Flavor puzzles of the Standard Model effective field theory

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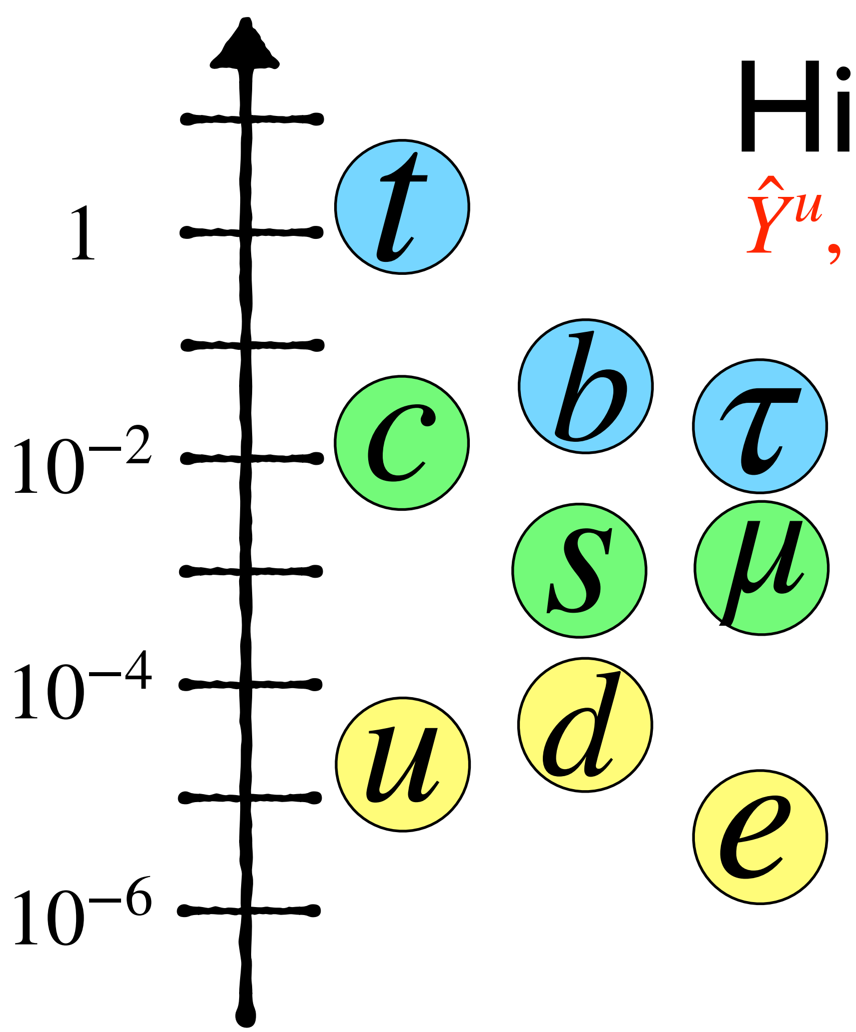
The Flavour Puzzle

- Peculiar patterns observed in $\dim 4$ Yukawa interactions:

$$-\mathscr{L}_{\rm Yuk} = \bar{q} V^\dagger \hat{Y}^u \tilde{H} u + \bar{q} \hat{Y}^d H d + \bar{\ell} \hat{Y}^e H e$$

$[U(3)^5$ + Singular Value Decomposition$]$



Hierarchy

$\hat{Y}^u, \hat{Y}^d, \hat{Y}^e$

?

Alignment

Y^u / Y^d

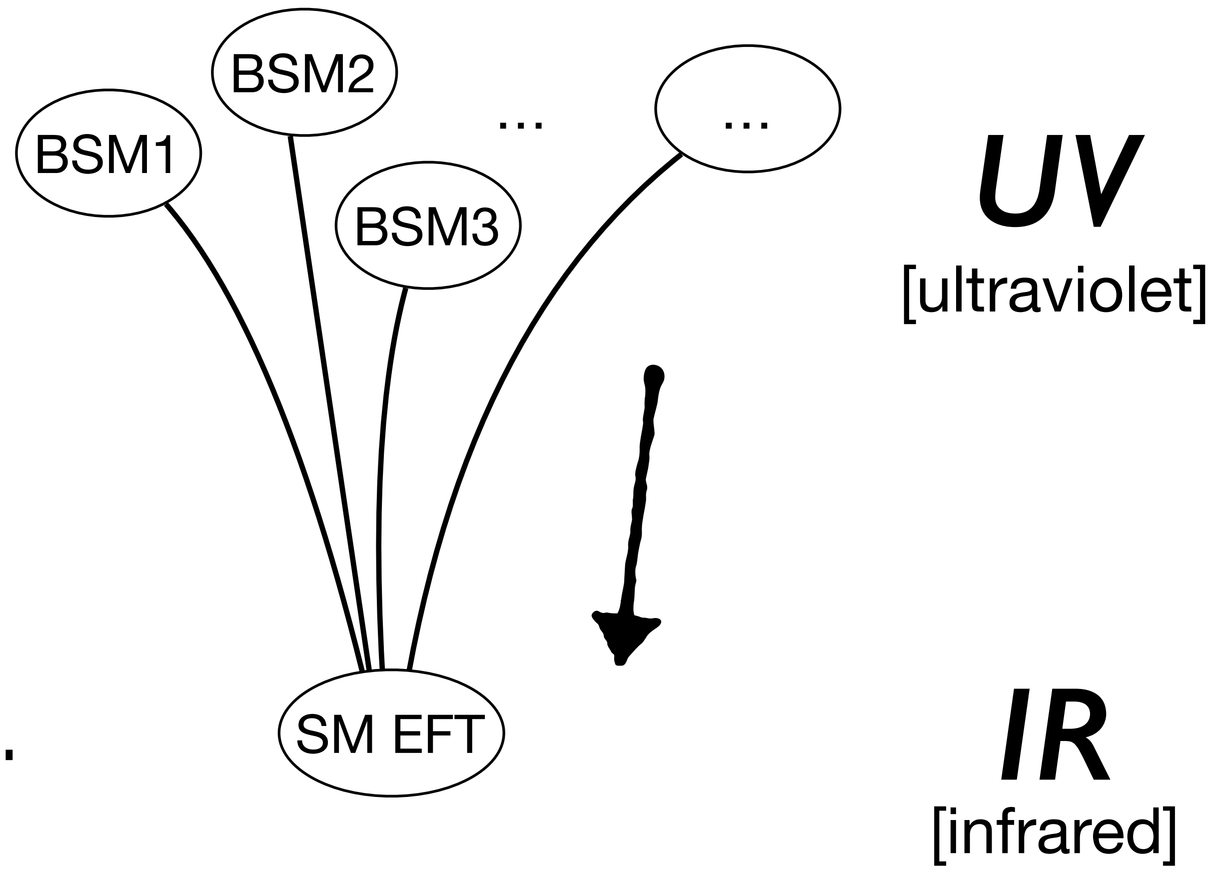
$$V \sim \begin{bmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{bmatrix}$$

The CKM mixing

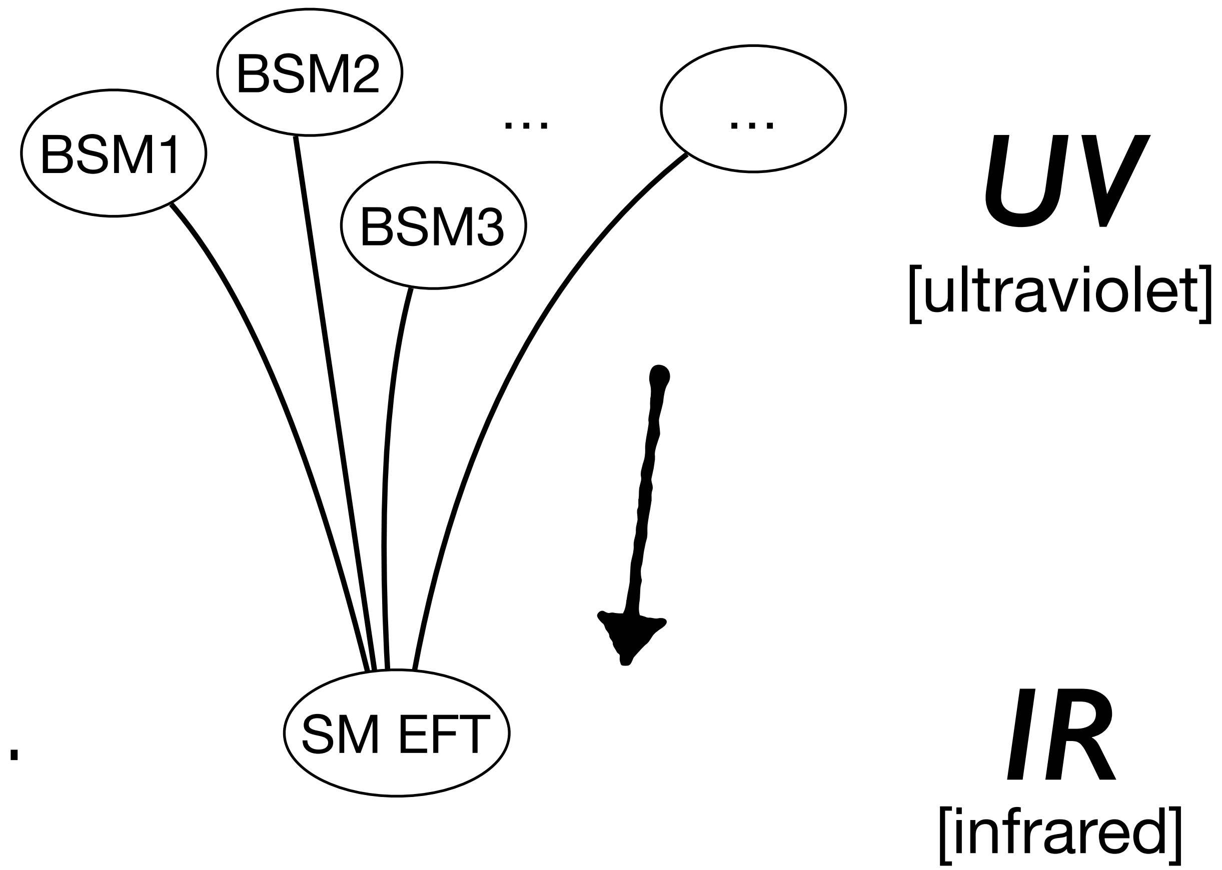
*We neglect neutrino masses and mixings in this work

SMEFT

Pragmatic, bottom-up, . . .



SMEFT



Pragmatic, bottom-up, . . .

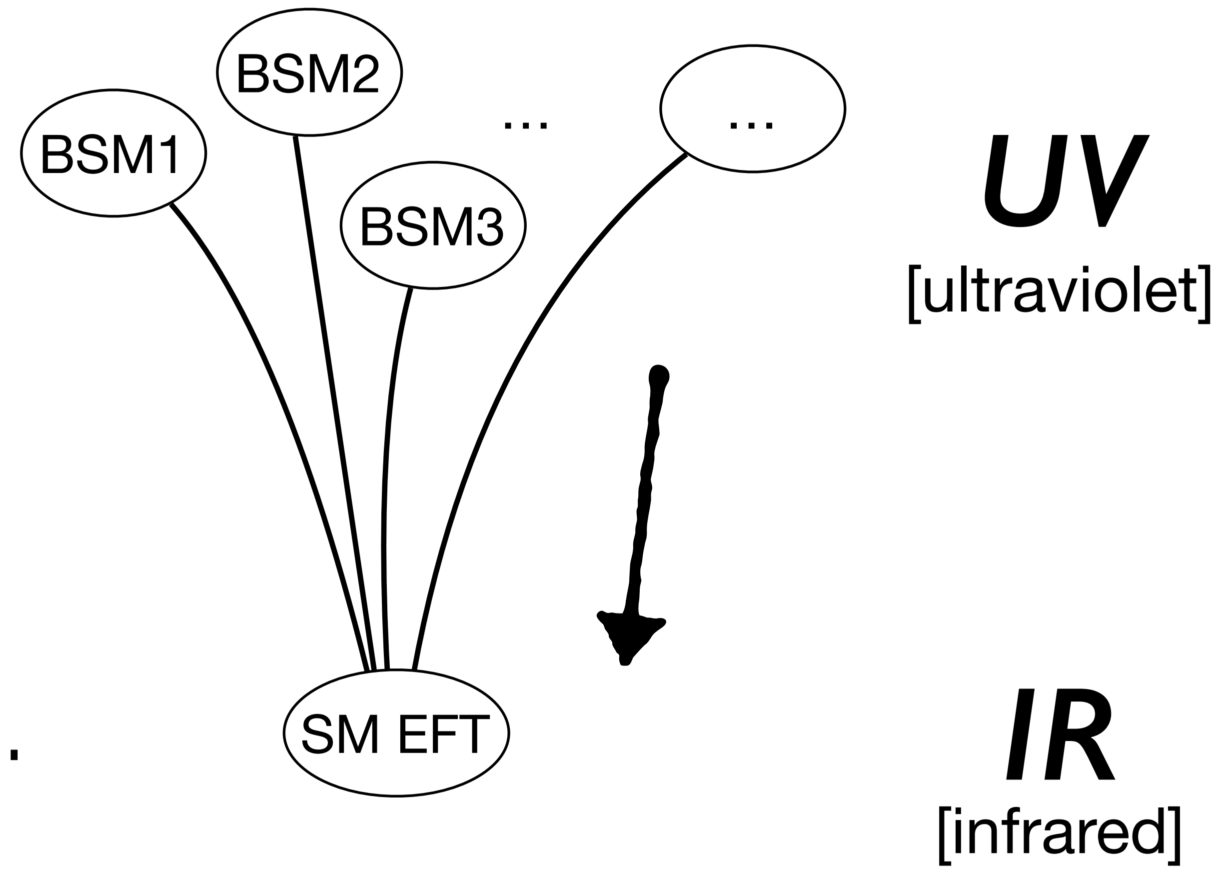
What?

- SM fields & Symmetries (Gauge + Poincaré)
- Scale separation $\Lambda_Q \gg v_{EW}$
- Higher-dimensional operators encode short-distance physics:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{Q} \frac{C_Q}{\Lambda_Q^{[Q]-4}} Q$$

SMEFT

Pragmatic, bottom-up, …



Why?

1. Our BSM expectations failed so far
2. No clear/preferred model
3. Short-distance direction still the most compelling (to many of us)
4. Experiments headed towards the precision/luminosity era

SMEFT is challenging!

- Price for generality: **Large number of independent parameters!**
- **2499** at $\dim[\mathcal{O}] = 6$ $(\Delta B = \Delta L = 0)$
- Why? (Partially due to) FLAVOUR $i = 1,2,3$
- If there was a single generation => **59**

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A$

$(\bar{L}R)(\bar{R}L)$ 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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C\right.$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C\right.$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T\right.$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Grzadkowski et al, 1008.4884

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$

$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
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_{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_{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_{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_{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_{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_{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_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$\mathscr{L}_{\rm SM}$: Accidental symmetries

$$q_i, \ell_i, u_i, d_i, e_i \qquad i = 1,2,3$$

$\mathscr{L}_{\rm SM}$ sans Yukawa: $U(3)_q \times U(3)_U \times U(3)_D \times U(3)_l \times U(3)_E$

↓

$$-\mathscr{L}_{\rm Yuk} = \bar{q} V^\dagger \hat{Y}^u \tilde{H} u + \bar{q} \hat{Y}^d H d + \bar{l} \hat{Y}^e H e$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

$\mathscr{L}_{\rm SM}$: $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

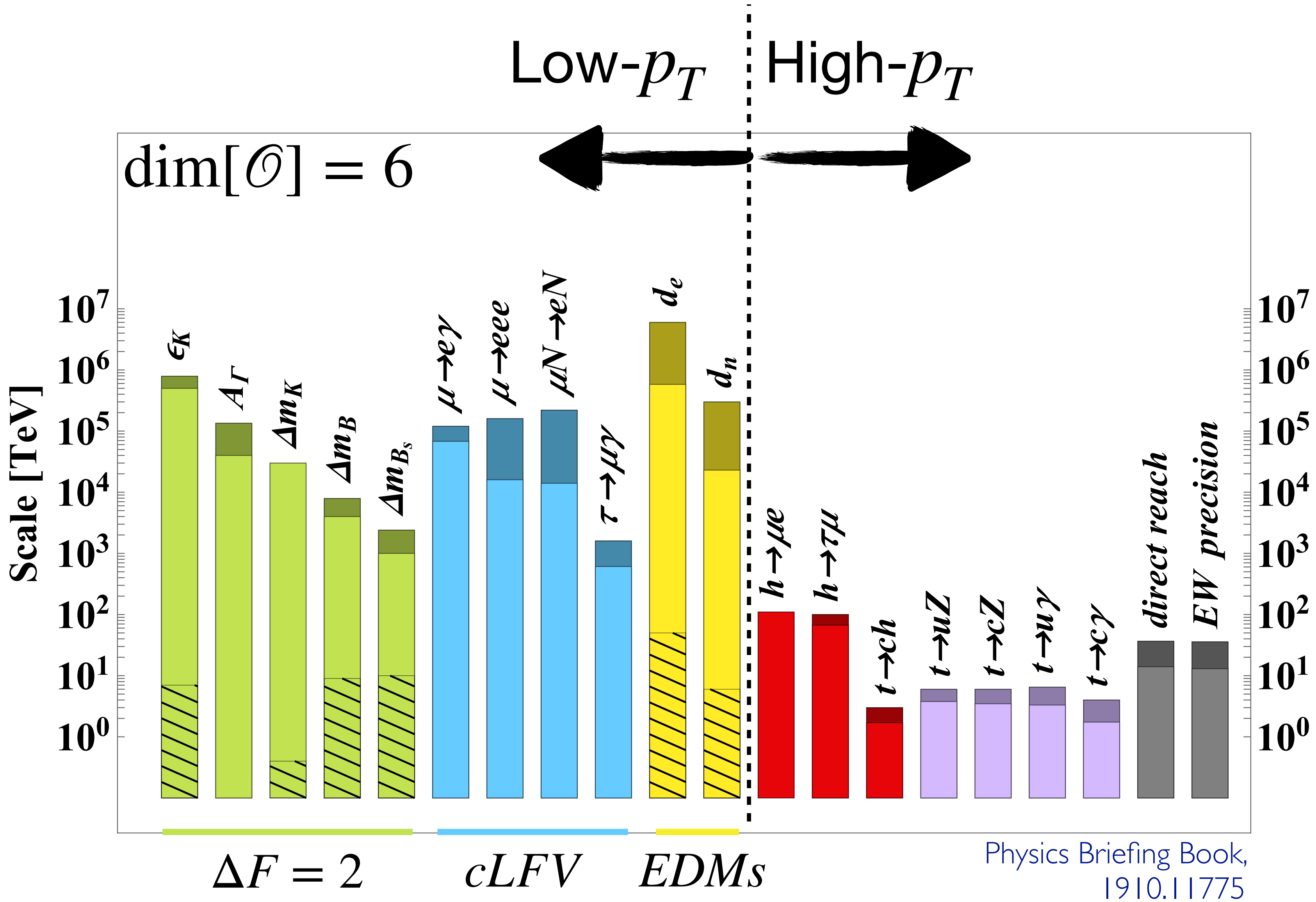
Exact (classical) accidental symmetries

However:

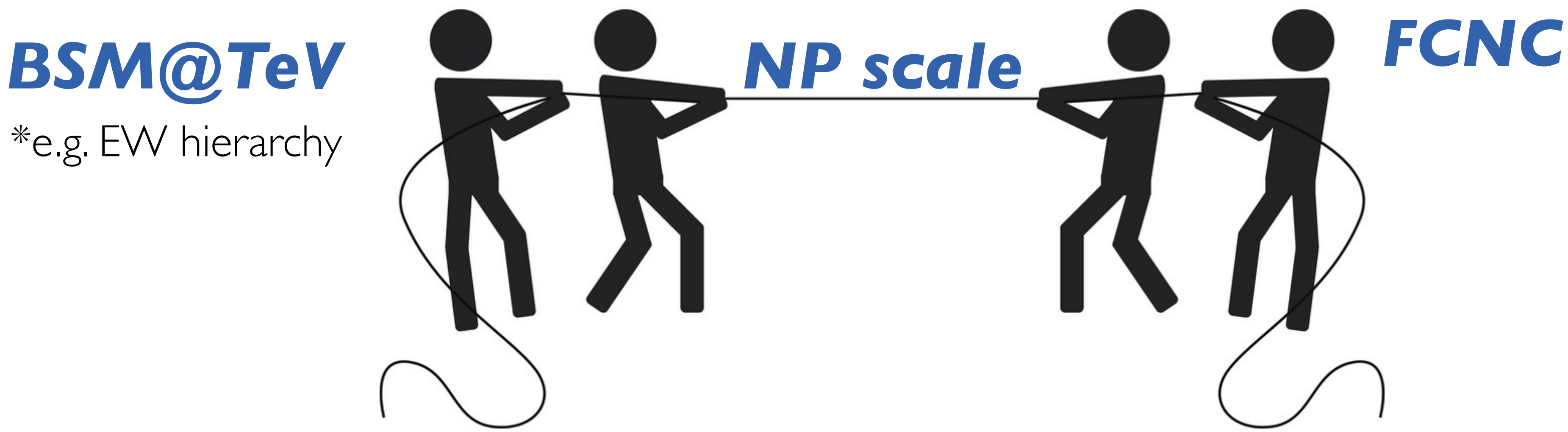
- Peculiar observed values of $Y^{u,d,e}$ $\Longrightarrow$ **Approximate** accidental symmetries
  [Mass hierarchy & CKM alignment] [suppression in FCNC, EDM, etc]

Flavour violation

- SMEFT at $\dim[\mathcal{O}] = 6$
  $\Longrightarrow$ New sources of violation of (approximate) accidental symmetries
- Already strong constraints!



Physics Briefing Book, 1910.11775



- A viable BSM at the TeV-scale should no excessively violate accidental symmetries of the SM
- Key ingredient for BSM@TeV:
  Flavour symmetry and its breaking pattern
  *Just like with the B number

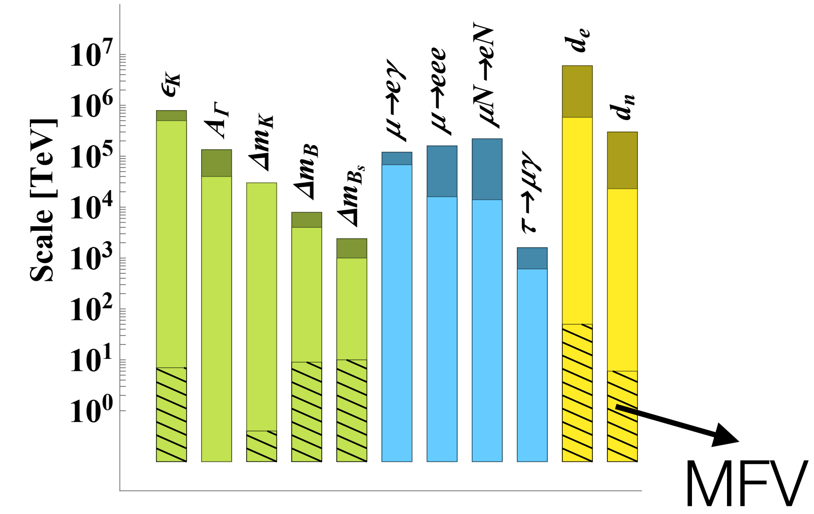
Minimal Flavour Violation

- No new sources of flavour breaking

$$G_Q = \mathrm{U}(3)_q \times \mathrm{U}(3)_u \times \mathrm{U}(3)_d$$
$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}).$$

- The MFV brings the cutoff to the TeV scale!

D'Ambrosio et al; hep-ph/0207036



Minimal Flavour Violation

- No new sources of flavour breaking

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$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}).$$

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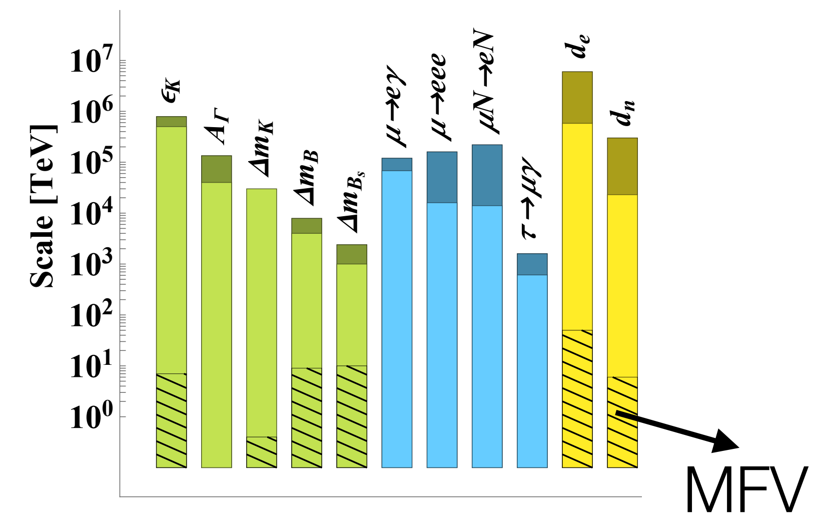
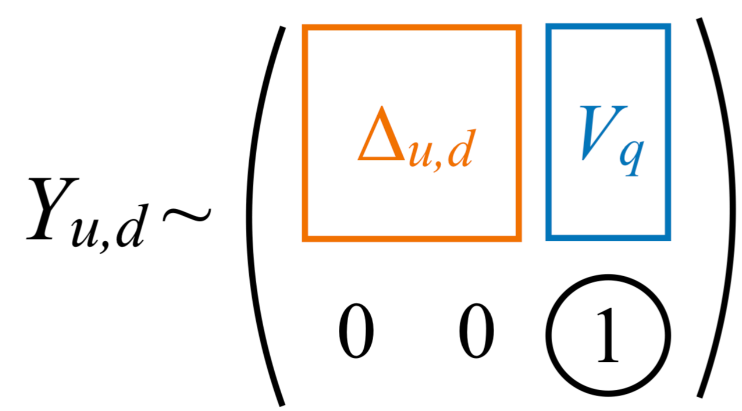


- The MFV brings the cutoff to the TeV scale!

U(2)^3

- Approximate symmetry of the SM
- Small spurions $\Longrightarrow$ consistent power counting
- Some protection against FCNC

Barbieri et at; 1105.2296



$$G = \mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$$
$$V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1}) \ , \qquad \Delta_u \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1}) \ , \qquad \Delta_d \sim (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$$

$$\Delta \ll V \ll 1 \qquad V^\dagger \propto (V_{td}, V_{ts})$$

Adding Flavour to the SMEFT

AG, Thomsen, Palavric; 2203.09561

Contents

- Charting the space of BSM by flavour symmetries
- Formulate several competing flavour hypothesis for $\dim 6$ SMEFT ($\Delta B = 0$)
- Systematic approach: $U(3) \supset U(2) \supset U(1)$ (smaller symmetry $\Longrightarrow$ more terms)
- 28 different case
- Minimal set of flavor-breaking spurions needed to reproduce masses and mixings
- Construct explicit (ready-for-use) operator bases order by order in the spurion expansion starting from the Warsaw basis

Example: $U(2)^3$ quark

- Examples of bilinear structures

$(\bar{q}q)$

$$\begin{aligned} &\mathcal{O}(1): \ (\bar{q}q)\,, \quad (\bar{q}_3 q_3)\,, \qquad \mathcal{O}(V): \ (\bar{q}V_q q_3)\,, \quad V_q^a \varepsilon_{ab}(\bar{q}_3 q^b)\,, \quad \text{H.c.}\,, \\ &\mathcal{O}(V^2): \ (\bar{q}V_q V_q^\dagger q)\,, \quad \left[\epsilon_{bc}(\bar{q}V_q V_q^c q^b)\,, \quad \text{H.c.}\right]\,. \end{aligned} \tag{2.12}$$

$(\bar{u}u)$

$$\begin{aligned} \mathcal{O}(1): \quad & (\bar{u}u)\,, \quad (\bar{u}_3 u_3)\,, \\ \mathcal{O}(\Delta V): \quad & (\bar{u}\Delta_u^\dagger V_q u_3)\,, \quad (\bar{u}_a u_3)\varepsilon^{ab}(V_q^\dagger \Delta_u)_b\,, \quad \epsilon^{ad}\epsilon_{bc}[\bar{u}^a V_q^b (\Delta_u)^c{}_d u_3]\,, \quad \text{H.c.}\,, \\ & \epsilon_{bc}[\bar{u}_3 V_q^b (\Delta_u)^c{}_a u^a]\,, \quad \text{H.c.}\,. \end{aligned} \tag{2.13}$$

$(\bar{d}d)$

$$\begin{aligned} \mathcal{O}(1): \quad & (\bar{d}d)\,, \quad (\bar{d}_3 d_3)\,, \\ \mathcal{O}(\Delta V): \quad & (\bar{d}\Delta_d^\dagger V_q d_3)\,, \quad (\bar{d}_a d_3)\varepsilon^{ab}(V_q^\dagger \Delta_d)_b\,, \quad \epsilon^{ad}\epsilon_{bc}[\bar{d}^a V_q^b (\Delta_d)^c{}_d d_3]\,, \quad \text{H.c.}\,, \\ & \epsilon_{bc}[\bar{d}_3 V_q^b (\Delta_d)^c{}_a d^a]\,, \quad \text{H.c.}\,. \end{aligned} \tag{2.14}$$

Watch out redundancies
$\varepsilon^{ij}\varepsilon_{k\ell} = \delta^i{}_\ell \delta^j{}_k - \delta^i{}_k \delta^j{}_\ell$

- Examples of quartic structures

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

$$\begin{aligned} \mathcal{O}(1): \quad & (\bar{q}_a q^b)(\bar{q}_b q^a)\,, \quad (\bar{q}_a q_3)(\bar{q}_3 q^a)\,, \\ \mathcal{O}(V): \quad & (\bar{q}_a q_3)(\bar{q}V_q q^a)\,, \quad (\bar{q}_3 q^a)(\bar{q}_a \epsilon_{bc} V_q^c q^b)\,, \quad (\bar{q}_3 q^a)(\bar{q}V_q \epsilon_{ac} q^c)\,, \quad \text{H.c.}\,, \\ \mathcal{O}(V^2): \quad & (\bar{q}_a V_q^\dagger q)(\bar{q}V_q q^a)\,. \end{aligned} \tag{2.18}$$

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

$$\begin{aligned} \mathcal{O}(1): \ & (\bar{u}_a u^b)(\bar{u}_b u^a)\,, \quad (\bar{u}_a u_3)(\bar{u}_3 u^a)\,, \\ \mathcal{O}(\Delta V): \ & (\bar{u}_a u_3)(\bar{u}\Delta_u^\dagger V_q u^a)\,, \quad (\bar{u}_a u_3)\epsilon^{ab}\epsilon_{de}[\bar{u}_b V_q^d (\Delta_u)^e{}_c u^c]\,, \quad \epsilon^{be}\epsilon_{cd}(\bar{u}_a u_3)[\bar{u}_b V_q^c (\Delta_u)^d{}_e u^a]\,, \quad \text{H.c.}\,, \\ & (\bar{u}_3 u^a)[\bar{u}_a V_q^c \epsilon_{cd}(\Delta_u)^d{}_b u^b]\,, \quad (\bar{u}_3 u^a)[\bar{u}_a \epsilon_{bd} V_q^c (\Delta_u^*)_c{}^d u^b]\,, \quad \epsilon_{ac}(\bar{u}_3 u^a)[\bar{u}_b V_q^d (\Delta_u^*)_d{}^b u^c]\,, \quad \text{H.c.}\,. \end{aligned} \tag{2.19}$$

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

$$\begin{aligned} \mathcal{O}(1): \ & (\bar{d}_a d^b)(\bar{d}_b d^a)\,, \quad (\bar{d}_a d_3)(\bar{d}_3 d^a)\,, \\ \mathcal{O}(\Delta V): \ & (\bar{d}_a d_3)(\bar{d}\Delta_d^\dagger V_q d^a)\,, \quad (\bar{d}_a d_3)\epsilon^{ab}\epsilon_{de}[\bar{d}_b V_q^d (\Delta_d)^e{}_c d^c]\,, \quad \epsilon^{be}\epsilon_{cd}(\bar{d}_a d_3)[\bar{d}_b V_q^c (\Delta_d)^d{}_e d^a]\,, \quad \text{H.c.}\,, \\ & (\bar{d}_3 d^a)[\bar{d}_a V_q^c \epsilon_{cd}(\Delta_d)^d{}_b d^b]\,, \quad (\bar{d}_3 d^a)[\bar{d}_a \epsilon_{bd} V_q^c (\Delta_d^*)_c{}^d d^b]\,, \quad \epsilon_{ac}(\bar{d}_3 d^a)[\bar{d}_b V_q^d (\Delta_d^*)_d{}^b d^c]\,, \quad \text{H.c.}\,. \end{aligned} \tag{2.20}$$

*the new structures that appear in case of $SU(2)^3$ symmetry are denoted in blue

Example: $U(2)^3$ quark

AG, Thomsen, Palavric; 2203.09561

$\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$		$\mathcal{O}(1)$		$\mathcal{O}(V)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^3)$		$\mathcal{O}(\Delta)$		$\mathcal{O}(\Delta V)$	
$\psi^2 H^3$	Q_{uH}	1	1	1	1					1	1	1	1
	Q_{dH}	1	1	1	1					1	1	1	1
$\psi^2 XH$	$Q_{u(G,W,B)}$	3	3	3	3					3	3	3	3
	$Q_{d(G,W,B)}$	3	3	3	3					3	3	3	3
$\psi^2 H^2 D$	$Q_{Hq}^{(1,3)}$	4		2	2	2							
	Q_{Hu}, Q_{Hd}	4										2	2
	Q_{Hud}	1	1									2	2
$(LL)(LL)$	$Q_{qq}^{(1,3)}$	10		6	6	10	2	2	2				
$(RR)(RR)$	Q_{uu}, Q_{dd}	10										6	6
	$Q_{ud}^{(1,8)}$	8										8	8
$(LL)(RR)$	$Q_{qu}^{(1,8)}, Q_{qd}^{(1,8)}$	16		8	8	8				4	4	12	12
$(LR)(LR)$	$Q_{quqd}^{(1,8)}$	2	2	4	4	2	2			8	8	12	12
Total		63	11	28	28	22	4	2	2	20	20	50	50

Table 2. Counting of the pure quark SMEFT operators (see Appendix A) assuming $\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$ symmetry in the quark sector. The counting is performed taking up to three insertions of V_q spurion, one insertion of $\Delta_{u,d}$ and one insertion of the $\Delta_{u,d} V_q$ spurion product. Left (right) numerical entry in each column gives the number of CP even (odd) coefficients at the given order in spurion counting.

See also Faroughy et al; 2005.05366

Tools

- Mathematica package **SMEFTflavor** to facilitate the use of flavor symmetries

https://github.com/aethomsen/SMEFTflavor

```
In[•]:= CountingTable[{"quark:3U2", "lep:2U2"}, SpurionCount → 1, SMEFToperators → semiLeptonicOperators]
```

Out[•]=

{quark:3U2, lep:2U2}		O[1]		O[Vl]		O[Vq]	
(LL)(LL)	Olq(1,3)	8		4	4	4	4
(RR)(RR)	Oeu	4					
	Oed	4					
(LL)(RR)	Olu	4		2	2		
	Old	4		2	2		
	Oqe	4				2	2
(LR)(LR)	Olequ(1,3)	2	2	2	2	2	2
(LR)(RL)	Oledq	1	1	1	1	1	1
Total		31	3	11	11	9	9

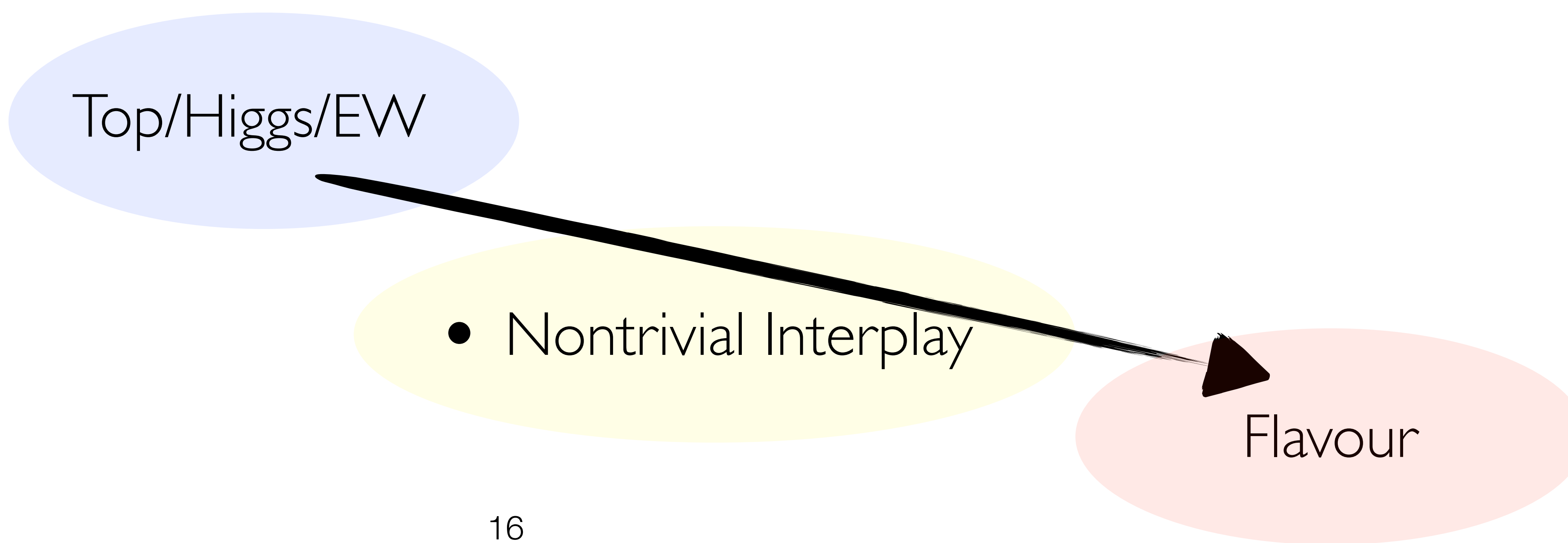
```
In[•]:= AddSMEFTSymmetry["Lepton", "lep:U2xU1" → <|
    Groups → <|"U2l" → SU@2|>,
    FieldSubstitutions → <|"l" → {"l12", "l3"}, "e" → {"e12", "e3"}|>,
    Spurions → {"Δl", "Vl", "Xτ"},
    Charges → <|"l12" → {1, 0}, "l3" → {0, 1}, "e12" → {-1, 0}, "e3" → {0, -1},
        "Δl" → {2, 0}, "Vl" → {1, 1}, "Xτ" → {0, 2}|>,
    Representations → <|"l12" → {"U2l"@ fund}, "e12" → {"U2l"@ fund},
        "Vl" → {"U2l"@ fund}, "Δl" → {"U2l"@ adj}|>,
    SpurionCounting → <|"Xτ" → 1, "Vl" → 2, "Δl" → 3|>,
    SelfConjugate → {"Δl"}
  |>]
```

Summary

AG, Thomsen, Palavric; 2203.09561

Dim-6 SMEFT operators		Lepton sector					
B-conserving $\mathcal{O}(1)$ terms		MFV_L	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV_Q	47	65	71	87	111	339
	$U(2)_q \times U(2)_u \times U(3)_d$	82	105	115	132	168	450
	$U(2)^3 \times U(1)_{b_R}$	96	121	128	150	186	480
	$U(2)^3$	110	135	147	164	206	512
	No symmetry	1273	1347	1407	1425	1611	2499

- Flavour-symmetric operator bases (no spurion insertions)
- Systematically from MFV towards anarchy: $U(3) \supset U(2) \supset U(1)$



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AG, Palavric; wip

Dim-8 SMEFT operators B-conserving $\mathcal{O}(1)$ terms		Lepton sector					
		MFV_L	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV_Q	456	631	735	840	1266	4032
	$U(2)_q \times U(2)_u \times U(3)_d$	962	1205	1361	1482	2064	5550
	$U(2)^3 \times U(1)_{b_R}$	1124	1384	1546	1678	2278	5902
	$U(2)^3$	1366	1646	1838	1960	2650	6574
	No symmetry	19459	20512	21384	21599	24329	36971

Next slide

Summary

AG, Thomsen, Palavric; 2203.09561

Dim-6 SMEFT operators B-conserving $\mathcal{O}(1)$ terms		Lepton sector					
		MFV_L	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV_Q	47	65	71	87	111	339
	$U(2)_q \times U(2)_u \times U(3)_d$	82	105	115	132	168	450
	$U(2)^3 \times U(1)_{b_R}$	96	121	128	150	186	480
	$U(2)^3$	110	135	147	164	206	512
	No symmetry	1273	1347	1407	1425	1611	2499

AG, Palavric; wip

Dim-8 SMEFT operators B-conserving $\mathcal{O}(1)$ terms		Lepton sector					
		MFV_L	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV_Q	456	631	735	840	1266	4032
	$U(2)_q \times U(2)_u \times U(3)_d$	962	1205	1361	1482	2064	5550
	$U(2)^3 \times U(1)_{b_R}$	1124	1384	1546	1678	2278	5902
	$U(2)^3$	1366	1646	1838	1960	2650	6574
	No symmetry	19459	20512	21384	21599	24329	36971

$U(3)^5$ flavour-symmetric basis

Class	Label	Operator	Label	Operator
$(\bar{L}L)(\bar{L}L)$	$\mathcal{O}_{\ell\ell}^{D}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{\ell}_j\gamma_\mu\ell^j)$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{q}_j\gamma_\mu q^j)$
	$\mathcal{O}_{\ell\ell}^{E}$	$(\bar{\ell}_i\gamma^\mu\ell^j)(\bar{\ell}_j\gamma_\mu\ell^i)$	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)D}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{q}_j\gamma_\mu q^j)$	$\mathcal{O}_{qq}^{(3)D}$	$(\bar{q}_i\gamma^\mu\sigma^a q^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)E}$	$(\bar{q}_i\gamma^\mu q^j)(\bar{q}_j\gamma_\mu q^i)$	$\mathcal{O}_{qq}^{(3)E}$	$(\bar{q}_i\gamma^\mu\sigma^a q^j)(\bar{q}_j\gamma_\mu\sigma^a q^i)$
$(\bar{R}R)(\bar{R}R)$	$\mathcal{O}_{ee}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{dd}^{D}$	$(\bar{d}_i\gamma^\mu d^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{uu}^{D}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{dd}^{E}$	$(\bar{d}_i\gamma^\mu d^j)(\bar{d}_j\gamma_\mu d^i)$
	$\mathcal{O}_{uu}^{E}$	$(\bar{u}_i\gamma^\mu u^j)(\bar{u}_j\gamma_\mu u^i)$	$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{eu}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_i\gamma^\mu T^A u^i)(\bar{d}_j\gamma_\mu T^A d^j)$
	$\mathcal{O}_{ed}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{d}_j\gamma_\mu d^j)$		
$(\bar{L}L)(\bar{R}R)$	$\mathcal{O}_{\ell e}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{u}_j\gamma_\mu u^j)$
	$\mathcal{O}_{qe}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{u}_j\gamma_\mu T^A u^j)$
	$\mathcal{O}_{\ell u}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{\ell d}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{d}_j\gamma_\mu d^j)$	$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{d}_j\gamma_\mu T^A d^j)$
$\psi^2\phi^2 D$	$\mathcal{O}_{\phi\ell}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{\ell}_i\gamma^\mu\ell^i)$	$\mathcal{O}_{\phi e}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_i\gamma^\mu e^i)$
	$\mathcal{O}_{\phi\ell}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)$	$\mathcal{O}_{\phi u}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_i\gamma^\mu u^i)$
	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_i\gamma^\mu q^i)$	$\mathcal{O}_{\phi d}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_i\gamma^\mu d^i)$
	$\mathcal{O}_{\phi q}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}_i\gamma^\mu\sigma^a q^i)$		

Class	Label	Operator	Label	Operator
X^3 Loop generated	$\mathcal{O}_W$	$\varepsilon_{abc}W_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_G$	$f_{ABC}G_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu}$
	$\mathcal{O}_{\tilde{W}}$	$\varepsilon_{abc}\tilde{W}_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_{\tilde{G}}$	$f_{ABC}\tilde{G}_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu}$
ϕ^6	$\mathcal{O}_\phi$	$(\phi^\dagger\phi)^3$		
$\phi^4 D^2$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi D}$	$(\phi^\dagger D_\mu\phi)[(D^\mu\phi)^\dagger\phi]$
$X^2\phi^2$ Loop generated	$\mathcal{O}_{\phi B}$	$(\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger\sigma^a\phi)W^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi\tilde{B}}$	$(\phi^\dagger\phi)\tilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\tilde{W}B}$	$(\phi^\dagger\sigma^a\phi)\tilde{W}^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi W}$	$(\phi^\dagger\phi)W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\,\mu\nu}$
	$\mathcal{O}_{\phi\tilde{W}}$	$(\phi^\dagger\phi)\tilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\tilde{G}}$	$(\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$

- Explicit operator basis: 41 CP even, 6 CP odd

$U(3)^5$ flavour-symmetric basis

Class	Label	Operator	Label	Operator
$(\bar{L}L)(\bar{L}L)$	$\mathcal{O}_{\ell\ell}^{D}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{\ell}_j\gamma_\mu\ell^j)$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{q}_j\gamma_\mu q^j)$
	$\mathcal{O}_{\ell\ell}^{E}$	$(\bar{\ell}_i\gamma^\mu\ell^j)(\bar{\ell}_j\gamma_\mu\ell^i)$	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)D}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{q}_j\gamma_\mu q^j)$	$\mathcal{O}_{qq}^{(3)D}$	$(\bar{q}_i\gamma^\mu\sigma^a q^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)E}$	$(\bar{q}_i\gamma^\mu q^j)(\bar{q}_j\gamma_\mu q^i)$	$\mathcal{O}_{qq}^{(3)E}$	$(\bar{q}_i\gamma^\mu\sigma^a q^j)(\bar{q}_j\gamma_\mu\sigma^a q^i)$
$(\bar{R}R)(\bar{R}R)$	$\mathcal{O}_{ee}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{dd}^{D}$	$(\bar{d}_i\gamma^\mu d^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{uu}^{D}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{dd}^{E}$	$(\bar{d}_i\gamma^\mu d^j)(\bar{d}_j\gamma_\mu d^i)$
	$\mathcal{O}_{uu}^{E}$	$(\bar{u}_i\gamma^\mu u^j)(\bar{u}_j\gamma_\mu u^i)$	$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{eu}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_i\gamma^\mu T^A u^i)(\bar{d}_j\gamma_\mu T^A d^j)$
	$\mathcal{O}_{ed}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{d}_j\gamma_\mu d^j)$		
$(\bar{L}L)(\bar{R}R)$	$\mathcal{O}_{\ell e}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{u}_j\gamma_\mu u^j)$
	$\mathcal{O}_{qe}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{u}_j\gamma_\mu T^A u^j)$
	$\mathcal{O}_{\ell u}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{\ell d}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{d}_j\gamma_\mu d^j)$	$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{d}_j\gamma_\mu T^A d^j)$
$\psi^2\phi^2 D$	$\mathcal{O}_{\phi\ell}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{\ell}_i\gamma^\mu\ell^i)$	$\mathcal{O}_{\phi e}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_i\gamma^\mu e^i)$
	$\mathcal{O}_{\phi\ell}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)$	$\mathcal{O}_{\phi u}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_i\gamma^\mu u^i)$
	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_i\gamma^\mu q^i)$	$\mathcal{O}_{\phi d}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_i\gamma^\mu d^i)$
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Class	Label	Operator	Label	Operator
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	$\mathcal{O}_{\tilde{W}}$	$\varepsilon_{abc}\tilde{W}_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_{\tilde{G}}$	$f_{ABC}\tilde{G}_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu}$
ϕ^6	$\mathcal{O}_\phi$	$(\phi^\dagger\phi)^3$		
$\phi^4 D^2$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi D}$	$(\phi^\dagger D_\mu\phi)[(D^\mu\phi)^\dagger\phi]$
$X^2\phi^2$ Loop generated	$\mathcal{O}_{\phi B}$	$(\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger\sigma^a\phi)W^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi\tilde{B}}$	$(\phi^\dagger\phi)\tilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\tilde{W}B}$	$(\phi^\dagger\sigma^a\phi)\tilde{W}^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi W}$	$(\phi^\dagger\phi)W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\,\mu\nu}$
	$\mathcal{O}_{\phi\tilde{W}}$	$(\phi^\dagger\phi)\tilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\tilde{G}}$	$(\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$

- Green: Can be generated at tree-level in a renormalisable UV completion!

Q: What are all tree-level UV completions? AG, Palavric; 2305.08898

Leading (flavour-blind) directions

- Assume weakly coupled, perturbative UV with new spin-0, 1/2, 1 fields
- New fields have $M_X \gg v_{EW}$ and leading (renormalisable) interactions
- Goal: identify all possible ways to generate $\dim 6$ operator in the $U(3)^5$ flavour-symmetric basis
- Start from the UV/IR dictionary of 1711.10391 and impose $U(3)^5$:

  - New fields are irreps of the flavor group: 1, 3, 6, 8

  - Parameter reduction: Flavour tensors fixed by group theory

- In most cases, a single flavour irrep integrates to a single Hermitian operator with a definite sign (**a leading direction**)
- These define a UV motivated operator basis suitable for 1D fits

AG, Palavric; 2305.08898

Example: Fermions

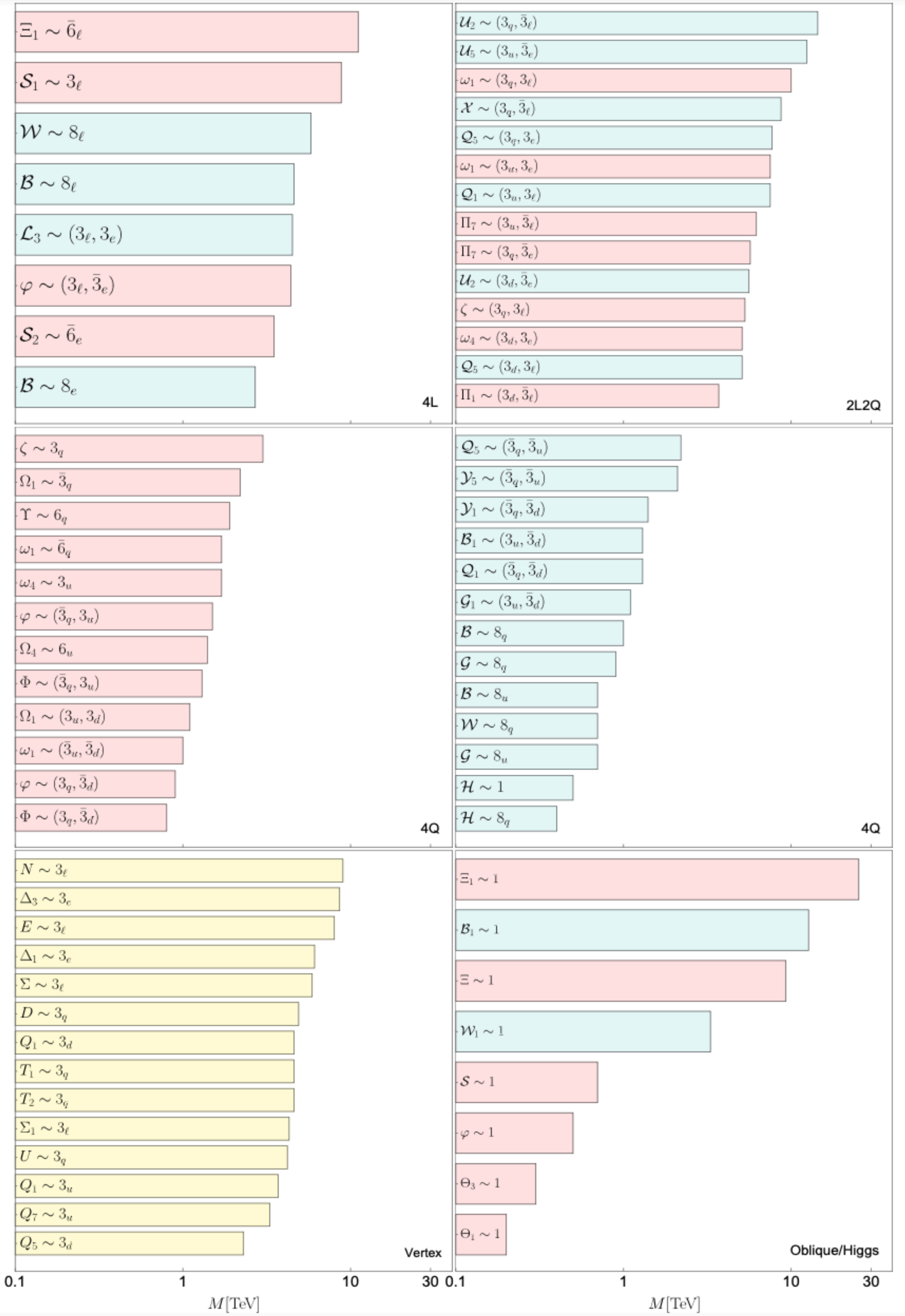
Field	Irrep	Normalization	Operator
$N \sim (\mathbf{1},\mathbf{1})_0$	$\mathbf{3}_\ell$	$\lvert\lambda_N\rvert^2/(4M_N^2)$	$\mathcal{O}_{\phi\ell}^{(1)} - \mathcal{O}_{\phi\ell}^{(3)}$
$E \sim (\mathbf{1},\mathbf{1})_{-1}$	$\mathbf{3}_\ell$	$-\lvert\lambda_E\rvert^2/(4M_E^2)$	$\mathcal{O}_{\phi\ell}^{(1)} + \mathcal{O}_{\phi\ell}^{(3)} - [2y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Delta_1 \sim (\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$\mathbf{3}_e$	$\lvert\lambda_{\Delta_1}\rvert^2/(2M_{\Delta_1}^2)$	$\mathcal{O}_{\phi e} + [y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Delta_3 \sim (\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	$\mathbf{3}_e$	$-\lvert\lambda_{\Delta_3}\rvert^2/(2M_{\Delta_3}^2)$	$\mathcal{O}_{\phi e} - [y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Sigma \sim (\mathbf{1},\mathbf{3})_0$	$\mathbf{3}_\ell$	$\lvert\lambda_\Sigma\rvert^2/(16M_\Sigma^2)$	$3\mathcal{O}_{\phi\ell}^{(1)} + \mathcal{O}_{\phi\ell}^{(3)} + [4y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Sigma_1 \sim (\mathbf{1},\mathbf{3})_{-1}$	$\mathbf{3}_\ell$	$\lvert\lambda_{\Sigma_1}\rvert^2/(16M_{\Sigma_1}^2)$	$\mathcal{O}_{\phi\ell}^{(3)} - 3\mathcal{O}_{\phi\ell}^{(1)} + [2y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$U \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$\mathbf{3}_q$	$\lvert\lambda_U\rvert^2/(4M_U^2)$	$\mathcal{O}_{\phi q}^{(1)} - \mathcal{O}_{\phi q}^{(3)} + [2y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
$D \sim (\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$\mathbf{3}_q$	$-\lvert\lambda_D\rvert^2/(4M_D^2)$	$\mathcal{O}_{\phi q}^{(1)} + \mathcal{O}_{\phi q}^{(3)} - [2y_d^*\mathcal{O}_{d\phi} + \text{h.c.}]$
$Q_1 \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$\mathbf{3}_u$	$-\lvert\lambda_{Q_1}^u\rvert^2/(2M_{Q_1}^2)$	$\mathcal{O}_{\phi u} - [y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
	$\mathbf{3}_d$	$\lvert\lambda_{Q_1}^d\rvert^2/(2M_{Q_1}^2)$	$\mathcal{O}_{\phi d} + [y_d^*\mathcal{O}_{d\phi} + \text{h.c.}]$
$Q_5 \sim (\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$\mathbf{3}_d$	$-\lvert\lambda_{Q_5}\rvert^2/(2M_{Q_5}^2)$	$\mathcal{O}_{\phi d} - [y_d^*\mathcal{O}_{d\phi} + \text{h.c.}]$
$Q_7 \sim (\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$\mathbf{3}_u$	$\lvert\lambda_{Q_7}\rvert^2/(2M_{Q_7}^2)$	$\mathcal{O}_{\phi u} + [y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
$T_1 \sim (\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$	$\mathbf{3}_q$	$\lvert\lambda_{T_1}\rvert^2/(16M_{T_1}^2)$	$\mathcal{O}_{\phi q}^{(3)} - 3\mathcal{O}_{\phi q}^{(1)} + [2y_d^*\mathcal{O}_{d\phi} + 4y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
$T_2 \sim (\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$\mathbf{3}_q$	$\lvert\lambda_{T_2}\rvert^2/(16M_{T_2}^2)$	$\mathcal{O}_{\phi q}^{(3)} + 3\mathcal{O}_{\phi q}^{(1)} + [4y_d^*\mathcal{O}_{d\phi} + 2y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$

- See scalars, vectors and exceptional cases in AG, Palavric; 2305.08898

Compilation of EFT limits on leading directions

AG, Palavric; 2305.08898

- Automatic protection against FCNC
- The case for Top/Higgs/EW fits



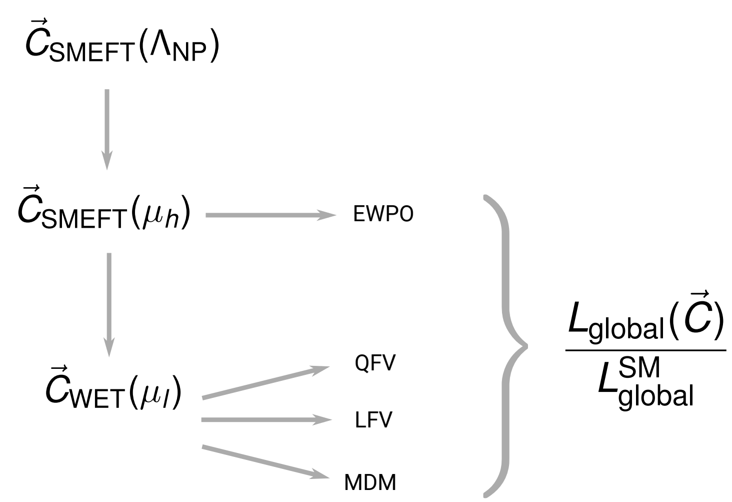
Global SMEFT likelihood

Towards a global SMEFT likelihood

- Building a global likelihood (GL) is very useful.

- Say you've got a new model and want to confront it against data.
  Step 1: Match it to the SMEFT (now automated to one-loop)
  Step 2: Plug into the GL

$$L(\vec{C}) \approx \prod_i L^i_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C},\vec{\theta}_0)) \times \tilde{L}_{\text{exp}}(\vec{O}_{\text{th}}(\vec{C},\vec{\theta}_0))$$



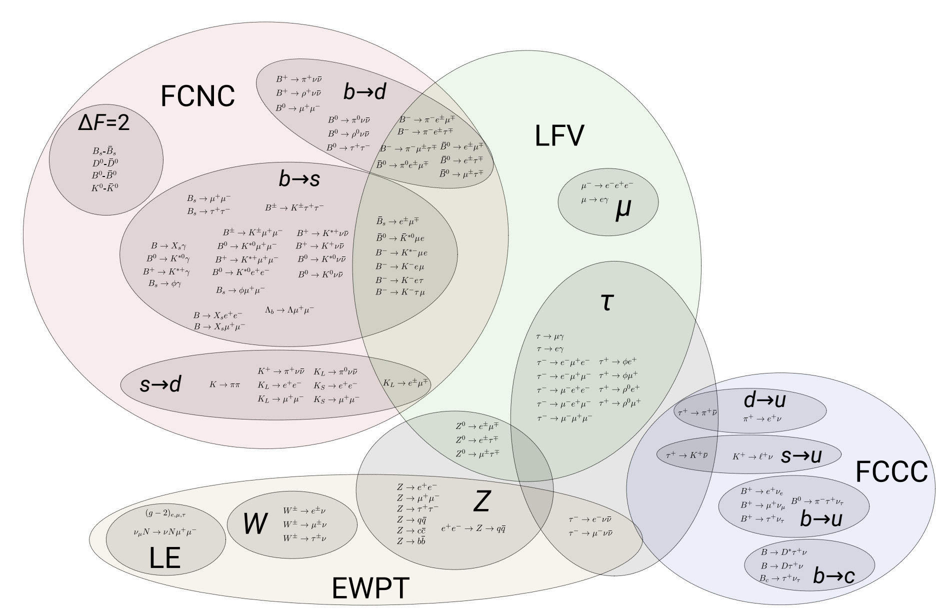
https://flav-io.github.io/

- Challenges for constructing the GL:
  Compute huge number of observables in the SMEFT (a theory of many parameters) BUT once and for all

smelli Aebischer, Kumar, Stangl, Straub, 1810.07698

wilson Aebischer, Kumar, Straub, 1804.05033

flavio Straub, 1810.08132



Towards a global SMEFT likelihood

Example: AG, Salko, Smolkovic, Stangl; 2212.10497, 2306.09401

- Flavio implementation of the high-mass Drell-Yan data

Data

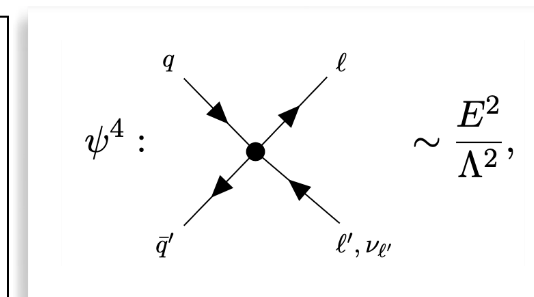
Search	Ref.	Channel	Luminosity
ATLAS	[45]	$pp \to ee$	139 fb^{-1}
		$pp \to \mu\mu$	139 fb^{-1}
CMS	[46]	$pp \to ee$	137 fb^{-1}
		$pp \to \mu\mu$	140 fb^{-1}
ATLAS	[47]	$pp \to e\nu$	139 fb^{-1}
		$pp \to \mu\nu$	139 fb^{-1}
CMS	[48]	$pp \to e\nu$	138 fb^{-1}
		$pp \to \mu\nu$	138 fb^{-1}

Drell-Yan data used

Theory

$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$
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_{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_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

4F SMEFT operators with arbitrary flavor



855 ops

SMEFT example

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l \gamma_\mu l_l)(\bar{q}_s \gamma^\mu q_t)$$

$$[C_{lq}^{(1)}]^{(\ell)} \equiv [C_{lq}^{(1)}]^{(e)} = [C_{lq}^{(1)}]^{(\mu)}$$

$$Q_{lq}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$

AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l \gamma_\mu l_l)(\bar{q}_s \gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}^{(l)} + \dots$$

$$[C_{lq}^{(1)}]^{(\ell)} \equiv [C_{lq}^{(1)}]^{(e)} = [C_{lq}^{(1)}]^{(\mu)}$$

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

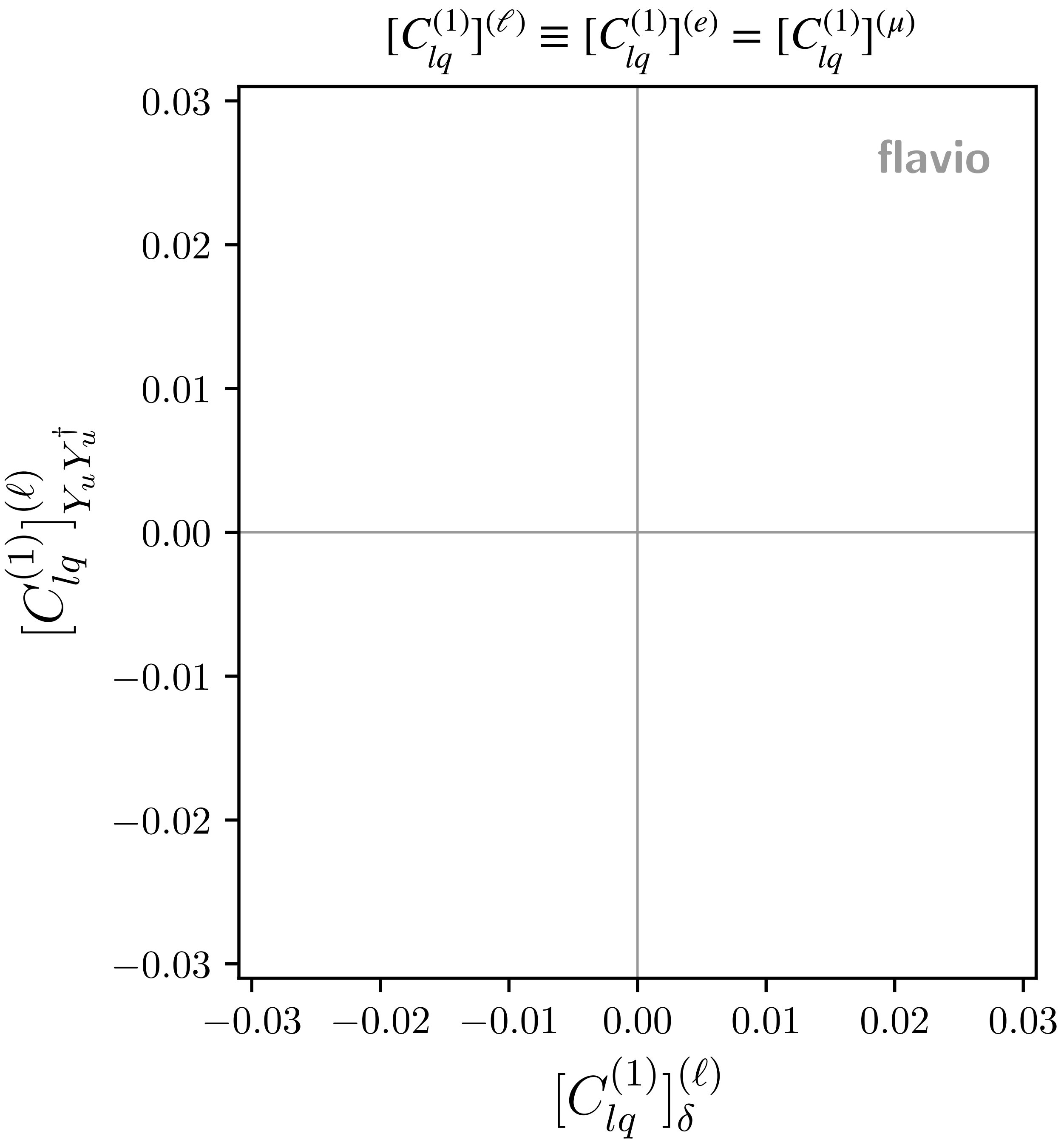
AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_u Y_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_u Y_u^\dagger}^{(l)} + \dots$$

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$



AG, Salko, Smolkovic, Stangl; 2212.10497

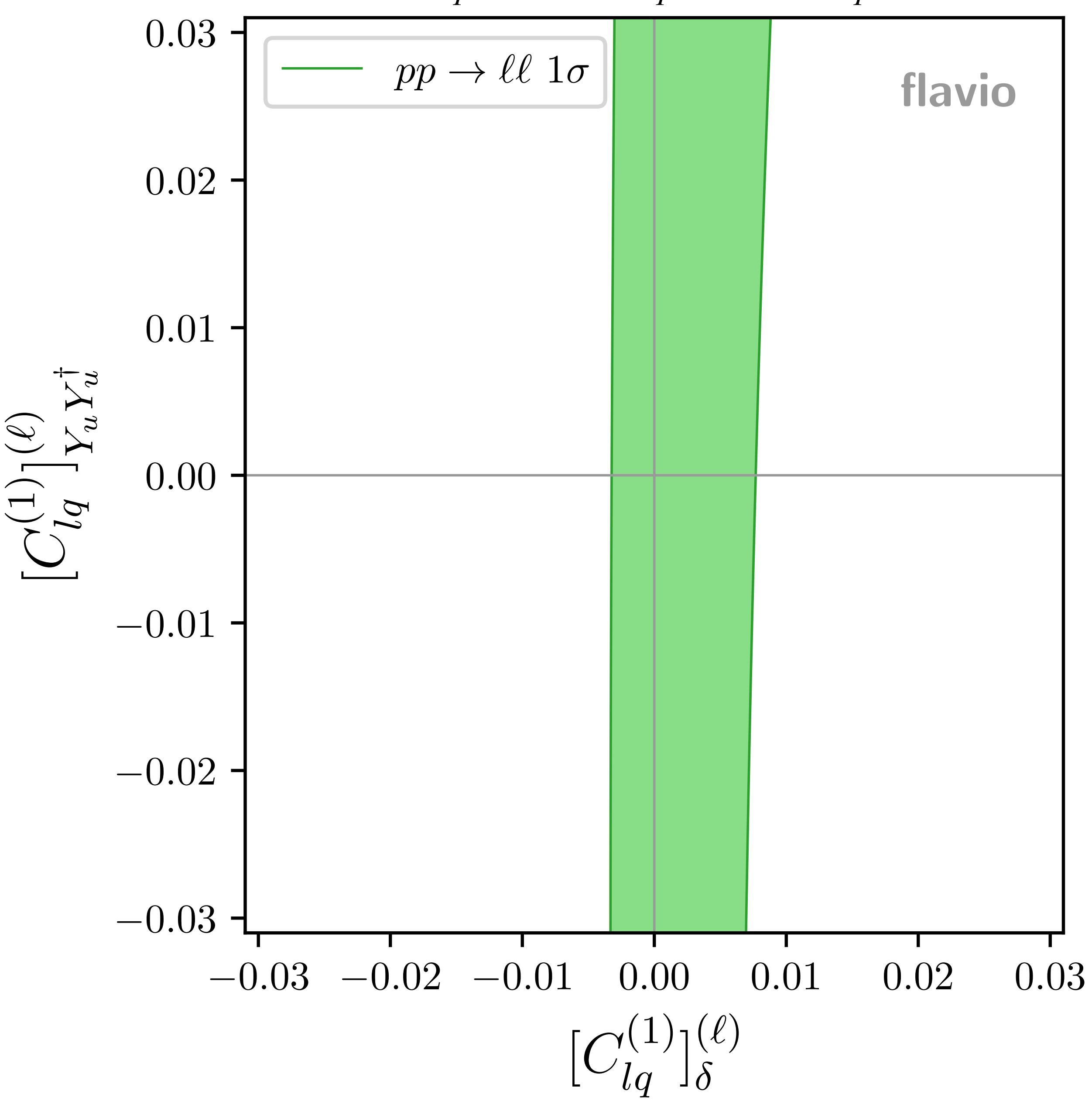
SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}^{(l)} + \dots$$

$$(Y_uY_u^\dagger) \sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

$[C_{lq}^{(1)}]^{(\ell)} \equiv [C_{lq}^{(1)}]^{(e)} = [C_{lq}^{(1)}]^{(\mu)}$



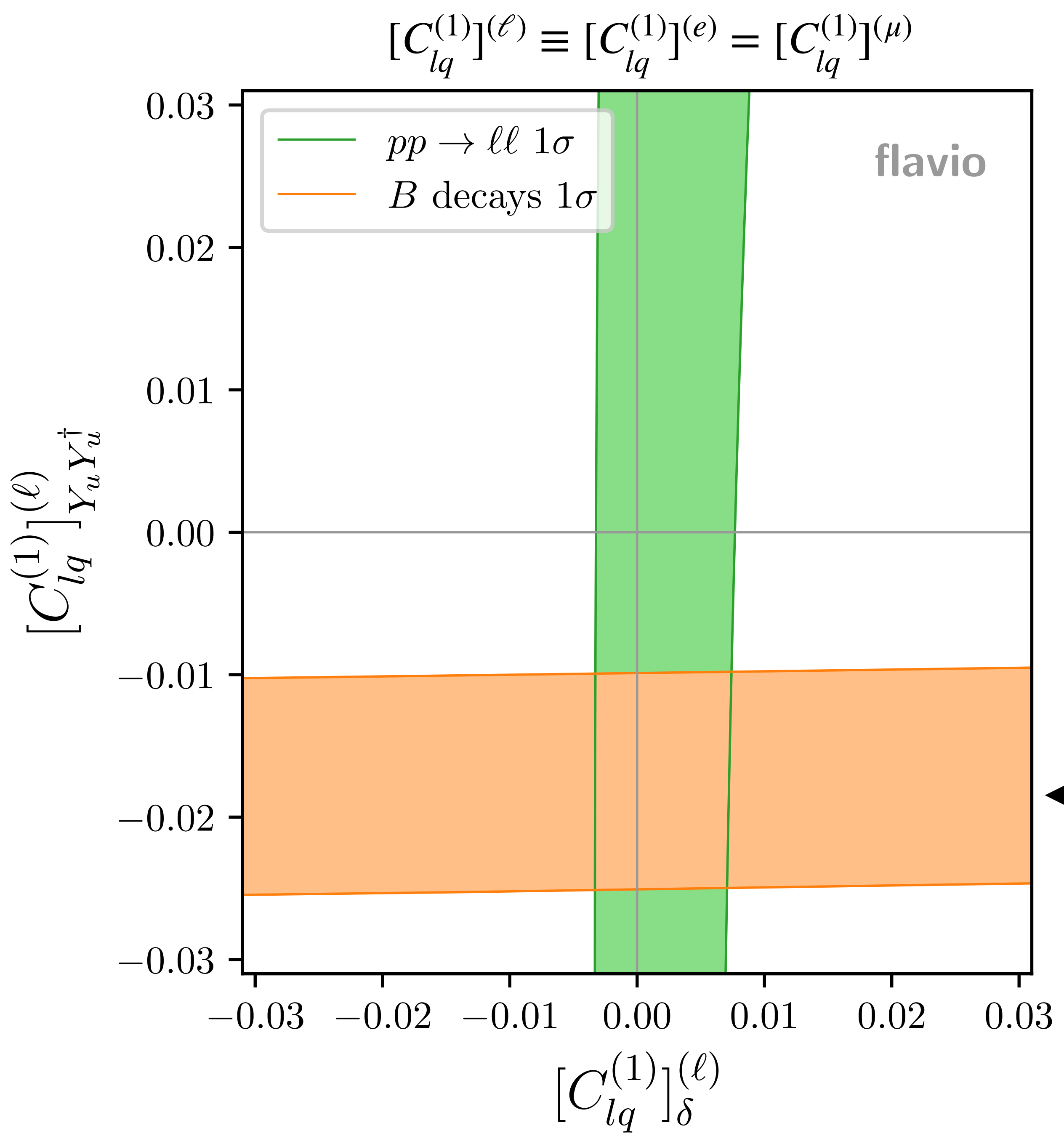
AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}^{(l)} + \dots$$

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$



Dominated by $b \to s\mu\mu$

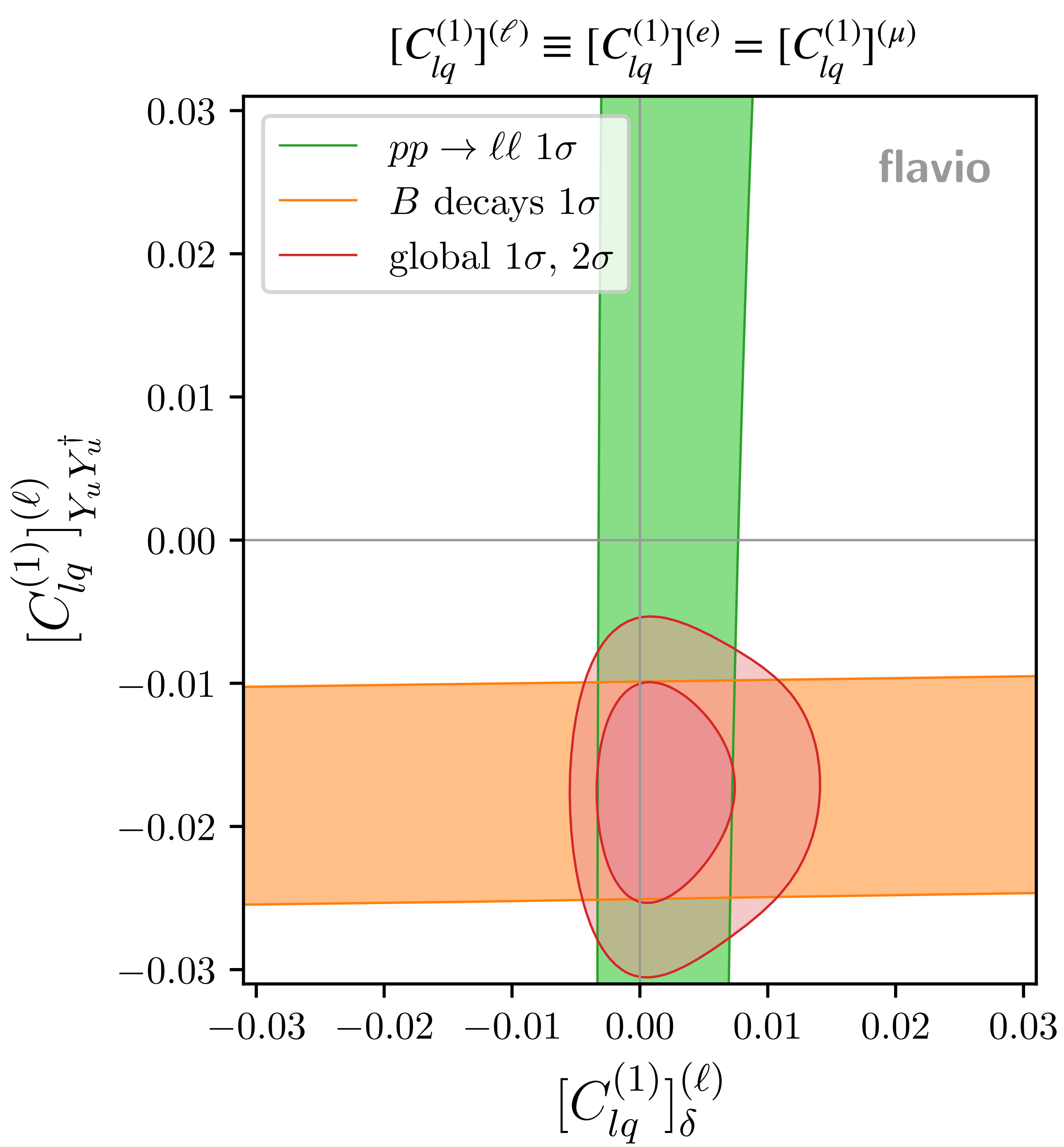
AG, Salko, Smolkovic, Stangl; 2212.10497

SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}^{(l)} + \dots$$

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$



AG, Salko, Smolkovic, Stangl; 2212.10497

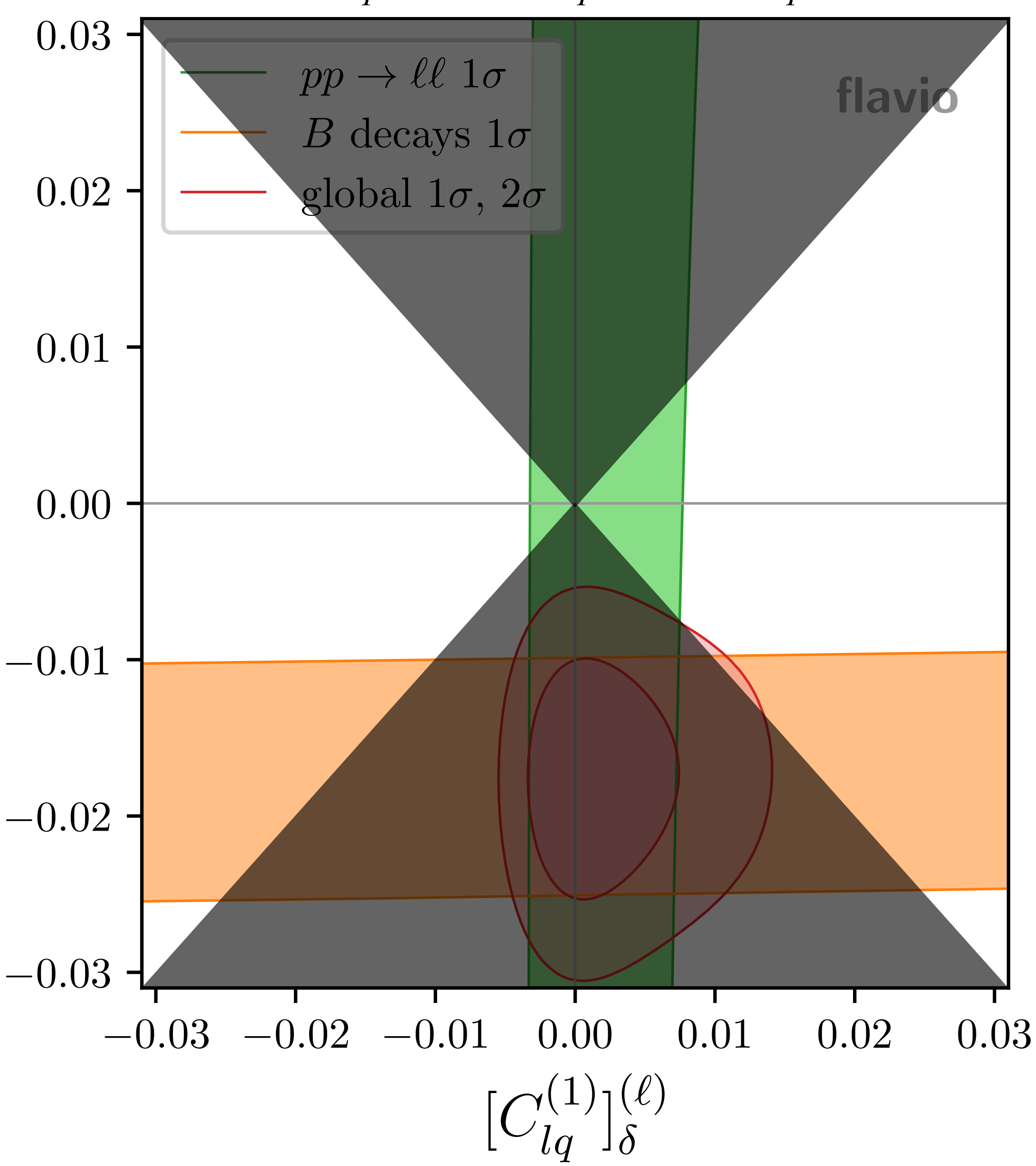
SMEFT example

MFV expansion

$$[C_{lq}^{(1)}]_{st}^{(l)}(\bar{l}_l\gamma_\mu l_l)(\bar{q}_s\gamma^\mu q_t) \to [C_{lq}^{(1)}]_{st}^{(l)} = \delta_{st}[C_{lq}^{(1)}]_{\delta}^{(l)} + (Y_uY_u^\dagger)_{st}[C_{lq}^{(1)}]_{Y_uY_u^\dagger}^{(l)} + \dots$$

$$\sim y_t^2 \begin{pmatrix} V_{td}V_{td}^* & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & V_{ts}V_{ts}^* & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & V_{tb}V_{tb}^* \end{pmatrix}$$

$$[C_{lq}^{(1)}]^{(\ell)} \equiv [C_{lq}^{(1)}]^{(e)} = [C_{lq}^{(1)}]^{(\mu)}$$



MFV Expansion validity?

Linear MFV: $|[C_{lq}^{(1)}]_{Y_uY_u^\dagger}| \ll |[C_{lq}^{(1)}]_\delta|$ 0903.1794

A large class of models ruled out!

AG, Marzocca; 1704.09015

AG, Salko, Smolkovic, Stangl; 2212.10497

Conclusions

- A UV theory will leave imprints on the flavor structure of the SMEFT.
- The selection rules implied have the advantage of reducing the number of important SMEFT operators by truncating the flavor-spurion expansion.
- We constructed operator bases order by order in the spurion expansion for 28 different flavour symmetry assumptions.
- Ready-for-use setups for phenomenological studies and global fits.
- Classification of new physics mediators contributing at leading order in both the MFV and the SMEFT power counting (leading flavour-blind directions).
- High-mass Drell-Yan data added to the global SMEFT likelihood and studied its interplay with flavour data.

Alhambra of Granada

Thank you

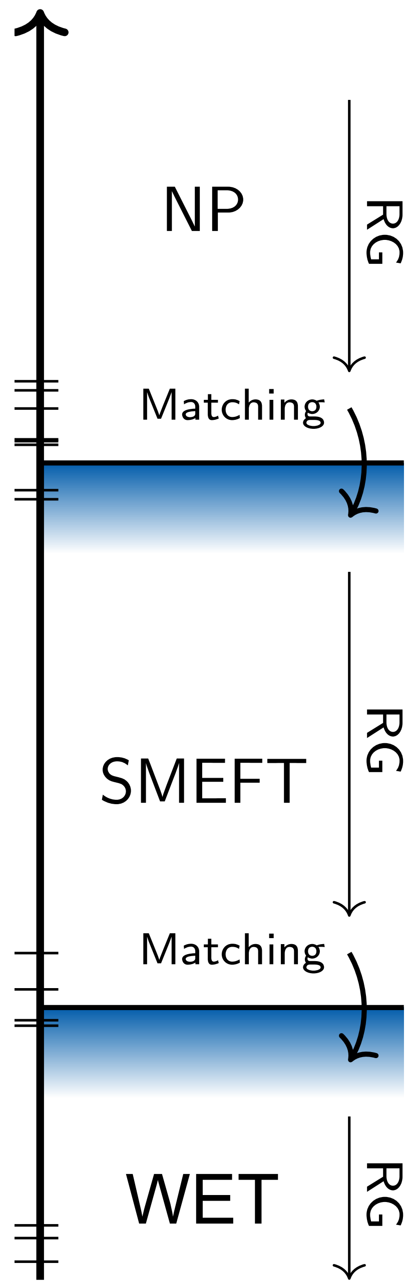
University of Basel

https://physik.unibas.ch/en/persons/admir-greljo/

admir.greljo@unibas.ch

Backup

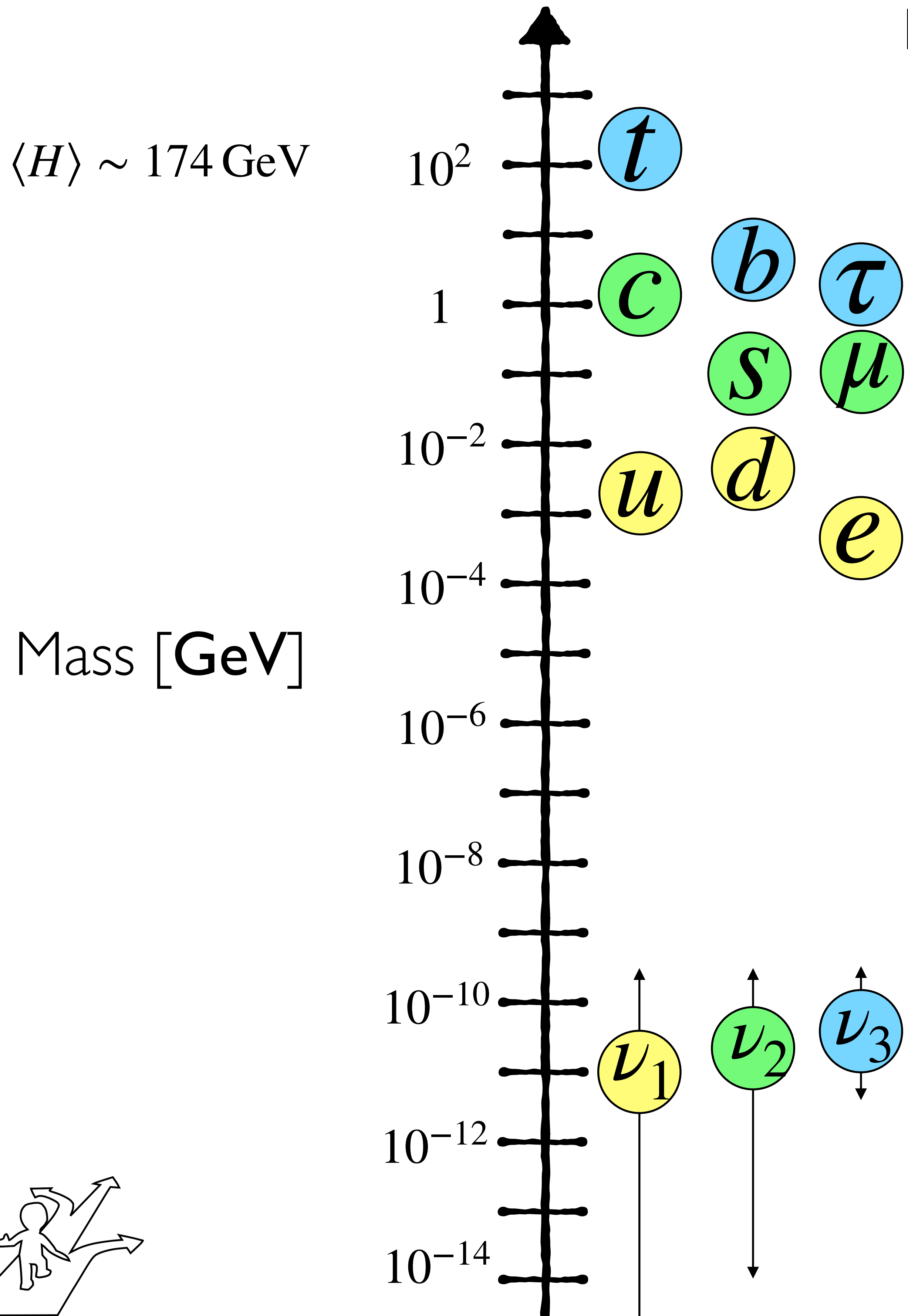
SMEFT: Systematic BSM



1308.2627,
1310.4838,
1312.2014,
1709.04486,
1711.05270,
1711.10391,
1710.06445,
1804.05033,
1908.05295,
2010.16341,
2012.08506,
2012.07851,
...

Flavour Puzzle

Empirical



?

The Weak Force Mixing:

$V_{\mathrm{CKM}} \sim$

$$-\mathcal{L}_{\mathrm{SM}} \supset \bar{q}_i Y_u^{ij} u_j \tilde{H} + \bar{q}_i Y_d^{ij} d_j H + \bar{\ell}_i Y_e^{ij} e_j H$$

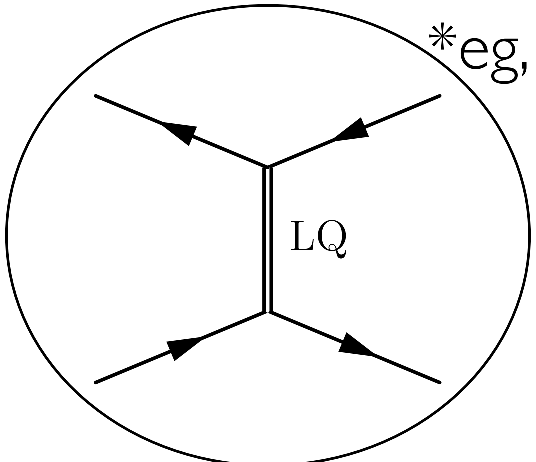
$$\Im \det[Y_d Y_d^\dagger, Y_u Y_u^\dagger] \approx \mathcal{O}(10^{-22})$$

*sample uniformly in [0,1] interval $\approx \mathcal{O}(1)$

$$-\mathcal{L}_{\mathrm{SMEFT}} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H$$

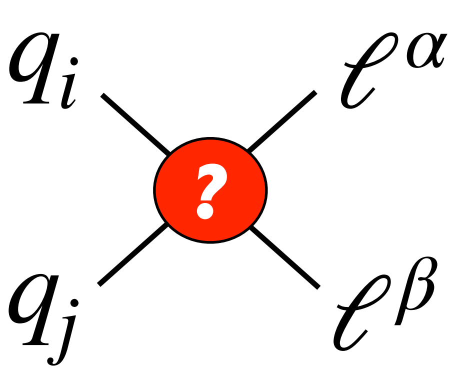
$V_{\mathrm{PMNS}} \sim$

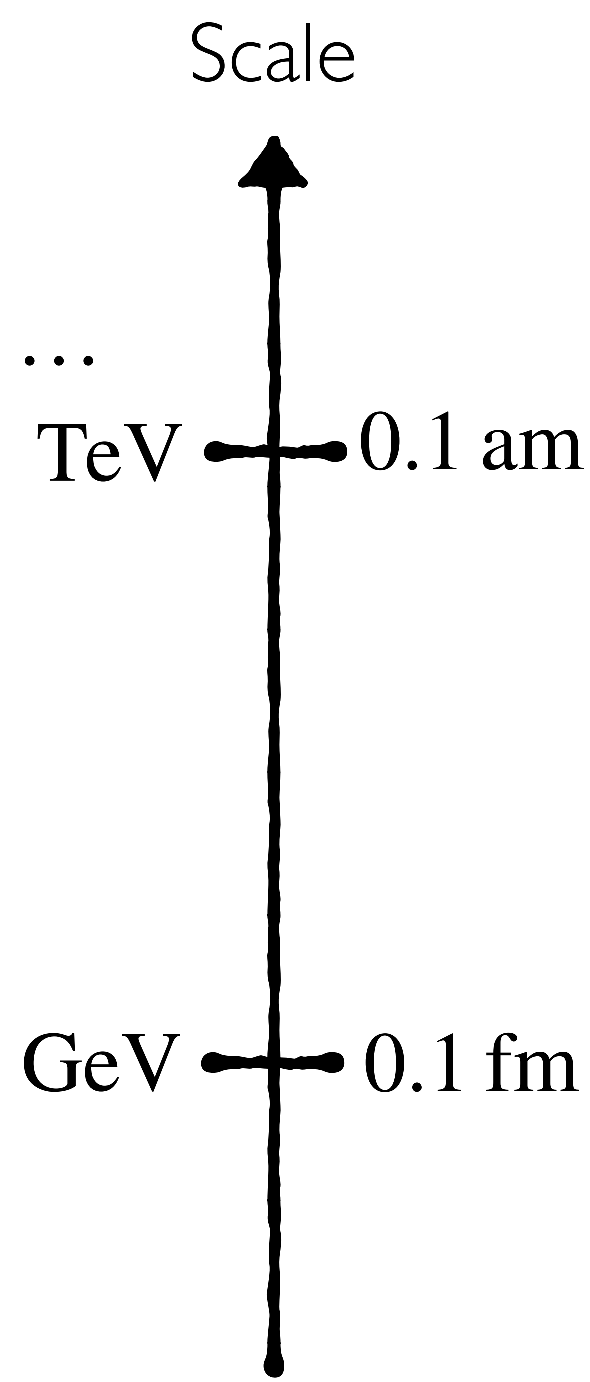
Drell-Yan versus Weak Decays



*eg, a heavy LQ

$$pp \to \ell_\alpha^+ \ell_\beta^- (j), \ \ldots$$





Example: $b \to s\mu\mu$ vs Drell-Yan

AG, Marzocca; 1704.09015

Implementation and systematic study in `flavio`

AG, Salko, Smolkovic, Stangl; 2212.10497

A Warsaw basis

Here we list the $\Delta B = 0$ dimension-6 fermionic SMEFT operators in the Warsaw basis [13] with division into classes as presented in [14].

5–7: Fermion Bilinears

non-hermitian ($\bar{L}R$)							
5: $\psi^2 H^3$		6: $\psi^2 XH$					
Q_{eH}	$(H^\dagger H)(\bar{\ell}_p e_r H)$	Q_{eW}	$(\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{H} G^A_{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \tilde{H})$	Q_{eB}	$(\bar{\ell}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{H} W^I_{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H W^I_{\mu\nu}$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$			Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{H} B_{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$

hermitian (+ Q_{Hud}) $\sim$ 7: $\psi^2 H^2 D$					
$(\bar{L}L)$		$(\bar{R}R)$		$(\bar{R}R')$	
$Q^{(1)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}_p \gamma^\mu \ell_r)$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	Q_{Hud}	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$
$Q^{(3)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$		
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$		
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$				

8: Fermion Quadrilinears

hermitian					
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$Q_{\ell e}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{e}_s \gamma^\mu e_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$Q_{\ell u}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{u}_s \gamma^\mu u_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{\ell d}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{d}_s \gamma^\mu d_t)$
$Q^{(1)}_{\ell q}$	$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q^{(3)}_{\ell q}$	$(\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q^{(1)}_{ud}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

non-hermitian			
$(\bar{L}R)(\bar{R}L)$		$(\bar{L}R)(\bar{L}R)$	
$Q_{\ell edq}$	$(\bar{\ell}^j_p e_r)(\bar{d}_s q_{tj})$	$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
		$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\epsilon_{jk}(\bar{q}^k_s T^A d_t)$
		$Q^{(1)}_{\ell equ}$	$(\bar{\ell}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$
		$Q^{(3)}_{\ell equ}$	$(\bar{\ell}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$

Phenomenology of leading directions

- Automatic protection against FCNC
- The case for Top/Higgs/EW fits
- Example:

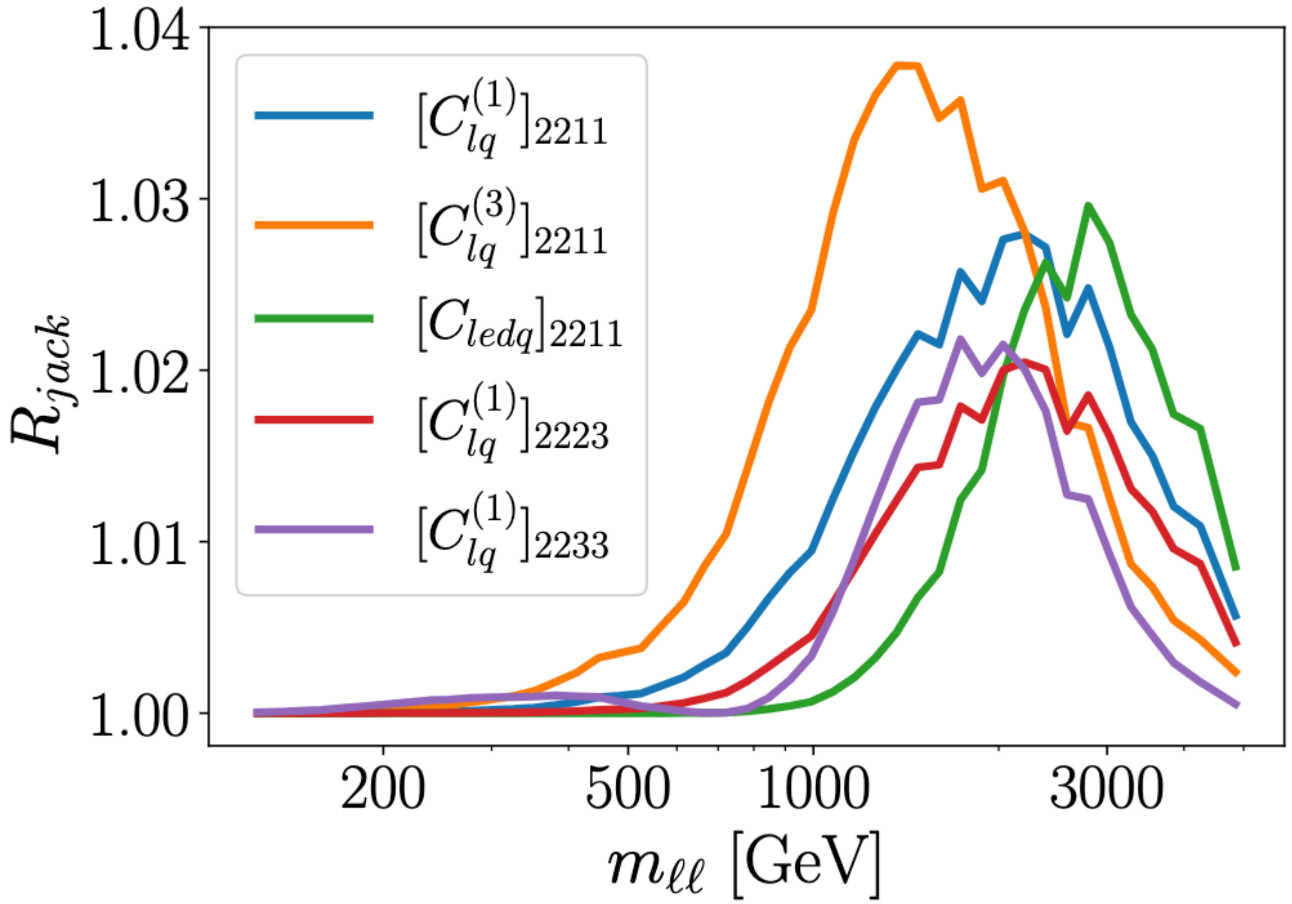
AG, Palavric; 2305.08898

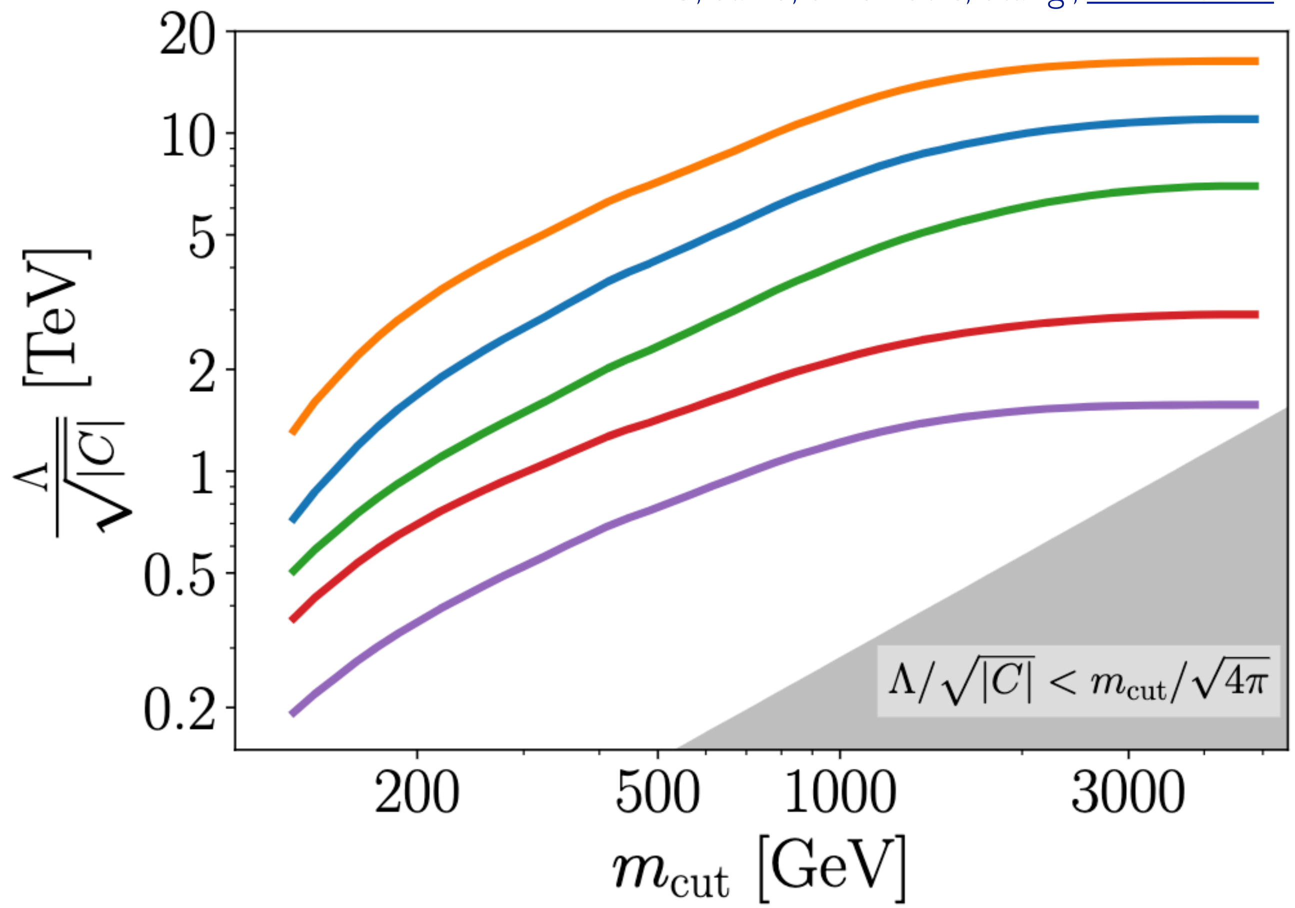
Scalars				Vectors			
Field	Irrep	$M^{\rm LE}$ [TeV]	$M^{\rm DY}$ [TeV]	Field	Irrep	$M^{\rm LE}$ [TeV]	$M^{\rm DY}$ [TeV]
$\omega_1 \sim (\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3}_q, \mathbf{3}_\ell)$	10.0	8.8	$\mathcal{U}_2 \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}_d, \bar{\mathbf{3}}_e)$	3.7	5.6
$\omega_1 \sim (\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3}_u, \mathbf{3}_e)$	4.7	7.5	$\mathcal{U}_2 \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3}_q, \bar{\mathbf{3}}_\ell)$	14.4	8.3
$\omega_4 \sim (\mathbf{3},\mathbf{1})_{-\frac{4}{3}}$	$(\mathbf{3}_d, \mathbf{3}_e)$	3.6	5.1	$\mathcal{U}_5 \sim (\mathbf{3},\mathbf{1})_{\frac{5}{3}}$	$(\mathbf{3}_u, \bar{\mathbf{3}}_e)$	3.5	12.4
$\Pi_1 \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}_d, \bar{\mathbf{3}}_\ell)$	3.7	2.8	$\mathcal{Q}_1 \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}_u, \mathbf{3}_\ell)$	4.0	7.5
$\Pi_7 \sim (\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3}_u, \bar{\mathbf{3}}_\ell)$	3.5	6.2	$\mathcal{Q}_5 \sim (\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3}_d, \mathbf{3}_\ell)$	3.4	5.1
$\Pi_7 \sim (\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3}_q, \bar{\mathbf{3}}_e)$	3.4	5.7	$\mathcal{Q}_5 \sim (\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3}_q, \mathbf{3}_e)$	7.7	6.6
$\zeta \sim (\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$	$(\mathbf{3}_q, \mathbf{3}_\ell)$	4.3	5.3	$\mathcal{X} \sim (\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$(\mathbf{3}_q, \bar{\mathbf{3}}_\ell)$	3.1	8.7

Table 7: **2-quark-2-lepton phenomenology (Class II)**: The first two columns indicate gauge and flavor representations of the new scalars (left panel) and vectors (right panel). The third and fourth columns contain the lower bounds at 95% CL on the mediator masses (couplings set to unity) obtained by the low-energy experiments ($M^{\rm LE}$) and the Drell-Yan production at the LHC ($M^{\rm DY}$), respectively. For the induced SMEFT operators, consult the Tables 1 and 3 and Appendices C.1 and C.3 for more details.

NP in the Drell-Yan Tails

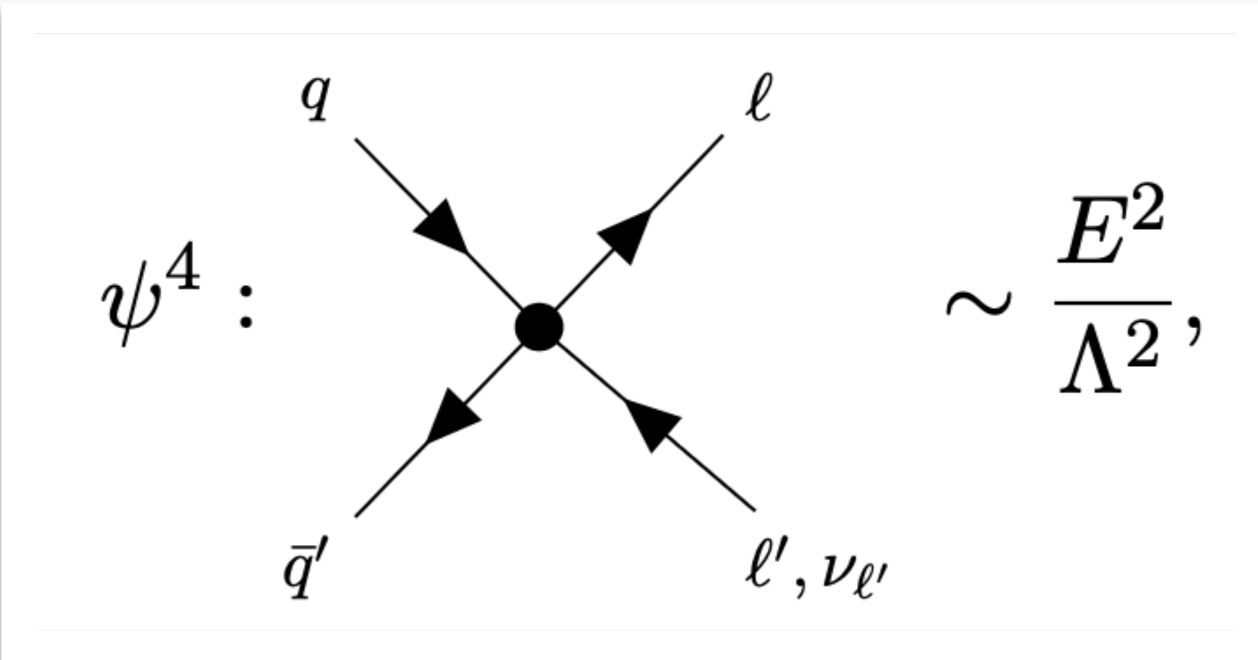
AG, Salko, Smolkovic, Stangl; 2212.10497

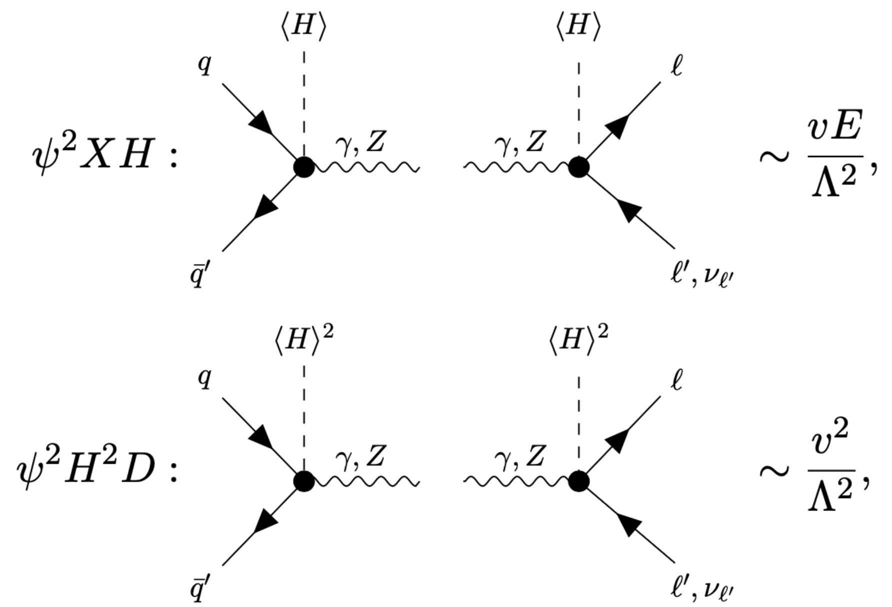




Search	Ref.	Channel	Luminosity
ATLAS	[45]	$pp \to ee$	139 fb^{-1}
		$pp \to \mu\mu$	139 fb^{-1}
CMS	[46]	$pp \to ee$	137 fb^{-1}
		$pp \to \mu\mu$	140 fb^{-1}
ATLAS	[47]	$pp \to e\nu$	139 fb^{-1}
		$pp \to \mu\nu$	139 fb^{-1}
CMS	[48]	$pp \to e\nu$	138 fb^{-1}
		$pp \to \mu\nu$	138 fb^{-1}

Drell-Yan in the SMEFT





AG, Palavric; wip

DY dim-6 ψ^4 $\mathcal{O}(1)$ terms		Lepton sector					
		MFV$_L$	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV$_Q$	7	14	14	21	21	63
	$U(2)_q \times U(2)_u \times U(3)_d$	10	20	20	30	30	90
	$U(2)^3 \times U(1)_{b_R}$	12	24	24	36	36	108
	$U(2)^3$	12	24	26	36	42	126
	No symmetry	53	106	148	159	285	855

Table 3: Flavor counting of the dimension-6 operators of the type ψ^4 which contribute to Drell-Yan scattering.

SMEFT fit: 1D

4F SMEFT operators with arbitrary flavor

$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$
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_{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_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Drell-Yan data used

Search	Ref.	Channel	Luminosity
ATLAS	[45]	$pp \to ee$	139 fb^{-1}
		$pp \to \mu\mu$	139 fb^{-1}
CMS	[46]	$pp \to ee$	137 fb^{-1}
		$pp \to \mu\mu$	140 fb^{-1}
ATLAS	[47]	$pp \to e\nu$	139 fb^{-1}
		$pp \to \mu\nu$	139 fb^{-1}
CMS	[48]	$pp \to e\nu$	138 fb^{-1}
		$pp \to \mu\nu$	138 fb^{-1}

Table 4: The 2σ bounds on different flavor structures of single Wilson coefficients at $\Lambda = 1$ TeV. See Sec. 5.1 for details.

		Drell-Yan tails		B decays	
Operator	Flavor	NC	CC	$b \to q\ell\ell$	$b \to q\nu\nu$
$\mathcal{O}_{lq}^{(1)}$	1113	[-0.068, 0.068]	-	[-0.005, 0.002]	[-0.035, 0.039]
	2213	[-0.031, 0.032]	-	[-4.96, 0.78]$\times 10^{-4}$	[-0.035, 0.039]
	1123	[-0.145, 0.152]	-	[-4.26, 0.98]$\times 10^{-4}$	[-0.038, 0.017]
	2223	[-0.066, 0.071]	-	[7.71, 51.86]$\times 10^{-5}$	[-0.038, 0.017]
$\mathcal{O}_{lq}^{(3)}$	1113	[-0.068, 0.068]	[-0.017, 0.017]	[-0.005, 0.002]	[-0.037, 0.033]
	2213	[-0.032, 0.031]	[-0.029, 0.029]	[-4.85, 0.7]$\times 10^{-4}$	[-0.037, 0.033]
	1123	[-0.152, 0.145]	[-0.054, 0.051]	[-4.26, 0.98]$\times 10^{-4}$	[-0.015, 0.035]
	2223	[-0.071, 0.066]	[-0.089, 0.089]	[7.71, 51.86]$\times 10^{-5}$	[-0.015, 0.035]
$\mathcal{O}_{ld}$	1113	[-0.068, 0.068]	-	[-0.005, 0.002]	[-0.038, 0.038]
	2213	[-0.032, 0.032]	-	[-2.79, 2.43]$\times 10^{-4}$	[-0.038, 0.038]
	1123	[-0.149, 0.149]	-	[-4.04, 1.09]$\times 10^{-4}$	[-0.007, 0.023]
	2223	[-0.069, 0.069]	-	[-1.68, 2.14]$\times 10^{-4}$	[-0.007, 0.023]
$\mathcal{O}_{qe}$	1311	[-0.068, 0.068]	-	[-0.003, 0.004]	-
	1322	[-0.032, 0.032]	-	[-3.35, 7.56]$\times 10^{-4}$	-
	2311	[-0.148, 0.149]	-	[-0.003, 0.001]	-
	2322	[-0.068, 0.069]	-	[-2.39, 4.97]$\times 10^{-4}$	-
$\mathcal{O}_{ed}$	1113	[-0.068, 0.068]	-	[-0.003, 0.004]	-
	2213	[-0.032, 0.032]	-	[-7.03, 3.76]$\times 10^{-4}$	-
	1123	[-0.149, 0.149]	-	[-0.002, 0.002]	-
	2223	[-0.069, 0.069]	-	[-4.05, 4.37]$\times 10^{-4}$	-
$\mathcal{O}_{ledq}$	1113	[-0.079, 0.079]	-	[-1.19, 1.18]$\times 10^{-4}$	-
	1131	[-0.079, 0.079]	[-0.037, 0.037]	[-1.18, 1.18]$\times 10^{-4}$	-
	2213	[-0.037, 0.037]	-	[-3.48, 0.67]$\times 10^{-5}$	-
	2231	[-0.037, 0.037]	[-0.061, 0.061]	[-3.49, 0.68]$\times 10^{-5}$	-
	1123	[-0.173, 0.173]	-	[-1.78, 1.79]$\times 10^{-4}$	-
	1132	[-0.173, 0.173]	[-0.113, 0.113]	[-1.77, 1.78]$\times 10^{-4}$	-
	2223	[-0.08, 0.08]	-	[-6.82, 16.57]$\times 10^{-6}$	-
	2232	[-0.08, 0.08]	[-0.194, 0.194]	[-6.8, 16.48]$\times 10^{-6}$	-

AG, Salko, Smolkovic, Stangl; 2212.10497

Example

Example:

$$\mathcal{L}_{NP}^{\Delta C=1} \approx \frac{\epsilon_V^{\ell\ell}}{(15\,\text{TeV})^2}(\bar{u}_R\gamma^\mu c_R)(\bar{\ell}_R\gamma^\mu\ell_R)$$

Rare $c \to u\ell^+\ell^-$ decays

Theory:

$BR(D^0 \to \mu^+\mu^-)_{SM} \sim \mathcal{O}(10^{-13})$

- Efficient GIM suppression
- Long-distance dominated

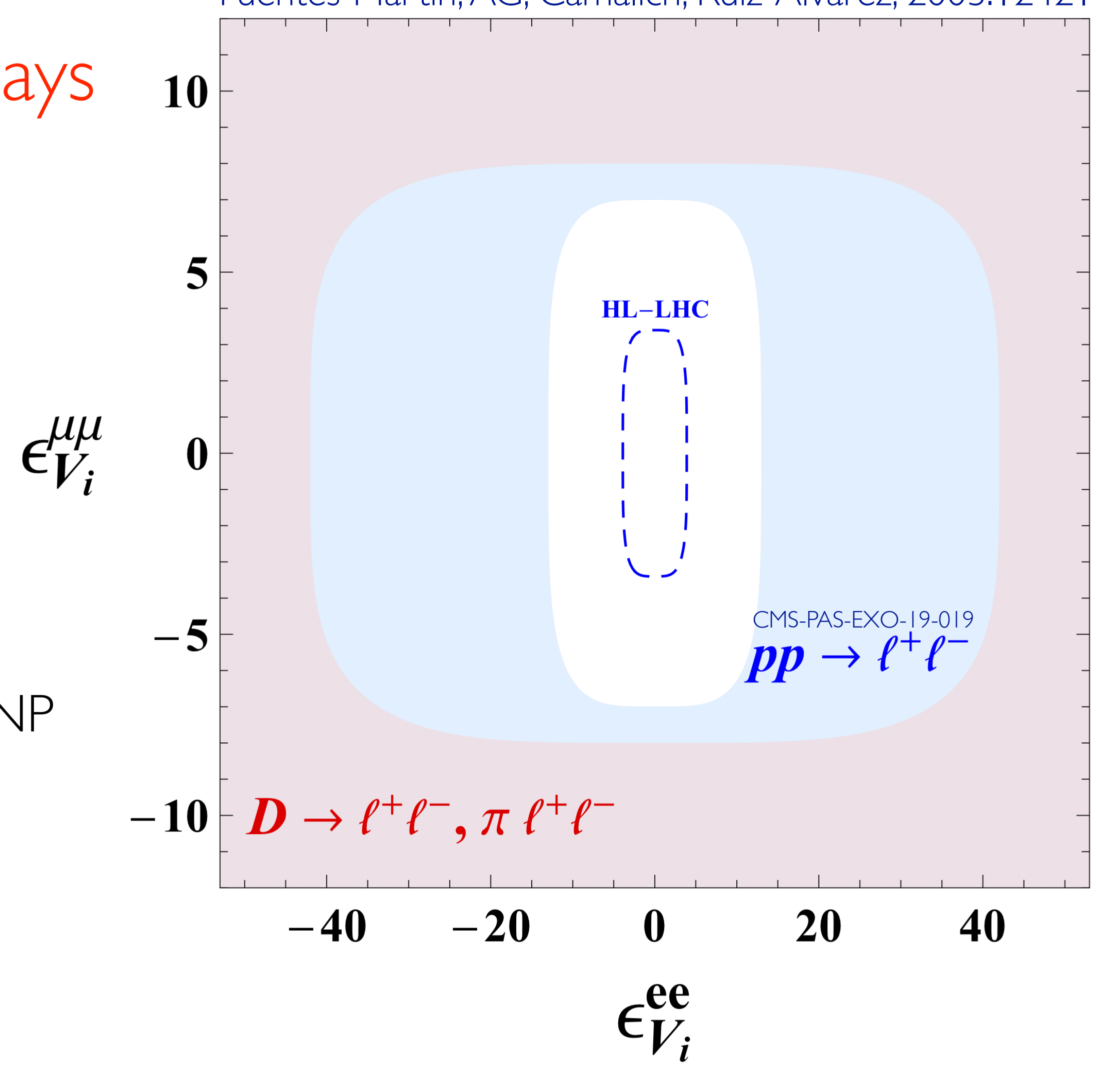
Experiment:

$BR(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-9}$

LHCb, 1305.5059

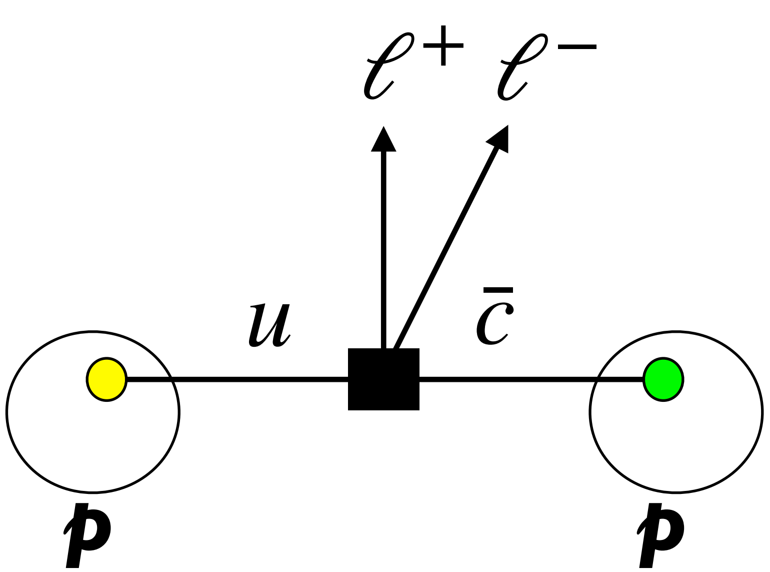
Null test of the SM sensitive to NP

Fuentes-Martin, AG, Camalich, Ruiz-Alvarez; 2003.12421



Drell-Yan $cu \to \ell^+\ell^-$

- Energy enhancement
- PDF suppression



Systematic exploration of the low-p_T / high-p_T interplay

1609.07138, 1704.09015, 1811.07920, 1805.11402, 1912.00425, 2002.05684, 2008.07541, 2104.02723, 2111.04748, …

Field	Irrep	Normalization	Operator
$\mathcal{S}_1 \sim (\mathbf{1},\mathbf{1})_1$	$\mathbf{3}_\ell$	$\lvert y_{\mathcal{S}_1}\rvert^2/M^2_{\mathcal{S}_1}$	$\mathcal{O}^D_{\ell\ell} - \mathcal{O}^E_{\ell\ell}$
$\mathcal{S}_2 \sim (\mathbf{1},\mathbf{1})_2$	$\bar{\mathbf{6}}_e$	$\lvert y_{\mathcal{S}_2}\rvert^2/(2M^2_{\mathcal{S}_2})$	$\mathcal{O}_{ee}$
$\varphi \sim (\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$(\bar{\mathbf{3}}_e, \mathbf{3}_\ell)$	$-\lvert y^e_\varphi\rvert^2/(2M^2_\varphi)$	$\mathcal{O}_{\ell e}$
	$(\bar{\mathbf{3}}_d, \mathbf{3}_q)$	$-\lvert y^d_\varphi\rvert^2/(6M^2_\varphi)$	$\mathcal{O}^{(1)}_{qd} + 6\mathcal{O}^{(8)}_{qd}$
	$(\bar{\mathbf{3}}_q, \mathbf{3}_u)$	$-\lvert y^u_\varphi\rvert^2/(6M^2_\varphi)$	$\mathcal{O}^{(1)}_{qu} + 6\mathcal{O}^{(8)}_{qu}$
$\Xi_1 \sim (\mathbf{1},\mathbf{3})_1$	$\bar{\mathbf{6}}_\ell$	$\lvert y_{\Xi_1}\rvert^2/(2M^2_{\Xi_1})$	$\mathcal{O}^D_{\ell\ell} + \mathcal{O}^E_{\ell\ell}$
$\omega_1 \sim (\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3}_q, \mathbf{3}_\ell)$	$\lvert y^{q\ell}_{\omega_1}\rvert^2/(4M^2_{\omega_1})$	$\mathcal{O}^{(1)}_{\ell q} - \mathcal{O}^{(3)}_{\ell q}$
	$(\mathbf{3}_e, \mathbf{3}_u)$	$\lvert y^{eu}_{\omega_1}\rvert^2/(2M^2_{\omega_1})$	$\mathcal{O}_{eu}$
	$\bar{\mathbf{6}}_q$	$\lvert y^{qq}_{\omega_1}\rvert^2/(4M^2_{\omega_1})$	$\mathcal{O}^{(1)D}_{qq} - \mathcal{O}^{(3)D}_{qq} + \mathcal{O}^{(1)E}_{qq} - \mathcal{O}^{(3)E}_{qq}$
	$(\bar{\mathbf{3}}_d, \bar{\mathbf{3}}_u)$	$\lvert y^{du}_{\omega_1}\rvert^2/(3M^2_{\omega_1})$	$\mathcal{O}^{(1)}_{ud} - 3\mathcal{O}^{(8)}_{ud}$
$\omega_2 \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$\mathbf{3}_d$	$\lvert y_{\omega_2}\rvert^2/M^2_{\omega_2}$	$\mathcal{O}^D_{dd} - \mathcal{O}^E_{dd}$
$\omega_4 \sim (\mathbf{3},\mathbf{1})_{-\frac{4}{3}}$	$(\mathbf{3}_e, \mathbf{3}_d)$	$\lvert y^{ed}_{\omega_4}\rvert^2/(2M^2_{\omega_4})$	$\mathcal{O}_{ed}$
	$\mathbf{3}_u$	$\lvert y^{uu}_{\omega_4}\rvert^2/M^2_{\omega_4}$	$\mathcal{O}^D_{uu} - \mathcal{O}^E_{uu}$
$\Pi_1 \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\bar{\mathbf{3}}_\ell, \mathbf{3}_d)$	$-\lvert y_{\Pi_1}\rvert^2/(2M^2_{\Pi_1})$	$\mathcal{O}_{\ell d}$
$\Pi_7 \sim (\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$(\bar{\mathbf{3}}_\ell, \mathbf{3}_u)$	$-\lvert y^{\ell u}_{\Pi_7}\rvert^2/(2M^2_{\Pi_7})$	$\mathcal{O}_{\ell u}$
	$(\bar{\mathbf{3}}_e, \mathbf{3}_q)$	$-\lvert y^{qe}_{\Pi_7}\rvert^2/(2M^2_{\Pi_7})$	$\mathcal{O}_{qe}$
$\zeta \sim (\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$	$(\mathbf{3}_q, \mathbf{3}_\ell)$	$\lvert y^{q\ell}_\zeta\rvert^2/(4M^2_\zeta)$	$3\mathcal{O}^{(1)}_{\ell q} + \mathcal{O}^{(3)}_{\ell q}$
	$\mathbf{3}_q$	$\lvert y^{qq}_\zeta\rvert^2/(2M^2_\zeta)$	$3\mathcal{O}^{(1)D}_{qq} + \mathcal{O}^{(3)D}_{qq} - 3\mathcal{O}^{(1)E}_{qq} - \mathcal{O}^{(3)E}_{qq}$
$\Omega_1 \sim (\mathbf{6},\mathbf{1})_{\frac{1}{3}}$	$(\mathbf{3}_u, \mathbf{3}_d)$	$\lvert y^{ud}_{\Omega_1}\rvert^2/(6M^2_{\Omega_1})$	$2\mathcal{O}^{(1)}_{ud} + 3\mathcal{O}^{(8)}_{ud}$
	$\bar{\mathbf{3}}_q$	$\lvert y^{qq}_{\Omega_1}\rvert^2/(4M^2_{\Omega_1})$	$\mathcal{O}^{(1)D}_{qq} - \mathcal{O}^{(3)D}_{qq} - \mathcal{O}^{(1)E}_{qq} + \mathcal{O}^{(3)E}_{qq}$
$\Omega_2 \sim (\mathbf{6},\mathbf{1})_{-\frac{2}{3}}$	$\mathbf{6}_d$	$\lvert y_{\Omega_2}\rvert^2/(4M^2_{\Omega_2})$	$\mathcal{O}^D_{dd} + \mathcal{O}^E_{dd}$
$\Omega_4 \sim (\mathbf{6},\mathbf{1})_{\frac{4}{3}}$	$\mathbf{6}_u$	$\lvert y_{\Omega_4}\rvert^2/(4M^2_{\Omega_4})$	$\mathcal{O}^D_{uu} + \mathcal{O}^E_{uu}$
$\Upsilon \sim (\mathbf{6},\mathbf{3})_{\frac{1}{3}}$	$\mathbf{6}_q$	$\lvert y_\Upsilon\rvert^2/(8M^2_\Upsilon)$	$3\mathcal{O}^{(1)D}_{qq} + \mathcal{O}^{(3)D}_{qq} + 3\mathcal{O}^{(1)E}_{qq} + \mathcal{O}^{(3)E}_{qq}$
$\Phi \sim (\mathbf{8},\mathbf{2})_{\frac{1}{2}}$	$(\bar{\mathbf{3}}_q, \mathbf{3}_u)$	$-\lvert y^{qu}_\Phi\rvert^2/(18M^2_\Phi)$	$4\mathcal{O}^{(1)}_{qu} - 3\mathcal{O}^{(8)}_{qu}$
	$(\bar{\mathbf{3}}_d, \mathbf{3}_q)$	$-\lvert y^{dq}_\Phi\rvert^2/(18M^2_\Phi)$	$4\mathcal{O}^{(1)}_{qd} - 3\mathcal{O}^{(8)}_{qd}$

Table 1: **New scalars** (nontrivial flavor irreps): The first column presents the names

Field	Irrep	Normalization	Operator
$\mathcal{B} \sim (\mathbf{1},\mathbf{1})_0$	$\mathbf{8}_\ell$	$-(g^\ell_\mathcal{B})^2/(12M^2_\mathcal{B})$	$3\mathcal{O}^E_{\ell\ell} - \mathcal{O}^D_{\ell\ell}$
	$\mathbf{8}_e$	$-(g^e_\mathcal{B})^2/(6M^2_\mathcal{B})$	$\mathcal{O}_{ee}$
	$\mathbf{8}_q$	$-(g^q_\mathcal{B})^2/(12M^2_\mathcal{B})$	$3\mathcal{O}^{(1)E}_{qq} - \mathcal{O}^{(1)D}_{qq}$
	$\mathbf{8}_u$	$-(g^u_\mathcal{B})^2/(12M^2_\mathcal{B})$	$3\mathcal{O}^E_{uu} - \mathcal{O}^D_{uu}$
	$\mathbf{8}_d$	$-(g^d_\mathcal{B})^2/(12M^2_\mathcal{B})$	$3\mathcal{O}^E_{dd} - \mathcal{O}^D_{dd}$
$\mathcal{B}_1 \sim (\mathbf{1},\mathbf{1})_1$	$(\bar{\mathbf{3}}_d, \mathbf{3}_u)$	$-\lvert g^{du}_{\mathcal{B}_1}\rvert^2/(3M^2_{\mathcal{B}_1})$	$\mathcal{O}^{(1)}_{ud} + 6\mathcal{O}^{(8)}_{ud}$
$\mathcal{W} \sim (\mathbf{1},\mathbf{3})_0$	$\mathbf{8}_q$	$-(g^q_\mathcal{W})^2/(48M^2_\mathcal{W})$	$3\mathcal{O}^{(3)E}_{qq} - \mathcal{O}^{(3)D}_{qq}$
	$\mathbf{8}_\ell$	$(g^\ell_\mathcal{W})^2/(48M^2_\mathcal{W})$	$5\mathcal{O}^E_{\ell\ell} - 7\mathcal{O}^D_{\ell\ell}$
$\mathcal{L}_3 \sim (\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	$(\mathbf{3}_e, \mathbf{3}_\ell)$	$\lvert g_{\mathcal{L}_3}\rvert^2/M^2_{\mathcal{L}_3}$	$\mathcal{O}_{\ell e}$
$\mathcal{U}_2 \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\bar{\mathbf{3}}_e, \mathbf{3}_d)$	$-\lvert g^{ed}_{\mathcal{U}_2}\rvert^2/M^2_{\mathcal{U}_2}$	$\mathcal{O}_{ed}$
	$(\bar{\mathbf{3}}_\ell, \mathbf{3}_q)$	$-\lvert g^{\ell q}_{\mathcal{U}_2}\rvert^2/(2M^2_{\mathcal{U}_2})$	$\mathcal{O}^{(1)}_{\ell q} + \mathcal{O}^{(3)}_{\ell q}$
$\mathcal{U}_5 \sim (\mathbf{3},\mathbf{1})_{\frac{5}{3}}$	$(\bar{\mathbf{3}}_e, \mathbf{3}_u)$	$-\lvert g_{\mathcal{U}_5}\rvert^2/M^2_{\mathcal{U}_5}$	$\mathcal{O}_{eu}$
$\mathcal{Q}_1 \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3}_u, \mathbf{3}_\ell)$	$\lvert g^{u\ell}_{\mathcal{Q}_1}\rvert^2/M^2_{\mathcal{Q}_1}$	$\mathcal{O}_{\ell u}$
	$(\bar{\mathbf{3}}_d, \bar{\mathbf{3}}_q)$	$2\lvert g^{dq}_{\mathcal{Q}_1}\rvert^2/(3M^2_{\mathcal{Q}_1})$	$\mathcal{O}^{(1)}_{qd} - 3\mathcal{O}^{(8)}_{qd}$
$\mathcal{Q}_5 \sim (\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3}_d, \mathbf{3}_\ell)$	$\lvert g^{d\ell}_{\mathcal{Q}_5}\rvert^2/M^2_{\mathcal{Q}_5}$	$\mathcal{O}_{\ell d}$
	$(\mathbf{3}_e, \mathbf{3}_q)$	$\lvert g^{eq}_{\mathcal{Q}_5}\rvert^2/M^2_{\mathcal{Q}_5}$	$\mathcal{O}_{qe}$
	$(\bar{\mathbf{3}}_u, \bar{\mathbf{3}}_q)$	$2\lvert g^{uq}_{\mathcal{Q}_5}\rvert^2/(3M^2_{\mathcal{Q}_5})$	$\mathcal{O}^{(1)}_{qu} - 3\mathcal{O}^{(8)}_{qu}$
$\mathcal{X} \sim (\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$(\bar{\mathbf{3}}_\ell, \mathbf{3}_q)$	$-\lvert g_\mathcal{X}\rvert^2/(8M^2_\mathcal{X})$	$3\mathcal{O}^{(1)}_{\ell q} - \mathcal{O}^{(3)}_{\ell q}$
$\mathcal{Y}_1 \sim (\bar{\mathbf{6}},\mathbf{2})_{\frac{1}{6}}$	$(\bar{\mathbf{3}}_d, \bar{\mathbf{3}}_q)$	$\lvert g_{\mathcal{Y}_1}\rvert^2/(3M^2_{\mathcal{Y}_1})$	$2\mathcal{O}^{(1)}_{qd} + 3\mathcal{O}^{(8)}_{qd}$
$\mathcal{Y}_5 \sim (\bar{\mathbf{6}},\mathbf{2})_{-\frac{5}{6}}$	$(\bar{\mathbf{3}}_u, \bar{\mathbf{3}}_q)$	$\lvert g_{\mathcal{Y}_5}\rvert^2/(3M^2_{\mathcal{Y}_5})$	$2\mathcal{O}^{(1)}_{qu} + 3\mathcal{O}^{(8)}_{qu}$
$\mathcal{G} \sim (\mathbf{8},\mathbf{1})_0$	$\mathbf{8}_q$	$-(g^q_\mathcal{G})^2/(144M^2_\mathcal{G})$	$11\mathcal{O}^{(1)D}_{qq} - 9\mathcal{O}^{(1)E}_{qq} + 9\mathcal{O}^{(3)D}_{qq} - 3\mathcal{O}^{(3)E}_{qq}$
	$\mathbf{8}_u$	$(g^u_\mathcal{G})^2/(36M^2_\mathcal{G})$	$3\mathcal{O}^E_{uu} - 5\mathcal{O}^D_{uu}$
	$\mathbf{8}_d$	$(g^d_\mathcal{G})^2/(36M^2_\mathcal{G})$	$3\mathcal{O}^E_{dd} - 5\mathcal{O}^D_{dd}$
$\mathcal{G}_1 \sim (\mathbf{8},\mathbf{1})_1$	$(\bar{\mathbf{3}}_d, \mathbf{3}_u)$	$\lvert g_{\mathcal{G}_1}\rvert^2/(9M^2_{\mathcal{G}_1})$	$-4\mathcal{O}^{(1)}_{ud} + 3\mathcal{O}^{(8)}_{ud}$
$\mathcal{H} \sim (\mathbf{8},\mathbf{3})_0$	$\mathbf{8}_q$	$-(g_\mathcal{H})^2/(576M^2_\mathcal{H})$	$27\mathcal{O}^{(1)D}_{qq} - 9\mathcal{O}^{(1)E}_{qq} - 7\mathcal{O}^{(3)D}_{qq} - 3\mathcal{O}^{(3)E}_{qq}$

Table 3: **New vectors** (nontrivial flavor irreps): The first column presents the names

Field	Irrep	Normalization	Operator
$\varphi \sim (\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$\mathbf{1}$	$\lvert\lambda_\varphi\rvert^2/M_\varphi^2$	$\mathcal{O}_\phi$
$\Theta_1 \sim (\mathbf{1},\mathbf{4})_{\frac{1}{2}}$	$\mathbf{1}$	$\lvert\lambda_{\Theta_1}\rvert^2/(6M_{\Theta_1}^2)$	$\mathcal{O}_\phi$
$\Theta_3 \sim (\mathbf{1},\mathbf{4})_{\frac{3}{2}}$	$\mathbf{1}$	$\lvert\lambda_{\Theta_3}\rvert^2/(2M_{\Theta_3}^2)$	$\mathcal{O}_\phi$
$\mathcal{S} \sim (\mathbf{1},\mathbf{1})_0$	$\mathbf{1}$	$-\kappa_{\mathcal{S}}^2/(2M_{\mathcal{S}}^4)$	$\mathcal{O}_{\phi\Box} - \bar{\mathcal{C}}_{\mathcal{S}}\mathcal{O}_\phi$
$\Xi \sim (\mathbf{1},\mathbf{3})_0$	$\mathbf{1}$	$\kappa_\Xi^2/(2M_\Xi^4)$	$-4\mathcal{O}_{\phi D} + \mathcal{O}_{\phi\Box} + \bar{\mathcal{C}}_\Xi\mathcal{O}_\phi + 2\left[\sum_f y_f^* \mathcal{O}_{f\phi} + \text{h.c.}\right]$
$\Xi_1 \sim (\mathbf{1},\mathbf{3})_1$	$\mathbf{1}$	$\lvert\kappa_{\Xi_1}\rvert^2/M_{\Xi_1}^4$	$4\mathcal{O}_{\phi D} + 2\mathcal{O}_{\phi\Box} + \bar{\mathcal{C}}_{\Xi_1}\mathcal{O}_\phi + 2\left[\sum_f y_f^* \mathcal{O}_{f\phi} + \text{h.c.}\right]$
$\mathcal{B}_1 \sim (\mathbf{1},\mathbf{1})_1$	$\mathbf{1}$	$-\lvert g_{\mathcal{B}_1}^\phi\rvert^2/(2M_{\mathcal{B}_1}^2)$	$4(\lambda_\phi + C_{\phi 4}^{\mathcal{B}_1})\mathcal{O}_\phi - 2\mathcal{O}_{\phi D} + \mathcal{O}_{\phi\Box} + \left[\sum_f y_f^* \mathcal{O}_{f\phi} + \text{h.c.}\right]$
$\mathcal{W}_1 \sim (\mathbf{1},\mathbf{3})_1$	$\mathbf{1}$	$-\lvert g_{\mathcal{W}_1}\rvert^2/(8M_{\mathcal{W}_1}^2)$	$4(\lambda_\phi + C_{\phi 4}^{\mathcal{W}_1})\mathcal{O}_\phi + 2\mathcal{O}_{\phi D} + \mathcal{O}_{\phi\Box} + \left[\sum_f y_f^* \mathcal{O}_{f\phi} + \text{h.c.}\right]$
$\mathcal{H} \sim (\mathbf{8},\mathbf{3})_0$	$\mathbf{1}$	$(g_{\mathcal{H}})^2/(96M_{\mathcal{H}}^2)$	$2\mathcal{O}_{qq}^{(3)D} + 3\mathcal{O}_{qq}^{(3)E} - 9\mathcal{O}_{qq}^{(1)E}$

Table 4: **Flavor singlets**: First six rows are scalars (spin-0) while the last three are vectors (spin-1). The table format is the same as for Tables 1, 2 and 3. The f index in the $\mathcal{O}(y_f)$ terms goes over all three right-handed fields, i.e., $f = \{e, u, d\}$. The flavor indices are suppressed to reduce clutter. Parameters $C_{\phi 4}^X$ are fixed in terms of the normalisation, while $\bar{\mathcal{C}}_X$ are independent. See Appendices C.1 and C.3 for details.

Field	Irrep	# of parameters	Operators
$\mathcal{B} \sim (\mathbf{1},\mathbf{1})_0$	$\mathbf{1}$	$5\mathbb{R} + 1\mathbb{C}$	$\mathcal{O}_{\ell\ell}^D$, $\mathcal{O}_{qq}^{(1)D}$, $\mathcal{O}_{\ell q}^{(1)}$, $\mathcal{O}_{ee}$, $\mathcal{O}_{dd}^D$, $\mathcal{O}_{uu}^D$, $\mathcal{O}_{ed}$, $\mathcal{O}_{eu}$, $\mathcal{O}_{ud}^{(1)}$ $\mathcal{O}_{\ell e}$, $\mathcal{O}_{\ell d}$, $\mathcal{O}_{\ell u}$, $\mathcal{O}_{qe}$, $\mathcal{O}_{qu}^{(1)}$, $\mathcal{O}_{qd}^{(1)}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi u}$ $\mathcal{O}_{\phi d}$, $\mathcal{O}_{\phi e}$, $\mathcal{O}_{\phi\ell}^{(1)}$, $\mathcal{O}_{\phi q}^{(1)}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$
$\mathcal{W} \sim (\mathbf{1},\mathbf{3})_0$	$\mathbf{1}$	$2\mathbb{R} + 1\mathbb{C}$	$\mathcal{O}_{\ell\ell}^D - 2\mathcal{O}_{\ell\ell}^E$, $\mathcal{O}_{qq}^{(3)D}$, $\mathcal{O}_{\ell q}^{(3)}$, $\mathcal{O}_\phi$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{\phi\ell}^{(3)}$, $\mathcal{O}_{\phi q}^{(3)}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$
$\mathcal{G} \sim (\mathbf{8},\mathbf{1})_0$	$\mathbf{1}$	$3\mathbb{R}$	$\mathcal{O}_{dd}^D - 3\mathcal{O}_{dd}^E$, $\mathcal{O}_{uu}^D - 3\mathcal{O}_{uu}^E$, $\mathcal{O}_{qq}^{(3)E}$, $\mathcal{O}_{qu}^{(8)}$, $\mathcal{O}_{qd}^{(8)}$, $2\mathcal{O}_{qq}^{(1)D} - 3\mathcal{O}_{qq}^{(1)E}$, $\mathcal{O}_{ud}^{(8)}$

Table 5: **Flavor singlets** (exceptions): Three vector (spin-1) fields match at tree-level to dimension-6 SMEFT operators shown in the last column. The corresponding WCs can be parameterised by a number of parameters indicated in the third column. See Appendix C.3 for details.

Significant simplification transpires, even for trivial flavor irreps, upon enforcing $U(3)^5$ symmetry on $\mathcal{L}_{\text{BSM}}$. Flavor singlets can only be either spin 0 or spin 1. In total, 12 such instances are shown in Tables 4 and 5. The former table presents nine straightforward cases, six expressible by a single parameter and three cases comprising a direction plus a free Wilson coefficient for the $\mathcal{O}_\phi$ operator. Remarkably, only three exceptional vector fields necessitate three or more parameters (at most seven) for describing the tree-level matching to dimension-6 SMEFT (Table 5).

In a UV theory featuring multiple new fields (flavor irreps), besides simply aggregating their WCs, nontrivial matching contributions may arise from diagrams involving several BSM fields. All such instances are charted in Appendix D. They involve either two or three new scalars and always match to a single dimension-6 operator at the tree level, $\mathcal{O}_\phi$.