New Physics in $b \to s\nu\bar{\nu}$ and $s \to d\nu\bar{\nu}$

Based on `2410.21444` with M. Bordone, G. Isidori, G. Piazza, and A. Stanzione

Lukas Allwicher

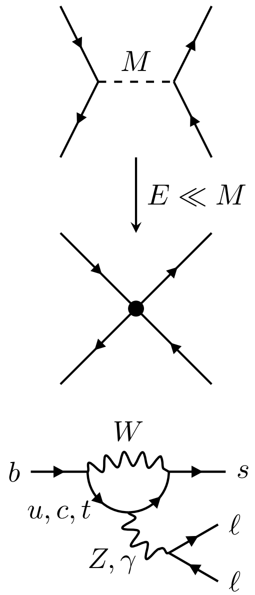
Moriond EW 2026, La Thuile, 15.-22.03.2026

HELMHOLTZ

DESY.

Rare Decays as BSM Probes

(see talk by Zoltan Ligeti)



- Insights into very high scales from indirect effects:

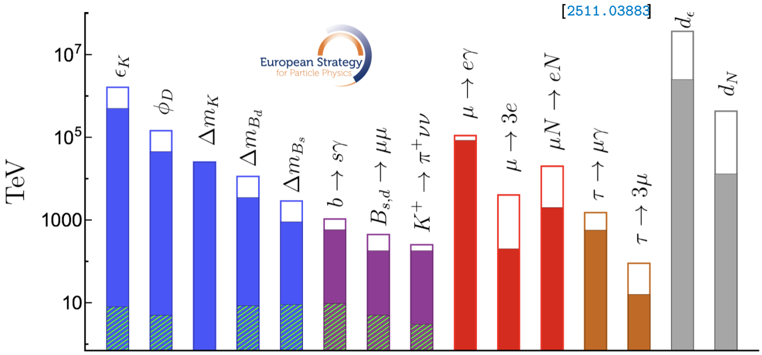
$$\boxed{\frac{1}{M^2} \leftrightarrow \frac{\varepsilon}{v^2}}$$

- Particularly powerful when the SM is suppressed:
  - FCNCs (e.g. $b \to s\ell\ell$)
  - LFV (e.g $\mu \to e\gamma$)
- E.g. $b \to s\ell\ell$

$$\varepsilon \sim \frac{1}{16\pi^2} V_{ts} V_{tb}$$

Current Status

Indirect Searches



It is clear that “nearby” New Physics cannot have a generic flavour structure

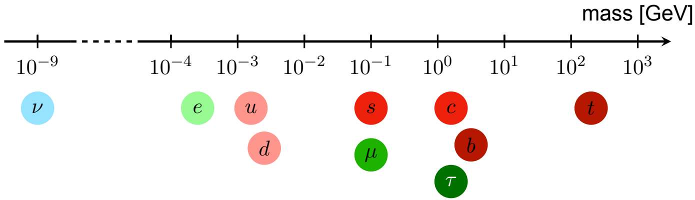
Flavour in the SM

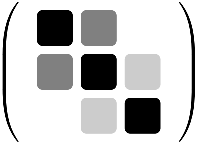
> SM gauge Lagrangian has a large flavour symmetry

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

> Broken by Yukawa terms:

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



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

It doesn't look accidental!

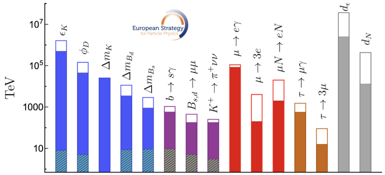
The $U(2)$ Paradigm

Guidance from the Standard Model

- Need to address the flavor structure of NP
- Yukawas:

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

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



Approximate (accidental) $U(2)^5$ symmetry!

- **What if New Physics follows the same structure?**
- Starting point to address the SM flavour puzzle

$U(2)$ in SMEFT

Taming flavour constraints

> $U(2)$ **imposes flavour conservation for New Physics:**

$$c_{ij}\,\bar{q}_i\gamma_\mu q_j \xrightarrow{U(2)_q} a\,\bar{q}_3\gamma_\mu q_3 + b\sum_{i=1}^{2}\bar{q}_i\gamma_\mu q_i$$

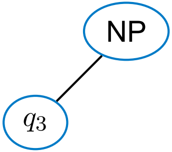
> But it is already broken at dimension-four ($y \lesssim 10^{-2}$)
$\rightarrow$ parametrise with **spurions**

$$Y = y_3\begin{pmatrix}\Delta & \tilde{V}\\ 0 & 1\end{pmatrix} \qquad \tilde{V} = -\varepsilon V_{ts}\begin{pmatrix}\kappa V_{td}/V_{ts}\\ 1\end{pmatrix}$$

> Flavour-changing processes follow CKM-like (GIM) suppression
$\rightarrow$ similar to MFV

(see talk by Dave Sutherland)

New Physics in the Third Generation?



- $U(2)$ **naturally singles out the third generation**

$$\bar{c}_{ij}\, q_i \gamma_\mu q_j \xrightarrow{U(2)_q} a\, \bar{q}_3 \gamma_\mu q_3 + b \sum_{i=1}^{2} \bar{q}_i \gamma_\mu q_i$$

- If New Physics couples to the third gen. $\rightarrow$ **accidental** $U(2)$ symmetry
  $\rightarrow$ take e.g. a Z'

$$\mathcal{L}_{Z'} \supset g Z'_\mu \begin{pmatrix} \bar{q}_1 & \bar{q}_2 & \bar{q}_3 \end{pmatrix} \gamma^\mu \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

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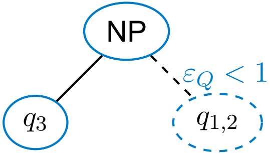

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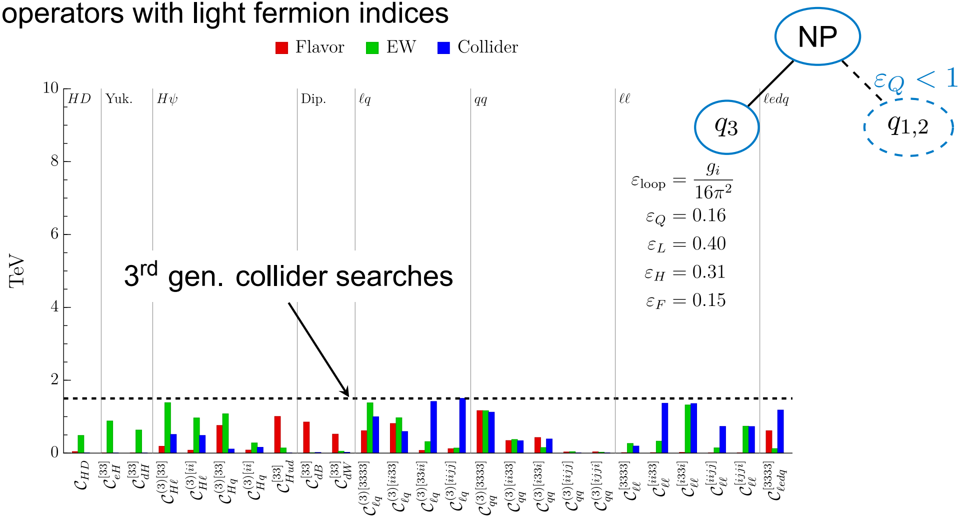
- **How much do we need to suppress the light generations?**

$$\mathcal{L}_{Z'} \supset g Z'_\mu \begin{pmatrix} \bar{q}_1 & \bar{q}_2 & \bar{q}_3 \end{pmatrix} \gamma^\mu \begin{pmatrix} \varepsilon_Q^2 & 0 & 0 \\ 0 & \varepsilon_Q^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

New Physics in the Third Generation?

[LA, Cornella, Isidori, Stefanek 2311.00020]

> Suppress operators with light fermion indices



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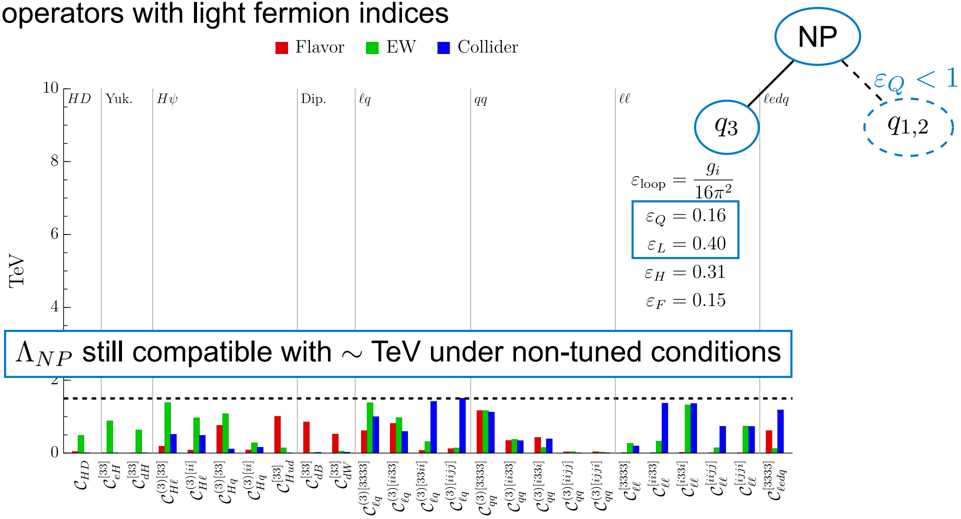
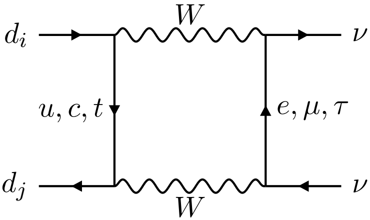
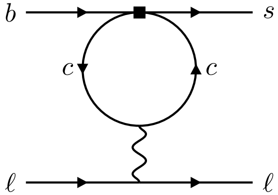


Λ_{NP} still compatible with $\sim$ TeV under non-tuned conditions

$d_i \to d_j \nu\bar{\nu}$ Transitions



- FCNCs: Loop + GIM suppressed in the SM
- $K \to \pi\nu\bar{\nu}$, $B \to K^{(*)}\nu\bar{\nu}$
- **Clean:** not affected by theoretical uncertainties from charm loops
- Currently, only probes with **third-gen. leptons** (ν_τ)

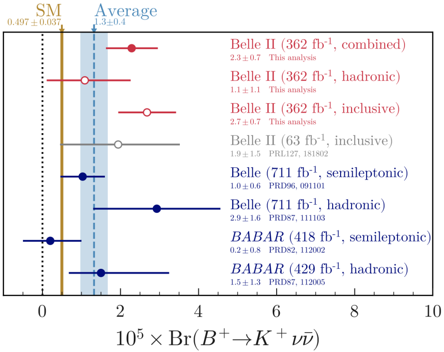


Experimental Status

(see talk by Meihong Liu)

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

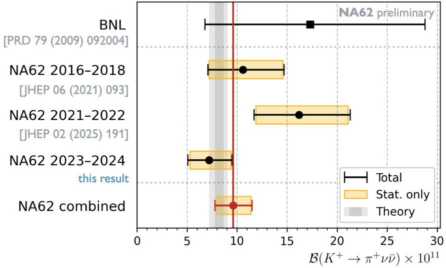
> Belle-II 2023



(see talk by Xiafei Chang)

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

> NA62 2026 (La Thuile)



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

[1903.10954]

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

$$\ell_L^3 = \begin{pmatrix} \nu_\tau \\ \tau_L \end{pmatrix}$$

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

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

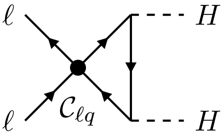
$$Q_{lq}^+ : \; d_i \to d_j \tau\tau$$
$$Q_{lq}^- : \; d_i \to d_j \nu_\tau \bar{\nu}_\tau$$

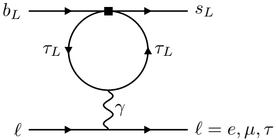
- $U(2)_q$-breaking spurion

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

- 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





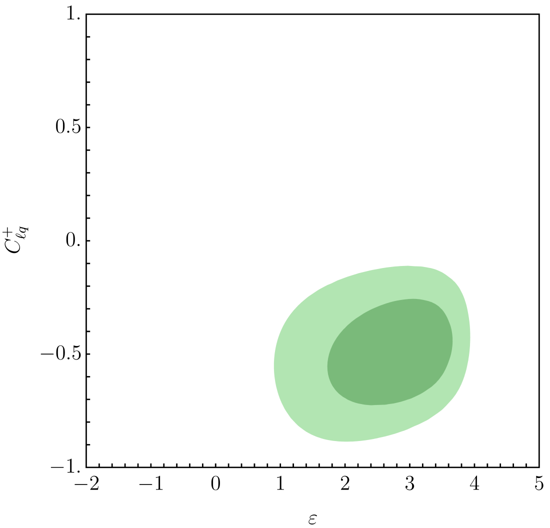
	C_S	$C_{\ell q}^+$	$C_{\ell q}^-$	ε	κ	Exp. indication
$\sigma(pp \to \ell\ell)$	✓	✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
EWPO		✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
R_D, R_{D^*}	✓	✓	✓	✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}} > 0$
$\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})$		✓		✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}}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

Results: $C^+_{\ell q}$-ε

- Global fit without di-neutrino modes (don't affect $C^+_{\ell q}$)
- LHC Drell-Yan + EWPO: $C^\pm_{\ell q}$ 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



Results: $C_{\ell q}^{-}$-ε

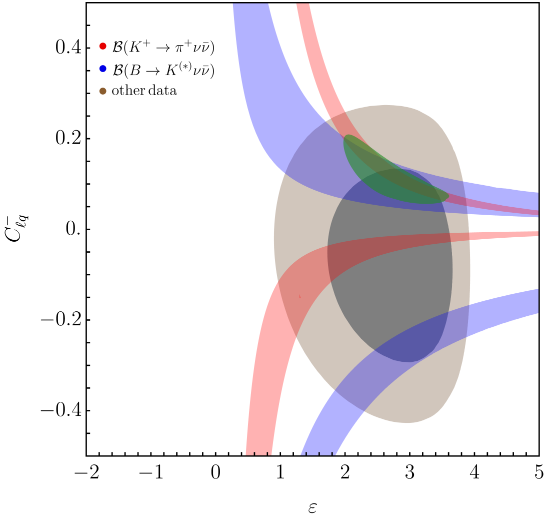
- Grey: Global fit without di-neutrino modes, $\kappa = 1$
- $C_{\ell q}^{-}$ largely unconstrained
- Good compatibility with di-neutrino modes for $\kappa = 1$

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

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

- Select $C_{\ell q}^{-} > 0$

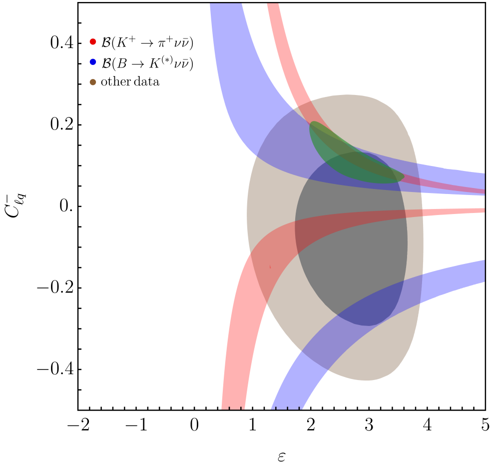
(Before 2026 NA62 update)



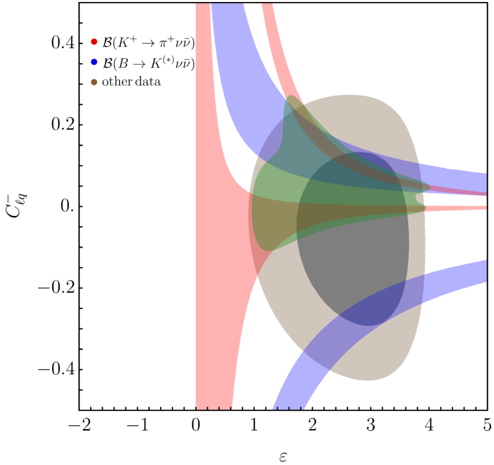
Results: $C_{\ell q}^{-}$-ε

[Thanks to Marzia Bordone for updated plot]

2024:



March 2026:



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
- 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
$\|g_\tau/g_\mu\|$	1	1.0009 ± 0.0014	–	± 0.0001 [15]
$\|g_\tau/g_e\|$	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]
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- Subset of observables, relevant for our example study

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$\mathcal{B}(B \to K^*\nu\bar{\nu})$	$(9.8 \pm 1.4) \times 10^{-6}$	$< 1.2 \times 10^{-5}$ (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

Third-gen. Semileptonics: Future Prospects

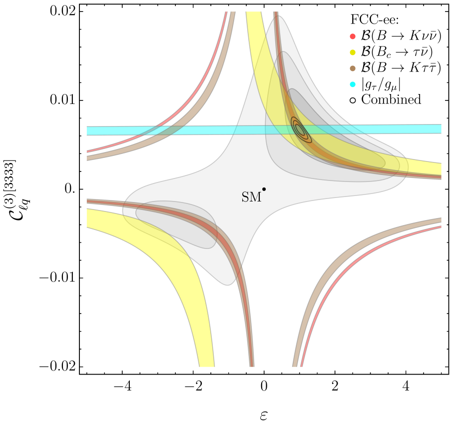
SMEFT Analysis

- $[\mathcal{O}_{lq}^{(3)}]_{3333} = (\bar{\ell}_3 \gamma_\mu \sigma^I \ell_3)(\bar{q}_3 \gamma^\mu \sigma^I q_3)$
- Flavour-violating effects:

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

- Assume a signal compatible with current measurements (gray region), and project for FCC-ee expected errors

[LA, Isidori, Pešut 2503.17019]



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

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)
- These modes will remain important probes of New Physics also in the future

Thank you!

Backup

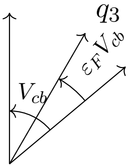
Flavour alignment in the 3rd generation

[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:

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

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



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

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

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]

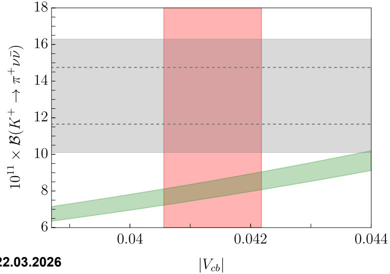
$$|V_{cb}|_{\text{incl+excl}} = (41.37 \pm 0.81) \times 10^{-3}$$

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

> $b \to s\nu\bar\nu$: Bečirević et al. 2301.06990

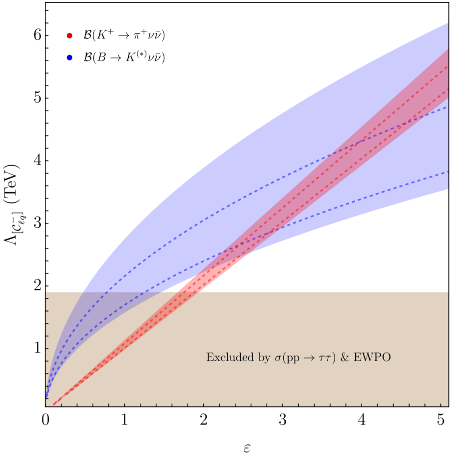
$$\mathcal{B}(B^+ \to K^+ \nu\bar\nu)/|\lambda^t_{bs}|^2 = (2.87 \pm 0.10) \times 10^{-3}$$

> First measurement by NA62 in 2024!

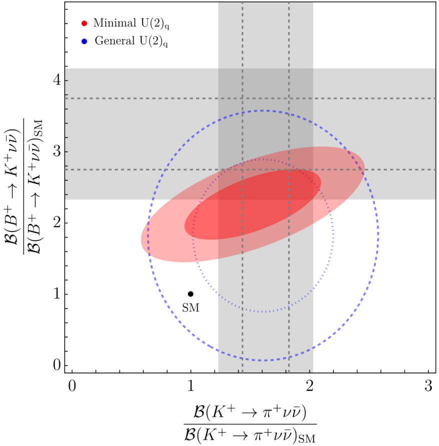


Future prospects

> Measure ε with dineutrino modes

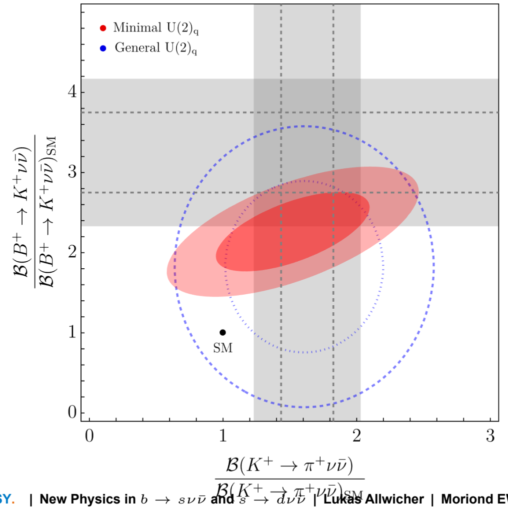


> Minimal vs. non-minimal $U(2)_q$ breaking

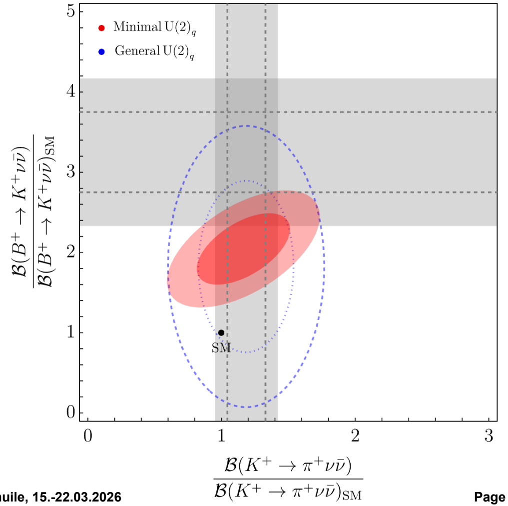


Non-minimal v. minimal $U(2)_q$ breaking

2024:



March 2026:



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

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

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

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

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

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

$K \to \pi\nu\bar{\nu}$ v. ε