A SMEFT Analysis of Third-generation New Physics

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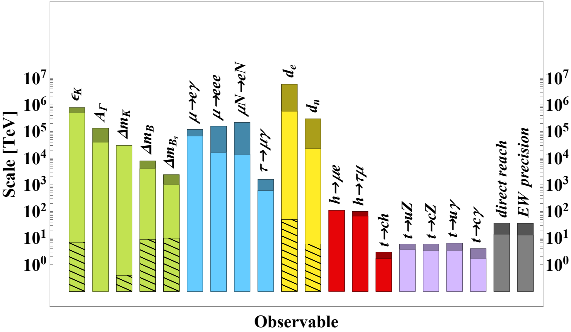
Based on 2311.00020 with C. Cornella, G. Isidori and B. Stefanek

What is the scale of new physics?

- Only lower bounds for now
- From collider searches: $\Lambda_{\rm NP} \gtrsim 10$ TeV
- $\Delta F = 2$ (K-$\bar{K}$): $\Lambda_{\rm NP} \gtrsim 10^{5-6}$ TeV



Flavour structure is key!

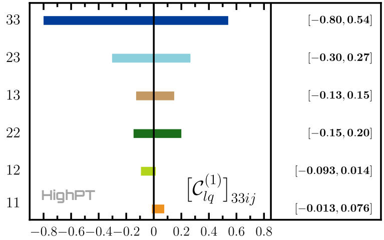
How does NP couple to the different generations/flavours?

Exploring the flavour structure

[*LA, Faroughy, Jaffredo, Sumensari, Wilsch* 2207.10714]

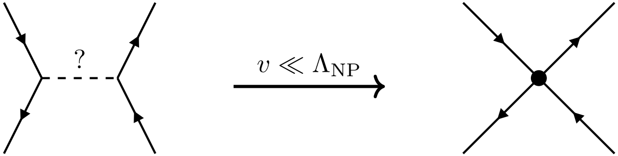
- Take e.g. Drell-Yan at LHC: $pp \to \ell_\alpha \ell_\beta$
- Lighter quark flavours are more constrained
- The same applies also to other observables (see flavour, electroweak)

$pp \to \tau\tau$



NP coupling mostly to the third generation is still compatible with $\Lambda_{\rm NP} \sim \mathcal{O}(1)$ TeV

EFTs parametrise our ignorance



- In the presence of a mass gap $v \ll \Lambda_{\rm NP}$, we can encode NP effects in coefficients of higher-dimensional operators

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2} \sum_i \mathcal{C}_i \mathcal{O}_i^{(6)} + \cdots$$

- Allows for model-independent analyses
- **But**: 2499 independent parameters at $d = 6$!

$\rightarrow$ flavour assumptions to reduce the parameter count

Flavour symmetries: the $U(2)$ paradigm

- Yukawa terms break $U(3)^5$ flavour symmetry of $\mathcal{L}_{\rm SM}^{\rm gauge}$:

$$U(3)^5 \xrightarrow{\mathcal{L}_{\rm Yukawa}} U(1)_B \times U(1)_L$$

- However, light family Yukawas very small: approximate $U(2)^5$ symmetry [*Barbieri, Isidori, Lodone, Straub* 1105.2296]

$$Y \simeq y_3 \left(\begin{array}{cc|c} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \hline 0 & 0 & 1 \end{array}\right) \qquad U(2)^5 = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

Minimal breaking:

$$Y = y_3 \left(\begin{array}{c|c} \Delta & V \\ \hline 0 & 1 \end{array}\right) \qquad |V_q| = \epsilon_q = \mathcal{O}(y_t V_{ts}) \quad |\Delta| \sim y_{c,s,\mu}$$

- **idea**: impose $U(2)^5$ on the SMEFT

$U(2)^5$ symmetry at work

- ψ^2 operators: e.g. $\mathcal{C}_{He}$

$$\mathcal{L}_{\text{SMEFT}} \supset [\mathcal{C}_{He}]_{ij}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_i \gamma^\mu e_j)$$

$$\xrightarrow{U(2)^5} \mathcal{C}_{He}^{[33]}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_3 \gamma^\mu e_3) + \mathcal{C}_{He}^{[ii]}(H^\dagger i \overleftrightarrow{D}_\mu H)\sum_{i=1}^{2}(\bar{e}_i \gamma^\mu e_i)$$

- $6 \to 2$ independent coefficients
- ψ^4 operators: e.g. $\mathcal{C}_{lequ}$

$$\mathcal{L}_{\text{SMEFT}} \supset [\mathcal{C}_{\ell equ}]_{ijkl}(\bar{\ell}_i e_j)(\bar{q}_k u_l) \xrightarrow{U(2)^5} \mathcal{C}_{\ell equ}^{[3333]}(\bar{\ell}_3 e_3)(\bar{q}_3 u_3)$$

- $81 \to 1$ independent coefficients!

Third generation New Physics and $U(2)$

- NP is not flavour universal
- Mainly coupled to the 3rd generation
- Coupling to light generations dynamically suppressed
  $\rightarrow$ avoid flavour and collider constraints
- Mimicks the SM Yukawa sector $\leftrightarrow$ SM flavour puzzle
- Approximate $U(2)$ symmetry
- Construct invariants from bilinears:

Exact $U(2)^5$

$$\bar{q}_L^3 \gamma_\mu q_L^3 + \epsilon \bar{q}_L^i \gamma_\mu q_L^i$$

good way of suppressing the light families

Minimally broken $U(2)^5$

$$\bar{q}_L^i V_q^i \gamma_\mu q^3 \qquad V_q \sim \mathcal{O}\begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix}$$

flavour violating couplings

Which scales are we currently probing?

SMEFT and $U(2)^5$

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i \mathcal{O}_i^{(6)} + \cdots$$

- 2499 independent parameters at $d = 6$
- Exact $U(2)^5$: 124 CPC + 23 CPV

[*Faroughy, Isidori, Wilsch, Yamamoto* 2005.05366]

	$U(2)^5$ [terms summed up to different orders]													
Operators	Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1V^1)$		$\mathcal{O}(V^3,\Delta^1V^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6
ψ^2H^3	3	3	6	6	6	6	9	9	9	9	12	12	12	12
ψ^2XH	8	8	16	16	16	16	24	24	24	24	32	32	32	32
ψ^2H^2D	15	1	19	5	23	5	19	5	23	5	28	10	28	10
$(\bar{L}L)(\bar{L}L)$	23	–	40	17	67	24	40	17	67	24	67	24	74	31
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–	53	24	53	24
$(\bar{L}L)(\bar{R}R)$	32	–	48	16	64	16	53	21	69	21	90	42	90	42
$(\bar{L}R)(\bar{R}L)$	1	1	3	3	4	4	5	5	6	6	10	10	10	10
$(\bar{L}R)(\bar{L}R)$	4	4	12	12	16	16	24	24	28	28	48	48	48	48
total:	124	23	182	81	234	93	212	111	264	123	349	208	356	215

Table 6: Number of independent operators in the SMEFT assuming a minimally broken $U(2)^5$ symmetry, including breaking terms up to $\mathcal{O}(V^3,\Delta^1V^1)$. Notations as in Table 1.

$\rightarrow$ Study 124 CPC operators one-by-one

Data at different energy scales

E

TeV — $pp \to \ell_\alpha \ell_\beta$, $pp \to t\bar{t}, b\bar{b}$

LEP-II $e^+e^- \to \ell^+$

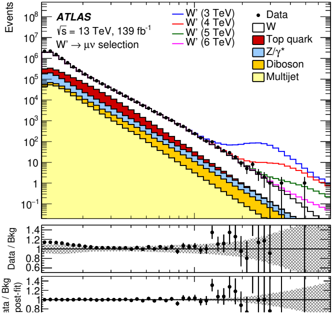
m_W — EWPO, $h \to f\bar{f}$

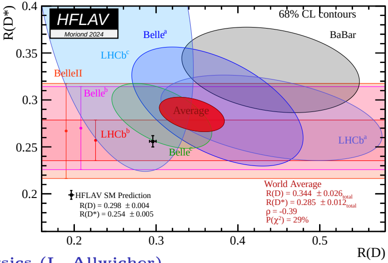
$\Delta F = 1$

m_b — $\Delta F = 2$

m_c — $b \to c\tau\nu$

τ-LFU





Analysis strategy

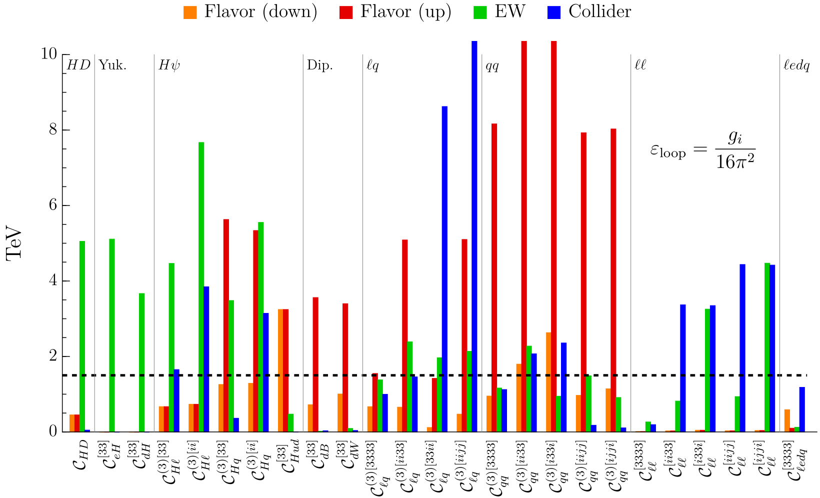
[*Fuentes-Martín, Ruiz-Femenia, Vicente, Virto* 2010.16341]

- Take into account RGE effects by running up the Wilson coefficients entering the observables up to $\Lambda = 3$ TeV
  $\rightarrow$ approximate full resummation using `DsixTools`
- Impose exact $U(2)$ at the high scale
- Distinguish two cases for flavour-violating couplings:
  - $U(2)$ basis up-aligned
  - $U(2)$ basis down-aligned
- Construct the combined likelihood from collider, EW, and flavour observables as a function of the 124 CP conserving invariants
- Switch on one operator at a time
  $\rightarrow$ get lower bound on $\Lambda_{\rm NP}$ (quote everything at 3σ)

Bounds on $U(2)$-symmetric operators

[*LA, Cornella, Isidori, Stefanek 2311.00020*]

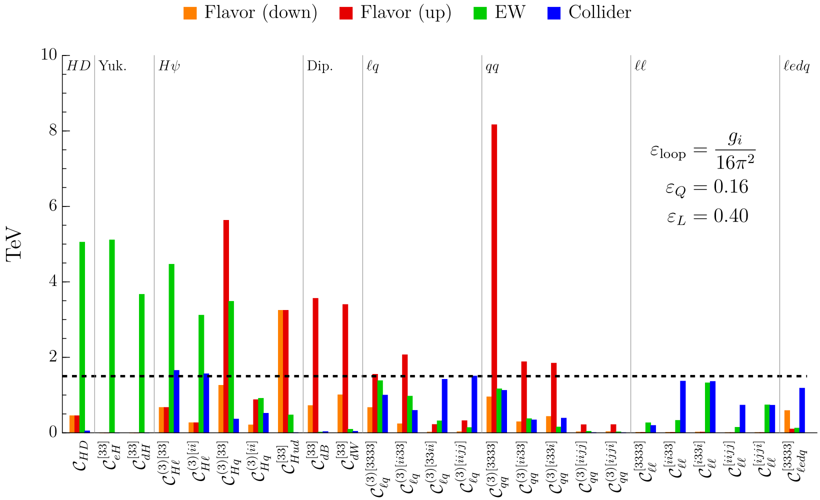
- $\mathcal{O}(5-10)$ TeV bounds
- Can we go below $\Lambda_0 = 1.5$ TeV? 3^{rd} gen. New Physics?



Suppressing the light families

[LA, Cornella, Isidori, Stefanek 2311.00020]

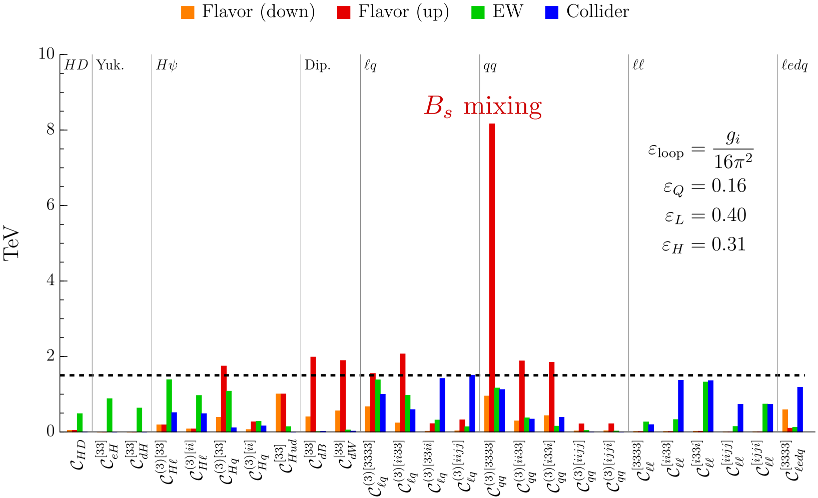
- ε_Q for each light quark field
- ε_L for each light lepton field
- Operators with Higgs fields still give strong bounds (EWPO)



Suppressing Higgs couplings

[*LA, Cornella, Isidori, Stefanek 2311.00020*]

- ε_H for each Higgs field
- Some flavour bounds still large (in the up-aligned case)



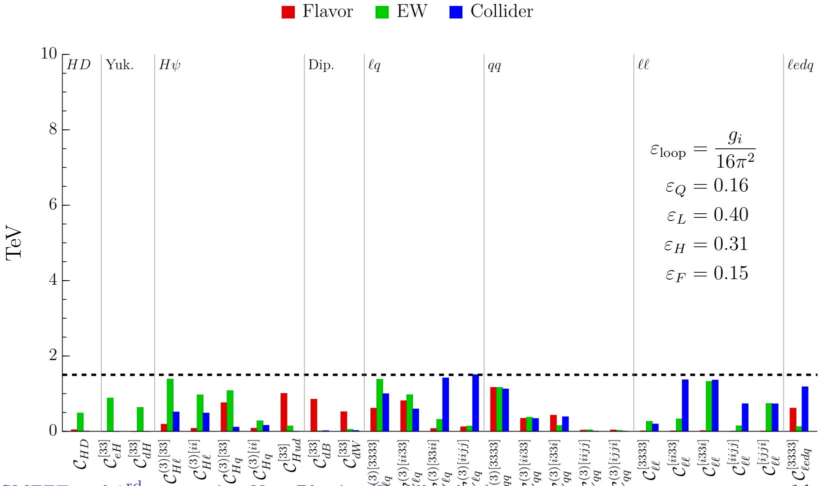
Flavour alignment

[LA, Cornella, Isidori, Stefanek 2311.00020]

$$q_3 = \left[(1-\varepsilon_F)\delta_{3r} + \varepsilon_F V_{3r}\right] q_r^{(d)} \approx q_b + \varepsilon_F (V_{ts} q_s + V_{td} q_d)$$

$$= \left[(1-\varepsilon_F)(V^\dagger)_{3r} + \varepsilon_F \delta_{3r}\right] q_r^{(u)} \approx \varepsilon_F q_t + (1-\varepsilon_F)(V_{cb}^* q_c + V_{ub}^* q_u)$$

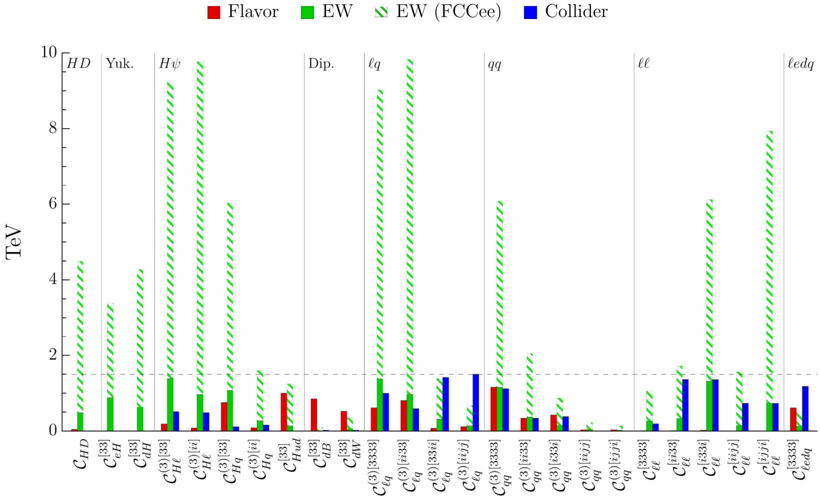
- 15% down-alignment needed to pass B_s mixing constraint



Projections for FCC-ee (Z-pole)

[LA, Cornella, Isidori, Stefanek 2311.00020]

- 5×10^{12} Z bosons at FCC
- Precision in EWPO improved by up to 2 orders of magnitude



Summary

- Investigated the SMEFT in the $U(2)^5$-symmetric limit, including flavour, EW, and collider data
- Accounted for RG effects from a NP scale $\Lambda = 3$ TeV
- Third-generation NP scenario "enforced" by introducing suppression factors ε_i
- For

$$\varepsilon_Q \lesssim 0.16 \qquad \varepsilon_L \lesssim 0.40 \qquad \varepsilon_H \lesssim 0.31 \qquad \varepsilon_F \lesssim 0.15$$

  NP scale can be as low as $\Lambda_0 = 1.5$ TeV
- Expect one order of magnitude improvement at FCC-ee (driven by EWPO)

Thank you!

Backup

Suppressing the light families

[*LA, Cornella, Isidori, Stefanek 2311.00020*]

- So far, only $U(2)^5$ protection
- No suppression of operators involving the light families
- ε_Q for each light quark field
- ε_L for each light lepton field

Examples:

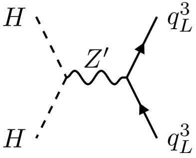
$$\mathcal{C}_{He}^{[ii]}(H^\dagger i\overleftrightarrow{D}_\mu H)\sum_{i=1}^{2}(\bar{e}_i\gamma^\mu e_i) \to \varepsilon_L^2\,\mathcal{C}_{He}^{[ii]}(H^\dagger i\overleftrightarrow{D}_\mu H)\sum_{i=1}^{2}(\bar{e}_i\gamma^\mu e_i)$$

$$\mathcal{C}_{\ell q}^{(1)[iijj]}\sum_{i,j=1}^{2}(\bar{\ell}^i\gamma^\mu\ell^i)(\bar{q}^j\gamma_\mu q^j) \to \varepsilon_L^2\varepsilon_Q^2\,\mathcal{C}_{\ell q}^{(1)[iijj]}\sum_{i,j=1}^{2}(\bar{\ell}^i\gamma^\mu\ell^i)(\bar{q}^j\gamma_\mu q^j)$$

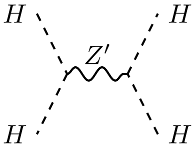
- Dial down ε_i until collider bounds are below $\Lambda_0 = 1.5$ TeV

The Higgs and $U(2)^5$

- If we want to address both the Higgs hierarchy problem and the flavour puzzle, NP should couple to the Higgs as well
- Take e.g. a Z' model, one generically gets contributions to EWPO



$\mathcal{C}_{Hq}^{(1)[33]}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$



$\mathcal{C}_{HD}|H^\dagger \overleftrightarrow{D}_\mu H|^2$

$U(2)^5$ does not offer protection for these contributions

- Need to suppress the NP couplings to the Higgs to avoid EWPO constraints
- ε_H for each Higgs field in the EFT

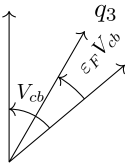
Flavour alignment in the 3rd generation

[*LA, Cornella, Isidori, Stefanek 2311.00020*]

- q_L^3 is somewhere in-between down-aligned and up-aligned
- ε_F to parametrise the amount of down-alignment:

$$\theta \sim V_{cb}\varepsilon_F$$

$$\begin{pmatrix} t_L \\ V_{td}d_L + V_{ts}s_L + V_{tb}b_L \end{pmatrix} = q_t$$



$$q_b = \begin{pmatrix} V_{ub}^* u_L + V_{cb}^* c_L + V_{tb}^* t_L \\ b_L \end{pmatrix}$$

$$\begin{aligned} q_3 &= \left[(1-\varepsilon_F)\delta_{3r} + \varepsilon_F V_{3r}\right] q_r^{(d)} \approx q_b + \varepsilon_F (V_{ts}q_s + V_{td}q_d) \\ &= \left[(1-\varepsilon_F)(V^\dagger)_{3r} + \varepsilon_F \delta_{3r}\right] q_r^{(u)} \approx \varepsilon_F q_t + (1-\varepsilon_F)(V_{cb}^* q_c + V_{ub}^* q_u) \end{aligned}$$