Flavor and SMEFT:
some comments on future directions

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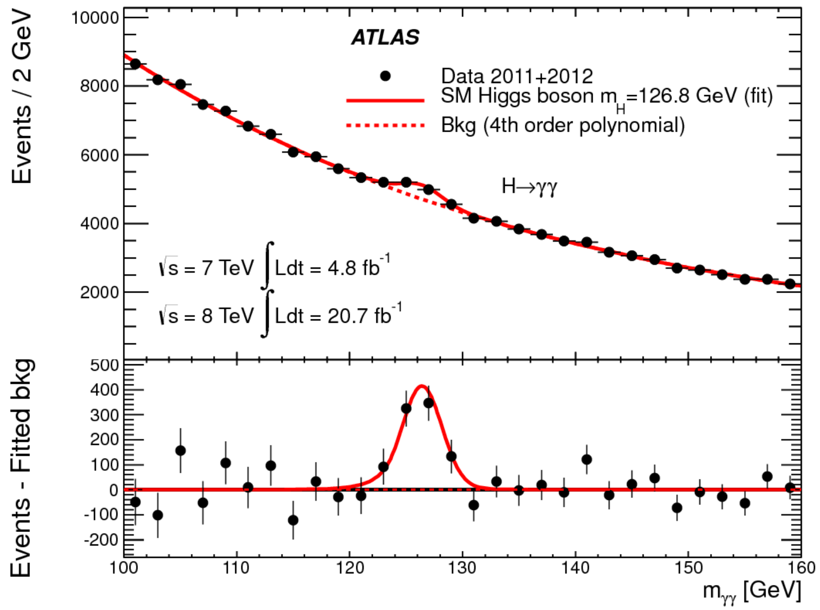
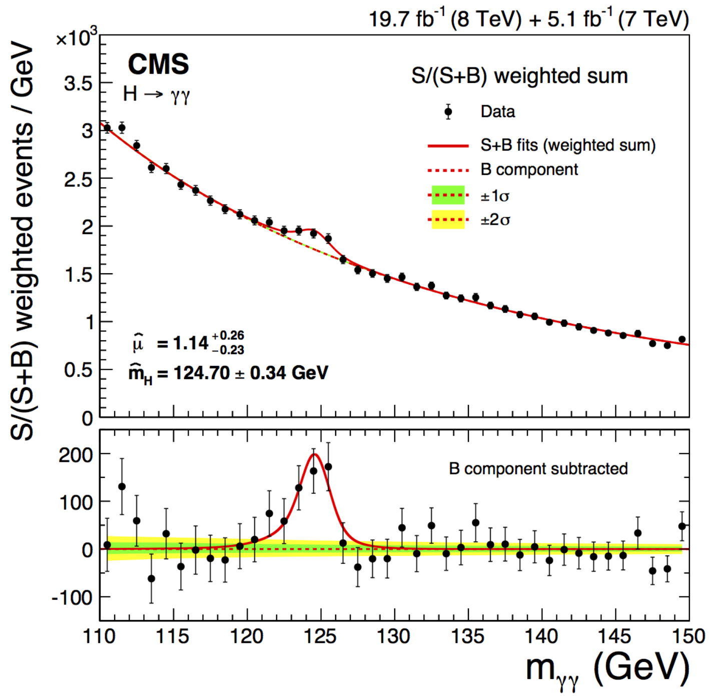
Outline

- Motivation
- MFV and beyond: a framework for flavor [M.Bordone, O.C., T.Feldmann, in prep.]
- SMEFT vs HEFT [O.C., M.Jung'15]
- Conclusions

Motivation

- Higgs discovery and tests at the LHC confirm the Standard Model as an excellent low-energy approximation to the electroweak interactions (within the current precision). Higgsless alternatives ruled out.





- Clear indications that there is life beyond SM but no direct signal (yet).

- Given the current experimental status, EFT expansions are the right tool for indirect searches.

Effective Field Theories

- EFTs are the most efficient way of describing the physics at a certain scale μ, if
  - There is a mass gap between typical scales, such that μ/Λ can be a good expansion parameter.
  - The particle content (φ) and symmetries at μ are known
- One can then generally write

$$\mathcal{L}_{\rm eff}(\varphi) = \mathcal{L}_0(\varphi) + \underbrace{\mathcal{L}_1(\varphi)}_{\mathcal{O}(\mu^2/\Lambda^2)} + \ldots$$

Each term satisfies in turn

$$\mathcal{L}_j = \sum_n c_n^{(j)}\, \mathcal{O}_n^{(j)}(\varphi)$$

- $\mathcal{O}_n(\varphi)$, IR-sensitive (φ and symmetries); c_n, UV-sensitive (Λ physics).
- UV/IR factorization allows to use EFTs not just as top-down theories (efficiency), but also bottom-up (UV-physics probes).

A tale of two EFTs

Assuming:

- observed particle content.
- a mass gap: $\dfrac{v^2}{M_{NP}^2} \ll 1$
- known symmetries valid up to probed scales, $SU(3)_c \times SU(2)_L \times U(1)_Y$.

the corresponding EFT at LO is either

$$\mathcal{L}_{\rm SMEFT} = -\frac{1}{4} X^a_{\mu\nu} X^{\mu\nu\, a} + i \sum_j \bar{\psi}_j \not{D} \psi_j + D_\mu H^\dagger D^\mu H - V(H) \\ - \left[y_d \bar{Q}_L H d + y_u \bar{Q}_L \tilde{H} u + y_e \bar{E}_L H e + \text{h.c.} \right] + \sum_j \frac{\mathcal{C}_j}{\Lambda^2} \mathcal{O}_j^{(6)}$$

or

$$\mathcal{L}_{\rm EWChL} = -\frac{1}{4} X^a_{\mu\nu} X^{\mu\nu\, a} + i \sum_j \bar{\psi}_j \not{D} \psi_j + \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{v^2}{4} \text{tr} \left[D_\mu U D^\mu U^\dagger \right] f(h) \\ - v \left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.} \right] - V(h) + \mathcal{L}_{\rm NLO}$$

Every model compatible with the assumptions looks at low energies like SMEFT or EWChL.

Flavor in SMEFT

- Most of the free parameters of the SM are related to flavor. This number increases dramatically when considering SMEFT: at NLO $(59 \to 2499)$.

- Example:

$$\frac{1}{\Lambda^2}[\mathcal{C}_{lq}]^{ij\alpha\beta}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_\alpha\gamma^\mu L_\beta)$$

- Generically, 81 unknown complex parameters for each flavor tensor.

1. What are the sizes of the entries?
2. Are there patterns?

- Guidance needed before any fit: flavor power counting and/or flavor symmetries.

Flavor power countings: eFN mechanism

- A flavor power counting does not reduce the number of parameters, but establishes a hierarchy.

- In the flavor sector of the SM, phenomenologically

$$M_u \sim \begin{pmatrix} \lambda^8 & & \\ & \lambda^4 & \\ & & 1 \end{pmatrix} ; \; M_d \sim \begin{pmatrix} \lambda^7 & & \\ & \lambda^5 & \\ & & \lambda^3 \end{pmatrix} ; \; M_e \sim \begin{pmatrix} \lambda^9 & & \\ & \lambda^5 & \\ & & \lambda^3 \end{pmatrix}$$

  together with

$$V_{CKM} = V_{u_L}^{\dagger} V_{d_L}^{\dagger} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

- FN mechanism: the flavor hierarchies can be reproduced if one assumes the existence of a spontaneously broken $U(1)_{FN}$ symmetry.

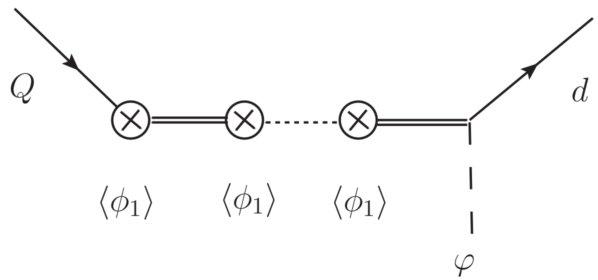
- Simple, self-consistent, embeds the SM and also MFV.

FN mechanism

- The simplest implementation consists of an extended scalar sector:

$$\phi_0(R=0); \qquad \phi_1(R=R_1); \qquad \varphi(R=0)$$

- A set of heavy fermions is ordered in R-space such that $R[\Psi_{i+1}] - R[\Psi_i] = R_1$.



- SM fermions have (different) FN charges, such that masses only get generated upon SSB.

$$m_j \sim \left(\frac{\langle\phi_{FN}\rangle}{\Lambda_{FN}}\right)^{|b_Q^j - b_d^j|} \langle\varphi\rangle \sim \lambda^{|b_Q^j - b_d^j|}$$

- Additionally,

$$(V_{CKM})_{ij} \sim \lambda^{|b_Q^i - b_Q^j|}; \quad (Y_u)_{ij} \sim \lambda^{|b_Q^i - b_u^j|}; \quad (Y_d)_{ij} \sim \lambda^{|b_Q^i - b_d^j|}$$

Extended FN mechanism

- FN is originally a theory of flavor but can be upgraded to a mechanism. Define $R-$charges for every field

$$b_Q^j; \qquad b_u^j; \qquad b_d^j; \qquad b_L^j; \qquad b_e^j$$

- 12 combinations of the 15 charges fixed by the SM. The more distance in $R-$space, the more suppression.

- In our example, $(\bar{Q}_i \gamma_\mu Q_j)(\bar{L}_\alpha \gamma^\mu L_\beta)$:

$$\text{FN:} \qquad [\mathcal{C}_{lq}]^{ij\alpha\beta} \sim \lambda^{\left|b_Q^i - b_Q^j + b_L^\alpha - b_L^\beta\right|}$$

- Not a reduction of coefficients, but the size of the different entries well-defined and compatible with SM power counting, which it should embed.

- The unconstrained charges should be fixed phenomenologically.

Minimal Flavor Violation

- Starting point: maximal flavor group commuting with gauge symmetry

$$\mathcal{G}_F = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R} \ \times \ SU(3)_{L_L} \times SU(3)_{E_R}$$

- In the SM this group is (completely) broken by the Yukawa terms

$$\mathcal{L}_Y = -\bar{Q} Y_u \varphi u - \bar{Q} Y_d \tilde{\varphi} d - \bar{L} Y_e \tilde{\varphi} e$$

ASSUMPTIONS:

1. New physics breaks $\mathcal{G}_F$ as in the SM
2. The spurions of flavor breaking scale as the Yukawa matrices

- In our example:

$$\text{MFV:} \qquad [\mathcal{C}_{lq}]^{ij\alpha\beta} = \left(\#\delta^{ij} + \#(Y_U Y_U^\dagger)^{ij} + \#(Y_D Y_D^\dagger)^{ij} \right) \delta^{\alpha\beta}$$

- Reduction of free parameters.

eMFV schemes

- Rationale: certain flavor pattern (e.g. B anomalies) do not fit the MFV scheme.
- Find the minimal setup that does accommodate experimental data.

FIRST STEP (ASSUMPTION): bosonic spurions (30 possibilities), e.g.

Dirac bilinear	Spurion field	$SU(3)\times SU(2)\times U(1)$	$\mathcal{G}_{\text{flavor}}$	$(\Delta B;\Delta L)$
$\bar{Q}\gamma^\mu L$	Δ_{QL}	$(3,1\oplus 3,\frac{2}{3})$	$(3,1,1)(\bar{3},1)$	$(\frac{1}{3};-1)$
$\bar{u}\gamma^\mu e$	Δ_{ue}	$(3,1,\frac{5}{3})$	$(1,3,1)(1,\bar{3})$	$(\frac{1}{3};-1)$
$\bar{d}\gamma^\mu e$	Δ_{de}	$(3,1,\frac{2}{3})$	$(1,1,3)(1,\bar{3})$	$(\frac{1}{3};-1)$
$\bar{Q}e$	S_{Qe}	$(3,2,\frac{7}{6})$	$(3,1,1)(1,\bar{3})$	$(\frac{1}{3};-1)$
$\bar{u}L$	S_{uL}	$(3,2,\frac{7}{6})$	$(1,3,1)(\bar{3},1)$	$(\frac{1}{3};-1)$
$\bar{d}L$	S_{dL}	$(3,2,\frac{1}{6})$	$(1,1,3)(\bar{3},1)$	$(\frac{1}{3};-1)$
$\bar{Q}^c\gamma^\mu e$	Δ_{Qe}	$(\bar{3},1,\frac{5}{6})$	$(\bar{3},1,1)(1,\bar{3})$	$(-\frac{1}{3};-1)$
$\bar{u}^c\gamma^\mu L$	Δ_{uL}	$(3,2,\frac{1}{6})$	$(1,3,1)(3,1)$	$(-\frac{1}{3};-1)$
$\bar{d}^c\gamma^\mu L$	Δ_{dL}	$(\bar{3},1,\frac{5}{6})$	$(1,1,\bar{3})(\bar{3},1)$	$(-\frac{1}{3};-1)$
$\bar{Q}^cL$	S_{QL}	$(\bar{3},1\oplus 3,\frac{1}{3})$	$(\bar{3},1,1)(\bar{3},1)$	$(-\frac{1}{3};-1)$
$\bar{u}^ce$	S_{ue}	$(\bar{3},1,\frac{1}{3})$	$(1,\bar{3},1)(1,\bar{3})$	$(-\frac{1}{3};-1)$
$\bar{d}^ce$	S_{de}	$(\bar{3},1,\frac{4}{3})$	$(1,1,\bar{3})(1,\bar{3})$	$(-\frac{1}{3};-1)$

eMFV schemes

SECOND STEP (ASSUMPTION): FN power counting

- The SM flavor structure should be preserved. eMFV and flavor power counting has to obey consistency conditions, e.g.

$$(\Delta_{QL})_{ij} \lesssim \max\left\{\delta_{ij}, (Y_u Y_u^\dagger)_{ij}, (Y_d Y_d^\dagger)_{ij}\right\}$$

- Advantage of FN power counting: Embeds the SM flavor structure and consistency conditions are automatically fulfilled (Schwarz inequalities)

In our example:

$$\text{LQ+FN:} \qquad [\mathcal{C}_{lq}]^{ij\alpha\beta} \sim (\Delta_{QL})^{i\beta}\,(\Delta_{QL}^\dagger)^{\alpha j} + \ldots \sim \lambda^{\left|b_Q^i - b_L^\beta\right|}\,\lambda^{\left|b_L^\alpha - b_Q^j\right|}$$

There is parameter reduction due to the spurion. This induces a factorization in the FN structure:

$$[\mathcal{C}_{lq}]^{ij\alpha\beta} \sim \lambda^{\left|b_Q^i - b_Q^j + b_L^\alpha - b_L^\beta\right|} \to \lambda^{\left|b_Q^i - b_L^\beta\right|}\,\lambda^{\left|b_L^\alpha - b_Q^j\right|}$$

Effectively, a suppression:

$$\left|b_Q^i - b_L^\beta\right| + \left|b_L^\alpha - b_Q^j\right| \geq \left|b_Q^i - b_Q^j + b_L^\alpha - b_L^\beta\right|$$

eMFV schemes

THIRD STEP (ASSUMPTION): adding flavor symmetries

- Phenomenologically, 3rd generation special status. Formally, start from

$$(\mathcal{G}_F)^{\rm red} = SU(2)_{Q_L} \times SU(2)_{U_R} \times SU(3)_{D_R} \; \times \; SU(3)_{L_L} \times SU(3)_{E_R}$$

- Motivation example: given that no mixing between 1st and 2nd generations is required, impose that

$$SU(2)_{Q_L} \times SU(2)_{U_R}$$

is preserved. Then,

$$\Delta_{QL} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \Delta_{QL}^{31} & \Delta_{QL}^{32} & \Delta_{QL}^{33} \end{pmatrix}$$

In practice, substitute

$$\Delta_{QL}^{i\beta} \to \left(V_Q \, \hat{\Delta}_{QL}\right)^{i\beta} \equiv V_Q^{i3} \, \Delta_{QL}^{3\beta} \sim \lambda^{\left|b_Q^i - b_Q^3\right|} \, \lambda^{\left|b_Q^3 - b_L^\beta\right|} \leq \lambda^{\left|b_Q^i - b_L^\beta\right|}$$

eMFV schemes

- With extra symmetries there is further reduction of parameters:

$$(\text{LQ+FN})_2: \quad [\mathcal{C}_{lq}]^{ij\alpha\beta} \sim (V_Q \hat{\Delta}_{QL})^{i\beta} (\hat{\Delta}^\dagger_{QL} V^\dagger_Q)^{\alpha j} + \ldots \sim \lambda^{\left|b^i_Q - b^3_Q\right|} \lambda^{\left|b^3_Q - b^j_Q\right|} \lambda^{\left|b^3_Q - b^\beta_L\right|} \lambda^{\left|b^\alpha_L - b^3_Q\right|}$$

- Summary of the strategic reduction:

Approach	$[\mathcal{C}_{lq}]^{ij\alpha\beta}$	NP parameters
generic EFT	$\sim \mathcal{O}(1)$	162
generic FN	$\sim \lambda^{\left\|b^i_Q - b^j_Q + b^\alpha_L - b^\beta_L\right\|}$	162
MFV	$\left(\#\delta^{ij} + \#(Y_U Y_U^\dagger)^{ij} + \#(Y_D Y_D^\dagger)^{ij}\right) \delta^{\alpha\beta}$	6
LQ+FN	$\#\,(\Delta_{QL})^{i\beta} (\Delta^\dagger_{QL})^{\alpha j} \sim \lambda^{\left\|b^i_Q - b^\beta_L\right\|} \lambda^{\left\|b^\alpha_L - b^j_Q\right\|}$	18 + 2
$(\text{LQ+FN})_2$	$\#\,(V_Q \hat{\Delta}_{QL})^{i\beta} (\hat{\Delta}^\dagger_{QL} V^\dagger_Q)^{\alpha j}$ $\sim \lambda^{\left\|b^i_Q - b^3_Q\right\|} \lambda^{\left\|b^3_Q - b^j_Q\right\|} \lambda^{\left\|b^3_Q - b^\beta_L\right\|} \lambda^{\left\|b^\alpha_L - b^3_Q\right\|}$	12 + 2

In a nutshell

- Step 1: Decide on the (bosonic) spurions (based on phenomenology and gauge quantum numbers). E.g.,

$$\Delta_{QL} : (3, 1, \tfrac{2}{3})(3, 1, 1)(\bar{3}, 1); \qquad \Delta_{de} : (3, 1, \tfrac{2}{3})(1, 1, 3)(1, \bar{3})$$

  could come from the same new-physics (simplified) model.

- Step 2: Choose a power counting, e.g. FN, simple and self-consistent.

- Step 3: Find a solution to the free FN charges, if possible.

$$|b_Q^i - b_Q^j|; \qquad |b_Q^i - b_u^i|; \qquad |b_Q^i - b_d^i|; \qquad |b_L^i - b_e^i|$$

  already fixed by the SM phenomenology. Plenty of remaining freedom.

- Step 4: Consider if data calls for some symmetries to be preserved. In particular, singling out the 3rd generation seems natural.

- Step 5: More spurions needed?

An example: top-bottom connection

- Top-bottom connection: depends on the spurion+power counting chosen (how is flavor symmetry broken?)

- With Δ_{QL} and FN one can fix the charges with

$$b \to s\mu^+\mu^- : \qquad [\mathcal{C}_{lq}]^{2322} \sim \lambda^{|b_L^2 - b_Q^2|}\lambda^{|b_Q^3 - b_L^2|} \sim \lambda^2$$

to

$$b_Q^2 = 2; \qquad b_Q^3 = 0; \qquad b_L^2 = 0$$

- The same charges enter

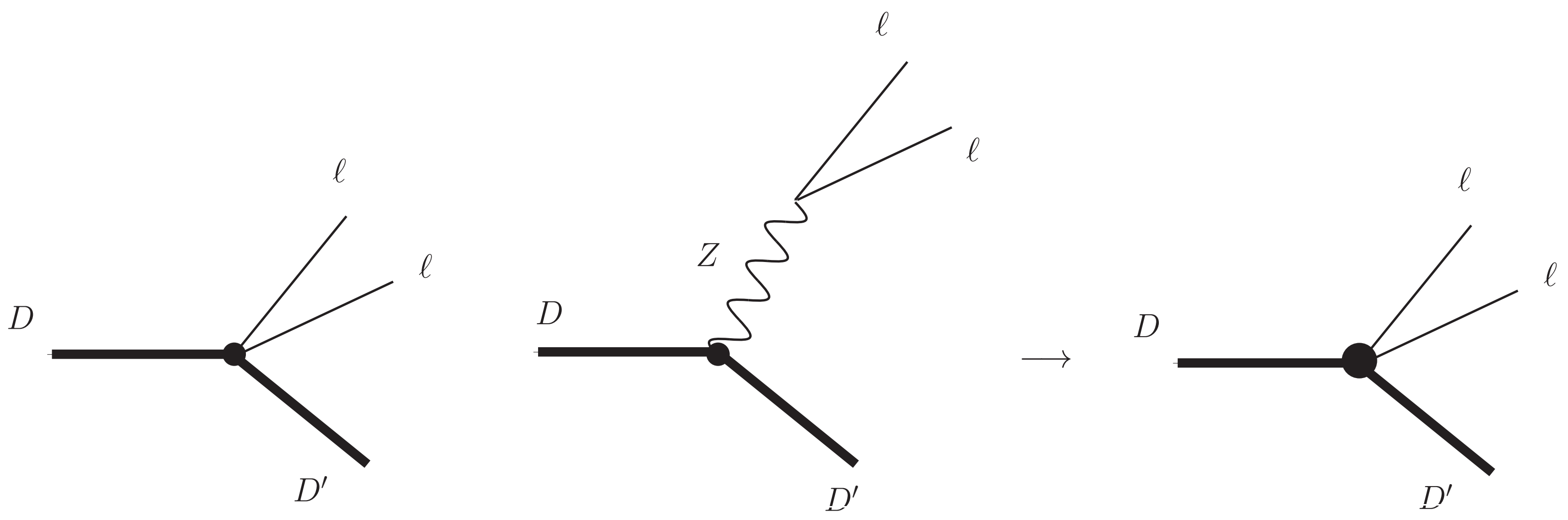
$$t \to b\mu^+\nu : \qquad [\mathcal{C}_{lq}]^{3322} \sim \lambda^{|b_L^2 - b_Q^3|}\lambda^{|b_Q^3 - b_L^2|} \sim 1$$

- The solution is not unique for the charges, but can be constrained if more observables are involved.

- Ideally, unique prediction for each framework (spurion plus flavor symmetries).

SMEFT vs HEFT

- The flavor structure discussion does not change from SMEFT to HEFT. Their difference is on the nature of UV dynamics, which affects the EW power counting.
- This different ordering of operators has phenomenological impact, though, also for flavor.
- Flavor EFTs, e.g. for B decays, incorporate QED+QCD (symmetries at $\Lambda = m_Q$).
- Match flavor EFTs to EW EFT(s) to exploit the full SM symmetry, e.g.



- In SMEFT (at tree level), strong correlations: [Alonso et al'14]

$$C_S = -C_P; \qquad C'_S = C'_P; \qquad C_T = C_{T5} = 0$$

which get erased in EWChL [O.C., Jung'15]

Physics of semileptonic decays

- Consider the EFT for $D \to D'\ell\ell$ decays at $\Lambda = m_Q$:

$$\mathcal{L}_{\text{eff}}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\lambda_{ts}\frac{e^2}{(4\pi)^2}\sum_i^{12} C_i^{(d)}\mathcal{O}_i^{(d)}$$

where

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_{R(L)}b)F_{\mu\nu};$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)\ \bar{l}\gamma^\mu l; \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)\ \bar{l}\gamma^\mu\gamma_5 l$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s}P_{R(L)}b)\ \bar{l}l; \qquad \mathcal{O}_P^{(\prime)} = (\bar{s}P_{R(L)}b)\ \bar{l}\gamma_5 l$$

$$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu}b)\ \bar{l}\sigma^{\mu\nu}l; \qquad \mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu}b)\ \bar{l}\sigma^{\mu\nu}\gamma_5 l$$

- Do the matching to the linear and nonlinear EFTs run down from the EW scale.

Scalar and tensor sector

- Three categories of operators in EWChL:

$$\mathcal{O}_{LR4} = \bar{Q}\gamma^\mu E\ \bar{e}\gamma_\mu d; \qquad \hat{\mathcal{O}}_{LR8} = \bar{Q}\gamma^\mu \hat{\tau}_3 E\ \bar{e}\gamma_\mu d$$

$$\mathcal{O}_{S1} = \epsilon_{ij}\bar{Q}^i u \bar{E}^j e; \qquad \mathcal{O}_{S2} = \epsilon_{ij}\bar{Q}^i \sigma_{\mu\nu} u \bar{E}^j \sigma^{\mu\nu} e$$

$$\hat{\mathcal{O}}_{S3} = \bar{Q}Uu\bar{E}Ue; \qquad \hat{\mathcal{O}}_{S4} = \bar{Q}\sigma_{\mu\nu}Uu\bar{E}\sigma^{\mu\nu}Ue$$

$$\hat{\mathcal{O}}_{Y1} = \bar{Q}Ud\bar{E}Ue; \qquad \hat{\mathcal{O}}_{Y2} = \bar{Q}\sigma_{\mu\nu}Ud\bar{E}\sigma^{\mu\nu}Ue$$

$$\hat{\mathcal{O}}_{Y3} = \bar{E}Ue\bar{d}U^\dagger Q; \qquad \hat{\mathcal{O}}_{Y4} = \bar{E}Ud\bar{d}U^\dagger E$$

- The first category can be Fierzed to a scalar-scalar structure.
- The second category does not contribute to $D \to D'\ell\ell$ (but it does to $U \to U'\ell\ell$).
- The third category is exclusive of the nonlinear case (at NLO). NNLO in the linear case:

$$\hat{\mathcal{O}}_{Y1} = \bar{Q}Hd\bar{E}He$$

Scalar and tensor sector

Matching relations:

$$C_S = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c_S + \hat{c}_{Y1}\right]; \qquad C_P = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[-c_S + \hat{c}_{Y1}\right]$$

$$C'_S = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c'_S + \hat{c}'_{Y1}\right]; \qquad C'_P = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c'_S - \hat{c}'_{Y1}\right]$$

$$C_T = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[\hat{c}_{Y2} + \hat{c}'_{Y2}\right]; \qquad C_{T5} = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[\hat{c}_{Y2} - \hat{c}'_{Y2}\right]$$

with

$$c_S^{(\prime)} = 2(\hat{c}_{LR8}^{(\prime)} - c_{LR4}^{(\prime)})$$

- Strong correlations in the linear case:

$$C_S = -C_P; \qquad C'_S = C'_P; \qquad C_T = C_{T5} = 0$$

  valid up to NNLO corrections, but not a consequence of electroweak symmetry.

- Nonlinear case: correlations erased and nonzero tensor operators.
- Flavor might be relevant for Higgs physics. No Higgs final states but imprint of EWSB!

Summary

- An ansatz for flavor is needed for SMEFT, otherwise not predictive.

- MFV is an EFT-oriented approach but does not describe generic new physics of flavor. eMFV scenarios should be catalogued and investigated.

- Ingredients for a predictive setting: choice for spurions (phenomenological guidance) plus a self-consistent power counting.

- Once the framework fits the known data, predictions to other processes can be made.

- The flavor setup does not change whether SMEFT or EWChL, but the phenomenology does. Dedicated study for each EFT necessary.