Flavour & precision and new energy scales

Beyond the next collider?

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HELMHOLTZ

DESY.

This talk

Q: Which are the (flavour) models which will be interesting to probe beyond the next collider? Why could the 10 TeV scale be important?

$\rightarrow$ Clearly very hard to say, we don't even know what the next collider will be...

- Exploration of the TeV scale and beyond
- Focus on indirect probes, i.e. precision measurements (intensity frontier)
- May give us pointers for the NNCollider

Beyond the next collider?

Local definitions

- **Current**: currently active and/or approved projects
  - (HL-)LHC
  - Belle-II, NA62

- **Next**: a precision machine (Electoweak/Higgs/Flavour factory)
  For practical purposes: **FCC-ee**

- **Next-to-next**: High-energy, $\gtrsim 10$ TeV
  - FCC-hh
  - Muon Collider

Outline

I (SM)EFT considerations

- Flavour puzzle(s)
- SMEFT (and flavour assumptions)
- New Physics in the third generation

II FCC-ee

- Electroweak Precision Observables
- Flavour prospects

III Selected models and phenomenology

- Flavour deconstruction
- $U(2)_{q+e}$

(SM)EFT Considerations

The Standard Model flavour puzzle

- SM gauge interactions are flavour-blind:

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

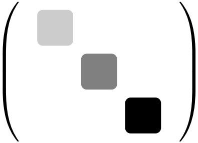
- Flavour symmetry:

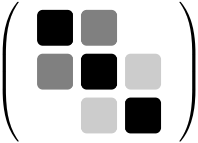
$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

- Only breaking: Higgs Yukawa interactions:

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

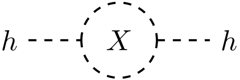
The pattern of masses and mixings doesn't look accidental at all!

$m_\psi \sim$ 

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

Light new physics: the NP flavour problem

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



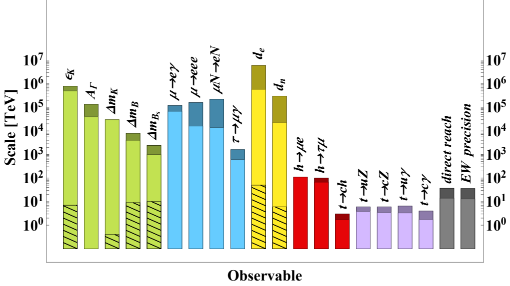
$$\longrightarrow \delta m_h^2 \approx \frac{g^2}{16\pi^2} M_X^2$$

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

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

NP flavour problem

[Physics Briefing Book '19]



Flavour assumptions: MFV

[Isidori, Straub 1202.0464]

- Minimal Flavour Violation: only breaking $U(3)^5$ symmetry comes from SM Yukawas
- e.g. $q_L \sim (\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$ under

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

- $Y_u \sim (\mathbf{3},\mathbf{1},\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$
- Yukawas promoted to spurions keeping track of $U(3)^5$ breaking

$$\bar{q}_L^i \gamma^\mu q_L^j (a\delta_{ij} + b[Y_u Y_u^\dagger]_{ij} + \ldots)$$

- Good to suppress flavour-changing processes:

$$\lambda_{\text{FC}} \approx (Y_u Y_u^\dagger)_{\text{FC}} \sim \begin{pmatrix} 0 & \lambda^5 & \lambda^3 \\ \lambda^5 & 0 & \lambda^2 \\ \lambda^3 & \lambda^2 & 0 \end{pmatrix}$$

- **But**: leading term is flavour-conserving and **universal**
  $\rightarrow$ collider searches push the scale to $\Lambda \gtrsim 10$ TeV

Flavour assumptions: $U(2)^5$

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

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

- However, light family Yukawas very small: approximate $U(2)^5$ symmetry

[Barbieri, Isidori, Lodone, Straub 1105.2296]

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

e.g.

$$q_L^{i=1,2} \sim (\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1}) \qquad q_L^3 \text{ singlet}$$

Minimal breaking:

$$Y = y_3 \left(\begin{array}{c|c} \Delta & V \\ \hline 0 & 1 \end{array}\right) \qquad \begin{array}{cc} V \sim (\mathbf{2},\mathbf{1}) & \Delta \sim (\mathbf{2},\bar{\mathbf{2}}) \\ |V_q| = \mathcal{O}(y_t V_{ts}) & |\Delta| \sim y_{c,s,\mu} \end{array}$$

SMEFT

- In presence of a mass-gap, somewhat model-independent approach
  $\rightarrow$ study classes of models
- Complement the SM with a tower of higher-dimensional operators, with SM fields and gauge symmetry

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

- Correct way of dealing with scale separations (RGE)
- Stop the expansion at $d = 6$
- 59 operator structures, 2499 independent coefficients
- Most of the parameters come from flavour $\rightarrow$ **flavour assumptions**

$U(2)^5$ 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. $\mathcal{C}_{lequ}$

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

- 81 $\to$ 1 independent coefficients!

The $U(2)$-symmetric SMEFT

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

[Faroughy, Isidori, Wilsch, Yamamoto 2005.05366]

Operators	$U(2)^5$ [terms summed up to different orders] Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1 V^1)$		$\mathcal{O}(V^3,\Delta^1 V^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6
$\psi^2 H^3$	3	3	6	6	6	6	9	9	9	9	12	12	12	12
$\psi^2 X H$	8	8	16	16	16	16	24	24	24	24	32	32	32	32
$\psi^2 H^2 D$	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 $\mathcal{O}(V^3,\Delta^1 V^1)$. Notations as in Table 1.

How low can the NP scale be?

- consider collider, electroweak and flavour observables

Flavour: $U(2)$ needs to be broken

- It is broken already at dimension four
- Use spurions to parametrise the breaking

Exact $U(2)^5$

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

- No flavour violation
- Get bounds from collider and EW observables

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
- Effects mainly in B physics ($b \to c, s$ transitions)

In single-parameter fits: **alignment** of the left-handed quark doublet:

down-aligned

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

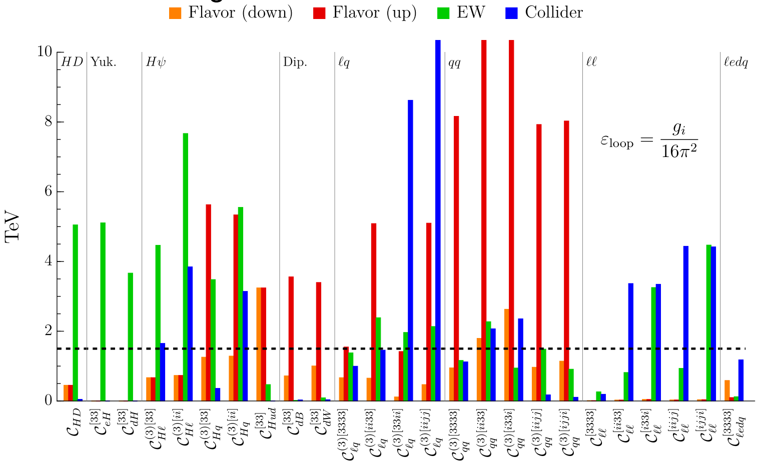
up-aligned

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

SMEFT fits to $U(2)$ operators

[LA, Cornella, Isidori, Stefanek 2311.00020]

- From 10^6 to ~ 10 TeV through $U(2)^5$
- Can we go even lower? 3rd gen. NP?



New Physics in the third generation?

- **Idea**: New Physics couples predominantly to the third generation
- Mimicks the SM Yukawas ($\leftrightarrow$ SM flavour puzzle?)
- Couplings to light families dynamically suppressed
- In the EFT, this is an extra assumption
- An accidental $U(2)$ symmetry on the light families arises naturally (cf. again SM Yukawas)

> Starting from the $U(2)$-symmetric case, add extra suppressions ”by hand”

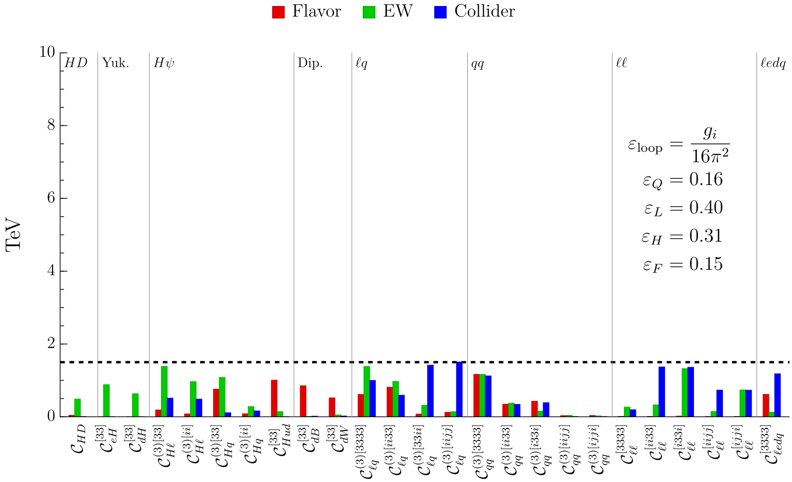
$$\bar{q}_L^i \gamma^\mu q_L^j \to a\, \bar{q}_L^3 \gamma^\mu q_L^3 + b \sum_{i=1}^{2} \bar{q}_L^i \gamma^\mu q_L^i$$

- a and b independent coefficients
- E.g. for quarks $q_i \to \varepsilon_Q q_i$ for $i = 1, 2$ (assume $b \ll a$)

New Physics in the third generation?

[LA, Cornella, Isidori, Stefanek 2311.00020]

- Suppress operators with light fermion indices, and Higgses
- Λ_{NP} still compatible with $\sim$ TeV under non-tuned conditions



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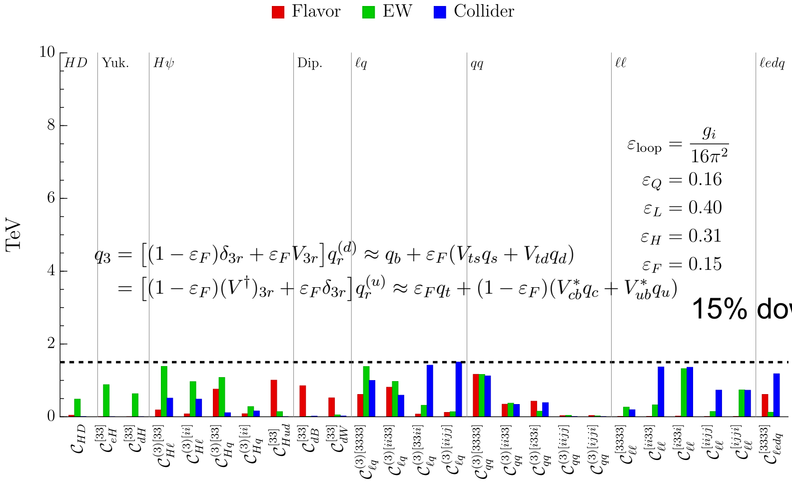


$$q_3 = \left[(1-\varepsilon_F)\delta_{3r} + \varepsilon_F V_{3r}\right] q_r^{(d)} \approx q_b + \varepsilon_F (V_{ts} q_s + V_{td} q_d)$$
$$= \left[(1-\varepsilon_F)(V^\dagger)_{3r} + \varepsilon_F \delta_{3r}\right] q_r^{(u)} \approx \varepsilon_F q_t + (1-\varepsilon_F)(V_{cb}^* q_c + V_{ub}^* q_u)$$

$$\varepsilon_{\text{loop}} = \frac{g_i}{16\pi^2}$$
$$\varepsilon_Q = 0.16$$
$$\varepsilon_L = 0.40$$
$$\varepsilon_H = 0.31$$
$$\varepsilon_F = 0.15$$

15% down-aligned

Wrap-up

Current status

- If New Physics couples mostly to the third generation, we are barely exploring the TeV scale today
- Avoid tough flavour constraints
- Possible link with the SM flavour puzzle, can solve large hierarchy problem
- Precision tests (flavour, EW) are powerful indirect probes of NP
- This picture can only improve with higher precision

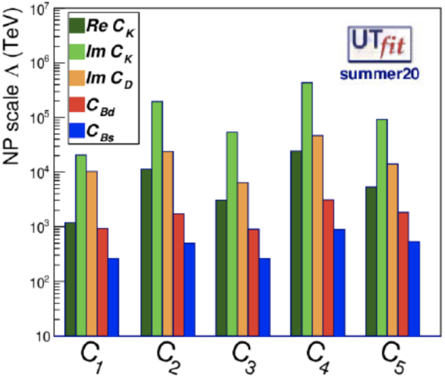
What can FCC-ee tell us?

Indirect probes at FCC-ee

Indirect searches

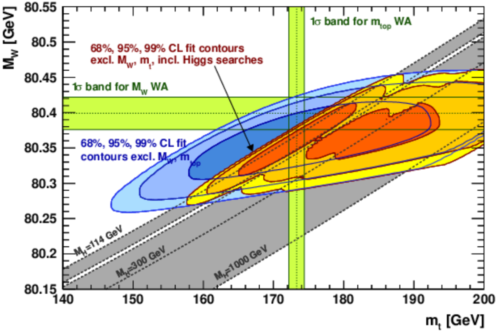
Absence of NP

- E.g. bounds from $\Delta F = 2$



With NP (a model)

- E.g. the Higgs before LHC



$\rightarrow$ What could similar plots look like at FCC?

Indirect searches at FCC-ee

[Table from FCC FSR 2404.12809]

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH + 65k WW $\rightarrow$ H	2×10^{6} $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

EWPOs

- Focus on Z- and W-pole obs.
- Constrain flavour-conserving NP

Flavour

- Large number of $b\bar{b}$ and $\tau^+\tau^-$ pairs from Z decays
- Constrain flavour-violating NP

$\rightarrow$ overall great potential for cornering NP indirectly

EWPOs at FCC-ee

- Measure Z- and W boson couplings to fermions through partial decay widths
- Current measurements largely from LEP, $\mathcal{O}(1‰)$ precision
- Expect an improvement by 10-100 at FCC-ee

[Table from FCC FSR 2404.12809]

	Observable	Definition
Z-pole	Γ_Z	$\sum_f \Gamma(Z \to f\bar{f})$
	σ_{had}	$\frac{12\pi}{m_Z}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
	R_f $(f = e, \mu, \tau, c, b)$	$\frac{\Gamma(Z\to f\bar{f})}{\sum_q \Gamma(Z\to q\bar{q})}$
	A_f $(f = e, \mu, \tau, s, c, b)$	$\frac{\Gamma(Z\to f_L\bar{f}_L)-\Gamma(Z\to f_R\bar{f}_R)}{\Gamma(Z\to f\bar{f})}$
	$A_{\text{FB}}^{0,\ell}$ $(\ell = e, \mu, \tau)$	$\frac{3}{4}A_e A_\ell$
	A_q^{FB} $(q = c, b)$	$\frac{3}{4}A_e A_q$
W-pole	m_W	
	Γ_W	$\sum_{f_1,f_2} \Gamma(W \to f_1 f_2)$
	$\text{Br}(W \to \ell\nu)$ $(\ell = e, \mu, \tau)$	

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\text{eff}}$ $(\times 10^6)$	231,480	±	160	**1.2**	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2)$ $(\times 10^3)$	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z $(\times 10^3)$	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ $(\times 10^4)$	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 $(\times 10^3)$ (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0}$ $(\times 10^4)$	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau}$ $(\times 10^4)$	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics

EWPOs in SMEFT at tree level

$$\mathcal{C}_{H\psi}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\psi\gamma^\mu\psi) \xrightarrow{H\to\langle H\rangle} -\frac{v^2}{2}\mathcal{C}_{H\psi}Z_\mu(\bar\psi\gamma^\mu\psi)$$

- Sensitive to 23 parameters

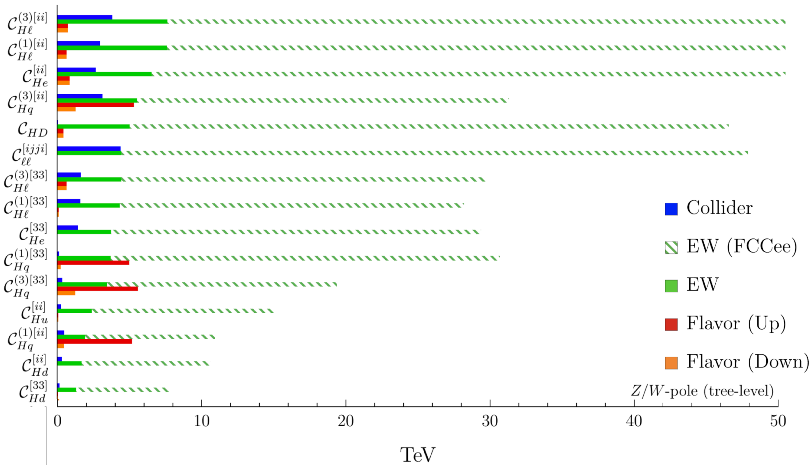
$[\mathcal{O}^{(1)}_{H\ell}]_{pr} =$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\ell_p\gamma^\mu\ell_r)$	$[\mathcal{O}_{Hu}]_{pr} =$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
$[\mathcal{O}^{(3)}_{H\ell}]_{pr} =$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar\ell_p\tau^I\gamma^\mu\ell_r)$	$[\mathcal{O}_{Hd}]_{pr} =$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$[\mathcal{O}^{(1)}_{Hq}]_{pr} =$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$	$\mathcal{O}_{HD} =$	$\lvert H^\dagger D_\mu H\rvert^2$
$[\mathcal{O}^{(3)}_{Hq}]_{pr} =$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$	$\mathcal{O}_{HWB} =$	$(H^\dagger\tau^I H)W^I_{\mu\nu}B^{\mu\nu}$
$[\mathcal{O}_{He}]_{pr} =$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$	$[\mathcal{O}_{\ell\ell}]_{1221} =$	$(\bar\ell_1\gamma^\mu\ell_2)(\bar\ell_2\gamma^\mu\ell_1)$

- $\mathcal{A} = \mathcal{A}_0\left(\frac{g_{\text{SM}}}{m_W^2} + \frac{g_{\text{NP}}}{\Lambda_{\text{NP}}^2}\right)$
- 10^5 improvement in statistics: $\Lambda_{\text{NP}} \to\simeq 20\Lambda_{\text{NP}}^{\text{now}}$
- Naive scaling, systematics (and theory errors) have an effect at such precision

Projections for tree-level operators

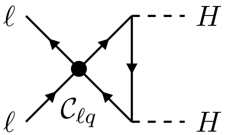
[LA, Cornella, Isidori, Stefanek 2311.00020]

- $U(2)^5$ symmetry acting on the light generations imposed on SMEFT
- From current $\mathcal{O}(\text{few})$TeV to 30 TeV range at FCC-ee



Sizeable RGE effects

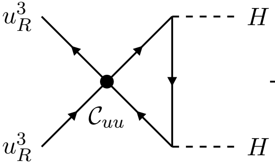
- Loop suppression $\frac{1}{16\pi^2} g^2 \log \frac{m_Z}{\Lambda} \simeq -(0.14)^2$ for $g = 1$ and $\Lambda = 2$ TeV
- Can still probe loop-suppressed effects up to the few TeV range
- LL effects:



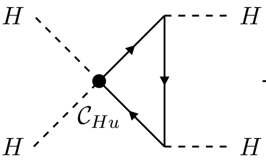
$$[\dot{\mathcal{C}}_{Hl}^{(3)}]_{\alpha\beta} \supset 2N_c [\mathcal{C}_{lq}^{(3)}]_{\alpha\beta kl} [Y_d^\dagger Y_d + Y_u^\dagger Y_u]_{lk}$$

- Particularly relevant if y_t is involved
- Effects e.g. in $Z \to \tau\tau$

- Sometimes even NLL effects can be relevant



$\longrightarrow \mathcal{C}_{Hu}$

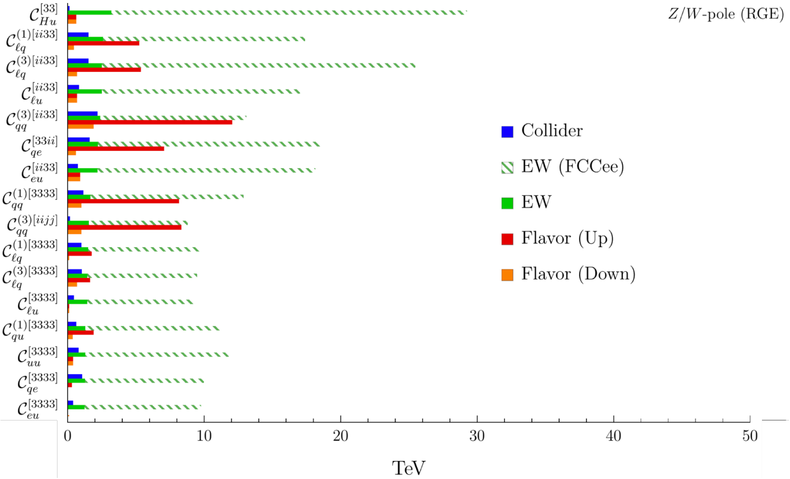


$\longrightarrow \mathcal{C}_{HD} \quad \to \delta m_W$

Projections from loop-level EWPOs

[LA, Cornella, Isidori, Stefanek 2311.00020]

- $\mathcal{O}(10)$ TeV constraints for four-fermion operators (3rd gen. quarks)



From SMEFT to the UV

- SMEFT as a “bookkeeping” tool
- Both single-parameter fits and global fits do not carry the same information as an explicit model
- Not all of the SMEFT parameter space can be spanned by UV models
- In particular, flat directions may not be populated
- Even if populated at tree-level, loops (RGE) will typically break them

Which models with heavy NP can be probed at FCC-ee? Which scales?

Linear extensions of the Standard Model

[De Blas et al. 1711.10391]

- Finite number of new states can couple linearly to the SM fields: *Granada dictionary*
- Matching to SMEFT at $d = 6$ well known

Scalar	$\mathcal{S}$ $(1,1)_0$	$\mathcal{S}_1$ $(1,1)_1$	$\mathcal{S}_2$ $(1,1)_2$	φ $(1,2)_{\frac{1}{2}}$	Ξ $(1,3)_0$	Ξ_1 $(1,3)_1$	Θ_1 $(1,4)_{\frac{1}{2}}$	Θ_3 $(1,4)_{\frac{3}{2}}$
	ω_1 $(3,1)_{-\frac{1}{3}}$	ω_2 $(3,1)_{\frac{2}{3}}$	ω_4 $(3,1)_{-\frac{4}{3}}$	Π_1 $(3,2)_{\frac{1}{6}}$	Π_7 $(3,2)_{\frac{7}{6}}$	ζ $(3,3)_{-\frac{1}{3}}$		
	Ω_1 $(6,1)_{\frac{1}{3}}$	Ω_2 $(6,1)_{-\frac{2}{3}}$	Ω_4 $(6,1)_{\frac{4}{3}}$	Υ $(6,3)_{\frac{1}{3}}$	Φ $(8,2)_{\frac{1}{2}}$			
Fermion	N $(1,1)_0$	E $(1,1)_{-1}$	Δ_1 $(1,2)_{-\frac{1}{2}}$	Δ_3 $(1,2)_{-\frac{3}{2}}$	Σ $(1,3)_0$	Σ_1 $(1,3)_{-1}$		
	U $(3,1)_{\frac{2}{3}}$	D $(3,1)_{-\frac{1}{3}}$	Q_1 $(3,2)_{\frac{1}{6}}$	Q_5 $(3,2)_{-\frac{5}{6}}$	Q_7 $(3,2)_{\frac{7}{6}}$	T_1 $(3,3)_{-\frac{1}{3}}$	T_2 $(3,3)_{\frac{2}{3}}$	
Vector	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

All (except very few) new states are probed by EWPOs at one-loop

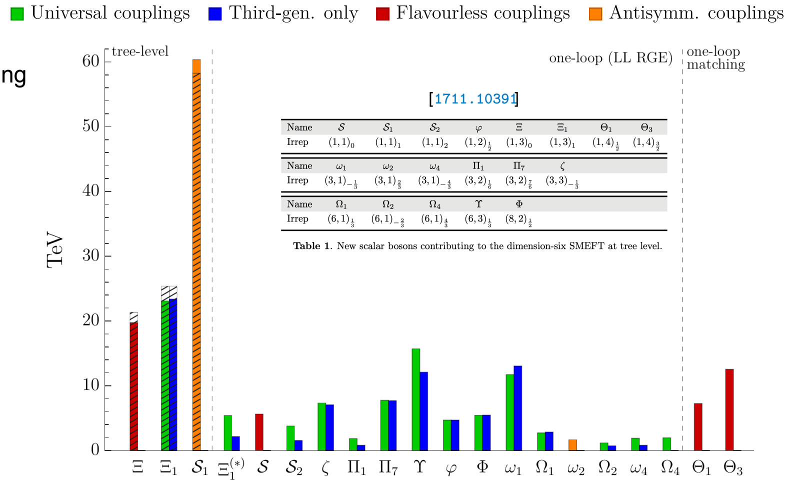
Analysis strategy

- Assume SM central values + FCC-ee expected errors
- Integrate out one state of the Granada dictionary at a time, assuming couplings are defined at a scale $\Lambda = 2$ TeV
- Consider only couplings at $d \leq 4$
- RGE evolve from 2 TeV to m_Z (first LL only)
  $\rightarrow$ use `DsixTools` [2010.16341]
- Get bounds on the mediator mass for $y, g, \lambda = 1$
  (dimensionful couplings $\kappa = 5$ TeV)
- Flavour assumptions:
  (a) **Flavour-universal** couplings: $y_{11} = y_{22} = y_{33}$ (or $y_1 = y_2 = y_3$ for fermions), and $y_{ij} = 0$ for $i \neq j$.
  (b) **Third-generation only** couplings: $y_{ij} = y\delta_{i3}\delta_{j3}$

Scalars

$^{(*)}$ = special choice of couplings to avoid tree-level EWPO

![hatched] = no running



[1711.10391]

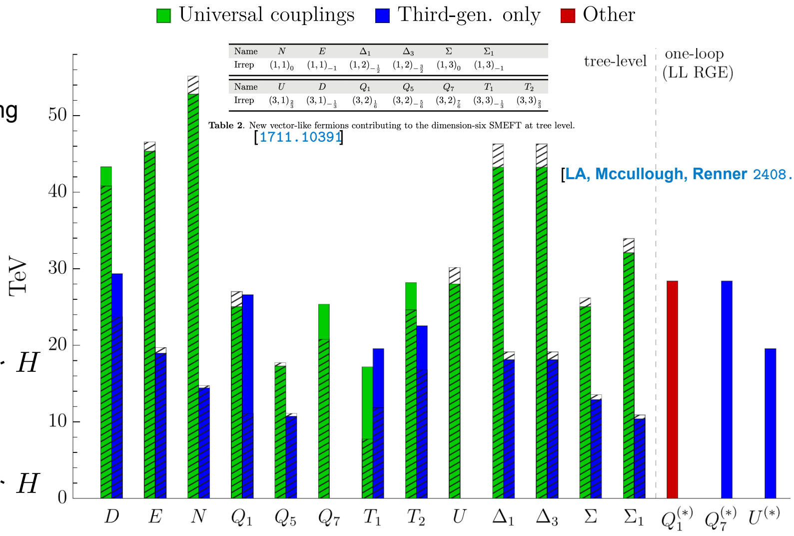
Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

[LA, Mccullough, Renner 2408.03992]

Fermions

$^{(*)}$ = special choice of couplings to avoid tree-level EWPO

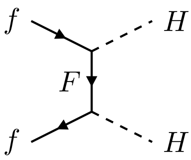


Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.
[1711.10391]

[LA, Mccullough, Renner 2408.03992]

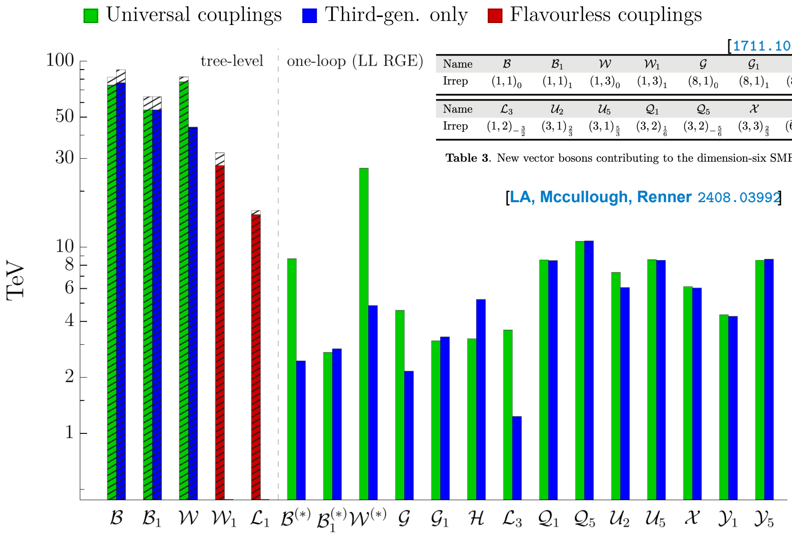
= no running



Vectors

$^{(*)}$ = special choice of couplings to avoid tree-level EWPO

▨ = no running



[1711.10391]

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Table 3. New vector bosons contributing to the dimension-six SMEFT at tree level.

[**LA, Mccullough, Renner** 2408.03992]

Flavour prospects at FCC-ee

Table 6: Yields of heavy-flavoured particles produced at FCC-ee for 6×10^{12} Z decays [190].

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

- $\sim 10^3$ more $b\bar{b}$ and $\tau^+\tau^-$ w.r.to Belle
- $\sim \times 5$ improvement in Λ_{NP} reach
- ~ 30 more than Belle-II projections
- Access to B_s and B_c - not produced at b factories
- Great advantage due to clean environment and boosted final states

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	(✓)
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

[Kamenik et al. '25]

Projections for flavour observables

[LA, Isidori, Pešut 2503.17019]

Observable	SM	Current value [14]	Pre-FCC projection	FCC-ee expected
$\lvert g_\tau/g_\mu \rvert$	1	1.0009 ± 0.0014	–	± 0.0001 [15]
$\lvert g_\tau/g_e \rvert$	1	1.0027 ± 0.0014	–	± 0.0001 [15]
corr.		0.51		
$\mathcal{B}(\tau \to \mu\bar{\mu}\mu)$	0	$< 2.1 \times 10^{-8}$	$< 0.37 \times 10^{-8}$ [*] [16]	$< 1.5 \times 10^{-11}$ [*] [15]
R_D	0.298 ± 0.004	0.342 ± 0.026 [17]	$\pm 3.0\%$ [16]	
R_{D^*}	0.254 ± 0.005	0.287 ± 0.012 [17]	$\pm 1.8\%$ [16]	
corr.		-0.39		
$\mathcal{B}(B_c \to \tau\bar{\nu})$	$(1.95 \pm 0.09) \times 10^{-2}$	< 0.3 (68%C.L.)	–	$\pm 1.6\%$ [8]
$\mathcal{B}(B \to K\nu\bar{\nu})$	$(4.44 \pm 0.30) \times 10^{-6}$	$(1.3 \pm 0.4) \times 10^{-5}$	$\pm 14\%$ [16]	$\pm 3\%$ [7]
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	$(9.8 \pm 1.4) \times 10^{-6}$	$< 1.2 \times 10^{-5}$ (68%C.L.)	$\pm 33\%$ [16]	$\pm 3\%$ [7]
$\mathcal{B}(B \to K\tau\bar{\tau})$	$(1.42 \pm 0.14) \times 10^{-7}$	$< 1.5 \times 10^{-3}$ (68%C.L.)	$< 2.7 \times 10^{-4}$	$\pm 20\%$ [**] [18]
$\mathcal{B}(B \to K^*\tau\bar{\tau})$	$(1.64 \pm 0.06) \times 10^{-7}$	$< 2.1 \times 10^{-3}$ (68%C.L.)	$< 6.5 \times 10^{-4}$ [*] [16]	$\pm 20\%$ [**] [18]
$\mathcal{B}(B_s \to \tau\bar{\tau})$	$(7.45 \pm 0.26) \times 10^{-7}$	$< 3.4 \times 10^{-3}$ (68%C.L.)	$< 4.0 \times 10^{-4}$ [*] [16]	$\pm 10\%$ [**] [18]
$\Delta M_{B_s}/\Delta M_{B_s}^{\rm SM}$	1	$\pm 7.6\%$	$\pm 3.3\%$ [19]	$\pm 1.5\%$ [19]
$\mathcal{B}(B \to K\tau\bar{\mu})$	0		$< 1.0 \times 10^{-6}$ [*] [20]	
$\mathcal{B}(B_s \to \tau\bar{\mu})$	0		$< 1.0 \times 10^{-6}$ [*] [20]	

- Subset of observables, relevant for our example study

  [**] = under the assumption of an enhanced rate due to NP

Third-gen. semileptonics: future prospects

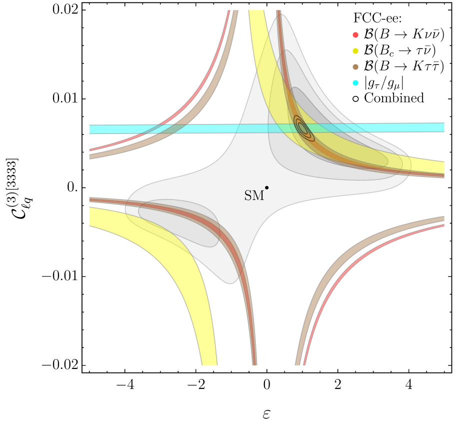
SMEFT analysis

[LA, Isidori, Pešut 2503.17019]

- Only third-gen. flavour indices:
  $\mathcal{L} \supset -\frac{2}{v^2}(\bar{\ell}^3_L \sigma^I \gamma_\mu \ell^3_L)(\bar{q}^3_L \sigma^I \gamma^\mu q^3_L)$
- Flavour-violating effects via $U(2)_q$ breaking spurion

$$\tilde{V} = -\varepsilon V_{ts} \begin{pmatrix} V_{td}/V_{ts} \\ 1 \end{pmatrix} \qquad \varepsilon \sim \mathcal{O}(1)$$

- $q^3_L \to q^3_L + \tilde{V}_i q^i_L$
- Assume a signal compatible with current measurements (grey region), and project for FCC-ee expected errors



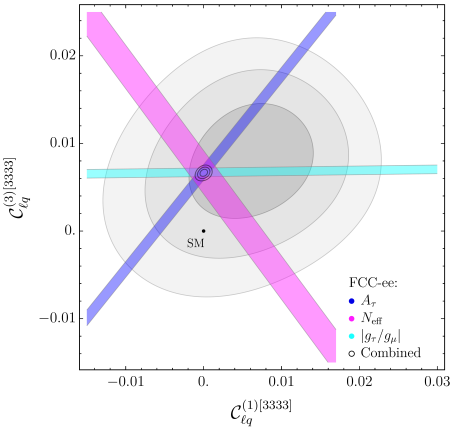
Flavour v. EWPOs

[LA, Isidori, Pešut 2503.17019]

$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_L^3 \gamma_\mu \ell_L^3)(\bar{q}_L^3 \gamma^\mu q_L^3)$$
$$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_L^3 \sigma^I \gamma_\mu \ell_L^3)(\bar{q}_L^3 \sigma^I \gamma^\mu q_L^3)$$

- Flavour-conserving directions (no spurions) badly probed by flavour
- Interplay with EWPOs: independent probes
- y_t running into $\mathcal{C}_{H\ell}^{(1\pm3)}$

Complementarity!

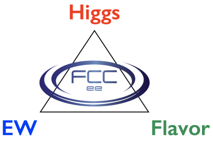


An explicit (simplified) model: S_1 scalar leptoquark

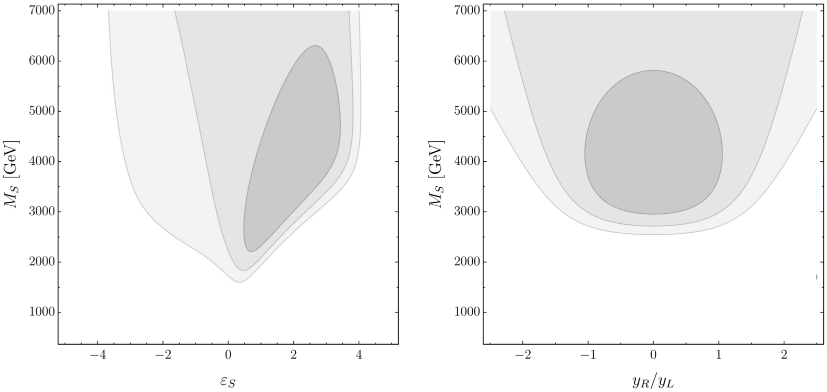
Synergies between Higgs/EW/Flavour

$$S_1 \sim (\mathbf{3}, \mathbf{1}, 1/3)$$

$$\mathcal{L}_{S_1} \supset i y_L S_1 \left(\bar{q}_L^{c\,3} \sigma_2 \ell_L^3\right) + y_R S_1 \left(\bar{u}^{3c} e_R^3\right) + \text{h.c.}$$



- Third-generation couplings only
- Current data



$$q_L^3 \to q_L^3 - \varepsilon_S V_{ti} q_L^i$$

[Courtesy of G. Isidori]

An explicit (simplified) model: S_1 scalar leptoquark

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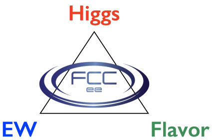
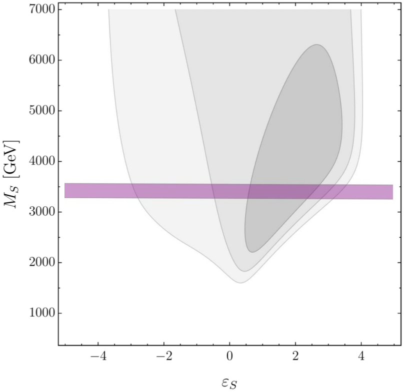
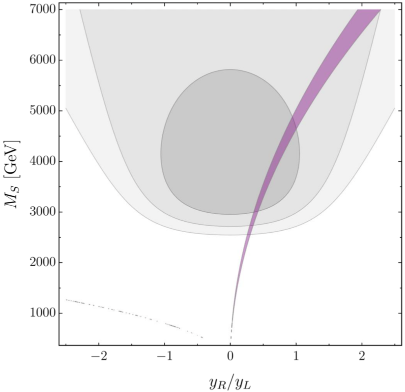


- Third-generation couplings only
- Current data
- $H \to \tau\tau$ (1%)





$$q_L^3 \to q_L^3 - \varepsilon_S V_{ti} q_L^i$$

[Courtesy of G. Isidori]

An explicit (simplified) model: S_1 scalar leptoquark

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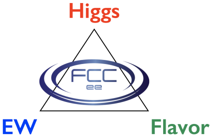
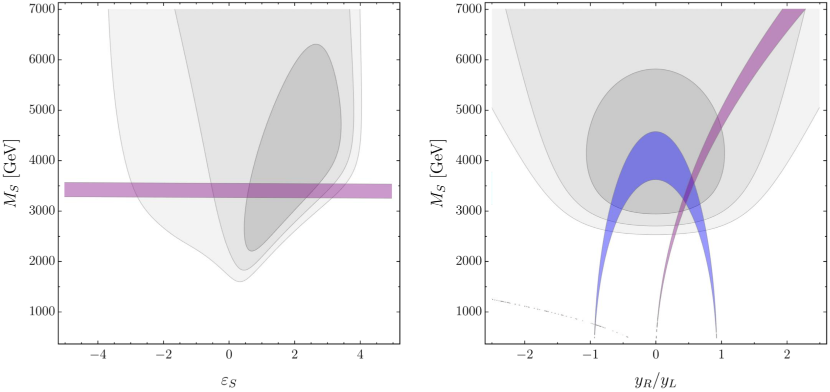


- Third-generation couplings only
- Current data
- $H \to \tau\tau$ (1%)
- A_τ $(\sim 10^{-4})$



$$q_L^3 \to q_L^3 - \varepsilon_S V_{ti} q_L^i$$

[Courtesy of G. Isidori]

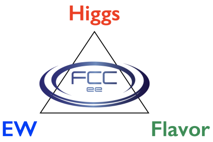
An explicit (simplified) model: S_1 scalar leptoquark

Synergies between Higgs/EW/Flavour

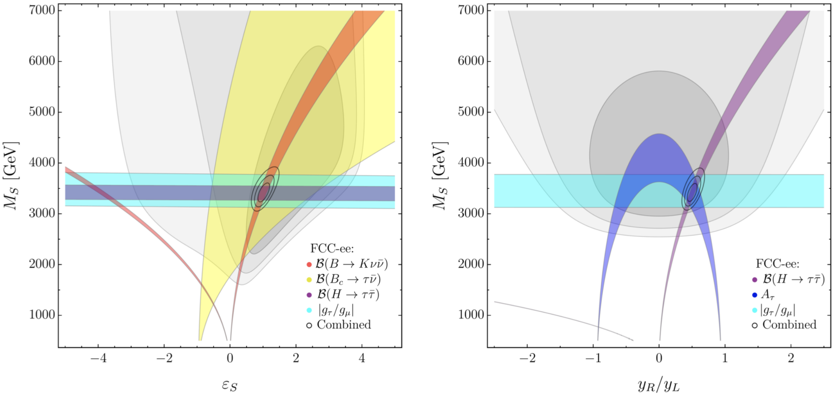
$$S_1 \sim (\mathbf{3}, \mathbf{1}, 1/3)$$

$$\mathcal{L}_{S_1} \supset i y_L S_1 \left(\bar{q}_L^{c\,3} \sigma_2 \ell_L^3\right) + y_R S_1 \left(\bar{u}^{3c} e_R^3\right) + \text{h.c.}$$

[LA, Isidori, Pešut 2503.17019]



- Third-generation couplings only
- Current data
- $H \to \tau\tau$ (1%)
- A_τ ($\sim 10^{-4}$)
- $B \to K\nu\bar{\nu}$ (3%)



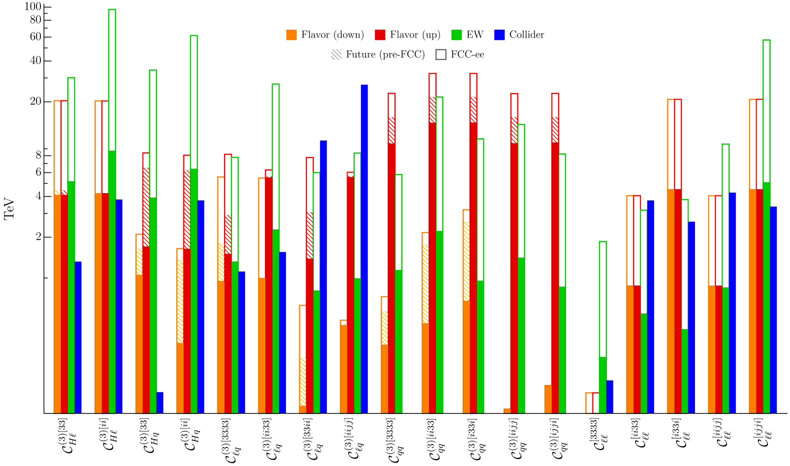
$$q_L^3 \to q_L^3 - \varepsilon_S V_{ti} q_L^i$$

Sensitivity to NP scales: $U(2)$-symmetric SMEFT

One-parameter fits to SMEFT coefficients

[LA, Isidori, Pešut 2503.17019]

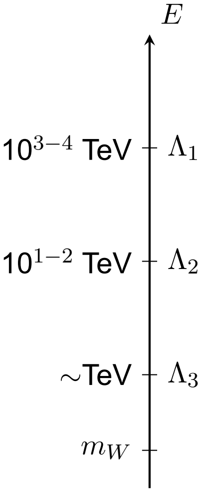
- Assume SM central values and FCC-ee projected errors



Selected Models

Flavour deconstruction

Li, Ma, ’81, Arkani-Hamed, Cohen, Georgi `hep-th/0104005`
Craig, Green, Katz `1103.3708`, Bordone, Cornella, Fuentes-Martin, Isidori `1712.01368`
Davighi, Isidori `2303.01520`, Fernández Navarro, King `2305.07690`
Davighi, Stefanek `2305.16280`, Davighi, Gosnay, Miller, Renner `2312.13346`
Capdevila, Crivellin, Lizana, Pokorski `2401.00848`, ...



- Flavour non-universality arising from gauging the different SM families under different groups
- At the $\sim$ TeV scale, unify light families

$$G_1 \times G_2 \times G_{3+H} \xrightarrow{10^{2-3}\text{ TeV}} G_{12} \times G_{3+H} \xrightarrow{\sim\text{TeV}} G_{\text{SM}}$$

- A $U(2)$ symmetry acting on the light families arises naturally!
- Define $\tan\theta \equiv g_{12}/g_3$
- $\delta m_h^2 \sim \dfrac{g_{\text{SM}}^2 \tan^2\theta M^2}{16\pi^2}$ from flavoured scalars and gauge bosons

What to deconstruct?

Davighi, Isidori 2303.01520

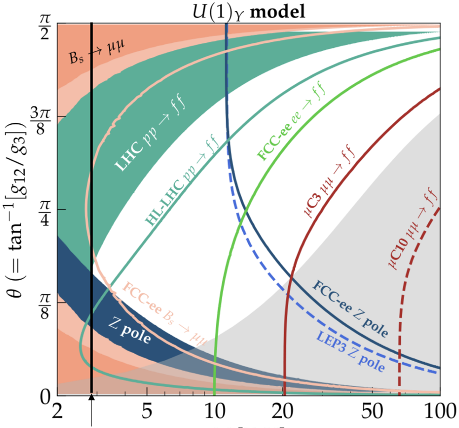
	Deconstructed group	$SU(3)$	$SU(2)_L$	$SU(2)_R$	$U(1)_Y$	$U(1)_{B-L}$
Flavour	$\lvert V_{cb}\rvert \ll 1$	✓	✓	✗	✓	✓
	$y_i \ll y_3$	✗	✓	✓	✓	✗
	Yukawa structure	$\begin{pmatrix} \times & \times & \\ \times & \times & \\ & & \times \end{pmatrix}$	$\begin{pmatrix} & & \\ & & \\ \times & \times & \times \end{pmatrix}$	$\begin{pmatrix} & & \times \\ & & \times \\ & & \times \end{pmatrix}$	$\begin{pmatrix} & & \\ & & \\ & & \times \end{pmatrix}$	$\begin{pmatrix} \times & \times & \\ \times & \times & \\ & & \times \end{pmatrix}$
EW	$\lvert\tan\theta\rvert M$ upper limit	90 Tev	20 TeV	40 TeV	40 TeV	500 TeV
	EWPO order (δm_W)	1-loop	tree	tree	tree	1-loop

- Need to deconstruct the EW group to tackle the flavour puzzle
- δm_h^2 at one loop, but OK if last step of decontruction near the TeV scale
- Tree-level EWPOs $\rightarrow$ constraints

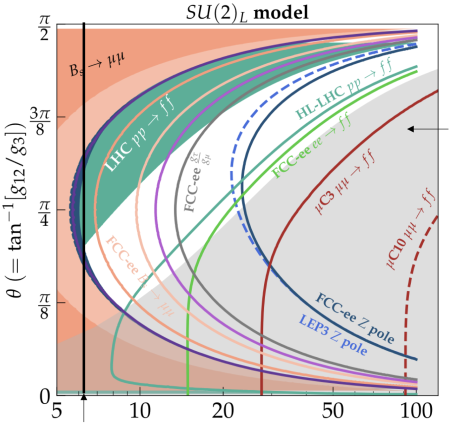
Electroweak deconstruction: phenomenology

Slide from J. Davighi

Updated plots courtesy of Sophie Renner 🙏



Currently, $M \gtrsim 3$ TeV



$M \gtrsim 6$ TeV

$\delta m_h^2 > \text{TeV}^2$

Davighi, MITP, 18/06/25

30

Flavour deconstruction + composite Higgs

Covone, Davighi, Isidori, Pesut 2407.10950

$$Sp(4) \longrightarrow SU(2)_L \times SU(2)_R^{[3]} \times U(1)_Y^{[12]} \longrightarrow U(1)_Y^{\text{SM}}$$

- One step further: address the hierarchy problem by making the Higgs composite

$$m_h^2 = \frac{1}{16\pi^2}\left[4N_c y_t^2 M_T^2 - \frac{9}{2} g_{R,3}^2 M_\rho^2 \left(1 - \frac{2M_{W_R}^2}{M_\rho^2}\right)\right]$$

- Can have large $g_{R,3}$ and M_T (opposite sign)
- Require $2M_{W_R}^2 < M_\rho^2$

Minimal $U(2)$ symmetries

Antusch, Greljo, Stefanek, Thomsen 2311.09288

- Take $U(2)_q$:

$$Y_u \sim \begin{pmatrix} & & \\ & & \\ \times & \times & \times \end{pmatrix} \xrightarrow{U(3)_u \text{ rotation}} \begin{pmatrix} & & \\ & & \\ & & \times \end{pmatrix}$$

- Leads to **accidental** symmetry in the Yukawa couplings ($U(2)_u$)
- Consider $U(2)_{q+e} \xrightarrow{\text{accidental}} U(2)_u \times U(2)_d \times U(2)_\ell$!
- Get:
  - Hierarchy between 3rd generation and light families
  - Anarchic PMNS matrix (no selection rule for the Weinberg operator)
  - No $U(2)$ protection in the NP part (except for $U(2)_{q+e}$)

Hierarchies

[Antusch, Greljo, Stefanek, Thomsen 2311.09288]

Breaking the symmetry with spurions

- Introduce spurions

$$V^\alpha_{1,2} \sim \mathbf{2}_1 \qquad V^\alpha_2 = (0, a), \qquad V^\alpha_1 = (b, 0)$$

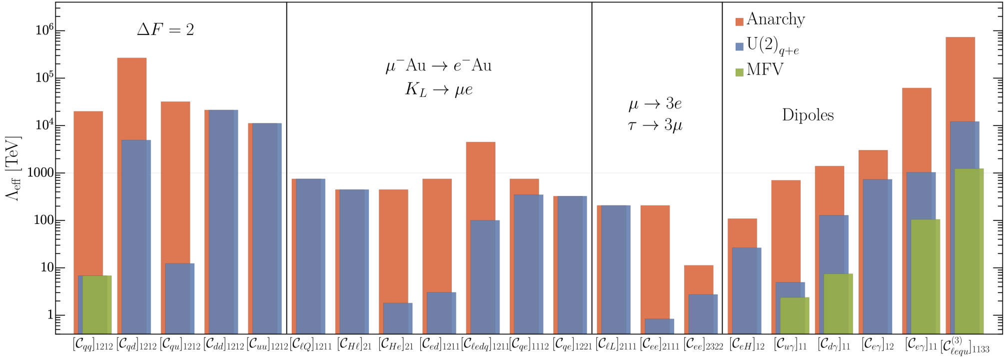
$$\mathcal{L} \supset -(x_{ui}\bar{q}_3 + (y_{ui}V^\alpha_2 + z_{ui}V^\alpha_1)\bar{q}_\alpha)\tilde{H}u_i$$

$$Y_u = \begin{pmatrix} z_{u1}b & z_{u2}b & z_{u3}b \\ & y_{u2}a & y_{u3}a \\ & & x_{u3} \end{pmatrix}$$

- Hierarchical if $0 < b \ll a \ll 1$
- CKM matrix close to the identity (left-handed rotation dominates)
- High-scale NP due to selection rules

Phenomenology

[Antusch, Greljo, Stefanek, Thomsen 2311.09288]



- Less flavour protection than e.g. MFV or $U(2)^5 \to 10^{3-4}$ TeV with current data
- Expect $\mathcal{O}(10)$ improvement in $\mu \to e$ conversion (Mu2e, COMET)

Possible UV completion: gauge $SU(2)_{q+e}$

$SU(3)_c \times SU(2)_L \times U(1)_Y \times SU(2)_{q+e}$

- Anomalous: need to add extra fermions (+ scalar(s) to break the gauge symmetry): Ψ, Φ
- Spurions generated by integrating out vector-like fermions: Q, E

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(2)_{q+e}$
Ψ_R^α	**1**	**1**	2	**2**
Ψ_L^i	**1**	**1**	2	**1**
Φ^α	**1**	**1**	0	**2**
Q	**3**	**2**	1/6	**1**
E	**1**	**1**	-1	**1**

$$\mathcal{L} \supset -y_{ui}\bar{Q}\tilde{H}u^i - y_{di}\bar{Q}Hd^i - y_{ei}\bar{\ell}^i HE$$

$$\mathcal{L} \supset -\kappa\bar{q}\Phi Q - \tilde{\kappa}\bar{q}\widetilde{\Phi}Q \supset -\kappa\bar{e}\Phi E - \tilde{\kappa}\bar{e}\widetilde{\Phi}E$$

$$V_2^\alpha = \frac{\kappa}{M}\langle\Phi^\alpha\rangle + \frac{\tilde{\kappa}}{M}\langle\widetilde{\Phi}^\alpha\rangle$$

- Rank-2 Yukawas $\to m_1 = 0$
- Get hierarchy for $M_Q = M_E \approx 100 v_\Phi$

- First family masses:
  - Heavier VLFs
  - Extra scalars: radiatively generated

[Antusch, Greljo, Stefanek, Thomsen 2311.09288]

Another interesting possibility: $U(2)_{q+e^c+u^c}$: **10** of $SU(5)$...

Summary

- New Physics with $U(2)$-like structure is generally compatible with the ~ 10 TeV cale
- If coupling to third generation is stronger, currently probing only $\sim$ TeV scale
- Before going to 10 TeV or above directly, indirect probes can provide important hints about the possible NP scale
  $\rightarrow \sim 10$ TeV bounds even suppressing light generations
- Huge leap in precision with FCC-ee
  - EWPOs can probe many different NP scenarios
    $\rightarrow$ sensitive to loop effects from heavy NP
  - Linear extensions of the SM probed from $\mathcal{O}(1)$ up to $\mathcal{O}(100)$ TeV scale
  - (Heavy) flavour prospects complementary to B factories and LHC
- Models with flavour non-universal (deconstructed) gauge interactions offer a possible dynamical explanation
- Models with $U(2)$ symmetries to address the flavour puzzle in the 10^{3-4} TeV range

Thank you!

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Backup

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}

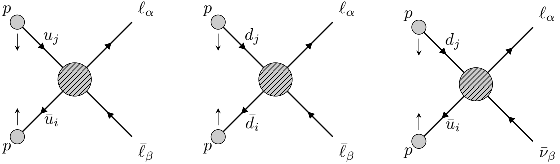
Phenomenology: EWPO

- 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 $U(2)^5$ limit
- Include also Higgs decays, τ LFU tests

#	Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]
1	cHWB	A_b^{FB}	9.63
2	CHl1[l]	σ_{had}	8.07
3	CHl3[l]	A_b^{FB}	7.96
4	CHe[l]	σ_{had}	6.93
5	cHD	A_b^{FB}	5.74
6	CHq3[l]	R_τ	5.73
7	CHl1[h]	R_τ	4.57
8	CHl3[h]	R_τ	4.48
9	Cll[l, p, p, l]	A_b^{FB}	4.43
10	CHe[h]	R_τ	3.97
11	CHq3[h]	R_b	3.43
12	CHq1[h]	R_b	3.43
13	CHu[l]	R_τ	2.58
14	CHq1[l]	R_c	2.07
15	CHd[l]	R_τ	1.81
16	CHd[h]	R_b	1.4

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, σ_{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]

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:

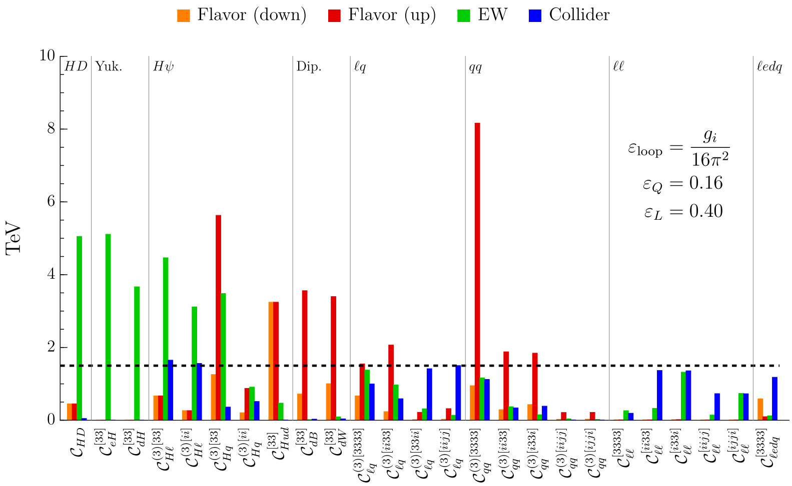
$$\mathcal{C}_{He}^{[ii]}(H^\dagger i \overleftrightarrow{D}_\mu H)\sum_{i=1}^{2}(\bar{e}_i\gamma^\mu e_i) \to \varepsilon_L^2\,\mathcal{C}_{He}^{[ii]}(H^\dagger i \overleftrightarrow{D}_\mu H)\sum_{i=1}^{2}(\bar{e}_i\gamma^\mu e_i)$$

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

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

Suppressing the light families

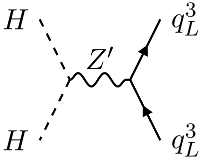
[LA, Cornella, Isidori, Stefanek 2311.00020]



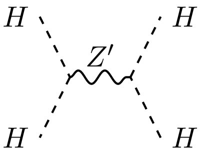
- operators with Higgs fields still give strong bounds (EWPO)

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



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



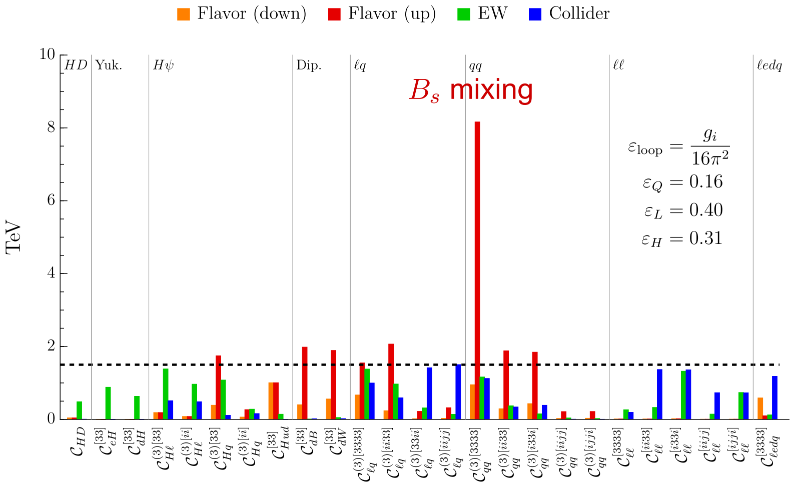
$\mathcal{C}_{HD}|H^\dagger\overleftrightarrow{D}_\mu H|^2$

$U(2)^5$ 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

Suppressing Higgs couplings

[LA, Cornella, Isidori, Stefanek 2311.00020]



- Some flavour bounds still large (in the up-aligned case)

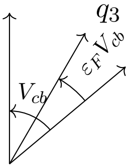
Flavour alignment in the 3rd generation

[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:

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

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



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

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

SM predictions: impact of $|V_{cb}|$

$$O^{\nu}_{\ell,ij} = (\bar{d}^i{}_L \gamma_\mu d^j_L)(\bar{\nu}^\ell_L \gamma^\mu \nu^\ell_L)$$

- At $\mu = m_{b,s}$: $\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi} \sum_{\ell=e,\mu,\tau} \left[\lambda^t_{sd} C^{\text{SM}}_{\ell,sd}\, O^{\nu}_{\ell,sd} + \lambda^t_{bs} C^{\text{SM}}_{\ell,bs}\, O^{\nu}_{\ell,bs}\right] + \text{h.c.}$
- Leading uncertainty from V_{cb}:

$$\lambda^t_{sd} = V_{ts}V^*_{td} = \lambda|V_{cb}|^2 \left[(\bar{\rho}-1)\left(1-\frac{\lambda^2}{2}\right) + i\bar{\eta}\left(1+\frac{\lambda^2}{2}\right)\right]$$

- Take average between inclusive and exclusive, inflating errors [Finauri+Gambino '24] [Bordone+Juttner '24]

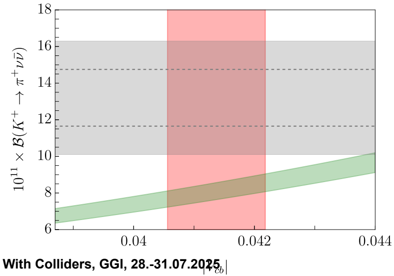
$$|V_{cb}|_{\text{incl+excl}} = (41.37 \pm 0.81) \times 10^{-3}$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})^{\text{SM}} = (8.09 \pm 0.63) \times 10^{-11}$$

- $b \to s\nu\bar{\nu}$: Bečirević et al. `2301.06990`

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})/|\lambda^t_{bs}|^2 = (2.87 \pm 0.10) \times 10^{-3}$$

- First measurement by NA62 in 2024!

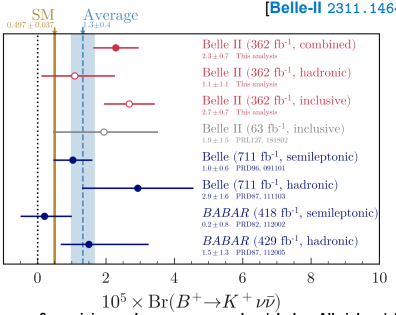


Example: $d_i \to d_j \nu\nu$ transitions

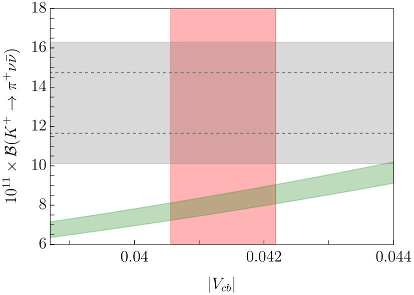
- FCNC: high-scale probes due to loop+GIM suppression
- Clean: no theory uncertainty due to charm rescattering
- Very rare, exp. challenging
- Only probes of third-gen. leptons so far

- First measurement in 2023 by Belle-II:

[Belle-II 2311.14647]



- NA62 2024



SMEFT description of $d_i \to d_j \nu\bar{\nu}$

[LA, Bordone, Isidori, Piazza, Stanzione 2410.21444]

[1903.10954]

- Start with third-generation indices only: **rank-one hypothesis**

$$Q_{\ell q}^{\pm} = (\bar{q}_L^3 \gamma^\mu q_L^3)(\bar{\ell}_L^3 \gamma_\mu \ell_L^3) \pm (\bar{q}_L^3 \gamma^\mu \sigma^a q_L^3)(\bar{\ell}_L^3 \gamma_\mu \sigma^a \ell_L^3)$$

$$Q_S = (\bar{\ell}_L^3 \tau_R)(\bar{b}_R q_L^3)$$

- Third generation LH quarks: **down alignment**

$$q_L^3 = \begin{pmatrix} V_{ub} u_L + V_{cb} c_L + V_{tb} t_L \\ b_L \end{pmatrix}$$

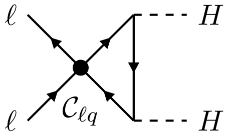
- $U(2)_q$-breaking spurion

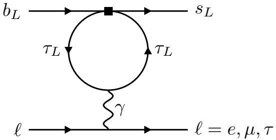
$$\tilde{V} = -\varepsilon V_{ts} \begin{pmatrix} \kappa V_{td}/V_{ts} \\ 1 \end{pmatrix}$$

- Replace $q_L^3 \to q_L^3 + \tilde{V}_i q_L^i$
- System described by 5 parameters: C_S, $C_{\ell q}^+$, $C_{\ell q}^-$, ε, κ

Correlated observables

[LA, Bordone, Isidori, Piazza, Stanzione 2410.21444]





	C_S	$C_{\ell q}^{+}$	$C_{\ell q}^{-}$	ε	κ	Exp. indication
$\sigma(pp \to \ell\ell)$	✓	✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
EWPO		✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
R_D, R_{D^*}	✓	✓	✓	✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}} > 0$
$\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})$		✓		✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}} < 0$
$\mathcal{B}(B \to K\nu\bar{\nu})$			✓	✓		$\lvert\mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{NP}}\rvert^2 > \lvert\mathcal{A}_{\text{SM}}\rvert^2$
$\mathcal{B}(K \to \pi\nu\bar{\nu})$			✓	✓	✓	$\lvert\mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{NP}}\rvert^2 > \lvert\mathcal{A}_{\text{SM}}\rvert^2$

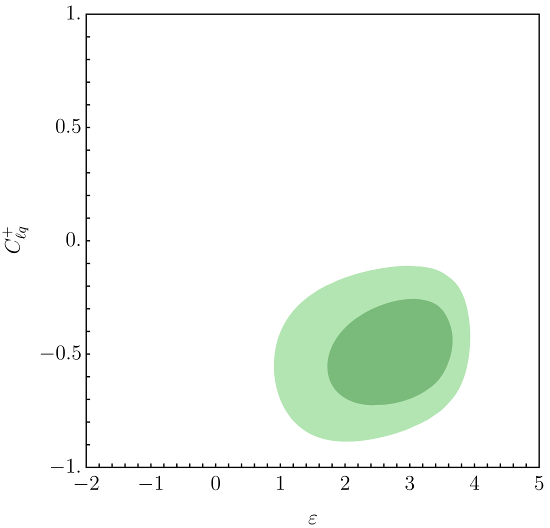
Results: $C^{+}_{\ell q}$-ε

[LA, Bordone, Isidori, Piazza, Stanzione 2410.21444]

- Global fit without di-neutrino modes (don't affect $C^{+}_{\ell q}$)
- LHC Drell-Yan + EWPO provide constraints on $C^{\pm}_{\ell q}$ and C_S
- C_S compatible with zero (LHC constraints strong)
- Non-zero $C_{\ell q^+}$ and ε driven by $R_{D^{(*)}}$:

$$\frac{R_{D^{(*)}}}{R^{\text{SM}}_{D^{(*)}}} \approx 1 + 2\text{Re}\left(C_{V_L}\right)$$
$$\approx 1 - v^2\left(1+\varepsilon\right)\left(C^{+}_{\ell q} - C^{-}_{\ell q}\right)$$

- Suppress $|\varepsilon| > 3$ with theoretical likelihood



[LA, Bordone, Isidori, Piazza, Stanzione 2410.21444]

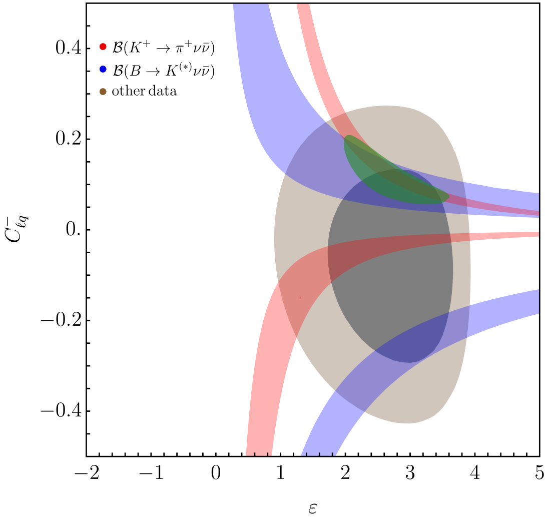
Results: $C^-_{\ell q}$-ε

- Grey: Global fit without di-neutrino modes, $\kappa = 1$
- $C^-_{\ell q}$ largely unconstrained
- Good compatibility with di-neutrino modes for $\kappa = 1$

$$|C^{\rm SM}_{\tau,bs}| \to \left| C^{\rm SM}_{\tau,bs} - \varepsilon \frac{\pi v^2}{\alpha} C^-_{\ell q} \right| ,$$

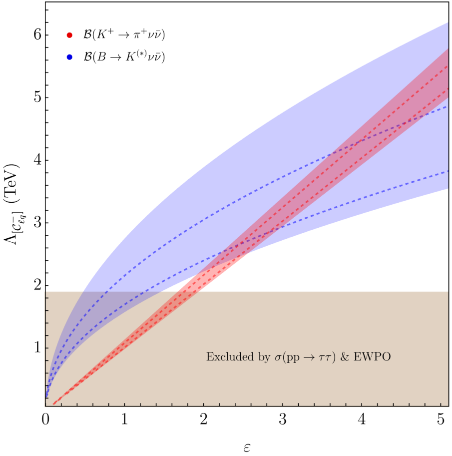
$$|C^{\rm SM}_{\tau,sd}| \to \left| C^{\rm SM}_{\tau,sd} + \kappa\varepsilon^2 \frac{\pi v^2}{\alpha} C^-_{\ell q} \right| .$$

- Select $C^-_{\ell q} > 0$

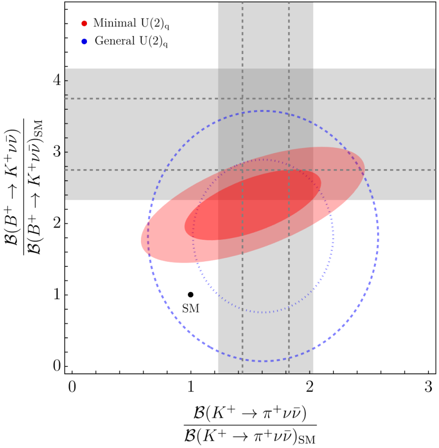


Future prospects

> Measure ε with dineutrino modes



> Minimal vs. non-minimal $U(2)_q$ breaking



Z- and W Lagrangian

- Effective description at the EW scale:

$$\begin{aligned}\mathcal{L}_{\text{eff}} \supset &-\frac{g_L}{\sqrt{2}} W^{+\mu}\left[\bar{u}^i_L\gamma_\mu\left(V_{ij}+\delta g^{Wq}_{ij}\right)d^j_L+\bar{\nu}^i_L\gamma_\mu\left(\delta_{ij}+\delta g^{W\ell}_{ij}\right)e^j_L\right]+\text{h.c.}\\ &-\sqrt{g_L^2+g_Y^2}\,Z^\mu\left(\bar{f}^i_L\gamma_\mu\left(g^{Zf}_L\delta_{ij}+\delta g^{Zf}_{L\,ij}\right)f^j_L+\bar{f}^i_R\gamma_\mu\left[g^{Zf}_R\delta_{ij}+\delta g^{Zf}_{R\,ij}\right]f^j_R\right)\\ &+\frac{g_L^2v^2}{4}(1+\delta m_W)^2W^{+\mu}W^-_\mu+\frac{g_L^2v^2}{8c_W^2}Z^\mu Z_\mu\end{aligned}$$

- Given already current exp. precision, expect small NP effects $\to$ consider only flavour-conserving pieces (interference with SM)
- $SU(2)_L$ fixes

$$\delta g^{Z\nu}_L=\delta g^{W\ell}_L+\delta g^{Ze}_L\,,\quad \delta g^{Wq}_L=\delta g^{Zu}_L V-V\delta g^{Zd}_L$$

- 20 independent parameters:

$$\begin{aligned}\delta g \in \{&\delta g^{Z\nu}_{L\,11(22,33)},\delta g^{Ze}_{L\,11(22,33)},\delta g^{Ze}_{R\,11(22,33)},\\ &\delta g^{Zu}_{L\,11(22)},\delta g^{Zu}_{R\,11(22)},\delta g^{Zd}_{L\,11(22,33)},\delta g^{Zd}_{R\,11(22,33)},\delta m_W\}\end{aligned}$$

Mapping to SMEFT: basis

- Use Warsaw basis [1008.4884]
- $\psi^2 H^2 D$ operators

$$\mathcal{C}_{H\psi}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\psi}\gamma^\mu\psi) \xrightarrow{H\to\langle H\rangle} -\frac{v^2}{2}\mathcal{C}_{H\psi}Z_\mu(\bar{\psi}\gamma^\mu\psi)$$

$[\mathcal{O}_{H\ell}^{(1)}]_{pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}_p\gamma^\mu\ell_r)$	$[\mathcal{O}_{He}]_{pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$[\mathcal{O}_{H\ell}^{(3)}]_{pr} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p\tau^I\gamma^\mu\ell_r)$	$[\mathcal{O}_{Hu}]_{pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$[\mathcal{O}_{Hq}^{(1)}]_{pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$[\mathcal{O}_{Hd}]_{pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$[\mathcal{O}_{Hq}^{(3)}]_{pr} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	

- Bosonic operators

$$\mathcal{O}_{HD} = |H^\dagger D_\mu H|^2 \quad \mathcal{O}_{HWB} = (H^\dagger\tau^I H)W^I_{\mu\nu}B^{\mu\nu}$$

$\to$ associated with T and S parameters

- Four-fermion operator

$$[\mathcal{O}_{\ell\ell}]_{1221} = (\bar{\ell}_1\gamma^\mu\ell_2)(\bar{\ell}_2\gamma^\mu\ell_1)$$

Mapping to SMEFT: matching

- Matching of the δgs:

$$\delta g^{Z\nu}_{L\,ii} = -\frac{v^2}{2}\left([\mathcal{C}^{(1)}_{H\ell}]_{ii} - [\mathcal{C}^{(3)}_{H\ell}]_{ii}\right) + \delta^U(1/2,0)$$
$$\delta g^{Ze}_{L\,ii} = -\frac{v^2}{2}\left([\mathcal{C}^{(1)}_{H\ell}]_{ii} + [\mathcal{C}^{(3)}_{H\ell}]_{ii}\right) + \delta^U(-1/2,-1)$$
$$\delta g^{Ze}_{R\,ii} = -\frac{v^2}{2}[\mathcal{C}_{He}]_{ii} + \delta^U(0,-1)$$
$$\delta g^{Zu}_{L\,ii} = -\frac{v^2}{2}\left([\mathcal{C}^{(1)}_{Hq}]_{ii} - [\mathcal{C}^{(3)}_{Hq}]_{ii}\right) + \delta^U(1/2,2/3),$$
$$\delta g^{Zu}_{R\,ii} = -\frac{v^2}{2}[\mathcal{C}_{Hu}]_{ii} + \delta^U(0,2/3)$$
$$\delta g^{Zd}_{L\,ii} = -\frac{v^2}{2}\left([\mathcal{C}^{(1)}_{Hq}]_{ii} + [\mathcal{C}^{(3)}_{Hq}]_{ii}\right) + \delta^U(-1/2,-1/3)$$
$$\delta g^{Zd}_{R\,ii} = -\frac{v^2}{2}[\mathcal{C}_{Hd}]_{ii} + \delta^U(0,-1/3)$$

$$\delta m_W = -\frac{v^2 g_L^2}{4(g_L^2-g_Y^2)}\mathcal{C}_{HD} - \frac{v^2 g_L g_Y}{g_L^2-g_Y^2}\mathcal{C}_{HWB} + \frac{v^2 g_Y^2}{4(g_L^2-g_Y^2)}\left([\mathcal{C}_{\ell\ell}]_{1221} - 2[\mathcal{C}^{(3)}_{H\ell}]_{22} - 2[\mathcal{C}^{(3)}_{H\ell}]_{11}\right)$$

- Universal contribution:

$$\delta^U(T^3,Q) = -v^2\left(T^3 + Q\frac{g_Y^2}{g_L^2-g_Y^2}\right)\left(\frac{1}{4}\mathcal{C}_{HD} + \frac{1}{2}[\mathcal{C}^{(3)}_{H\ell}]_{22} + \frac{1}{2}[\mathcal{C}^{(3)}_{H\ell}]_{11} - \frac{1}{4}[\mathcal{C}_{\ell\ell}]_{1221}\right) - v^2 Q\frac{g_L g_Y}{g_L^2-g_Y^2}\mathcal{C}_{HWB}$$

Input redefinitions

- Universal contribution:

$$\delta^U(T^3,Q) = -v^2\left(T^3 + Q\frac{g_Y^2}{g_L^2-g_Y^2}\right)\left(\frac{1}{4}\mathcal{C}_{HD} + \frac{1}{2}[\mathcal{C}_{H\ell}^{(3)}]_{22} + \frac{1}{2}[\mathcal{C}_{H\ell}^{(3)}]_{11} - \frac{1}{4}[\mathcal{C}_{\ell\ell}]_{1221}\right) - v^2 Q\frac{g_L g_Y}{g_L^2-g_Y^2}\mathcal{C}_{HWB}$$

- Input scheme: α, G_F, m_Z
- G_F is extracted from $\mu \to e\nu\bar{\nu}$ decay
  $\to$ anything modifying the decay rate in SMEFT is not observable, but gets propagated through the inputs (vev, gauge couplings)
  - $[\mathcal{C}_{H\ell}^{(3)}]_{11,22}$: W-coupling modifications
  - $[\mathcal{C}_{\ell\ell}]_{1221}$: direct four-fermion contact interaction
- m_Z gets a contribution from $\mathcal{C}_{HD}$ and $\mathcal{C}_{HWB}$ in SMEFT

The set of Electroweak Wilson Coefficients

- From matching conditions + input redefinitions:

$$\vec{\mathcal{C}}_{\text{ew}} = ([\mathcal{C}_{H\ell}^{(1,3)}]_{ii}, [\mathcal{C}_{Hq}^{(1,3)}]_{ii}, [\mathcal{C}_{He}]_{ii}, [\mathcal{C}_{Hu}]_{ii}, [\mathcal{C}_{Hd}]_{ii}, \mathcal{C}_{HD}, \mathcal{C}_{HWB}, [\mathcal{C}_{\ell\ell}]_{1221})$$

- Note: For $\mathcal{C}_{Hu}$ $i = 1, 2$ only (no RH tops)
- Total of **23 parameters**
- Assuming all 20 δgs can be constrained individually, one expects 3 flat directions in the SMEFT EW fit

$$\mathcal{C}_0^{(1)} \propto [\mathcal{C}_{Hq}^{(1)}]_{33} - [\mathcal{C}_{Hq}^{(3)}]_{33}$$

[cf. also hep-ph/0602154 and 1701.06424]

$$\mathcal{C}_0^{(2)} \propto -\frac{g_Y}{g_L}\mathcal{C}_{HWB} + \sum_{i=1}^{3}\left([\mathcal{C}_{H\ell}^{(3)}]_{ii} + [\mathcal{C}_{Hq}^{(3)}]_{ii}\right)$$

$$\mathcal{C}_0^{(3)} \propto 2\,\mathcal{C}_{HD} - \frac{1}{2}\frac{g_L}{g_Y}\mathcal{C}_{HWB} + \sum_{\psi}\sum_{i} Y_\psi [\mathcal{C}_{H\psi}]_{ii}$$

RGE effects, systematically

- RGE equations for EW operators (y_t, g_1 and g_2 contributions)

$$
\begin{aligned}
\dot{\mathcal{C}}_{HD} &= N_c\left(\frac{16}{3}Y_H Y_u g_1^2 - 8y_t^2\right)\mathcal{C}_{Hu}^{33} + \frac{80}{3}g_1^2 Y_H^2 \mathcal{C}_{H\Box} \\
\dot{\mathcal{C}}_{Hf_1}^{(1)jj} &= 2N_c y_t^2\left(-S_{f_1 u}\mathcal{C}_{uf_1}^{33jj} + S_{f_1 q}\mathcal{C}_{qf_1}^{33jj}\right) \\
\dot{\mathcal{C}}_{Hl}^{(3)jj} &= -2N_c y_t^2 \mathcal{C}_{lq}^{(3)jj33} \\
\dot{\mathcal{C}}_{Hq}^{(3)jj} &= -2y_t^2\left(2N_c\mathcal{C}_{qq}^{(3)jj33} + \mathcal{C}_{qq}^{(1)j33j} - \mathcal{C}_{qq}^{(3)j33j}\right) \\
\dot{\mathcal{C}}_{Hf_1}^{(1)jj} &= \frac{4}{3}g_1^2 Y_h \sum_k \Big[Y_e S_{f_1 e}\mathcal{C}_{f_1 e}^{jjkk} + 2Y_l S_{f_1 l}\mathcal{C}_{f_1 l}^{jjkk} \\
&\quad + N_c\left(Y_u S_{f_1 u}\mathcal{C}_{f_1 u}^{jjkk} + Y_d S_{f_1 d}\mathcal{C}_{f_1 d}^{jjkk} + 2Y_q S_{f_1 q}\mathcal{C}_{f_1 q}^{jjkk}\right)\Big] \\
\dot{\mathcal{C}}_{Hl}^{(3)jj} &= \frac{2}{3}g_2^2 \sum_k \left(\mathcal{C}_{ll}^{jkkj} + N_c\mathcal{C}_{lq}^{(3)jjkk}\right), \\
\dot{\mathcal{C}}_{Hq}^{(3)jj} &= \frac{2}{3}g_2^2 \sum_k \left(\mathcal{C}_{lq}^{(3)kkjj} + 2N_c\mathcal{C}_{qq}^{(3)kkjj} + \mathcal{C}_{qq}^{(1)jkkj} - \mathcal{C}_{qq}^{(3)jkkj}\right) \\
\dot{\mathcal{C}}_{ll}^{1221} &= \frac{2}{3}g_2^2\left[\mathcal{C}_{ll}^{2222} + \mathcal{C}_{ll}^{2332} + \mathcal{C}_{ll}^{1111} + \mathcal{C}_{ll}^{1331} + N_c\sum_k\left(\mathcal{C}_{lq}^{(3)22kk} + \mathcal{C}_{lq}^{(3)11kk}\right)\right]
\end{aligned}
$$

To avoid EWPOs at one loop, need to have R.H.S.$=0$ for all the above *at the same time*

Scalars

State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
$\mathcal{S}$	✓	✗	A_e
$\mathcal{S}_1$	✓ if $(y_{\mathcal{S}_1})_{12} = 0$	✗	A_e
$\mathcal{S}_2$	✓	✗	A_e (R_τ)
φ	✓	✗	Γ_Z
Ξ	✗	✗	m_W
Ξ_1	✓ if $\kappa_{\Xi_1} = 0$ & $(y_{\Xi_1})_{12} = 0$	✗	m_W
Θ_1	✓	✓*	m_W
Θ_3	✓	✓*	m_W
ω_1	✓	✗	Γ_Z
ω_2	✓	✗	Γ_Z
ω_4	✓	✗	A_e (R_τ)
Π_1	✓	✗	A_e (R_τ)
Π_7	✓	✗	R_τ
ζ	✓	✗	Γ_Z (R_τ)
Ω_1	✓	✗	Γ_Z
Ω_2	✓	✗	Γ_Z
Ω_4	✓	✓ if $(y_{\Omega_4})_{33} \neq 0$, all else zero	Γ_Z (-)
Υ	✓	✗	Γ_Z
Φ	✓	✗	Γ_Z

Fermions

State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
N	✗	✗	A_e (Γ_Z)
E	✗	✗	Γ_Z (R_τ)
Δ_1	✗	✗	A_e (R_τ)
Δ_3	✗	✗	A_e (R_τ)
Σ	✗	✗	Γ_Z (R_τ)
Σ_1	✗	✗	A_e (Γ_Z)
U	✓ if $(\lambda_U)_3 \neq 0$, all else zero	✗	Γ_Z (m_W)
D	✗	✗	Γ_Z
Q_1	✓ if $(\lambda^u_{Q_1})_3 \neq 0$, all else zero	✗	m_W
Q_5	✗	✗	Γ_Z
Q_7	✓ if $(\lambda_{Q_7})_3 \neq 0$, all else zero	✗	m_W
T_1	✗	✗	m_W (Γ_Z)
T_2	✗	✗	Γ_Z

Vectors

State	Tree level zero possible?	1-loop RGE zero possible?	Bounding obs.
$\mathcal{B}$	✓ if $(g^{\phi}_{\mathcal{B}}) = 0$ & $(g^{l}_{\mathcal{B}})_{12} = 0$	✓ if eqns. (**??**)	m_W
$\mathcal{B}_1$	✓ if $(g^{\phi}_{\mathcal{B}_1}) = 0$	✗	m_W
$\mathcal{W}$	✓ if $(g^{\phi}_{\mathcal{W}}) = 0$ & $K_{12}(g^{l}_{\mathcal{W}}) = 0$	✓ if eqns. (**??**)	A_e (Γ_Z)
$\mathcal{W}_1$	✗	✗	m_W
$\mathcal{G}$	✓	✓ if $(g^{u}_{\mathcal{G}})_{33} \neq 0$, all else zero	Γ_Z
$\mathcal{G}_1$	✓	✗	Γ_Z
$\mathcal{H}$	✓	✗	Γ_Z
$\mathcal{L}_1$	✗	✗	A_e
$\mathcal{L}_3$	✓	✗	A_e (A_τ)
$\mathcal{U}_2$	✓	✗	Γ_Z
$\mathcal{U}_5$	✓	✗	R_τ
$\mathcal{Q}_1$	✓	✗	R_τ
$\mathcal{Q}_5$	✓	✗	Γ_Z
$\mathcal{X}$	✓	✗	R_τ
$\mathcal{Y}_1$	✓	✗	Γ_Z
$\mathcal{Y}_5$	✓	✗	Γ_Z

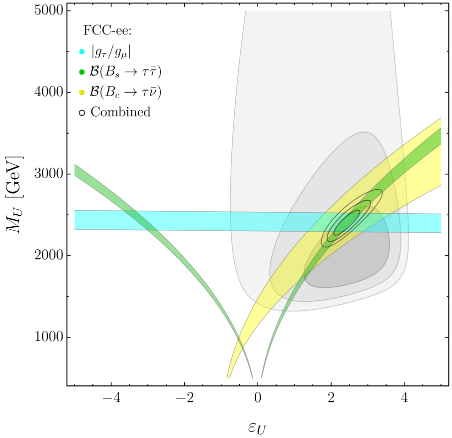
An explicit (simplified) model

U_1 leptoquark + Z'

[LA, Isidori, Pešut 2503.17019]

$$\mathcal{L}_{\text{int}} \supset \frac{g_4}{\sqrt{2}} \left[U_\mu \left(\bar{q}_L^3 \gamma^\mu \ell_L^3 \right) + \text{H.c.} \right] + \frac{g_4}{2\sqrt{6}} Z'_\mu \left(\bar{q}_L^3 \gamma^\mu q_L^3 \right) - \frac{3}{2} \frac{g_4}{\sqrt{6}} Z'_\mu \left(\bar{\ell}_L^3 \gamma^\mu \ell_L^3 \right)$$

- $SU(4)$-unification inspired construction
- Heavy $U_1 \sim (3,1,2/3)$ and Z' vectors with third-gen. coupling
- $\mathcal{C}_{\ell q}^{(1)[3333]} = \mathcal{C}_{\ell q}^{(3)[3333]} = \frac{g_4^2 v^2}{8 M_U^2}$
- $\mathcal{C}_{\ell q}^{(1)[3333]} = -\frac{g_4^2 v^2}{32 M_Z^2}$



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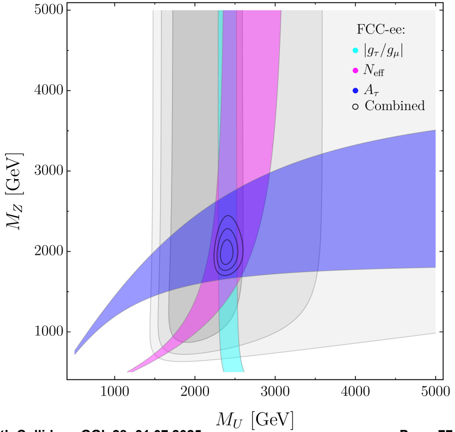


$U_1 + Z'$

> Central values and errors used in the FCC projections

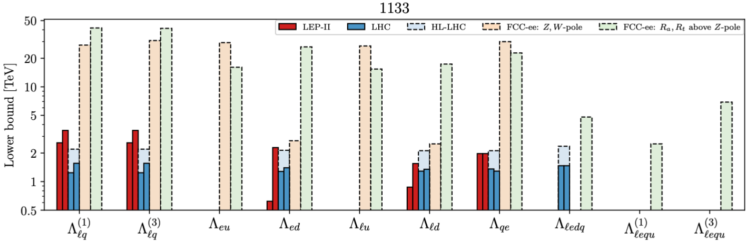
Observable	SM	FCC projection
$B_c \to \tau\nu$	$(1.95 \pm 0.09) \times 10^{-2}$	$(2.09 \pm 0.03) \times 10^{-2}$
$B \to K\nu\bar{\nu}$	$(4.44 \pm 0.30) \times 10^{-6}$	$(5.64 \pm 0.17) \times 10^{-6}$
$B \to K^*\nu\bar{\nu}$	$(9.8 \pm 1.4) \times 10^{-6}$	$(12.4 \pm 0.4) \times 10^{-6}$
$B \to K\tau\tau$	$(1.64 \pm 0.06) \times 10^{-7}$	$(4.2 \pm 0.8) \times 10^{-6}$
$B_s \to \tau\tau$	$(7.45 \pm 0.26) \times 10^{-7}$	$(2.18 \pm 0.22) \times 10^{-5}$
$\Delta M_{B_s} / \Delta M_{B_s}^{\text{SM}}$	1.0	0.862 ± 0.015
$\lvert g_\tau / g_\mu \rvert$	1.0	$0.99926(7)$
N_{eff}	3.0	$2.9979(6)$
A_τ	0.147	$0.14668(21)$
A_b	0.935	$0.93502(22)$

EWPOs off the pole: four-fermion operators

Energy-enhancement compensates luminosity

- Four-fermion operators, e.g. $eebb$, have negligible contribution on the pole to e.g. R_b
- Off the pole, energy-enhanced amplitudes in the EFT
- Comparable sensitivity w.r.to the pole (loop effects)
- Can dominate when the RGE effect is smaller (e.g. gauge coupling running)
- At $t\bar{t}$, define $R_t = \sigma(e^+e^- \to t\bar{t})/\sigma(e^+e^- \to q\bar{q})$

[Greljo, Tiblom, Valenti 2411.02485]

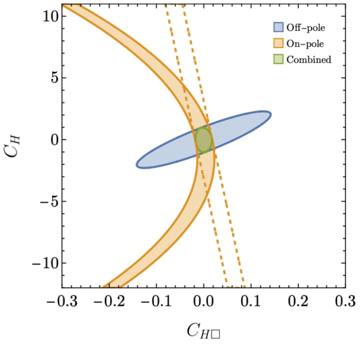


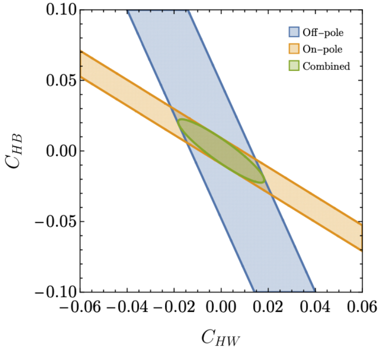
Higgs on the Z-pole

[Maura, Stefanek, You 2412.14241]

Precision against loops

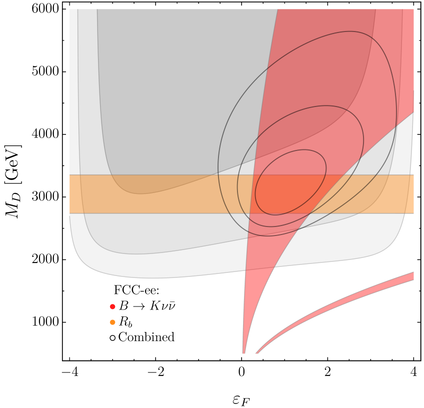
- Modified hVV coupling gives, at NLO, contribution in gauge boson self-energy
- EWPOs on the Z-pole can be sensitive and complementary probes
- See Ben Stefanek's talk for this and more





Vector-like fermions

- $D \sim (3, 1, -1/3)$
- Flavour: modified $Z\bar{b}_L s_L$ vertex
- Sensitivity to ε_F (spurion)



- $E \sim (1, 1, -1)$
- Flavour: insensitive to M_E
- EW: modified $Z\tau_L\tau_L$ vertex