Theory Insights on New Physics from Rare Decays

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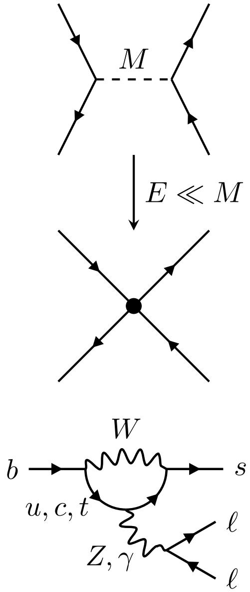
HELMHOLTZ

Rare decays as BSM probes

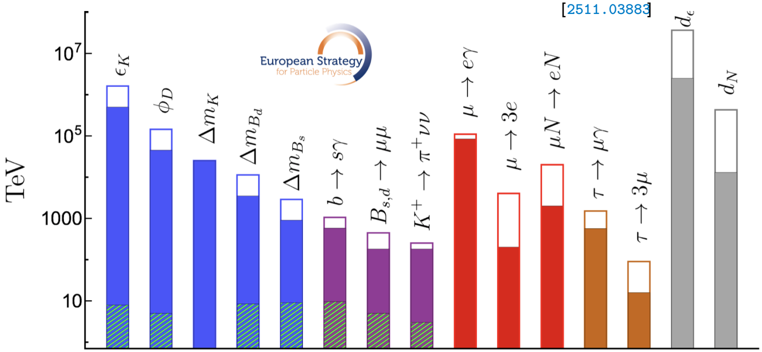


- Through indirect effects, precision measurements can give insights into scales much higher than the ones involved in the process
- Particularly powerful when the SM rate for a process is suppressed:
  - FCNCs (e.g. $b \to s\ell\ell$)
  - LFV (e.g $\mu \to e\gamma$)
- In recent years, also tests of universality
  - LFU ratios (R_K, R_D, ...)

$$\frac{1}{M^2} \leftrightarrow \frac{1}{16\pi^2}\frac{\varepsilon}{v^2}$$

Current status

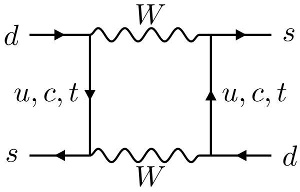
- In the absence of any BSM signals, set bounds
- Each observable mediated by a contact interaction $\frac{1}{\Lambda^2}\mathcal{O}^{d=6}_{\text{eff}} \to \Lambda > \cdots$
- European Strategy for Particle Physics ’26



What is the scale of New Physics?

- Depends on the assumptions! Doesn't have to be 10^6 TeV ($\leftrightarrow$ anarchic flavour)
- Take again $K - \bar{K}$ mixing in the SM:

$$\frac{e^{i\phi}}{\Lambda^2} = \frac{(V_{td}V_{ts}^*)^2 G_F^2 m_t^2}{16\pi^2}$$



$\rightarrow$ much lower scale (m_W, m_t) through CKM suppression!

- What if NP follows a similar structure/mechanism?
  $\rightarrow$ flavour-changin contributions form NP may be suppressed as well

$\boxed{\text{What is the flavour structure of TeV-scale NP?}}$

The New Physics Flavour Puzzle

Exploring the UV systematically

Standard Model Effective Field Theory

- 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**

Flavour assumptions: $U(2)^5$

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

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

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

$$Y \simeq y_3 \left(\begin{array}{cc|c} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \hline 0 & 0 & 1 \end{array}\right)$$

[**Barbieri, Isidori, Lodone, Straub** 1105.2296]

$$U(2)^5 = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

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:

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

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	$U(2)^5$ 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
$\psi^2 H^3$	3	3	6	6	6	6	9	9	9	9	12	12	12	12
$\psi^2 XH$	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 $\mathcal{O}(V^3,\Delta^1V^1)$. Notations as in Table 1.

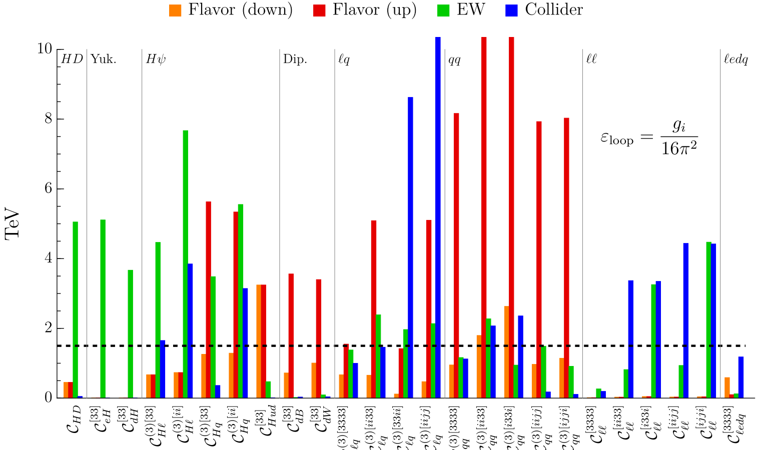
How low can the NP scale be?

- consider collider, electroweak and flavour observables

SMEFT fits to $U(2)$ operators

[LA, Cornella, Isidori, Stefanek 2311.00020]

- From 10^6 to ~ 10 TeV through $U(2)^5$
- $U(2) \neq$ third-gen. new physics:
  light families unsuppressed $\rightarrow$ bounds from flavour-conserving transitions

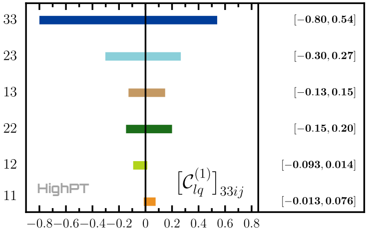


Third-generation New Physics?

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

- Even with $U(2)$ symmetry, direct bounds from colliders are in the 10 TeV range
- Take e.g. Drell-Yan, light quarks in the initial state are much more constrained
- What if NP couples mainly to the third generation?
  $\rightarrow$ assume some dynamical suppression mechanism exists, shielding the light fields from heavy new physics
- In the EFT, introduce suppression factors, e.g.
  $q_i \rightarrow \varepsilon_Q q_i$ for each light quark field

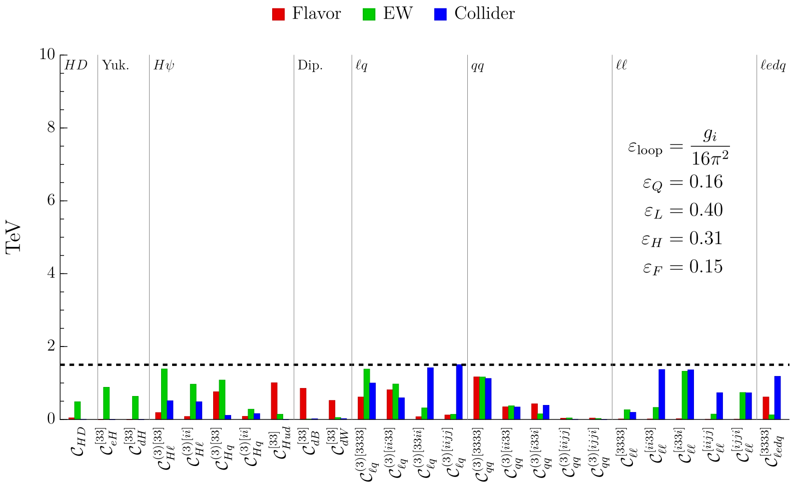
$pp \to \tau\tau$



[LA, Cornella, Isidori, Stefanek 2311.00020]

Third-generation hypothesis

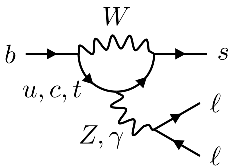
- Suppress operators with light fermion indices
- Λ_{NP} still compatible with $\sim$ TeV under non-tuned conditions



FCNCs as BSM probes

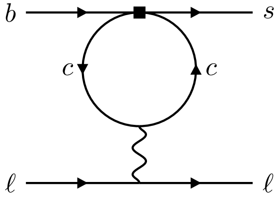
A case study

- FCNCs are Loop + GIM suppressed in the SM
  $\to$ sensitive to high scales of NP



Here, focus on **di-neutrino modes** $d_i \to d_j \nu\bar{\nu}$:

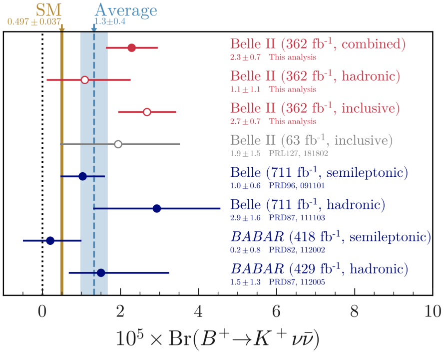
- $K \to \pi\nu\bar{\nu}$, $B \to K^{(*)}\nu\bar{\nu}$
- Not affected by theoretical uncertainties e.g. from charm loops
- Very rare decays, experimentally challenging
- Currently, only probes with third-gen. leptons (ν_τ)



Experimental status in $d_i \to d_j \nu\bar{\nu}$

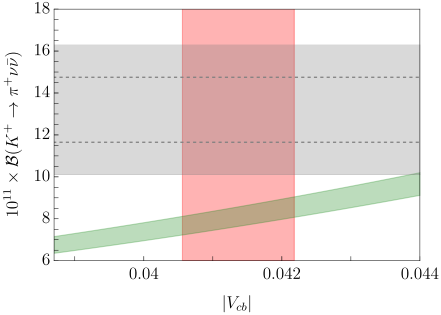
$B \to K\nu\bar{\nu}$

> Belle-II 2023



$K \to \pi\nu\bar{\nu}$

> NA62 2024



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

[1903.10954]

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

$$Q^{\pm}_{\ell q} = (\bar{q}^3_L \gamma^\mu q^3_L)(\bar{\ell}^3_L \gamma_\mu \ell^3_L) \pm (\bar{q}^3_L \gamma^\mu \sigma^a q^3_L)(\bar{\ell}^3_L \gamma_\mu \sigma^a \ell^3_L)$$

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

$$Q^+_{lq} : d_i \to d_j \tau\tau$$
$$Q^-_{lq} : d_i \to d_j \nu_\tau \bar{\nu}_\tau$$

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

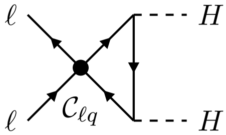
$$q^3_L = \begin{pmatrix} V_{ub} u_L + V_{cb} c_L + V_{tb} t_L \\ b_L \end{pmatrix}$$

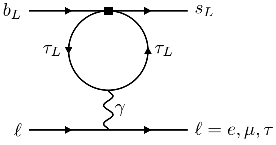
- $U(2)_q$-breaking spurion

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

- Replace $q^3_L \to q^3_L + \tilde{V}_i q^i_L$
- System described by 5 parameters: C_S, $C^+_{\ell q}$, $C^-_{\ell q}$, ε, κ

Correlated observables





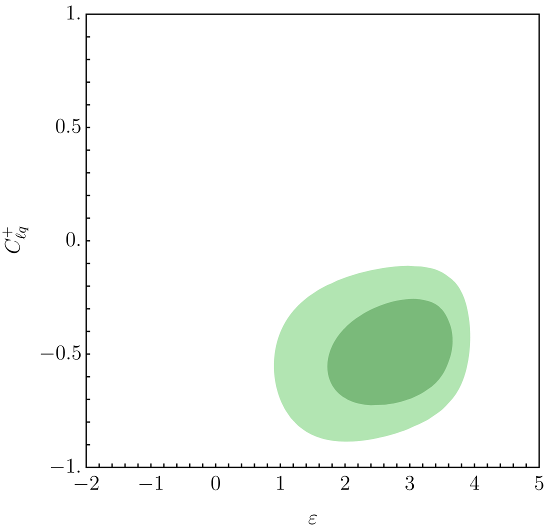
	C_S	$C^+_{\ell q}$	$C^-_{\ell q}$	ε	κ	Exp. indication
$\sigma(pp \to \ell\ell)$	✓	✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
EWPO		✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
R_D, R_{D^*}	✓	✓	✓	✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}} > 0$
$\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})$		✓		✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}}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

Results: $C_{\ell q}^{+}$-ε

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

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

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



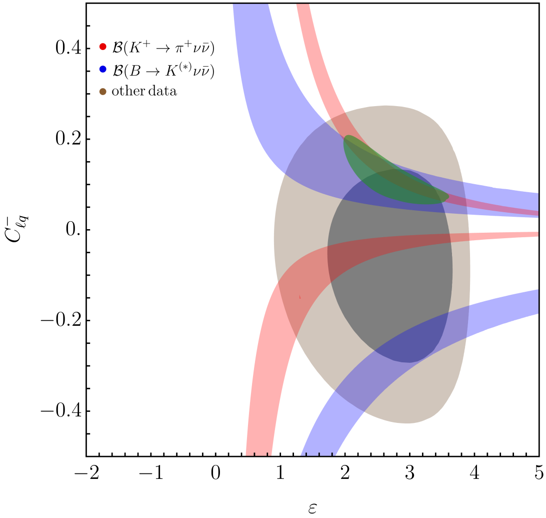
Results: $C^-_{\ell q}$-ε

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

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

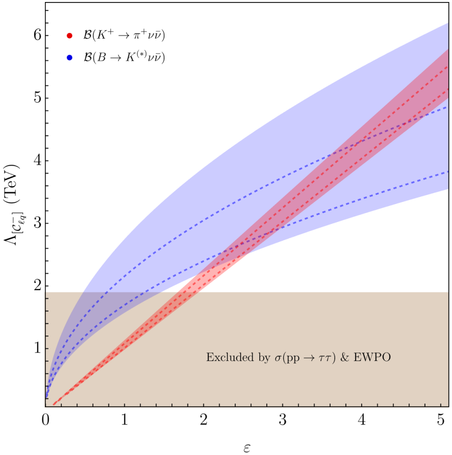
$$|C^{\text{SM}}_{\tau,sd}| \to \left| C^{\text{SM}}_{\tau,sd} + \kappa \varepsilon^2 \frac{\pi v^2}{\alpha} C^-_{\ell q} \right| .$$

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

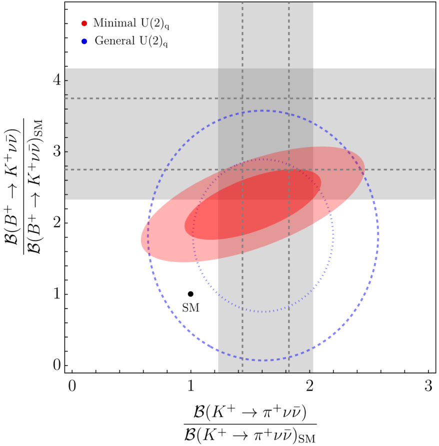


Future prospects

> Measure ε with dineutrino modes



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



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

- ~ 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

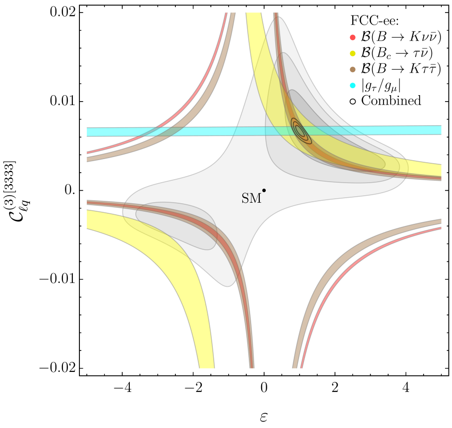
SMEFT analysis

[LA, Isidori, Pešut 2503.17019]

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

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

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



Summary

- FCNCs are very sensitive probes of New Physics
- Studied $d_i \to d_j \nu\bar{\nu}$ in the context of NP coupled dominantly to the third generation
- Compatible with a $U(2)$-type scaling of the coefficients in the EFT and with other observables (flavour + EWPO + collider)
- In the future, use these modes to probe the nature of $U(2)$ breaking in the quark sector

Thank you!

Backup

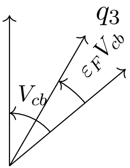
Flavour alignment in the 3rd generation

[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]

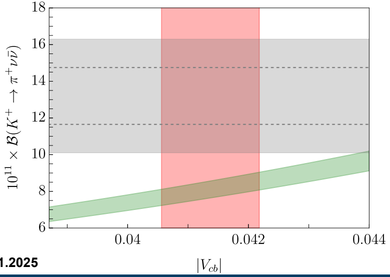
$$|V_{cb}|_{\text{incl+excl}} = (41.37 \pm 0.81) \times 10^{-3}$$

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

- $b \to s\nu\bar{\nu}$: 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!



Simplified models

$$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

$$\mathcal{L}_{U_1} \supset \frac{g}{\sqrt{2}}(\bar{q}_L^3 + \tilde{V}_i^* \bar{q}_L^i)\not{U}_1 \ell_L^3 + \text{h.c.}$$

- At tree-level:

$$C_{\ell q}^+ \neq 0 \qquad C_{\ell q}^- = 0$$

- Loop-level $C_{\ell q}^-$ explains $|C_{\ell q}^+| \gg |C_{\ell q}^-|$
- Good compatibilty with data

$$Z' \sim (\mathbf{1}, \mathbf{1}, 0)$$

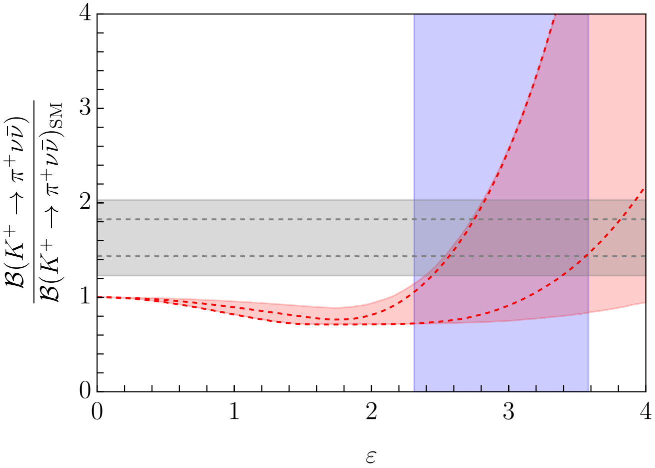
$$J_{Z'}^\mu = Q_q(\bar{q}_L^3 + \tilde{V}_i^* \bar{q}_L^i)\gamma^\mu(q_L^3 + \tilde{V}_i q_L^i) + Q_\tau \bar{\ell}_L^3 \gamma^\mu \ell_L^3$$

$$C_{\ell q}^- = C_{\ell q}^+ = -\frac{g^2}{M_{Z'}^2} Q_q Q_\tau$$

$$C_{qq}^{(1)[3333]} = -\frac{g^2}{2M_{Z'}^2} Q_q^2$$

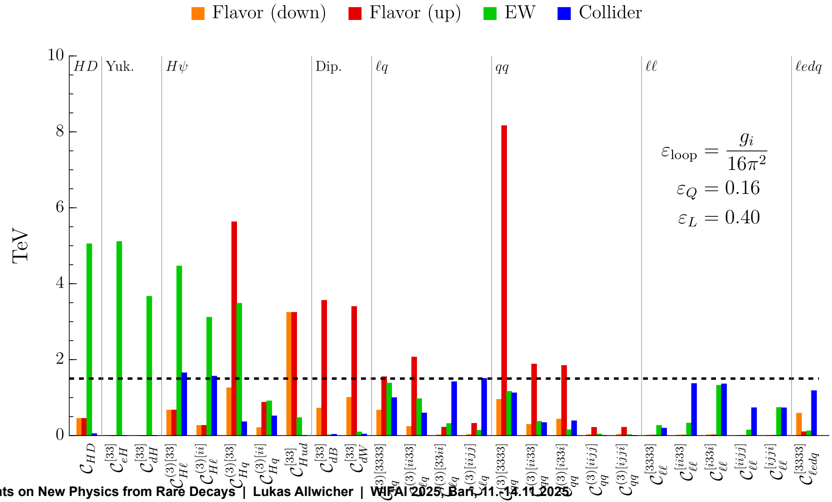
- B_s mixing constraints
- Requires $|Q_\tau / Q_q| \gtrsim 30$

$K \to \pi\nu\bar{\nu}$ v. ε



Suppressing the light families

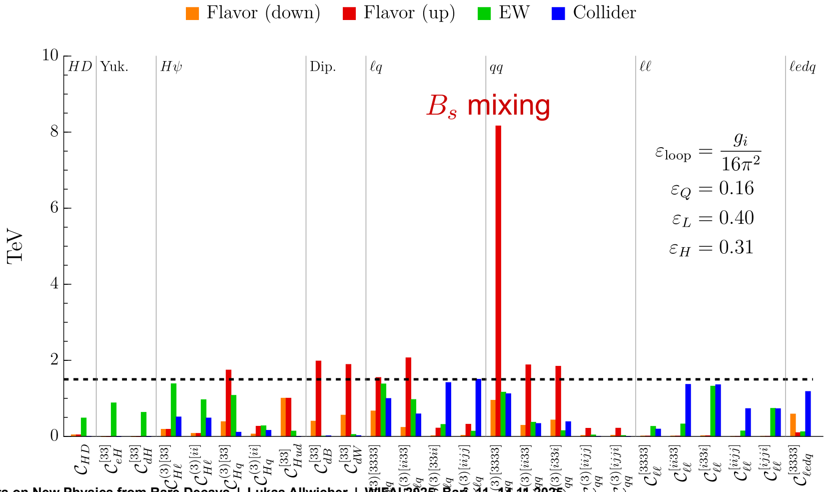
- ε_Q (ε_L) for each light quark (lepton) field
- Operators with Higgs fields still give strong bounds (EWPO)



[LA, Cornella, Isidori, Stefanek 2311.00020]

Suppressing Higgs couplings

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

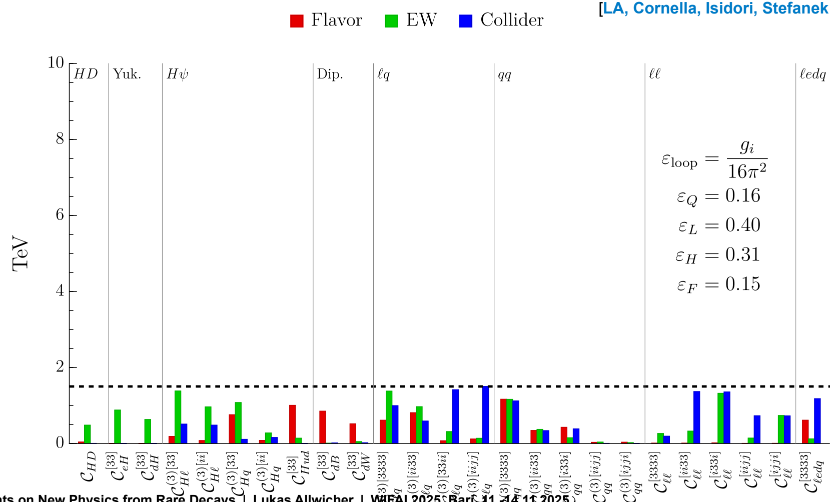


Flavour alignment

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

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

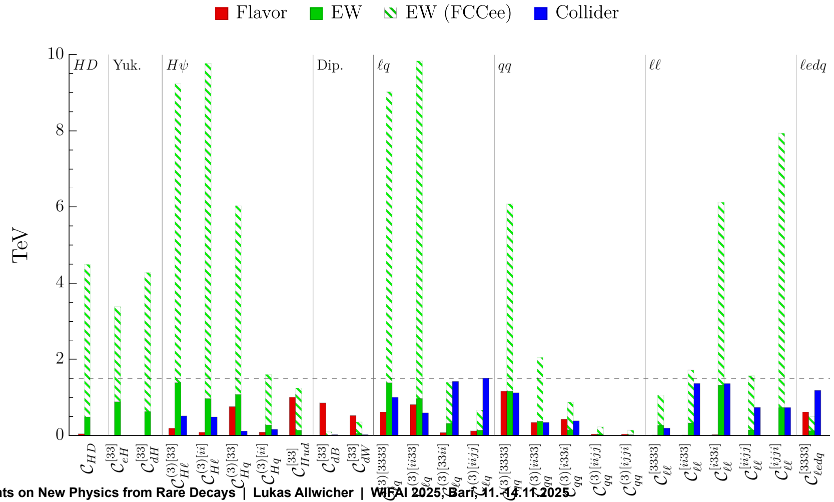
[LA, Cornella, Isidori, Stefanek 2311.00020]



[LA, Cornella, Isidori, Stefanek 2311.00020]

Projections for FCC-ee (Z-pole)

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



$U(2)$ symmetry and SMEFT

- Flavour assumptions (symmetries) help addressing the NP flavour problem
- In the (SM)EFT, organising principle and reduction of number of free parameters
- Inspired by the Yukawa couplings in the SM, start with a $U(2)^5$ symmetry

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

[Barbieri, Isidori, Lodone, Straub 1105.2296]

- E.g. in SMEFT: $\mathcal{C}_{He}$

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

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

- Protection from flavour-violating effects
- Need to break $U(2)$: spurions

Comments on $B \to K\nu\bar{\nu}$

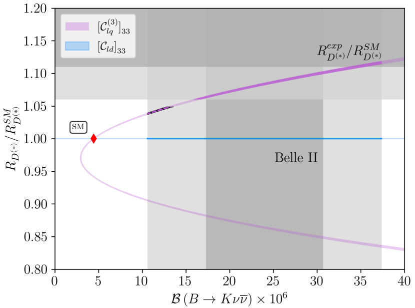
[LA, Bečirević, Piazza, Rosauro-Alcaraz, Sumensari 2309.02246]

- Excess in $B \to K\nu\bar{\nu}$
- Assume it's due to heavy New Physics ($\Lambda \gg v$) $\to$ **SMEFT**

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

$$[\mathcal{O}_{lq}^{(3)}]_{23ii} \supset (\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_i\gamma^\mu\nu_i)$$

- What is the neutrino flavour?
- In SMEFT, $\ell_{L\,i} = (\nu_L \quad e_L)_i^{\mathsf{T}}$
- Needs to be ν_τ to avoid constraints from e.g. $B_s \to \mu\mu$, R_K
- $SU(2)_L$-connection with $b \to c\tau\nu$
- Get scale $\Lambda \simeq \text{TeV}/\sqrt{V_{cb}}$



Flavour assumptions: Minimal Flavour Violation

[Isidori, Straub 1202.0464]

- Only breaking of $U(3)^5$ 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

From $U(2)$ to third-gen. NP

- In models with NP coupled to the third generation, a $U(2)$ symmetry acting on the light families arises naturally as an accidental symmetry
- From an EFT perspective, use $U(2)$ as a proxy to third-gen. NP

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

Comment: b$\rightarrow$ d

- Two parameters govern the breaking of $U(2)_q$: ε, κ
- With FCNCs, constrained by two modes: $b \to s$, $s \to d$

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

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

- Adding $b \to d$: $|C_{\tau,bd}^{\text{SM}}| \to \left| C_{\tau,bd}^{\text{SM}} - \kappa \varepsilon \frac{\pi v^2}{\alpha} C_{\ell q}^{-} \right|$
- Independent (orthogonal) probe of the $U(2)_q$ pattern