Flavor Prospects at FCC-ee

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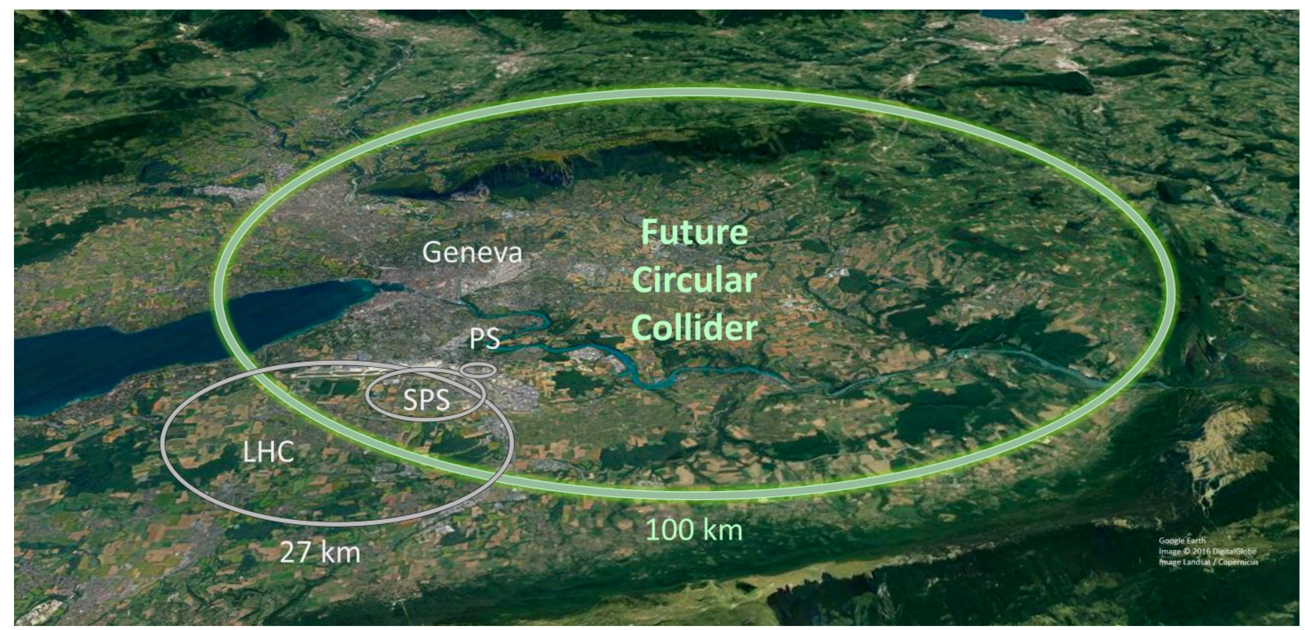

Flavourful Opportunities in Semileptonic B Decays

July 9th, 2026

GENERALITAT VALENCIANA
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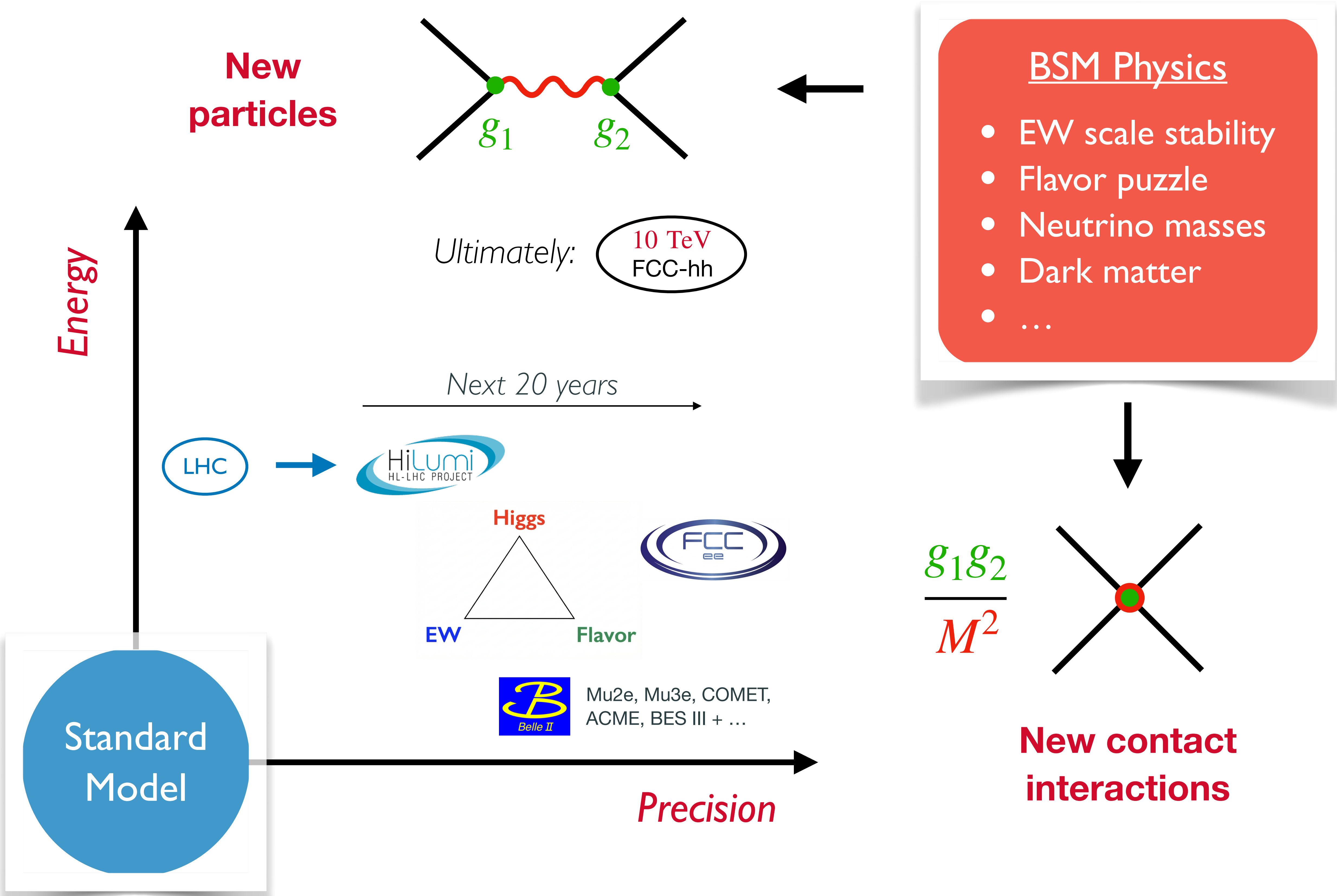
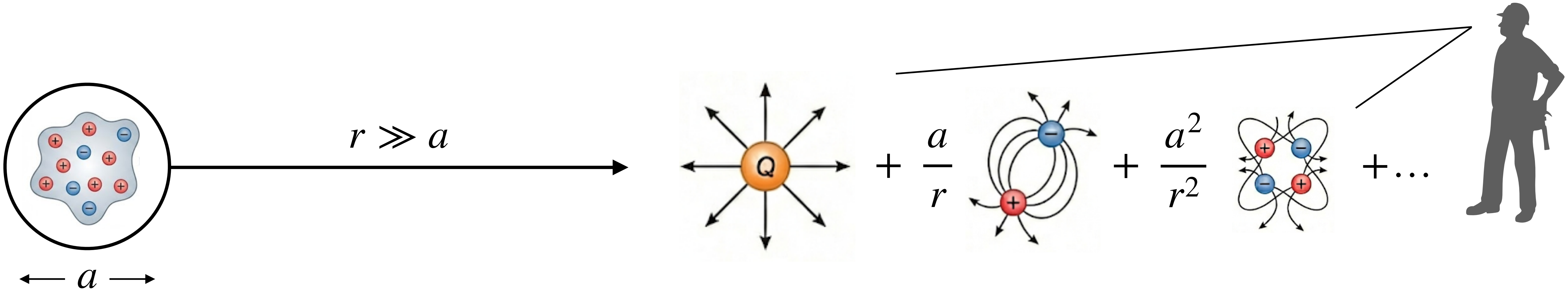
A global strategy for collider physics



Tools for the precision era: Separation of scales

- How does short-distance physics manifest at large distances (low energy)?

Classic example of scale separation: Multipole expansion in electrostatics



Organized as irreducible representations of the symmetry respected at long distance, $SO(3)$!

$$V(\mathbf{r}) = \frac{1}{r}\left[\boxed{Q} + \frac{\boxed{d_i}}{r}\hat{r}_i + \frac{\boxed{Q_{ij}}}{r^2}\hat{r}_i\hat{r}_j + \dots\right]$$

Short-distance physics completely encoded into the moments! (constant coefficients)

The rest is "IR dynamics"! (how the potential changes as you move around)

Tools for the precision era: Effective field theory

- The SM effective field theory (SMEFT) is *based on exactly the same concepts*!

Constant coefficients containing info about the UV theory at $\Lambda_{\rm NP}$

Dynamics given by local operators built with SM fields and respecting IR symmetries

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda_{\rm NP}^2} \mathcal{O}_i(x) + \ldots$$

$$\text{IR Effects} \sim \left(\frac{v, E}{\Lambda_{\rm NP}}\right)^2$$

Heavy mass scale where new states should appear

☑ General unifying framework

☒ More parameters than independent observables

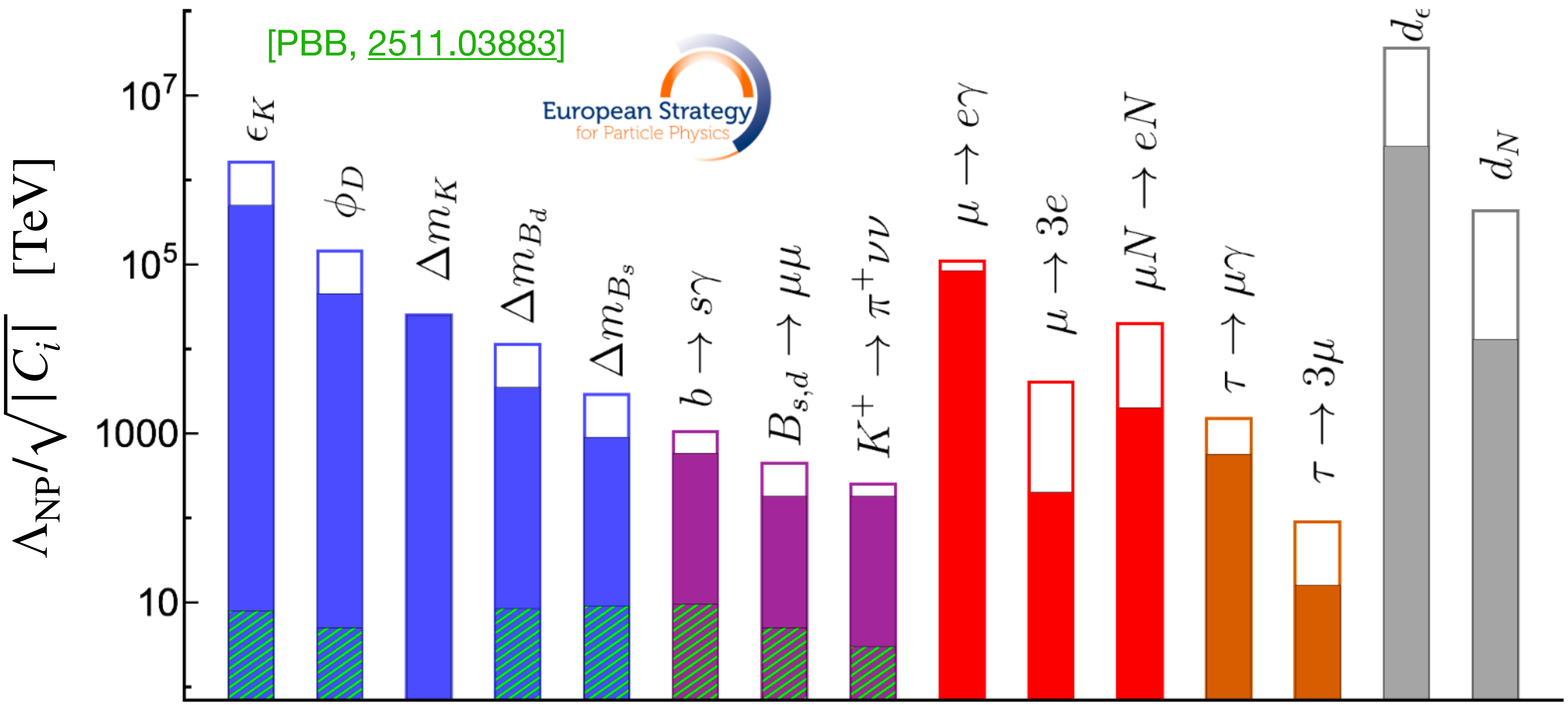
- Dimension-6 SMEFT: 59 unique operator structures, but 2499 parameters with 3 generations. Large # parameters ⇔ flavor multiplicity

Flavor symmetries in the IR that organize these parameters?

Flavor data and anarchy

- Vast majority of SMEFT operators are flavor-changing (>85%)

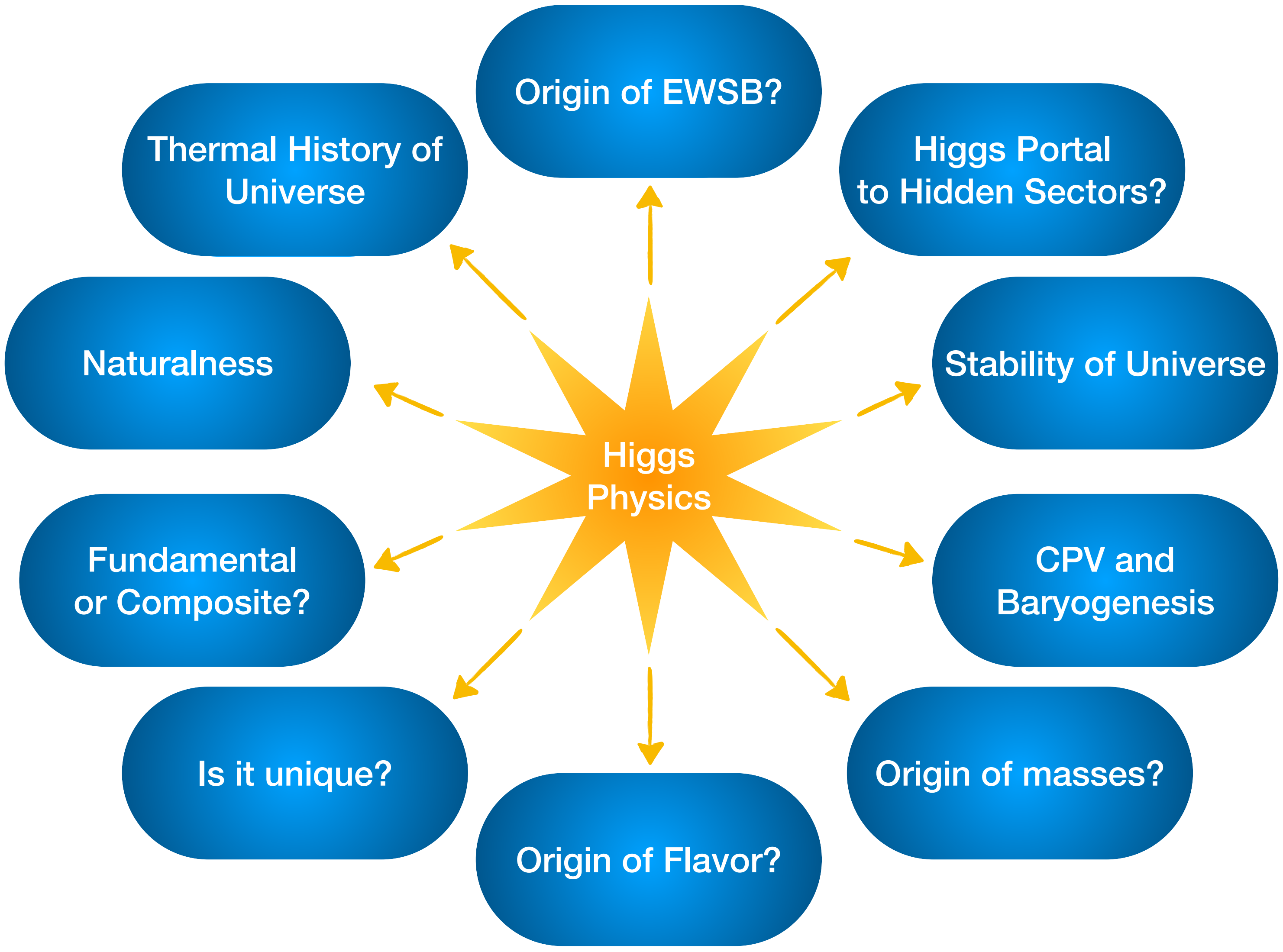
$$\mathscr{L}_{\text{SMEFT}} \supset \sum_{i=1}^{2499} \frac{C_i}{\Lambda_{\text{NP}}^2} \mathscr{O}_i$$



$C_i \sim O(1)$ does not look at all compatible with TeV-scale physics!

Why TeV-scale new physics?

Understanding: What is the microscopic theory of the Higgs?

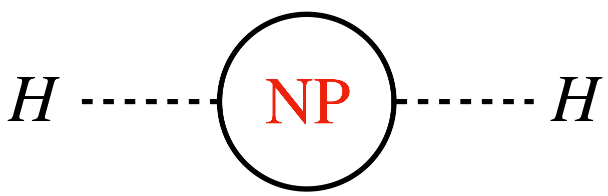


[Figure: Dawson, Meade, Ojalvoc, Vernieri, 2209.07510]

Why TeV-scale new physics?

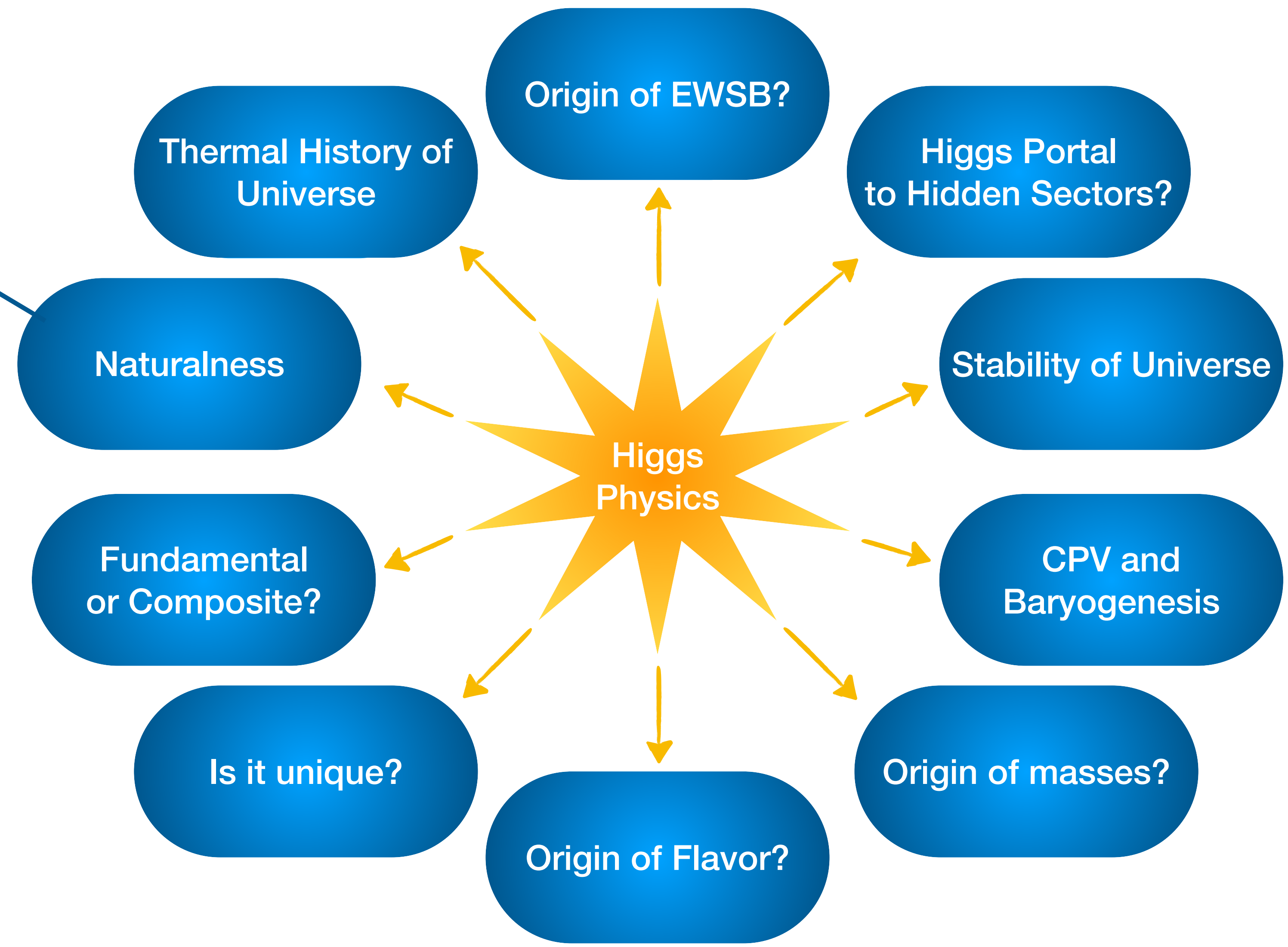
Understanding: What is the microscopic theory of the Higgs?

SM Higgs sector famously introduces an unstable scale



$$\delta m_H^2 \propto \Lambda_{\mathrm{NP}}^2$$

Puts a theoretical prior on TeV-scale physics!



Exploration: It's the energy frontier of collider physics! LHC → FCC

1-10 TeV

[Figure: Dawson, Meade, Ojalvoc, Vernieri, 2209.07510]

Higgs, Electroweak, and Flavor

- All involve the Higgs and its interactions with the fermions + gauge bosons.

$$\mathscr{L}_{\text{Higgs}} = (D_\mu H)^\dagger (D^\mu H) - Y_\psi^{ij} \bar{\psi}_L^i H \psi_R^j - m_H^2 |H|^2 - \lambda |H|^4 + \sum_i \frac{C_i}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$$

Z+W masses

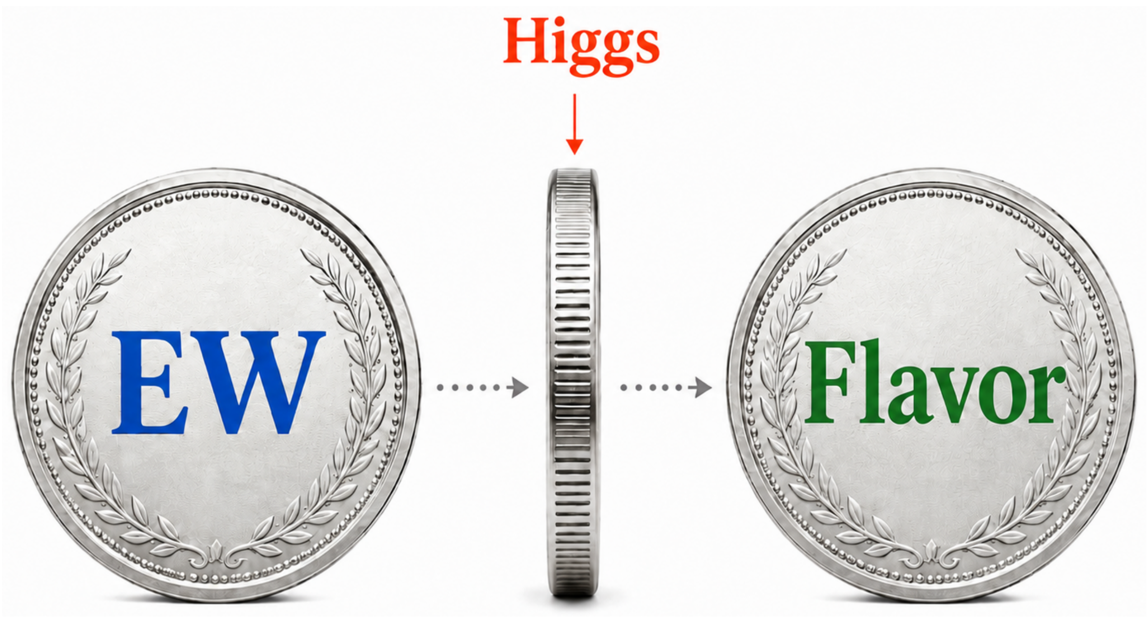
Flavor non-degeneracy

Higgs self coupling

EW precision physics

Flavor physics

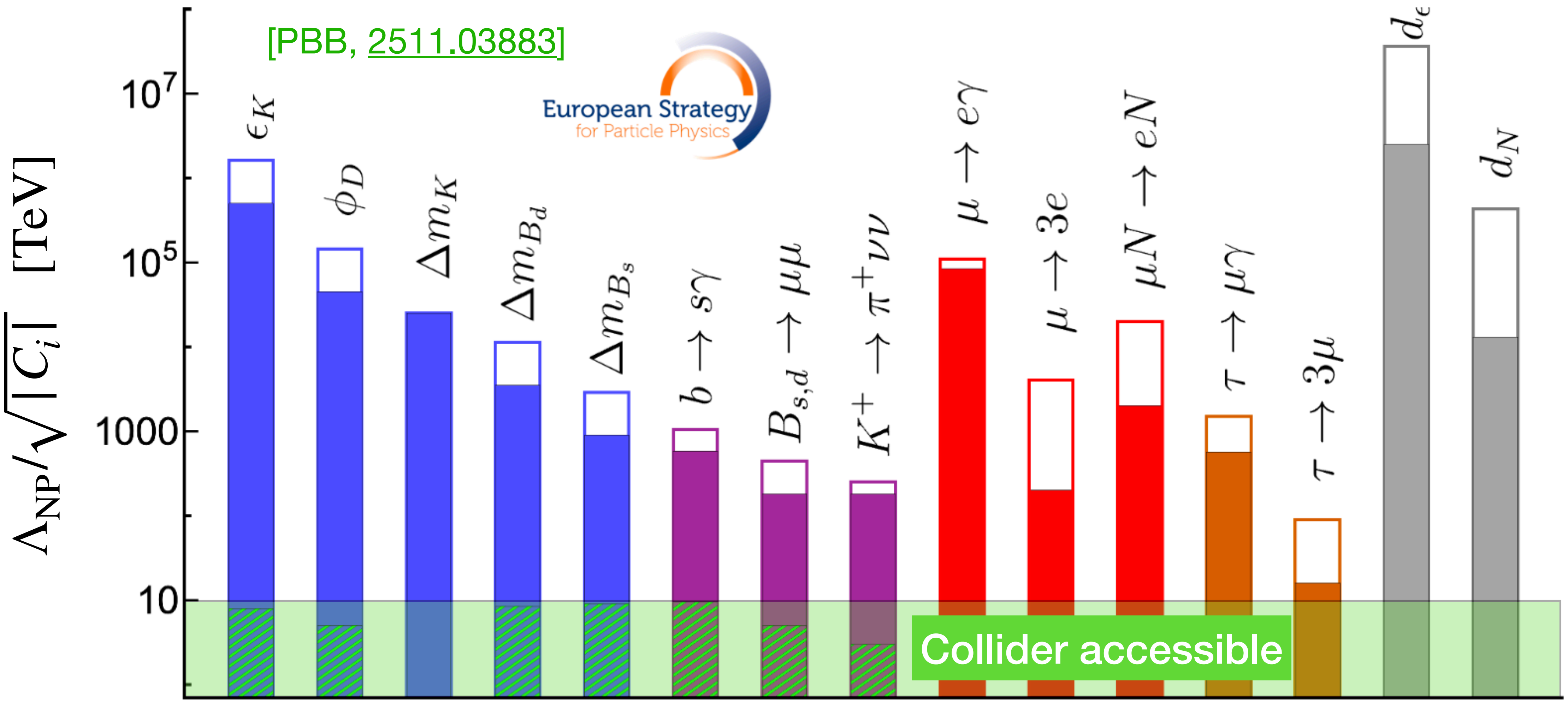
Higgs physics



- Three sides of the same coin…

The BSM flavor puzzle

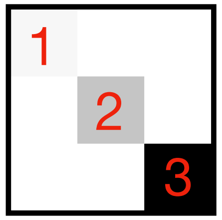
- How is a microscopic theory of the Higgs compatible with flavor data?



$\Longrightarrow$ TeV-scale new physics requires a *very specific structure* for C_i

Radiatively-stable structure ⇔ symmetries

- Hierarchical structure observed in the SM Yukawa couplings Y_f^{ij}



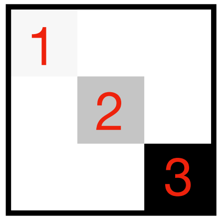
$\Longrightarrow$ Approximate flavor symmetries in the SM!

$\mathscr{L}_{\rm SM}$ without Yukawas: $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$ Flavor universality

- Only large breaking is $y_t \sim 1$ $\longrightarrow$ $U(2)_q \times U(2)_u \times U(1)_t \times U(3)^3$
- Next breaking $y_{b,\tau} \sim 10^{-2}$ $\longrightarrow$ $U(2)^5 \times U(1)_{B_3} \times U(1)_{L_3}$
- Residual exact symmetry $\longrightarrow$ $U(1)_B \times U(1)^3$

Hierarchical Y_f^{ij} $\Longrightarrow$ Approximate symmetries of increasing quality

Radiatively-stable structure ⇔ symmetries



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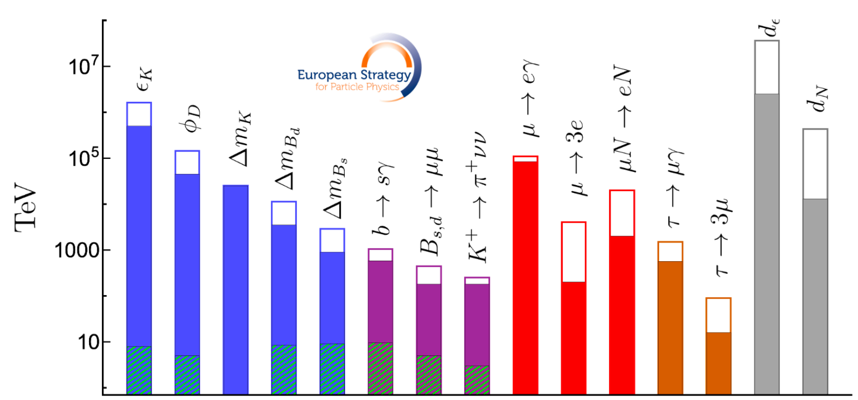


$\Longrightarrow$

New physics at collider-accessible energies must respect (a part) of the approximate symmetries of the SM.

Minimal Flavor Violation

- Pioneering idea: The only sources of $U(3)^5$ and CP violation for BSM physics are the SM Yukawa couplings themselves.

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

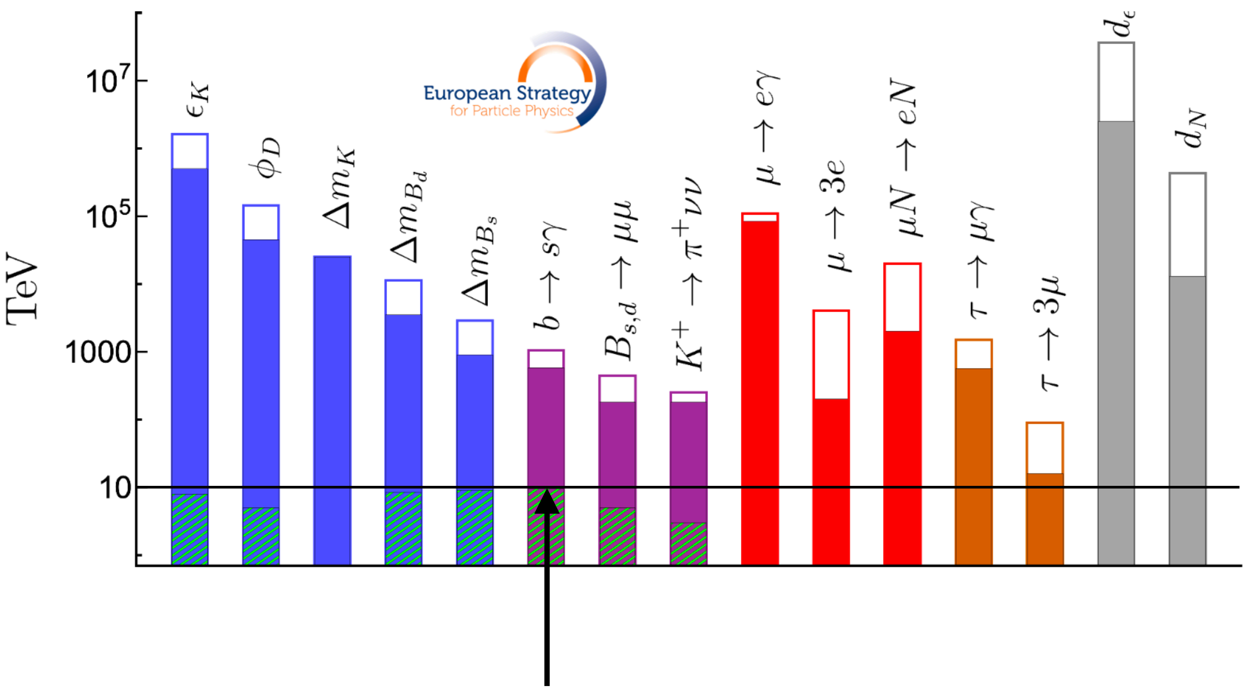
Symmetry-breaking spurions: $Y_u \sim (\mathbf{3}_q, \bar{\mathbf{3}}_u)$, $Y_d \sim (\mathbf{3}_q, \bar{\mathbf{3}}_d)$, $Y_e \sim (\mathbf{3}_\ell, \bar{\mathbf{3}}_e)$

SM fermions: $\mathbf{3}_f$ under $U(3)^5$

Wilson coefficients C_i built from positive powers of Y_f that form symmetry invariants:

$$\frac{1}{\Lambda_{\rm NP}^2}(\bar{q}Y_uY_u^\dagger q)^2\,, \qquad [Y_uY_u^\dagger]_{ij} \approx y_t^2 V_{3i}^* V_{3j}$$

BSM couplings C_i now inherit SM flavor selection rules!



MFV $\Lambda_{\rm NP} \lesssim 10$ TeV

[G. D'Ambrosio, G.F. Giudice, G. Isidori, A. Strumia, hep-ph/0207036]

Minimal Flavor Violation

- Shortcomings:

1. **Flavor-sterile TeV scale dynamics**
   Not an appropriate interpretation framework for EFT in the era of precision flavor physics experiments!
2. **No hint of a resolution to the SM flavor puzzle**
   Structure of Y_f^{ij} is simply assumed, but not explained.
3. **EFT power counting issues since $y_t \sim 1$***

MFV guarantees sufficient flavor protection, but it is ***not strictly necessary*** and is ***overly restrictive***. It excludes a broad class of potentially interesting flavor phenomena that could still be compatible with TeV-scale dynamics.

[*Kagan, Perez, Volansky, Zupan, 0903.1794]

The next step: $U(2)^5$

- Key idea: Universality in the light families passes strongest flavor bounds, allow non-trivial third-family dynamics. [Barbieri, Isidori, Jones-Perez, Lodone, Straub, hep-ph/0207036]

Symmetry group: $U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$ $\qquad \mathbf{2}_f \oplus \mathbf{1}_f$

Symmetry-breaking spurions: $V_q \sim \mathbf{2}_q\,, \quad \Delta_u \sim (\mathbf{2}_q, \bar{\mathbf{2}}_u), \quad \Delta_d \sim (\mathbf{2}_q, \bar{\mathbf{2}}_d), \quad \Delta_e \sim (\mathbf{2}_\ell, \bar{\mathbf{2}}_e)$

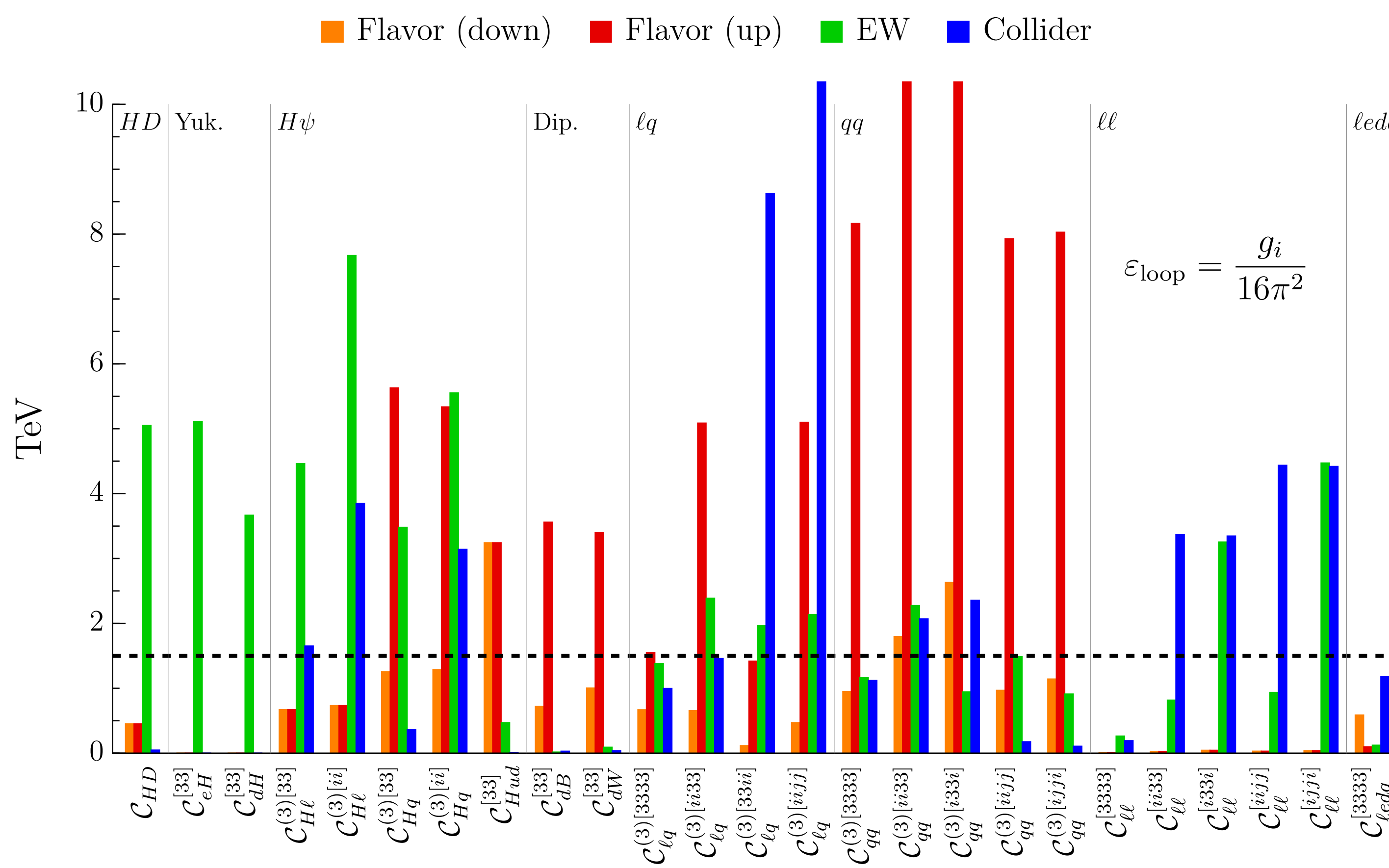
$$Y_{u,d} = \left(\begin{array}{c|c} \Delta_{u,d} & V_q \\ \hline 0 & y_{t,b} \end{array}\right)$$

EFT ops classified as $U(2)^5$ invariants:

$$\frac{1}{\Lambda_{\rm NP}^2}(\bar{q}_i V_q^i q_3)^2 \qquad B_{d,s} \text{ mixing}$$

- Allows $\Lambda_{\rm NP} \lesssim 10$ TeV, option to couple more to 3rd generation:

$$\bar{q}_p \gamma_\mu q_p \to \epsilon_Q(\bar{q}_i \gamma_\mu q_i) + (\bar{q}_3 \gamma_\mu q_3) \qquad (i = 1,2)$$



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

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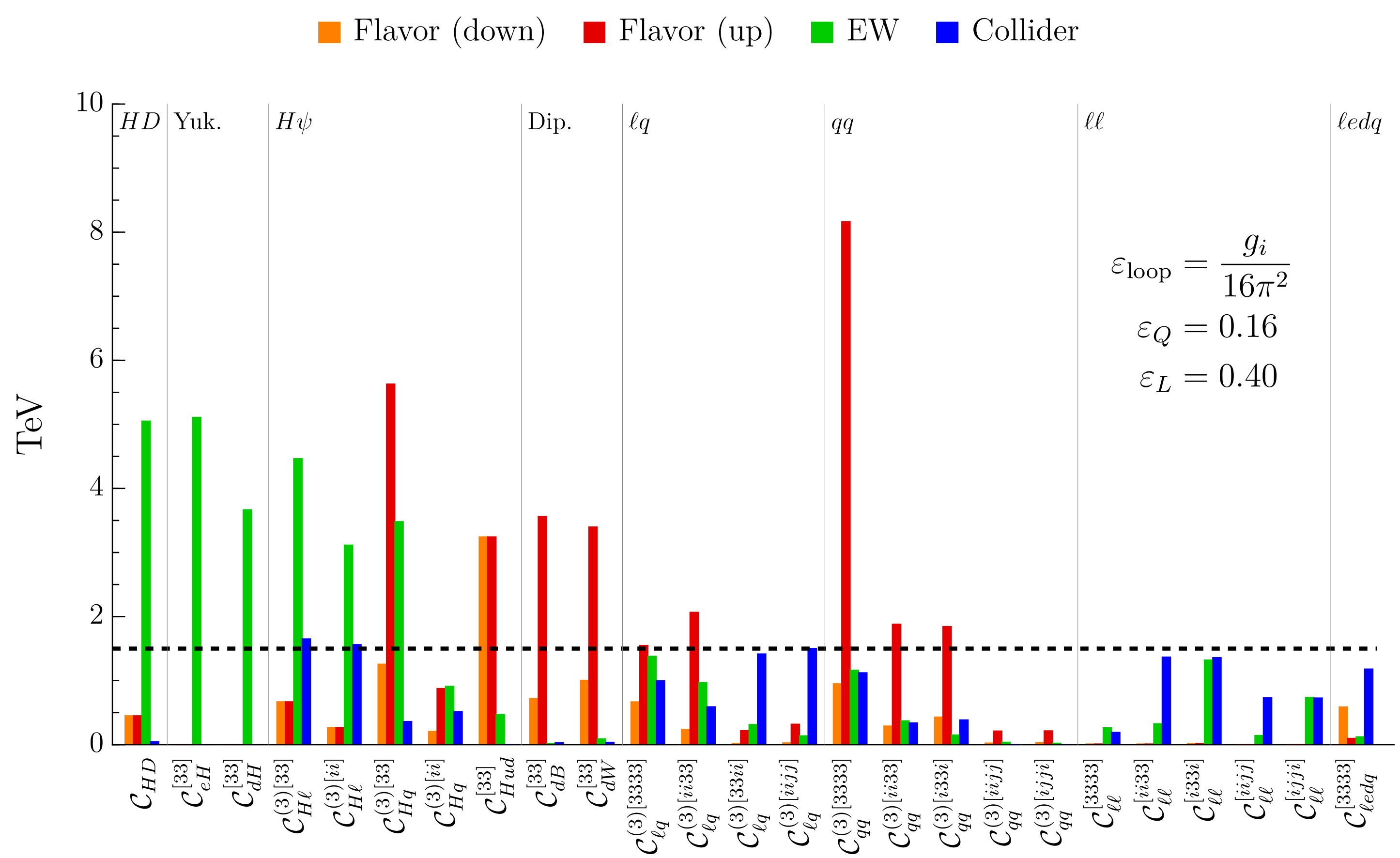


[Allwicher, Cornella, Isidori, BAS, 2311.00020]

The next step: $U(2)^5$

- Solves some MFV shortcomings:

1. **Non-trivial third-family TeV scale dynamics.**
   The leading interpretation framework in the past decade of b physics!

2. **Partial resolution to the SM flavor puzzle.**
   Separates the 3rd family from the light from the start.
   Still hierarchical eigenvalues in $\Delta_{u,d,e}$ unexplained!

3. **No issues with power counting**
   The largest breaking is $V_q \sim O(V_{ts}) \sim 10^{-2}$

And perhaps still too restrictive! What is the most general interpretation framework for TeV-scale BSM? And can we find a more complete explanation of the flavor puzzle?

Minimal Flavor Protection

What is the maximum amount TeV-scale BSM can break $U(3)^5$ while respecting all bounds from FCNC and CP-violating observables?

- Least symmetry ⇔ largest allowed parameter space for TeV-scale new physics!

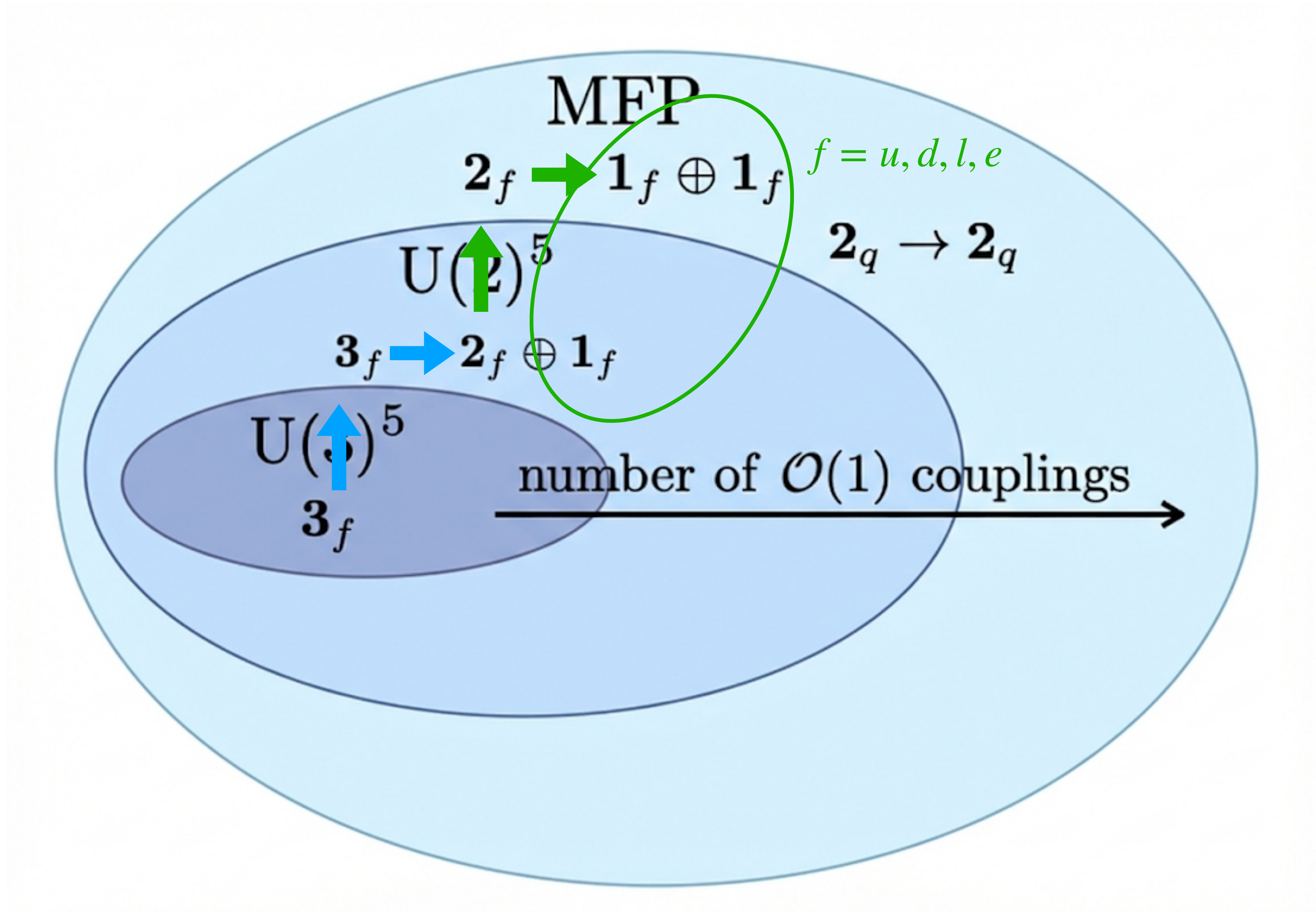
Find the minimal continuous subgroup $H_{\mathrm{MFP}} \subset U(3)^5$ where:

1. All other directions in flavor space can be maximally violated, i.e., BSM can induce $\mathcal{O}(1)$ breaking of $U(3)^5 \to H_{\mathrm{MFP}}$
2. Small spurions exist that reproduce all observed flavor parameters.
3. Structural protection against FCNC and CPV for the ***entire*** SMEFT.

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection

Symmetry: $SU(2)_q \times U(1)_X$



MFP: A novel symmetry-spurion framework for TeV-scale new physics

[Greljo, Palavrić, BAS, 2512.04159]

[Figure: 2601.07921]

The necessity of $SU(2)_q$

- Why not just a single $U(1)_X$? Let's try it- choose $X_{q_1} \neq X_{q_2} \neq X_{q_3}$ for no FV in interaction basis:

$$c\bar{q}\gamma_\mu M_{\rm int} q \qquad\qquad M_{\rm int} = {\rm diag}(a, b, 1)$$

- CKM guarantees that LH rotations ($L_u L_d^\dagger = V_{\rm CKM}$) generate FV which is of order

$$M_{\rm mass} = L M_{\rm int} L^\dagger \sim \begin{pmatrix} a & \lambda(b-a) & A\lambda^3[a-b+(1-a)z^*] \\ \lambda(b-a) & b & A\lambda^2(1-b) \\ A\lambda^3[a-b+(1-a)z] & A\lambda^2(1-b) & 1 \end{pmatrix}$$

K/D meson mixing

$$\frac{(a-b)^2\lambda^2}{\Lambda^2}(\bar{q}_1 q_2)^2 \lesssim \frac{1}{(2\times 10^4\ {\rm TeV})^2} \implies |a-b| \lesssim 10^{-3}\left(\frac{\Lambda}{10\ {\rm TeV}}\right)$$

**$SU(2)_q$ must be a very good symmetry of any BSM below 10 TeV!

[Greljo, Palavrić, BAS, 2512.04159] [Blum, Grossman, Nir, Perez, 0903.2118]

Right-handed rotations

- Ok so we need $SU(2)_q$. But what about $U(2)_u \times U(2)_d$? In general, RH rotations are not fixed, but they cannot be smaller than chirally-suppressed LH ones:

$$Y_{u,d} \sim \begin{pmatrix} \times & \times & \times \\ 0 & \times & \times \\ 0 & 0 & \times \end{pmatrix} \qquad \Longrightarrow \quad \theta_R^{ij} \approx \frac{m_i}{m_j}\theta_L^{ij} \quad (i < j)$$

Light mass ratios: $\quad m_d/m_s \approx 5 \times 10^{-2} \qquad m_u/m_c \approx 2 \times 10^{-3}$

$$\bar{K} - K: \quad \frac{(a-b)^2\lambda^2}{\Lambda^2}\frac{m_d^2}{m_s^2}(\bar{d}_1 d_2)^2 \lesssim \frac{1}{(2 \times 10^4 \text{ TeV})^2} \quad \Longrightarrow \quad |a-b| \lesssim 0.05\left(\frac{\Lambda}{10 \text{ TeV}}\right)$$

$$\bar{D} - D: \quad \frac{(a-b)^2\lambda^2}{\Lambda^2}\frac{m_u^2}{m_c^2}(\bar{u}_1 u_2)^2 \lesssim \frac{1}{(2 \times 10^4 \text{ TeV})^2} \quad \Longrightarrow \quad |a-b| \lesssim O(1)\left(\frac{\Lambda}{10 \text{ TeV}}\right)$$

**$U(2)_{u,d}$ could be broken at 10 TeV if the Cabibbo angle comes mostly from L_u.

(Limits are weaker by a factor ~20 if the rotation is real)

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Symmetry group

- What about the rest? $U(1)_X \subset U(1)^{14} \subset U(3)^5$

A single linear combination of the remaining Cartan generators is enough!

(Perhaps the most surprising discovery… would have expected a larger group!)

- Our ansatz for the minimal continuous symmetry is therefore:

$$H_{\mathrm{MFP}} = SU(2)_q \times U(1)_X$$

$\Delta F = 2$, cLFV $\Longrightarrow X_{f_1} \neq X_{f_2}$

$\cancel{(\bar{u}_1 u_2)^2, (\bar{d}_1 d_2)^2, (\bar{l}_1 l_2), (\bar{e}_1 e_2)}$

Forbidden in SMEFT interaction basis

Fermion fields

$$\mathbf{3}_{x_q} \to \mathbf{2}_{x_q} \oplus \mathbf{1}_{x_{q3}} \,,$$

$$\mathbf{3}_{x_f} \to \mathbf{1}_{x_{f_1}} \oplus \mathbf{1}_{x_{f_2}} \oplus \mathbf{1}_{x_{f_3}}$$

$$f \;=\; u,\, d,\, \ell,\, e$$

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Lepton Yukawas

- Start with lepton Yukawas, which require just a single spurion:

$$z \sim (\mathbf{1}, X_z) \qquad [l_i] = X_i\,, \qquad [e_i] = X_i - (4-i)X_z$$

- For $z \approx 2 \times 10^{-2}$, we get a Froggatt-Nielsen like solution for lepton Yukawas

$$Y_e = \begin{pmatrix} y_1^e z^3 & 0 & 0 \\ 0 & y_2^e z^2 & 0 \\ 0 & 0 & y_3^e z \end{pmatrix}$$

Off-diagonals and cLFV forbidden if:

$$(X_i - X_j) \bmod X_z \neq 0 \quad \forall\, i \neq j$$

- What about neutrinos? In general, we would also imprint hierarchies there

$$\mathscr{L}_{d=5} = C_{ij} \frac{z^{N_{ij}}}{\Lambda} \bar{l}_i^c l_j H H$$

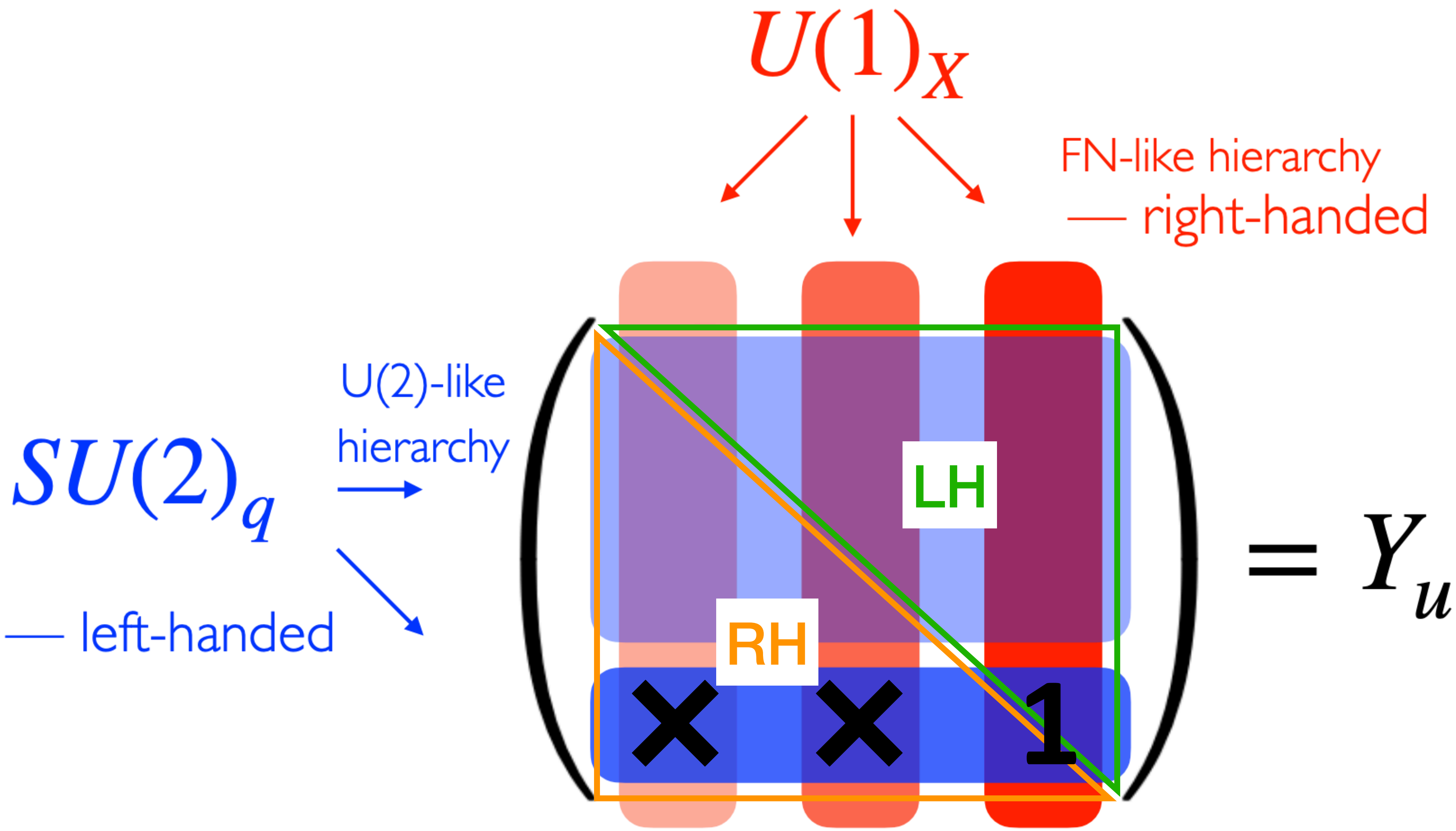
Weinberg operator forbidden if:

$$(X_i + X_j) \bmod X_z \neq 0 \quad \forall\, i, j$$

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Quark Yukawas

- Quark Yukawas arise essentially as hybrid between $U(2)$ and Froggatt-Nielson:



✖ *Cannot be populated if $Y_{u,d}$ arise from $SU(2)_q$-doublet spurions*

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Quark Yukawas

- The quark Yukawas require a minimum of three $SU(2)_q$-doublet spurions:

$SU(2)_q$ spurions: $\boldsymbol{V} \sim (\mathbf{2}, X_V) \quad \boldsymbol{W} \sim (\mathbf{2}, X_W), \quad \boldsymbol{U} \sim (\mathbf{2}, X_U)$

Quarks	$d_1,\ u_1$	d_2	u_2	d_3	$q_3,\ u_3$
$U(1)_X$ charge	$-X_V - 2X_z$	$X_V + X_z$	$-X_W$	$X_z - X_U$	$2X_z - X_U$

- With these charges, the up and down Yukawas have the following texture:

$$Y_u = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad Y_d = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \widetilde{\boldsymbol{V}} \boldsymbol{z}^* & \boldsymbol{U} \boldsymbol{z}^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}$$

$$\widetilde{\boldsymbol{V}} = i\sigma_2 \boldsymbol{V}^*$$

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Quark Yukawas

$$Y_u = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad Y_d = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \widetilde{\boldsymbol{V}} \boldsymbol{z}^* & \boldsymbol{U} \boldsymbol{z}^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}.$$

- Without loss of generality, we can choose a basis where:

$$\boldsymbol{z} = z, \; \boldsymbol{V} = v \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \; \boldsymbol{W} = w \begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix}, \; \boldsymbol{U} = u \begin{pmatrix} \sin\beta \, e^{i\phi} \\ \cos\beta \end{pmatrix}$$

12 down alignment

$\tan\alpha \approx V_{us}/V_{cs}$

$\tan\beta e^{i\phi} \approx V_{td}^*/V_{ts}^*$

$\boxed{\text{All mass hierarchies explained for } v, w, u, z \sim \mathcal{O}(10^{-2})}$ ✓

11 hierarchical SM parameters traded for 4 of the same order!
Towards a solution to the SM flavor puzzle…

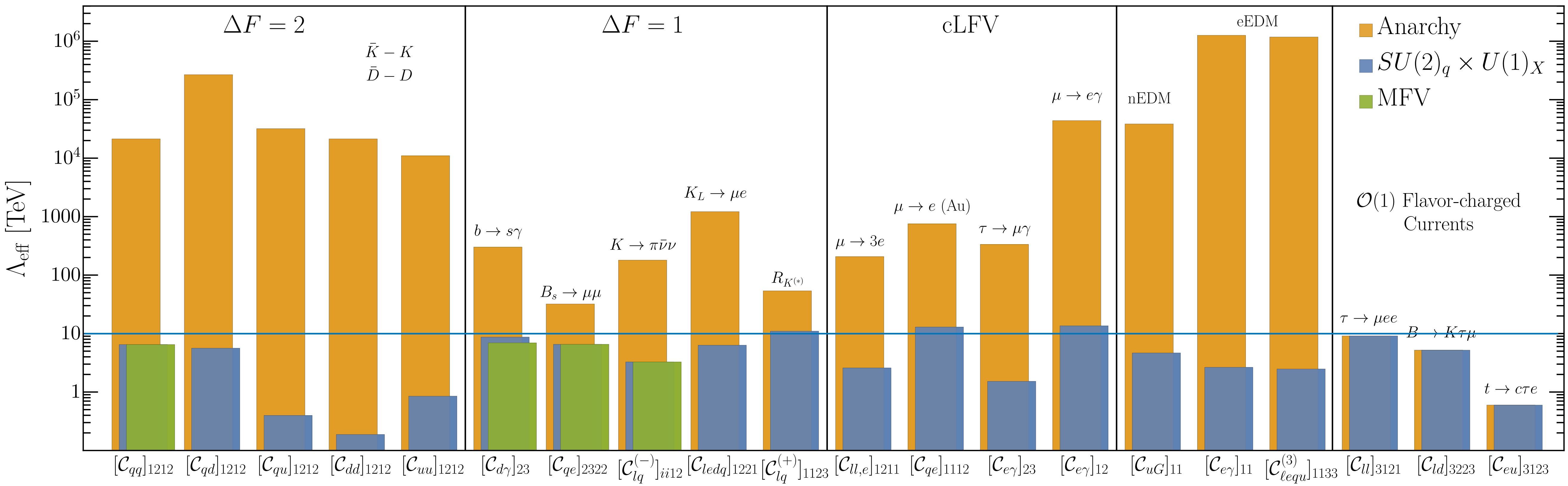
[Greljo, Palavrić, BAS, 2512.04159]

Flavor violation in MFP

$$\{X_V,\, X_W,\, X_U,\, X_z\} = \{1,\, \text{-}2,\, \text{-}3,\, 7\}\,,$$
$$\{X_1,\, X_2,\, X_3\} = \{\text{-}2,\, \text{-}3,\, \text{-}1\}\,.$$

- SMEFT now admits a series expansion in small spurions $S = V, W, U, z$ about the MFP-symmetric point:

$$\mathcal{L}_{\rm SMEFT} = \frac{1}{\Lambda^2} \sum_{H_{\rm MFP}} \left[S^0\, \mathcal{O}_6^{[0]} + S^1\, \mathcal{O}_6^{[1]} + S^2\, \mathcal{O}_6^{[2]} + \cdots \right]$$



MFP allows for rich flavor dynamics: "TeV-scale flavor anarchy"!

[Greljo, Palavrić, BAS, 2512.04159]

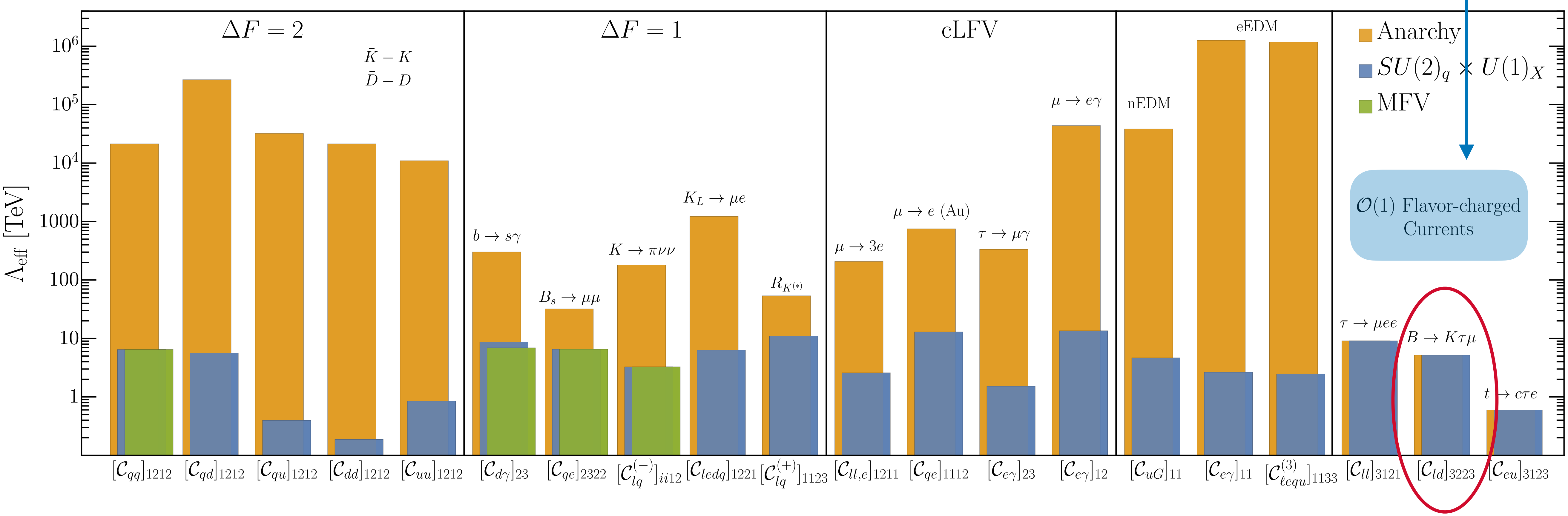
Flavor-charged currents

$$\{X_V,\, X_W,\, X_U,\, X_z\} = \{1,\, \text{-}2,\, \text{-}3,\, 7\}\,,$$
$$\{X_1,\, X_2,\, X_3\} = \{\text{-}2,\, \text{-}3,\, \text{-}1\}\,.$$

- SMEFT now admits a series expansion in small spurions about the MFP-symmetric point:

Flavor violation possible at $O(S^0)$, e.g: $\frac{1}{\Lambda_{\text{eff}}^2}(\bar{l}_3\gamma_\mu l_2)(\bar{d}_2\gamma^\mu d_3)$

We call these flavor-charged currents!



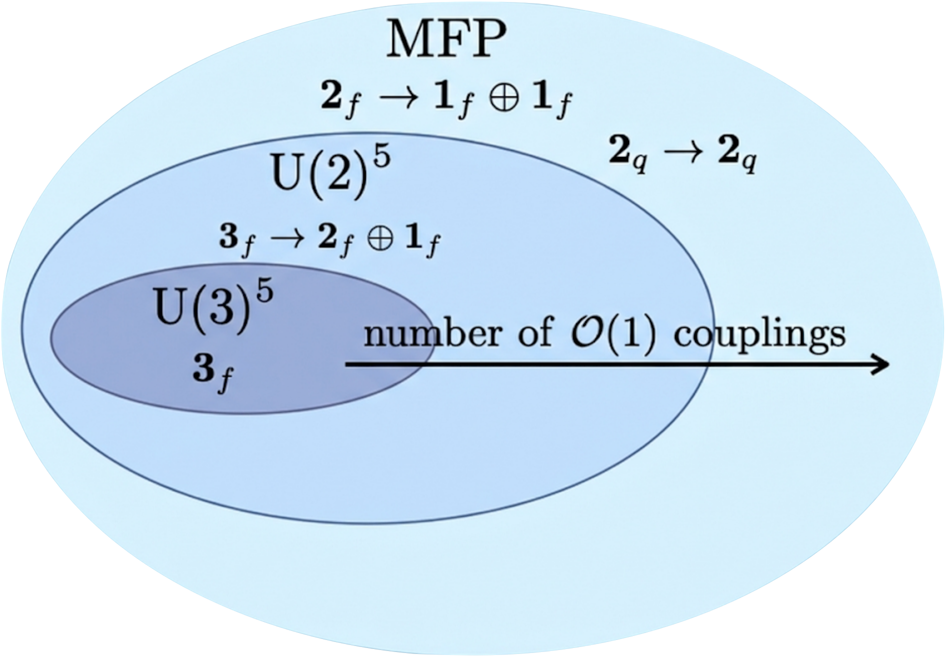
MFP provides new targets for LHCb/Belle II, but also ATLAS/CMS!

[Greljo, Palavrić, BAS, 2512.04159]

Flavor-universality violation

Dimension-6 SMEFT $(\Delta B = 0)$

Operator basis w/ exact symmetry: $O(S^0)$



Operator class	$U(3)^5$		$U(2)^5$		$SU(2)_q \times U(1)_X$	
CP	even	odd	even	odd	even	odd
Bosonic	9	6	9	6	9	6
$\psi^2 H^3$	-	-	3	3	1	1
$\psi^2 X H$	-	-	8	8	3	3
$\psi^2 H^2 D$	7	-	15	1	20	1
$(\bar{L}L)(\bar{L}L)$	8	-	23	-	32	1
$(\bar{R}R)(\bar{R}R)$	9	-	29	-	61	1
$(\bar{L}L)(\bar{R}R)$	8	-	32	-	58	1
$(\bar{L}R)(\bar{R}L)$	-	-	1	1	1	1
$(\bar{L}R)(\bar{L}R)$	-	-	4	4	-	-
Total	41	6	124	23	185	15

Large reduction of O(1) parameters!

$$2499 \to \lesssim 200$$

MFP: More flavor-universality violation possible than in MFV and $U(2)^5$

[Greljo, Palavrić, BAS, 2512.04159]

Flavor-universality violation in MFP

- Start from the Cartan group, $U(1)^{15}$:

$$U(1)^{15} = U(1)^3_q \times U(1)^3_u \times U(1)^3_d \times U(1)^3_l \times U(1)^3_e$$

- Under this group, *fermion number cannot change, chirality cannot flip*. Counts self-conjugate operators.

Operator class	$U(1)^{15}$	
CP	even	odd
Bosonic	9	6
$\psi^2 H^3$	–	–
$\psi^2 X H$	–	–
$\psi^2 H^2 D$	21	–
$(\bar{L}L)(\bar{L}L)$	45	–
$(\bar{R}R)(\bar{R}R)$	60	–
$(\bar{L}L)(\bar{R}R)$	72	–
$(\bar{L}R)(\bar{R}L)$	–	–
$(\bar{L}R)(\bar{L}R)$	–	–
Total	**207**	**6**

207 CP even (8% of SMEFT)

H^6 and $H^4 D^2$	
Q_H	$(H^\dagger H)^3$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$

$\psi^2 H^2 D$		$X^2 H^2$ and X^3	
$Q_{H\ell}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu \ell)_{pp}$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\ell}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}\tau^I\gamma^\mu \ell)_{pp}$	Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)_{pp}$		

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)_{pprr}$
$Q_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)_{pprr}$
$Q_{\ell q}^{(1)}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{\ell q}^{(3)}$	$(\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)_{pprr}$	Q_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)_{pprr}$
		$Q_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)_{pprr}$
		$Q_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)_{pprr}$
				$Q_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)_{pprr}$

Flavor-universality violation in MFP

- But if we want the top Yukawa unsuppressed, we should break

$$U(1)_{q_3} \times U(1)_{u_3} \rightarrow U(1)_{\rm diag} \equiv U(1)_{\rm top} \qquad \Longrightarrow \qquad U(1)^{15} \rightarrow U(1)^{14}$$

Operator class	$U(1)^{15}$		$U(1)^{14}$	
CP	even	odd	even	odd
Bosonic	9	6	9	6
$\psi^2 H^3$	–	–	1	1
$\psi^2 X H$	–	–	3	3
$\psi^2 H^2 D$	21	–	21	–
$(\bar{L}L)(\bar{L}L)$	45	–	45	–
$(\bar{R}R)(\bar{R}R)$	60	–	60	–
$(\bar{L}L)(\bar{R}R)$	72	–	72	–
$(\bar{L}R)(\bar{R}L)$	–	–	–	–
$(\bar{L}R)(\bar{L}R)$	–	–	–	–
Total	**207**	**6**	**211**	**10**

$\psi^2 H^3$ and $\psi^2 X H$	
Q_{uH}^{33}	$(H^\dagger H)(\bar{q}_3 u_3 \widetilde{H})$
Q_{uB}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} u_3 \widetilde{H}) B_{\mu\nu}$
Q_{uW}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} \tau^I u_3 \widetilde{H}) W_{\mu\nu}^I$
Q_{uG}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} T^A u_3 \widetilde{H}) G_{\mu\nu}^A$

- *Only 4 new operators- top dipoles and Yukawa modification. FUV.*
- *The leading irreducible chiral flipping + non-hermitian operators.*

Flavor-universality violation in MFP

- Now let's add $SU(2)_q$ to the picture: $q \equiv (q_1, q_2)^T$.

$SU(2)_q$ *invariance requires:* $U(1)_{q_1} \times U(1)_{q_2} \to U(1)_q \quad \Longrightarrow \quad U(1)^{14} \to U(1)^{13}$

Operator class	$U(1)^{15}$		$U(1)^{14}$		$SU(2)_q \times U(1)^{13}$	
CP	even	odd	even	odd	even	odd
Bosonic	9	6	9	6	9	6
$\psi^2 H^3$	–	–	1	1	1	1
$\psi^2 X H$	–	–	3	3	3	3
$\psi^2 H^2 D$	21	–	21	–	19	–
$(\bar{L}L)(\bar{L}L)$	45	–	45	–	31	–
$(\bar{R}R)(\bar{R}R)$	60	–	60	–	60	–
$(\bar{L}L)(\bar{R}R)$	72	–	72	–	57	–
$(\bar{L}R)(\bar{R}L)$	–	–	–	–	–	–
$(\bar{L}R)(\bar{L}R)$	–	–	–	–	–	–
Total	**207**	**6**	**211**	**10**	**180**	**10**

- *$SU(2)_q$ correlates the WCs of operators w/ LH light quarks.*
- *Same operator classes, just less parameters.*
- *No change of phases.*

$$C_1(H^\dagger D_\mu H)(\bar{q}_1\gamma^\mu q_1) + C_2(H^\dagger D_\mu H)(\bar{q}_2\gamma^\mu q_2) + C_3(H^\dagger D_\mu H)(\bar{q}_3\gamma^\mu q_3) \to C_{12}(H^\dagger D_\mu H)(\bar{q}_i\gamma^\mu q_i) + C_3(H^\dagger D_\mu H)(\bar{q}_3\gamma^\mu q_3)$$

Flavor-universality violation in MFP

- The breaking $U(1)^{13} \to U(1)_X$ lands on MFP, thus $SU(2)_q \times U(1)^{13}$ *counts the charge-invariant MFP operators! They violate universality but not flavor*.
- The difference counts charge-dependent operators, which are necessarily non-Hermitian. Can violate both flavor and universality!

Operator class	$SU(2)_q \times U(1)^{13}$		$SU(2)_q \times U(1)_X$	
CP	**even**	**odd**	**even**	**odd**
Bosonic	9	6	9	6
$\psi^2 H^3$	1	1	1	1
$\psi^2 XH$	3	3	3	3
$\psi^2 H^2 D$	19	–	20	1
$(\bar{L}L)(\bar{L}L)$	31	–	32	1
$(\bar{R}R)(\bar{R}R)$	60	–	61	1
$(\bar{L}L)(\bar{R}R)$	57	–	58	1
$(\bar{L}R)(\bar{R}L)$	–	–	1	1
$(\bar{L}R)(\bar{L}R)$	–	–	–	–
Total	**180**	**10**	**185**	**15**

[Greljo, Palavrić, BAS, 2512.04159]

Flavor-universality violation in MFP

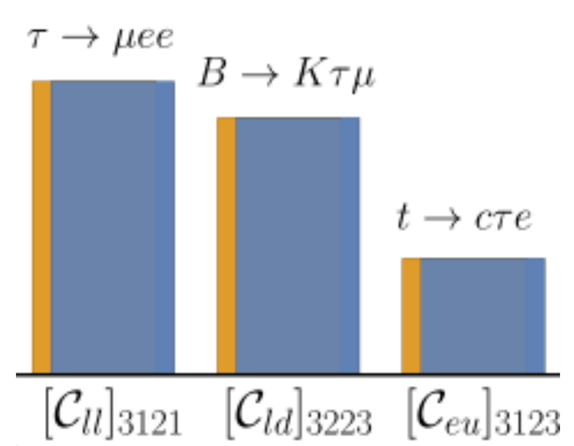
- The breaking $U(1)^{13} \to U(1)_X$ lands on MFP, thus $SU(2)_q \times U(1)^{13}$ *counts the charge-invariant MFP operators! They violate universality but not flavor*.
- The difference counts charge-dependent operators, which are necessarily non-Hermitian. Can violate both flavor and universality!

Operator class	$SU(2)_q \times U(1)^{13}$		$SU(2)_q \times U(1)_X$	
CP	even	odd	even	odd
Bosonic	9	6	9	6
$\psi^2 H^3$	1	1	1	1
$\psi^2 XH$	3	3	3	3
$\psi^2 H^2 D$	19	–	20	1
$(\bar{L}L)(\bar{L}L)$	31	–	32	1
$(\bar{R}R)(\bar{R}R)$	60	–	61	1
$(\bar{L}L)(\bar{R}R)$	57	–	58	1
$(\bar{L}R)(\bar{R}L)$	–	–	1	1
$(\bar{L}R)(\bar{L}R)$	–	–	–	–
Total	**180**	**10**	**185**	**15**

$[Q_{Hud}]_{11} \leftarrow$

$[Q_{\ell edq}]_{3333} \leftarrow$

3 flavor-charged currents



[Greljo, Palavrić, BAS, 2512.04159]

Irreducible interactions for TeV-scale BSM

- 180 CP-even, charge-independent MFP operators are special because i) they can be O(1) at the TeV scale and ii) they cannot be set to zero by symmetry.

EWPOs

Higgs physics

Flavor (non-universality)

H^6 and H^4D^2	
Q_H	$(H^\dagger H)^3$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$

$\psi^2 H^3$ and $\psi^2 XH$	
Q_{uH}^{33}	$(H^\dagger H)(\bar{q}_3 u_3 \widetilde{H})$
Q_{uB}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} u_3 \widetilde{H})B_{\mu\nu}$
Q_{uW}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} \tau^I u_3 \widetilde{H})W^I_{\mu\nu}$
Q_{uG}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} T^A u_3 \widetilde{H})G^A_{\mu\nu}$

$\psi^2 H^2 D$		X^2H^2 and X^3	
$Q_{H\ell}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu \ell)_{pp}$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\ell}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}\tau^I\gamma^\mu \ell)_{pp}$	Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)_{pp}$		

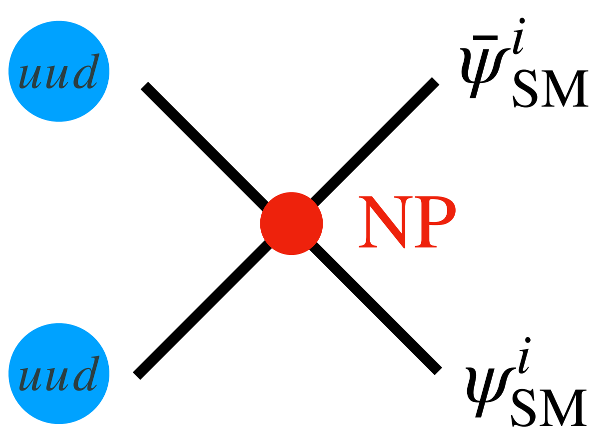
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)_{pprr}$
$Q_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)_{pprr}$
$Q_{\ell q}^{(1)}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{\ell q}^{(3)}$	$(\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)_{pprr}$	Q_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)_{pprr}$
		$Q_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)_{pprr}$
		$Q_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)_{pprr}$
				$Q_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)_{pprr}$

[Greljo, Palavrić, BAS, work in progress]

Why is this important for collider physics?

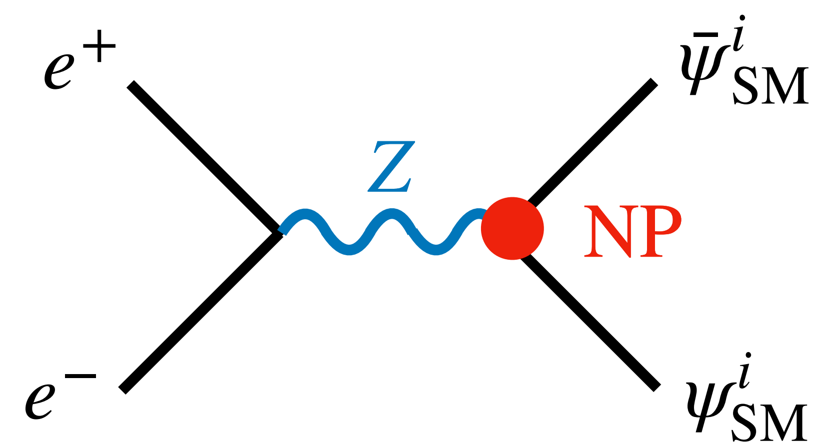
- These irreducible interactions are self-conjugate, just like tree-level neutral currents in the SM. They can interfere with SM neutral-current processes: Z-pole, DY, etc.

Non-resonant LHC physics



$pp \to \bar{\psi}_{\mathrm{SM}}\psi_{\mathrm{SM}}$

Z-pole physics



$e^+e^- \to \bar{\psi}_{\mathrm{SM}}\psi_{\mathrm{SM}}$

$$|\mathscr{A}|^2 = |\mathscr{A}_{\mathrm{SM}} + \mathscr{A}_{\mathrm{NP}}|^2 = |\mathscr{A}_{\mathrm{SM}}|^2 + 2\mathrm{Re}(\mathscr{A}_{\mathrm{SM}}\mathscr{A}^*_{\mathrm{NP}}) + |\mathscr{A}_{\mathrm{NP}}|^2$$

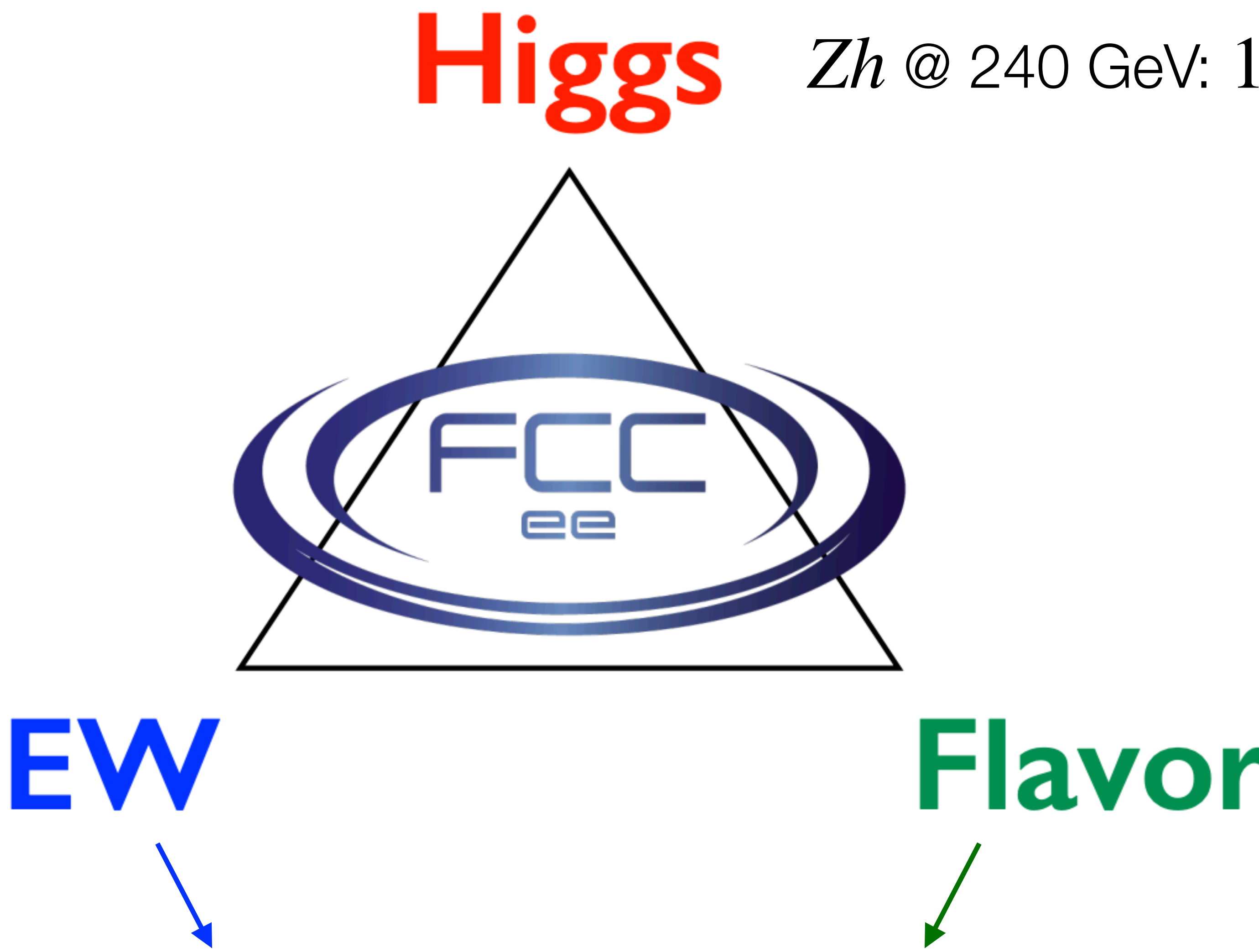
Self-conjugate SMEFT operators have the right chiral/analytic structure

[Greljo, Palavrić, BAS, work in progress]

Flavor prospects at FCC-ee
(talk starts now)

FCC is the flagship for BSM exploration

- Wide agreement: *An e^+e^- Higgs factory is the highest priority future collider*.



Zh @ 240 GeV: 10^6 $h's$

Tera-Z program: 10^{12} $Z's$

- FCC-ee is not only a Higgs factory, but also an electroweak and flavor factory!

Flavor non-universality at FCC-ee (aka, EW precision)

Tera-Z factory brings novel precision challenges

Stat precision: $\frac{\delta O}{O} \sim 10^{-6} \approx \frac{v^2}{\Lambda^2} \implies \Lambda \sim 100\ \mathrm{TeV} \quad (\mathrm{Loops}:\ 10\ \mathrm{TeV})$

$\delta O/O \sim$	10^{-4}	10^{-5}	10^{-6}
	Scenario S1	**Scenario S2**	**Scenario S3**
Observable	**TH PO+TH agg.+EXP** (10^{-5})	**TH agg.+EXP** (10^{-5})	**EXP Only** (10^{-5})
Γ_Z	1.55	0.820	0.510
σ_{had}	4.33	2.06	1.93
R_e	2.21	1.05	0.410
R_μ	2.20	1.02	0.330
R_τ	2.20	1.03	0.350
R_b	20.1	1.63	0.180
R_c	100	1.19	0.260
A_{FB}^e	126	25.7	25.2
A_{FB}^μ	125	21.1	20.6
A_{FB}^τ	126	23.3	22.8
A_{FB}^b	87.8	6.42	5.50
A_{FB}^c	89.1	10.2	9.62
A_{FB}^s	88.2	10.7	10.2
$\sin^2\theta_W$	6.87	0.780	0.730
A_e	87.9	9.78	9.20
A_μ	90.1	22.1	21.8
A_τ	90.5	23.4	23.2
A_b	11.7	10.5	10.5
A_c	16.9	9.00	8.99
A_s	14.2	13.2	13.2
M_W	0.490	0.320	0.300
Γ_W	16.1	16.1	16.1

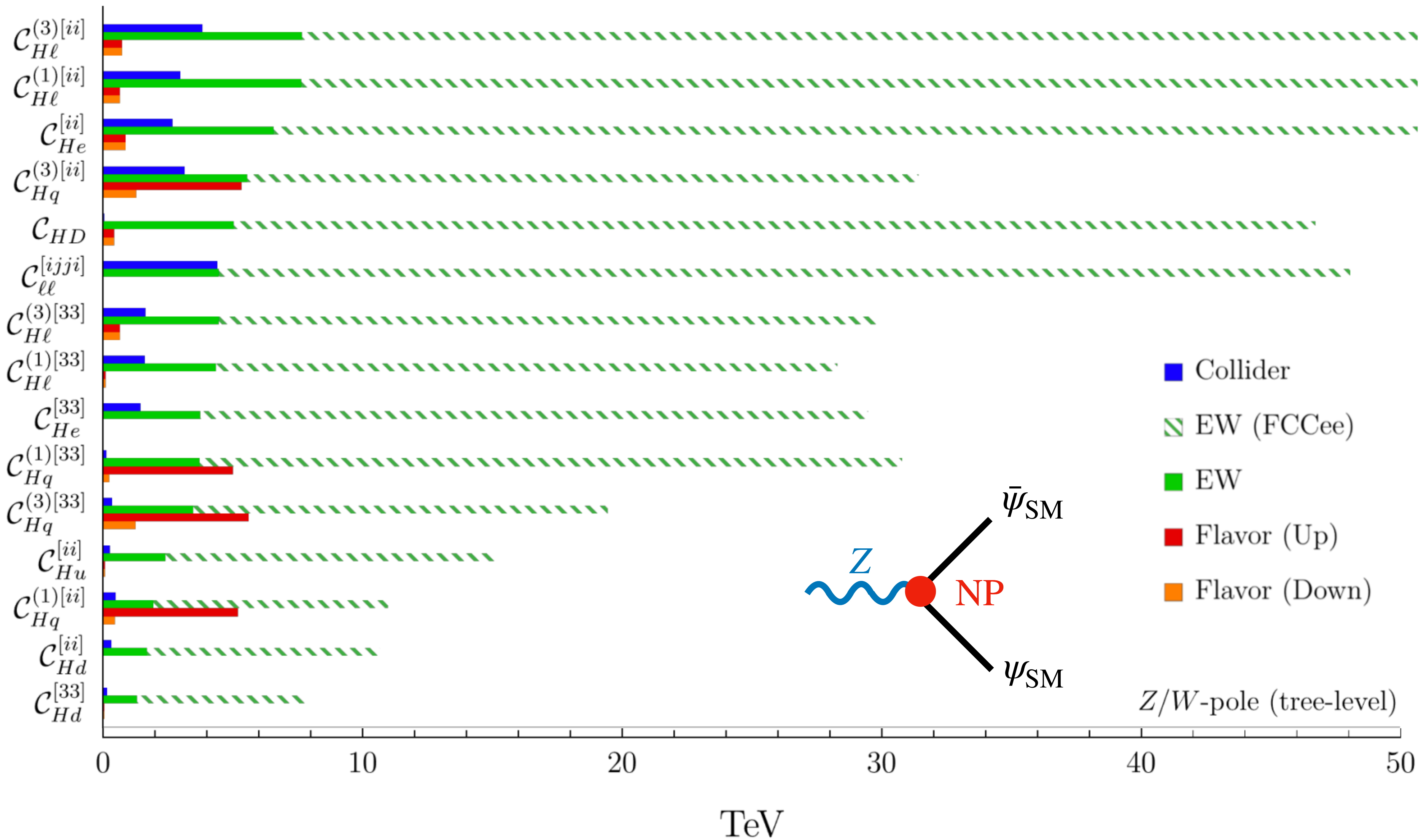
More conservative ⟵⟶ More aggressive

[Greljo, BAS, Valenti, 2507.03073] [FCC-ee FSR, 2505.00272] [EW PPG EWPO TH Discussion]

Tera-Z at Tree Level (S1)

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

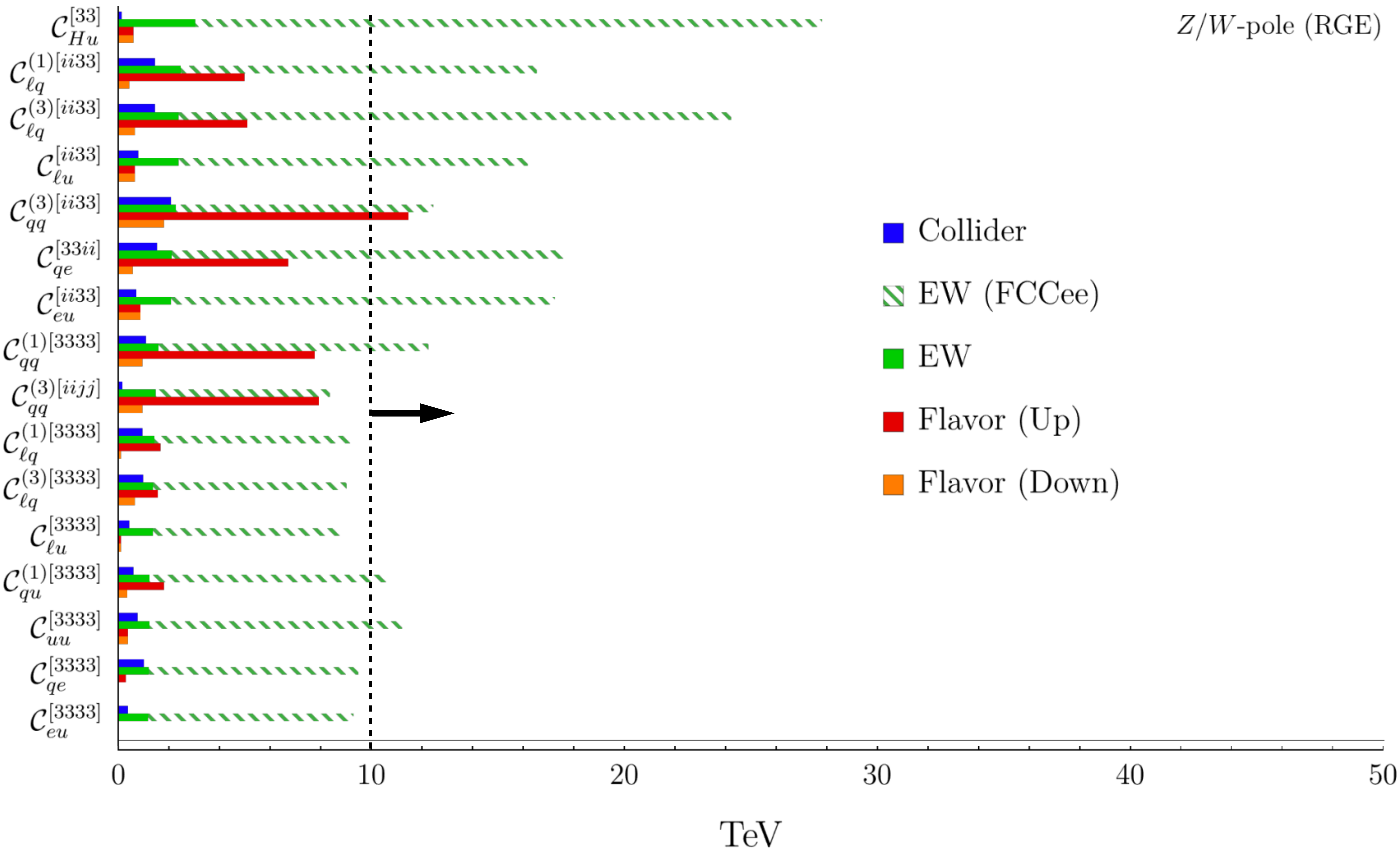
- Here are the Wilson coefficients entering the Z-pole at tree level in the $U(2)^5$ limit.



Loops at Tera-Z (S1)

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

- Top loops bring 10 TeV+ sensitivity, due to large RGE effects with top Yukawa



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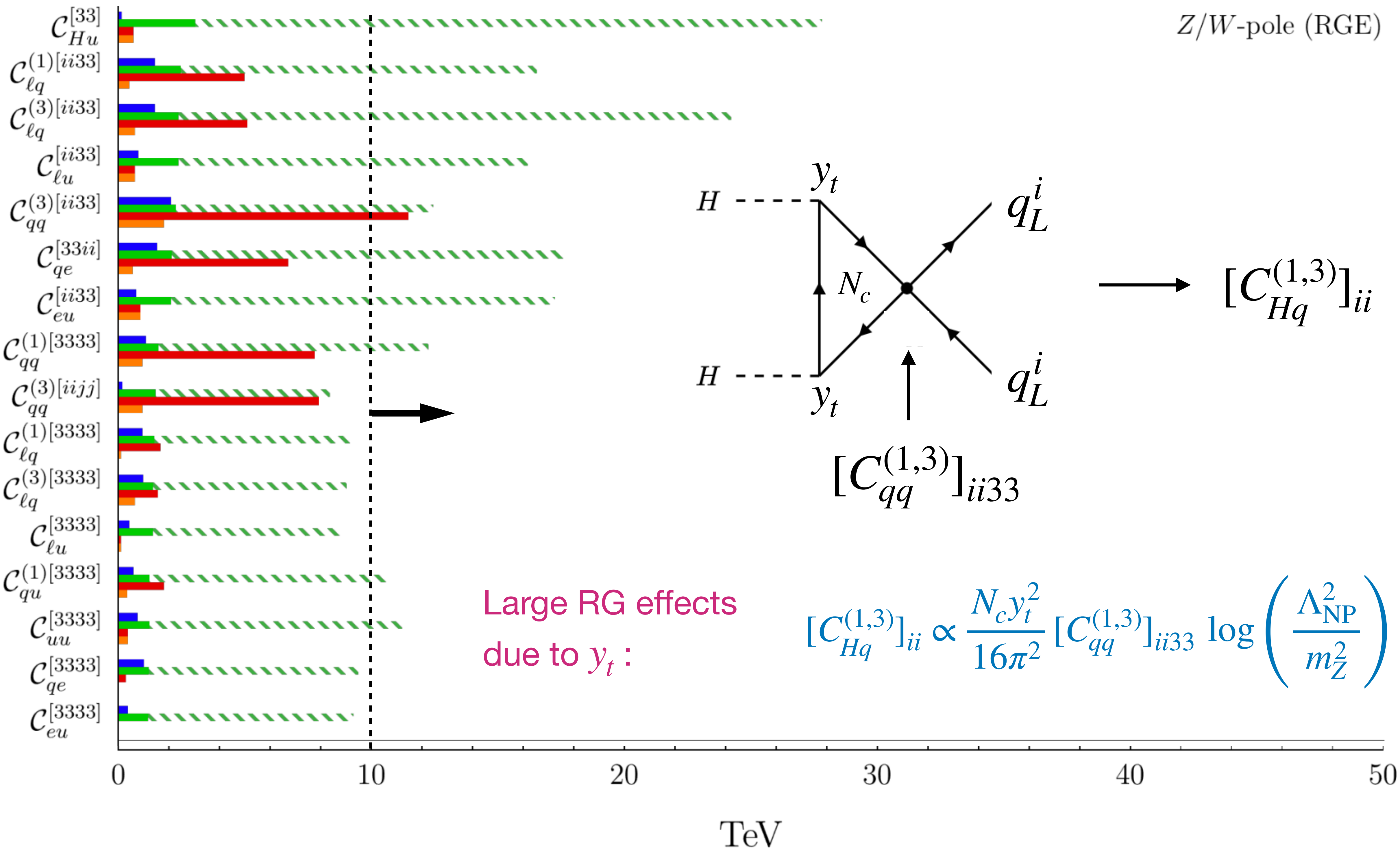


Large RG effects due to y_t :

$$[C_{Hq}^{(1,3)}]_{ii} \propto \frac{N_c y_t^2}{16\pi^2} [C_{qq}^{(1,3)}]_{ii33} \log\left(\frac{\Lambda_{\rm NP}^2}{m_Z^2}\right)$$

EW precision observables beyond 1-loop

- Can combine 1-loop fixed-order predictions with the 2-loop RGE to improve EWPOs to next-to-leading logarithmic accuracy. All ops $\gtrsim 1\ \mathrm{TeV}$ even for S1.

Tree level

Leading-log effect

Next-to-leading log effect

H^6 and H^4D^2	
Q_H	$(H^\dagger H)^3$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$

$\psi^2 H^3$ and $\psi^2 XH$	
Q^{33}_{uH}	$(H^\dagger H)(\bar q_3 u_3 \widetilde H)$
Q^{33}_{uB}	$(\bar q_3 \sigma^{\mu\nu} u_3 \widetilde H) B_{\mu\nu}$
Q^{33}_{uW}	$(\bar q_3 \sigma^{\mu\nu} \tau^I u_3 \widetilde H) W^I_{\mu\nu}$
Q^{33}_{uG}	$(\bar q_3 \sigma^{\mu\nu} T^A u_3 \widetilde H) G^A_{\mu\nu}$

$\psi^2 H^2 D$		X^2H^2 and X^3	
$Q^{(1)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\ell\gamma^\mu\ell)_{pp}$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q^{(3)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar\ell\tau^I\gamma^\mu\ell)_{pp}$	Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d\gamma^\mu d)_{pp}$		

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$Q_{\ell\ell}$	$(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar e\gamma_\mu e)(\bar e\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar\ell\gamma_\mu\ell)(\bar e\gamma^\mu e)_{pprr}$
$Q^{(1)}_{qq}$	$(\bar q\gamma_\mu q)(\bar q\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar u\gamma_\mu u)(\bar u\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar\ell\gamma_\mu\ell)(\bar u\gamma^\mu u)_{pprr}$
$Q^{(3)}_{qq}$	$(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar d\gamma_\mu d)(\bar d\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar\ell\gamma_\mu\ell)(\bar d\gamma^\mu d)_{pprr}$
$Q^{(1)}_{\ell q}$	$(\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar e\gamma_\mu e)(\bar u\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar q\gamma_\mu q)(\bar e\gamma^\mu e)_{pprr}$
$Q^{(3)}_{\ell q}$	$(\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q)_{pprr}$	Q_{ed}	$(\bar e\gamma_\mu e)(\bar d\gamma^\mu d)_{pprr}$	$Q^{(1)}_{qu}$	$(\bar q\gamma_\mu q)(\bar u\gamma^\mu u)_{pprr}$
		$Q^{(1)}_{ud}$	$(\bar u\gamma_\mu u)(\bar d\gamma^\mu d)_{pprr}$	$Q^{(8)}_{qu}$	$(\bar q\gamma_\mu T^A q)(\bar u\gamma^\mu T^A u)_{pprr}$
		$Q^{(8)}_{ud}$	$(\bar u\gamma_\mu T^A u)(\bar d\gamma^\mu T^A d)_{pprr}$	$Q^{(1)}_{qd}$	$(\bar q\gamma_\mu q)(\bar d\gamma^\mu d)_{pprr}$
				$Q^{(8)}_{qd}$	$(\bar q\gamma_\mu T^A q)(\bar d\gamma^\mu T^A d)_{pprr}$

[Haisch, BAS, to appear]

[2-loop RGE: Born, Fuentes-Martin, Thomsen 2601.19974]

Flavor-changing processes at FCC-ee

**Universality violation typically implies flavor violation in the mass basis*

Roadmap for flavor-changing transitions

- Summary: Major improvements @ FCC-ee for tau physics + neutrino modes.

Flavour Transition	Transition type					
	γ	quarks	μ	e	τ	ν
$\mathbf{3_q} \to \mathbf{2_q}$	$b \to s\gamma\,[\ast]$	$B_s \leftrightarrow \bar{B}_s\,[\ast]$	$b \to s\,\bar{\mu}\mu\,[\ast]$ $b \to c\,\mu\bar{\nu}$	$R_{bs}(e/\mu)\,[\ast]$ $R_{bc}(e/\mu)\,[\bullet]$	$b \to s\,\bar{\tau}\tau\,[\bullet]$ $b \to c\,\tau\bar{\nu}\,[\bullet]$	$b \to s\,\nu\bar{\nu}\,[\bullet]$
$\mathbf{3_q} \to \mathbf{1_q}$	$b \to d\gamma\,[\ast]$	$B_d \leftrightarrow \bar{B}_d\,[\ast]$	$b \to d\,\bar{\mu}\mu\,[\ast]$ $b \to u\,\mu\bar{\nu}$	$R_{bd}(e/\mu)\,[\ast]$ $R_{bu}(e/\mu)\,[\bullet]$	$b \to d\,\bar{\tau}\tau\,[\bullet]$ $b \to u\tau\bar{\nu}\,[\bullet]$	$b \to d\,\nu\bar{\nu}\,[\bullet]$
$\mathbf{2_q} \to \begin{matrix}\mathbf{2_q}\\ \mathbf{1_q}\end{matrix}$	$c \to u\,\gamma$	$D \leftrightarrow \bar{D}\,[\ast]$	$c \to u\,\bar{\mu}\mu$ $c \to s\,\bar{\mu}\nu$ $c \to d\,\bar{\mu}\nu$	$R_{cu}(e/\mu)\,[\ast]$ $R_{cs}(e/\mu)\,[\bullet]$ $R_{cd}(e/\mu)\,[\bullet]$		$c \to u\nu\bar{\nu}\,[\bullet]$
$\mathbf{3}_\ell \to \begin{matrix}\mathbf{2}_\ell\\ \mathbf{1}_\ell\end{matrix}$	$\tau \to \mu\,\gamma\,[\bullet]$ $\tau \to e\,\gamma\,[\bullet]$	$\tau \to \mu\,\bar{q}q\,[\bullet]$ $\tau \to e\,\bar{q}q\,[\bullet]$	$\tau \to \mu\,\bar{\mu}\mu\,[\bullet]$ $\tau \to e\,\bar{\mu}\mu\,[\bullet]$	$\tau \to \mu\,\bar{e}e\,[\bullet]$ $\tau \to e\,\bar{e}e\,[\bullet]$		$\tau \to \mu\,\nu\bar{\nu}\,[\bullet]$ $\tau \to e\,\nu\bar{\nu}\,[\bullet]$

$[\ast]$ = major progress @ HL-LHC, limited impact of e^+e^- colliders
$[\bullet]$ = major progress @ HL-LHC & Belle II + significant further progress @ FCC-ee
$[\bullet]$ = FCC-ee allows one order of magnitude precision improvement, or more, after HL-LHC & Belle II

$SU(2)_q$ expected

MFP enhanced

$\leq U(2)_{l,e}$

[ESPPU '26: Physics Briefing Book, 2511.03883]

Flavor-changing transitions: $3_q \to 2_q, 1_q$

Observable	Transition	Current	Pre-FCC	C→P	FCC-ee	P→F
$\Delta F = 2$ (mixing)						
$\Delta M_{B_s}/\Delta M_{B_s}^{\rm SM}$	$b \leftrightarrow s$ (ΔF=2)	7.6%	3.3%	2.3×	1.5%	2.2×
$\Delta M_{B_d}/\Delta M_{B_d}^{\rm SM}$	$b \leftrightarrow d$ (ΔF=2)	13%	3.7%	3.5×	1.9%	1.9×
$\ell\ell$						
$\mathcal{B}(B_s \to \mu\mu)$	$b \to s\mu\mu$	9%	1.6%	5.6×	5%	**0.3**× (worse)
$\mathcal{B}(B^0 \to \mu\mu)$	$b \to d\mu\mu$	< 1.6 SM	11%	1st meas.	12%	**0.9**× (worse)
R_{K^*} [1.1, 6]	$b \to s\ell\ell$	8%	1–2%	5×	0.5%	3×
$\tau\tau$						
$\mathcal{B}(B \to K\tau\tau)$	$b \to s\tau\tau$	$< 1.1 \times 10^4$ SM	< 1900 SM	5.6×	60%	1600×
$\mathcal{B}(B \to K^*\tau\tau)$	$b \to s\tau\tau$	$< 1.3 \times 10^4$ SM	< 4000 SM	3.2×	60%	3300×
$\mathcal{B}(B_s \to \tau\tau)$	$b \to s\tau\tau$	< 4600 SM	< 540 SM	8.5×	190%	140×
$\nu\nu$						
$\mathcal{B}(B \to K\nu\bar{\nu})$	$b \to s\nu\nu$	31%	14%	2.2×	1%	14×
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	$b \to s\nu\nu$	< 1.2 SM	15%	1st meas.	1%	15×
$\tau\nu$ (charged current)						
R_D	$b \to c\tau\nu$	7.6%	3.0%	2.5×	0.3%	10×
R_{D^*}	$b \to c\tau\nu$	4.2%	1.8%	2.3×	0.3%	6×
$R(D_s)$	$b \to c\tau\nu$	–	–	–	0.3%	1st meas.
$R(D_s^*)$	$b \to c\tau\nu$	–	–	–	0.3%	1st meas.
$\mathcal{B}(B_c \to \tau\nu)$	$b \to c\tau\nu$	< 15 SM	–	–	1.6%	1st meas.

[PBB, 2511.03883, Bordone, Cornella, Davighi 2503.22635, Allwicher, Isidori, Pesut, 2503.17019]

Flavor-changing transitions: $3_l \to 2_l, 1_l$ and $2_q \to 1_q$

Observable	Transition	Current	Pre-FCC	C→P	FCC-ee	P→F
$\mathbf{2q \to 1q}$ **(charm, $\boldsymbol{c \to u}$)**						
$A_{\rm pol}(\Lambda_c \to p\mu\mu)$	$c \to u\mu\mu$	–	–	–	1%	1st meas.
$\mathcal{B}(D^0 \to \pi\pi\nu\bar{\nu})$	$c \to u\nu\nu$	$< 2 \times 10^{-4}$	–	–	$< 2 \times 10^{-7}$	$10^3\times$
$\mathbf{3\ell \to 2\ell, 1\ell}$ **($\boldsymbol{\tau}$-LFV)**						
$\mathcal{B}(\tau \to \mu\gamma)$	$\tau \to \mu\gamma$	$< 4.2 \times 10^{-8}$	$< 8 \times 10^{-9}$	$5\times$	$< 10^{-9}$	$8\times$
$\mathcal{B}(\tau \to \mu\mu\mu)$	$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	$< 3.7 \times 10^{-9}$	$5.7\times$	$< 1.5 \times 10^{-11}$	$250\times$
$\mathcal{B}(\tau \to eee, \mu ee, e\mu\mu)$	$\tau \to 3\ell$	$< 3 \times 10^{-8}$	$< 4 \times 10^{-9}$	$5\times$	$< 1.5 \times 10^{-11}$	$250\times$
$\mathbf{3\ell \to 2\ell, 1\ell}$ **($\boldsymbol{\tau}$-LFU)**						
$\lvert g_\tau / g_\mu \rvert$	$\tau \to \mu\nu\nu$	0.14%	–	–	0.01%	$14\times$
$\lvert g_\tau / g_e \rvert$	$\tau \to e\nu\nu$	0.14%	–	–	0.01%	$14\times$

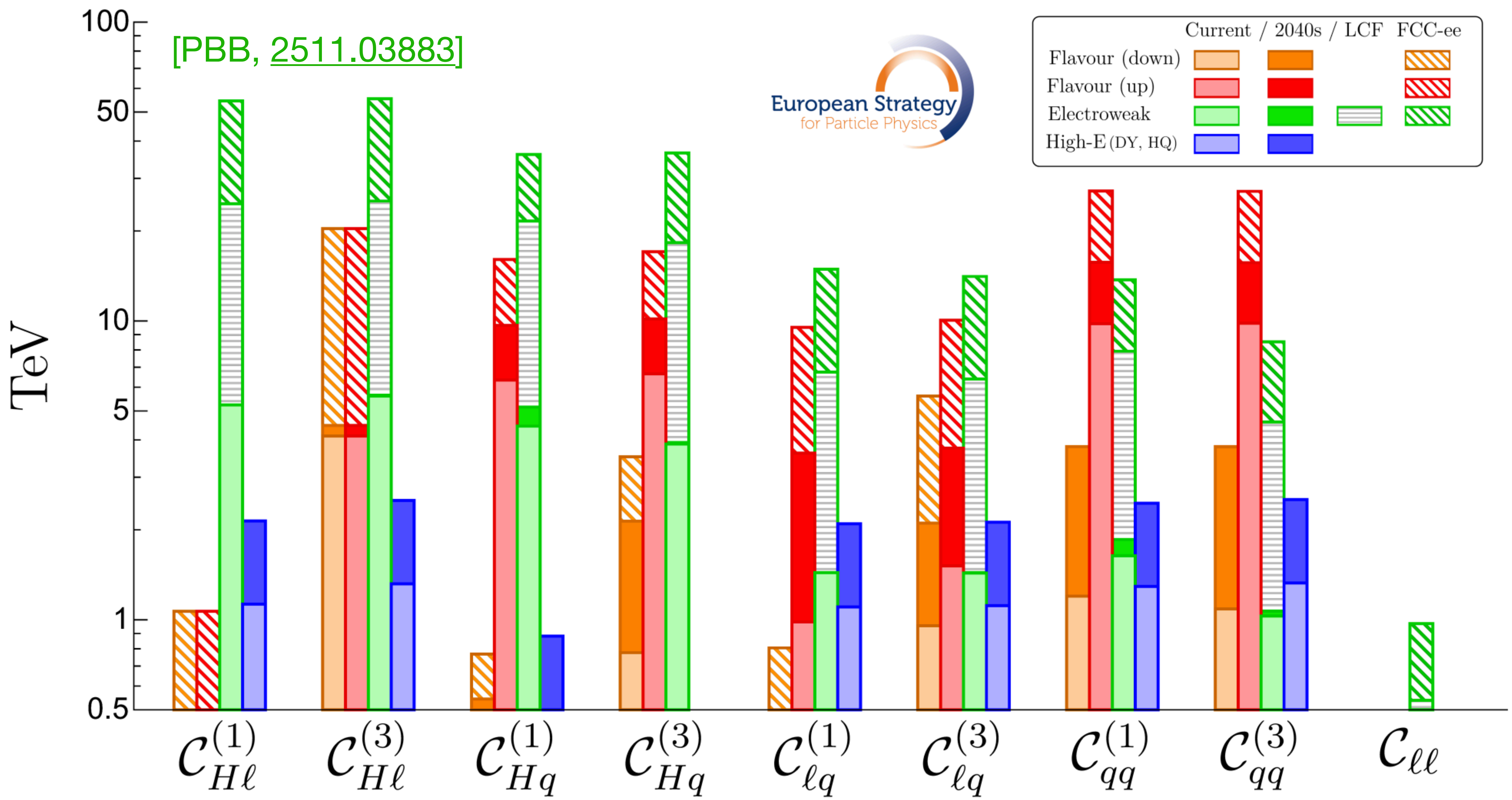
Progress in charm physics at FCC-ee via $\Delta C = 1$ null tests

- $c \to u\nu\bar{\nu}$ *($D^0 \to \pi\pi\nu\bar{\nu}$) and* $c \to ul\bar{l}$ *($\Lambda c \to p\ell\ell$) - interesting for MFP because* $\cancel{U(2)}_u$
- *Using the Λc polarization, both are essentially null tests in the SM (strong GIM supp.)*
- *BSM: Up to 5% polarization in muons, 14% in electrons compatible with other constraints*
- *FCC-ee Tera-Z program can measure ~1% polarization.*

[Di Canto, Hacheney, Hiller, Mitzel, Monteil, Röhrig, Suelmann 2509.10447]

Electroweak/flavor complementarity

- EFT benchmark: NP coupled dominantly to the 3rd family (described by $U(2)^5$)

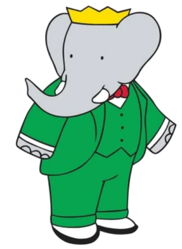


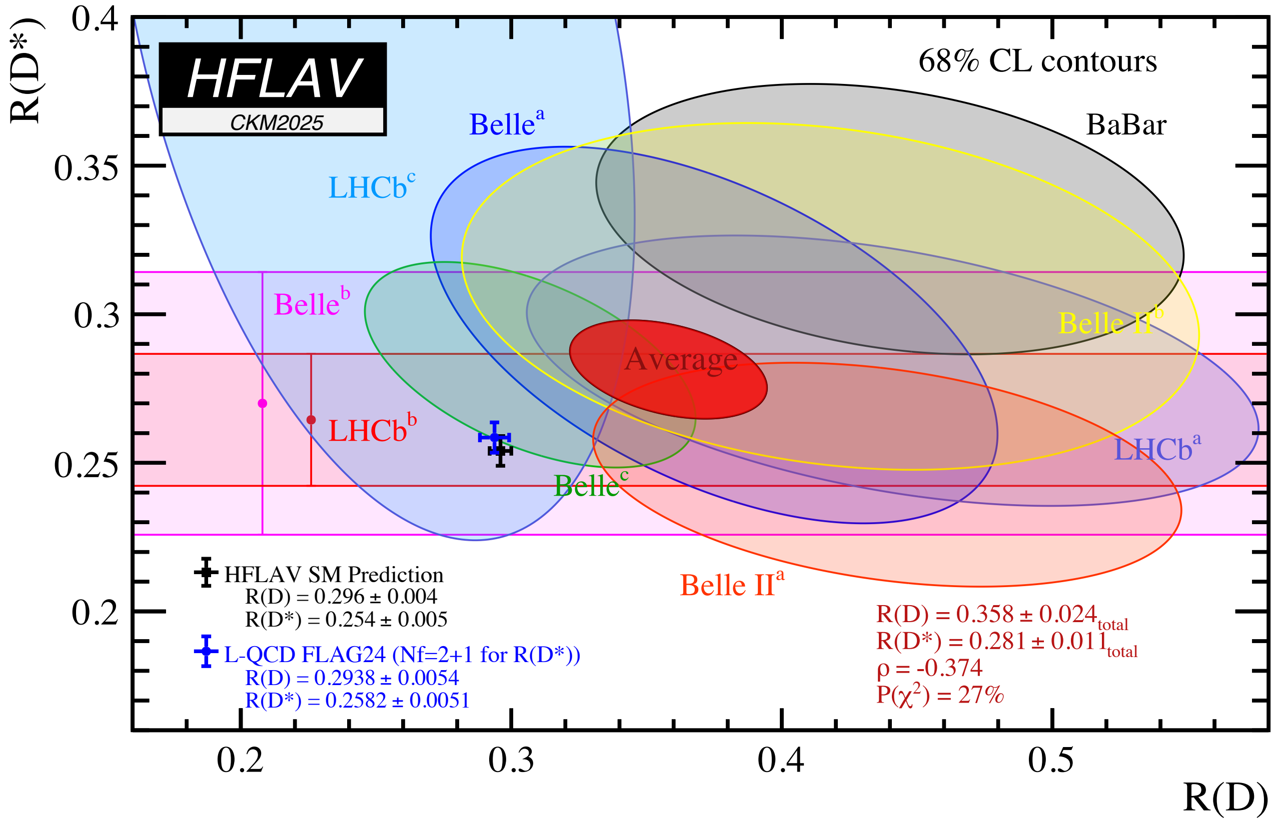
EW	$Z\tau\bar{\tau}$ (tree)	$Zb\bar{b}$ (tree)	$Z\tau\bar{\tau}$ (loop)	$Zb\bar{b}$ (loop)	$Z\tau\bar{\tau}$ (loop)
Flavor	τ-LFU	$B_s \to \mu\mu$ / $B \to K^{(*)}\nu\bar{\nu}$		B-mixing	—

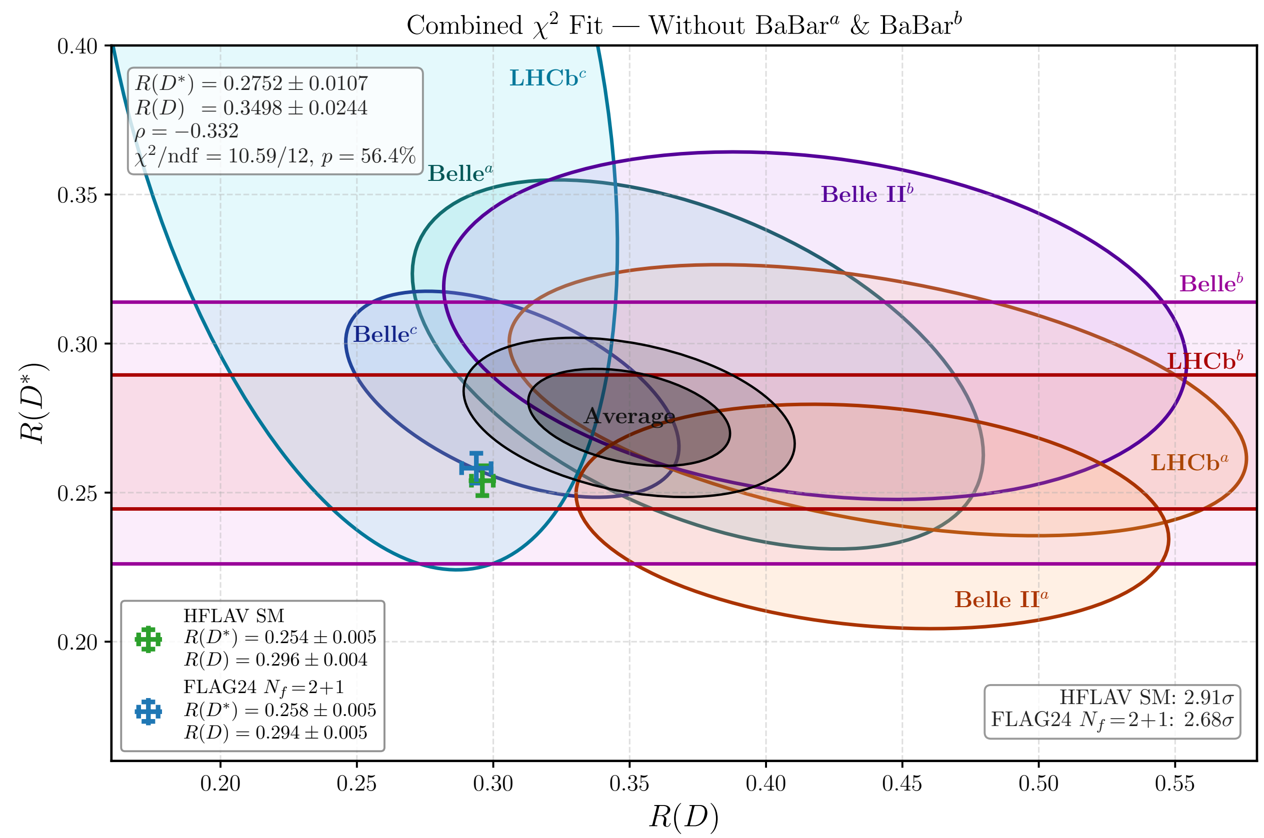
Connection with current flavor anomalies

$b \to c\tau\nu$ Anomalies

[BFA Santiago '26- thanks to Martin Novoa + Copilot]

*If we kick out the  in the room (for illustrative purposes only)





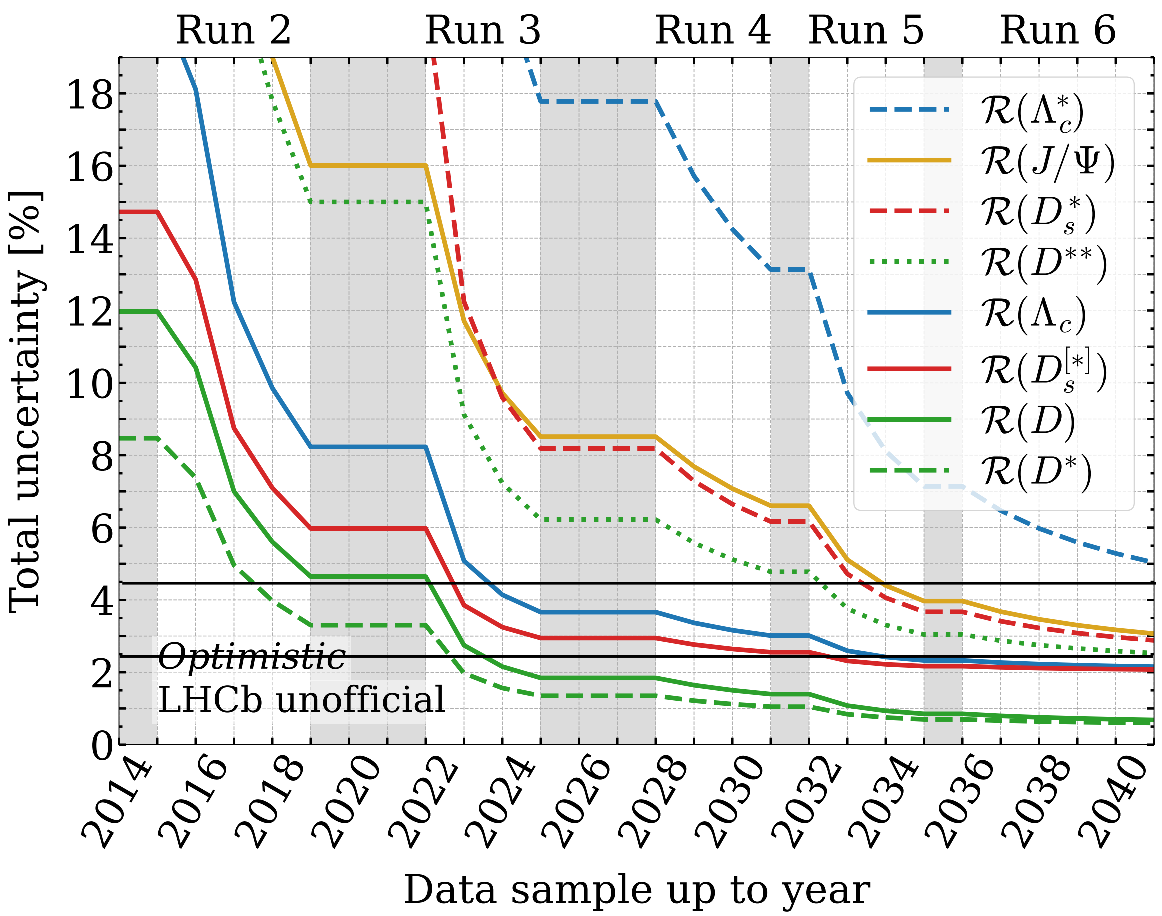
In either case, current error on the averages: $R_D \sim 7\,\%$, $R_{D*} \sim 4\,\%$

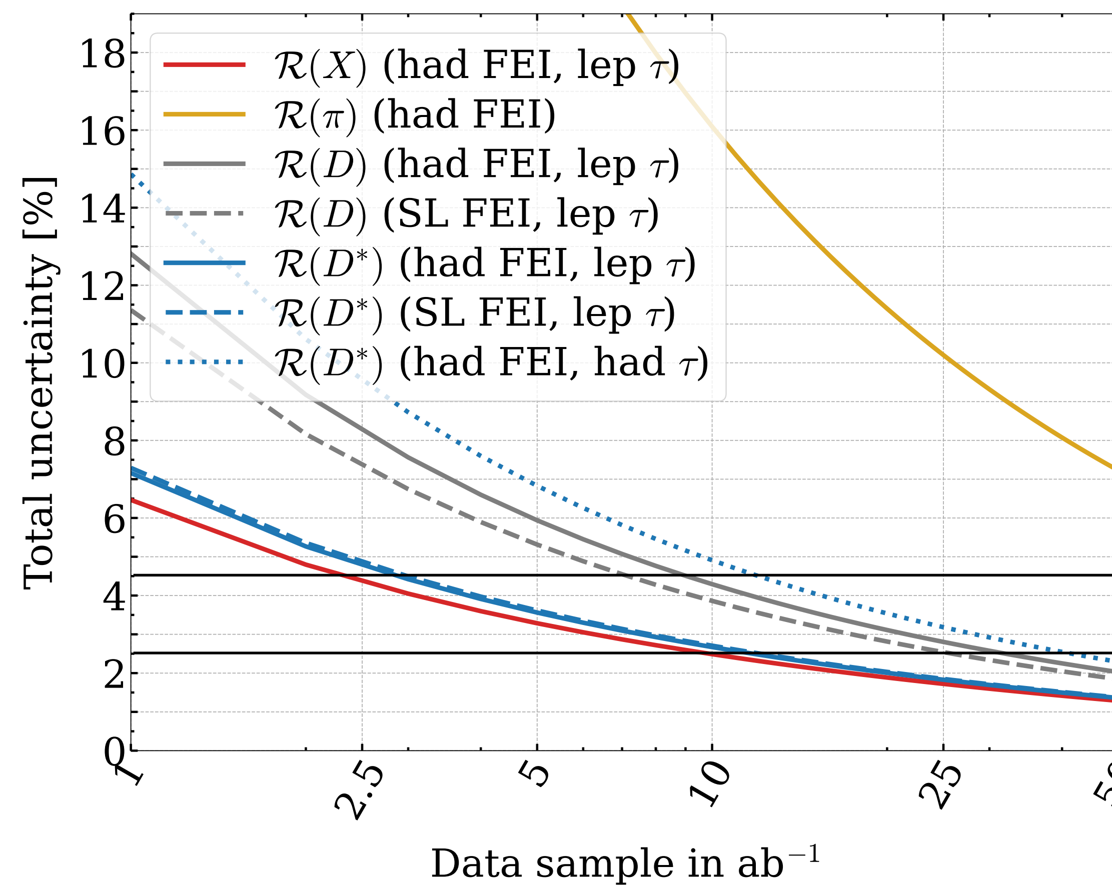
Tension: 3.8σ

Tension: 2.9σ

$b \to c\tau\nu$ Anomalies

- For more: *See Antonio Romero's talk*





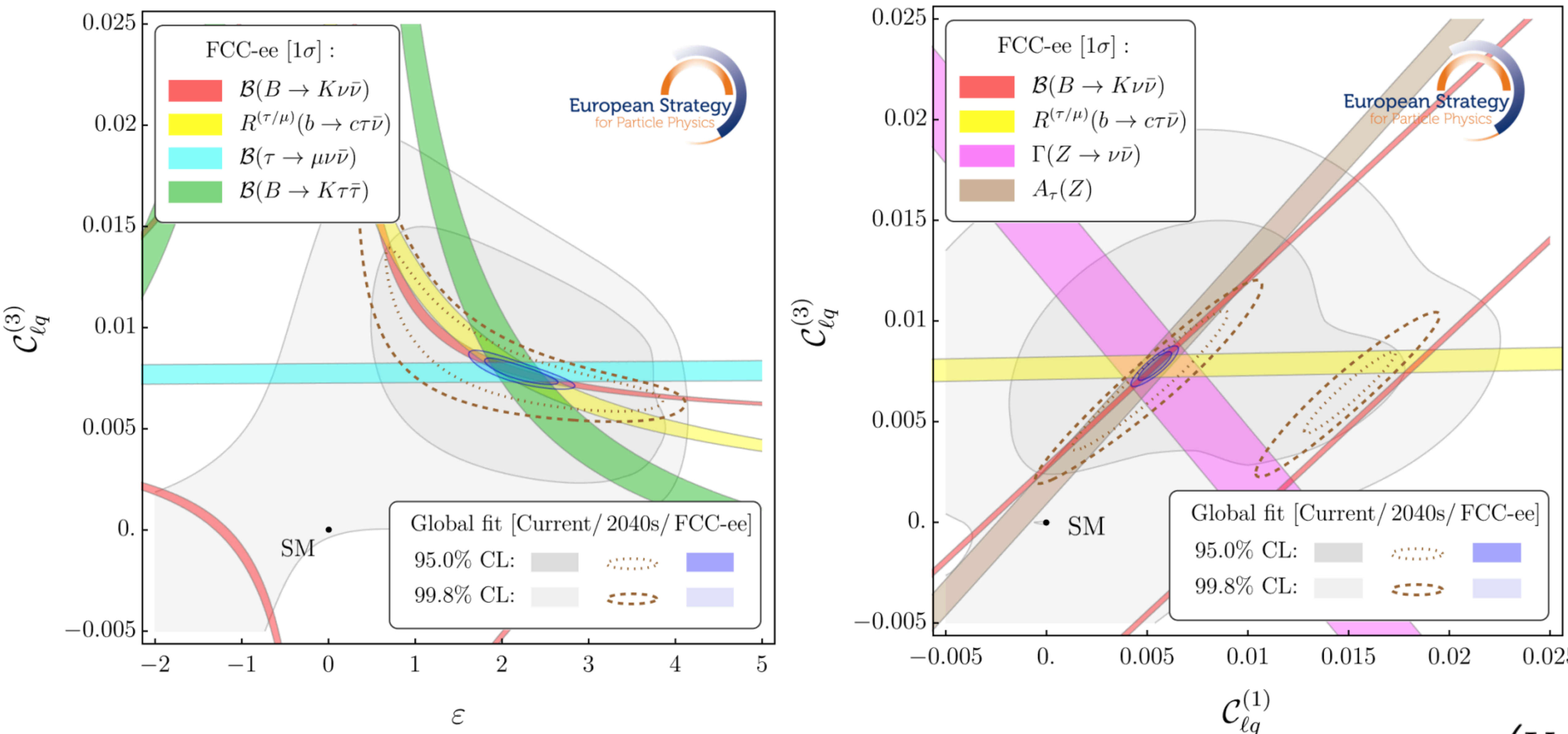
For fun, let's assume central values stay but errors reduced by a factor ~1.5: R_D around 4.5%, R_{D*} around 2.5%

HFLAV '25 tension w/ SM $\to 5.5\sigma$

HFLAV '25 tension w/ SM (no BaBar) $\to 4.3\sigma$

Electroweak/flavor complementarity

- Gray region preferred by current flavor anomalies. In case of discovery, flavor and EW observables can be combined to “fingerprint” the structure of NP.

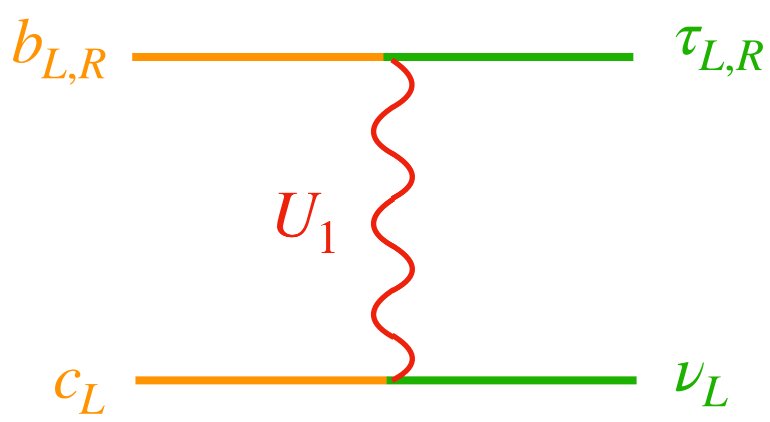


ε controls size of $U(2)_q$-breaking effects: $q_3 \to q_3 - \varepsilon V_q^i q_i$ $\qquad V_q = \begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix}$

[Allwicher, Isidori, Pesut, 2503.17019]

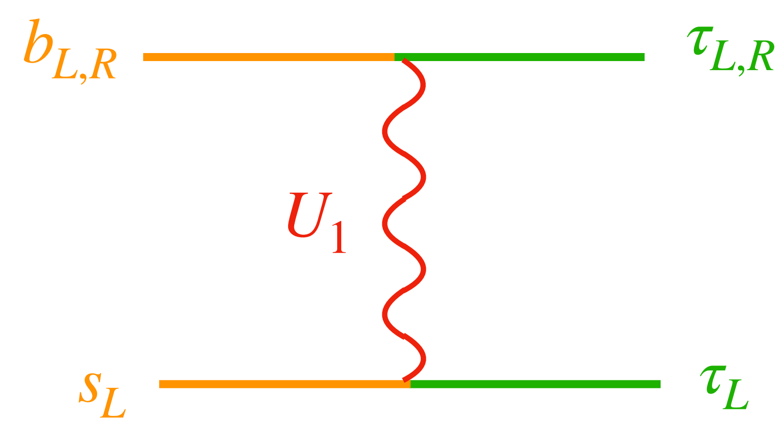
U_1 leptoquark for $R_{D^{(*)}}$ gives $b \to s\tau\tau$ transitions

- Best single mediator explanation for $R_{D^{(*)}}$ is $U_1 \sim (3,1,2/3)$



$b \to c\tau\nu$

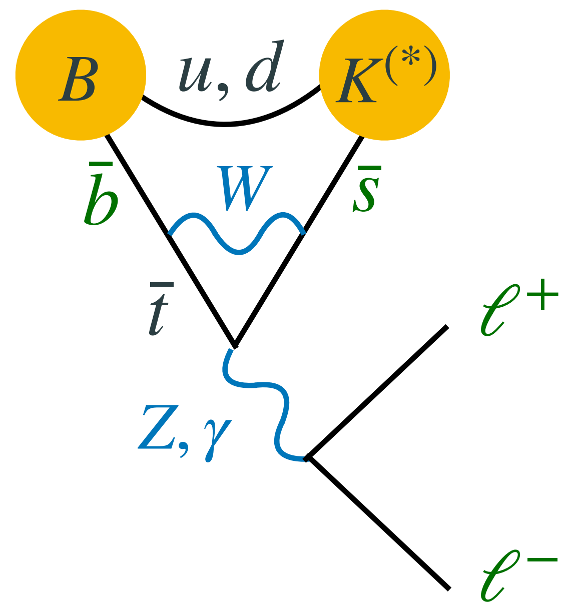
$SU(2)_L \Longrightarrow$



$b \to s\tau\tau$

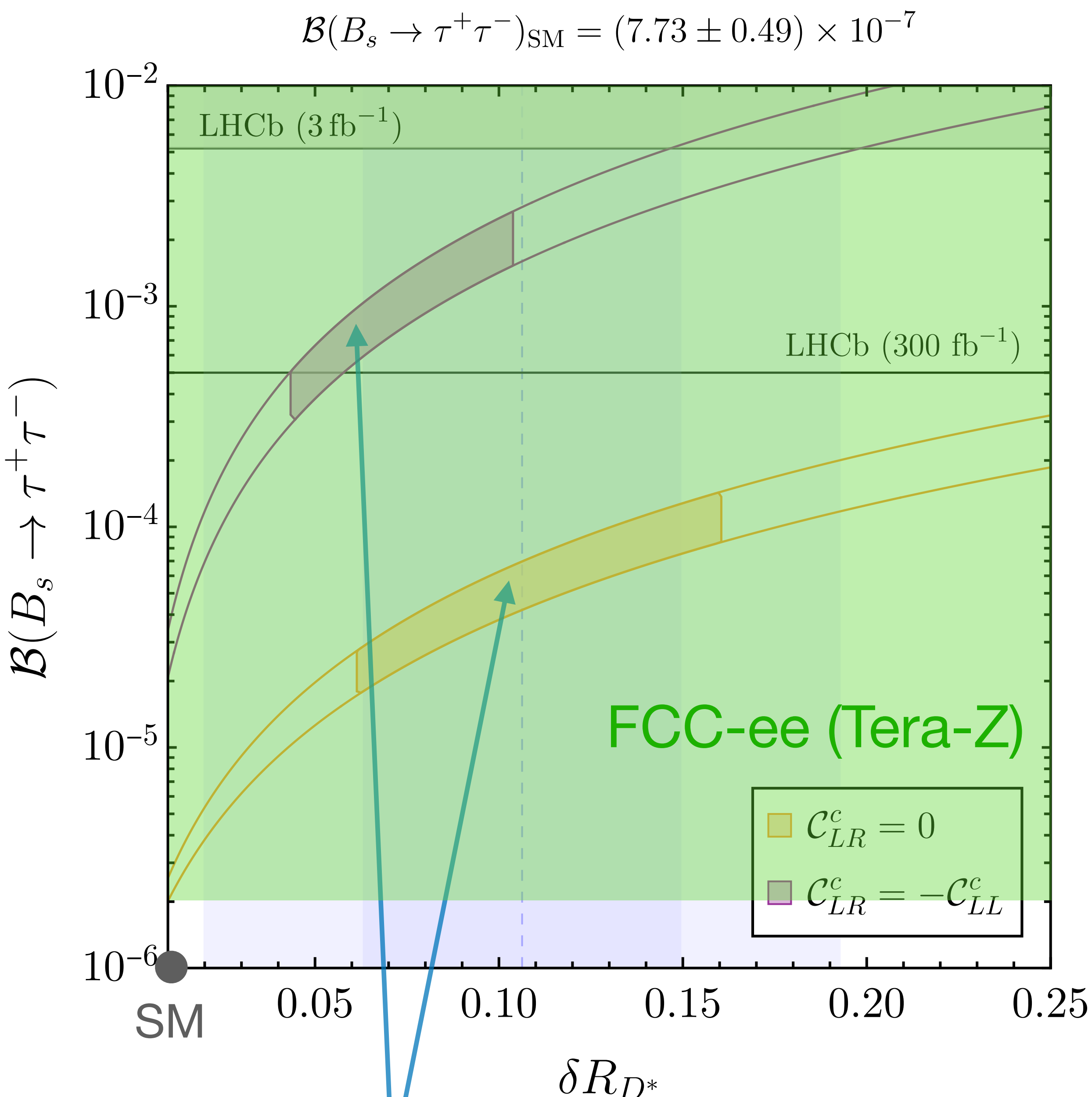
- Since $b \to s\tau\tau$ is a FCNC, it is a 1-loop process in the SM. We therefore expect a huge NP enhancement in $b \to s\tau\tau$!

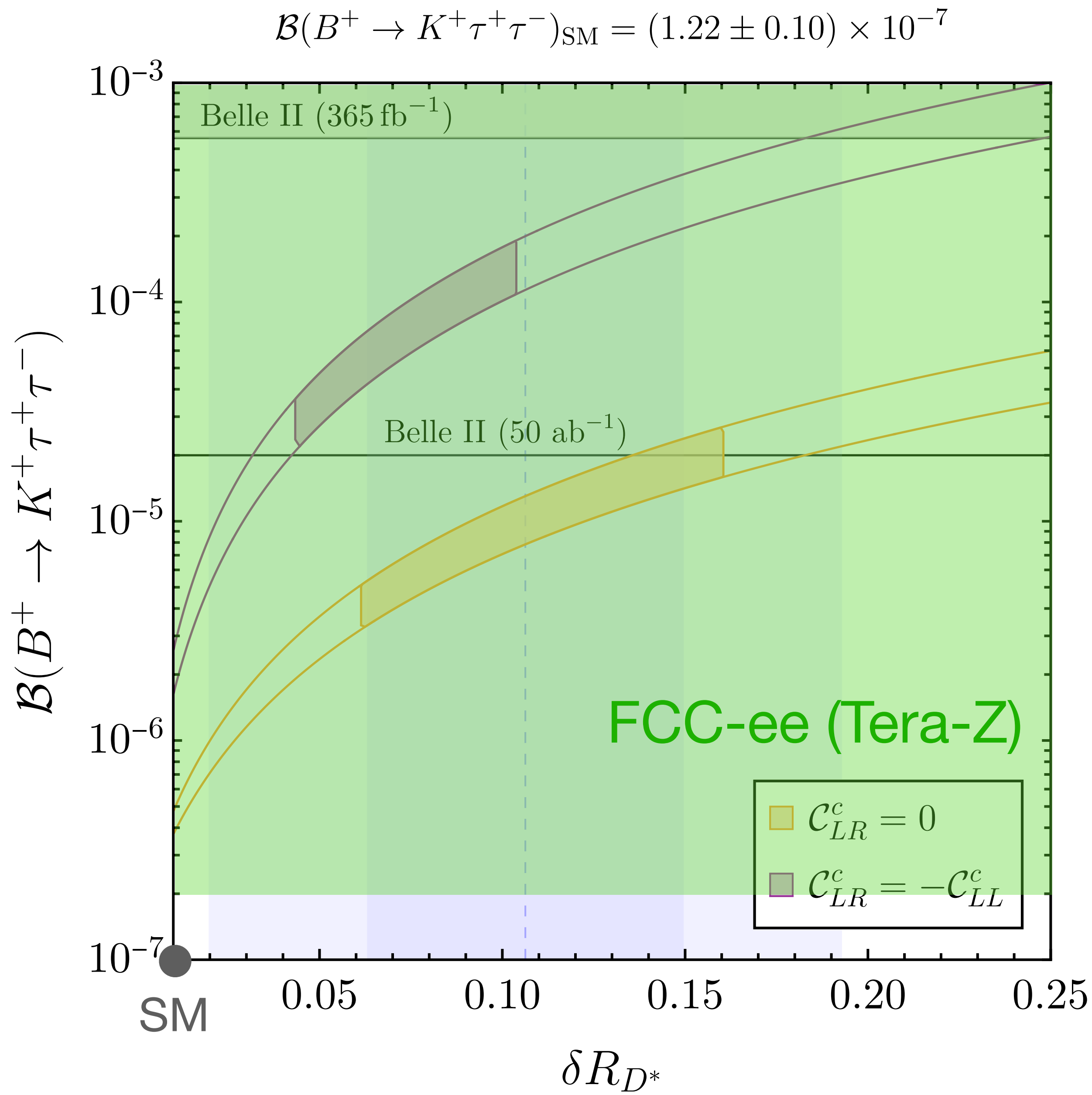
$$\frac{\mathscr{B}(B \to K^{(*)}\tau\tau)}{\mathscr{B}(B \to K^{(*)}\tau\tau)_{\rm SM}} \sim 16\pi^2 \frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}}$$



U_1 connects $R_{D^{(*)}}$ to $b \to s\tau\tau$ observables

- We have tree-level effects in $b \to s\tau\tau$ connected to the size of $R_{D^{(*)}}$



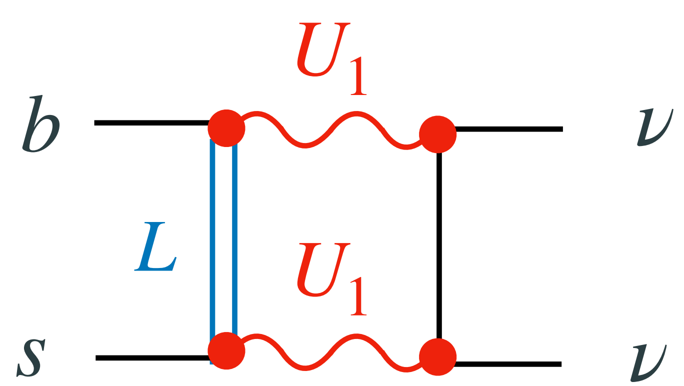


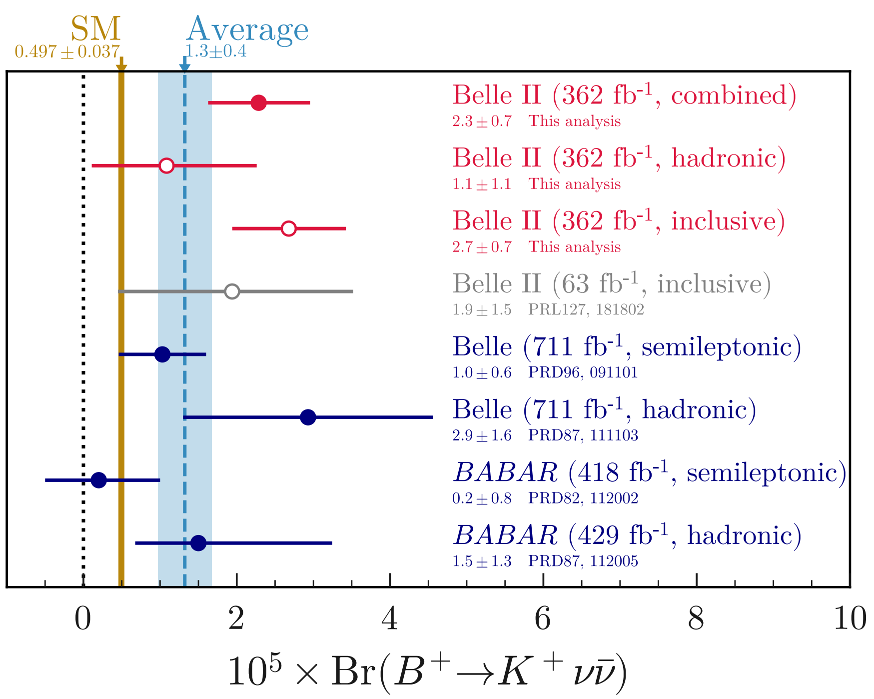
HFLAV '25 updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

Important 1-loop effects: $B \to K^{(*)}\nu\nu$ (4321 Model)

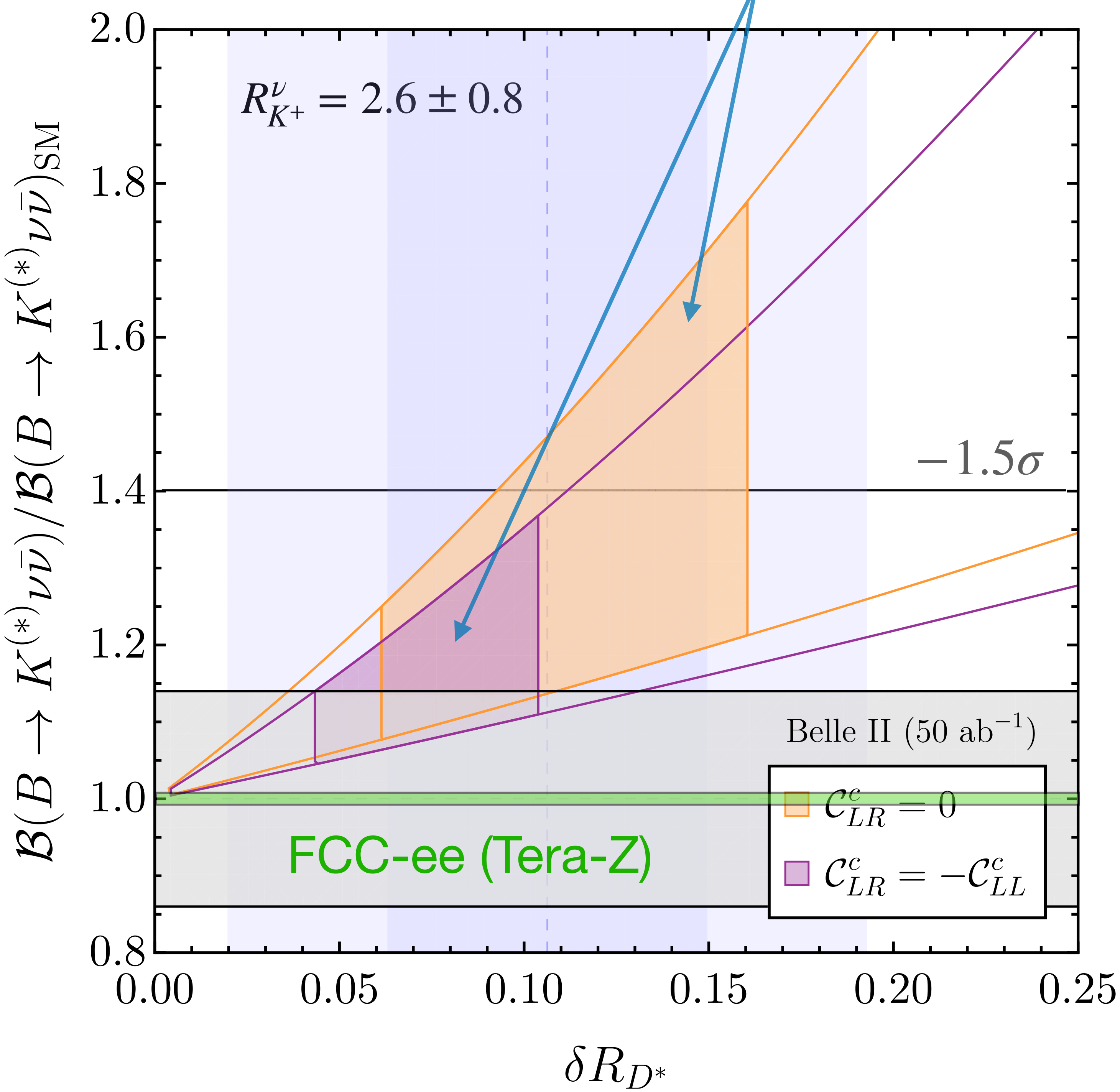
- Some (important) effects appear only at one loop. For U_1, requires UV model!





[Belle II Collaboration, 2311.14647]

HFLAV '25 updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data



[Fuentes-Martin, Isidori, König, Selimovic, 2009.11296]

Conclusions

- The era of precision BSM physics has already begun. The next 20 years will see a broad precision program culminating with FCC.
- Flavor data tells us that NP at the TeV scale has to be organized according to approximate global symmetries in the IR. However, MFP tells us that a large amount of flavor violation is still possible!
- We should stop thinking of EW+flavor as separate datasets. EW tests flavor non-universality (how does the Z couple to each generation), which typically implies flavor-changing processes in the mass basis.
- Combining the two (also Higgs) allows for broad coverage (and fingerprinting) of the symmetry-allowed operators up to 10 TeV. If NP is out there, my view is that this program is the best to find it.

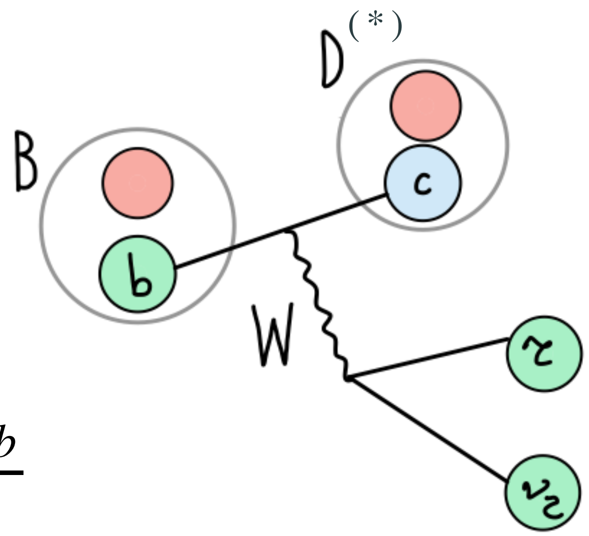
Backup

New physics in $b \to c\tau\nu$ transitions

$\delta R_{D^{(*)}} = R_{D^{(*)}} / R_{D^{(*)}}^{\mathrm{SM}} - 1$

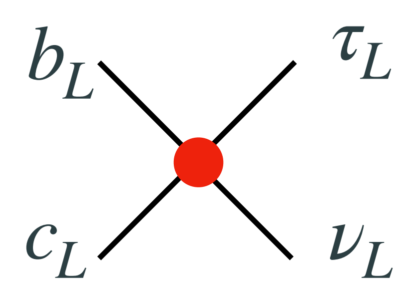
- We need ~10% of a tree-level SM process due to NP. Heavy NP should therefore also be tree-level to compete. Consider Fermi-like LH NP:

SM process



$$\mathscr{A}_{\mathrm{SM}} \sim \frac{g_L^2 V_{cb}}{2M_W^2} = \frac{2V_{cb}}{v^2}$$

Heavy new physics



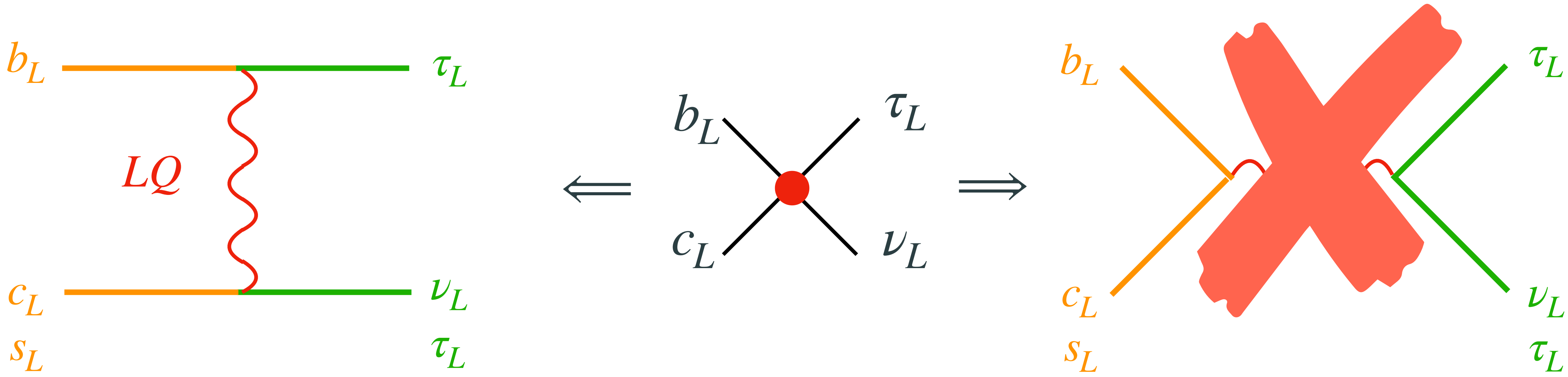
$$\mathscr{A}_{\mathrm{NP}} \sim \frac{1}{\Lambda_{\mathrm{NP}}^2}$$

- The charged current *B*-anomalies are calling for a low NP scale!

$$2\frac{\mathscr{A}_{\mathrm{NP}}}{\mathscr{A}_{\mathrm{SM}}} = \frac{v^2}{V_{cb}\Lambda_{\mathrm{NP}}^2} \approx \delta R_{D^*} \quad \Longrightarrow \quad \Lambda_{\mathrm{NP}} \approx \frac{v}{\sqrt{V_{cb}\,\delta R_{D^*}}} \approx 3.6\ \mathrm{TeV}\left(\frac{0.12}{\delta R_{D^*}}\right)^{1/2}$$

**Low NP scale for CC anomaly drives connection to high-p_T !*

What kind of new particles could we have?



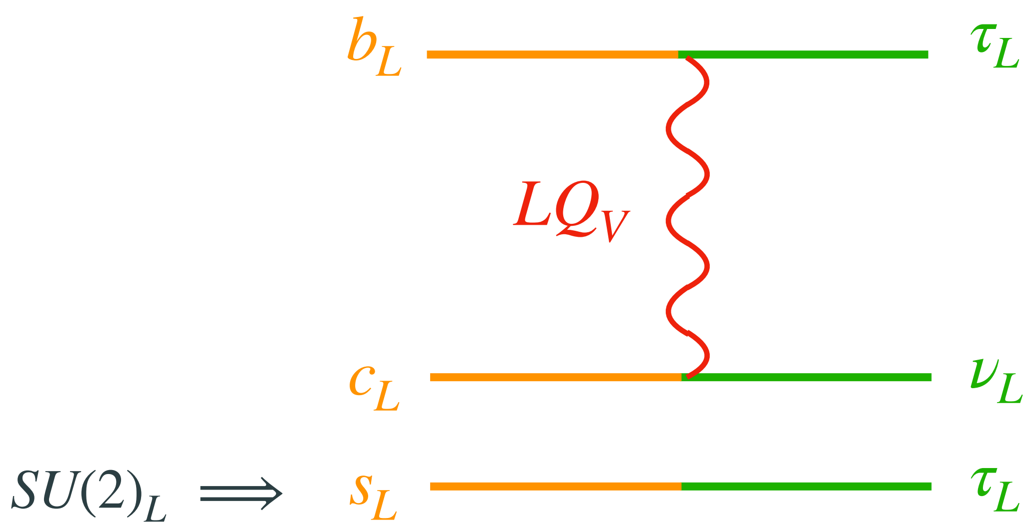
- LH NP $\Longrightarrow$ $b \to s\tau\tau(\nu\nu)$ couplings. LQ's have two important advantages

1. $\Delta F = 2:$

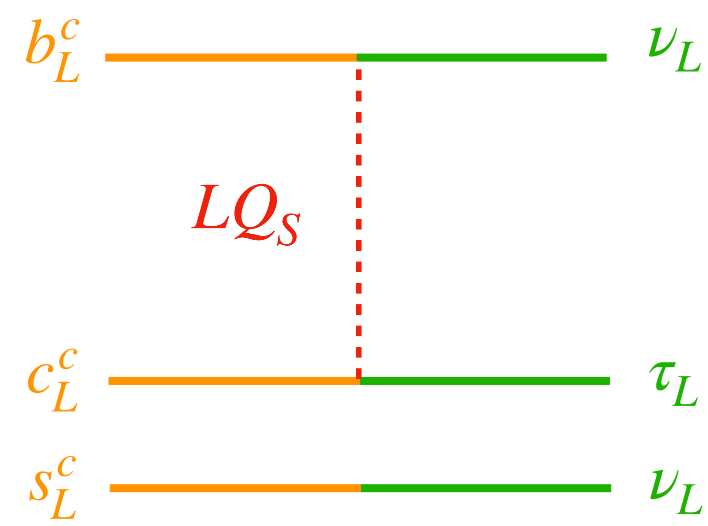
2. **Direct searches:** t-channel versus resonant s-channel production

$b \to c\tau\nu$ Anomalies: Shopping for leptoquarks

- Focus here on two possible options: U_1 vector LQ and S_1 scalar LQ.

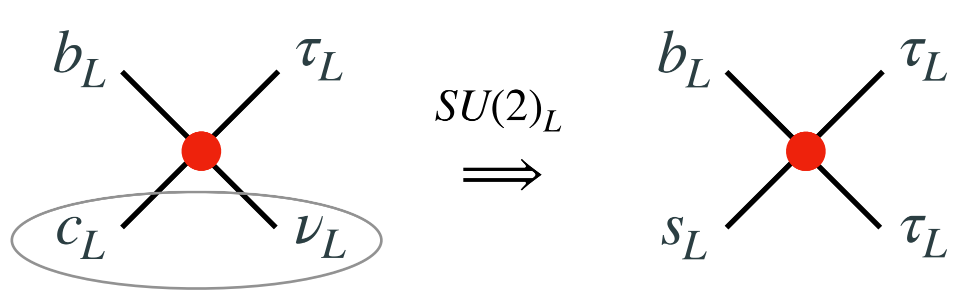


$U_1 \sim (3,1,2/3)$

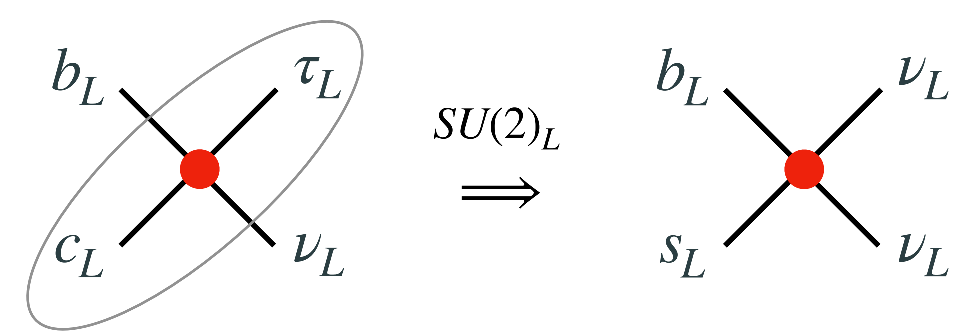


$S_1 \sim (\bar{3},1,1/3)$

- Vector LQ
- Tree level: $b \to c\tau\nu + b \to s\tau\tau$



- Scalar LQ
- Tree level: $b \to c\tau\nu + b \to s\nu_\tau\nu_\tau$



Simplified model for U_1 leptoquark

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

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[(\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta_L^{s\tau} (\bar{q}_L^2 \gamma_\mu \ell_L^3) + \beta_R^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] + \mathrm{h.c.}$$

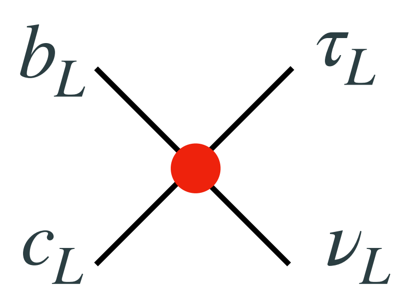
$U(2)_q$ breaking $\sim \mathcal{O}(V_{cb})$

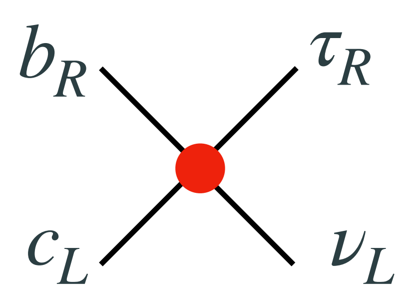
Integrate out the U_1 LQ: $\sim \dfrac{1}{\Lambda_{\rm NP}^2} = \dfrac{g_U^2}{2M_U^2}$

RUNNING to EW SCALE + MATCHING

$$\mathcal{L}_{b\to c\tau\bar{\nu}} = -\frac{2}{v^2} V_{cb} \left[\left(1 + C_{LL}^c\right) (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2\, C_{LR}^c\, (\bar{c}_L b_R)(\bar{\tau}_R \nu_L) \right]$$

Contact interaction:





Low-energy WC's $\leftrightarrow$ Model parameters:

$$C_{LL}^c = \frac{g_U^2 v^2}{4M_U^2} \left(1 + \frac{V_{cs}}{V_{cb}} \beta_L^{s\tau} \right), \qquad C_{LR}^c = \beta_R^{b\tau *} C_{LL}^c$$

Universality violation implies flavor violation

- Suppose new physics is flavor conserving but non-universal in the interaction basis

$$c\bar{f}\gamma_\mu M_{\text{int}} f \qquad\qquad M_{\text{int}} = \text{diag}(a, b, 1)$$

$$M_{\text{mass}} \sim \begin{pmatrix} a & (b-a)\theta_{12} & (a-b)\theta_{12}\theta_{23} + (1-a)e^{-i\delta}\theta_{13} \\ (b-a)\theta_{12} & b & (1-b)\theta_{23} \\ (a-b)\theta_{12}\theta_{23} + (1-a)e^{i\delta}\theta_{13} & (1-b)\theta_{23} & 1 \end{pmatrix}$$

- Even in the $U(2)_f$ limit ($a = b$), FCNC effects expected in $3_f \to 2_f, 1_f$ transitions.
- MFP breaks $U(2)$ for all fields except q- in this case, θ_{12} is physical and leads to enhanced $2_f \to 1_f$ transitions.

If Cabibbo angle from up sector: $\theta_{12}^{u_R} \approx \dfrac{m_u}{m_c}\lambda \approx 5 \times 10^{-4}$

UV Model: New flavor non-universal gauge interactions

Based on "4321" gauge symmetry:

$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix}$$

$$\overbrace{\underbrace{SU(4)_h \times SU(3)_l}_{SU(3)_c} \times SU(2)_L \times U(1)_{l+R}}^{U(1)_Y} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y \quad + U_1, G', Z'$$

Third-family quark-lepton unification at the TeV scale: [Greljo, BAS, 1802.04274]

$$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix} \qquad \psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix}$$

- 3rd family charged under $SU(4)_h$
  $\implies$ Direct NP couplings (L+R)
- Light families under 321 (SM-like)
- Accidental approximate $U(2)^5$ flavor symmetry: $\psi = (\psi_1\ \psi_2\ \psi_3)$
- Good starting point for CKM

Leptons as the fourth "color"

[Pati, Salam, Phys. Rev. D10 (1974) 275]
(only 7 years after the SM was proposed)

$$\psi_{L,R} = \begin{bmatrix} q^1_{L,R} \\ q^2_{L,R} \\ q^3_{L,R} \\ l_{L,R} \end{bmatrix}$$

4321 models

[di Luzio, Greljo, Nardecchia 1708.08450
Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368, 1805.09328;
Greljo, BAS, 1802.04274;
Cornella, Fuentes-Martin, Isidori 1903.11517]

Minimal Flavor Protection: Neutrinos

- Selection rules on the Weinberg operator: $\frac{c_{ij}}{\Lambda}\ell_i\ell_j HH$
- c_{ij} never populated by z when: $(X_i + X_j) \bmod X_z \neq 0 \quad \forall\, i,j$
- But, $SU(2)_q$ doublets can populate c_{ij} at $\mathcal{O}(s^2)$:

$$|X_i + X_j| = \left|[\boldsymbol{a}^\dagger \boldsymbol{b}] \text{ or } [\boldsymbol{a}^\dagger \widetilde{\boldsymbol{b}}]\right| \quad \forall\, i,j\,,$$

$\boldsymbol{a}^\dagger\boldsymbol{b}$ or $\boldsymbol{a}^\dagger\widetilde{\boldsymbol{b}}$, with $\boldsymbol{a},\boldsymbol{b} \in \{\boldsymbol{V},\boldsymbol{W},\boldsymbol{U}\}$ and $\boldsymbol{a} \neq \boldsymbol{b}$

Benchmark charges:
$c_{ij} \sim s^2$, **only** $c_{22} \sim s^3$

- Since ***all*** $s = v, w, u, z \sim 10^{-2}$, neutrino ***anarchy*** is predicted! ✔
- Large PMNS! Also, $\Lambda \sim O(10^{11})$ GeV from m_ν.

$$[c_{ij}] \sim |X_i + X_j| \sim \begin{pmatrix} 4 & 5 & 3 \\ 5 & 6 & 4 \\ 3 & 4 & 2 \end{pmatrix}$$

$$\left|[\boldsymbol{a}^\dagger \boldsymbol{b}] \text{ or } [\boldsymbol{a}^\dagger \widetilde{\boldsymbol{b}}]\right| \in \{1,2,3,4,5\}$$

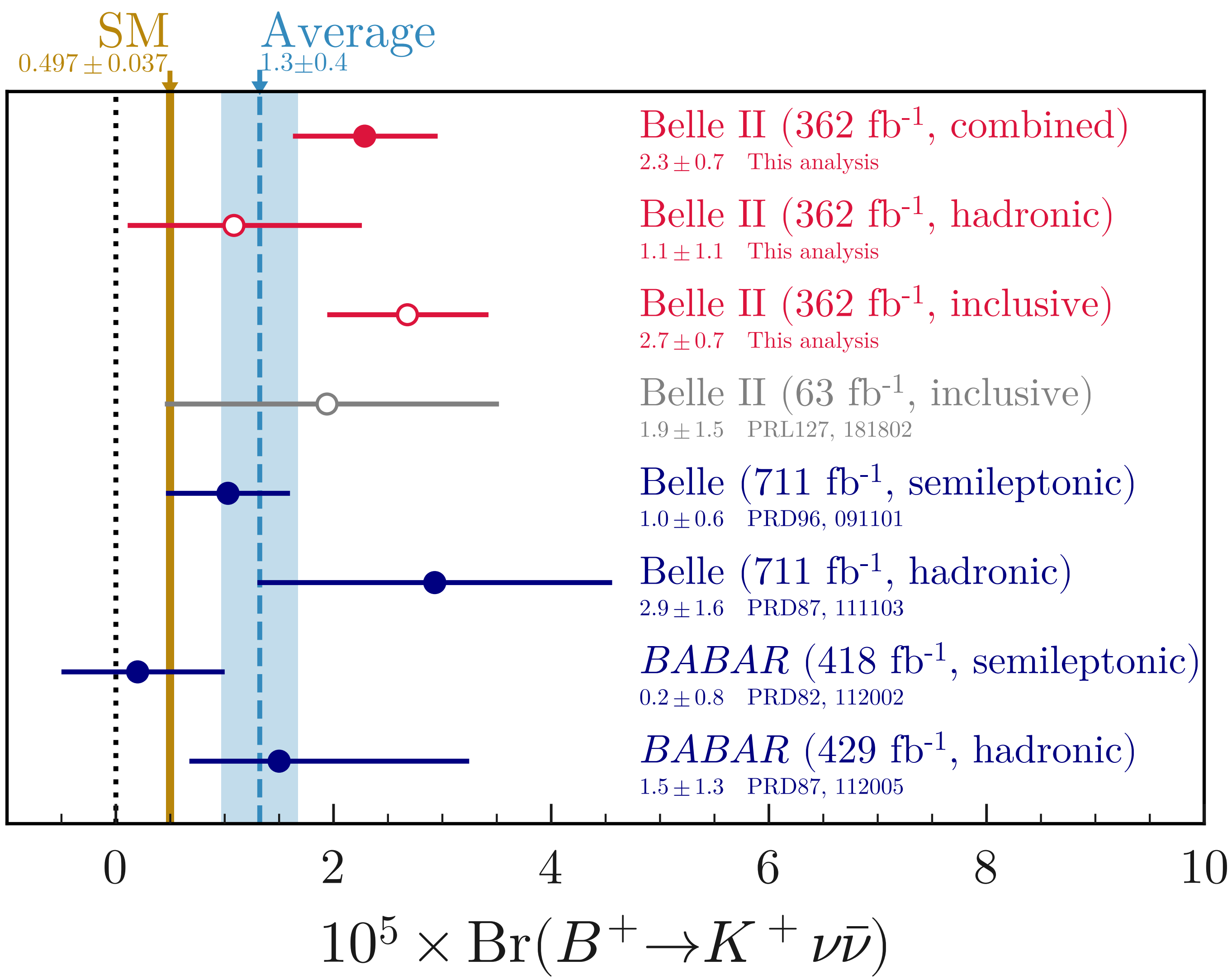
All $O(10^{-2})$

[Greljo, Palavrić, BAS, 2512.04159]

Connecting $b \to c\tau\nu$ and $b \to s\nu\bar{\nu}$

$B^+ \to K^+\nu\bar{\nu}$ measurement from Belle II

- Belle II has updated the measurement of $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ with 362/fb of data. For details of the analysis: See Sally's talk



[Belle II Collaboration, 2311.14647]

$$R^{\nu}_{K^{(*)}} = \frac{\mathscr{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathscr{B}(B^+ \to K^{(*)}\nu\bar{\nu})_{\mathrm{SM}}}$$

Belle II (362/fb combined):

$$R^{\nu}_{K^+} = 4.6 \pm 1.4$$

Average of measurements:

$$R^{\nu}_{K^+} = 2.6 \pm 0.8$$

Belle II combination is 2.6σ above the SM, while the average is 2σ above.

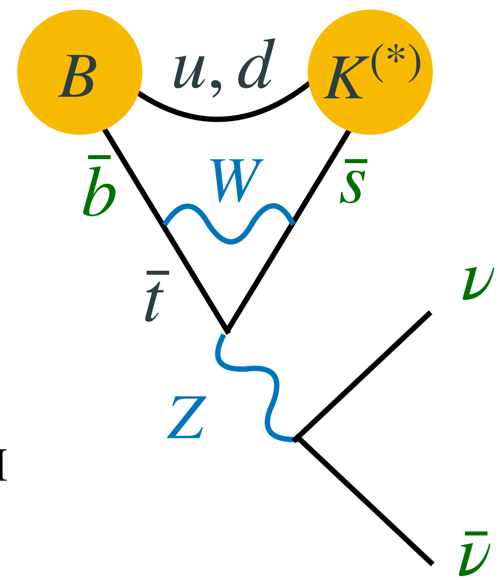
New physics in $b \to s\nu\bar{\nu}$ decays

- We need 2-3x a SM loop process due to NP. Large effect means heavy NP likely tree-level to compete. Consider Fermi-like LH NP:

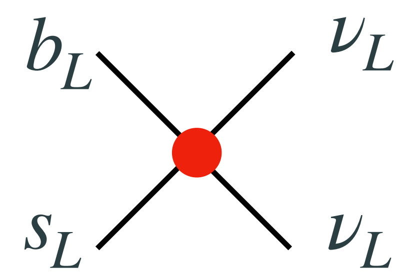
<u>SM process</u>

$$C_\nu^{\rm SM} \approx -1.47$$

$$\mathscr{A}_{\rm SM} \sim \frac{\alpha_L}{\pi v^2} V_{tb} V_{ts}^* \, C_\nu^{\rm SM}$$



<u>Heavy new physics</u>



$$\mathscr{A}_{\rm NP} \sim \frac{1}{\Lambda_{\rm NP}^2}$$

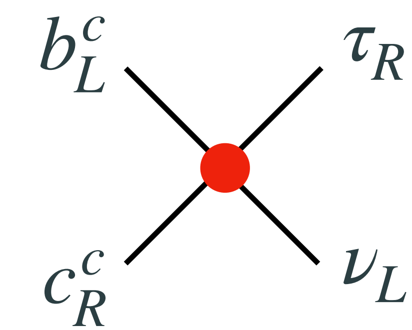
- If we assume a new physics effect ONLY in tau neutrinos:

$$R^\nu_{K^{(*)}} = \frac{2}{3} + \frac{1}{3}\left|1 + \frac{\mathscr{A}_{\rm NP}}{\mathscr{A}_{\rm SM}}\right|^2 \quad \Longrightarrow \quad \Lambda_{\rm NP} \approx 8.1 \ \text{TeV} \qquad (R^\nu_{K^{(*)}} = 2.6)$$

$$\Lambda_{\rm NP} \approx 650 \ \text{GeV} \qquad \text{(loop)}$$

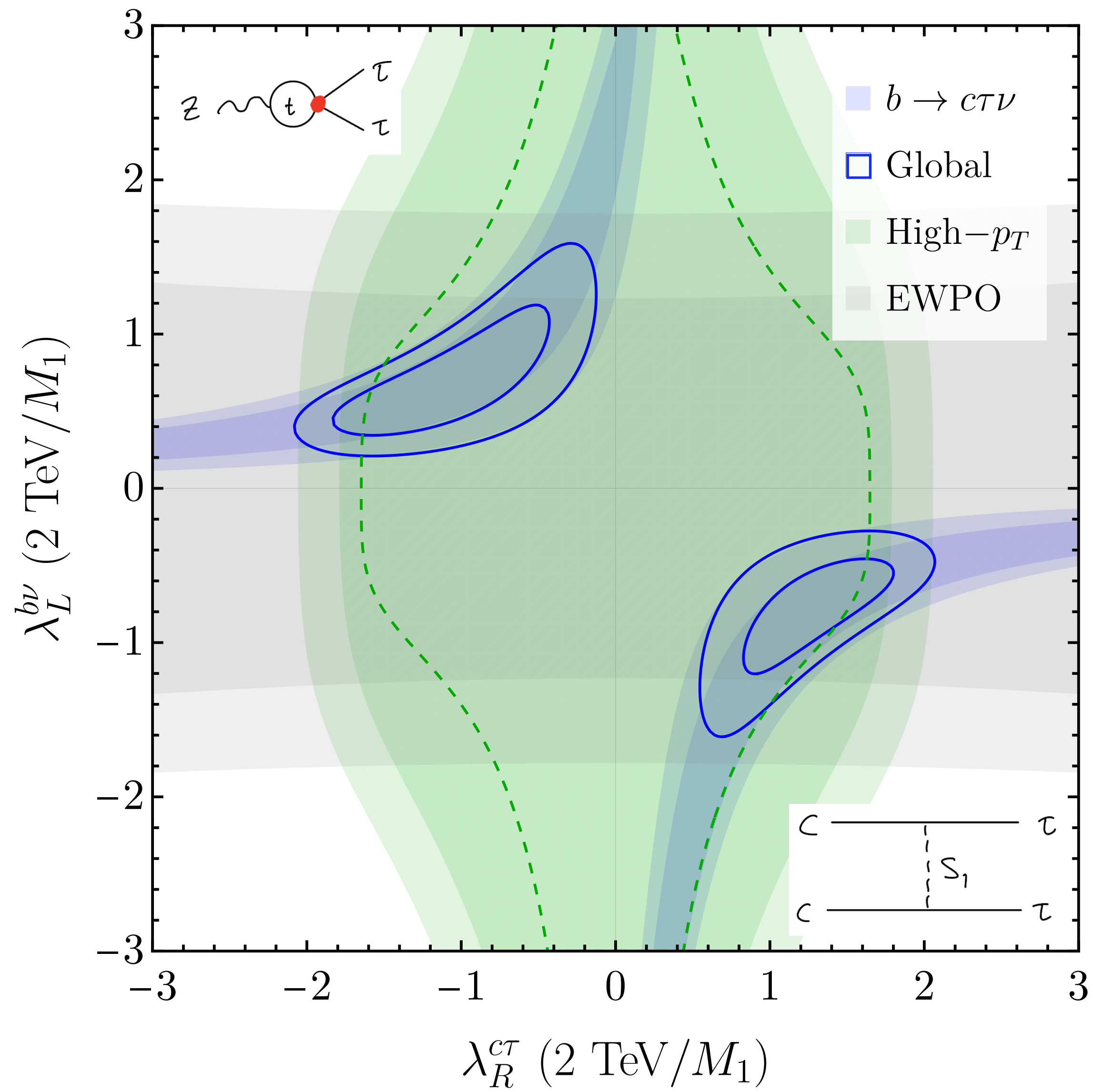
Simplified S_1 scalar LQ model and fit

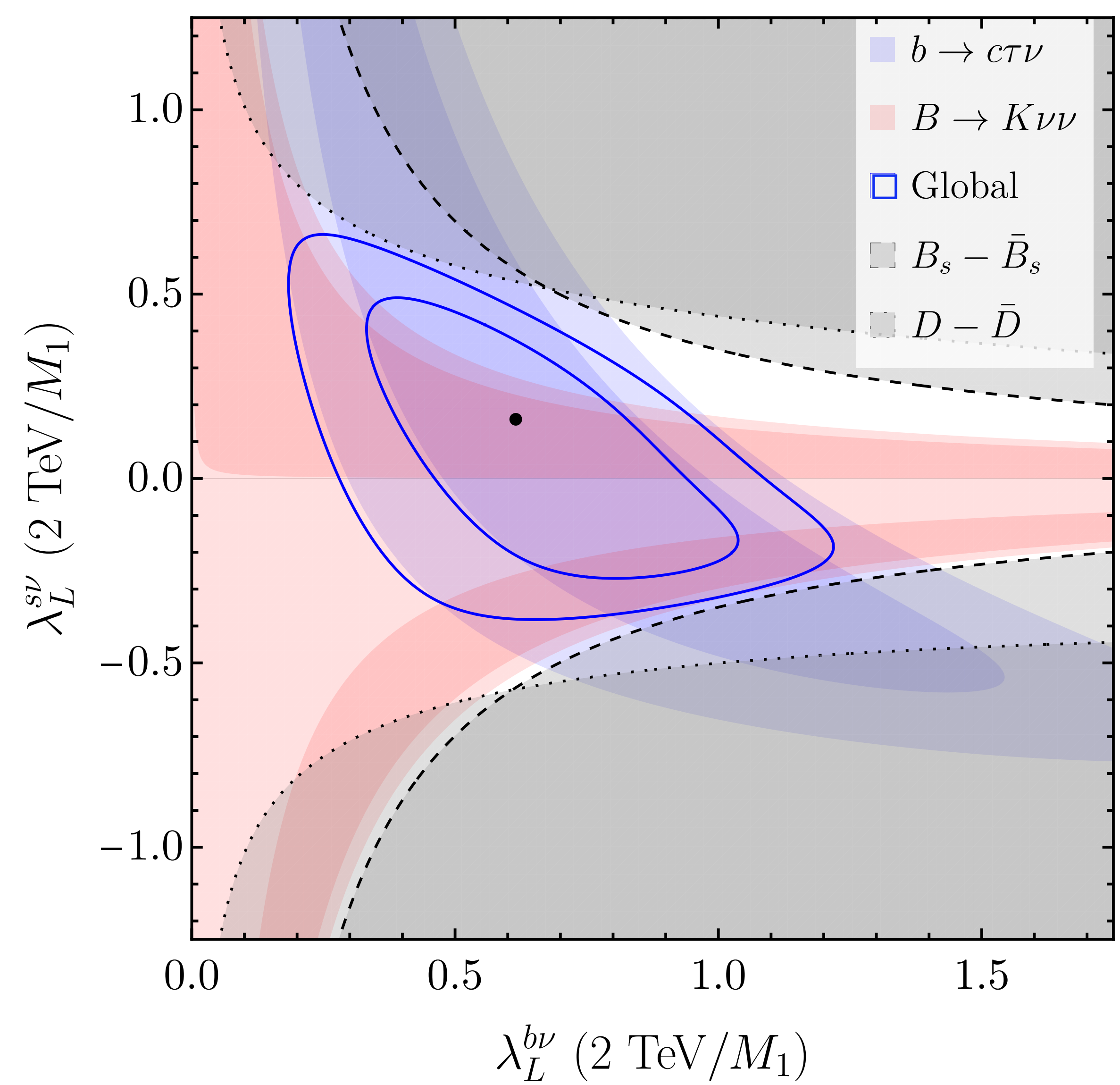
$C_{V_L},\, C_{S_L} = -4C_T$



$$\mathscr{L} \supset \underbrace{\overbrace{\lambda_L^{b\nu}\, \bar{q}_L^{c3}\epsilon \ell_L^3 S_1 + \lambda_R^{c\tau}\, \bar{c}_R^c \tau_R S_1}^{b \to c\tau\nu}}_{B \to K\nu\bar{\nu}:\ \lambda_L^{b\nu}\,\lambda_L^{s\nu}}$$

$$\mathscr{L} \supset \lambda_L^{b\nu}\, \bar{q}_L^{c3}\epsilon \ell_L^3 S_1 + \lambda_L^{s\nu}\, \bar{q}_L^{c2}\epsilon \ell_L^3 S_1 + \lambda_R^{c\tau}\, \bar{c}_R^c \tau_R S_1$$



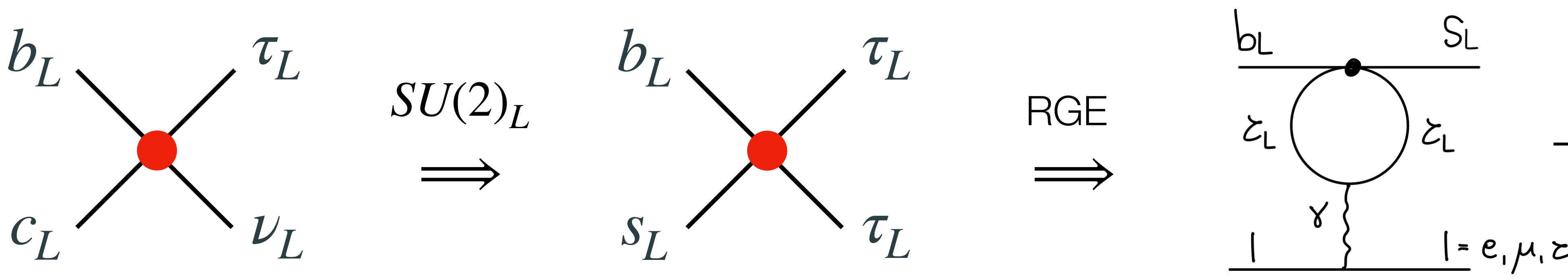


*This model can contribute to $B_{d,s} \to K^{(*)}\bar{K}^{(*)}$: [Lizana, Matias, BAS, 2306.09178]

Connecting $b \to c\tau\nu$ and $b \to s\ell\ell$

Connection: $b \to c\tau\nu$ and $b \to s\mu\mu$

- Some mediators that explain the charged-current anomalies give a *flavor-universal* effect in $b \to s\ell\ell$ via RGE. *Discussed also in Mauro's talk*



$\to \Delta C_9^U = C_9^U - C_9^{\rm SM}$

$$\mathscr{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i^\ell O_i^\ell \qquad O_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

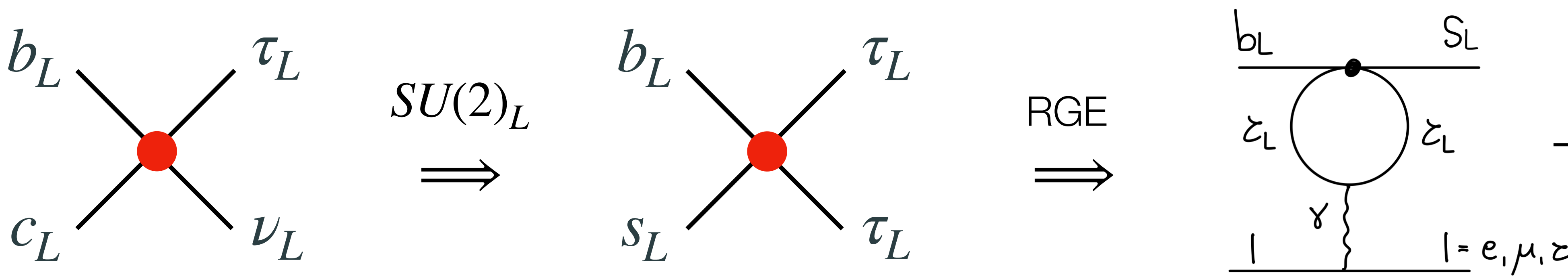
- Leading-log running gives

$$\Delta C_9^U = \frac{v_{\rm EW}^2}{3V_{tb}V_{ts}^*}\left([C_{lq}^{(3)}]_{3323} + [C_{lq}^{(1)}]_{3323}\right)\log\left(\frac{m_b^2}{M^2}\right)$$

[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]

Connection: $b \to c\tau\nu$ and $b \to s\mu\mu$

- Some mediators that explain the charged-current anomalies give a *flavor-universal* effect in $b \to s\ell\ell$ via RGE. *Discussed also in Mauro's talk*



$\to \Delta C_9^U = C_9^U - C_9^{\rm SM}$

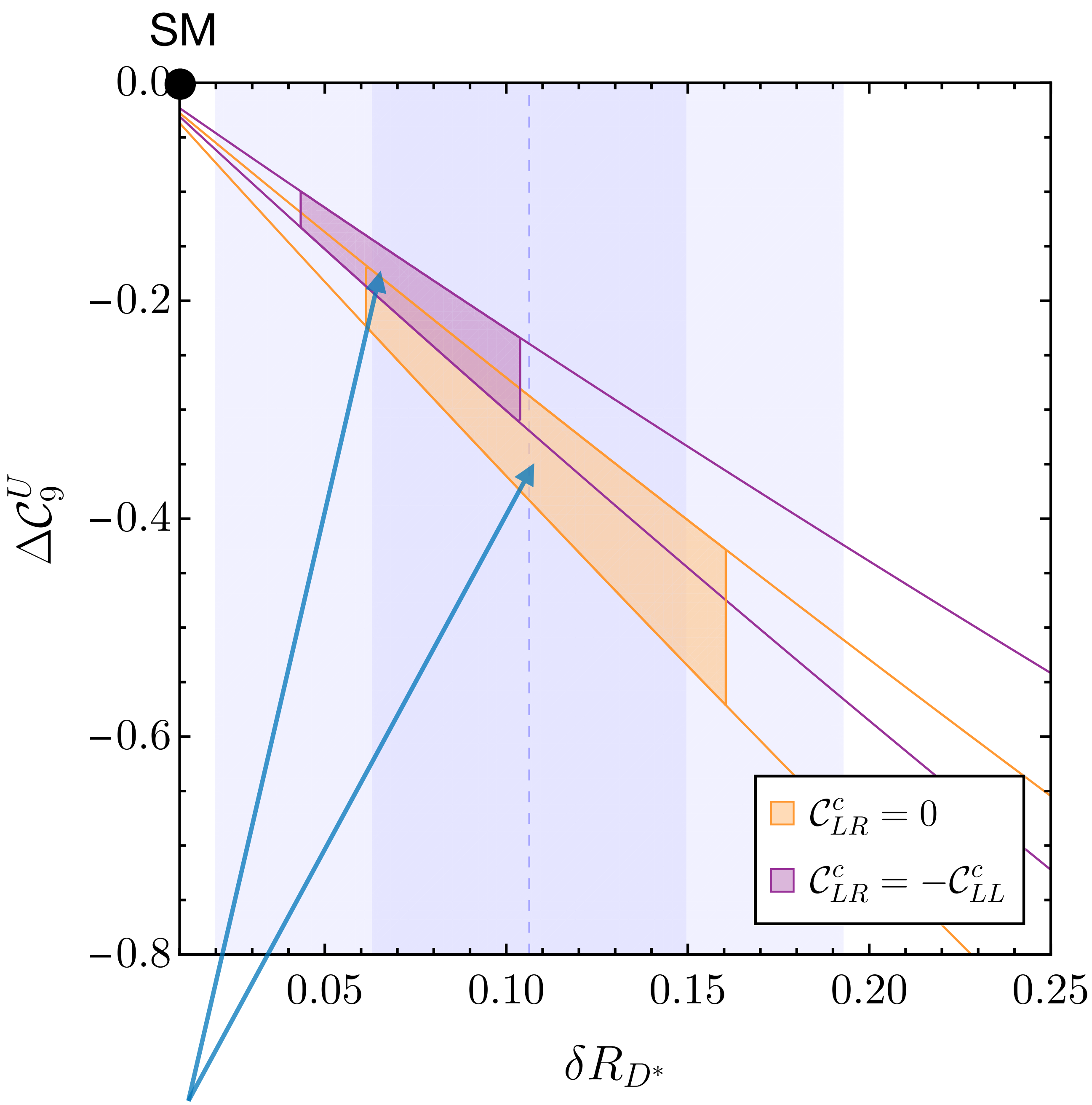
$$\Delta C_9^U = \frac{v_{\rm EW}^2}{3 V_{tb} V_{ts}^*} \left([C_{lq}^{(3)}]_{3323} + [C_{lq}^{(1)}]_{3323} \right) \log \left(\frac{m_b^2}{M^2} \right)$$

U_1	S_1
$C_{lq}^{(3)} = C_{lq}^{(1)}$	$C_{lq}^{(3)} = -C_{lq}^{(1)}$

[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]

U_1 connects $R_{D^{(*)}}$ to universal $b \to s\ell\ell$ observables

- Large $b \to s\tau\tau$ implies a sizable *flavor-universal* loop effect in $b \to s\ell\ell$!

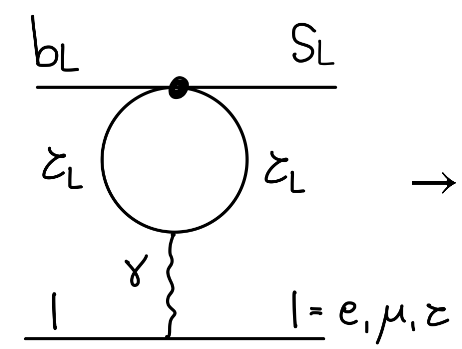


HFLAV ’25 updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i^\ell O_i^\ell$$

$$O_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

RGE $\Longrightarrow$



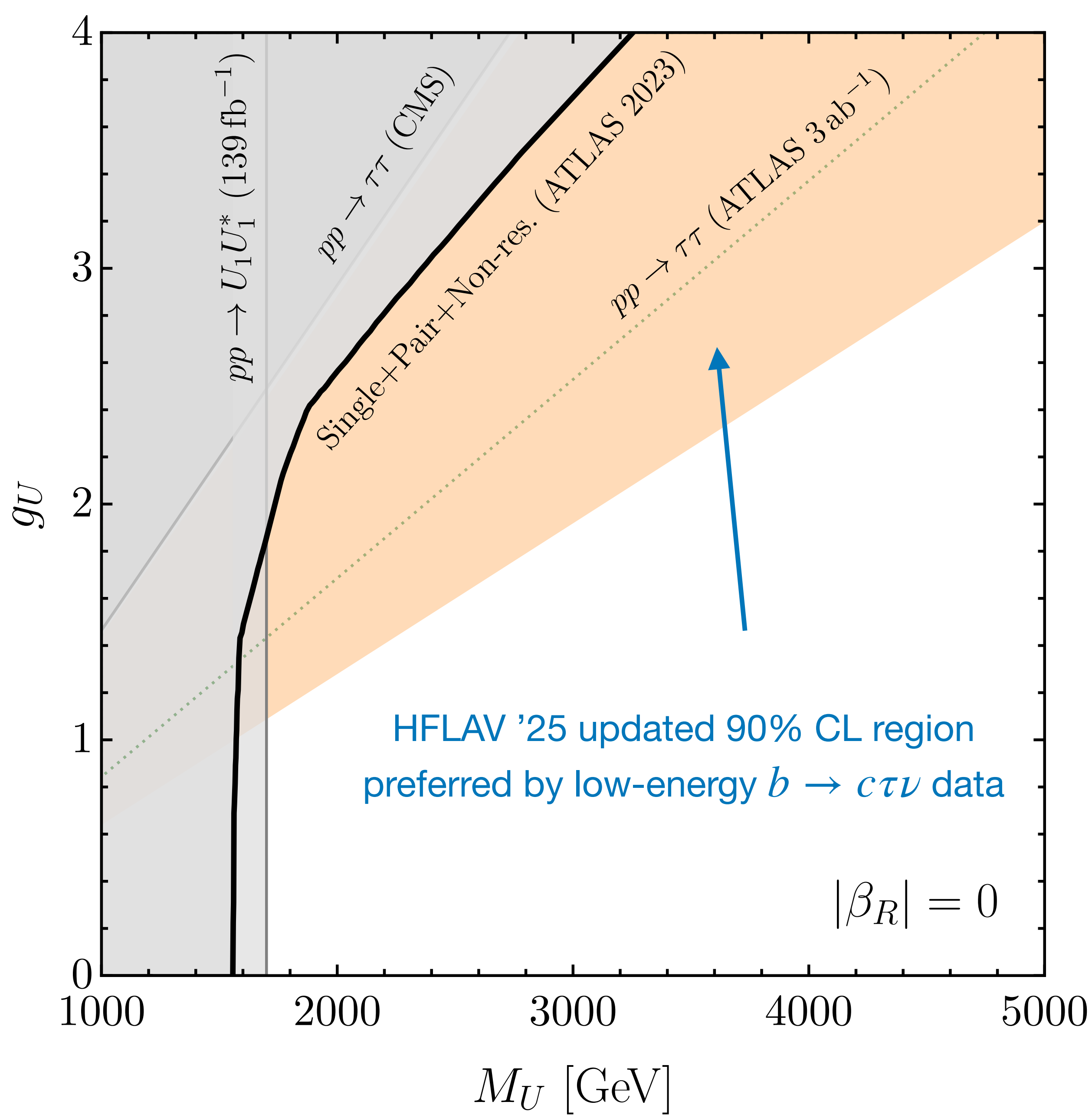
$\to \Delta C_9^U = C_9^U - C_9^{\text{SM}}$

Global Fits to $b \to s\ell^+\ell^-$ data:
$\Delta C_9^U \sim -C_9^{\text{SM}}/4$

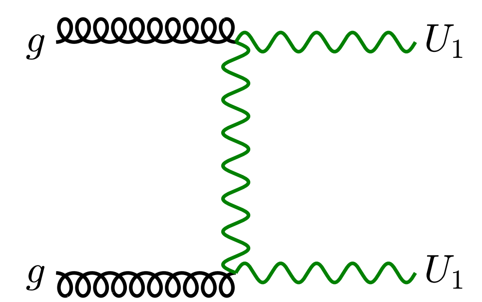
[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

High-energy searches: U_1 leptoquark model (LH)

- Of course, eventually we need to see something at high-pT. The LHC is already probing relevant parameter space.



U_1 pair production

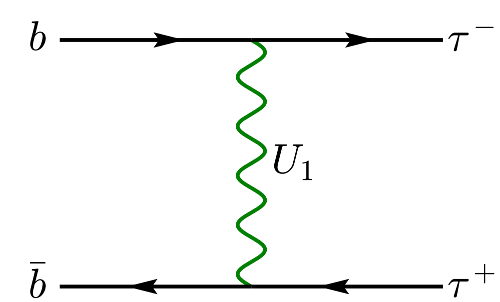


$U_1 \to b\tau^+, t\bar{\nu}$

$\mathscr{B}(U_1 \to b\tau^+) \approx 0.5$

$pp \to U_1^+ U_1^- \to b\tau\, t\nu$

Drell-Yan t-channel exchange: $\tau\tau$



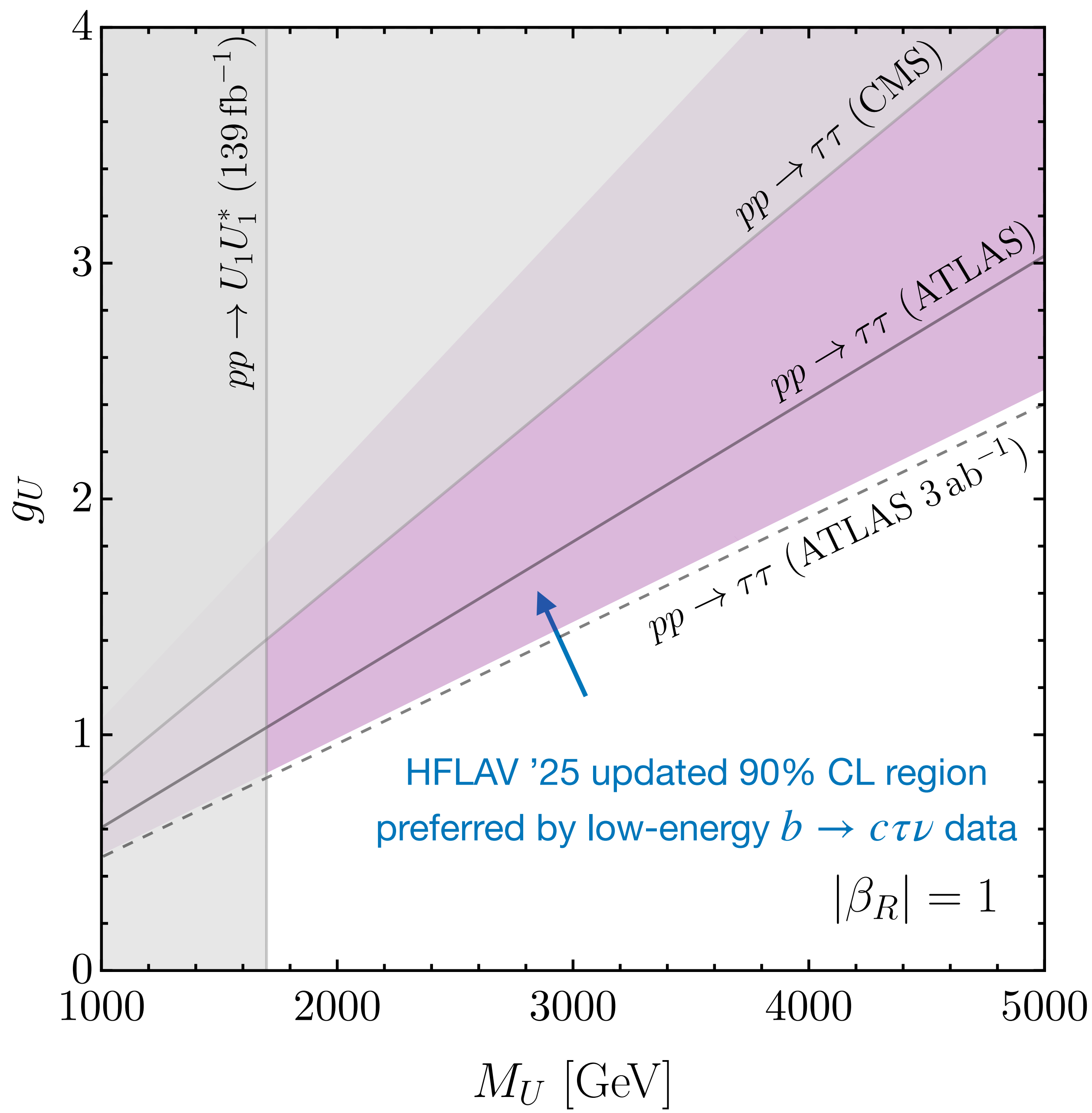
High mass Drell-Yan tails

QCD corrections: [U. Haisch, L. Schnell, S. Schulte, 2209.12780]

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

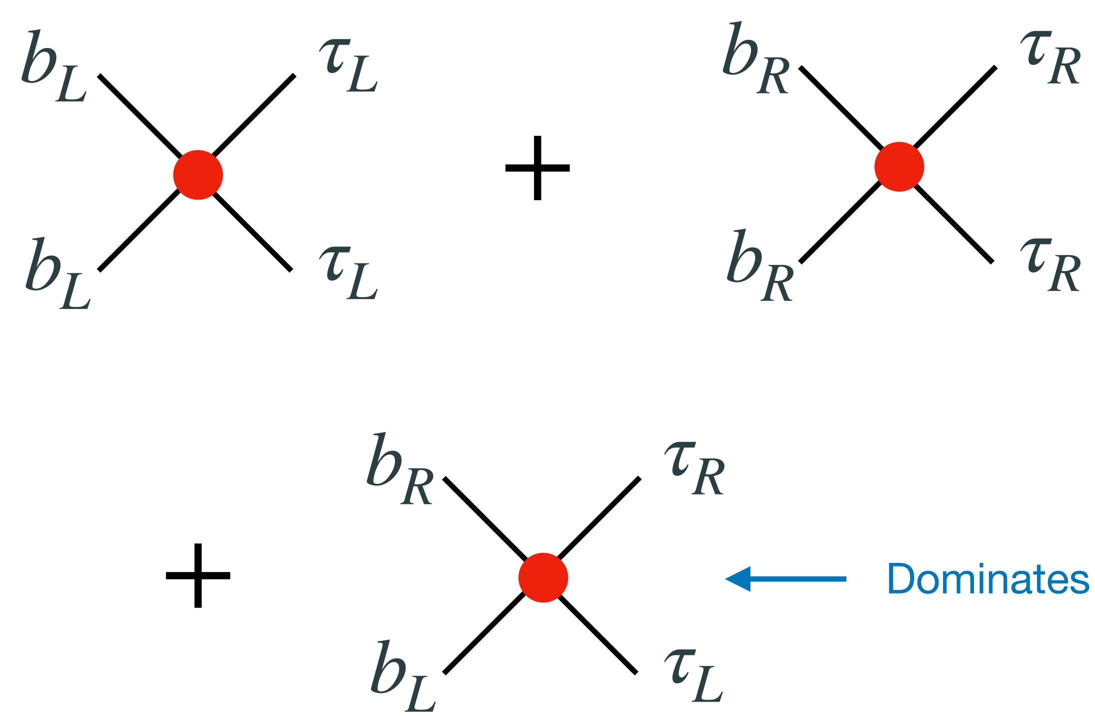
High-energy searches: U_1 leptoquark model (L&R)

- U_1 LQ model w/ RH currents preferred region fully within the HL-LHC reach!



$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[(\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta_R^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] \quad (\beta_R^{b\tau} = -1)$$

- Additional RH contributions give stronger bound from t-channel Drell-Yan $\tau\tau$:



[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]