Hints of New Physics and EFT: Flavor

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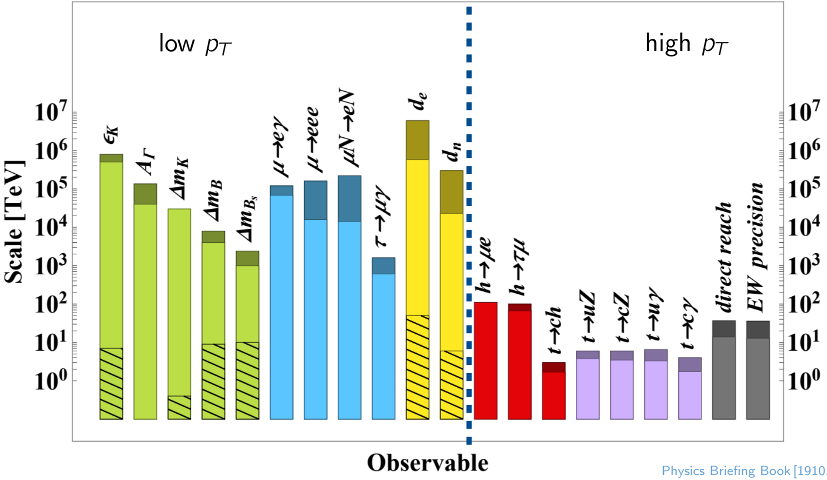
Based on work with A. Greljo and A. Palavrić

Workgroup 1 meeting, 1 July 2022

Probing high-scale new physics



Physics Briefing Book [1910.11775]

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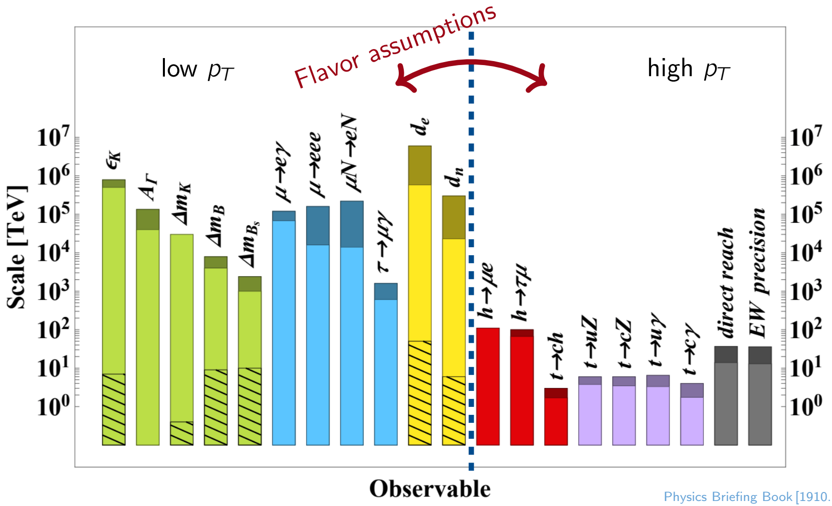

Physics Briefing Book [1910.11775]

Flavor assumptions in EFT fits discussed at LHC EFT topical meeting on flavor assumptions (January, 2022)

Flavor in the SM

The Standard Model

Symmetries: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \; \times$ Poincaré

Matter fields: $q_i,\; u_i,\; d_i,\; \ell_i,\; e_i,\; H$

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The Yukawa couplings break $G_F \to \mathrm{U}(1)_B \times \mathrm{U}(1)_{L_e} \times \mathrm{U}(1)_{L_\mu} \times \mathrm{U}(1)_{L_\tau}$:

$$\mathcal{L}_\mathrm{yuk} = -y_u \bar{q}\tilde{H}u - y_d \bar{q}Hd - y_e \bar{\ell}He \ + \ \mathrm{H.c.}$$

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But G_F identifies equivalent theories

$$\{y_u,\; y_d,\; y_e\} \;\sim\; \{U_q y_u U_u^\dagger,\; U_q y_d U_d^\dagger,\; U_\ell y_e U_e^\dagger\}, \qquad \text{for } U \in G_F$$

54 parameters $\longrightarrow$ 13 *physical* parameters

The flavor puzzle

Flavor of the SM:

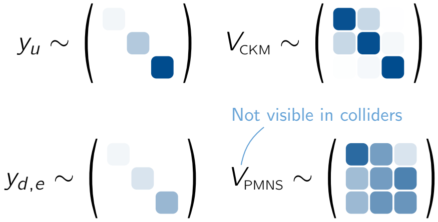
$y_u \sim$  $V_{\text{CKM}} \sim$ 

Not visible in colliders

$y_{d,e} \sim$  $V_{\text{PMNS}} \sim$ 

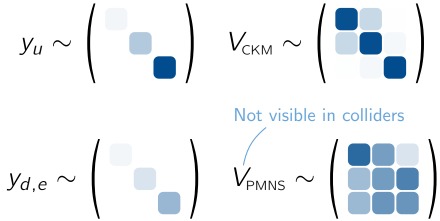
The flavor puzzle

Flavor of the SM:



- Is the structure in the flavor sector meaningful?
- How does potential new physics couple to flavor?
- What is (if any) the flavor symmetry of the SM?

Flavor of the SM:



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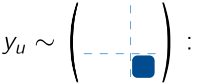
y_t is the leading (only non-perturbative) breaking of G_F in the SM:



$$G_F \to \mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(3)_d \times \mathrm{U}(3)_\ell \times \mathrm{U}(3)_e \times \mathrm{U}(1)_B$$

Flavor in the SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{O} \frac{C_O}{\Lambda^{\dim O - 4}} O$$

Constructed from the same fields and symmetries as $\mathcal{L}_{\text{SM}}$

$\dim O = 5$: 1 classes, 12 operators

$\dim O = 6$: 59 classes, 2499 operators ($\Delta B = 0$)

e.g. $C_{uu}^{psrt} (\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$

45 parameters

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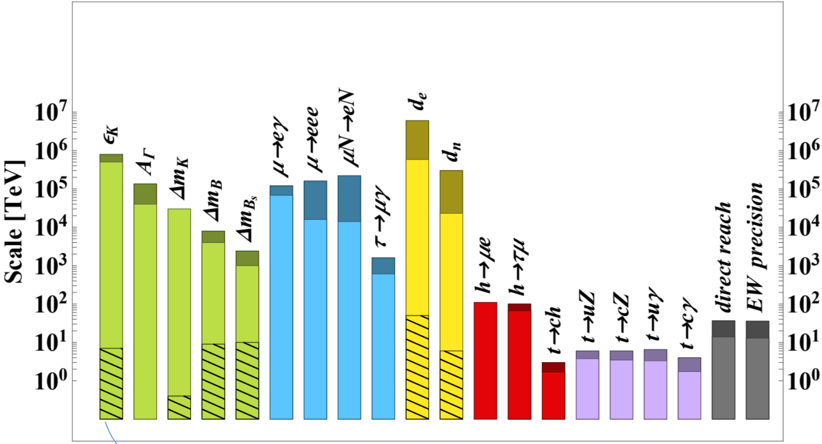
Chart the space of SMEFT with flavor symmetries

Greljo, Palavrìc, AET [2203.09561]
and also Faroughy *et al.* [2005.05366]

- Organization in perturbative spurion expansion, reduces the number of (relevant) operators
- Reduction in number of parameters makes global SMEFT fits possible
- Differentiation of SMEFT in universality classes pointing to different NP

NP with MFV



Physics Briefing Book [1910.11775]

NP with MFV assumption can reside at the TeV-scale, but it is very (too?) restrictive

D'Ambrosio *et al.* [hep-ph/0207036]

Seasoning the SMEFT

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector							
		MFV_L	$\mathrm{U}(3)_V$	$\mathrm{U}(2)^2 \times \mathrm{U}(1)^2$	$\mathrm{U}(2)^2$	$\mathrm{U}(2)_V$	$\mathrm{U}(1)^6$	$\mathrm{U}(1)^3$	No symm.
Quark sector	MFV_Q								
	$\mathrm{U}(2)^2 \times \mathrm{U}(3)_d$								
	$\mathrm{U}(2)^3 \times \mathrm{U}(1)_{d_3}$								
	$\mathrm{U}(2)^3$								
	No symmetry								

Greljo, Palavrìc, AET [2203.09561]

- 28 hypothesis for the flavor symmetries
- Systematic chart from MFV to anarchy

$$\mathrm{U}(3) \supset \mathrm{U}(2) \times \mathrm{U}(1) \supset \mathrm{U}(2) \supset \mathrm{U}(1)$$

- Spurions (minimal set) introduced to reproduce SM masses and mixings

Seasoning the SMEFT

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector							
		MFV$_L$	U(3)$_V$	U(2)$^2\times$U(1)^2	U(2)^2	U(2)$_V$	U(1)^6	U(1)^3	No symm.
Quark sector	MFV$_Q$								
	U(2)^2 $\times$ U(3)$_d$								
	U(2)^3 $\times$ U(1)$_{d_3}$								
	U(2)^3								
	No symmetry								

Greljo, Palavrìc, AET [2203.09561]

- Work from the Warsaw basis
- Construct the operators order by order in the spurions
- Generally:
  - Flavor-symmetric operators are relevant for EW/top/Higgs physics
  - Spurions are relevant for flavor physics (CKM is a result of spurions)

  But also examples of non-trivial interplay Bruggisser *et al.* [2101.07273]

Seasoning the SMEFT

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector															
		MFV_L		$\mathrm{U}(3)_V$		$\mathrm{U}(2)^2 \times \mathrm{U}(1)^2$		$\mathrm{U}(2)^2$		$\mathrm{U}(2)_V$		$\mathrm{U}(1)^6$		$\mathrm{U}(1)^3$		No symm.	
Quark sector	MFV_Q	41	6	45	9	59	6	62	9	67	13	81	6	93	18	207	132
	$\mathrm{U}(2)^2 \times \mathrm{U}(3)_d$	72	10	78	15	95	10	100	15	107	21	122	10	140	28	281	169
	$\mathrm{U}(2)^3 \times \mathrm{U}(1)_{d_3}$	86	10	92	15	111	10	116	12	123	21	140	10	158	28	305	175
	$\mathrm{U}(2)^3$	93	17	100	23	118	17	124	23	132	30	147	17	168	38	321	191
	No symmetry	703	570	734	600	756	591	786	621	818	652	813	612	906	705	1350	1149

Greljo, Palavrìc, AET [2203.09561]

The $\mathcal{O}(1)$ terms in the spurion expansion are expected to be the relevant ones for EW/top/Higgs fits.

Seasoning the SMEFT

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		MFV_L		$\mathrm{U}(3)_V$		$\mathrm{U}(2)^2 \times \mathrm{U}(1)^2$		$\mathrm{U}(2)^2$		$\mathrm{U}(2)_V$		$\mathrm{U}(1)^6$		$\mathrm{U}(1)^3$		No symm.	
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The $\mathcal{O}(1)$ terms in the spurion expansion are expected to be the relevant ones for EW/top/Higgs fits.

- The symmetry of the SM broken by y_t (also in suggestion by LHC EFT WG)
- Discriminates third family. Good description of e.g. b anomalies
- Allows generic LFUV. No cLFV

Example: SMEFT with $\mathrm{U}(2)^3 \times \mathrm{U}(1)_{d_3}$ symmetry

Flavor symmetry $G = \mathrm{U}(2)^3 \times \mathrm{U}(1)_{d_3}$ with quark fields

$$q = \begin{bmatrix} q^a \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})_0 \\ q_3 \sim (\mathbf{1}, \mathbf{1}, \mathbf{1})_0 \end{bmatrix}, \qquad u = \begin{bmatrix} u^a \sim (\mathbf{1}, \mathbf{2}, \mathbf{1})_0 \\ u_3 \sim (\mathbf{1}, \mathbf{1}, \mathbf{1})_0 \end{bmatrix}, \qquad d = \begin{bmatrix} d^a \sim (\mathbf{1}, \mathbf{1}, \mathbf{2})_0 \\ d_3 \sim (\mathbf{1}, \mathbf{1}, \mathbf{1})_1 \end{bmatrix}.$$

The spurions break G completely, and contains 9 physical parameters (incl. 1 phase)

$$V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})_0, \qquad \Delta_u \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})_0, \qquad \Delta_d \sim (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})_0 \qquad X_b \sim (\mathbf{1}, \mathbf{1}, \mathbf{1})_{-1}.$$

*Similar analyses available for all the symmetries

Example: SMEFT with $U(2)^3 \times U(1)_{d_3}$ symmetry

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$(\bar{q}q)(\bar{q}q)$

Examples from operator basis

$$\begin{aligned} &\mathcal{O}(1): \ (\bar{q}_a q^b)(\bar{q}_b q^a), \quad (\bar{q}_a q_3)(\bar{q}_3 q^a), \qquad \mathcal{O}(V): \ (\bar{q}_a q_3)(\bar{q} V_q q^a), \quad \text{H.c.}, \\ &\mathcal{O}(V^2): \ (\bar{q}_a V_q^\dagger q)(\bar{q} V_q q^a). \end{aligned} \tag{2.33}$$

$(\bar{u}u)(\bar{u}u)$

$$\mathcal{O}(1): \ (\bar{u}_a u^b)(\bar{u}_b u^a), \quad (\bar{u}_a u_3)(\bar{u}_3 u^a), \qquad \mathcal{O}(\Delta V): \ (\bar{u}_a u_3)(\bar{u}\Delta_u^\dagger V_q u^a), \quad \text{H.c.}. \tag{2.34}$$

$(\bar{d}d)(\bar{d}d)$

$$\mathcal{O}(1): \ (\bar{d}_a d^b)(\bar{d}_b d^a), \quad (\bar{d}_a d_3)(\bar{d}_3 d^a), \qquad \mathcal{O}(\Delta V X): \ (\bar{d}_a X_b d_3)(\bar{d}\Delta_d^\dagger V_q d^a), \quad \text{H.c.}. \tag{2.35}$$

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The SMEFTflavor package

In[14]:= `CountingTable["lep:U2diag"]`

Out[14]=

lep:U2diag		O[1]		O[Δl]	
$\psi^2 H^3$	OeH	2	2	1	1
$\psi^2 XH$	Oe(B,W)	4	4	2	2
$\psi^2 H^2 D$	OHl(1,3)	4		2	
	OHe	2		1	
(LL)(LL)	Oll	5		3	
(RR)(RR)	Oee	3		2	
(LL)(RR)	Ole	6	1	5	2
Total		26	7	16	5

- `SMEFTflavor` is a Mathematica package to derive operator bases for flavor symmetries
- It is possible to implement custom flavor scenarios
- Example: $U(2)_V$ lepton symmetry with $\Delta \sim \mathbf{3}$ spurion

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Explicit operator bases, e.g. $O_{\ell e} = (\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma_\mu e)$:

```
In[13]:= OperatorBasis["lep:U2diag"]["Ole", Spur["Δl"]] // TableForm // OpForm
```

Out[13]//OpForm=

$(\mathrm{Operator}[\{\overline{l12}_a, l12^b, \overline{e12}_b, e12^c\}, \mathrm{Spur}[\Delta l^d], \mathrm{CGs}[T_c^{da}]] + \mathrm{H.c.})$

$\mathrm{Operator}[\{\overline{l12}_a, l12^b, \overline{e12}_c, e12^c\}, \mathrm{Spur}[\Delta l^d], \mathrm{CGs}[T_b^{da}]]$

$\mathrm{Operator}[\{\overline{l12}_a, l12^b, \overline{e3}, e3\}, \mathrm{Spur}[\Delta l^c], \mathrm{CGs}[T_b^{ca}]]$

$(\mathrm{Operator}[\{\overline{l3}, l12^a, \overline{e12}_b, e3\}, \mathrm{Spur}[\Delta l^c], \mathrm{CGs}[T_a^{cb}]] + \mathrm{H.c.})$

$\mathrm{Operator}[\{\overline{l3}, l3, \overline{e12}_a, e12^b\}, \mathrm{Spur}[\Delta l^c], \mathrm{CGs}[T_b^{ca}]]$

Removing redundancies: $U(2)^3$

Problem: Generic Yukawas seem to contain many parameters in, e.g. $\mathrm{U}(2)^3$:

$$Y_{u,d} = \begin{bmatrix} a_1^{u,d}\Delta_{u,d} + a_2^{u,d}\Delta_u\Delta_u^\dagger\Delta_{u,d} + \ldots & b_1^{u,d}V_q + b_2^{u,d}\Delta_u\Delta_u^\dagger V_q + \ldots \\ c_1^{u,d}V_q^\dagger\Delta_{u,d} + \ldots & d_1^{u,d} + d_2^{u,d}V_q^\dagger V_q + \ldots \end{bmatrix}$$

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Solution: Additional freedom in the $G_F/G_{\mathrm{U}(2)^3}$ flavor space:

$$U_q = \exp\begin{bmatrix} 0 & \lambda_1^q V_q + \lambda_2^q \Delta_u\Delta_u^\dagger V_q + \ldots \\ -(\lambda_1^q)^* V_q^\dagger - (\lambda_2^q)^* V_q^\dagger\Delta_u\Delta_u^\dagger - \ldots & 0 \end{bmatrix}$$

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Going to e.g. down-aligned Yukawas (10 parameters)

Redefined spurions

$$Y_{u,d} \xrightarrow{U_{q,u,d}} Y_u' = \begin{bmatrix} \Delta_u' & V_q' \\ 0 & y_t' \end{bmatrix}, \qquad Y_d' = \begin{bmatrix} \Delta_d' & 0 \\ 0 & y_b' \end{bmatrix}$$

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explicitly $G_{\mathrm{U}(2)^3}$ covariant

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No redundancy in the SMEFT basis once minimal Yukawas are chosen

Summary

- Flavor structure of NP will leave imprints in the SMEFT
- TeV scale NP must posses flavor structure to remain viable
- Operator basses made available for 28 flavor scenarios: ready-for-use in phenomenological studies
- Operator bases for other scenarios can be determined with

`https://github.com/aethomsen/SMEFTflavor`

Greljo, Palavrìc, AET [2203.09561]