Universität Zürich[UZH]

Flavored Circular Collider: cornering New Physics at FCC-ee via flavor-changing processes*

25.09.2025, DESY

Marko Pesut

University of Zürich

*in collaboration with Lukas Allwicher (DESY) & Gino Isidori (UZH) [2503.17019]

Most theoretical & Pheno. aspects relevant to this work where already very well introduced in Claudia's talk on Tuesday

Objectives

Illustrate the discovery potential of a high-intensity e^+e^- collider @ $\boldsymbol{Z}$ pole via precision flavour measurements + flavour-EW interplay to constrain TeV-scale BSM models

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FCC-ee combines advantages of *B* factories and LHC + opens new frontiers

Monteil & Wilkinson [2106.01259]

➡ Clean environment + huge statistics + full range of (boosted) B mesons

Tremendous improvement in flavour from tera-$\boldsymbol{Z}$ run!

➡ Of the 10^{12} $\boldsymbol{Z}$-bosons produced at tera-$\boldsymbol{Z}$:

- 15% decay to b
- 12% decay to c
- 3% decay to τ

FCC-ee will allow precision flavour measurements of heavy SM flavours (*b* and *τ*)

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➡ We focus on models aimed at addressing the Higgs hierarchy problem & the Flavour Puzzle

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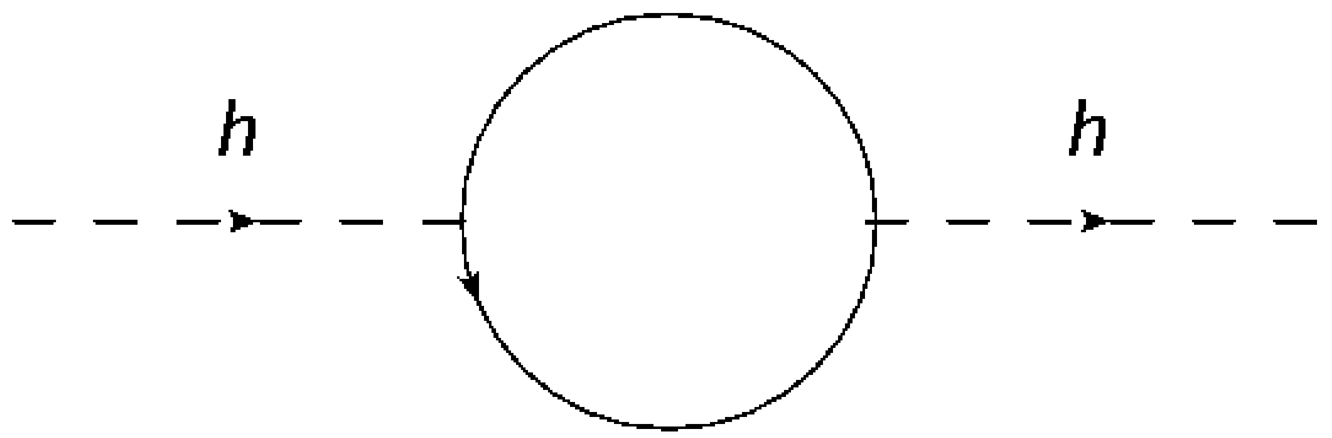
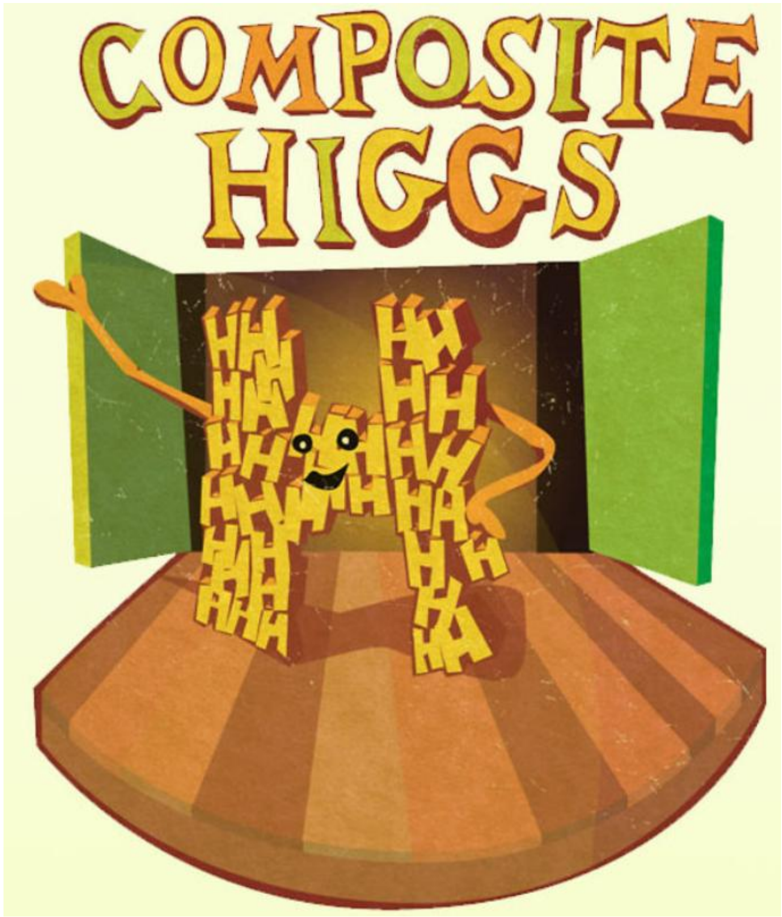
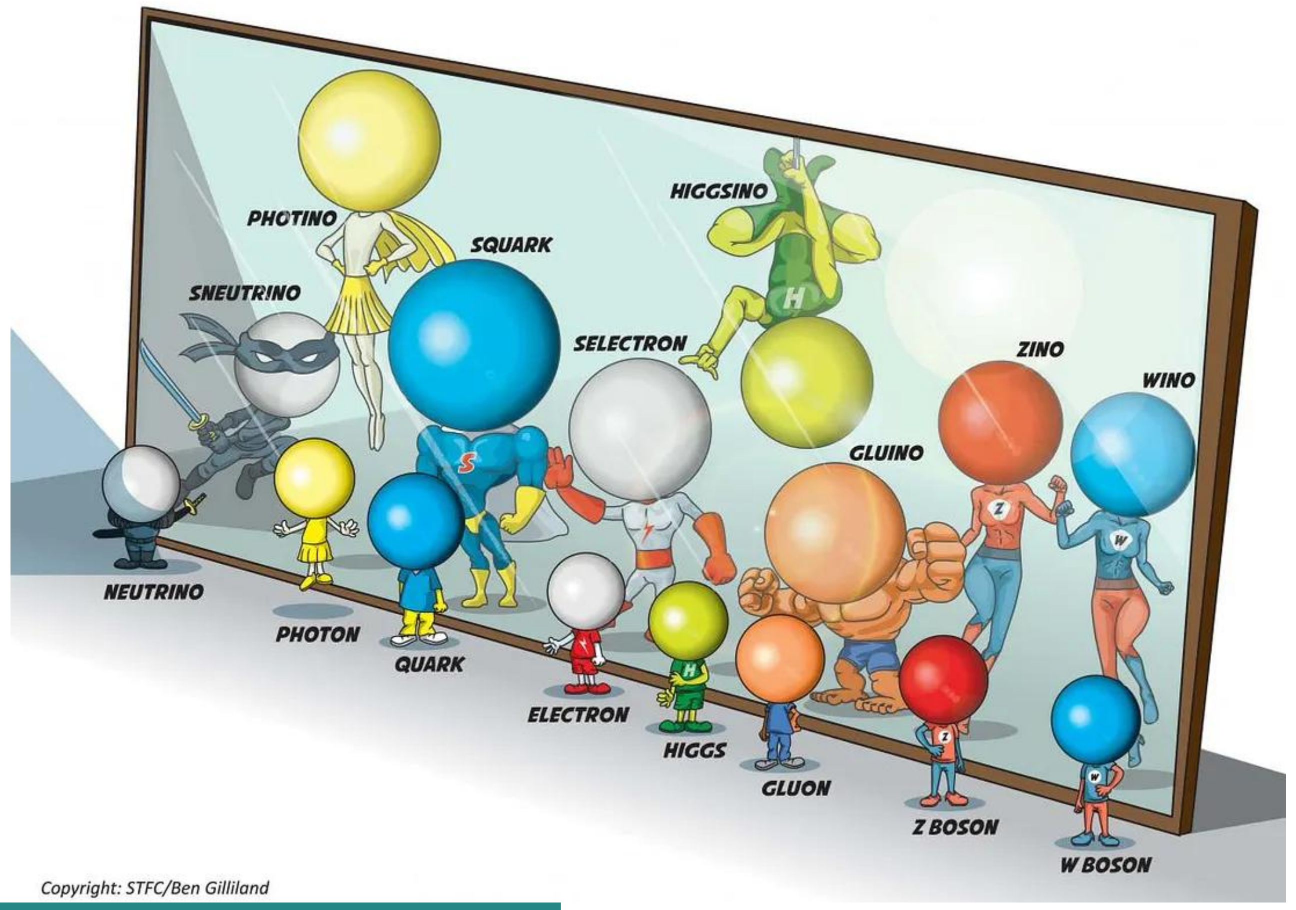
Any heavy NP will *destabilize* the Higgs mass



$$\delta m_H^2 \sim \frac{1}{16\pi^2} g^2 M^2$$

What could be the *protection mechanism* ?





See RT D'Agnolo's talk

Naturalness suggests NP close to the TeV scale*

**More exotic / cosmology-based explanations exists…*

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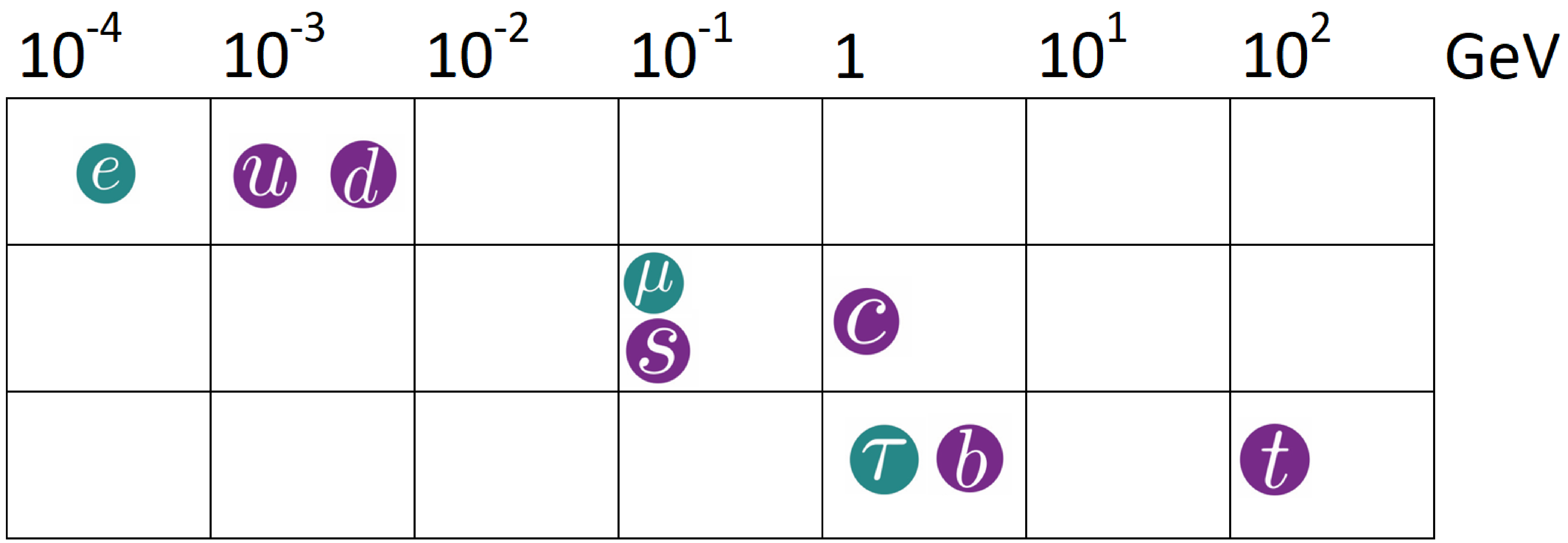

Hierarchical pattern of masses & mixing angles in the SM

$$U(3)^5 \to U(2)^n$$

$$Y_u \sim \begin{pmatrix} & < 0.01 & 0.04 \\ & & 1 \end{pmatrix}$$

(In the basis where Y_d is diagonal)

Approx. symmetries in the SM … but also relevant for NP!

If $\Lambda_{\rm NP} \lesssim 10^4$ TeV, NP has to be approx. *U(2)*-symmetric

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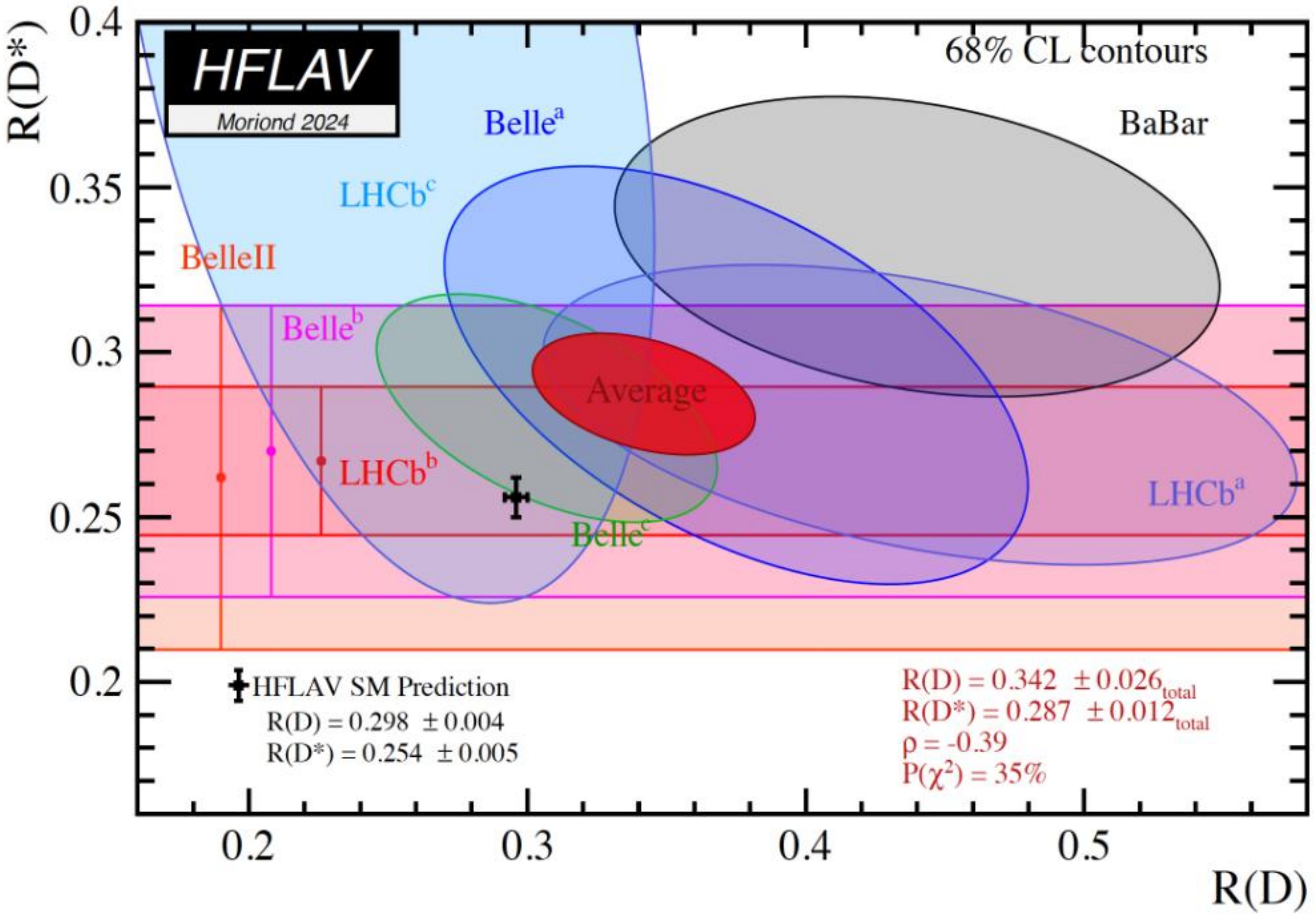
Experimental Motivation:
Tensions in semi-leptonic B decays

- LFU ratios (R_D and R_{D*}) -> 3σ tension w.r.t the SM
- Enhancement of $B^+ \to K^+\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ w.r.t the SM
- Tension in C_9 from $b \to s\ell\bar{\ell}$ -> 2σ tension w.r.t the SM

See also Bordone, Cornella & Davighi [2503.22635]

Relevant SMEFT operators

$$Q_{\ell q}^{(1)[3333]} = (\bar{\ell}^3\gamma_\mu\ell^3)(\bar{q}^3\gamma^\mu q^3)\,,$$
$$Q_{\ell q}^{(3)[3333]} = (\bar{\ell}^3\gamma_\mu\sigma^a\ell^3)(\bar{q}^3\gamma^\mu\sigma^a q^3)\,,$$
$$Q_{\ell e q d}^{[3333]} = (\bar{\ell}^3 e^3)(\bar{d}^3 q^3)\,.$$



These hints are compatible with NP at the TeV scale, dominantly coupled to 3rd family fields!

Objectives

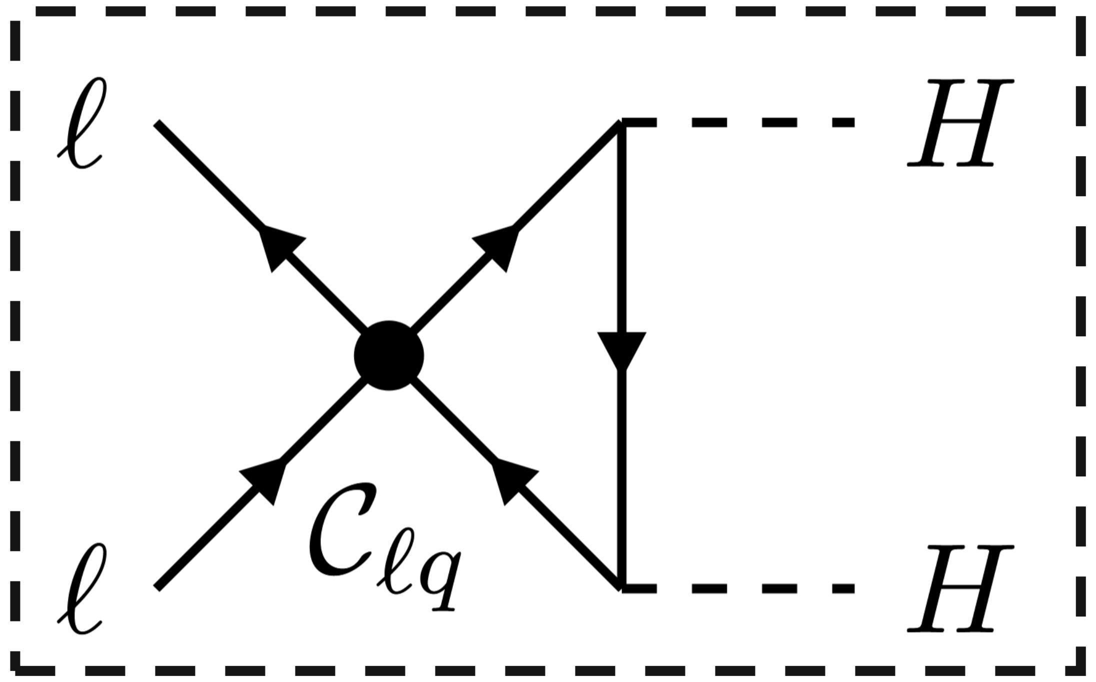
*Illustrate the discovery potential of a high-intensity e⁺e⁻ collider @ **Z** pole via precision flavour measurements*
+ flavour-EW interplay to constrain TeV-scale BSM models

Everything runs into EWPO!

UV Model
(e.g. LQ)

$$\xrightarrow{v_{\rm EW} \lesssim \Lambda_{\rm NP}} \mathcal{C}_{\ell q} \equiv \left(\bar{\ell}_3 \gamma_\mu \ell_3\right)\left(\bar{q}_3 \gamma^\mu q_3\right) \longrightarrow$$

E.g. for B-anomalies



$$\longrightarrow \mathcal{C}_{H\ell}^{33}$$

$$\Rightarrow \delta g_L^Z\big|_{33} \propto v^2 \mathcal{C}_{H\ell}^{33} \Rightarrow \text{Effect in } Z \to \tau\tau$$

Precision EW measurements, via RGE effects, can constrain wide classes of BSM models

EFT Analysis

- Motivated by discrepancies in *B* decays + flavour non-universality

$$Q_{\ell q}^{(1)[3333]} = (\bar{\ell}^3\gamma_\mu \ell^3)(\bar{q}^3\gamma^\mu q^3)\,,$$
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$$Q_{\ell e q d}^{[3333]} = (\bar{\ell}^3 e^3)(\bar{d}^3 q^3)\,.$$

$$q^3 \to q^{3\prime} = q^3 - \varepsilon \tilde{V}_q^i q^i$$

Heavy -> light via CKM spurion

- Global four-dimensional fit with current flavour, EW and Colliders data*

R_D	$\mathcal{B}(B \to K\nu\bar{\nu})$	Γ_Z	A_b
R_{D^*}	$\mathcal{B}(B \to K^*\nu\bar{\nu})$	σ^0_{had}	A_τ
$\mathcal{B}(B_c \to \tau\bar{\nu})$	$\mathcal{B}(B \to K\tau\bar{\tau})$	R_b	m_W
	$\mathcal{B}(B \to K^*\tau\bar{\tau})$	R_μ	Γ_W
	$\mathcal{B}(B_s \to \tau\bar{\tau})$	R_e	$\mathcal{B}(W \to \tau\nu)$
		R_τ	$\mu(H \to b\bar{b})$
		N_{eff}	$\mu(H \to \tau\bar{\tau})$

L. Allwicher, C. Cornella, G. Isidori and B.Stefanek, New physics in the third generation [2311.00020]

**c.f. the paper for the full list of observables with projected uncertainties*

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Heavy -> light via CKM spurion

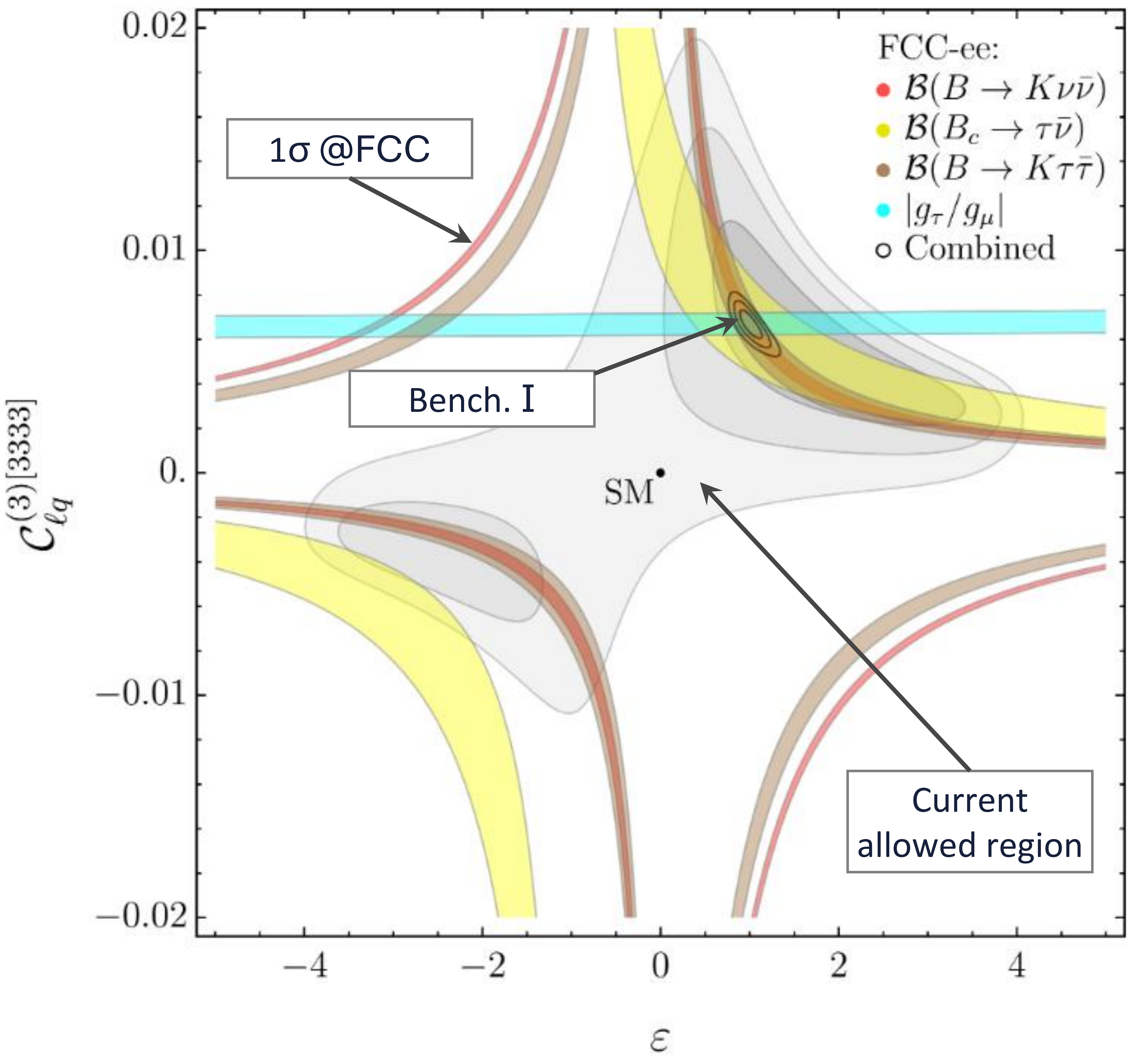
- Global four-dimensional fit with current flavour, EW and Colliders data*

- Projected* FCC-ee measurements assuming benchmark scenarios for NP

→ *Compatible and preferred by the current fit*

**c.f. the paper for the full list of observables with projected uncertainties*

$$\text{I. } \mathcal{C}_{\ell q}^{(3)[3333]} = 6.7 \times 10^{-3},\ \varepsilon = 1,\ \mathcal{C}_{\ell q}^{(1)[3333]} = \mathcal{C}_{\ell eqd}^{[3333]} = 0$$



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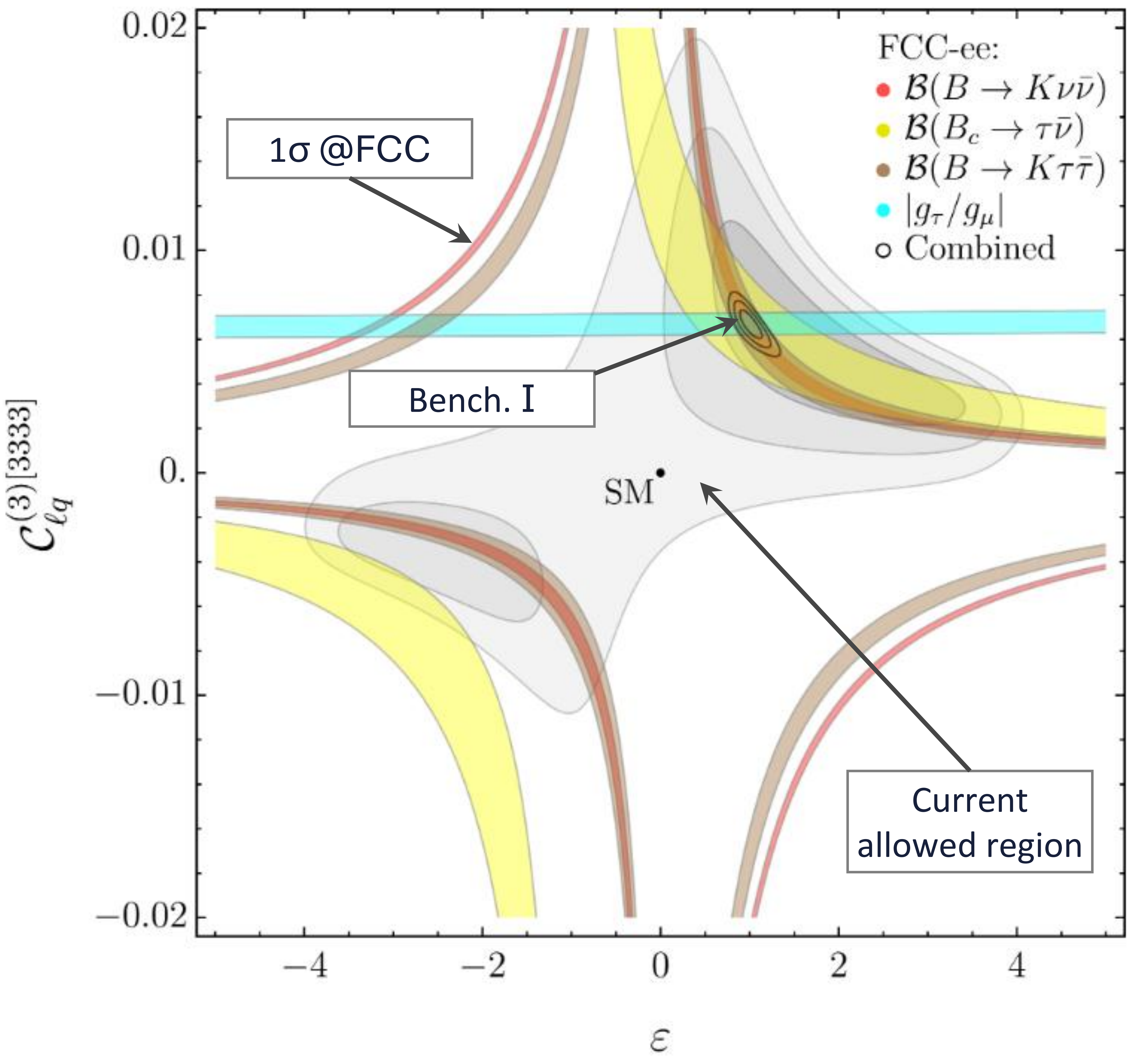

Key points

- *Redundancy* -> corroborate non-SM effect
- *Complementarity* -> Probe different NP directions

  - Several independent high-precision observables

  - Flavour + EW interplay -> Flavour of NP (ε)

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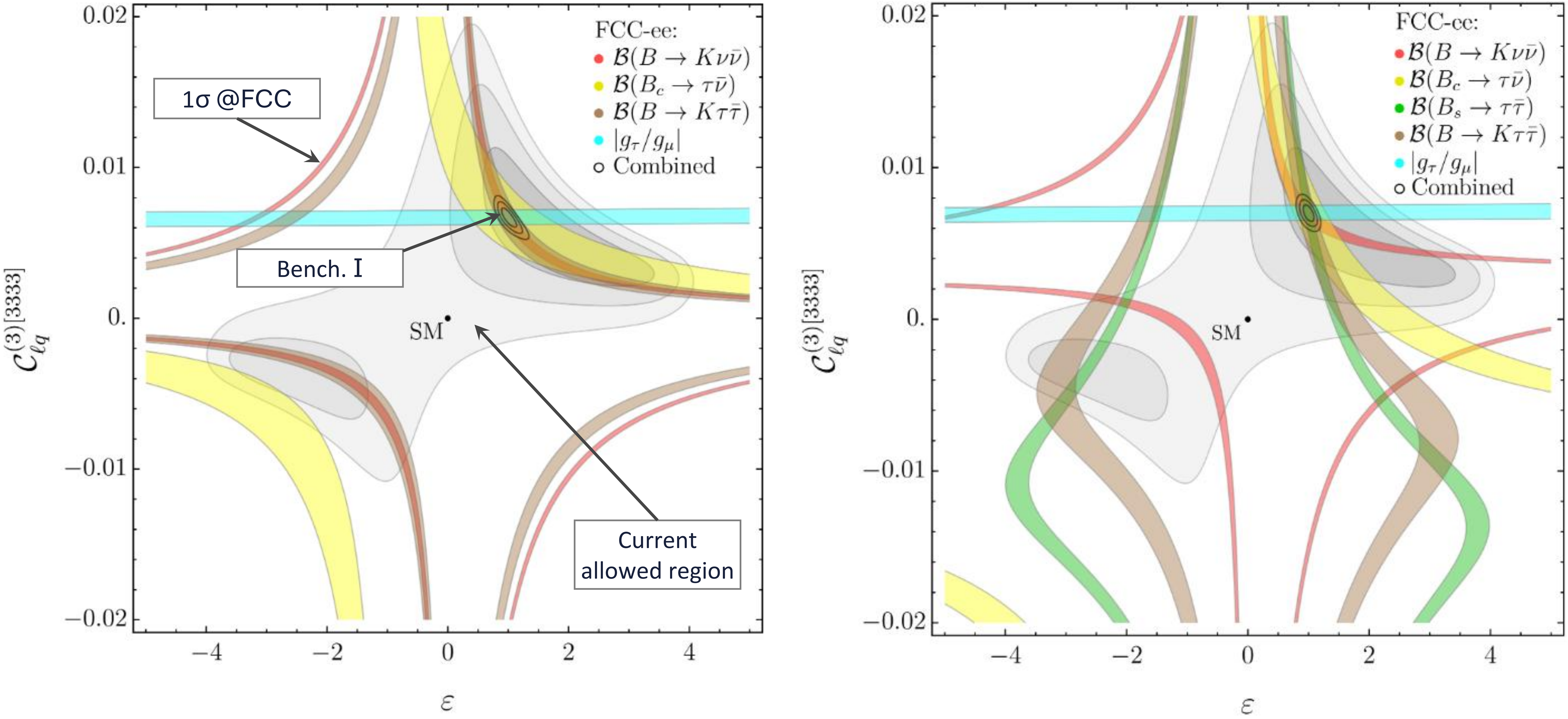
$$\text{II. } \mathcal{C}_{\ell q}^{(3)[3333]} = 6.7 \times 10^{-3},\ \varepsilon = 1,\ \mathcal{C}_{\ell q}^{(1)[3333]} = \mathcal{C}_{\ell e q d}^{[3333]} = 3.0 \times 10^{-3}$$



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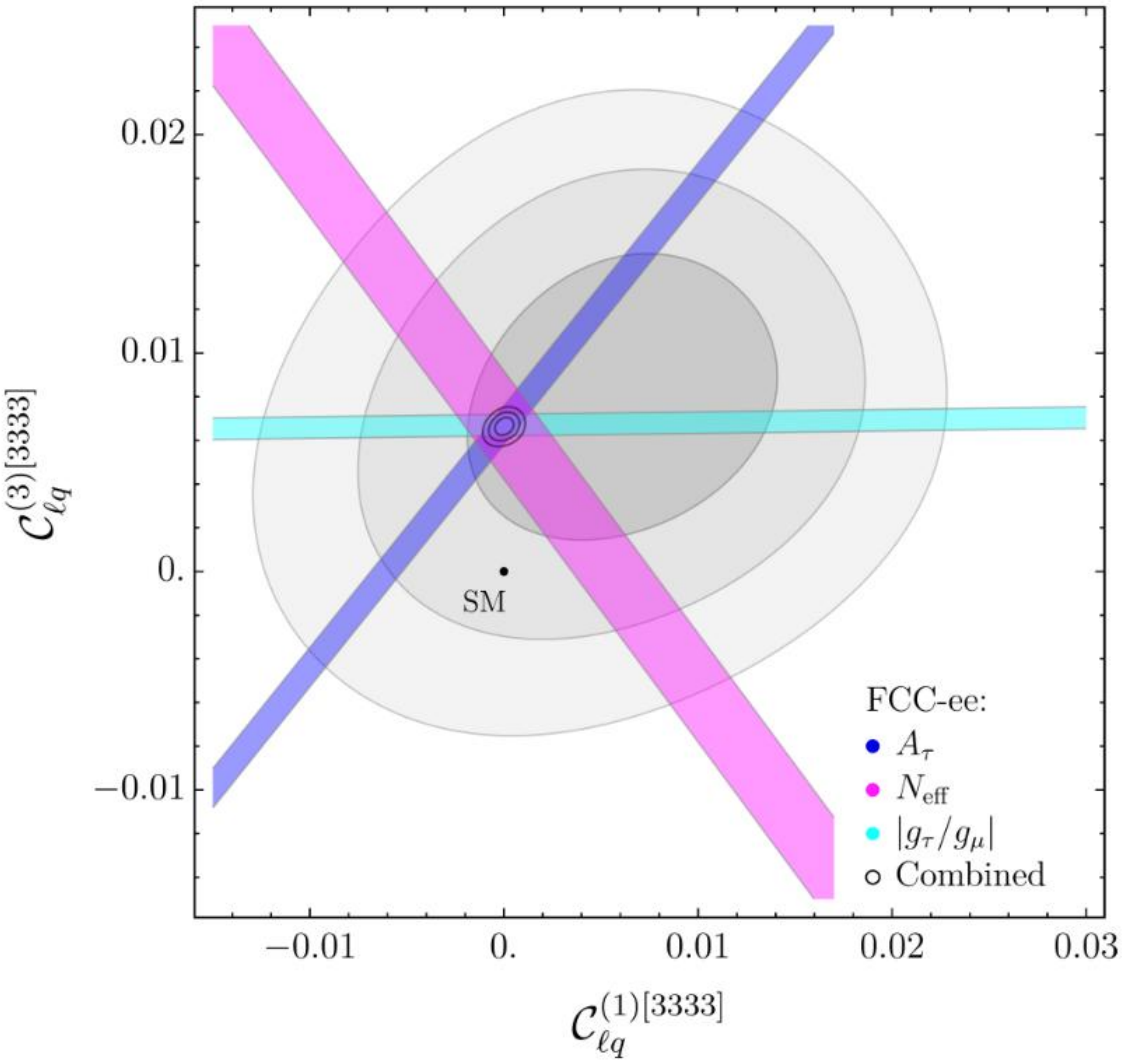


$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_L^3 \gamma_\mu \ell_L^3)(\bar{q}_L^3 \gamma^\mu q_L^3)$$

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

$$\Delta N_{eff} \sim \delta g_L^{Z\nu} \sim \left(\mathcal{C}_{H\ell}^{(1)[33]} - \mathcal{C}_{H\ell}^{(3)[33]}\right)$$

$$\Delta A_\tau \sim \delta g_L^{Z\tau} \sim \left(\mathcal{C}_{H\ell}^{(1)[33]} + \mathcal{C}_{H\ell}^{(3)[33]}\right)$$

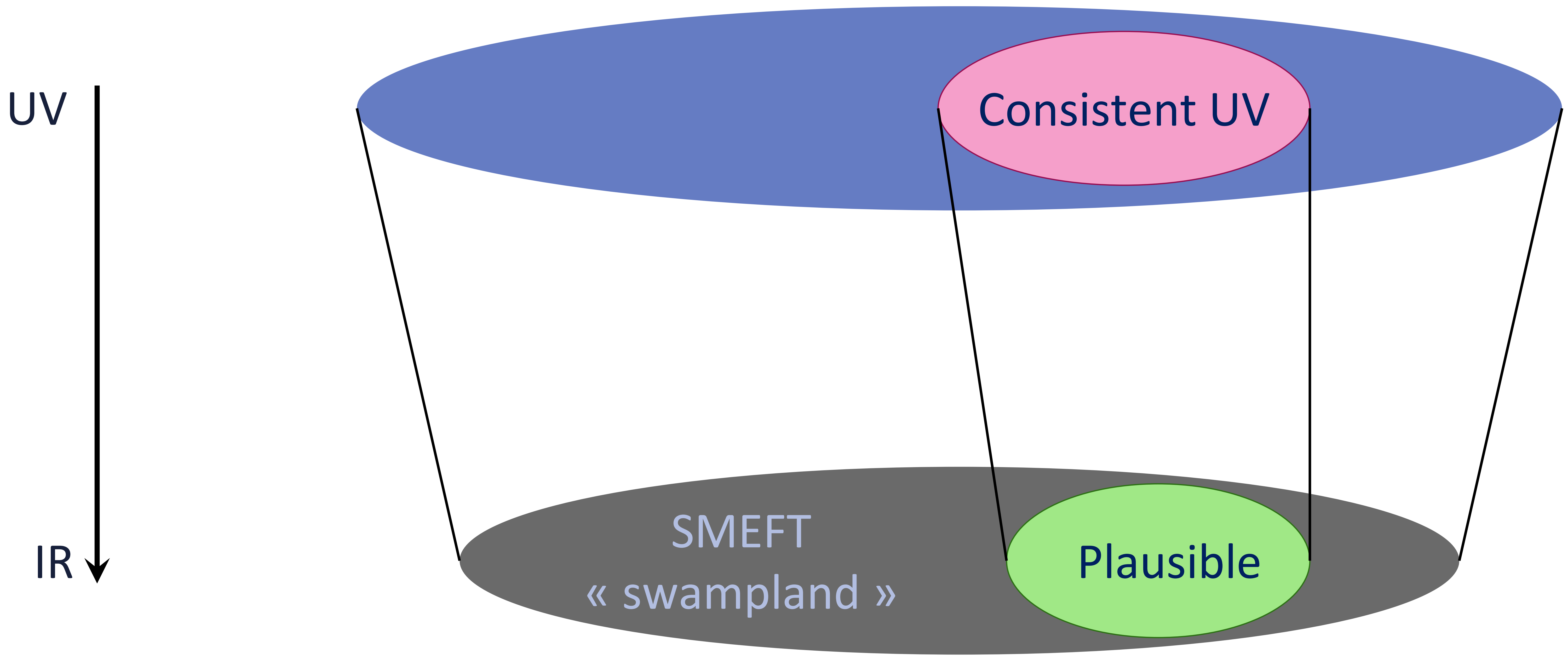
$$\Delta \left[g_\tau / g_\mu\right] \sim \mathcal{C}_{H\ell}^{(3)[33]}$$

Precision EW -> *disentangle* gauge structure of NP

-> *break degeneracies*

The Importance of Being (UV-)Earnest

Not all SMEFT parameter space can be spanned by (consistent) UV models



$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM}^{d\leq 4} + \frac{1}{\Lambda_{\rm UV}}\mathcal{L}^{d=5} + \frac{1}{\Lambda_{\rm UV}^2}\mathcal{L}^{d=6} + \dots$$

Fits are *not* enough … need to have a concrete UV picture in mind a.k.a a model !

Credits: Matthew McCullough's talk @FCC workshop 2025

Simplified Models: U_1 Vector Leptoquark

Flavour non-universality

$$SU(4)_{[3+\mathrm{H}]} \times SU(3)_{[12]} \times SU(2)_L \times U(1)_X \to \mathrm{SM}$$

➡ $U_1 \sim (3, 1, 2/3)$*: best mediator to address charged B decay tensions*

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

Tree-level → Matching

$$\mathcal{C}_{\ell q}^{(1)[3333]} = \mathcal{C}_{\ell q}^{(3)[3333]} = \frac{g_4^2 v^2}{8 M_U^2} \qquad \mathcal{C}_{\ell q}^{(1)[3333]} = -\frac{g_4^2 v^2}{32 M_Z^2}$$

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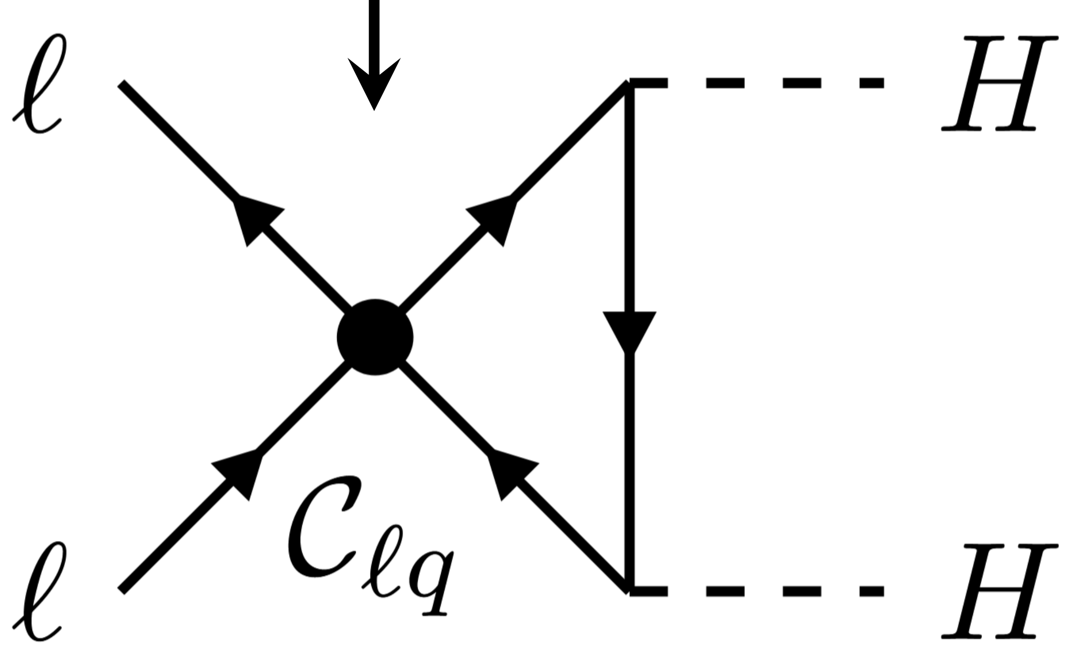
EW effect via running



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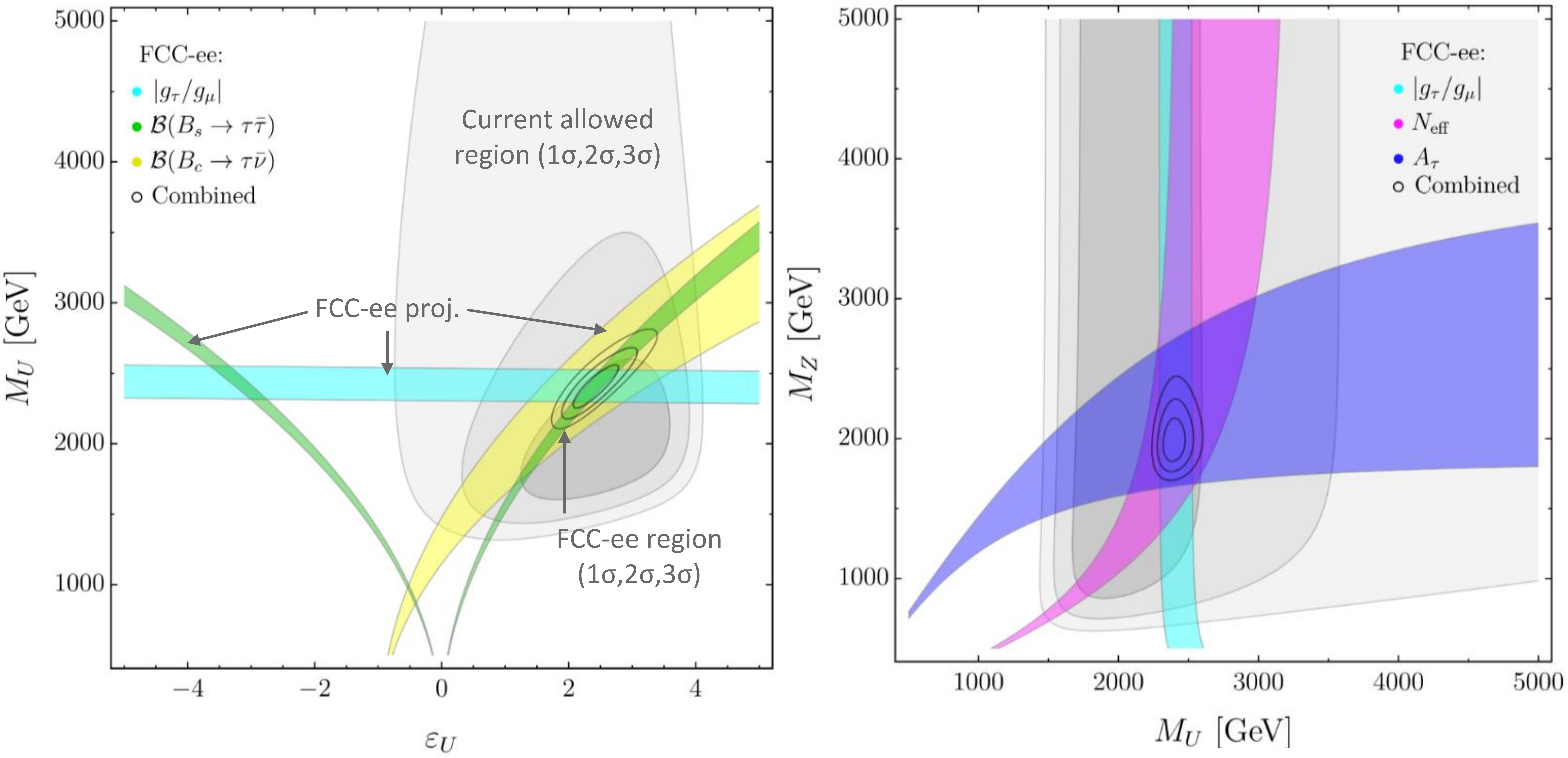


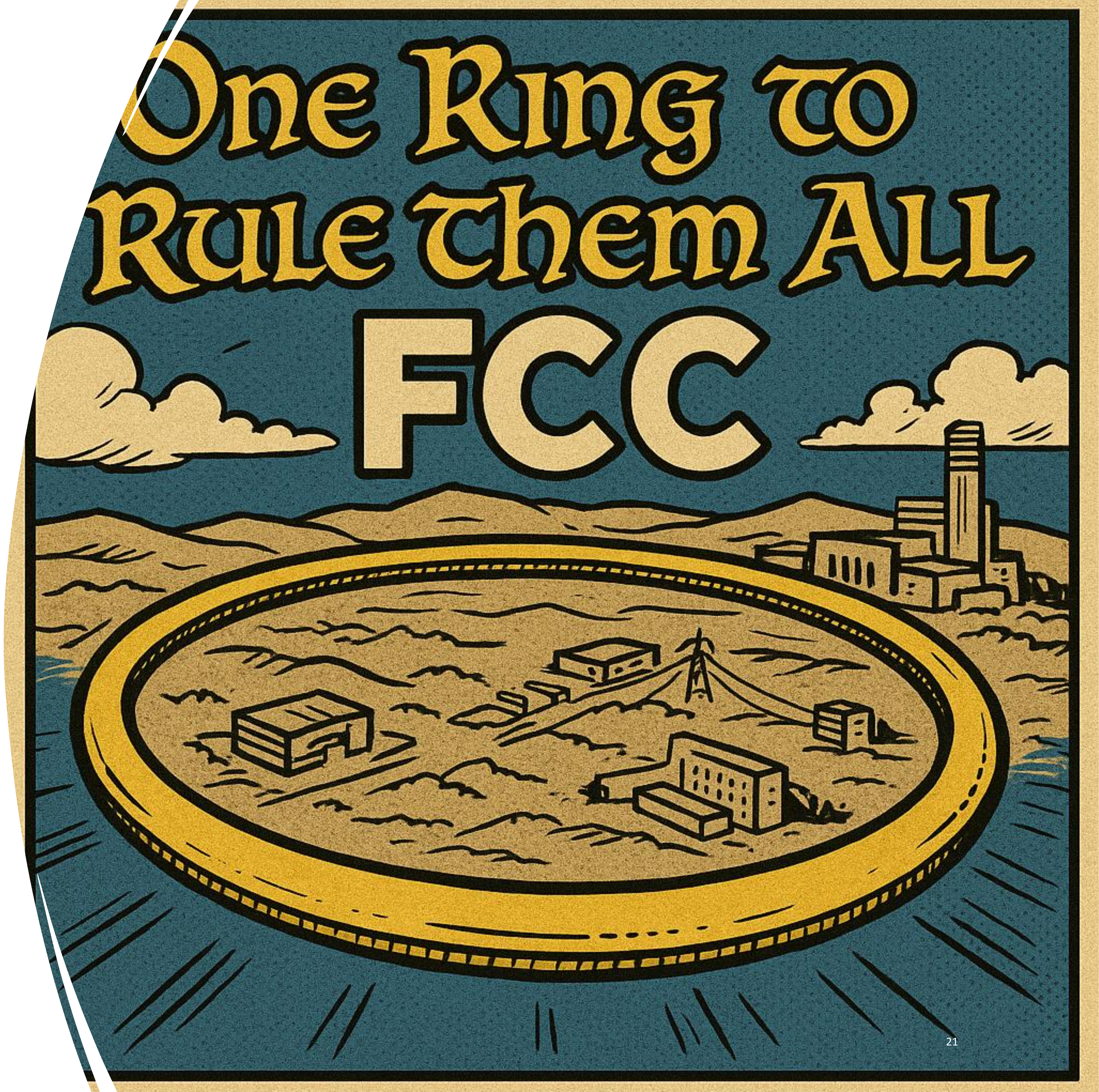
Take-Home Messages

- With no clear indication of the NP scale -> indirect + precision flavour & EW searches allow to probe, via RGE effects, *broad classes* of *well-motivated* BSM models up to *high scales*

- FCC-ee -> amazing machine for precision physics in several (*redundancy*) flavour & EW obs. (*complementarity*) + interplay with near future facilities: HL-LHC, *B* factories, ...

For more colourful plots -> look at the paper or come chat ;-) !

Thank you !



*Armin Ilg inspired illustration

Backup Slides

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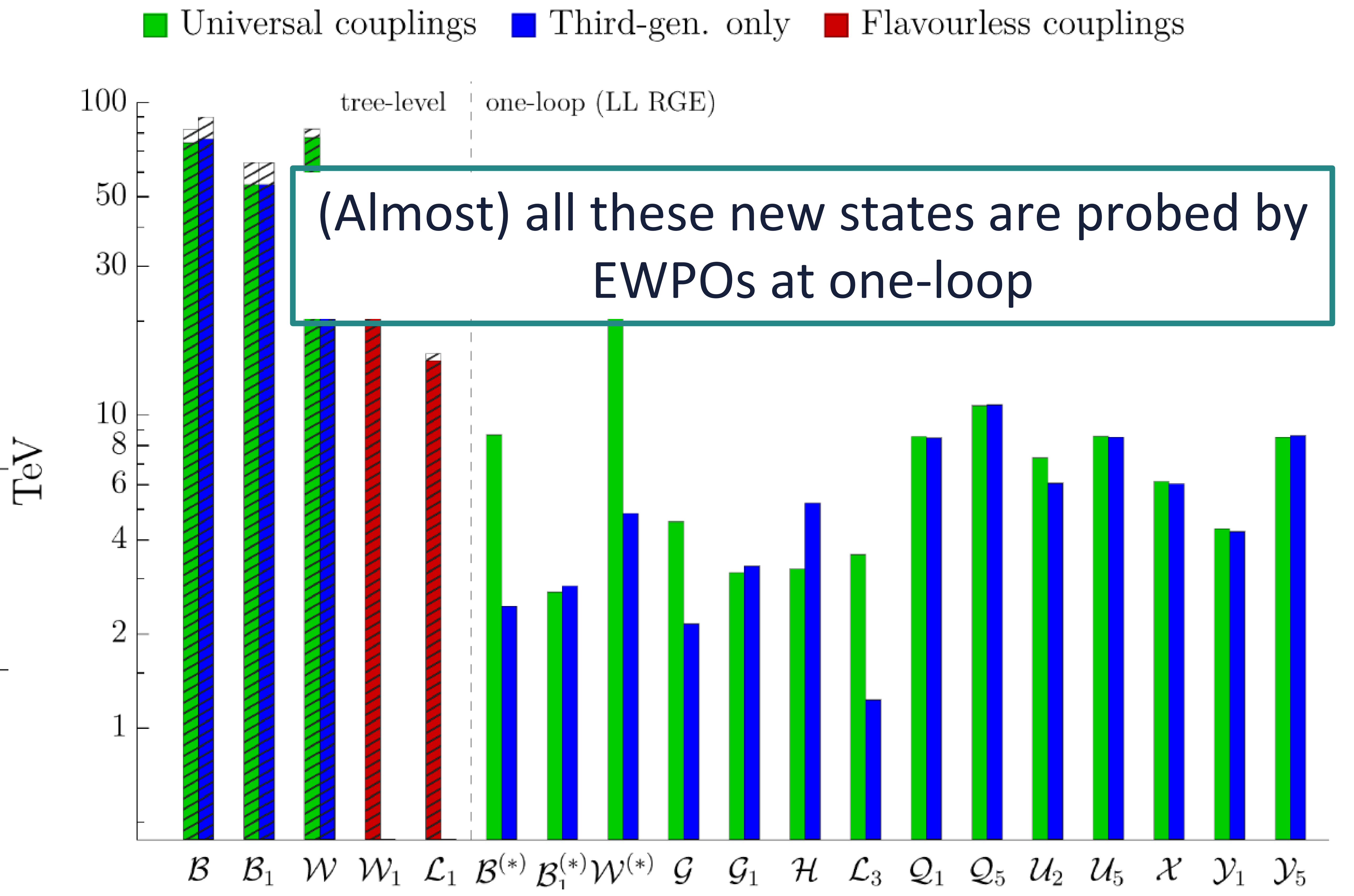
Illustrate the discovery potential of a high-intensity e^+e^- collider @ $\boldsymbol{Z}$ pole via precision flavour measurements + flavour-EW interplay to constrain TeV-scale BSM models

BSM states that match to dim-6 SMEFT (@ tree-level)

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

"Granada Dictionary"
de Blas, Criado, Perez-Victoria, Santiago [1711.10391]



See also Allwicher, McCullough & Renner [2408.03992]

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]
$\mathcal{B}(B \to K\tau\bar{\mu})$	0		$< 1.0 \times 10^{-6}$ [*] [20]	
$\mathcal{B}(B_s \to \tau\bar{\mu})$	0		$< 1.0 \times 10^{-6}$ [*] [20]	

Table 1: List of the flavor observables we consider in our analysis, with corresponding SM predictions, current experimental values, and expected future sensitivities before the start of FCC-ee and after its completion (see text for more details). The entries marked with [*] are upper bounds in the absence of a signal; the entries marked with [**] are relative errors assuming an enhanced rate over the SM expectation (by a factor $\gtrsim 3$); the other entries are relative errors assuming the SM value.

Observable	Relative uncertainty	Observable	Relative uncertainty
Γ_Z	1.0×10^{-5}	A_b	2.3×10^{-4}
σ^0_{had}	9.6×10^{-5}	A_τ	1.4×10^{-3}
R_b	3.0×10^{-4}	m_W	4.6×10^{-6}
R_μ	5.0×10^{-5}	Γ_W	5.1×10^{-4}
R_e	3.0×10^{-4}	$\mathcal{B}(W \to \tau\nu)$	3.0×10^{-4}
R_τ	1.0×10^{-4}	$\mu(H \to b\bar{b})$	3.0×10^{-3}
N_{eff}	0.6×10^{-3}	$\mu(H \to \tau\bar{\tau})$	9.0×10^{-3}

Table 2: Expected relative uncertainties for the relevant EWPOs at FCC-ee used in our analysis. For Z- and W-decay observables, the numbers are taken from [21], rescaled for 4 IPs and 205 ab^{-1} integrated luminosity (Z pole). The projection for the effective number of neutrinos N_{eff} is taken from [22] and adapted similarly. The projection for Higgs signal strengths follows [23].

Simplified Models: Scalar Leptoquarks

Case II:

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

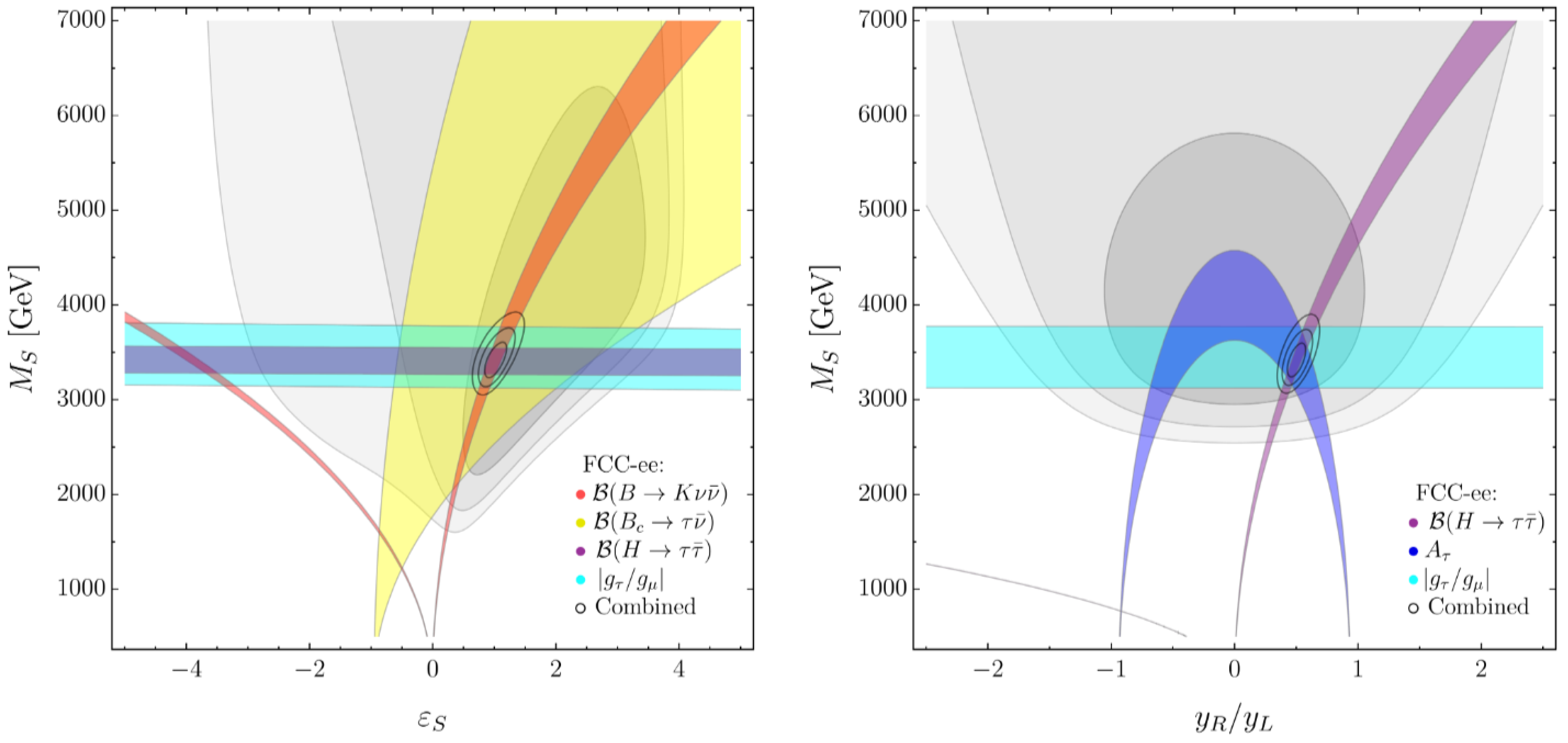
Tree-level → Matching

$$\mathcal{C}_{lq}^{(1)[3333]} = -\frac{v^2}{2}\frac{y_L^* y_L}{4M_S^2}, \qquad \mathcal{C}_{lq}^{(3)[3333]} = \frac{v^2}{2}\frac{y_L^* y_L}{4M_S^2}$$

$$\mathcal{C}_{lequ}^{(1)[3333]} = -\frac{v^2}{2}\frac{y_R y_L^*}{2M_S^2}, \qquad \mathcal{C}_{lequ}^{(3)[3333]} = \frac{v^2}{2}\frac{y_R y_L^*}{8M_S^2}$$

$$\mathcal{C}_{eu}^{[3333]} = -\frac{v^2}{2}\frac{y_R^* y_R}{2M_S^2}$$

Benchmark: $\{y_L = 2\,,\ M_S = 3.4\ \text{TeV}\,,\ y_R = 1\,,\ \varepsilon_S = 1\}$

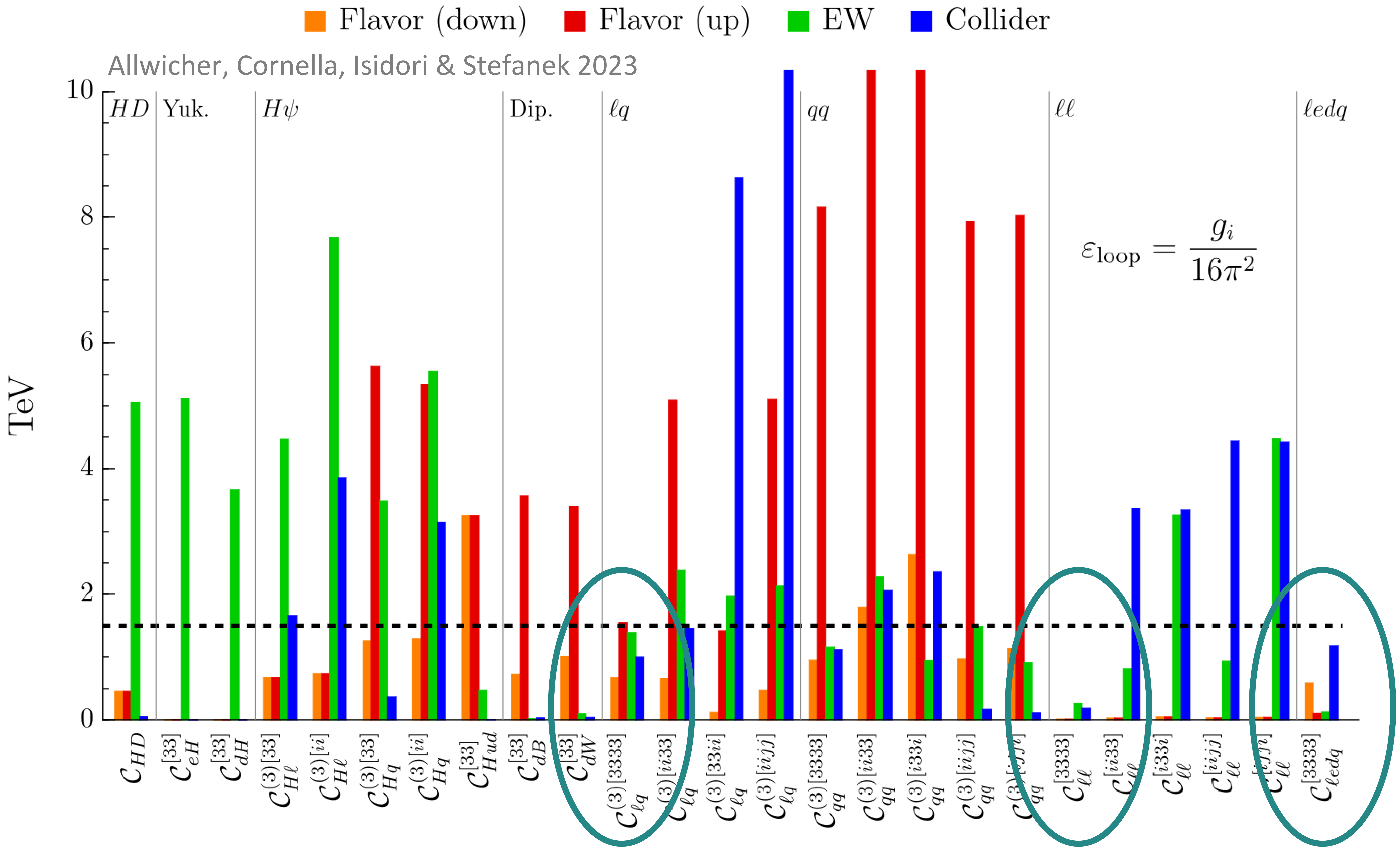


7000
6000
5000
4000
3000
2000
1000
M_S [GeV]
−4
−2
0
2
4
ε_S
FCC-ee:
$\mathcal{B}(B \to K\nu\bar{\nu})$
$\mathcal{B}(B_c \to \tau\bar{\nu})$
$\mathcal{B}(H \to \tau\bar{\tau})$
$|g_\tau/g_\mu|$
Combined
7000
6000
5000
4000
3000
2000
1000
M_S [GeV]
−2
−1
0
1
2
y_R/y_L
FCC-ee:
$\mathcal{B}(H \to \tau\bar{\tau})$
A_τ
$|g_\tau/g_\mu|$
Combined

Back to Flavour

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d\geq 5}\sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}}\mathcal{O}_i^{(d)}$$

3rd Gen. is the least constrained



Simplified Models: Vector Leptoquarks

Case I*: $U_1 \sim (3,1,2/3)$ and Z' *(SU(4)-inspired construction + R_D)*

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

(NP in 3rd gen.) [see Joe's talk]

Tree-level → Matching

$$\mathcal{C}_{\ell q}^{(1)[3333]} = \mathcal{C}_{\ell q}^{(3)[3333]} = \frac{g_4^2 v^2}{8 M_U^2} \qquad \mathcal{C}_{\ell q}^{(1)[3333]} = -\frac{g_4^2 v^2}{32 M_Z^2}$$

Benchmark: $\{g_4 = 2\,,\ M_U = 2.4 \text{ TeV}\,,\ M_Z = 2 \text{ TeV}\,,\ \varepsilon_U = 2.4\,,\ \varepsilon_Z = 0.9\}$

- Similar benchmark as in the EFT analysis <--> *B* discrepancies
- Compatible with direct searches

*Also Scalar LQ and VLF in the paper!

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