European Strategy for Particle Physics

PARALLEL SESSION / **FLAVOUR PHYSICS**

Theoretical landscape in flavour physics

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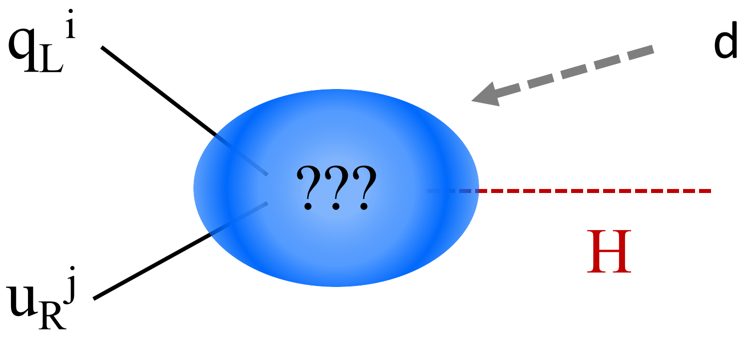
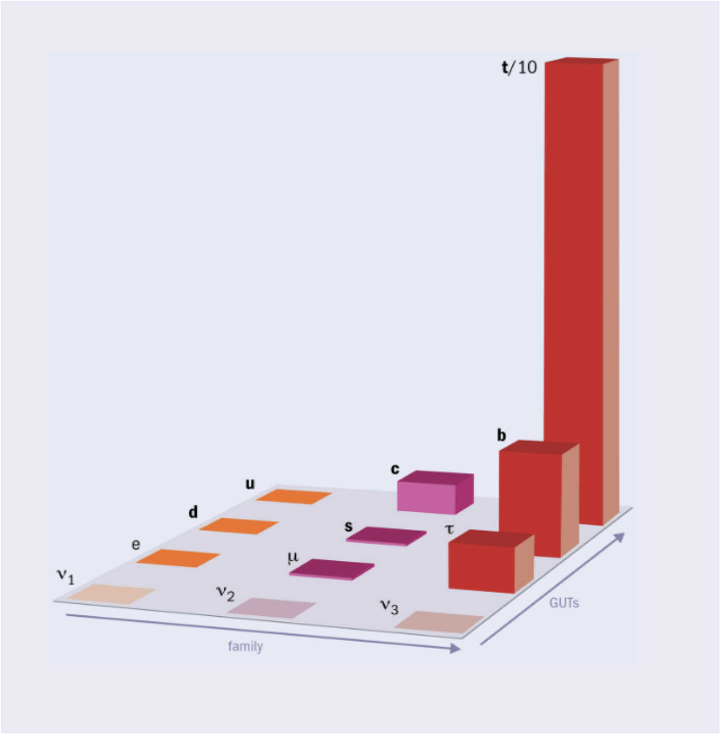
The open questions: *the SM flavour puzzle*

Fermion masses are the results of the Yukawa interactions → Inescapable link between Higgs and flavor, whose origin can be addressed only beyond the SM…



High-energy
degrees of freedom
(UV theory)

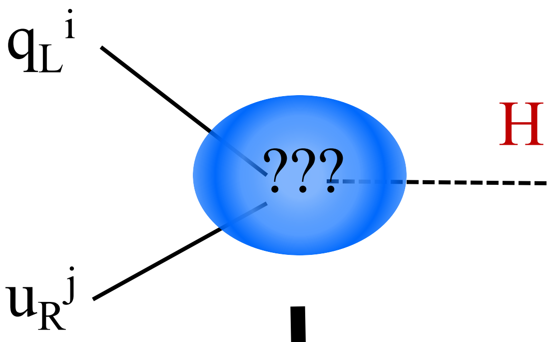
$$Y_U{}^{ij}\ \bar{q}_L{}^i\ u_R{}^j\ H$$



"Message from the UV"
that we need to "decode"

The open questions: *the NP flavour puzzle*

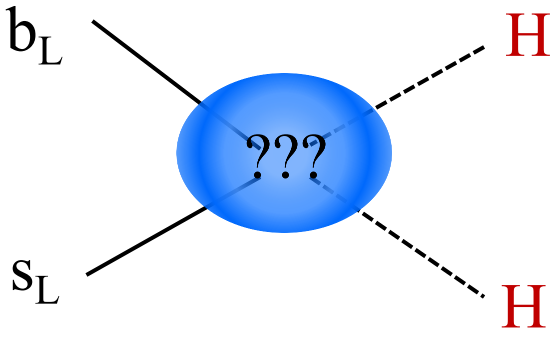
On general grounds, the flavor non-universal dynamics in the UV should give rise to effective contact interactions → violations of exact & approximate symmetries of the SM:



$$Y_U^{ij}\ \bar{q}_L^{\,i}\ u_R^{\,j}\ H$$

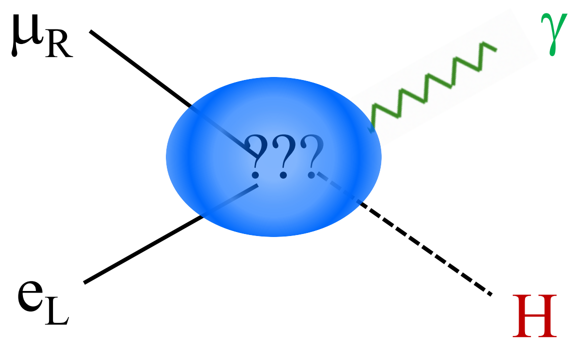
$$Y_U \sim \begin{pmatrix} < 0.01 & < 0.1 \\ & 1 \end{pmatrix}$$

E.g.:



Effective interaction which violates an <u>approximate symmetry</u> of the SM

$B_s \to \mu\mu$



Effective interaction which violates an <u>exact symmetry</u> of the SM

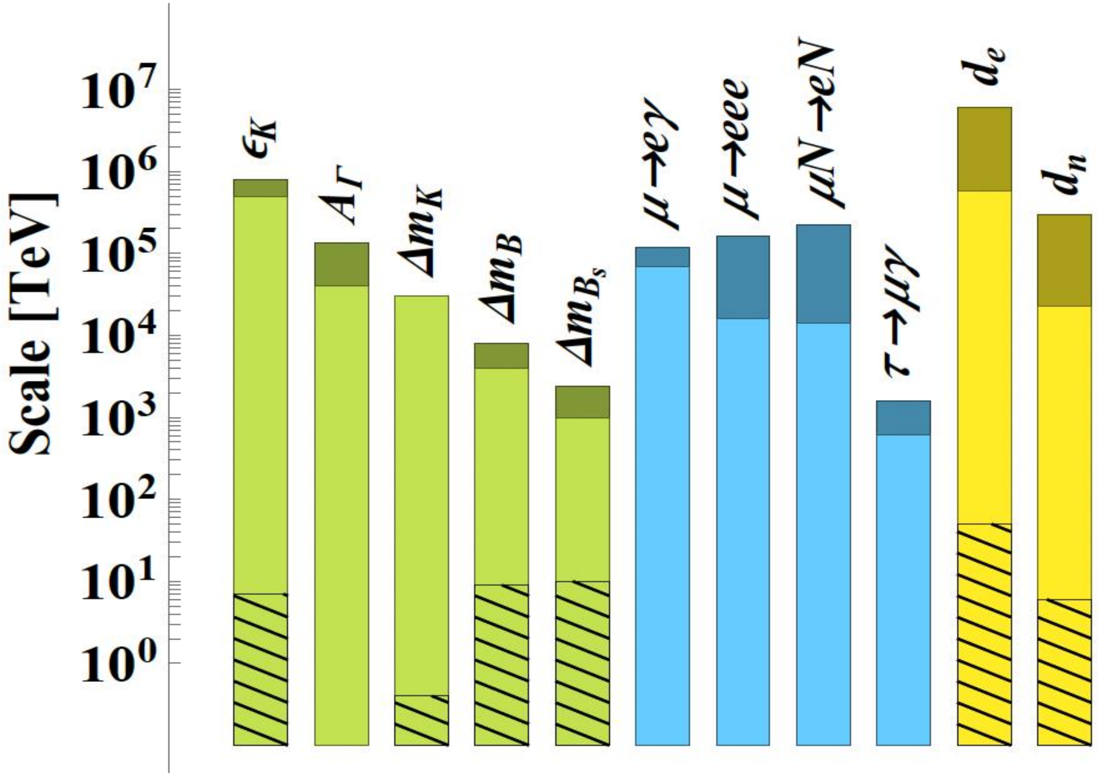
$\mu \to e\gamma$

Strength of the contact interaction $\sim C_{eff}/\Lambda^2$

The open questions: *the NP flavour puzzle*

On general grounds, the flavor non-universal dynamics in the UV should give rise to effective contact interactions $\longrightarrow$ violations of exact & approximate symmetries of the SM.

At present we do not see any of these effects, and this is often expressed in terms of strong bounds on effective NP scales:



N.B.: These bounds are obtained <u>assuming unit couplings for the effective coefficients</u>

E.g.:

$$\frac{C_{\mu e\gamma}}{\Lambda^2} \longrightarrow \frac{1}{\Lambda^2}$$

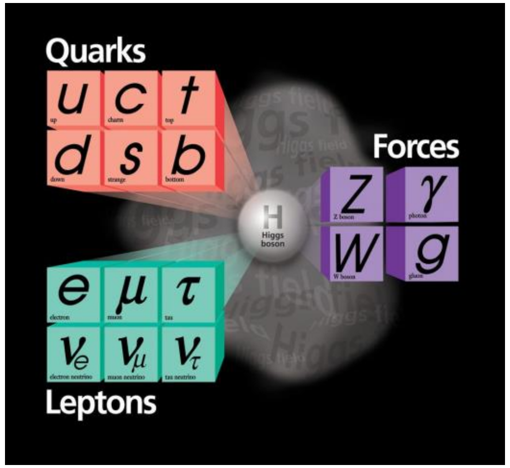
Useful to show the potential, but rather misleading…

How to address the challenges: *Flavour in the SM EFT*

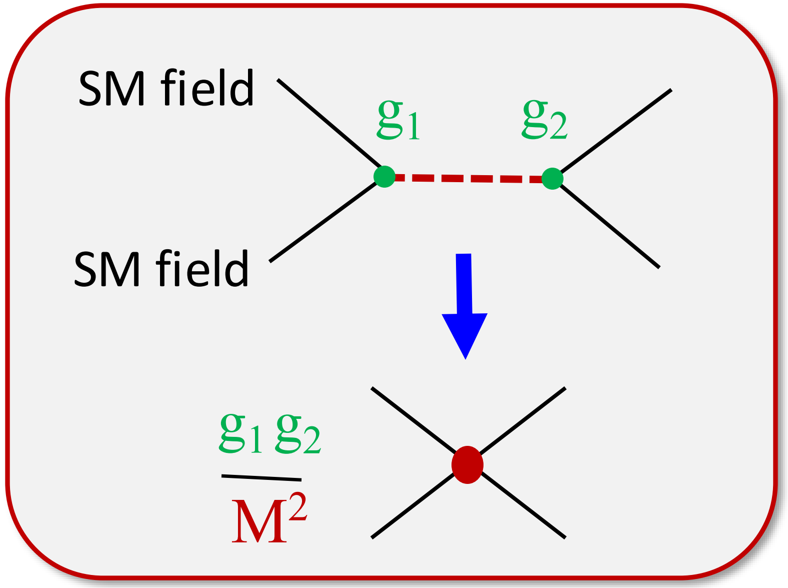
No matter if NP is at the TeV scale or well above, it is always very heavy compared to the energy scale of low-energy flavour experiments → systematic description via the "SM EFT"

$$\mathcal{L}_{\text{SM-EFT}} = \underline{\mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{[d]}(\psi_{\text{SM}})$$

Long-range structure of the theory



Most general description of heavy NP that we are not able to directly "excite"



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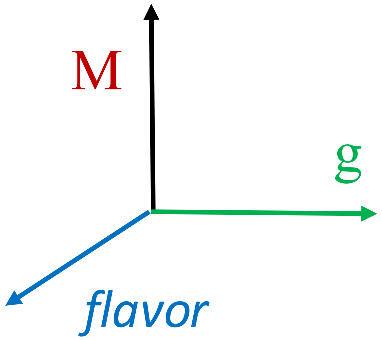
Understanding the flavour structure of the SM EFT is a question of pivotal importance.



Don't be scared by the large number of independent couplings of eff. operators!

N. of independent couplings:

- No flavor symmetry — 2499 [@d=6]
- Maximal flavor symmetry — 47 [@d=6]

They do not indicate model parameters, but rather the number of observables we can probe (*whose correlations depend on the unknown underlying model*)

How to address the challenges @ large-scale facilities [b,c,τ]

	γ	quarks	μ	e	τ	ν
$3_q \to 2_q$	$b \to s\,\gamma$	$B_s \leftrightarrow \bar{B}_s$	$b \to s\,\mu\mu$ $b \to c\,\mu\nu$	$R_{bs}\,(e/\mu)$ $R_{bc}\,(e/\mu)$	$b \to s\,\tau\tau$ $b \to c\,\tau\nu$	$b \to s\,\nu\nu$
$3_q \to 1_q$	$b \to$		$b \to d\,\mu\mu$ $b \to u\,\mu\nu$		$b \to d\,\tau\tau$ $b \to u\,\tau\nu$	
$2_q \to \begin{matrix} 2_q \\ 1_q \end{matrix}$	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}$	$c \to u\,\mu\mu$ $c \to s\,\mu\nu$ $c \to d\,\mu\nu$	$R_{cu}\,(e/\mu)$ $R_{cs}\,(e/\mu)$ $R_{cd}\,(e/\mu)$		$c \to u\,\nu\nu$
$3_l \to \begin{matrix} 2_l \\ 1_l \end{matrix}$	$\tau \to \mu\,\gamma$ $\tau \to e\,\gamma$	$\tau \to \mu\,qq$ $\tau \to e\,qq$	$\tau \to \mu\,\mu\mu$ $\tau \to \mu\,ee$	$\tau \to \mu\,ee$ $\tau \to e\,ee$		$\tau \to \mu\,\nu\nu$ $\tau \to e\,\nu\nu$

$B(B_s \to \mu\mu)$,
$B(B \to K^* \mu\mu)$,
$A_{FB}(B \to K^* \mu\mu)$,
□

$R^{\tau/\mu}(D)$,
$R^{\tau/\mu}(D^*)$, …

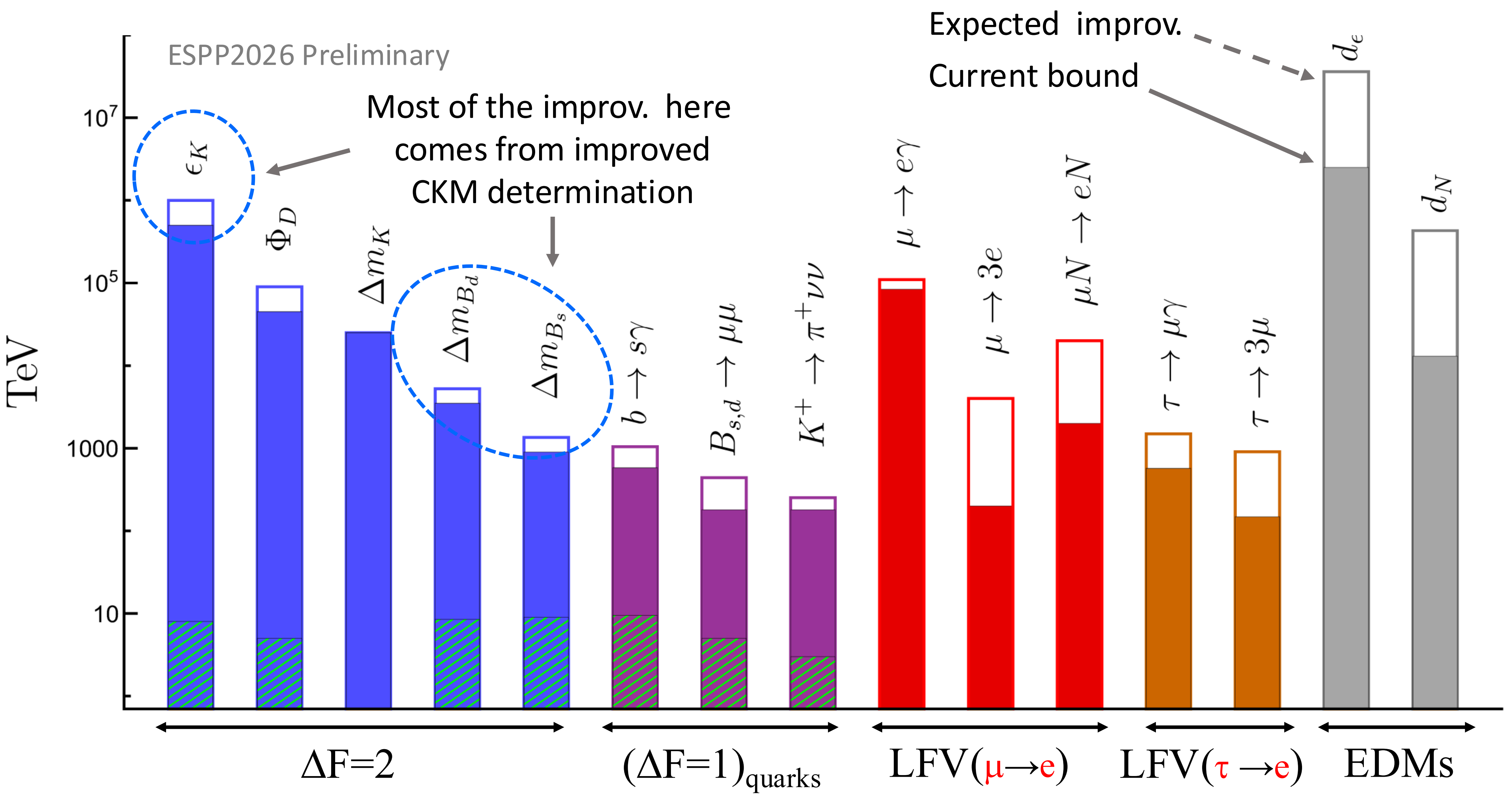
$B(B \to K\,\nu\nu)$,
$B(B \to K^*\nu\nu)$,
□

N.B.: *several observables for each transition*

How to address the challenges @ dedicated facilities [K, π, μ, EDMs]

	γ	quarks	μ	e	τ	ν
$\begin{matrix} 2_q \\ 1_q \end{matrix} \to 1_q$	$s \to d\,\gamma$	$K \leftrightarrow \bar{K}$	$s \to d\,\mu\mu$ $s \to u\,\mu\nu$ $d \to u\,\mu\nu$	$R_{sd}\,(e/\mu)$ $R_{su}\,(e/\mu)$ $R_{du}\,(e/\mu)$		$s \to d\,\nu\nu$
$2_l \to 1_l$	$\mu \to e\,\gamma$	$\mu N \to eN$		$\mu \to e\,ee$		$\mu \to e\,\nu\nu$
$2_l \to 2_l$	$g_\mu \quad d_\mu$					
$1_l \to 1_l$	d_e					
$1_q \to 1_q$	d_N					

I. Bounds on effective scales for generic (unit) couplings



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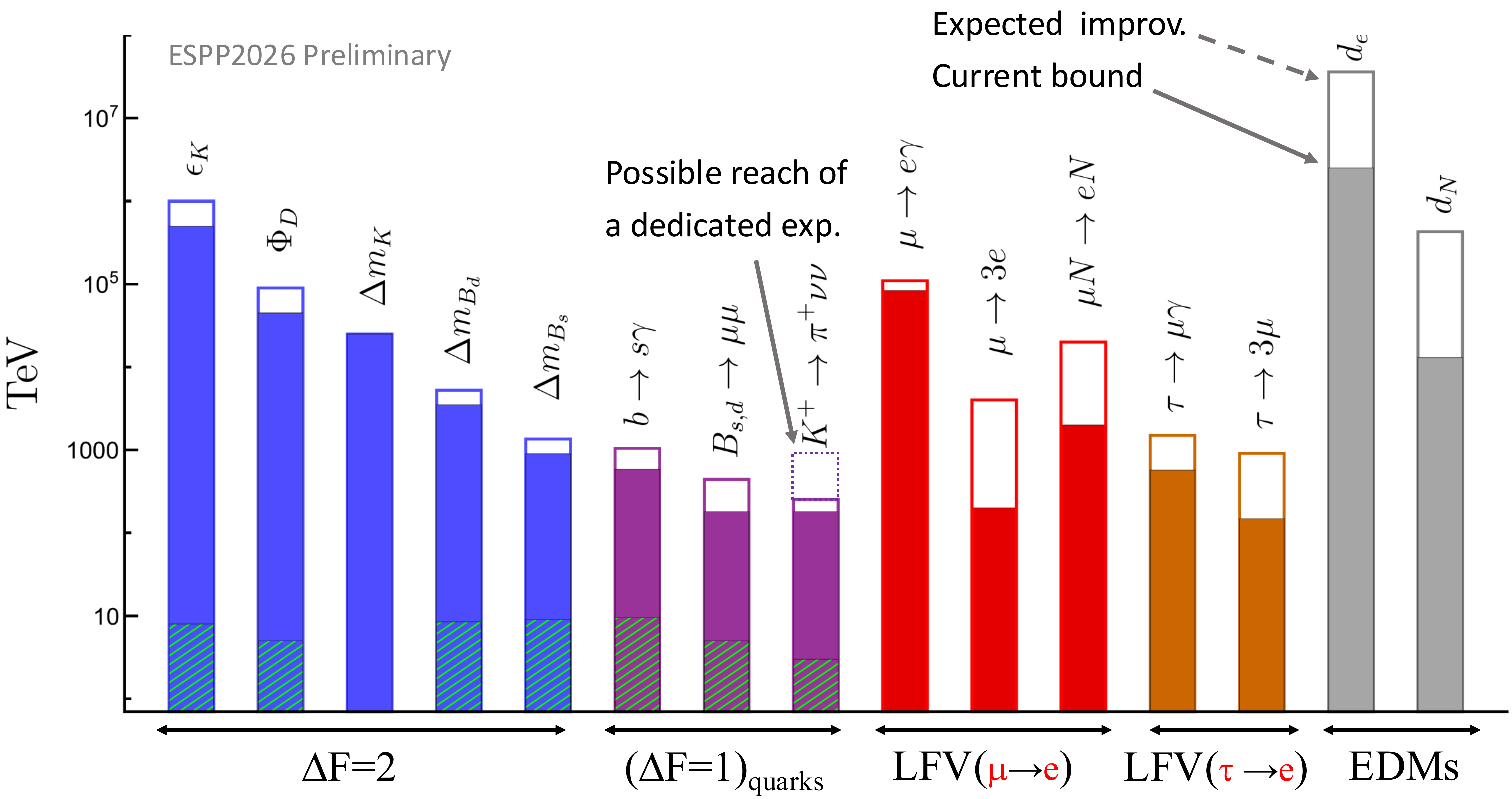
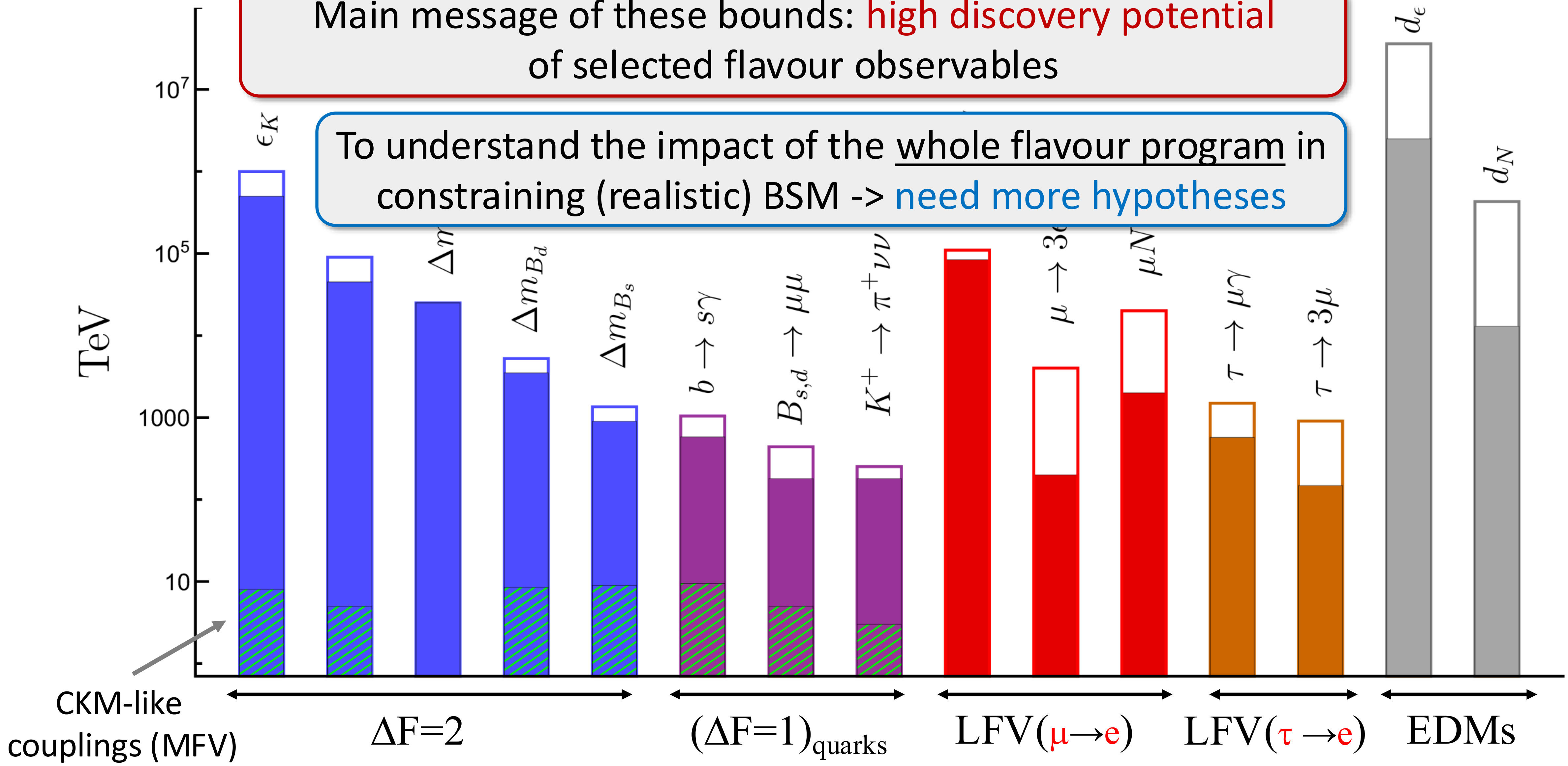


I. Bounds on effective scales for generic (unit) couplings

Main message of these bounds: high discovery potential of selected flavour observables

To understand the impact of the whole flavour program in constraining (realistic) BSM -> need more hypotheses

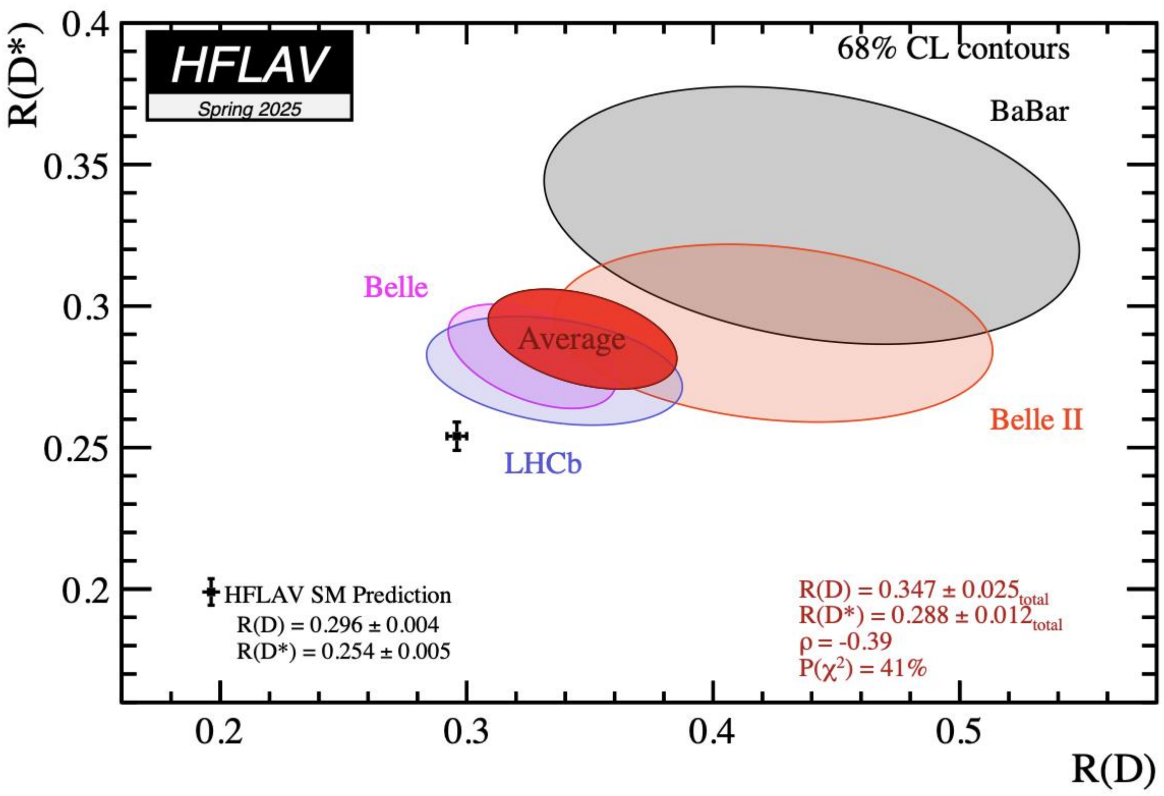


II. An explicit example of flavour – EW interplay (*assuming NP*)

Looking at bounds from individual observables misses the main point of indirect NP searches, which is the interplay of a large number of observables in "decoding" the underlying theory

To illustrate this point worth to consider an explicit example assuming a NP signal →

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$



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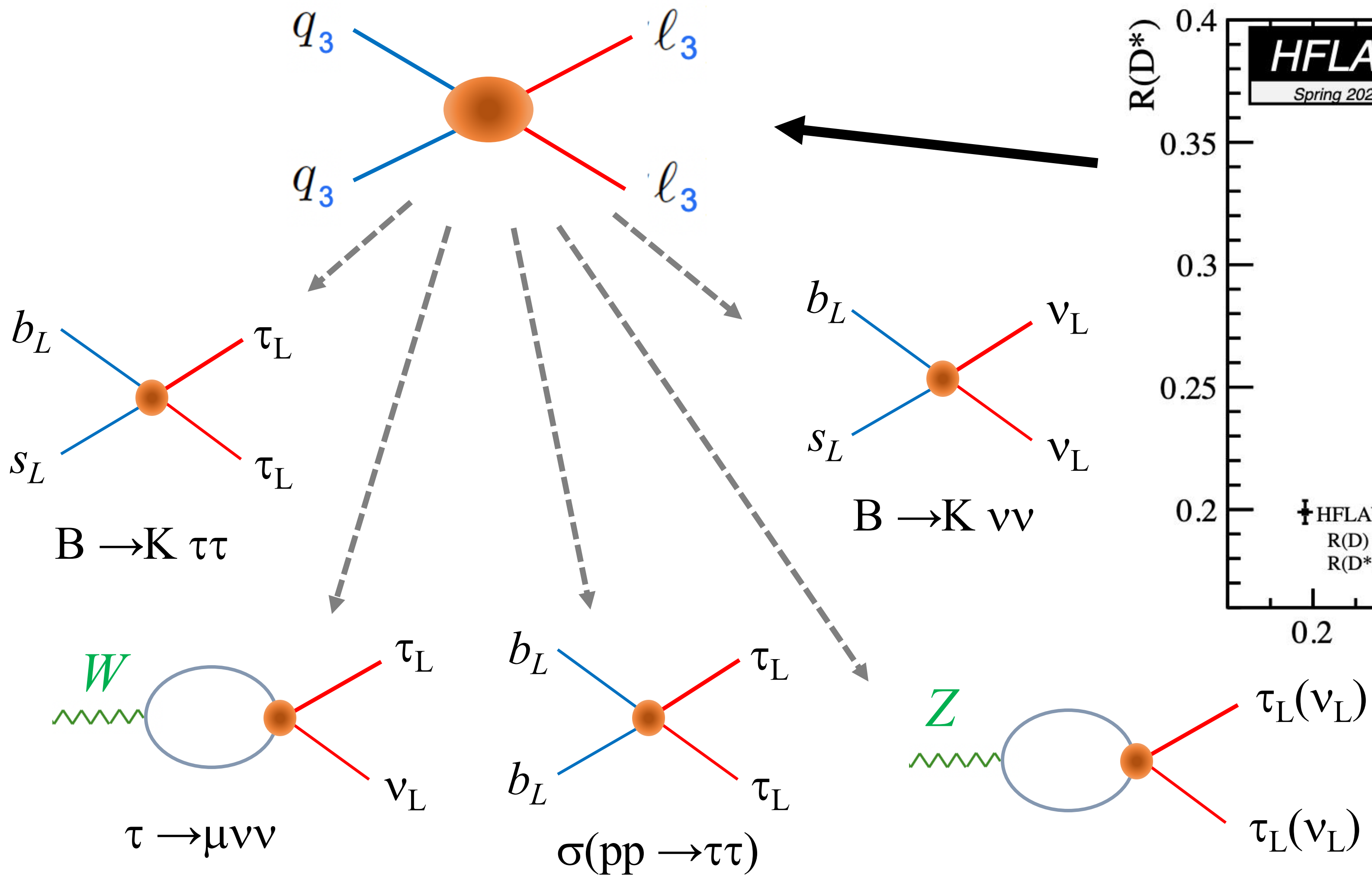

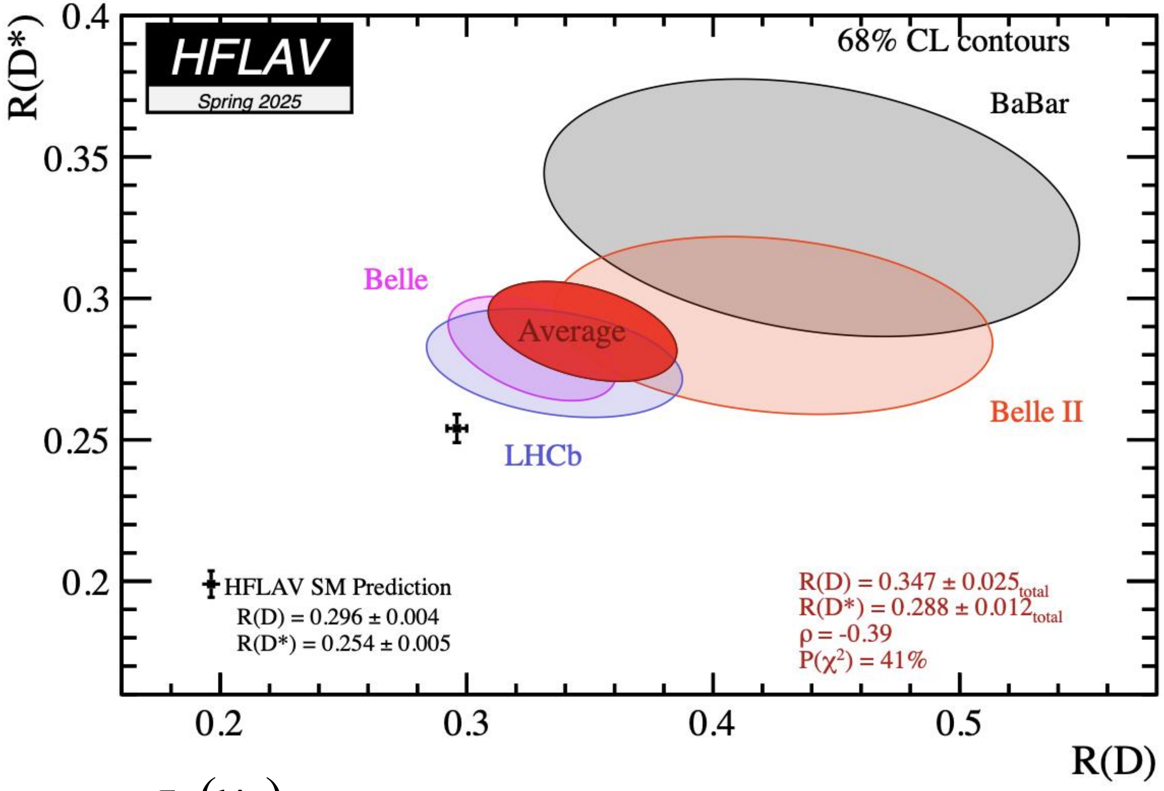

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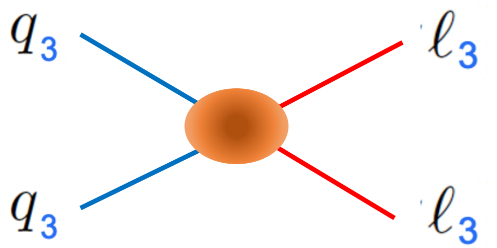
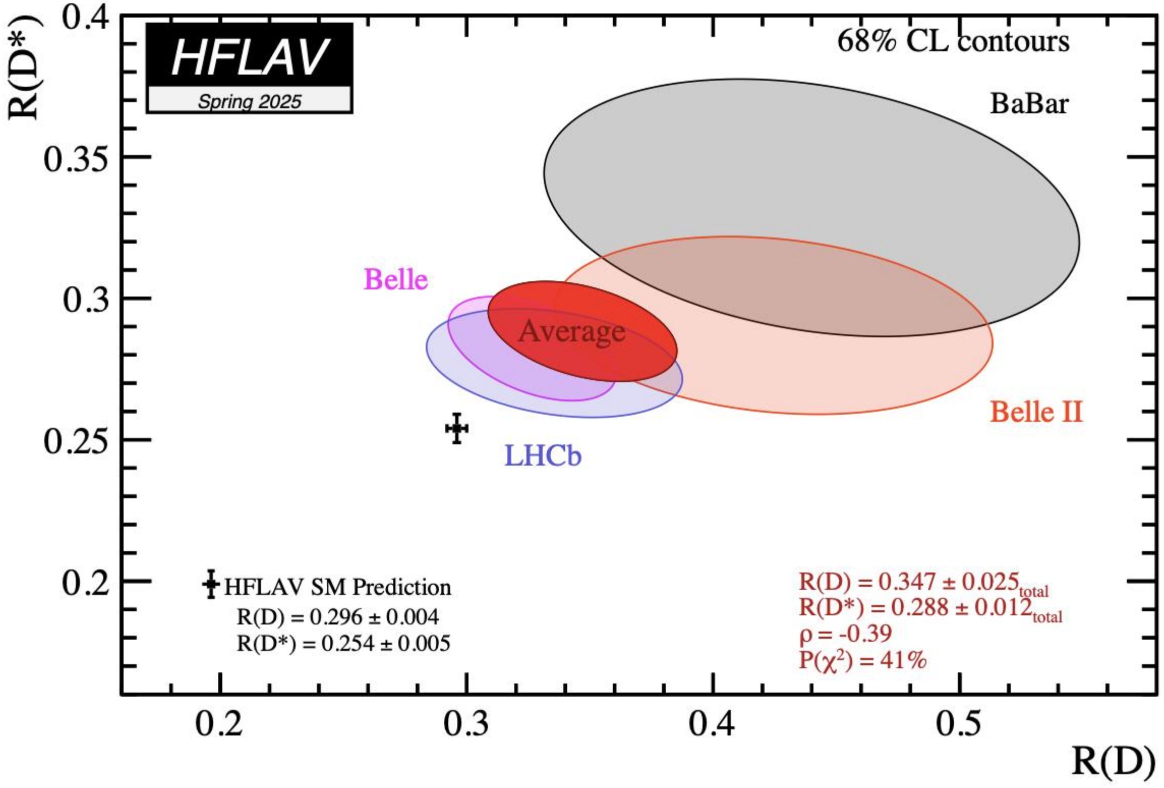


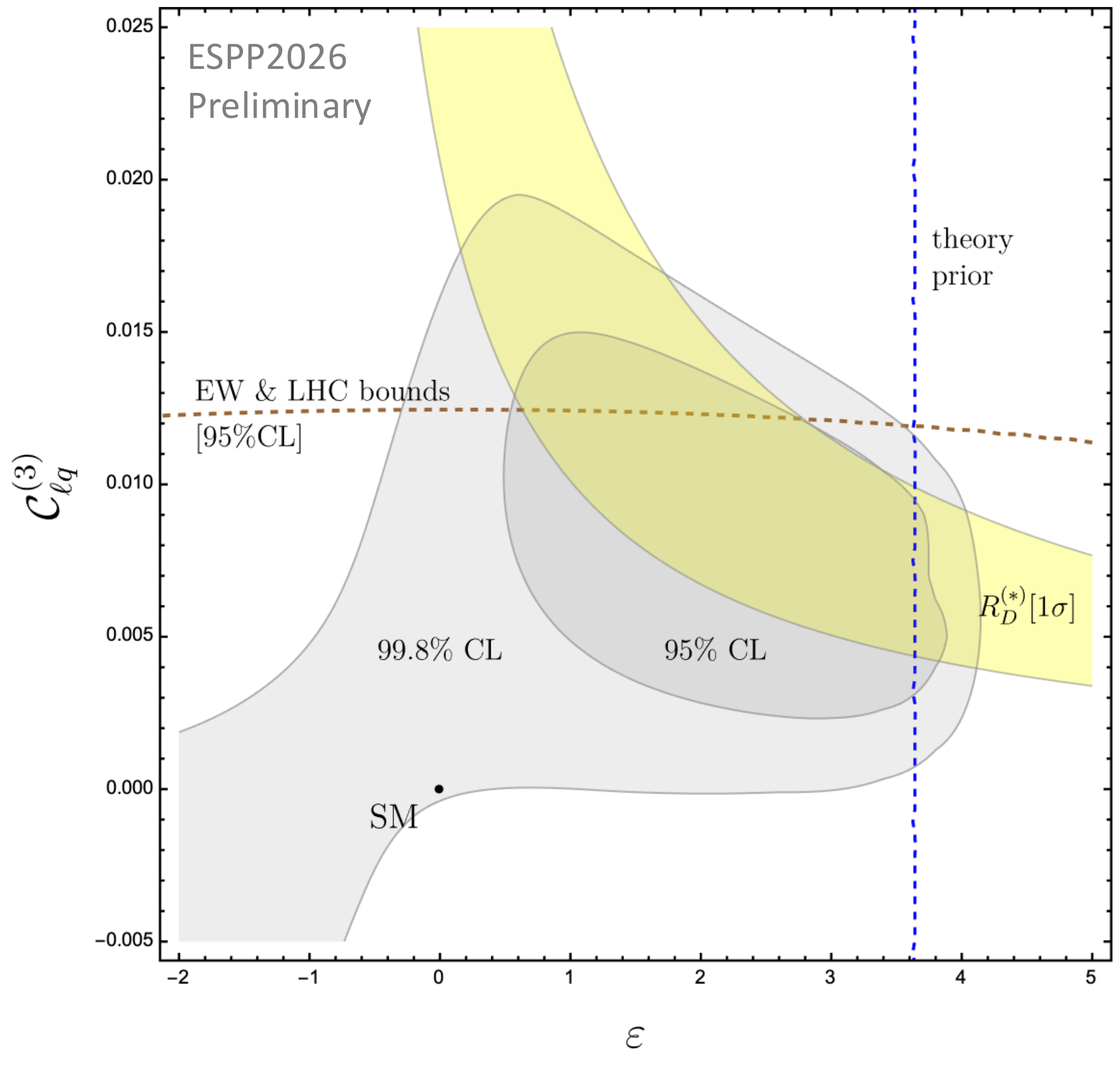


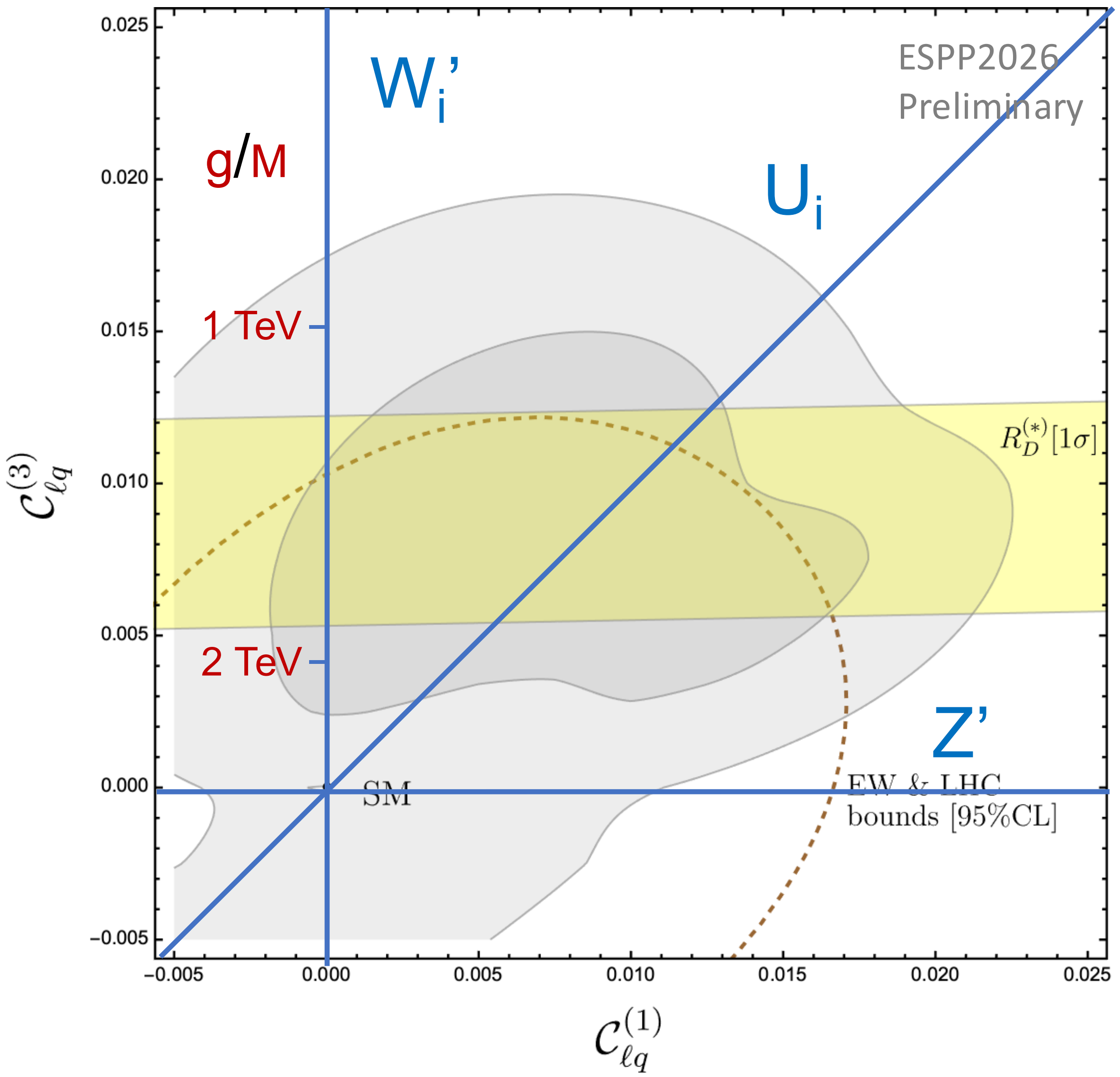
A simple, consistent, description of the system involves (*at least*) 3 parameters:

- Two Wilson coefficients, $\mathcal{C}^{(1)}_{\ell q}$ $\mathcal{C}^{(3)}_{\ell q}$

- One flavour-mixing parameter, $\varepsilon = O(1)$: $q_3 = b_L + \varepsilon\, |V_{ts}|\, s_L$

II. An explicit example of flavour – EW interplay (*assuming NP*)





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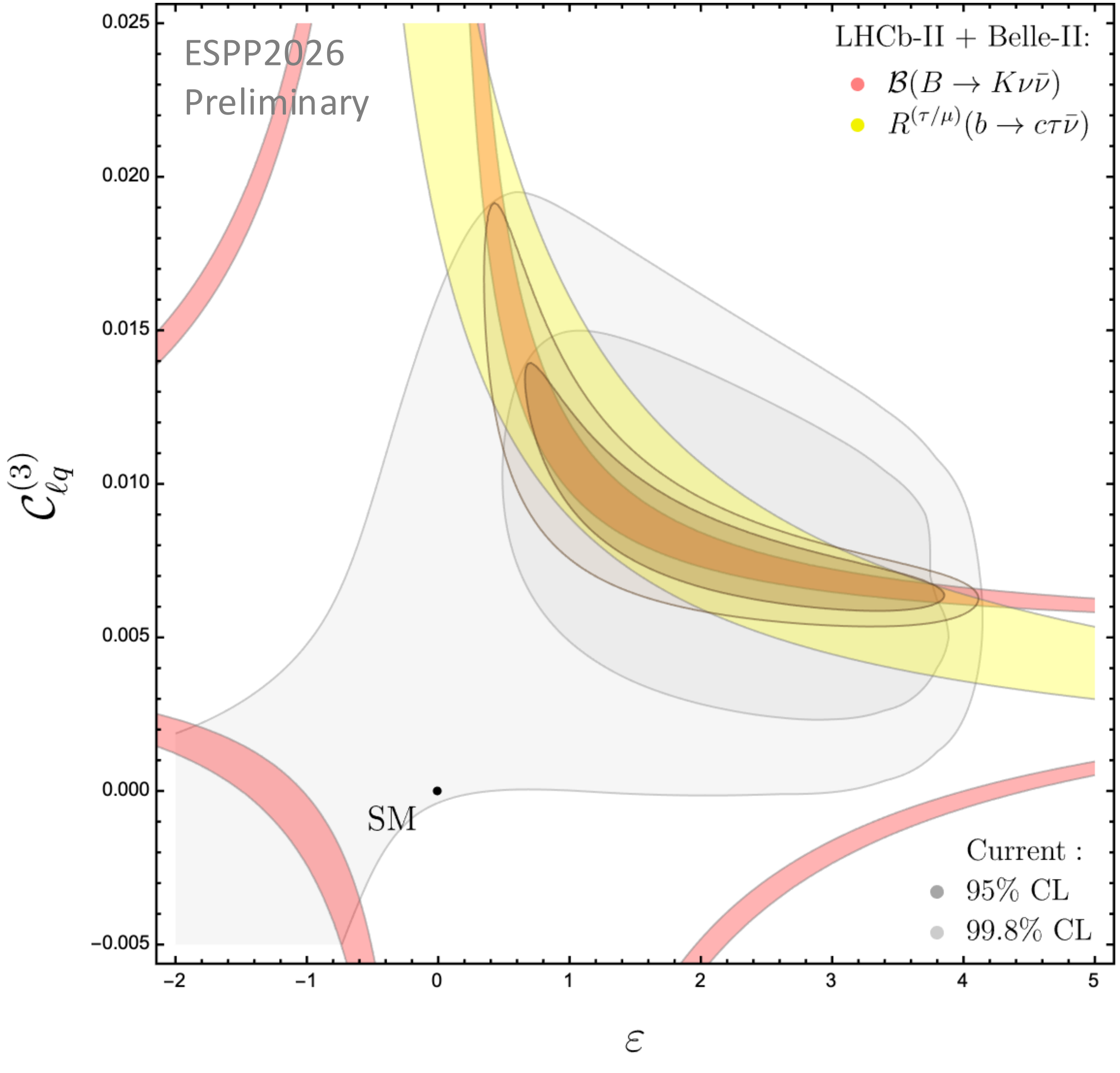

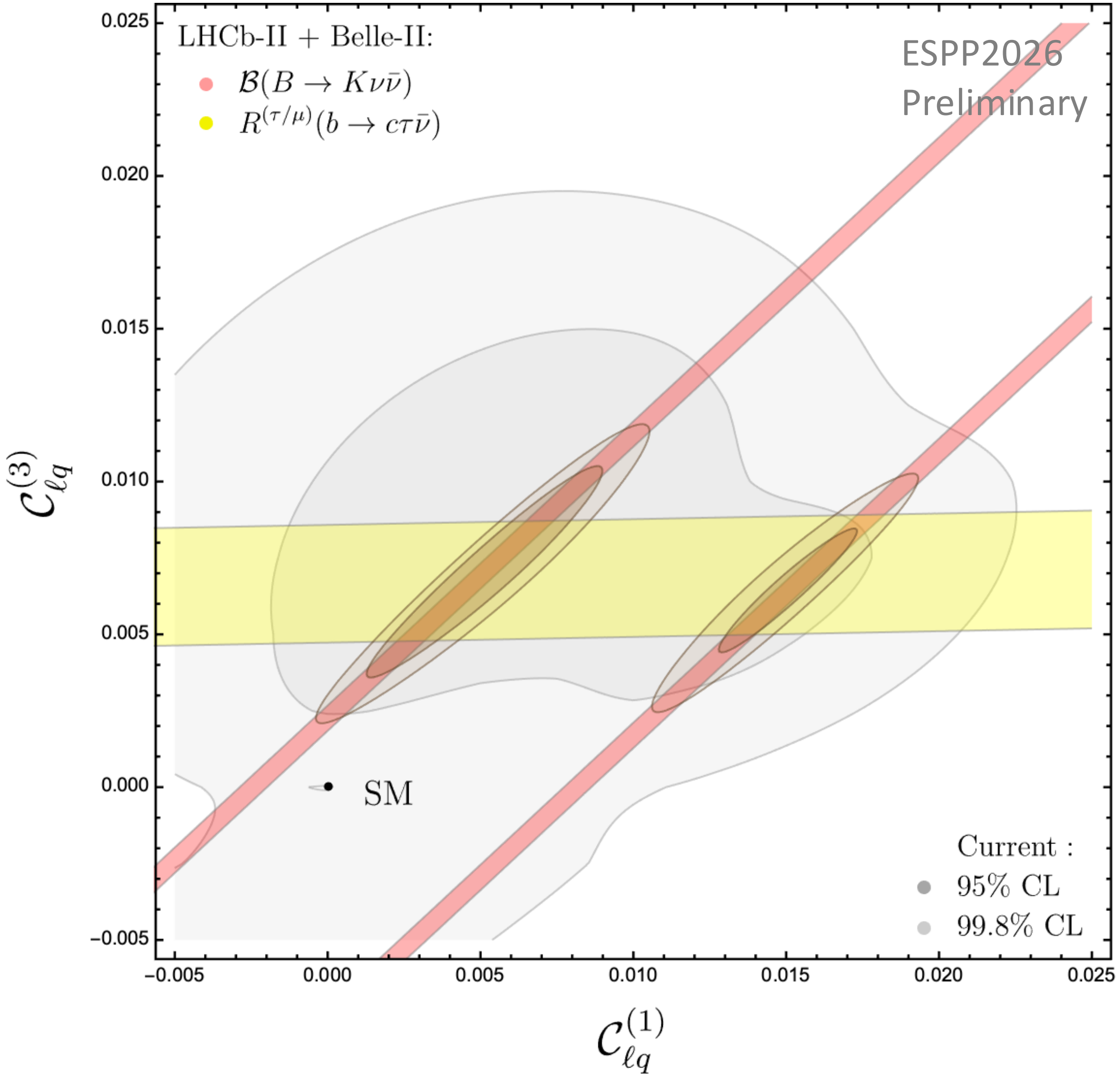

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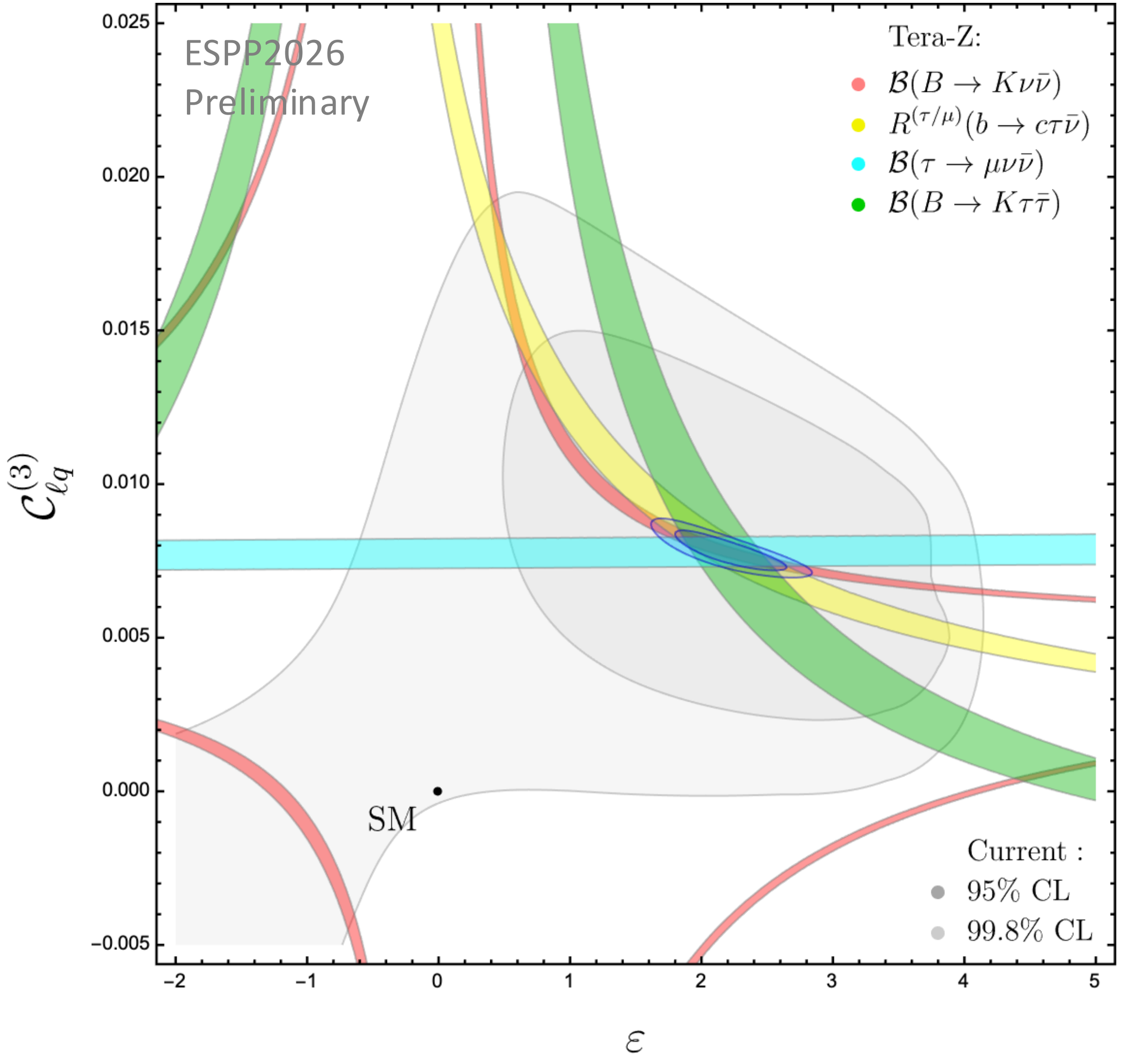

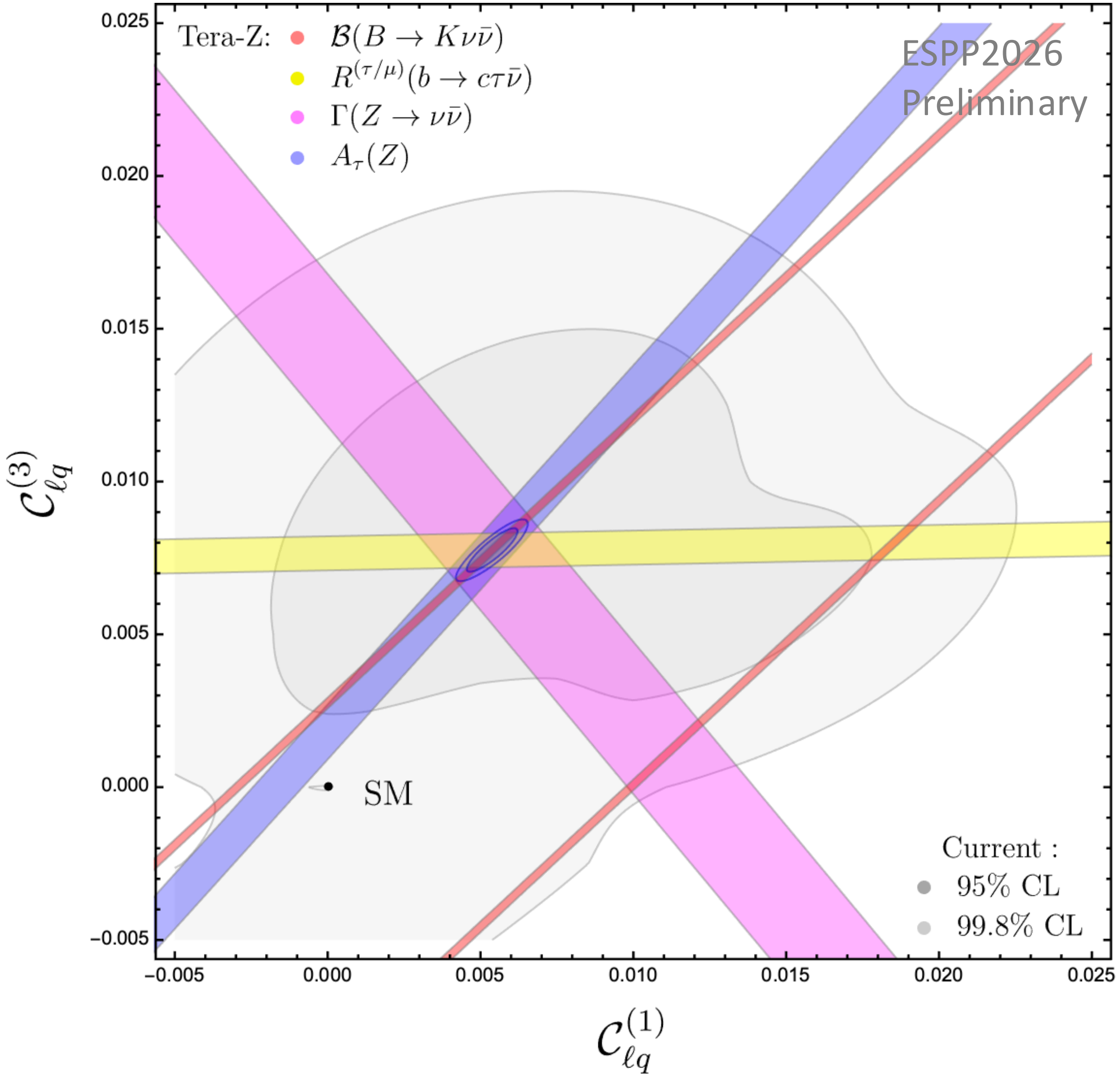

About flavour, EW, and Higgs physics interplay

What I have illustrated is only an example, but the conclusions are very general:

The interplay of a large number of observables is a key ingredient if we aim to "decode" the underlying theory via indirect measurements and/or "validate" indirect BSM evidences (*in concrete models there are no hundreds parameters, but likely more than three…*) and flavour physics represent a particularly "rich" domain of NP sensitive observables.

Precision Higgs, electroweak, and flavour physics are three faces of the same strategy:

- for all of them the primary objective is indirect discovery
- in realistic models, with TeV-scale NP, they provide very complementary information