\widetilde{G}_F \equiv \bar{G}_F\,(1 + \delta_{G_F})$$

$$\widetilde{M}_h^2 \equiv \bar{M}_h{}^2\left(1 + \delta_{M_h^2}\right)$$

3

Obtain δ's from the derived physical parameters and express in terms of input-scheme

Change of input-scheme:

3

$$\delta_\alpha = -\frac{\sqrt{2}\hat{C}_{\varphi WB}\tilde{s}_W\tilde{c}_W(1+3\delta_{G_F})}{\tilde{G}_F} - \frac{\hat{C}_{\varphi WB}(4\hat{C}_{\varphi W}+4\hat{C}_{\varphi B}+\hat{C}_{\varphi D})\tilde{s}_W\tilde{c}_W}{4\tilde{G}_F} + \dots$$

$$\delta_{M_Z^2} = \frac{1}{2^{3/2}\tilde{G}_F}\left(\hat{C}_{\varphi D}+4\hat{C}_{\varphi WB}\tilde{s}_W\tilde{c}_W\right) + \frac{1}{2^{3/2}\tilde{G}_F}\left(\hat{C}_{\varphi D}+6\hat{C}_{\varphi WB}\tilde{s}_W\tilde{c}_W\right)\delta_{G_F} + \frac{\hat{C}_{\varphi WB}}{4\tilde{G}_F^2}\left[(4\hat{C}_{\varphi W}+4\hat{C}_{\varphi B}+3\hat{C}_{\varphi D})\tilde{s}_W\tilde{c}_W + 2\hat{C}_{\varphi WB}(1+4\tilde{s}_W^2\tilde{c}_W^2)\right] + \dots$$

$$\delta_{G_F} = \hat{C}_{\varphi l}^{(3)11} + \hat{C}_{\varphi l}^{(3)22} - \frac{1}{2}\left(\hat{C}_{ll}^{1221}+\hat{C}_{ll}^{2112}\right) + \dots$$

$$\delta_{M_h^2} = \frac{4\hat{C}_{\phi\Box}-\hat{C}_{\phi D}}{2\sqrt{2}\tilde{G}_F}(1+\delta_{G_F}) - 3\hat{C}_\phi\widetilde{M}_h^2 - 9\hat{C}_\phi^2\widetilde{M}_h^4 + \frac{(4\hat{C}_{\phi\Box}-\hat{C}_{\phi D})^2}{8\tilde{G}_F^2} + \dots$$

$$M_h^2 = \lambda\bar{v}^2\left[1 - \bar{v}^2\left(\frac{3\hat{C}_\varphi}{\lambda} - 2\hat{C}_{\varphi\Box} + \frac{1}{2}\hat{C}_{\varphi D}\right) - \frac{\bar{v}^4}{2}(4\hat{C}_{\varphi\Box}-\hat{C}_{\varphi D})\left(\frac{3\hat{C}_\varphi}{\lambda} - 2\hat{C}_{\varphi\Box} + \frac{1}{2}\hat{C}_{\varphi D}\right) + \dots\right]$$

Change of input-scheme:

$$\{\bar{g}, \bar{g}', \bar{v}, \lambda\} \to \{\widetilde{\alpha}, \widetilde{M}_Z, \widetilde{G}_F, \widetilde{M}_h\} \text{ or } \{\widetilde{M}_W, \widetilde{M}_Z, \widetilde{G}_F, \widetilde{M}_h\}$$

1 Write relations among “barred” parameters:

$$\bar{g} = \sqrt{8\pi\bar{\alpha}}\left[1 - \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{g}' = \sqrt{8\pi\bar{\alpha}}\left[1 + \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{v} = \frac{1}{\sqrt{\sqrt{2}\bar{G}_F}}$$

$$\lambda = \frac{\bar{M}_h{}^2}{\bar{v}^2}$$

2 Write final input parameters (“tilded”) in terms of their “barred” and shifts:

$$\widetilde{\alpha} \equiv \bar{\alpha}\,(1 + \delta_\alpha)$$

$$\widetilde{M}_Z^2 \equiv \bar{M}_Z^2\left(1 + \delta_{M_Z^2}\right)$$

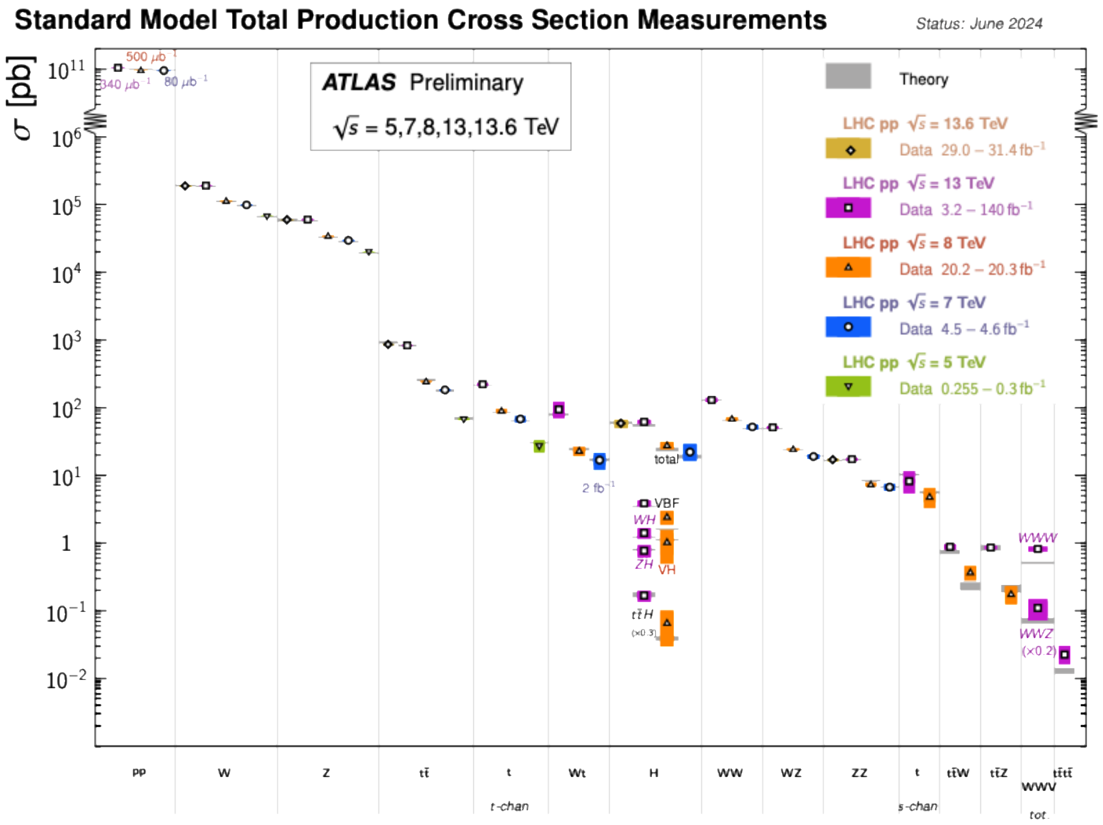
$$\widetilde{G}_F \equiv \bar{G}_F\,(1 + \delta_{G_F})$$

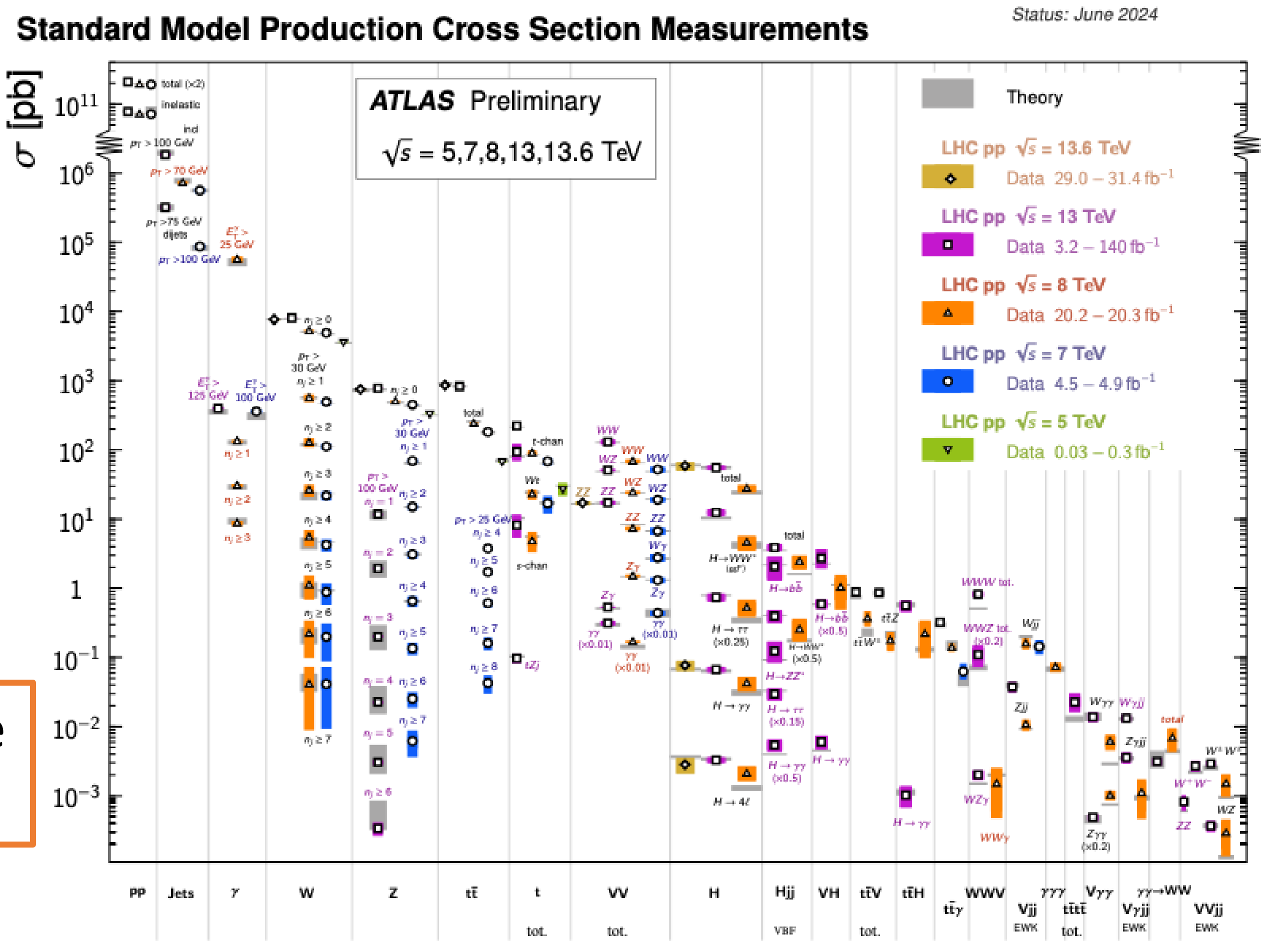
$$\widetilde{M}_h^2 \equiv \bar{M}_h{}^2\left(1 + \delta_{M_h^2}\right)$$

3 Obtain δ’s from the derived physical parameters and express in terms of input-scheme

4 Compute observables in the SMEFT

The breadth of LHC measurements





Literally hundreds of *observables* that all have to agree on the same new physics pattern!

Ideally suited for EFT approach