The flavor potential for New Physics

Status and prospects

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Setting the stage

1. **What do flavor measurements tell us about the flavor of physics beyond the SM?**

   Which flavor hypotheses allow for new physics within collider reach?

   How can we distinguish between these hypotheses experimentally?

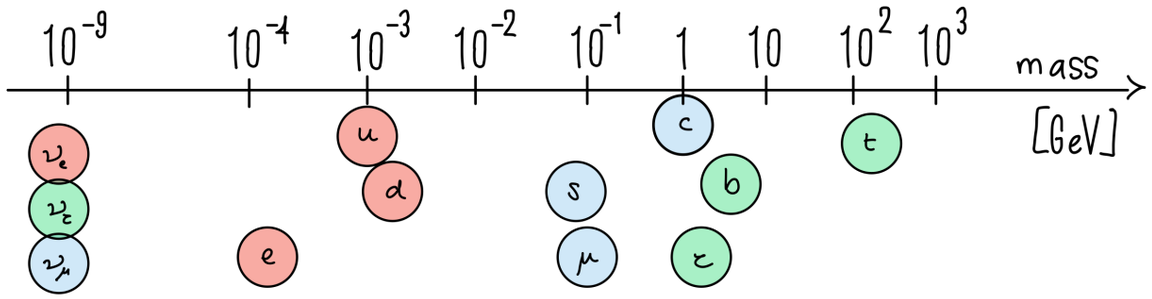
2. **Which challenges must we address to exploit future flavor measurements?**

Caveat: biased selection of topics, focus mainly on B physics and heavy new physics scenarios.

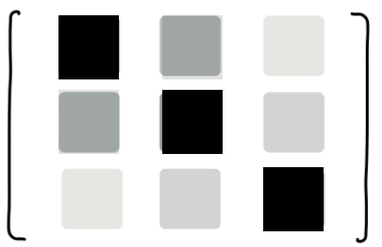
Flavor in the Standard Model: puzzling aspects

Flavor is arguably the most mysterious sector in the Standard Model.

Quarks and leptons appear in three families with identical gauge quantum numbers, but very different masses and mixings:



$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} =$$



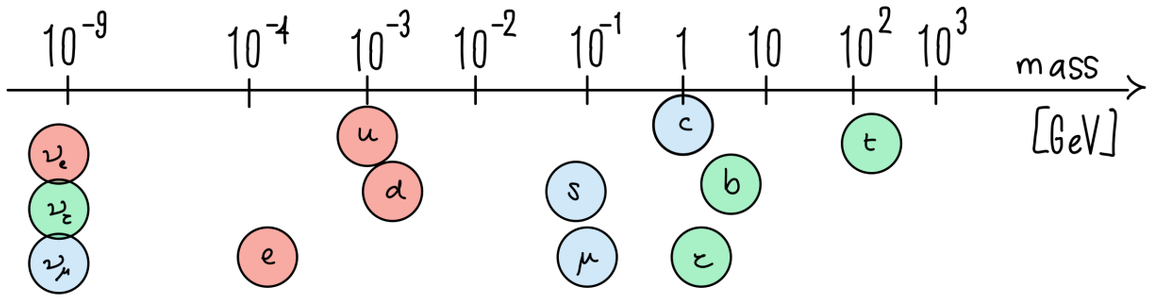
The SM has no explanation for these peculiar structures → **“flavor puzzle”**

Suggestive of an organising principle beyond the SM, where these structures have a dynamical origin.

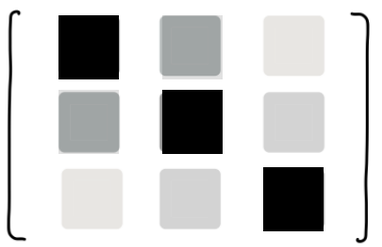
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Suggestive of an organising principle beyond the SM, where these structures have a dynamical origin.

The flavor puzzle does **not** point to a **scale** unless linked to other “problems”,
yet the dynamics behind it could also shape the couplings of nearby new particles

⇒ **flavor measurements could help uncover the origin of flavor hierarchies**

Flavor in the Standard Model: strong predictions

Despite its mysterious origin, the flavor structure of the SM leads to strong predictions:

- negligible charged lepton flavor violation
- lepton flavor universality
- suppression of quark flavor-changing neutral currents
- unitarity of the CKM matrix

…all expression of the SM matter content and the resulting accidental symmetries.

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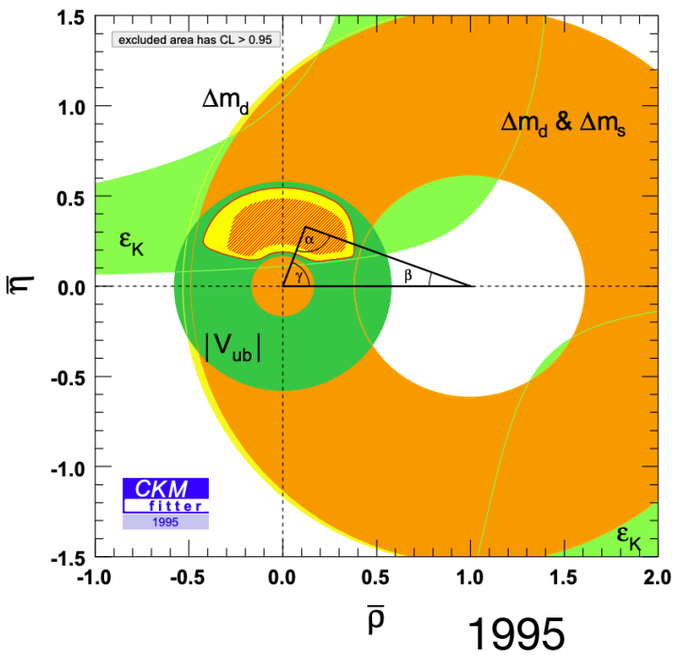
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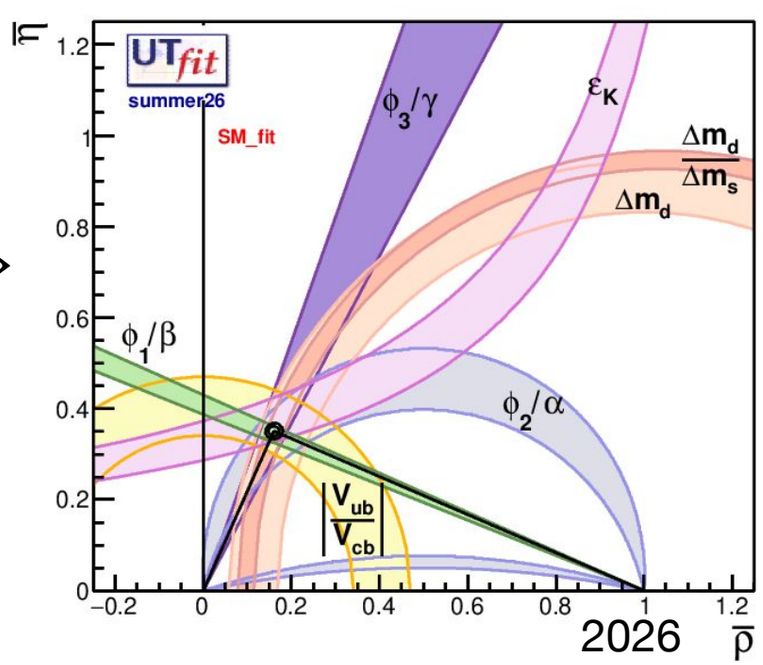
…all expression of the SM matter content and the resulting accidental symmetries.

Enormous progress was made in testing these predictions.

The CKM unitarity triangle is a striking example:



⇒



progress largely driven by

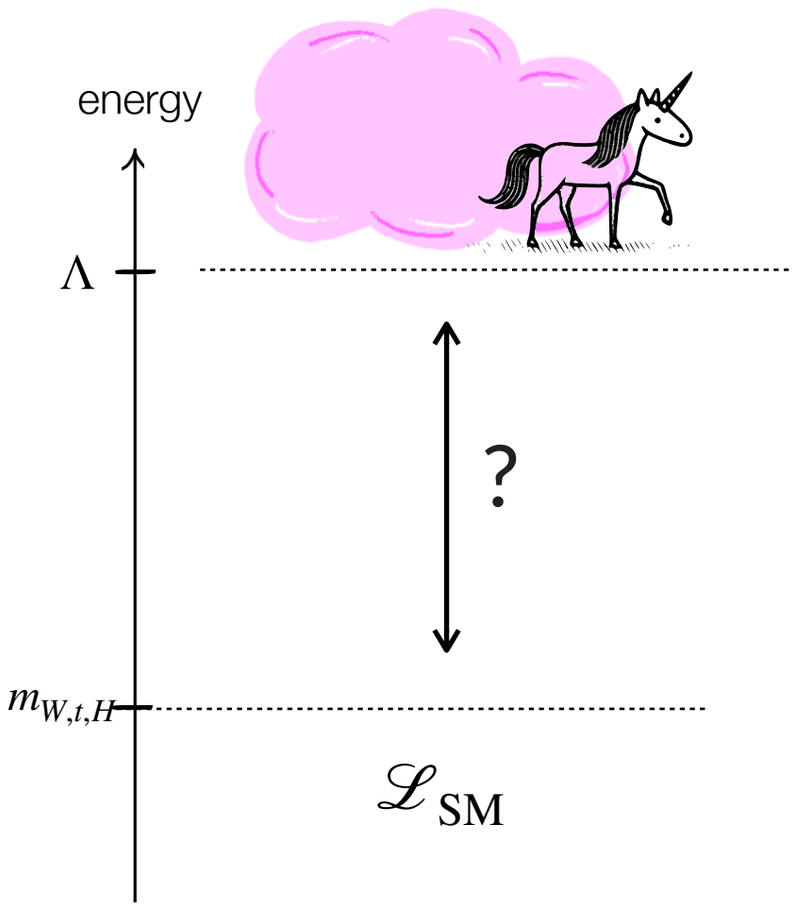
- exp. effort in B physics: Babar, Belle (II), LHCb
- improved SM predictions, especially lattice QCD

[see talk by M.Bona]

The scale of New Physics, from theory

Many more reasons for BSM beyond flavor, yet direct searches at the LHC have not revealed new particles so far ⇒ there is a **mass gap** between us and the next threshold.

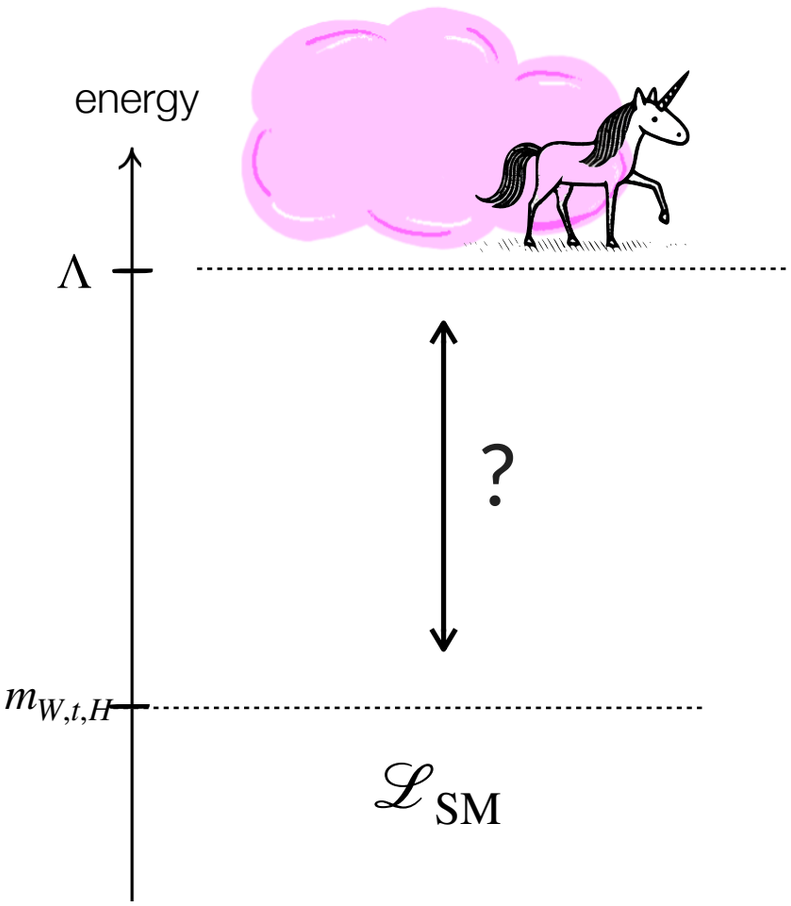
On top there could also be new light, very weakly coupled particles.



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Top-down considerations are of limited help:

- the main hint for a “low” scale is a natural solution to the hierarchy problem

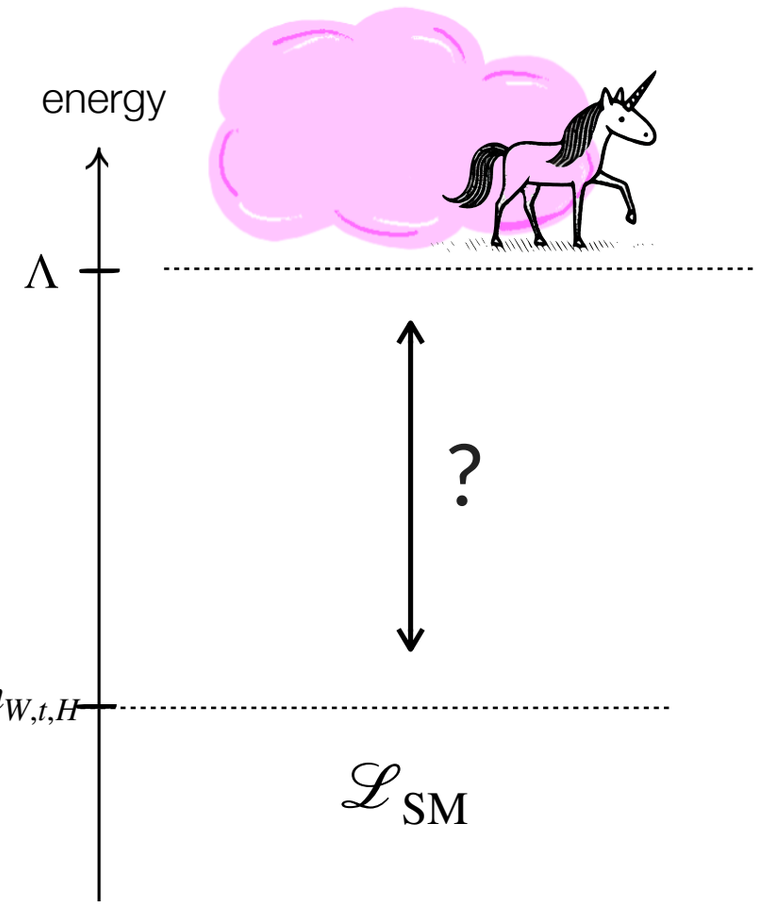
  New O(TeV) states coupled to Higgs & top needed to stabilise the Higgs mass. Generally they affect the Yukawa sector, hence flavor.

- other SM shortcomings (dark matter, flavor, baryogenesis…) are generally more difficult to link to a scale

The scale of New Physics, from data

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On top there could also be new light, very weakly coupled particles.



But we can proceed **bottom-up:**

indirect searches at $E \ll \Lambda$ probe scales well beyond direct reach, and a deviation from the SM would give a concrete target for future direct searches

[historical precedents: charm mass from K mixing, top from EW precision…]

Best performed with processes we can predict precisely

- forbidden: proton decay ($\cancel{U(1)_B}$), $0\nu\beta\beta$ ($\cancel{U(1)_L}$)…
- very rare: e.g. quark flavor-changing transitions
- not rare but known very precisely: EWPOs

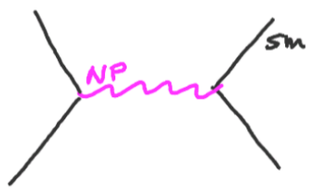
Will likely define the collider frontier for the next half century, with flavor as a crucial component

at ongoing experiments: LHCb, ATLAS, CMS, Belle II, NA62, KOTO, BESIII…
at a future e+e- machine like FCC-ee

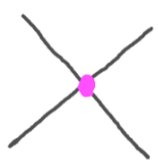
Effective theories as tools for indirect searches

To translate low-energy searches into info on heavy new physics, an **effective description** where the new heavy particles never appears is enough.

Simple consequence of scale separation:



$$\sim \frac{g^2}{E^2 - \Lambda^2} \xrightarrow{E \ll \Lambda}$$



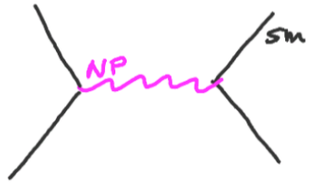
$$\sim -\frac{g^2}{\Lambda^2}\left[1 + \mathcal{O}\left(\frac{E^2}{\Lambda^2}\right)\right]$$

= coupling · local interaction

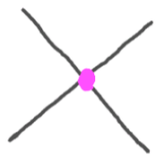
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For $\Lambda \gg E \gtrsim v = 246\,\mathrm{GeV}$, the appropriate effective theory is the **SMEFT** [see EFT session]

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_{i=1}^{N_d} C_i^{(d)} O_i^{(d)}(\varphi_{\mathrm{SM}})$$

all possible operators built out of SM fields

effects suppressed by powers of the new physics mass

couplings or "Wilson coefficients" unknown unless a model is specified

By now an established part of the “data to UV model” chain:

electroweak, flavor, high pT data → bounds on C_i i.e. $\Lambda^i_{\mathrm{eff}} = \dfrac{\Lambda}{\sqrt{C_i}} \sim \dfrac{M}{g}$ → simplified model → UV theory

If there’s an anomaly

The new physics flavor puzzle

With very few exceptions, flavor-changing processes agree very well will the SM.

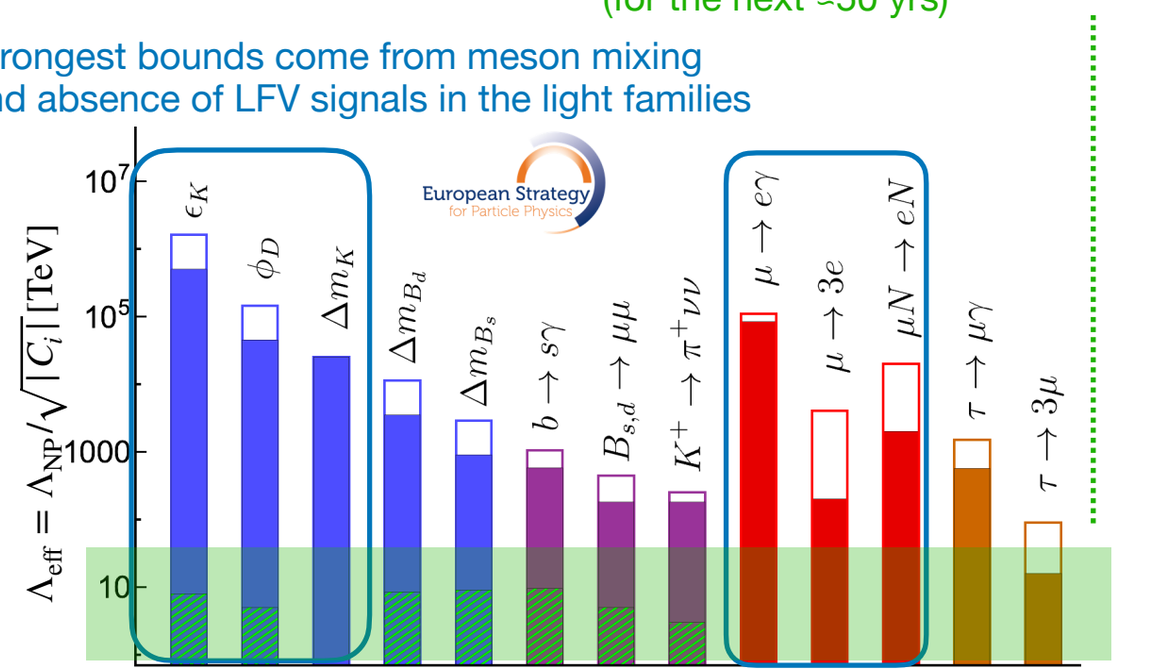
A non trivial fact: nothing forbids bad violations of the SM accidental symmetries, yet we don't see any nearby.

→ tight bounds on the effective scale of flavor-changing interactions:

$$\Lambda_{\text{eff}}^{\text{FV}} = \frac{\Lambda}{\sqrt{C_{\text{FV}}}} \gtrsim 10^{5-6}\,\text{TeV}$$

Scales directly testable at colliders (for the next ~50 yrs)

Strongest bounds come from meson mixing and absence of LFV signals in the light families



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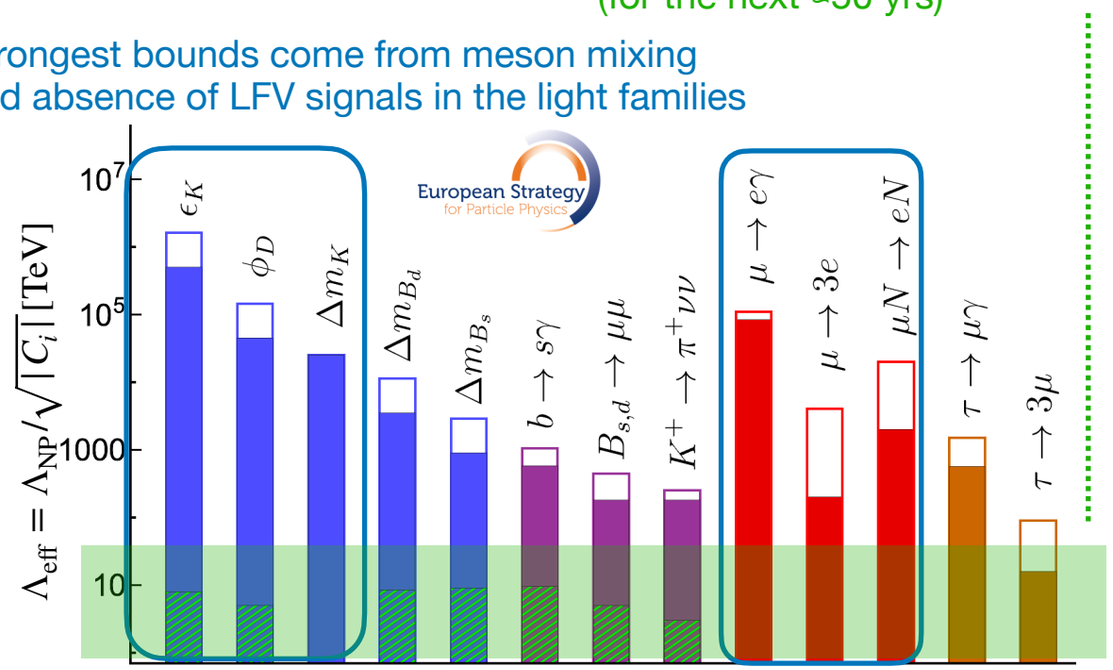
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Two "extreme" interpretations:

New physics is just very heavy.

definitely the case if it is anarchic

$$C_{\text{FV}} \sim \mathcal{O}(1) \;\Rightarrow\; \Lambda = \Lambda_{\text{eff}}$$

- no direct tests
- Higgs stabilised in some other way
- dynamical origin for flavor patterns possible, but beyond collider reach

New physics has a flavor structure

such that

$$C_{\text{FV}} \ll \mathcal{O}(1) \;\Rightarrow\; \Lambda \ll \Lambda_{\text{eff}}$$

- possibly testable directly
- possibly natural
- possibly related to a testable dynamical origin of flavor hierarchies

Approximate flavor symmetries in the SM and beyond

To figure out which one, we can **use the accidental symmetries of the SM as guidance.**

$$\mathscr{L}^{\text{fermions}}_{\text{SM}} = \sum_{\psi \in \{q_L, u_R, d_R, l_L, e_R\}} \bar{\psi} D_\mu \gamma^\mu \psi \qquad + \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{l}_L Y_e e_R H + \text{h.c.}$$

The gauge sector has a large flavor symmetry, broken almost fully by the Yukawas

$$\mathscr{G}_F = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

$$\xrightarrow{Y_d, Y_u, Y_e} \quad U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \quad \xrightarrow{m_\nu} \quad U(1)_B \times U(1)_L \;\; \text{or} \;\; U(1)_B$$

residual exact symmetry [classically]

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Empirically though we see **more "structure"** in masses and mixings than what is made manifest by this small symmetry.

$$V_{CKM} = \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

We can make sense of it in terms of **an approximate symmetry** (=a symmetry + a breaking pattern)

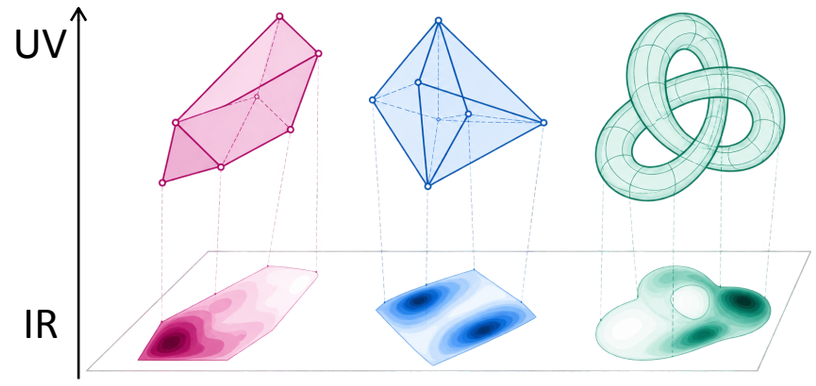
Approximate flavor symmetries in the SM and beyond

Several choices can reproduce the observed Y_i ,

Symmetr	Breaking pattern	
$U(3)^5$	$Y_{u,d} \sim (3_q, \bar{3}_{u,d}),\ Y_e \sim (3_\ell, \bar{3}_e)$	[Chivukula, Georgi 1987;.. D'Ambrosio et al., 0207036]
$U(2)^5$	$V_q \sim 2_q,\ \Delta_{u,d} \sim (2_q, \bar{2}_{u,d}),\ \Delta_e \sim (2_\ell, \bar{2}_e)$	[Barbieri et al, 1105.2296]
$U(1)_{\rm FN}$	$\epsilon = \langle\phi\rangle/\Lambda, \quad [Y_f]_{ij} = \epsilon^{Q_j - Q_i}$	[Froggatt, Nielsen 1978]

+ discrete and modular symmetries, Minimal Flavor Protection…

while allowing for **very different patterns of new-physics interactions.**



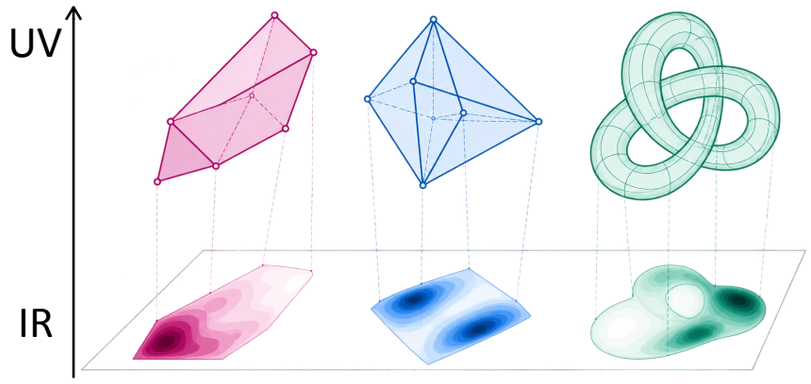
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To study these patterns, **implement approximate symmetries in the SMEFT**

Order by order less independent coefficients; spurions dictate characteristic suppressions & correlations.

- Physical meaning: postulating a flavor structure = studying a class of new physics models

  Doing it for different hypotheses is a way of mapping the UV.

- For EW and collider data working in the symmetric limit tipically captures the dominant effects, but flavor data requires the inclusion of breaking terms
  - "mandatory" ones to reproduce masses & mixings
  - additional sources of breaking, to be constrained from extra data

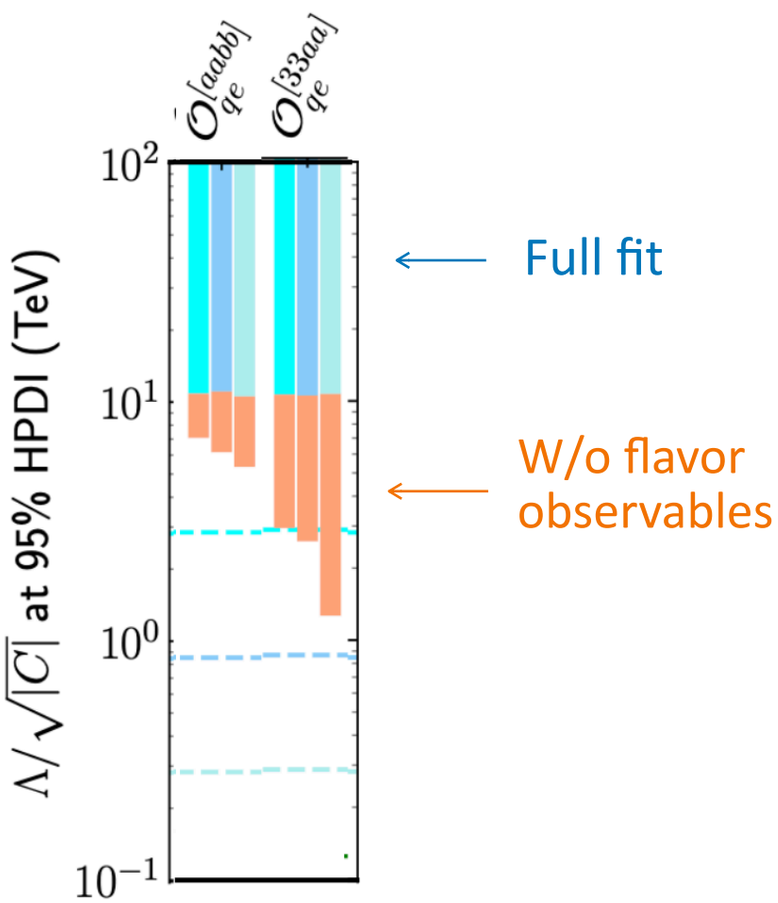
  Technically challenging, but an important opportunity to learn more about the UV.

Role of flavor data in probing new physics

And flavor data has a lot to say:

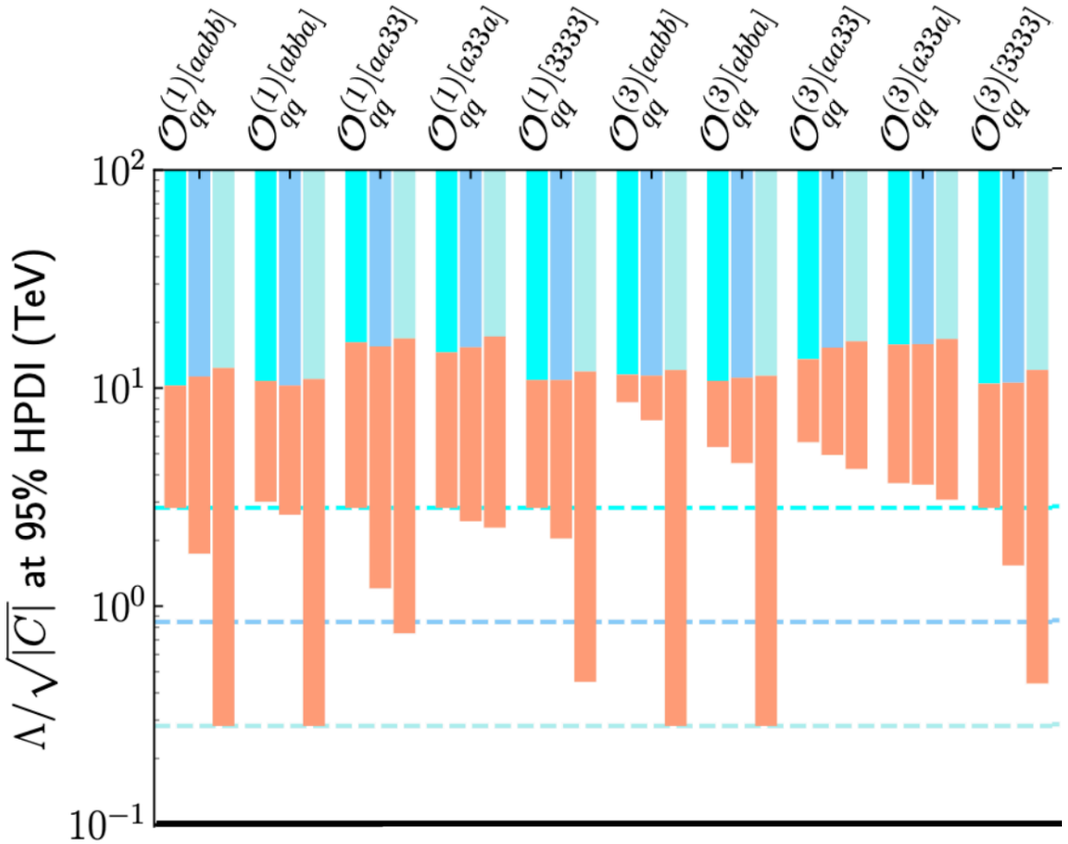
Complementarity: beyond the trivial U(3)^5 limit, flavour measurements play a crucial role in constraining also flavor-conserving new interactions!

Examples: $B_s \to \mu^+\mu^-$ for lepton-quark ops



[de Blas et al 2507.06191]

meson mixing for four-quark ops.



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Unicity: flavor provides unique info on the flavor structure of new physics

determine size of breaking terms

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Example: $U(2)^5$ + minimal breaking

Relation between $b \to s$ and $b \to d$ transitions, as in MFV:

$$\frac{b \to sX}{b \to dX} = \left.\frac{b \to sX}{b \to dX}\right|_{\rm SM} = \frac{V_{ts}}{V_{td}}$$

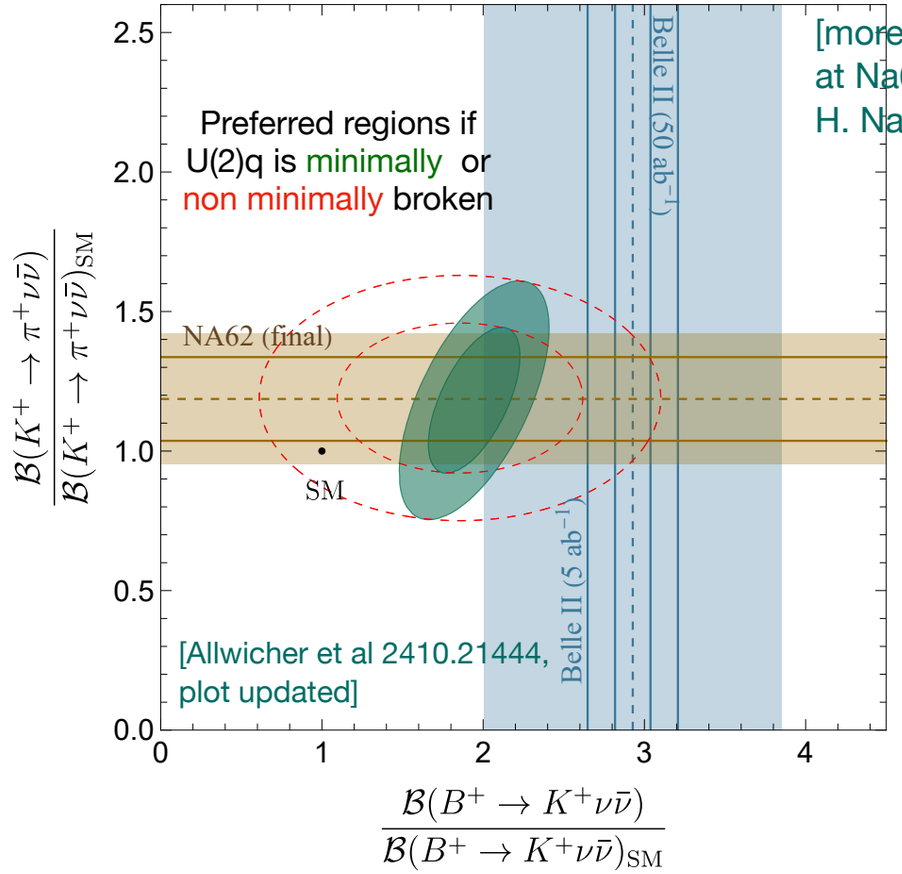
$$X = \ell^-\ell^+, \nu\bar{\nu}$$

testable e.g. via

$$\frac{\mathcal{B}(B_s \to \mu\mu)}{\mathcal{B}(B_d \to \mu\mu)}, \quad \frac{\mathcal{B}(B \to K\bar{\nu}\nu)}{\mathcal{B}(B \to \pi\bar{\nu}\nu)}$$

Relation between $b \to s$ and $s \to d$ transitions.

Only clean test is comparing $B \to K\nu\bar{\nu}$ vs $K \to \pi\nu\bar{\nu}$



[more on the K program at Na62 and KOTO in H. Nanjo's talk]

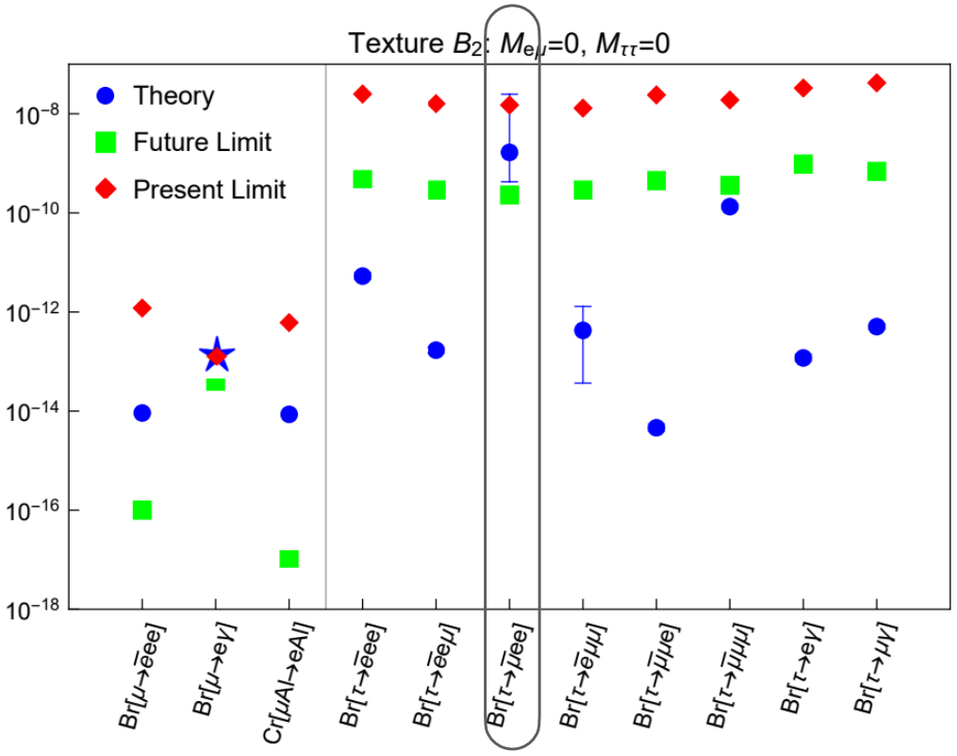
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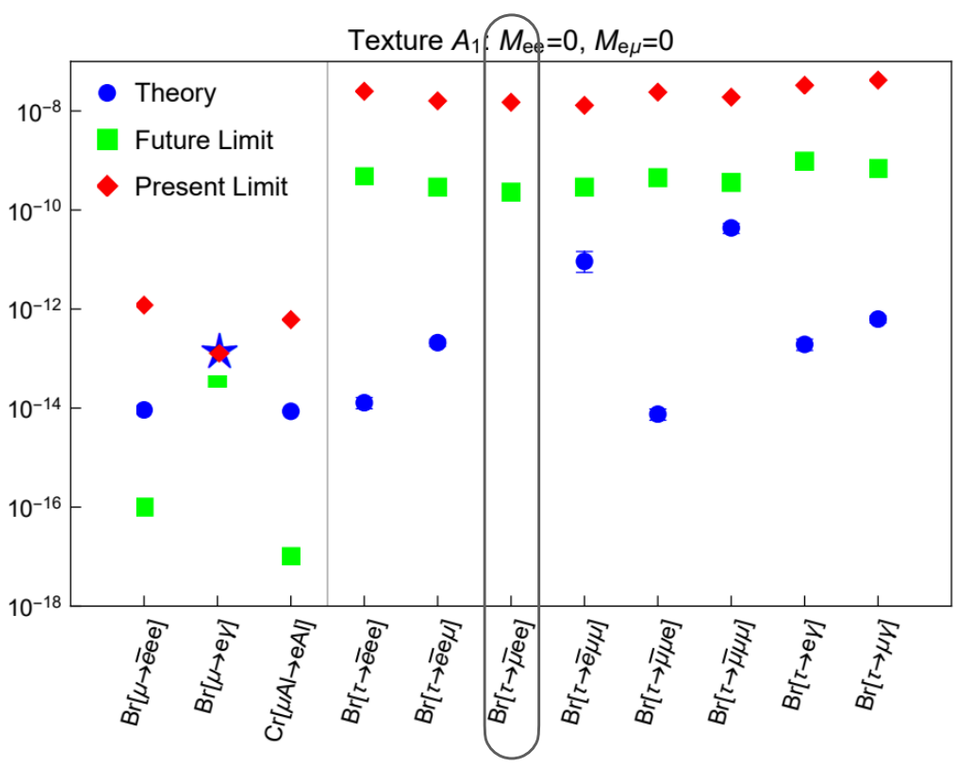
Example: type II see-saw, two-zero textures in the Majorana mass matrix [Calibbi, Gao, Yuan 2511.08679]

Different textures predict different muon and tau cLFV rates, e.g.

$$\frac{\mathscr{B}(\tau^- \to \mu^+ e^- e^-)}{\mathscr{B}(\mu \to e\gamma)} \sim 10^4 \quad (B_2, \text{right}), \qquad \ll 1 \quad (A_1, \text{left})$$

⇒ comparing muon and tau decays can distinguish among them! For example, if a $\mu \to e\gamma$ signal was just around the corner, $\tau \to \mu ee$ would be in the Belle II reach for B2.





[more on $\mu \to e$ LFV in W. Ootani's talk]

Flavor symmetries for “low”-scale new physics

Among the hypotheses able to account for the Y_i, **which ones allow new physics nearby**?
Which type of UV dynamics do they describe, and what are their typical signatures?

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Minimal Flavor Violation (MFV)

- MFV = the Yukawas are the only source of flavor violation, as in the SM.
  It describes new physics which is approximately flavor-universal
  [at least close by; Λ_F so high that it has no practical inprint]



- current bounds: CKM-like suppression of FCNCs, but unsuppressed valence-quark couplings → strong high pT constraints: **$\Lambda \gtrsim$ 10-20 TeV** for representative semileptonic interactions with O(1) coefficients.

- explicit realization: SUSY with universal soft masses and trilinear couplings proportional to the Yukawas. [D’Ambrosio et al., 0207036]

- signatures: new physics in flavor-changing quark transitions related by same CKM factors as in the SM; at zeroth order in Y_e, new interactions couple equally to e, μ, τ.

Flavor symmetries for “low”-scale new physics

U(2)^5



- U(2) places a clear distinction between light families and the 3rd
  ⇒ can host new physics coupling dominantly to the 3rd family
  theoretical motivation: link to flavor puzzle (and possibly hierarchy problem)

- current bounds: without other assumptions similar to MFV, but valence-quark couplings can be suppressed ⇒ high pT bounds relax to **$\Lambda \gtrsim$ O(1) TeV.** [Allwicher, CC, Isidori, Stefanek, 2311.00020]

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- explicit realisation: flavor deconstruction

$$G = G_{3,\mathrm{SM}} \times G_{12,\mathrm{SM}} \xrightarrow{\Lambda_3} G_{\mathrm{SM}}$$

acts on 3rd fam. & Higgs acts on light families

[Li, Ma, 1981; Arkani-Hamed, Cohen, Georgi 0104005; Craig, Green, Katz 1103.3708; Bordone, **CC**, Fuentes-Martin, Isidori, 1712.01368; Davighi, Isidori, 2303.01520….]

- The 3rd and the light families feel different gauge interactions → built-in U(2)^5 symmetry; only $y_3 \neq 0$
- SSB to SM generates new gauge bosons with $M \sim \mathcal{O}(\Lambda_3)$ coupled mostly to the 3rd family
- breaking of U(2)^5 generates both light Yukawas and couplings of the new gauge bosons to light families
- can be combined with composite Higgs solution to hierarchy problem [Covone et al. 2407.10950; Lizana, 2412.14243]

- signatures: by construction, larger effects in interactions with 3rd family fermions; large violations of universality (light vs 3rd family) are allowed.

Flavor symmetries for “low”-scale new physics

Minimal Flavor Protection (MFP) [Greljo, Palavrič, Stefanek,2512.04159]

- The “smallest” symmetry that still allows for low-scale new physics

$$SU(2)_q \times U(1)_X \quad \text{+ spurions}$$

The only really necessary SU(2) factor.
W/o it, K or D mixing lead to $\Lambda > 300$ TeV

linear combination of the remaining Cartan generators of $U(3)^5$; more than one choice possible

Quark and charged-lepton hierarchies can be reproduced with a few $\mathcal{O}(10^{-2})$ spurions.

- current bounds: $\Lambda \gtrsim 10$ TeV [similar to MFV but with a much smaller symmetry]

Flavor symmetries for “low”-scale new physics

Minimal Flavor Protection (MFP) [Greljo, Palavrič, Stefanek,2512.04159]

- The “smallest” symmetry that still allows for low-scale new physics

$$SU(2)_q \times U(1)_X \quad \text{+ spurions}$$

The only really necessary SU(2) factor.
W/o it, K or D mixing lead to Λ > 300 TeV

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- current bounds: $\Lambda \gtrsim 10$ TeV [similar to MFV but with a much smaller symmetry]

- explicit realisation: chains of TeV-scale vector-like fermions. Each small mass-mixing insertion along a chain introduces an additional suppression of the effective Yukawa coupling, à la Froggatt–Nielsen. [2512.04159; similar construction in Arkhani-Ahmed et al. 2602.17754]

- signatures: smaller symmetry ⇒ “more“ flavor violation possible than in MFV and $U(2)^5$. Signatures depend on X choice; e.g. one could have unsuppressed operators inducing LFV processes such as $B \to K\tau\mu$, $\tau \to \mu ee$ and $t \to c\tau e$

Some tensions in flavor data

Flavor hypotheses predict characteristic correlations, but generally leave the overall size of new effects undetermined*. Only an established deviation can provide an anchor.

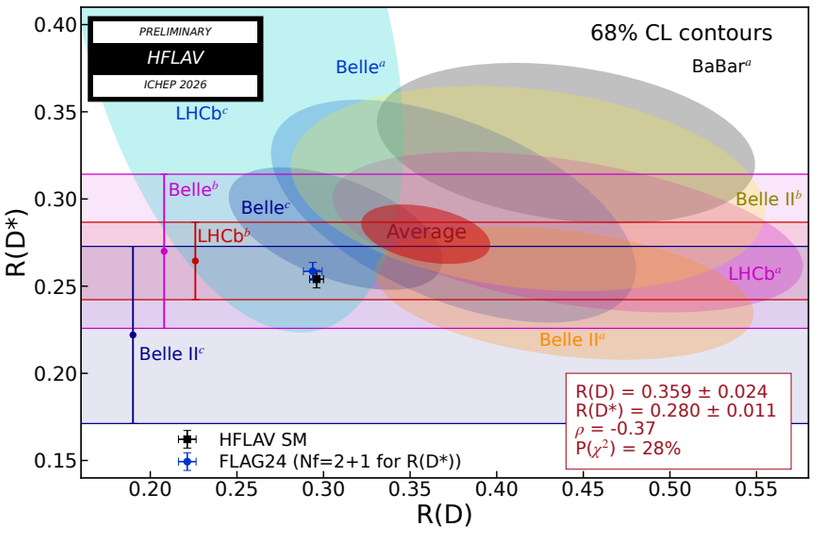
Exceptions: constructions aiming at taming the hierarchy pb, like U(2) realisations with composite Higgs

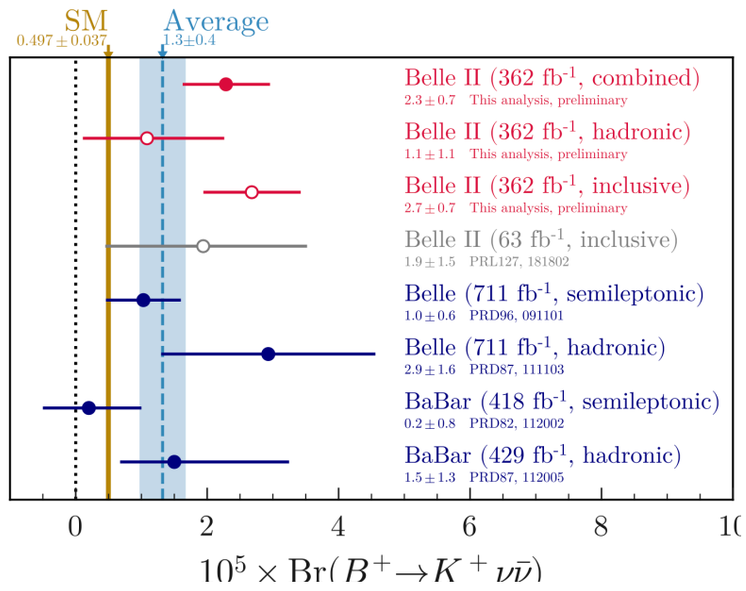
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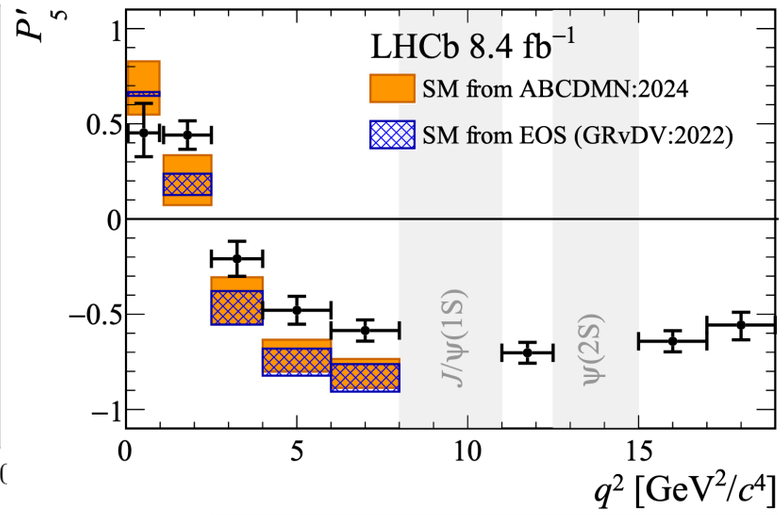
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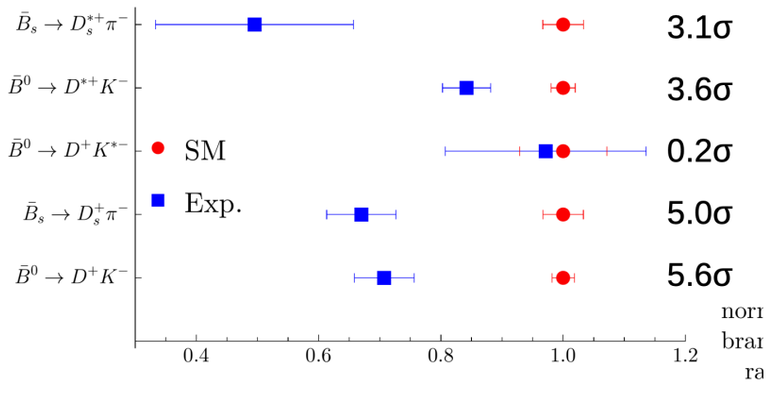
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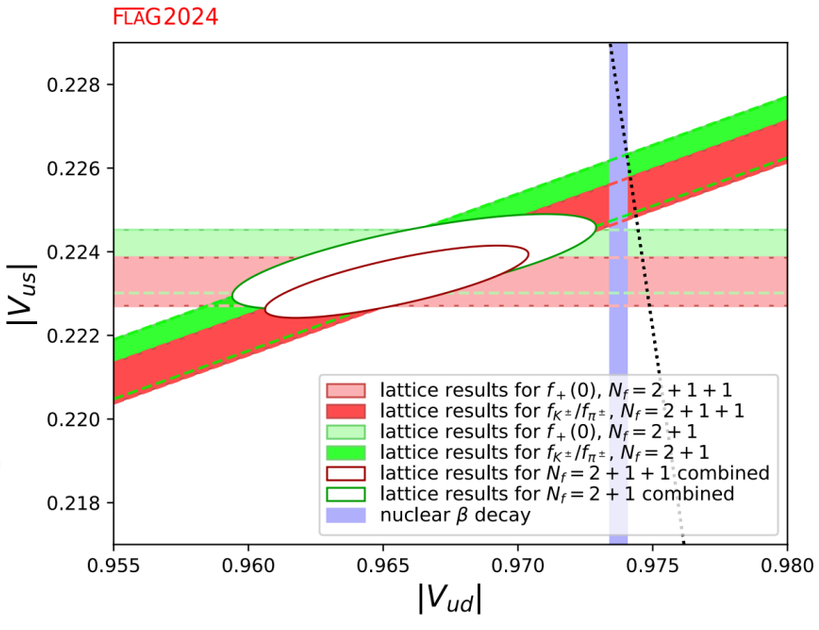
Some of the existing tensions in (quark) flavor physics:

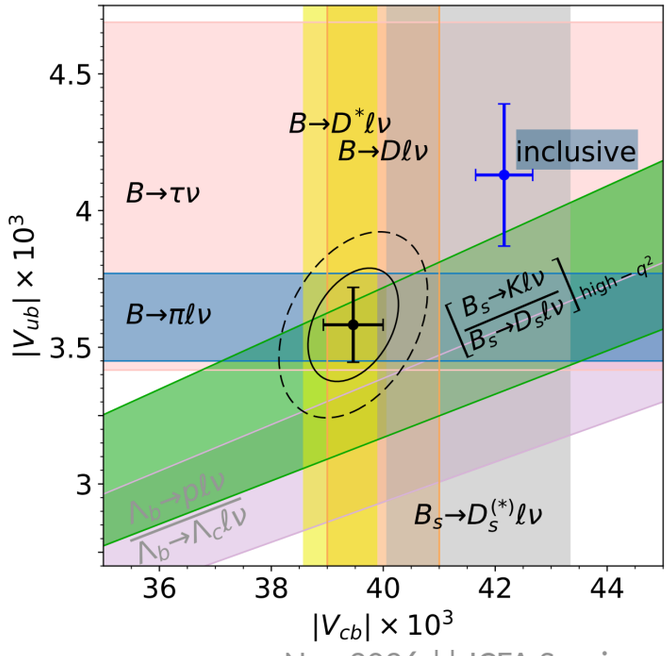












Lepton Flavor Universality tests in $b \to c\ell\nu$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})} \qquad \ell = e, \mu$$

Excess in the τ modes, still to be clarified:

3.7σ in the average shown

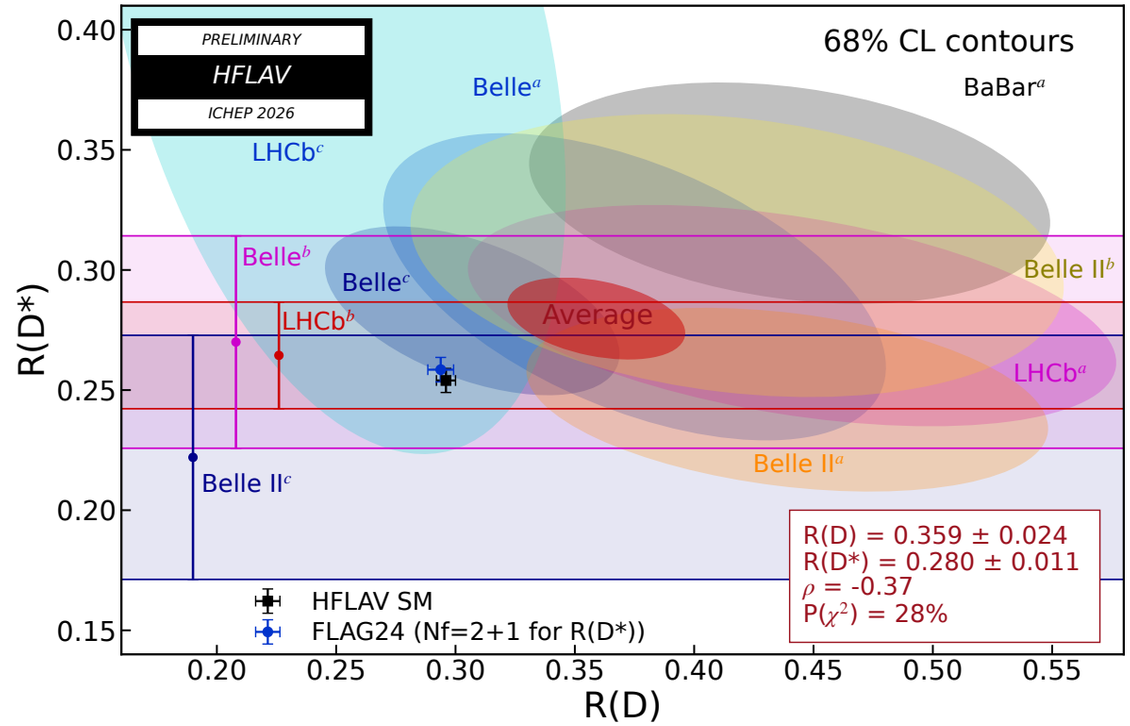
2σ including the last (preliminary) Babar result

[see M. Bona's talk]

Prospects: ~1% Belle II [50ab^{-1}], ~3% LHCb [300fb^{-1}]

[2503.24346; joint note by ATLAS, Belle II, CMS, LHCb]

SM prediction well under control



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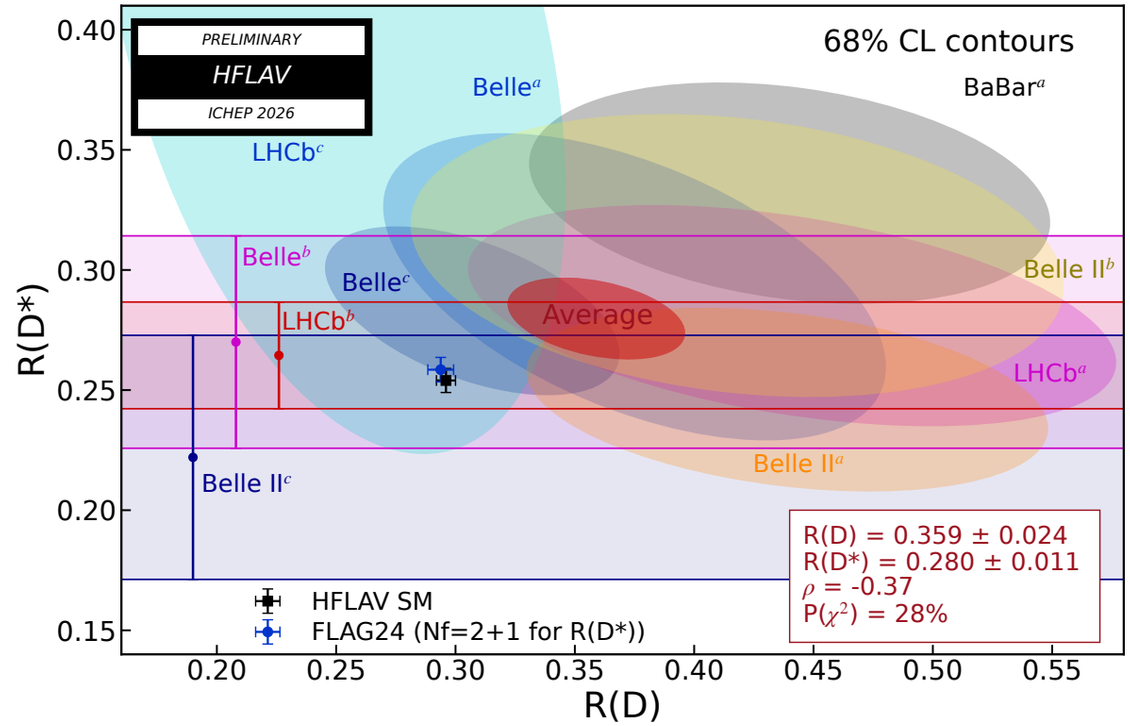
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SM prediction well under control

A **new physics interpretation** class for TeV-scale leptoquarks coupled mostly to the 3rd family.

[the vector leptoquark U1 arises, e.g., in flavor-deconstructed SU(4) models unifying 3rd family quarks and leptons.]

⇒ expect correlated excesses at low and high energies:

- Enhanced $B \to K\tau\tau$, $B_s \to \tau\tau$ ~ O(100) x SM [beyond the reach of present facilities]
- Distortion of the $pp \to \tau\tau$, $pp \to \tau\nu$ tails [ATLAS/CMS already constrain a relevant portion of parameter space]
- Enhanced $B \to K^{(*)}\bar{\nu}_{(\tau)}\nu_{(\tau)}$, though the size is more model dependent

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

First **evidence** for $B \to K\nu\bar{\nu}$ is 2.7σ above SM [Belle II, 2311.14647]

Prospects: O(10%) precision with 50ab^{-1}, and more channels: K^*, K_S, X_s

A **heavy new-physics** interpretation requires a large effect ($\Lambda_{\text{eff}} \sim 5\,\text{TeV}$) in $bs\nu_\tau\bar{\nu}_\tau$;
lighter families excluded by $B_s \to \mu\mu$ and $R_{K^{(*)}}$. [Bause et al, 2309.00075; Allwicher et al. 2309.02246]

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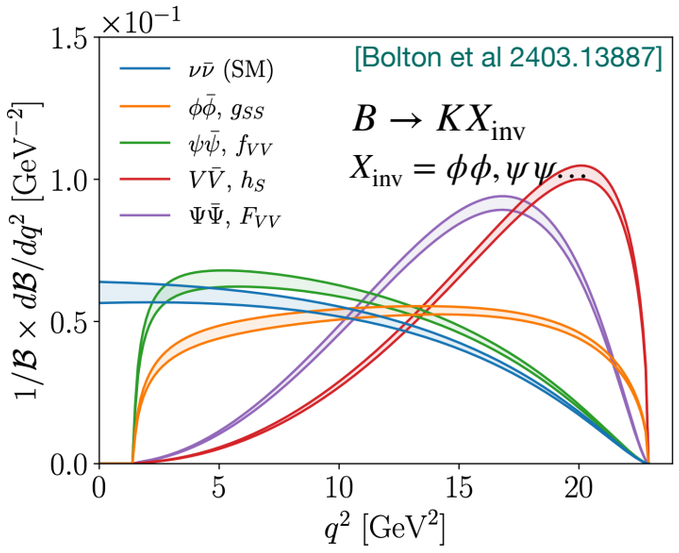
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Currently, a resonance at $m_X \simeq 2.1\,{\rm GeV}$ is preferred over the SM at 3σ [Bolton et al 2403.13887, Gärtner et al 2602.09666]



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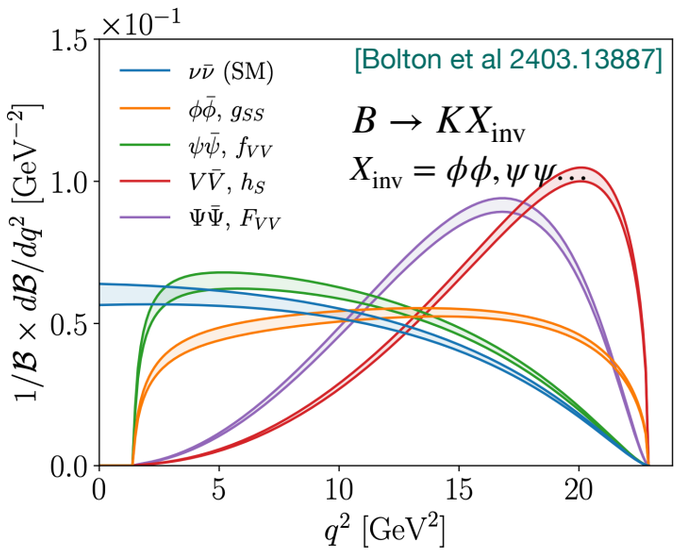
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SM prediction: two main sources of uncertainty, currently below exp. precision:

$$\frac{d\mathcal{B}}{dq^2} \propto |V_{tb}V_{ts}^*|^2 |f_+(q^2)|^2 = |V_{cb}|^2$$

- $B \to K$ form factor [$\sim 3\%$ on BR]
- CKM: inclusive vs exclusive $|V_{cb}|$ shifts prediction by O(10%)

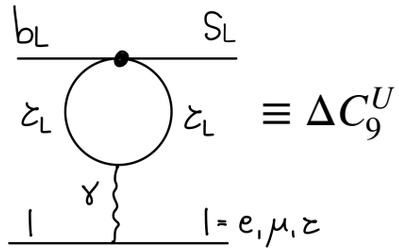
Other "clean" channels, such as $B_s \to \mu\mu$, suffer from the same issue.
→ **sorting this out is crucial to be able to profit from future exp. precision.**

$b \to s\mu^+\mu^-$: new physics or QCD?

Persisting tensions in exclusive $b \to s\mu\mu$ branching fractions and in the $B \to K^*\mu^+\mu^-$ angular analysis at LHCb (& CMS). Good prospects, e.g. the P_5' uncertainty will shrink by 10x at HL-LHC.

A new physics contribution to $O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell)$ can accommodate the tension
generated e.g. in most $R_{D^{(*)}}$ explanations by gauge invariance

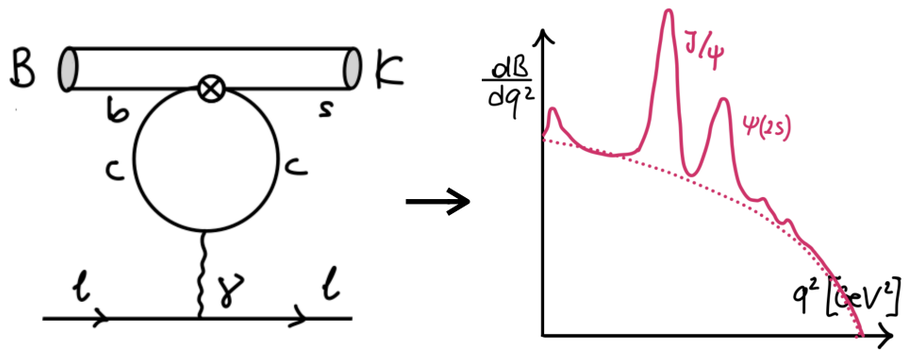
$$R_{D^{(*)}} \Rightarrow b_L \to c_L \tau_L \nu_L \overset{SU(2)_L}{\sim} b_L \to s_L \tau_L \tau_L \overset{\text{RG}}{\Rightarrow}$$



$$\equiv \Delta C_9^U$$

$b \to s\mu^+\mu^-$: new physics or QCD?

However claiming new physics remains difficult due to long-distance hadronic contributions, most notably the **charm loop**



It effectively appears as a shift in C_9

$$C_9^{\text{eff}} = C_9^{\text{SM}} + C_9^{\text{NP}} + Y(q^2)$$
$$= Y(q_0^2) + \Delta Y(q^2)$$

Its momentum dependence can be constrained by data within analytic parametrizations

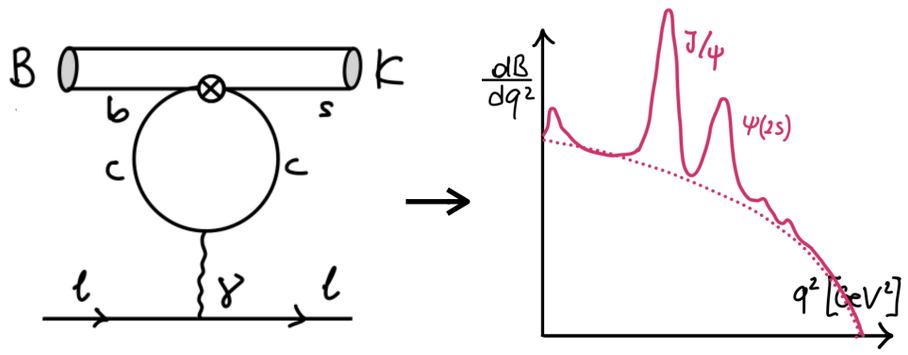
[for a discussion of the last LHCb unbinned analysis, see M. Bona's talk]

but its real constant component cannot be disentangled from new physics without an extra theory input. How well we understand this input is debated.

[recent refs: Ciuchini et al 2607.03531, Bordone et al 2607.09458]

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Some ways forward:

- work towards a lattice calculation [Frezzotti et al. 2508.03655]
- strong phases observables help test the dispersive description of the charm loop
- $B \to X_s \ell\ell$ at Belle II is a complementary test [Huber et al 2007.04191, Alvarez Cartelle et al. 2605.06567]

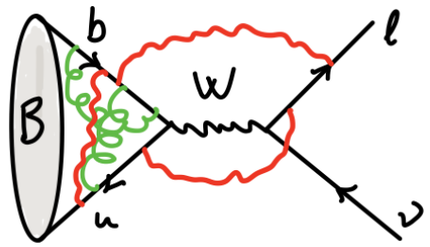
Structure-dependent QED effects in B decays

As LHCb & Belle II target O(1%) in several channels, **a major challenge is the proper treatment of QED effects**, including those due to composite nature of the B.

The standard approach is to treat the B meson as point-like

- only “universal” QED effects due to eikonal emissions are captured
- generally dominant but insufficient for O(1%) precision

⇒ **must include structure-dependent QED corrections**



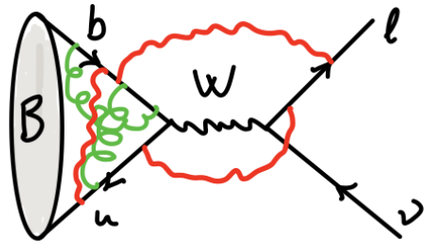
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Currently a very active area, as these effects are

- theoretically **interesting**
  In a joint QEDxQCD treatment, decay constants and form factors become process-dependent
- phenomenologically **relevant**
  they can induce qualitatively new effects: mimic the violation of lepton flavor universality, distort distributions, affect differently inclusive and exclusive decays….
- **difficult** to compute
  not (yet!) accessible on the lattice*, can be studied in the continuum using EFTs like Heavy Quark Effective Theory and Soft Collinear effective theory [*differently from light mesons]

Available results: $B_s \to \mu^+\mu^-,\ B \to \pi K,\ \ B \to D\pi,\ B_s \to \mu^+\mu^-\gamma,\ B \to \mu\nu, B \to \tau\nu$

[Beneke, Bobeth, Szafron, 1708.09152,1908.07011; Beneke, Böer et al 2008.10615,2107.03819; Beneke, Bobeth, Wang 2008.12494; CC, König, Neubert, 2212.14430; CC, König, Neubert, Ferré 2601.14361 & 2607.13144]

Looking forward: flavor at FCC-ee

FCC-ee is coinceived primarily as a Higgs factory, but operation at several energies opens a much broader precision program.

[see talks by F. Maltoni and J. de Blas]

For flavor, the most interesting run is at the Z-pole:

Z decays 16% $b\bar{b}$, 12% $c\bar{c}$, 3.4% $\tau\tau$ → a Tera-Z machine is a heavy flavor factory

It combines the best of two worlds:

high statistics, clean environment, constrained kinematics, high boost, access to all b hadrons…

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

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- b, c - hadron decays with $\tau\nu$ pair in the final state: $B \to \tau\nu$, $B_c \to \tau\nu$
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Exploiting them requires a joint theory and experimental effort:

- **feasibility**: achievable precision, exp and theory requirements
- **interpretation**: new-physics reach and interplay with the rest of the FCCee program

Feasibility: selected FCC-ee studies for B decays

FCCee superiority is clear

Channel	Projection	Comments
$B^+ \to \tau^+\nu$, $B_c^+ \to \tau^+\nu$ [Zuo et al., 2305.02998]	B^+ branching faction ~2-4% B_c^+ signal yield ~2%	V_{ub} at 1-2% , with $\sigma f_B = 1/2\ \sigma f_B^{now}$ B_c: ratio to $J/\psi\mu\nu$ at 2–3%
Excl. $b \to s\nu\bar{\nu}$ modes [Amhis et al., 2309.11353]	O(1%) (stat) precision for $K^*\nu\bar{\nu}$ and $\phi\nu\bar{\nu}$ if SM-like	O(10x) better than Belle 2 for $K^*\nu\bar{\nu}$, with $\sigma V_{cb}/V_{cb} = 1{,}5\%$ and $\sigma FF = 1/10\ \sigma FF^{now}$, new frontiers: B_s and baryon decays
$B^0 \to K^{*0}\tau^+\tau^-$ [Miralles, Phd thesis 2024; Miralles, Monteil, FCCee note doi:10.17181/wr1qx-45z38]	~3σ sensitivity to a SM signal depending on vertex resolution	τs reconstructed via $\tau \to 3\pi\nu$. Additional decay modes will improve the reach → to be assessed.

less clear

$B_s^0 \to \phi\mu^+\mu^-$ [Kwok et al., 2506.08089]	time-dependent CP coefficients C_f, S_f with abs. precision ~0.02	about 2x better than LHCb, mostly due to better flavor tagging
$B \to K^*\ell^+\ell^-$, ℓ = e, μ [Bordone, CC, Davighi, 2503.22635]	<1% (stat) precision in low-q^2 bins	comparable to HL-LHC for μ, better for e, but sensible theory improvement ($\sigma f_B = 1/5\ \sigma f_B^{now}$, $\sigma V_{cb}/V_{cb} = 0{,}5\%$) needed to exploit FCCee statistics

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Excl. $b \to s\nu\bar{\nu}$ modes [Amhis et al., 2309.11353]	O(1%) (stat) precision for $K^*\nu\bar{\nu}$ and $\phi\nu\bar{\nu}$ if SM-like	O(10x) better than Belle 2 for $K^*\nu\bar{\nu}$, with $\sigma V_{cb}/V_{cb}$ = 1,5% and $\sigma FF = 1/10\ \sigma FF^{now}$, new frontiers: B_s and baryon decays
$B^0 \to K^{*0}\tau^+\tau^-$ [Miralles, Phd thesis 2024; Miralles, Monteil, FCCee note doi:10.17181/wr1qx-45z38]	~3σ sensitivity to a SM signal depending on vertex resolution	τs reconstructed via $\tau \to 3\pi\nu$. Additional decay modes will improve the reach → to be assessed.
$B_s^0 \to \phi\mu^+\mu^-$ [Kwok et al., 2506.08089]	time-dependent CP coefficients C_f,S_f with abs. precision ~0.02	about 2x better than LHCb, mostly due to better flavor tagging
$B \to K^*\ell^+\ell^-$, ℓ = e, μ [Bordone, CC, Davighi, 2503.22635]	<1% (stat) precision in low-q^2 bins	comparable to HL-LHC for μ, better for e, but sensible theory improvement ($\sigma f_B = 1/5\ \sigma f_B^{now}$, $\sigma V_{cb}/V_{cb}$ = 0,5%) needed to exploit FCCee statistics

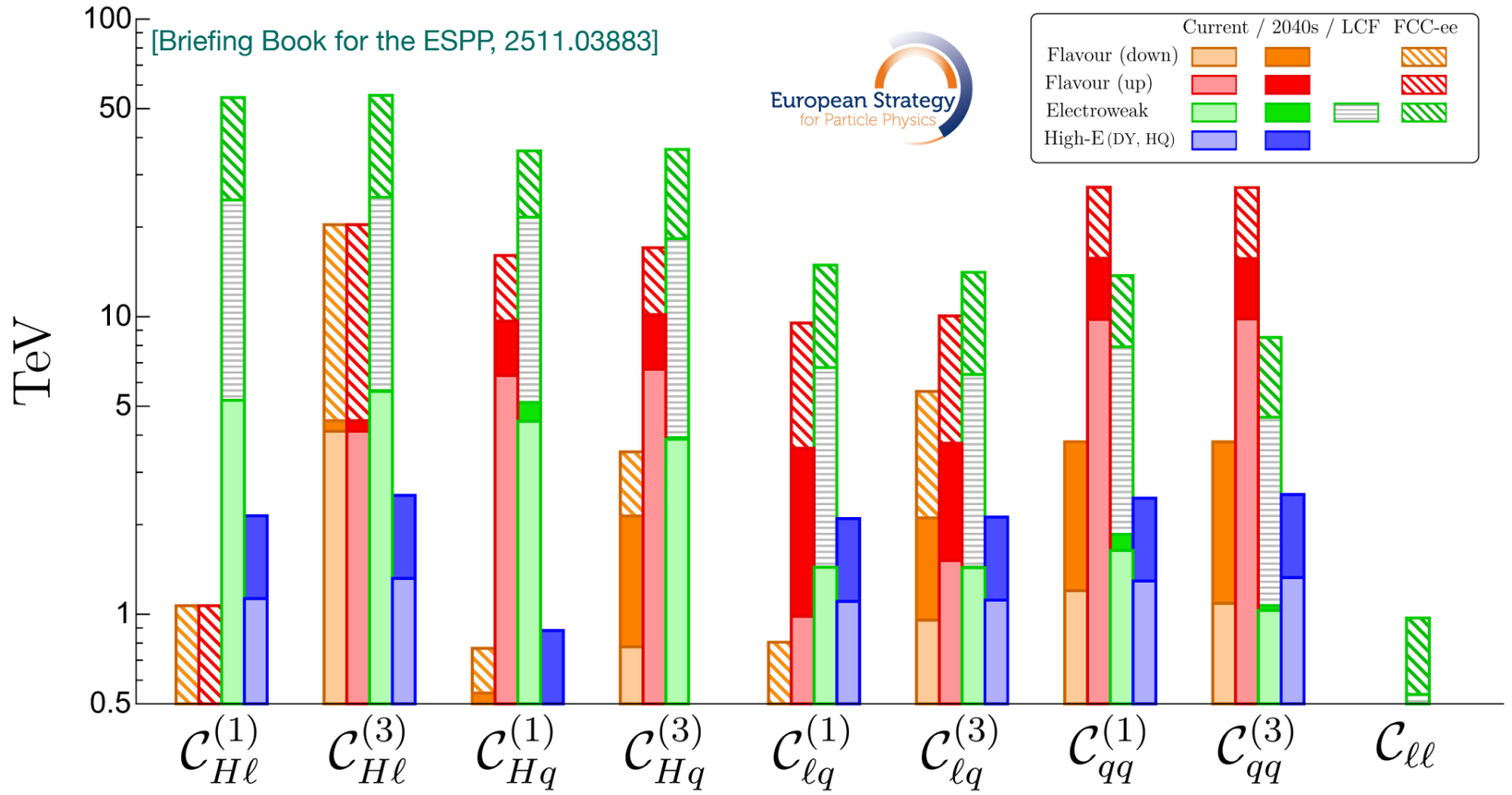
All studies but the last are based on fast simulation with Delphes + IDEA

Theory precision also enter projections

The level of exp. precision that will be reached demands substantial improvement in hadronic inputs for heavy flavor decays, including QED and strong isospin-breaking effects: a major challenge for lattice & continuum approaches.

Interpretation: the role of EW precision

Single op. bounds in the SMEFT with approximate $U(2)^5$ symmetry (3rd-family dominance)

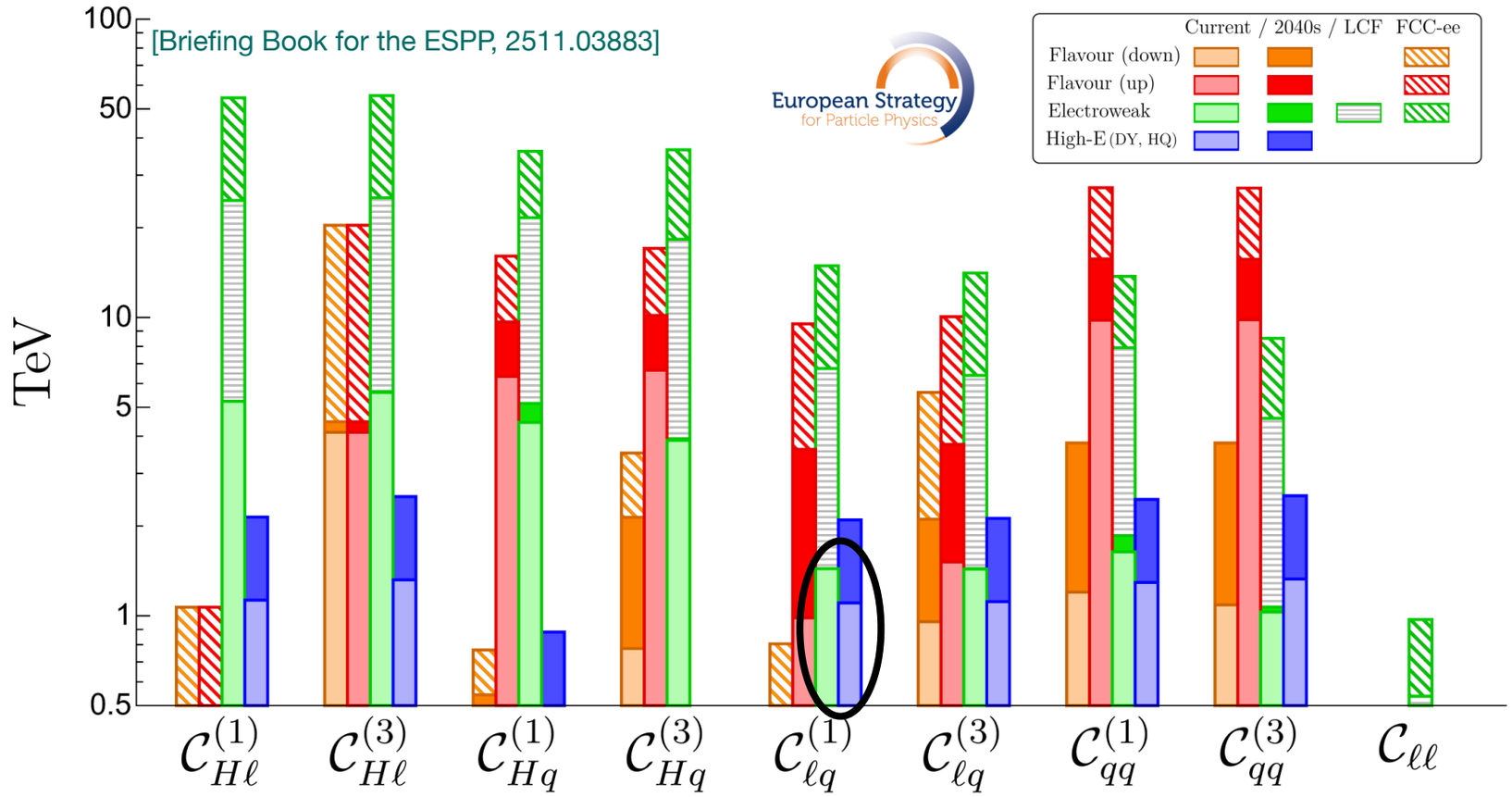


two extreme choices of flavor alignment

all fermion indices are 3rd family

Interpretation: the role of EW precision

Single op. bounds in the SMEFT with approximate $U(2)^5$ symmetry (3rd-family dominance)



two extreme choices of flavor alignment

all fermion indices are 3rd family

EWPOs are powerful probes of flavor non-universal new physics

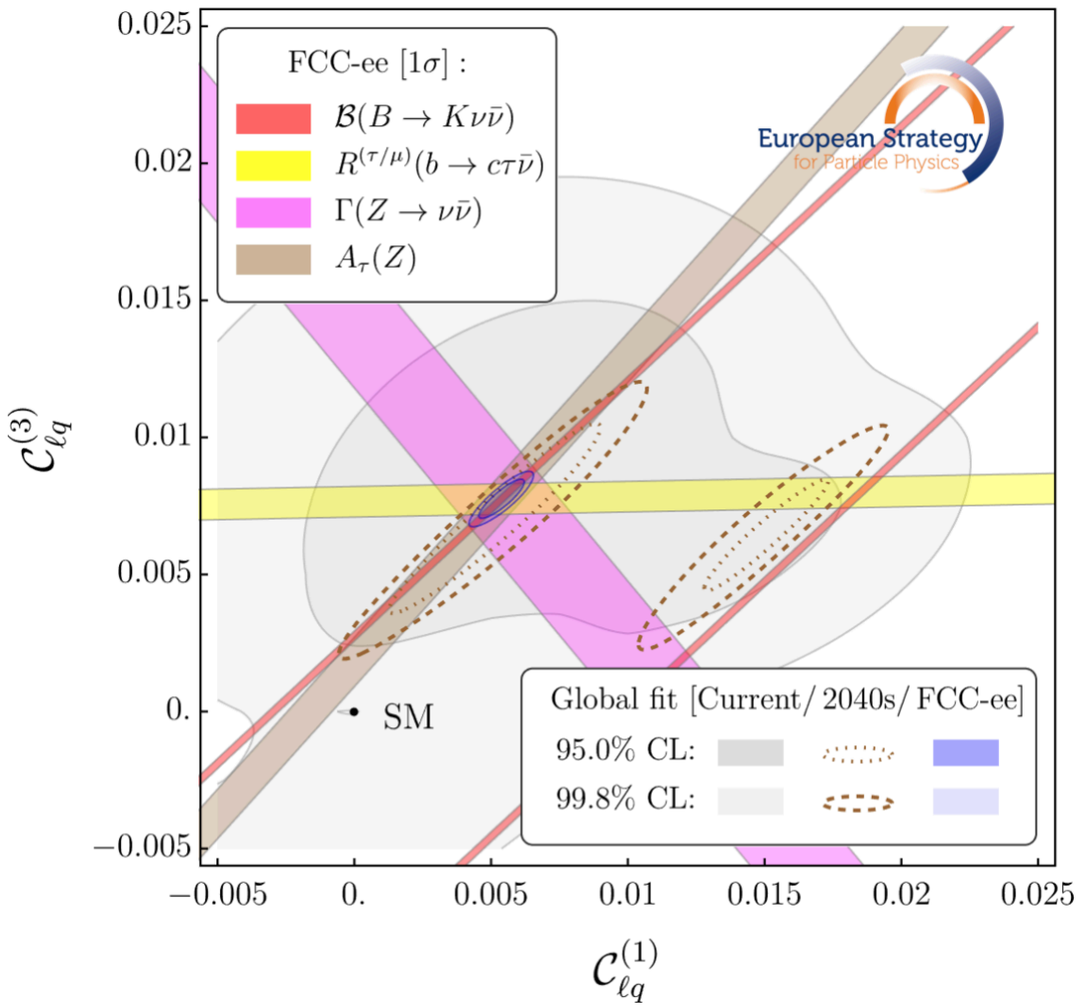
EW data (LEP) still compete with collider (LHC) for four-fermion operators with 3rd family quark indices, despite the different order at which these operators enter, e.g., Drell Yan (tree) and EWPOs (1 loop)

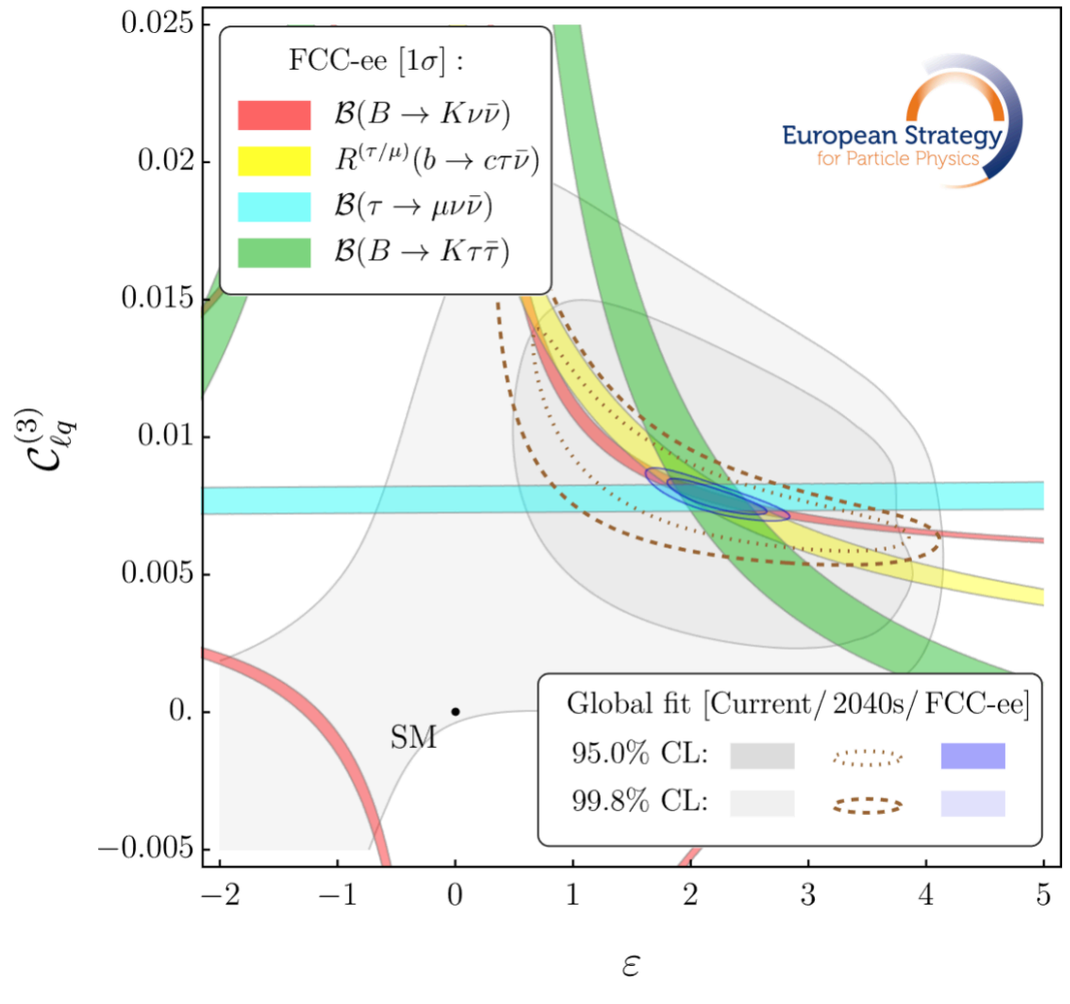
Alone with its EW program, FCCee can improve these bounds by 10x

Interpretation: combining EW precision and flavor

A Tera-Z facility can help test new physics via the <u>combination</u> of its EW & flavor program.

Example: 3rd-family LH semileptonic interactions, with approximate $U(2)^5$ symmetry





[Briefing Book for the ESPP 2511.03883; Allwicher, Isidori, Pesut, 2503.17019]

Interpretation: combining EW precision and flavor

A Tera-Z facility can help test new physics via the <u>combination</u> of its EW & flavor program.

Example: UV completion with S_1 leptoquark

[Allwicher, Isidori, Pesut, 2503.17019]

$$S_1 \sim (\overline{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}}$$

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

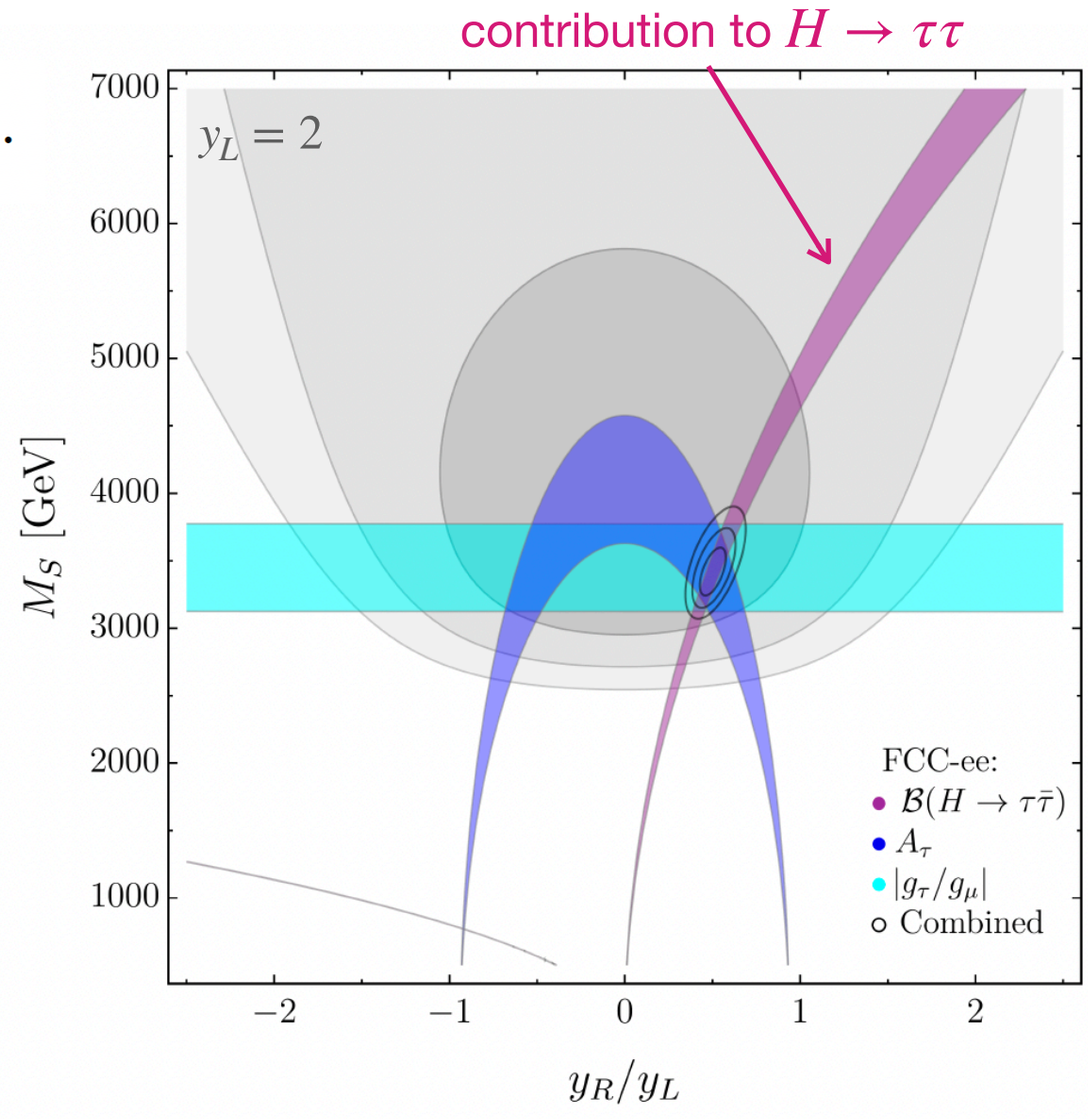
Three parameters: m_S, y_L, y_R

Tree-level matching gives

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

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

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



Conclusions

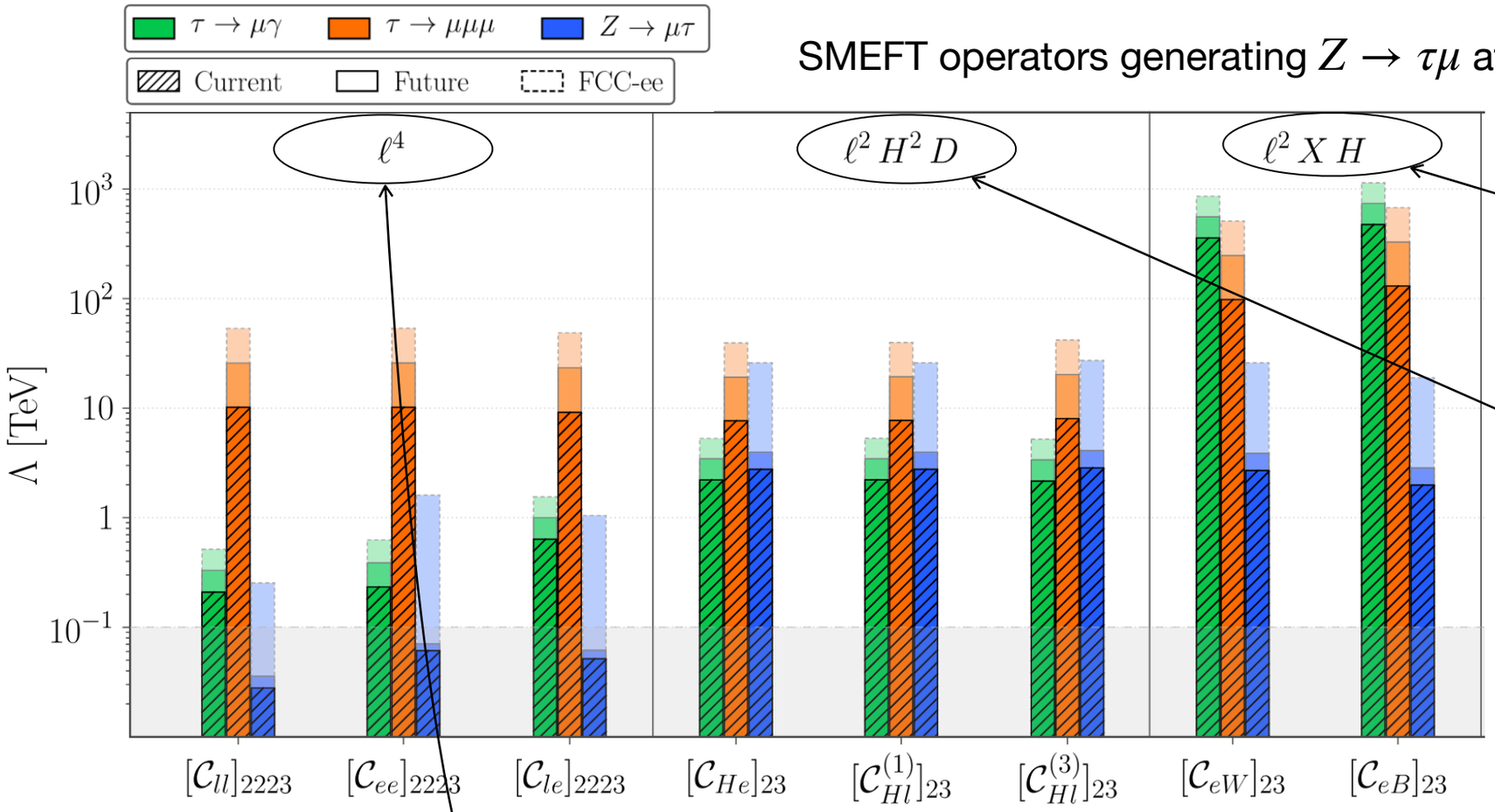
- **Flavor measurements constrain both the scale and the flavor structure of new physics.** Comparing effects across different transitions is essential to distinguish between underlying flavor hypotheses.
- **New physics with flavor protection can still exist in the 1-10 TeV range.** Models coupled mostly to the 3rd family are particularly close targets, with possible connections to the origin of flavor hierarchies.
- **Many complementary tests at ongoing experiments**; clarifying existing tensions remains an important priority.
- **Looking forward, FCC-ee offers new opportunities**, especially for rare decays with taus and neutrinos. Combining flavor measurements with the electroweak and Higgs precision can help determine the interactions responsible for a possible signal.
- **Theory progress is essential to exploit experimental precision:** non-local hadronic amplitudes in $b \to s\ell\ell$, reliable CKM inputs, radiative corrections, improvements on the lattice…This requires a sustained joint effort between theory and experiment.

Lepton flavor violation at FCCee

Charged LFV would provide an unambiguous signal of new physics.

At the Z-pole run of FCC-ee, one can study $\tau \to \mu$ LFV via τ and Z decays.

How do these searches compare for the same underlying interactions?



SMEFT operators generating $Z \to \tau\mu$ at tree level

dipoles

$\tau \to 3\mu$ and $\tau \to \mu\gamma$ generated at tree level

Higgs x fermion current

$\tau \to 3\mu$ tree level,
$\tau \to \mu\gamma$ one loop

In both cases, either $\tau \to 3\mu$ or $\tau \to \mu\gamma$ outperform Z decays!

Holds also for operators generating $Z \to \tau\mu$ radiatively
e.g. four-lepton operators

[Allwicher, CC et al., 2610.27057]

Lepton flavor violation at FCCee

Less clear-cut “hierarchy” among τ and Higgs LFV decays:

only $O_{eH} = (H^\dagger H)H(\bar{l}e)$ generates $h \to \tau\mu$ at tree level

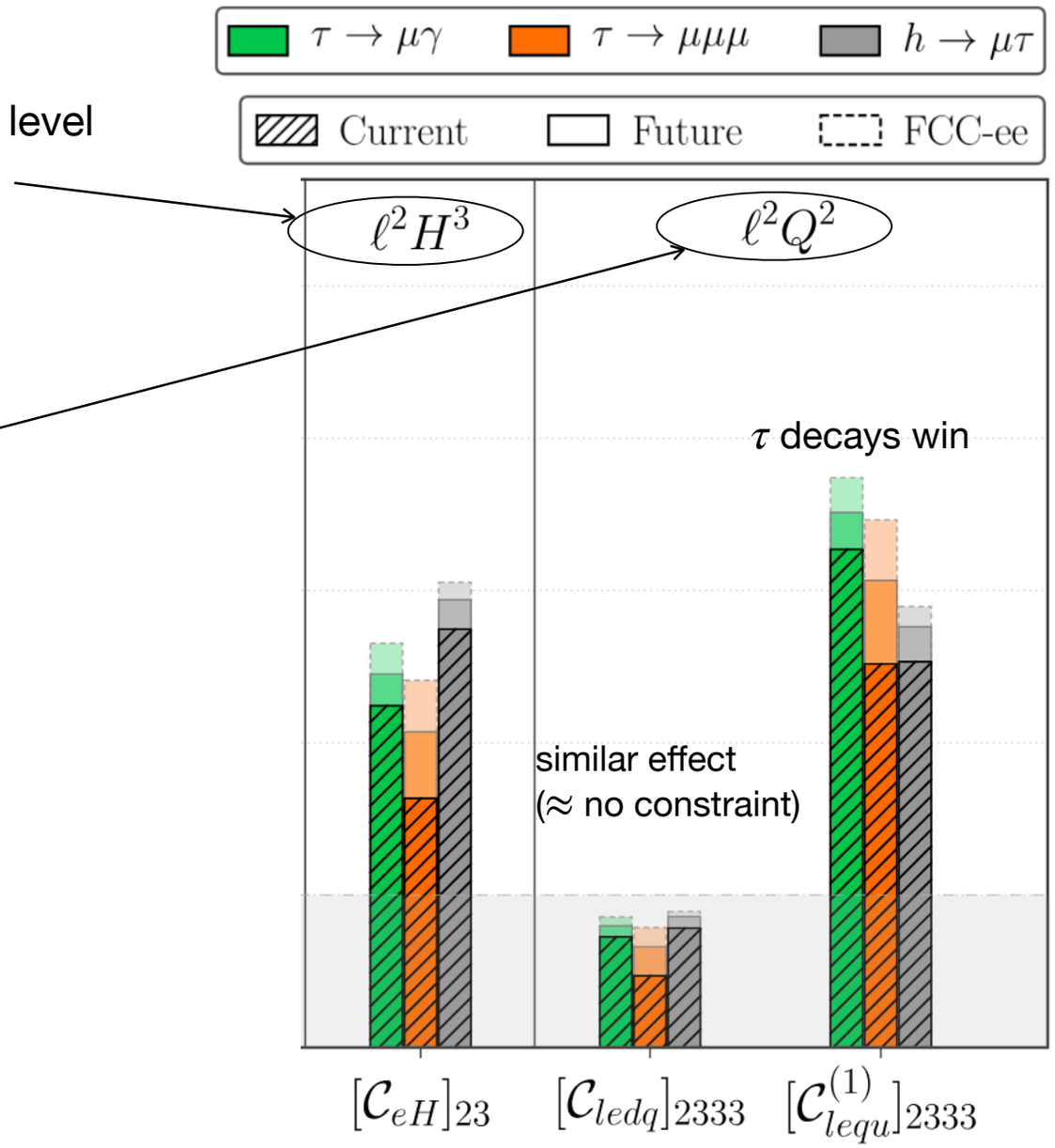
it contributes to τ decays radiatively

for this interaction Higgs decays are the dominant probe

$O^{(1)}_{lequ}$ and O_{ledq} with 3rd fam. quark indices generate $h \to \tau\mu$ at one loop

leading contribution to τ decays arises at two loops

hierarchy depends on the operator



[Allwicher, CC et al., 2610.27057]