Probing third-generation New Physics with $K \to \pi\nu\nu$ and $B \to K^{(*)}\nu\nu$

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

Lukas Allwicher

CERN, Geneva, 03.12.2024

HELMHOLTZ

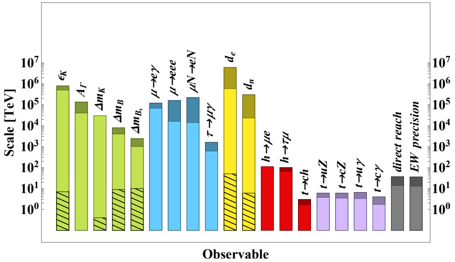
Intro: flavoured New Physics

- LHC seems to suggest $\Lambda_{\text{NP}} \gtrsim$ TeV
- Indirect constraints, e.g. from flavour, probe scales up to 10^6 TeV (flavour-anarchic NP)
- TeV-scale NP must comply with this by having a non-trivial flavour structure: **NP flavour problem**

In this talk:

- New physics coupled dominantly to the third generation
  $\rightarrow$ compatible with TeV scale
- Study the case of FCNCs with two neutrinos in the final state

[Physics Briefing Book 1910.11775]



$U(2)$ symmetry and SMEFT

(see talk by Ben this morning)

- 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

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

[Barbieri, Isidori, Lodone, Straub 1105.2296]

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

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

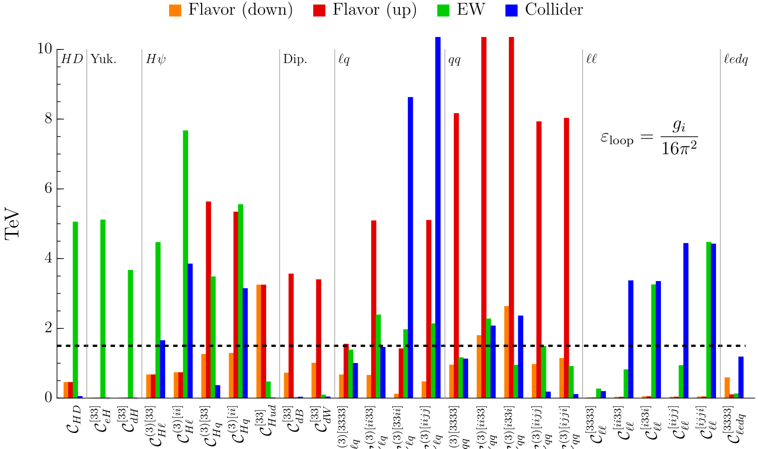
$$\xrightarrow{U(2)^5} \mathcal{C}_{He}^{[33]}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_3\gamma^\mu e_3) + \mathcal{C}_{He}^{[ii]}(H^\dagger i\overleftrightarrow{D}_\mu H)\sum_{i=1}^{2}(\bar{e}_i\gamma^\mu e_i)$$

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

[LA, Cornella, Isidori, Stefanek 2311.00020]

SMEFT fits to $U(2)$ operators

- 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



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 $U(2)^5$

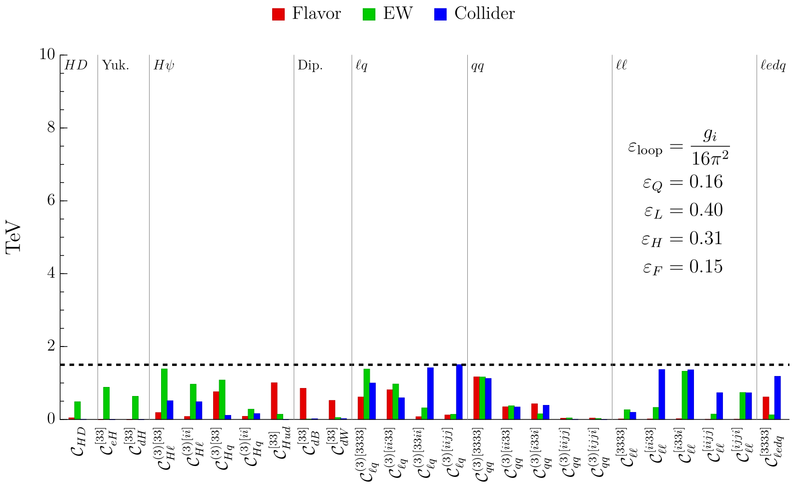
$$\bar{q}_L^i V_q^i \gamma_\mu q^3 \qquad V_q \sim \mathcal{O}\begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix}$$

flavour violating couplings

Third-generation hypothesis

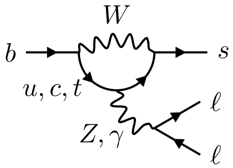
[LA, Cornella, Isidori, Stefanek 2311.00020]

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



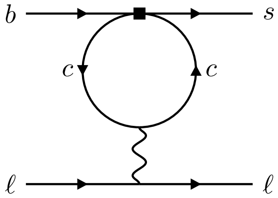
FCNCs as BSM probes

- Loop + GIM suppressed in the SM
- 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)



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 $\mu = m_{b,s}$: $\mathcal{L}_{\text{eff}} = \frac{4G_{\text{F}}}{\sqrt{2}} \frac{\alpha}{2\pi} \sum_{\ell=e,\mu,\tau} \left[\lambda^t_{sd} C^{\text{SM}}_{\ell,sd} O^\nu_{\ell,sd} + \lambda^t_{bs} C^{\text{SM}}_{\ell,bs} O^\nu_{\ell,bs}\right] + \text{h.c.}$
- 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]

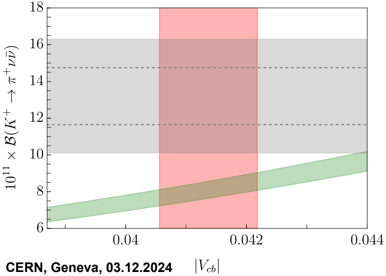
$$|V_{cb}|_{\text{incl+excl}} = (41.37 \pm 0.81) \times 10^{-3}$$

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

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

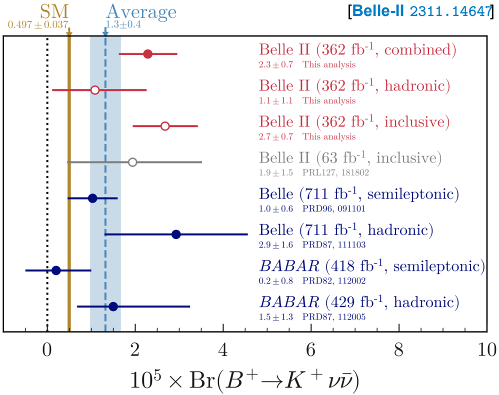


$B \to K\nu\bar{\nu}$

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

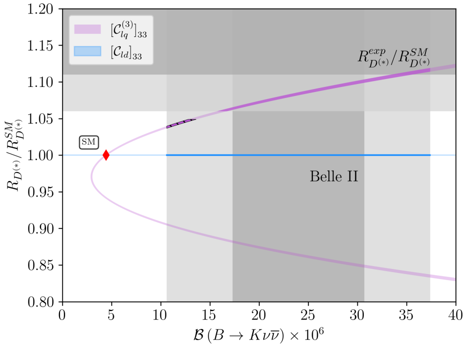
> First measurement in 2023 by Belle-II:

[**Belle-II** 2311.14647]



> Third-gen. leptons: avoid constraints from $b \to s\ell\ell$, $\ell = e, \mu$

> Correlation with R_D/R_{D^*}



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

[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**

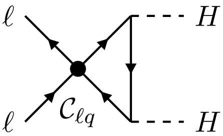
$$q_L^3 = \begin{pmatrix} V_{ub} u_L + V_{cb} c_L + V_{tb} t_L \\ b_L \end{pmatrix}$$

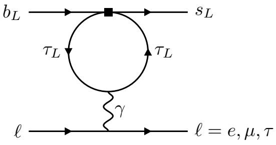
> $U(2)_q$-breaking spurion

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

> 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





(see talk by Arianna)

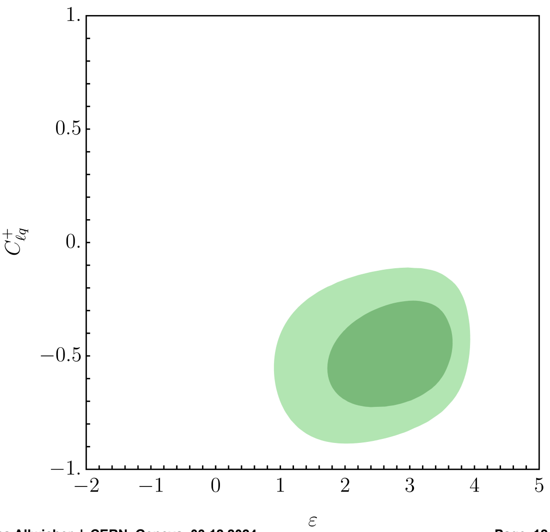
	C_S	$C^+_{\ell q}$	$C^-_{\ell q}$	ε	κ	Exp. indication
$\sigma(pp \to \ell\ell)$	✓	✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
EWPO		✓	✓			bounds on $\mathcal{A}_{\text{NP}}$
R_D, R_{D^*}	✓	✓	✓	✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}} > 0$
$\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})$		✓		✓		$\mathcal{A}_{\text{NP}}/\mathcal{A}_{\text{SM}}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

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 $R_{D^{(*)}}$:

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

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



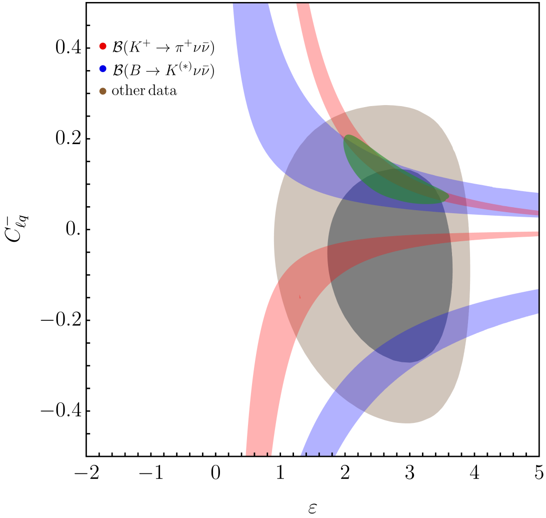
Results: $C^{-}_{\ell q}$-ε

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

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

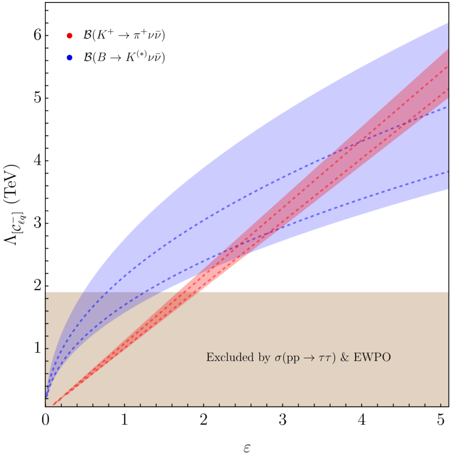
$$|C^{\text{SM}}_{\tau,sd}| \to \left| C^{\text{SM}}_{\tau,sd} + \kappa \varepsilon^2 \frac{\pi v^2}{\alpha} C^{-}_{\ell q} \right| .$$

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

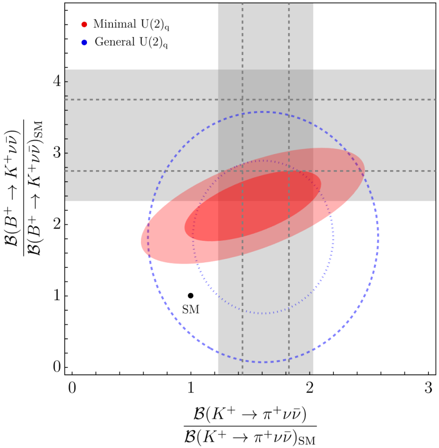


Future prospects

> Measure ε with dineutrino modes



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



Simplified models

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

$$\mathcal{L}_{U_1} \supset \frac{g}{\sqrt{2}}(\bar{q}_L^3 + \tilde{V}_i^* \bar{q}_L^i) \slashed{U}_1 \ell_L^3 + \text{h.c.}$$

> 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 $|Q_\tau / Q_q| \gtrsim 30$

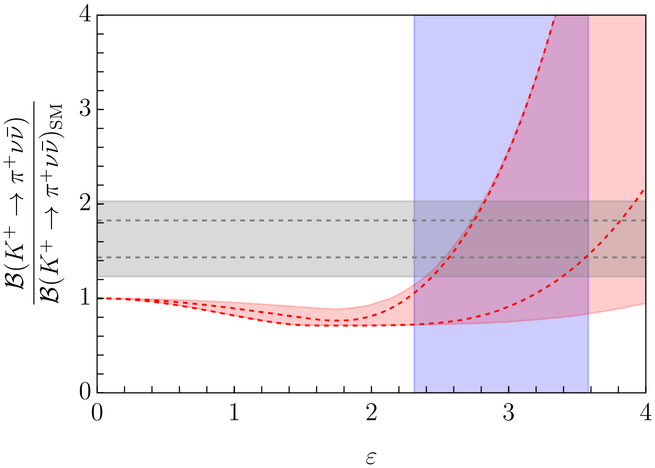
Summary

- 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
- Recent experimental process to the level of expected SM rates
- 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

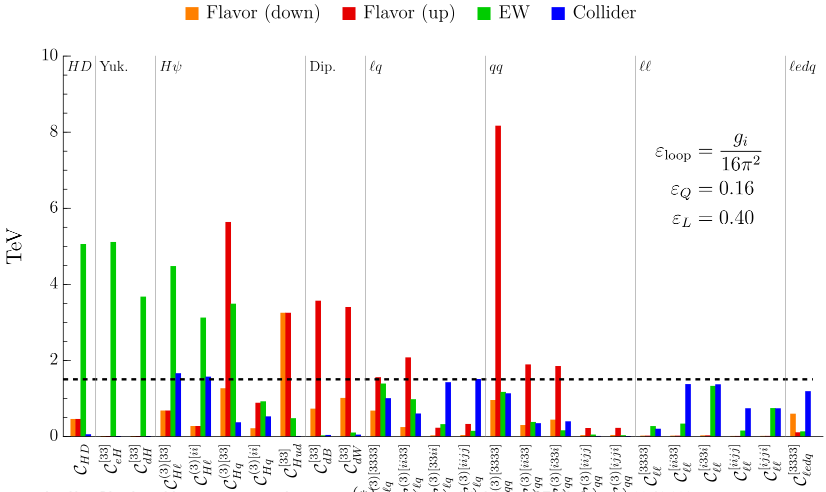
$K \to \pi\nu\bar{\nu}$ v. ε



[LA, Cornella, Isidori, Stefanek 2311.00020]

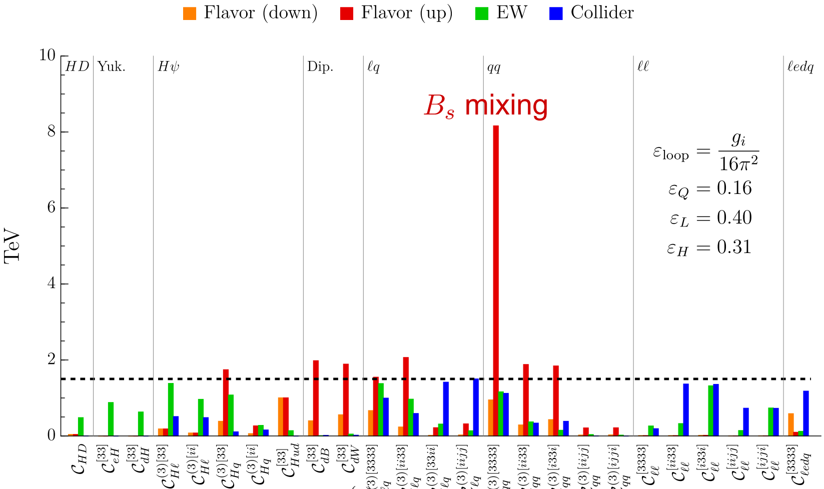
Suppressing the light families

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



Suppressing Higgs couplings

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

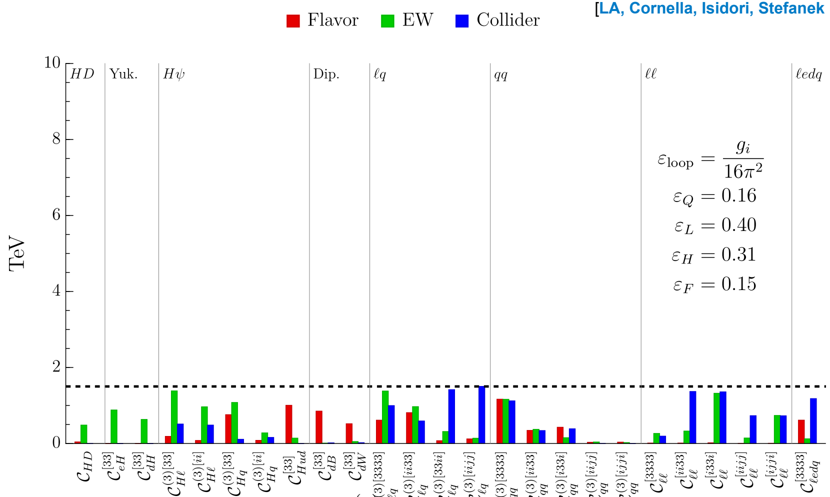


Flavour alignment

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

> 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