Searching for $U(2)$ New Physics with Flavour, Electroweak, and Collider Data

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Based on work (in progress) with:
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The Standard Model flavour puzzle

- SM gauge interactions are flavour-blind:

$$\mathcal{L}_{\text{gauge}} \supset \sum_{i=1}^{3} \sum_{\psi} \bar{\psi} i \not{D} \psi$$

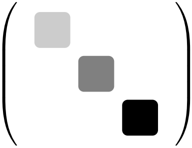
- flavour symmetry:

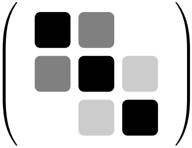
$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

- only breaking: Higgs Yukawa interactions:

$$\mathcal{L}_{\text{Yukawa}} = Y_u \bar{q} u \widetilde{H} + Y_d \bar{q} d H + Y_e \bar{\ell} e H + \text{h.c.}$$

The pattern of masses and mixings doesn't look accidental at all!

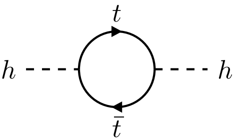
$m_\psi \sim$ 

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

$\boxed{\text{SM flavour puzzle}}$

Light new physics: the NP flavour problem

- **hierarchy problem**: Higgs mass term quadratically sensitive to UV physics:



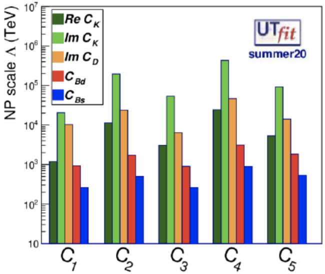
$$\longrightarrow \delta m_h^2 \approx \frac{3y_t^2}{4\pi^2}\Lambda_{\text{NP}}^2$$

$\Rightarrow$ need "light" NP to avoid tuning

- Stringent flavour bounds: what is the flavour structure of NP?
  $\rightarrow$ Non-trivial if we want TeV-scale

$\boxed{\text{NP flavour problem}}$

[*Barbieri* 2103.15635]



Flavour symmetries: the $U(2)$ paradigm

- Yukawa terms break the $U(3)^5$ symmetry:

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

- 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**: treat the SM as an effective description, with accidental flavour symmetries of UV origin
- does NP follow a similar structure?

Third generation New Physics and $U(2)$

- NP is not flavour universal
- mainly coupled to the 3$^{\text{rd}}$ 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 $U(2)$

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

good way of suppressing the light families

minimally broken $U(2)$

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

flavour violating couplings

Want to study this hypothesis in a generic EFT approach

SMEFT and $U(2)$

Consider the Standard Model as an Effective Field Theory

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

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

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

Operators	$U(2)^5$ Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1V^1)$		$\mathcal{O}(V^3,\Delta^1V^1)$	
	[terms summed up to different orders]													
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

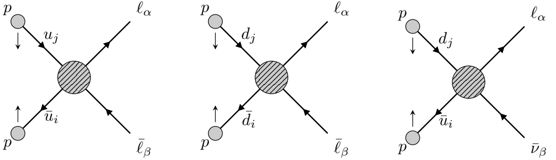
Table 6: Number of independent operators in the SMEFT assuming a minimally broken $U(2)^5$ symmetry, including breaking terms up to $\mathcal{O}(V^3,\Delta^1V^1)$. Notations as in Table 1.

$\boxed{\text{How low can the NP scale be?}}$

- consider collider, electroweak and flavour observables

Phenomenology: colliders

- High-p_T Drell-Yan Tails



  - In particular: $pp \to \tau\tau, \tau\nu$
  - Constrain semileptonic operators

[*LA, Faroughy, Jaffredo, Sumensari, Wilsch* 2207.10756]

- LEP-2 $e^+e^- \to \ell^+\ell^-$
  - $e^+e^- \to e^+e^-$ angular distributions
  - $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$: σ, $\sigma_{\rm FB}$
  - Constrain four-lepton operators

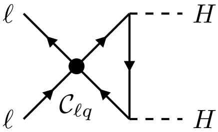
[*Allanach, Mullin* 2306.80669]

- four-quark observables
  - $t\bar{t}$, $b\bar{b}$, $b\bar{t}$ final states
  - Constrain e.g. $\mathcal{C}_{qu}^{(1)}$, $\mathcal{C}_{uG}$, ...

[*Ethier et al.* 2105.00006]

Phenomenology: EWPT

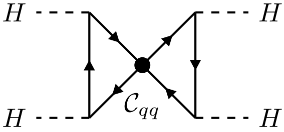
- Crucial precision tests of the SM & NP coupled to the Higgs
- At tree-level, constrain operators of the type $(H^\dagger i D_\mu H)(\bar{\psi}\gamma^\mu\psi)$
  $\rightarrow$ modification of SM gauge boson couplings
  $\rightarrow$ Only 15 such structures in the $U(2)$ limit
- RGE effects can be important! At one-loop:



Contribution to:

- $(H^\dagger i D_\mu H)(\bar{\ell}\gamma^\mu\ell)$
- $Z \rightarrow \tau\tau$

- Sometimes even NLL effects $\rightarrow$ need for full resummation



Contribution to:

- $|H^\dagger D_\mu H|^2$
- m_W

[*LA, Isidori, Lizana, Selimović, Stefanek* 2302.11584]

- **Potential for great improvement at FCC-ee!**
- Include also Higgs decays, τ LFU tests

Phenomenology: Flavour

- In principle, no flavour-violating couplings in the exact $U(2)$ limit
- but, need to specify a basis for the quark doublets
- Two choices:

down-aligned

$$q_L^{\text{down}} = \begin{pmatrix} V_{\text{CKM}}^{\dagger} u_L \\ d_L \end{pmatrix}$$

up-aligned

$$q_L^{\text{up}} = \begin{pmatrix} u_L \\ V_{\text{CKM}} d_L \end{pmatrix}$$

- main effects in the $U(2)$ hypothesis:
  - $\Delta F = 1$: $B \to X_s \gamma$, $B \to K \nu \bar{\nu}$, $K \to \pi \nu \bar{\nu}$, $B \to K \mu\mu$, ...
  - $\Delta F = 2$: $B_{s,d}$-, K-, D-mixing
  - $b \to c \tau \nu$ transitions: $R_{D^{(*)}}$, R_{Λ_c}

Analysis strategy

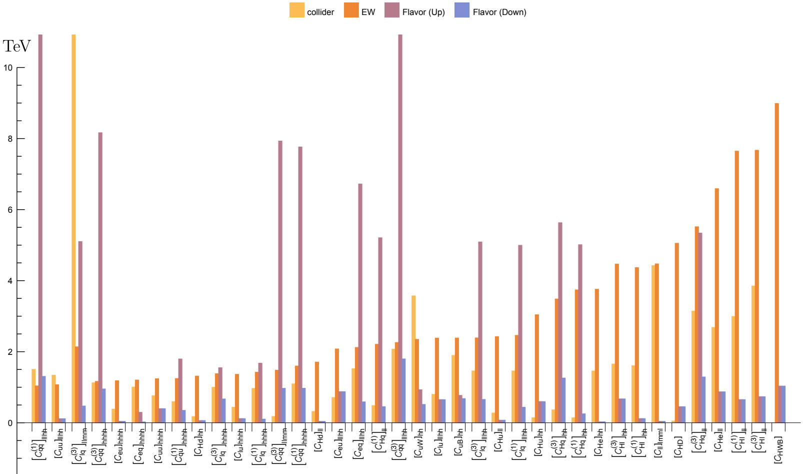
[*Fuentes-Martín, Ruiz-Femenia, Vicente, Virto* 2010.16341]

- 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)

Current bounds from EWPT

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

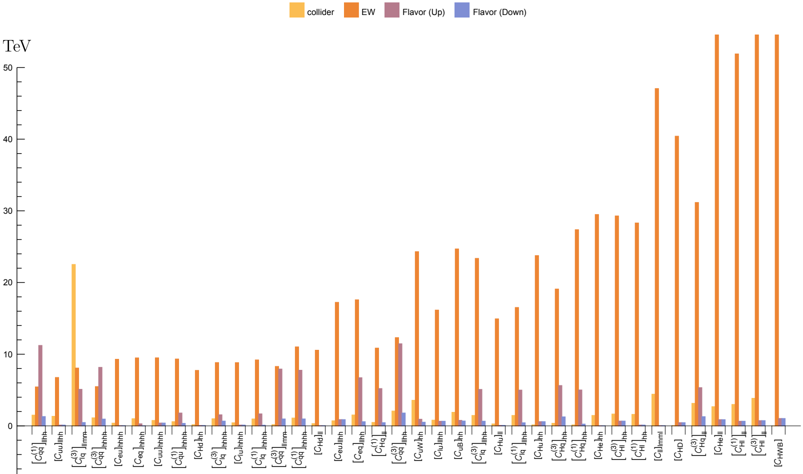
- EW already dominates 42 out of 124 bounds
- $\Lambda \gtrsim 1$ TeV, up to 10 TeV



EWPT - FCC projections

[LA, Cornella, Isidori, Stefanek WIP]

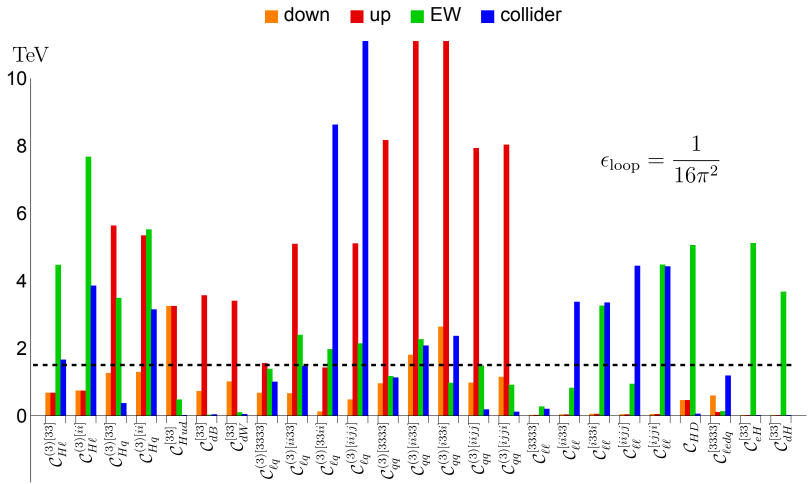
- 2×10^5 more Z bosons than LEP
- EWPT improved by 10-100 (systematics)
- now: 82/124 bounds dominated by EW
- $\Lambda \gtrsim 10$ TeV for the same operators



New Physics coupled to light families

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

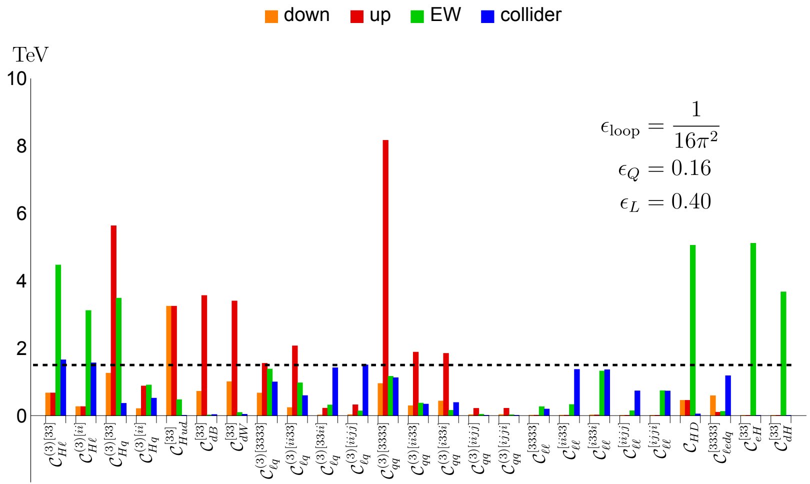
- suppress loop-generated operators: dipoles, $(H^\dagger \sigma^I H) W^I_{\mu\nu} B^{\mu\nu}$, ...
- $\mathcal{O}(5-10)$ TeV bounds
- Can we go below $\Lambda = 1.5$ TeV? 3[rd] gen. New Physics?



Third family New Physics

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

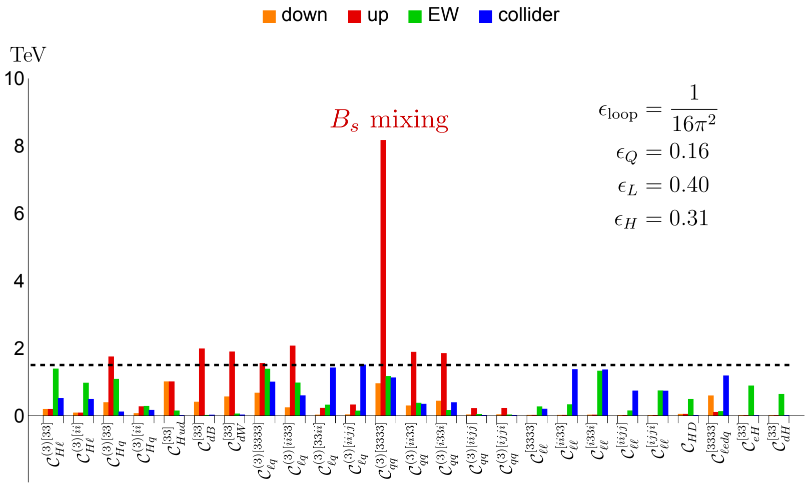
- ϵ_Q for each light quark field
- ϵ_L for each light lepton field
- Avoid collider constraints



Third family NP: Higgs couplings

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

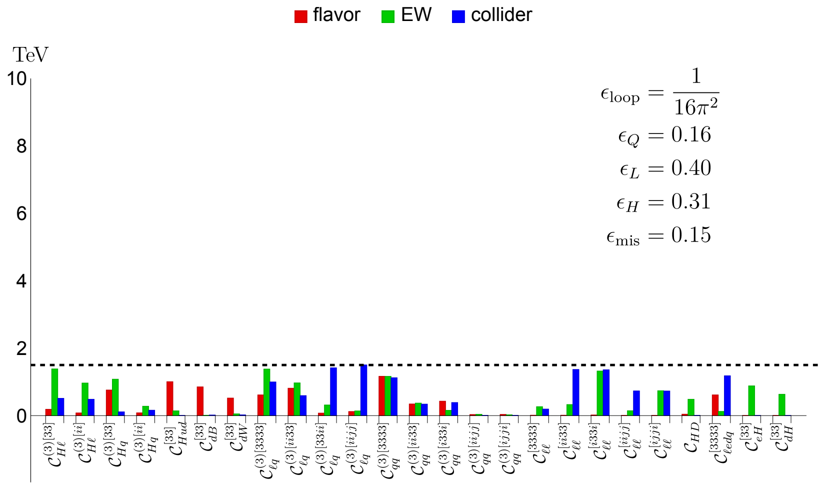
- suppress Higgs couplings: ϵ_H for each higgs field
- Avoid EW constraints



Third family NP: flavour alignment

[LA, Cornella, Isidori, Stefanek WIP]

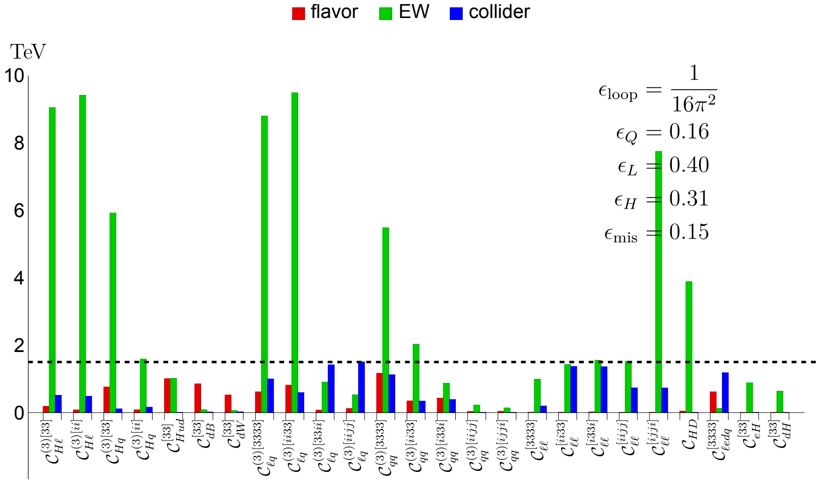
- 15% down-alignment does the trick
- alternatively: suppress four-quark couplings (Leptoquarks?)



FCC projections

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

- $3^{\rm rd}$ family NP at FCC-ee (Z-pole projections)
- back to $\mathcal{O}(10)$ TeV bounds, even with suppressions



Summary

- The SM flavour sector exhibits an approximate $U(2)^5$ symmetry
- $U(2)$ is a good starting point to address also the NP flavour problem
- Studied the SMEFT in the exact $U(2)$ limit, considering constraints from collider, electroweak and flavour observables
- Find generally bounds of $\mathcal{O}(5-10)$ TeV
  $\rightarrow$ mainly from light families
- All bounds can be relaxed to be below $\Lambda = 1.5$ TeV assuming 3^{rd} generation NP (and small Higgs couplings)
- Exciting prospects for FCC-ee, pushing the bounds back into the $\mathcal{O}(10)$ TeV range, independently of dynamical assumptions
- Great importance of EWPT, due also to RGE effects

Thanks for your attention!