Simplified Models and eDMEFT

(Lecture #2)

Simplified models

Unlike EFTs, simplified models are valid in a wider energy range. Here the SM is extended by only a couple of particles.

Some advantages of simplified models are the following. They:

- Include operators with all new (and old) particles regardless of their mass
- Allow the explicit search for the medicator
- Provide a good representation of NP scenarios within the energy reach of the LHC
- Give an accurate description of the physics at collider energy scales with a limited number of states and parameters

However ...

- Simp. models are model-dependent
- Certain type of relevant operators violate gauge invariance

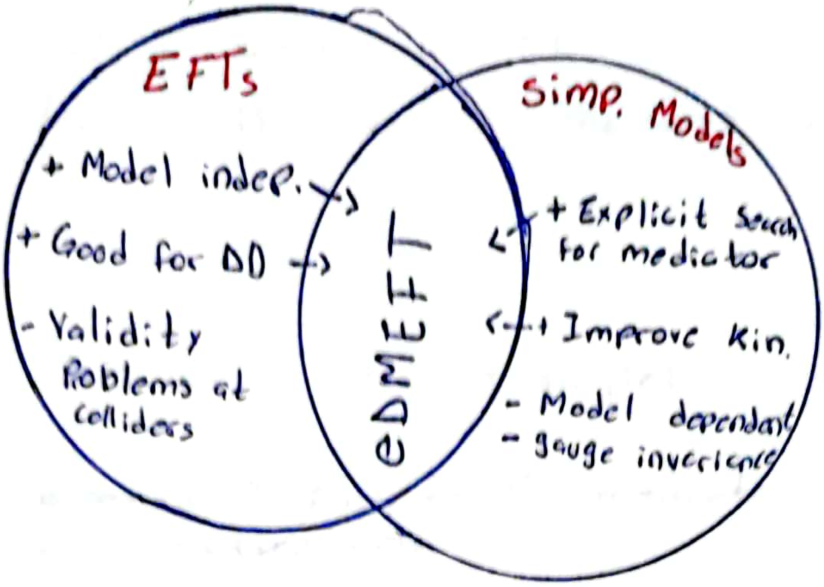
$$\gamma_5 \bar{F}_L S f_R + h.c.$$

DM simplified model

$$\mathcal{L}^{DM}_{simp} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 + i\bar{\chi}\not{\partial}\chi - m_\chi \bar{\chi}\chi - g_\chi S \bar{\chi}\chi - \cancel{\sum \frac{g_{sf}}{\sqrt{2}} S f_R \bar{f}_L} - V(S, \Phi)$$

- Four new parameters: m_χ, m_S, g_χ, and Γ_S
  - New unknown particles
  - Fixed
- All terms are $\dim \leq 4$

extended DMEFT (eDMEFT)



In the eDMEFT, the SM is extended by fermionic DM χ and a scalar (pseudo scalar) S ($\tilde{S}$)

$$\mathcal{L}_{eDMEFT} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}M_S^2 S^2 + \bar{\chi} i \not{\partial} \chi - m_\chi \bar{\chi}\chi$$

$$- \underline{\lambda'_{S_1} v^3 S} - \underline{\frac{\lambda'_S}{2\sqrt{2}} v S^3} - \frac{\lambda_S}{4} S^4$$

$$- \underline{\lambda'_{HS} v |H|^2 S} - \lambda_{HS} |H|^2 S^2 - (y_S S \bar{\chi}_L \chi_R + h.c.)$$

$$- \underline{\frac{S}{\Lambda}\left[C_{\lambda S} S^4 + C_{HS} |H|^2 S^2 + C_{\lambda H} |H|^4\right]}$$

$$- \frac{S}{\Lambda}\left[y_d^S \bar{Q}_L H d_R + y_u^S \bar{Q}_L \tilde{H} u_R + y_\ell^S \bar{L}_L H \ell_R + h.c.\right]$$

$$- \left[\frac{y_S^{(1)} S^2}{\Lambda} \bar{\chi}_L \chi_R + \frac{y_H^{(1)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + h.c.\right]$$

$$- \frac{S}{\Lambda}\frac{1}{16\pi^2}\left[g'^2 C_B^S B_{\mu\nu} B^{\mu\nu} + g^2 C_W^S W_{\mu\nu} W^{\mu\nu} + g_s^2 C_G^S G_{\mu\nu} G^{\mu\nu}\right]$$

■ operators removed in the pseudo scalar case ($S \leftrightarrow \tilde{S}$)

what about the problem of masses ?

$\boxed{\text{arxiv:1906.08007}}$

→ Dijet/e^+e^- search in eDMEFT

• focus on the pheno of the $D=5$ operator $S^2\bar{\chi}\chi$

General setup

→ We treat DM as a fermion singlet

→ We impose a negative Z_2 parity to the mediator and the RH fermions of the first generation only.

	χ	S	f_1	f_2	f_3
Z_2	$-$	$-$	$-$	$+$	$+$

Why?
→ $m_1 \ll m_2, m_3$

Then the Lagrangian reads:

$$\mathcal{L}_{Dirac} = \mathcal{L}_{SM'} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mu_S^2 S^2 + \bar{\chi} i \not{\partial}\chi - m_\chi \bar{\chi}\chi$$

$$- \frac{\lambda_S}{4} S^4 - \lambda_{HS} H^2 S^2$$

$$\boxed{- \frac{S}{\Lambda}\left[Y_{d_i}^S \bar{Q}_{L_i} H d_R + Y_{u_i}^S \bar{Q}_{L_i}\tilde{H} u_R + Y_{\ell_i}^S \bar{L}_L H \ell_R + h.c \right]}$$

$$- \left[\frac{Y_\chi^H H^2}{\Lambda}\bar{\chi}\chi + \boxed{\frac{Y_\chi^S S^2}{\Lambda}\bar{\chi}\chi} + h.c \right]$$

• $|\langle S \rangle| \equiv v_S \sim 10\,\text{MeV}$, Just enough to give mass to m_{f_1}

• The operator H^2S^2 is assumed negligible and therefore not considered

• The usual $S\bar{\chi}\chi$ operator is generated by the spontaneous breaking of the Z_2 symmetry and has a coefficient $\sim \frac{2Y_\chi^S v_S}{\Lambda}$

• We take $H^2\bar{\chi}\chi$ to be small and will not be discussed

Fermion masses

The resulting mass term after SSB (for up and down quarks) reads (Type, Type)

$$\mathcal{L} \supset -\sum_{q=u,d} \bar{q}_L \overbrace{\underbrace{\frac{v}{\sqrt{2}}\left(Y_q^H\right.}_{\substack{\text{SM}\\ m_{f2,3}}} + \underbrace{\left.\frac{v_s}{\Lambda} Y_q^s\right)}_{\substack{\text{BSM}\\ m_{f1}}}}^{M} q_R \equiv -\sum_{q=u,d} \bar{q}_L M^q q_R$$

where the Yukawa matrices are

$$Y_q^H = \begin{pmatrix} 0 & Y_{12}^q & Y_{13}^q \\ 0 & Y_{22}^q & Y_{23}^q \\ 0 & Y_{32}^q & Y_{33}^q \end{pmatrix} \quad \text{and} \quad Y_q^s = \begin{pmatrix} (Y_q^s)_1 & 0 & 0 \\ (Y_q^s)_2 & 0 & 0 \\ (Y_q^s)_3 & 0 & 0 \end{pmatrix}$$

We can see that without the Z_2 breaking via $v_s > 0$, the first fermion generation would be massless. Additionally a vev of around $v_s \sim \mathcal{O}(10)$ MeV is enough to generate m_{f1} with $\mathcal{O}(1)$ Yukawas. (remember $m_e = 0.5$ MeV, $m_u = 2.4$ MeV and $m_b = 4.8$ MeV) and $\Lambda \sim 1$ TeV

After performing a rotation in the mass basis

$$M^u_{diag} = U_L^u M U_R^{u\dagger} = \text{diag}(m_u, m_c, m_t)$$
$$M^d_{diag} = U_L^d M U_R^{d\dagger} = \text{diag}(m_d, m_s, m_b)$$

and $\hat{Y}_q^n = U_L^{q\dagger} Y_q^n U_R^q$, $q = u, d$ and $n = s, H$

entering in the interaction Lagrangian

$$\mathcal{L} \supset -\sum_q \bar{q}_L \left(\frac{\hat{Y}_q^H h + v_s/\Lambda\, \hat{Y}_q^s h}{\sqrt{2}} + \frac{v \hat{Y}_q^s}{\Lambda\sqrt{2}} s \right) q_R$$

↳ Important for collider searches $f \bar{f} \to s \to \chi\bar{\chi}$

- $\hat{Y} \neq \text{diag} \Rightarrow$ FCNCs appear!

Flavour-Changing-Neutral-currents (FCNCs)

There is no fundamental reason why there cannot be FCNC. Yet, experimentally, we see that they're strongly suppressed.

ex.

$Br(K^+ \to \mu^+ \nu) = 0.64$ $\qquad$ $Br(K_L \to \mu^+\mu^-) = 7\times10^{-9}$

$Br(B^- \to D^0 \ell \bar{\nu}) = 0.023$ $\qquad$ $Br(B^- \to K^* \ell^+ \ell^-) = 5\times10^{-7}$

$Br(D^\pm \to K^0 \mu^\pm \nu) = 0.09$ $\qquad$ $Br(D^0 \to \pi^0 \ell^+ \ell^-) = 1.8\times10^{-4}$

$\downarrow$ FCCC $\qquad$ $\downarrow$ FCNC

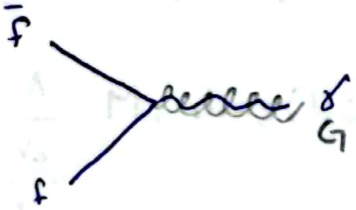
There are 4 neutral bosons that can mediate FCNCs in the SM: G, γ, H, Z

G and γ (massless gauge bosons)

→ Their couplings to fermions arise from the kinetic terms

→ when the kin. terms are canonical, the couplings to the gauge bosons are universal and Flavour conserving.

$$\sim \bar{\Psi} \not{D} \Psi \xrightarrow{\text{leptons}} (\bar{e}, \bar{\mu}, \bar{\tau}) \not{D} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \sim \bar{e}\not{D}e, \bar{\mu}\not{D}\mu, \bar{\tau}\not{D}\tau$$

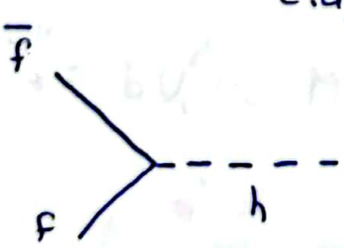


Higgs boson H

In the SM, we have one Higgs only, therefore the mass matrix is

$M_f = v Y_f$ ⇒ diagonalizing the mass matix ensures the diagonalization of the Yukawa matrix

⇒ No FCNCs at tree level

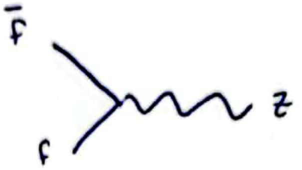


Z boson

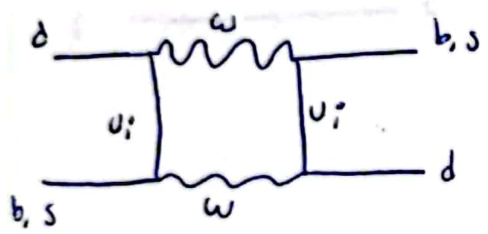
In the interaction basis, the Z couplings to the quarks are given by

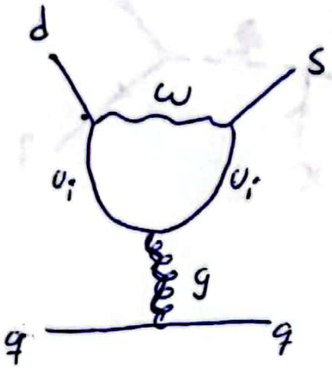
$$\mathcal{L}_Z = \frac{g}{\cos\theta_W}\left[\bar{u}_L^i \gamma^\mu \left(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W\right) u_L^i + \dots\right] Z_\mu + h.c.$$

$\bar{u}_L^i \to V_{u_L}$, $u_L^i \to V_{u_L}^\dagger$ $\qquad V_{u_L} V_{u_L}^\dagger = \mathbb{1}$



FCNC at loop level





→ Suppressed by GIM mechanism

Flavour structure (Di-jet l^+l^-)

$$\mathcal{L} \supset -\bar{q}_L \frac{v}{\sqrt{2}} \underbrace{\left(Y_q^H + \frac{v_S}{\Lambda} Y_q^S\right)}_{M} q_R$$

In the interaction basis the Yukawa matrices can be written as:

$$Y_q^S = \underbrace{\frac{\sqrt{2}\,\Lambda}{v\, v_S}}_{a} M_q \,\mathrm{diag}(1,0,0) = \frac{\sqrt{2}\,\Lambda}{v\, v_S} U_L^q M_{diag}^q U_R^{q\dagger}\, \mathrm{diag}(1,0,0)$$

$$Y_q^H = \underbrace{\frac{\sqrt{2}}{v}}_{b} M_q \,\mathrm{diag}(0,1,1) = \frac{\sqrt{2}}{v} U_L^q M_{diag}^q U_R^{q\dagger}\, \mathrm{diag}(0,1,1)$$

In the mass basis $(U_L^{q\dagger} Y U_R^q)$

$$\hat{Y}_q^S = a\, U_L^{q\dagger} U_L \underset{m_u}{M_{diag}^q} \underbrace{U_R^{q\dagger}\, \mathrm{diag}(1,0,0)\, U_R^q}$$

$$Y_q^H = b\, U_L^{q\dagger} U_L \underset{m_c,\, m_t}{M_{diag}^q} \underbrace{U_R^{q\dagger}\, \mathrm{diag}(0,1,1)\, U_R^q}_{\text{diag}}$$

$\Big\rangle \neq$ diag

$\rightarrow U_L^{u\dagger} U_L^d = U_{CKM}$ and $\boxed{U_R^u = U_R^d = \mathbb{1}}$ ⇒ No FCNC!

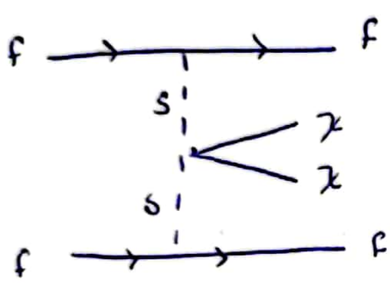
Collider Searches

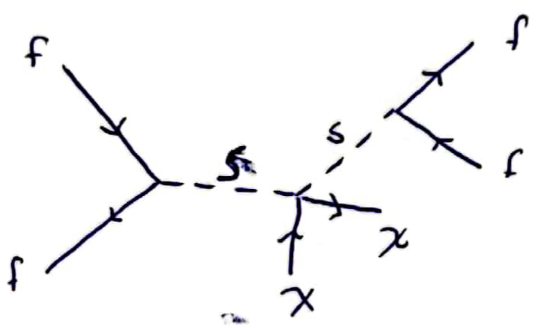
The relevant parameters of the theory are:

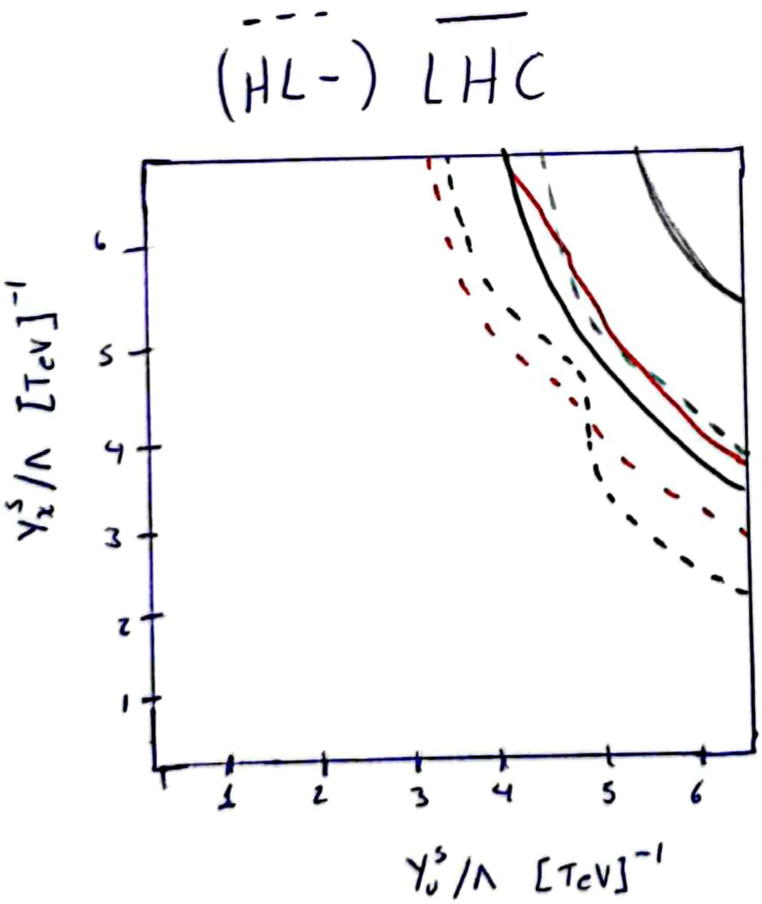
- DM mass m_χ
- Mediator mass m_S
- DM - S coupling Y_χ^S/Λ
- S - f coupling Y_u^S/Λ

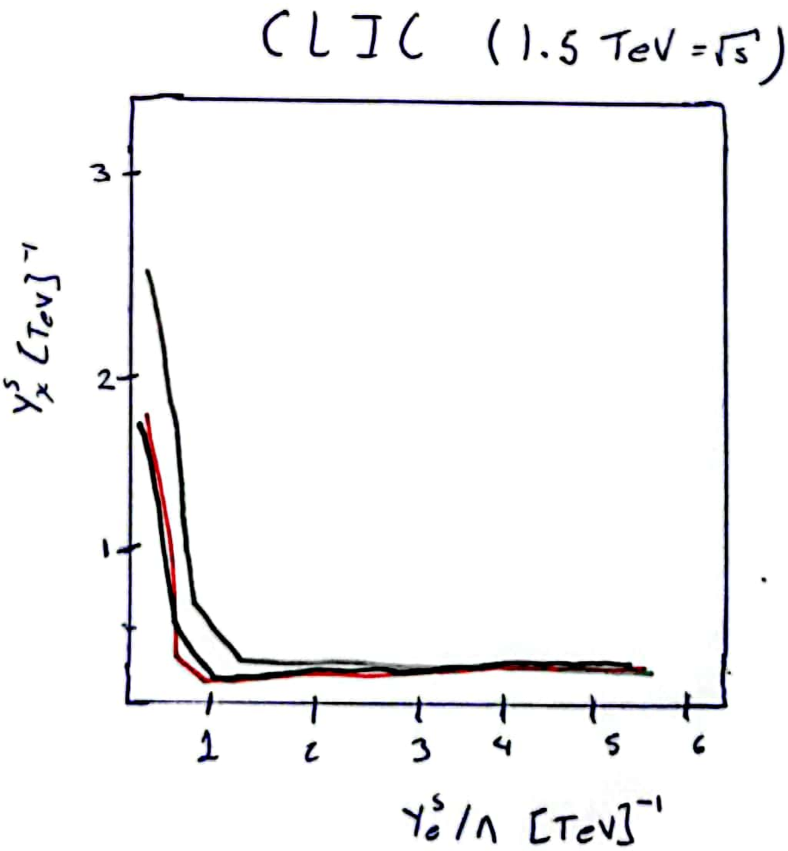
$Y_e^S = 0.1\, Y_d^S = 0.2\, Y_u^S$

$\hookrightarrow Y_u^S = (Y_U^{nS})_{11}$









$m_\chi = 100$ GeV

$m_\chi = 5$ GeV

$m_\chi = 300$ GeV