Current opportunities in flavor physics

Claudia Cornella (JGU Mainz)

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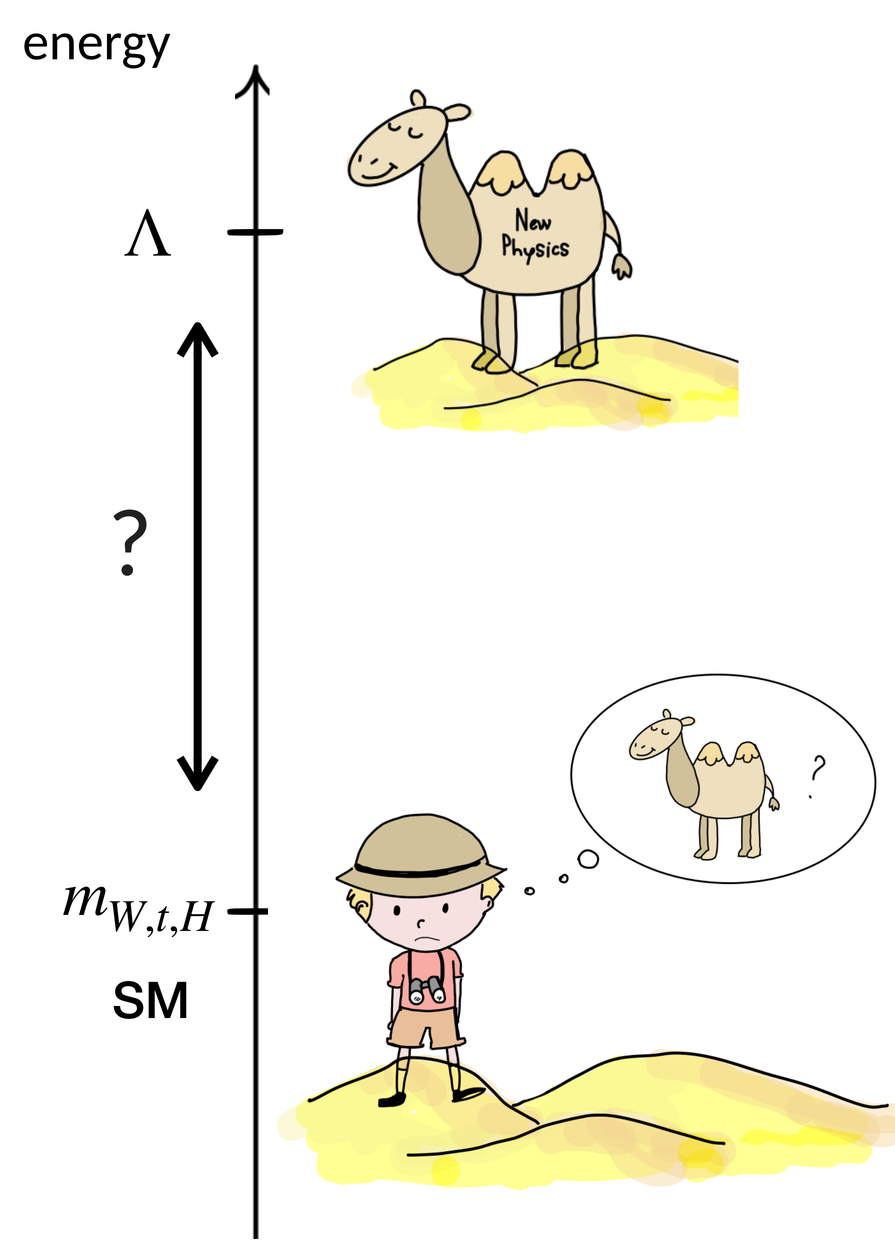
The scale of New Physics

No direct evidence of BSM,
we are facing a **mass gap**: NP is either very heavy, or light and weakly coupled to the SM.



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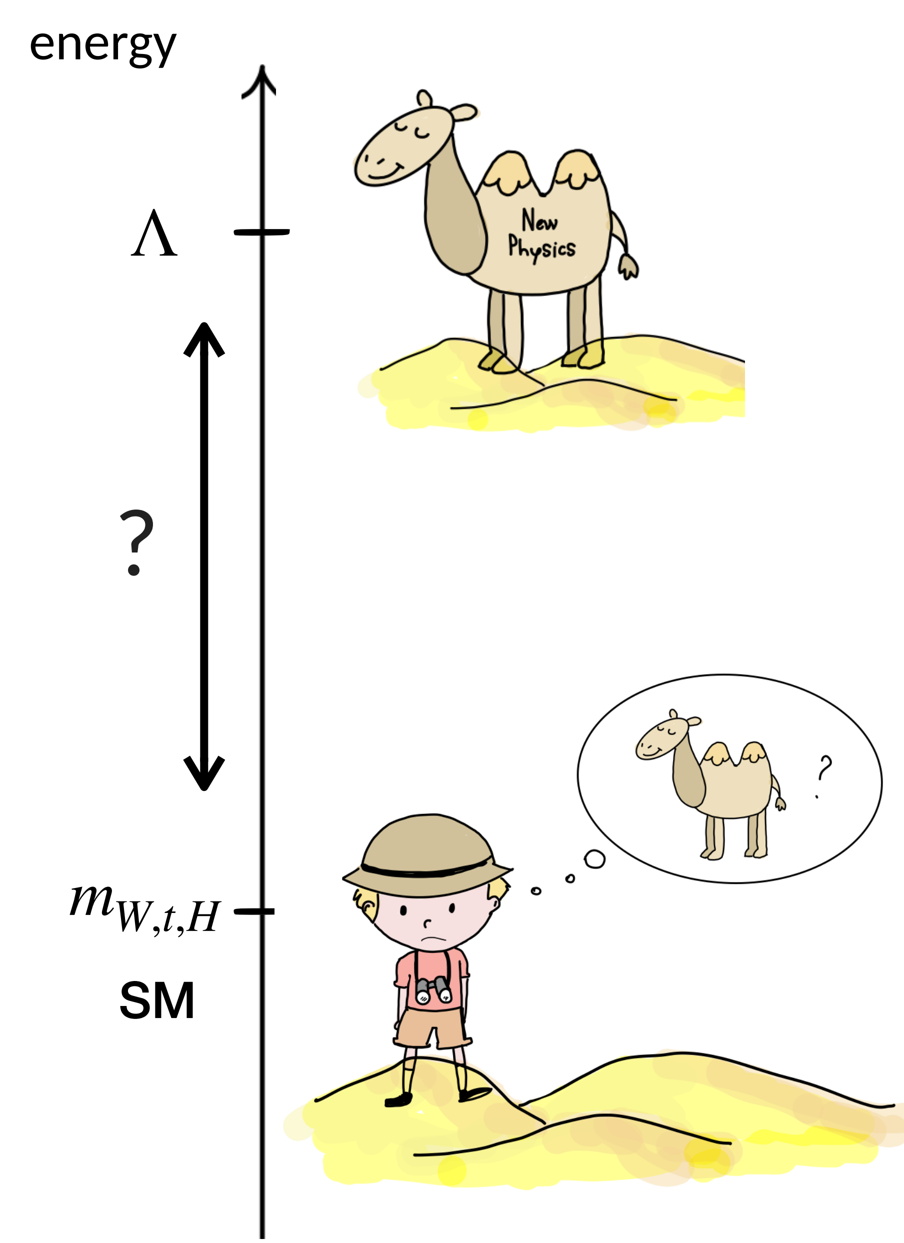
Use **EFTs** and **data** to bridge the gap:

- describe heavy NP via higher-dim. operators
- use data (electroweak, flavor & collider) to constrain the Wilson coefficients
- constraints are interpreted as lower bounds on an "effective" NP scale

Caveat: **interpreting** EFT bounds without additional assumptions can lead to overly pessimistic estimates.



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- In the 1970s, the "SM" had two quark families, & CP was an accidental symmetry. CP violation in K mixing suggested a huge NP scale. The actual scale was much lower:

$$\frac{1}{\Lambda_{\mathrm{CP}}^2}(\bar{s}\,\Gamma\,d\,)^2 \;\Rightarrow\; \Lambda_{\mathrm{CP}} \sim 10^4\,\mathrm{TeV} \qquad\qquad \frac{1}{\Lambda_{\mathrm{CP}}^2} \sim \frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2}$$

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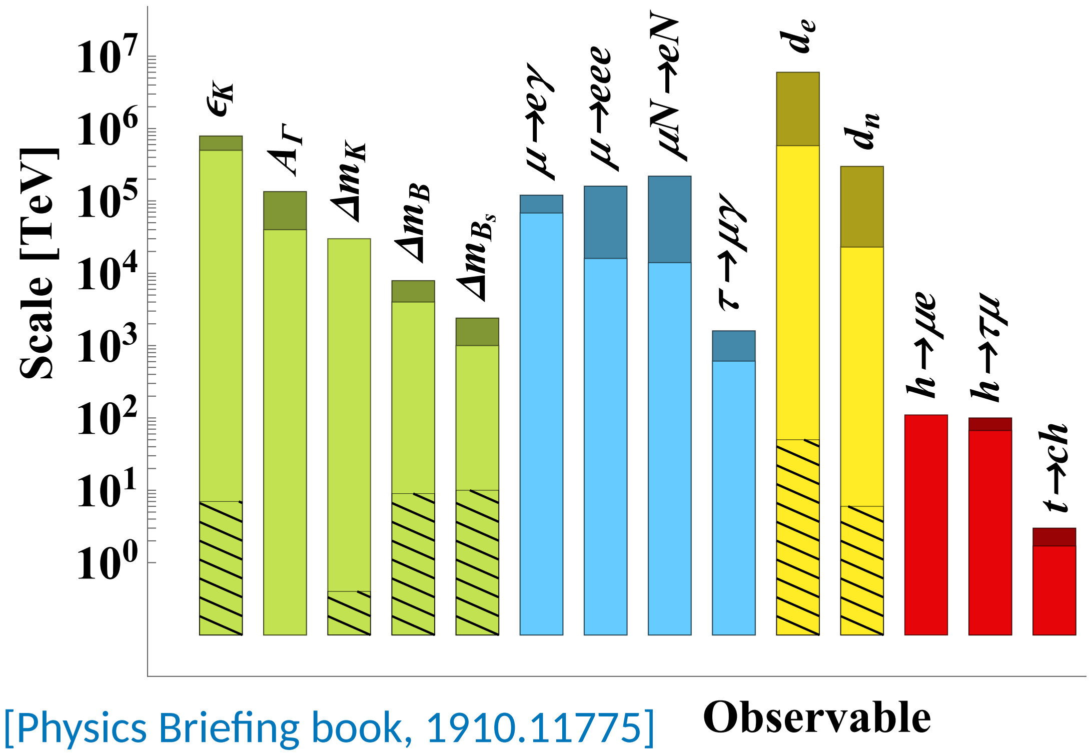

[Physics Briefing book, 1910.11775]

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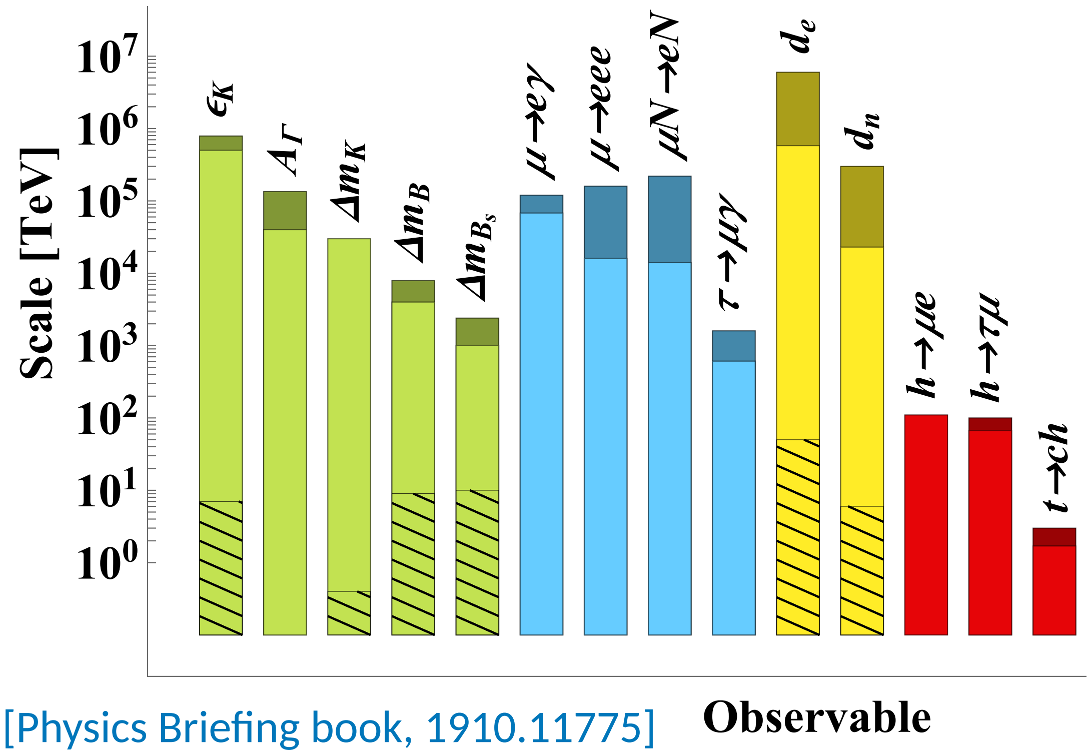

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  ....but in realistic models NP couplings can be suppressed: the real scale can be lower!

$\Rightarrow$ Educated assumptions about NP flavor structure can **guide** our **interpretation** of **SMEFT** bounds. Use **flavor & hierarchy** problem as guidance!

The flavor sector of the Standard Model

SM **gauge** interactions are **flavor-universal**, enjoying a large accidental flavor symmetry:

$$G_F = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

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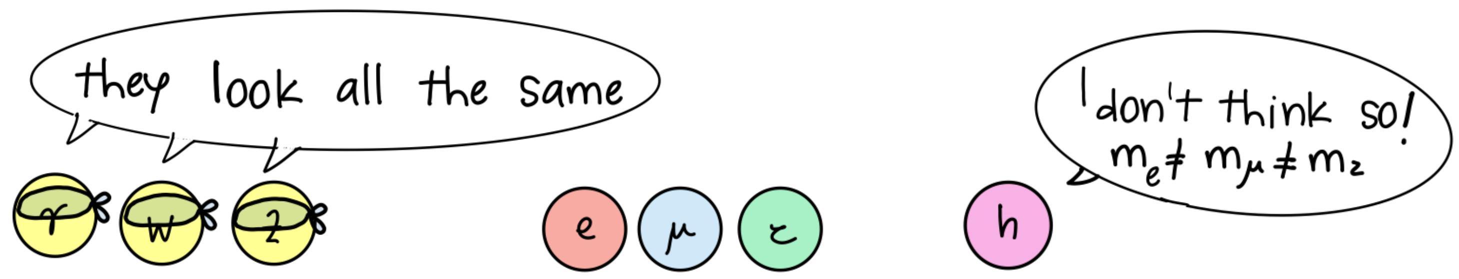

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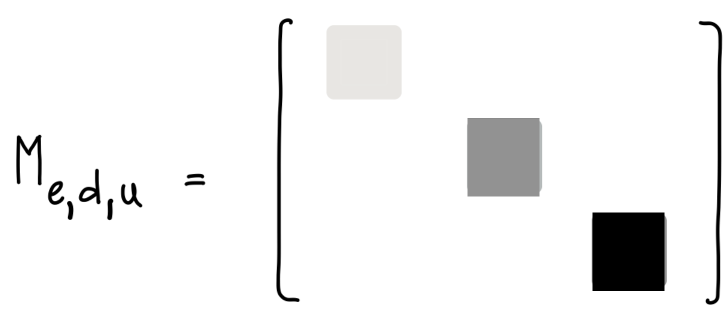
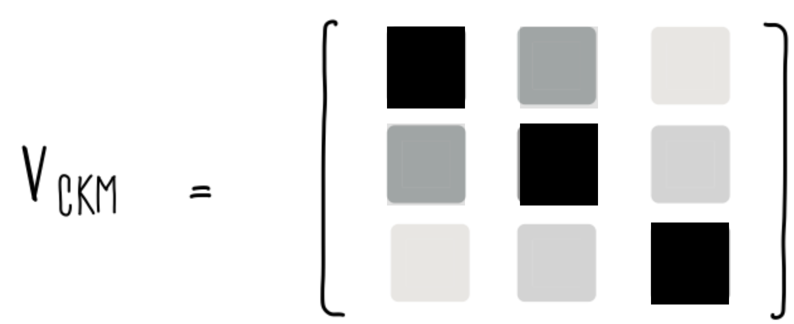
The interactions with the **Higgs** are the only source of flavor **non-universality & violation**. They break G_F to an approximate $U(2)^5$ symmetry:





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This structure is an empirical fact. Its **origin** remains a puzzle, the **flavor puzzle**.

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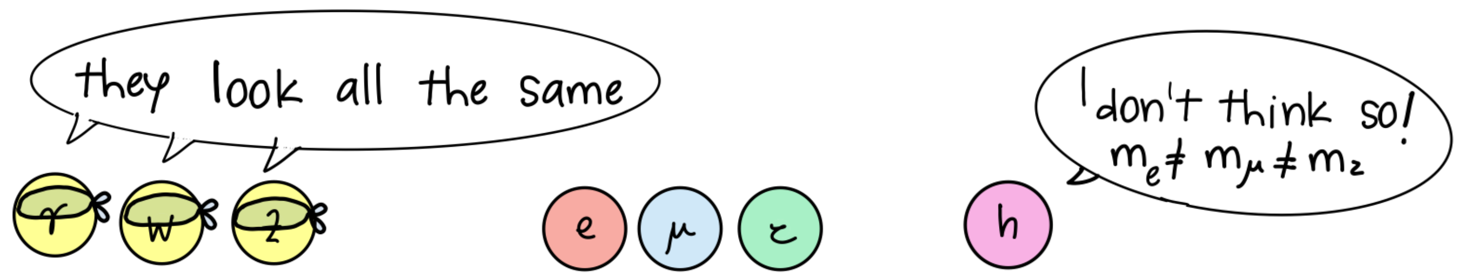

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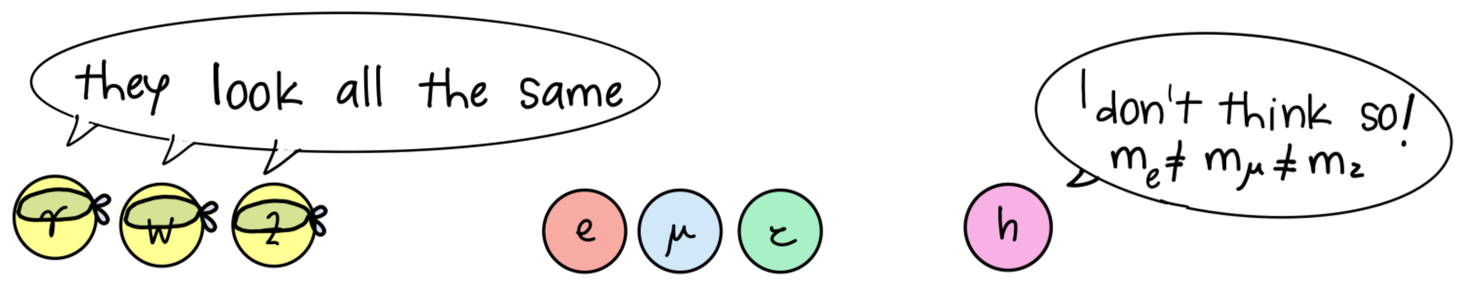

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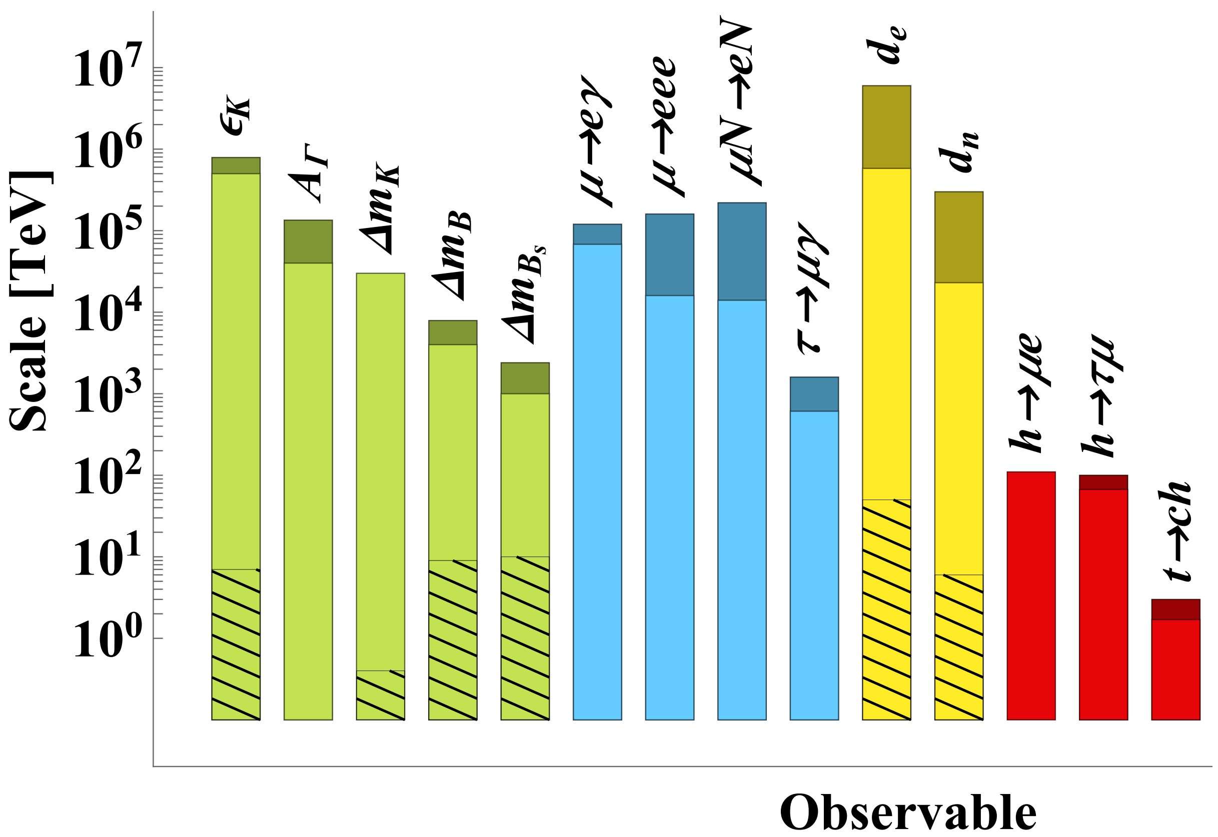
How to reconcile this with **flavor bounds**?



To reside at the TeV scale, NP must have some **flavor protection.**

Protecting New Physics from Flavor

Minimal Flavor Violating (MFV) new physics:

- Yukawas couplings are the only sources of flavor violation:
  MFV describes (perturbations around) **flavor-universal NP.**

- by construction, little to no effect in flavor-changing processes.
- but couplings to valence quarks are not suppressed
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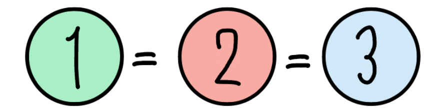

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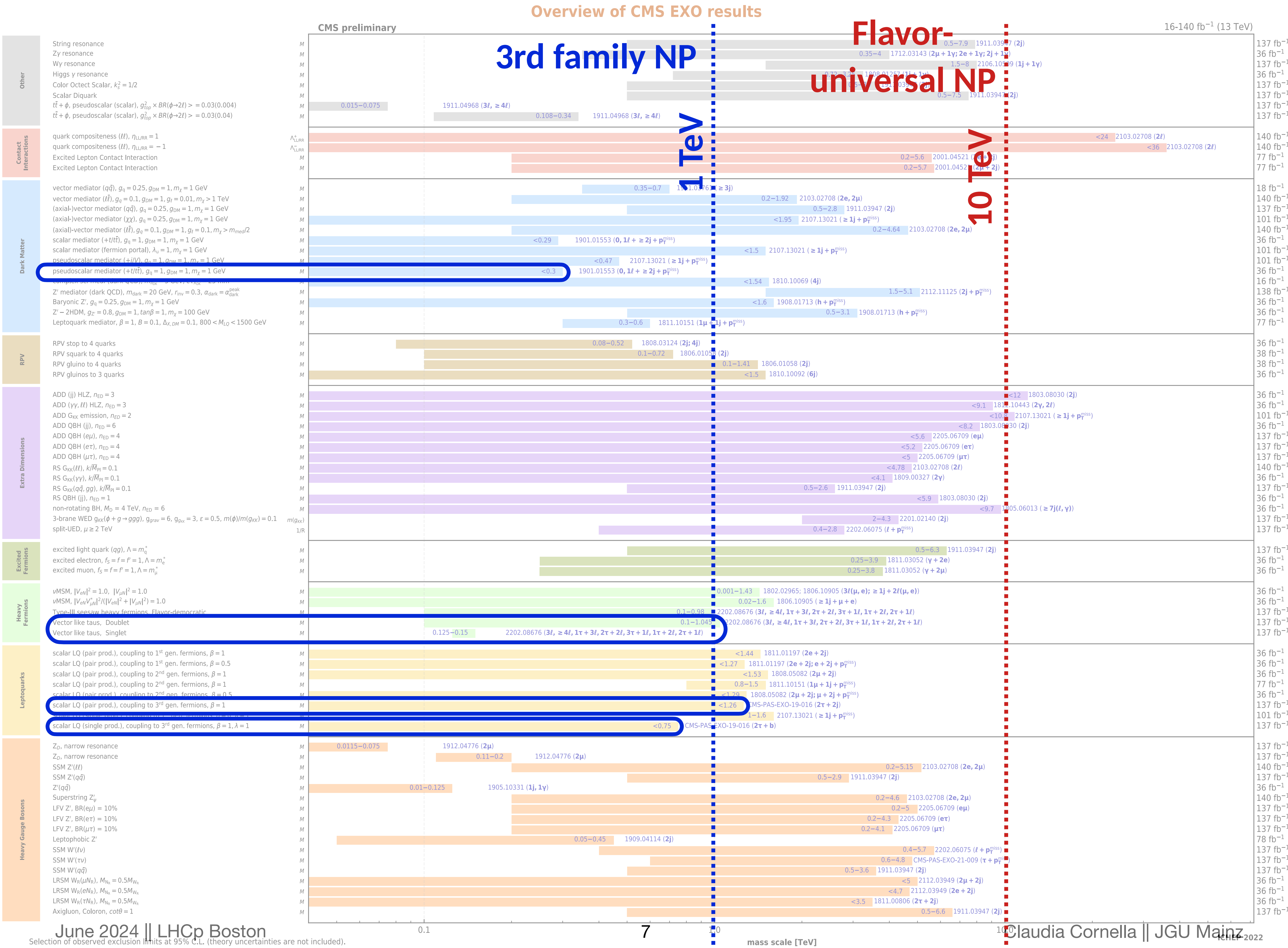
Flavor-dependent (3rd family) new physics:

- NP distinguishes among different flavors by coupling dominantly to the third family.

- Third family is "special": possible connection to hierarchy & flavor problem.
- NP has an approximate $U(2)^n$ symmetry, like the SM Yukawas.
- couplings to light families can be suppressed: can live at the TeV scale.


Overview of CMS EXO results
CMS preliminary
16-140 fb^{-1} (13 TeV)
3rd family NP
Flavor-universal NP
1 TeV
10 TeV
Other
Contact Interactions
Dark Matter
RPV
Extra Dimensions
Excited Fermions
Heavy Fermions
Leptoquarks
Heavy Gauge Bosons
pseudoscalar mediator (+t/tt̄), $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV
Vector like taus, Doublet
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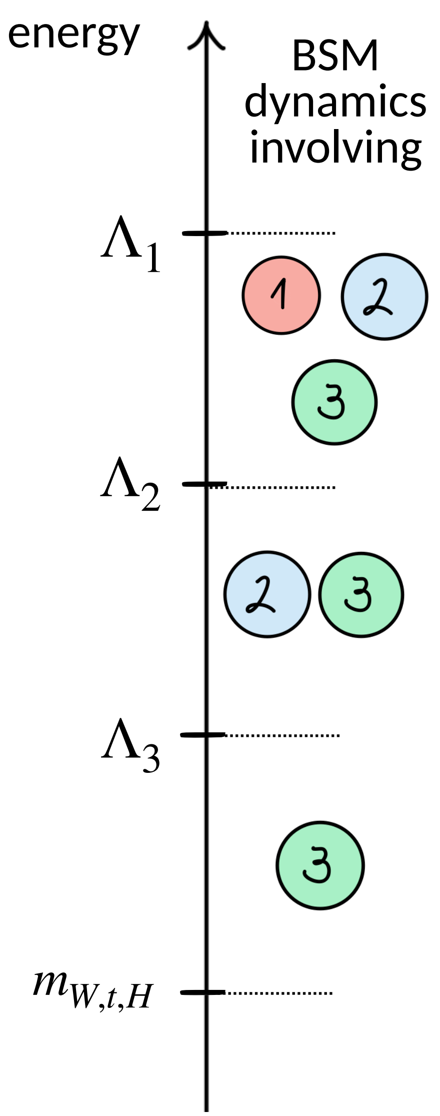
scalar LQ (pair prod.), coupling to 3rd gen. fermions, $\beta = 1$
scalar LQ (single prod.), coupling to 3rd gen. fermions, $\beta = 1, \lambda = 1$
0.1
1.0
10.0
mass scale [TeV]
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
ICHEP 2022

Flavor-non-universal New Physics

Key idea: The U(2) symmetry in the Yukawas and in the NP couplings has a single dynamical origin & is a remnant of a more fundamental difference.



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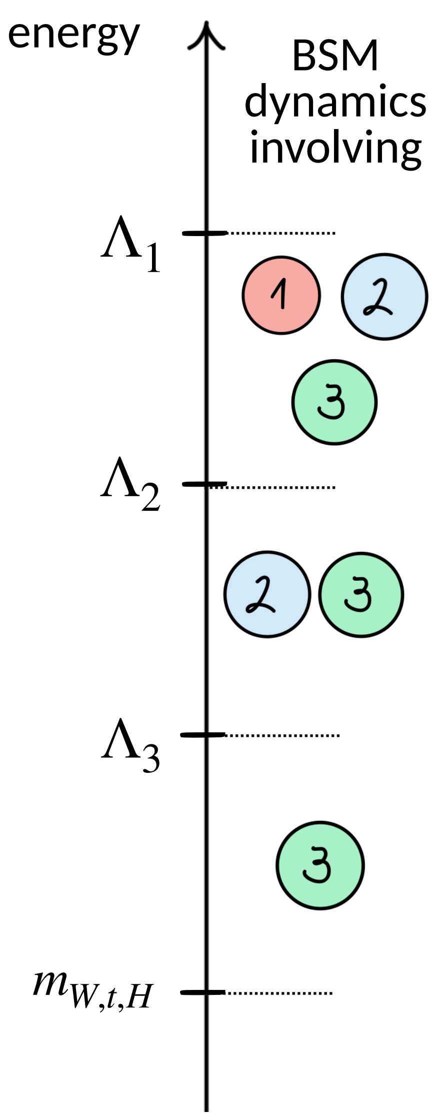

At high energies, the three **families** are **intrinsically different** objects.

Non-universal forces acting on the i-th SM family have characteristic scales $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$.

The **flavor universality** of SM gauge interactions is an accidental **low-energy property**.

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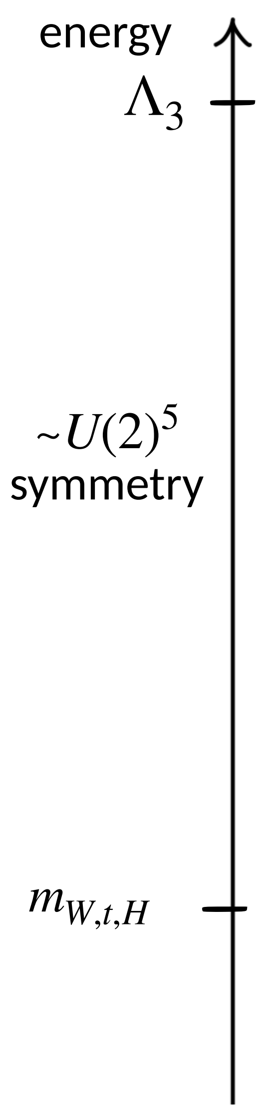

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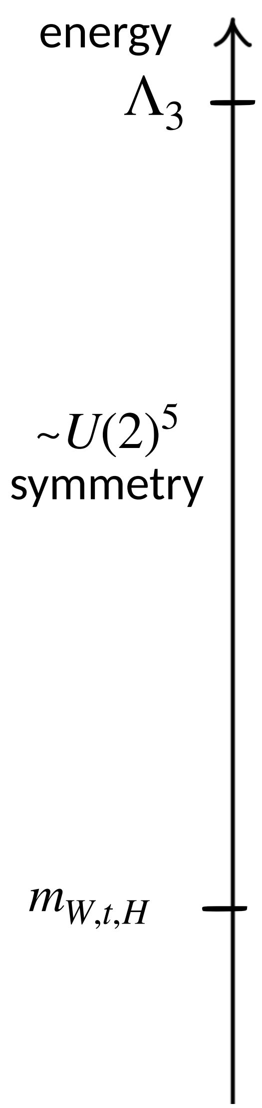

Around Λ_3, Yukawas & NP couplings have an approximate **U(2)** symmetry: largest entries in the 3rd family.

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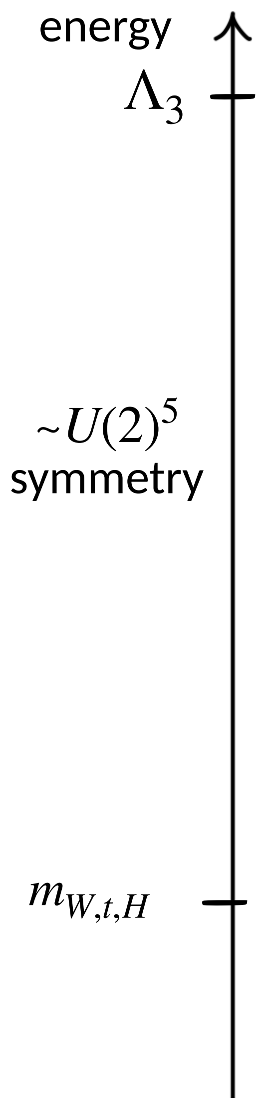

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Explicit realization: **deconstruct SM gauge group by flavor**

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

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

- built-in $U(2)^5$ in gauge sector, only 3rd family Yukawas
- SSB to SM breaks $U(2)^5$ generating subleading Yukawas and NP couplings for light families

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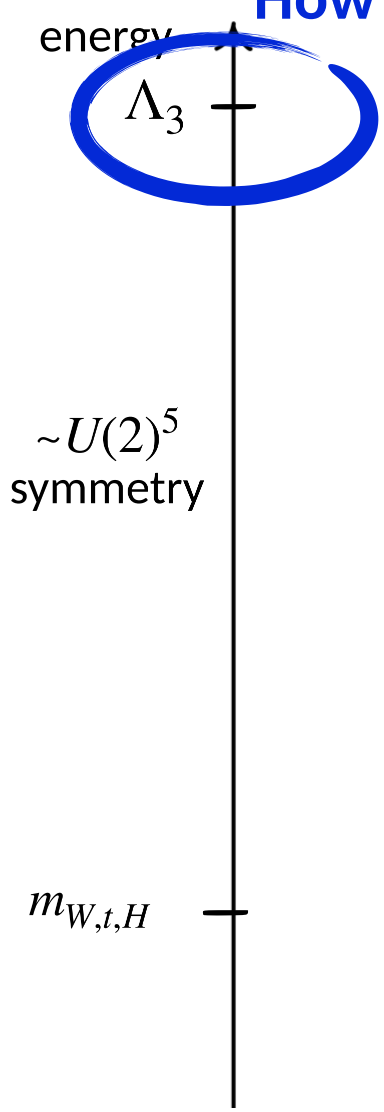
How low?



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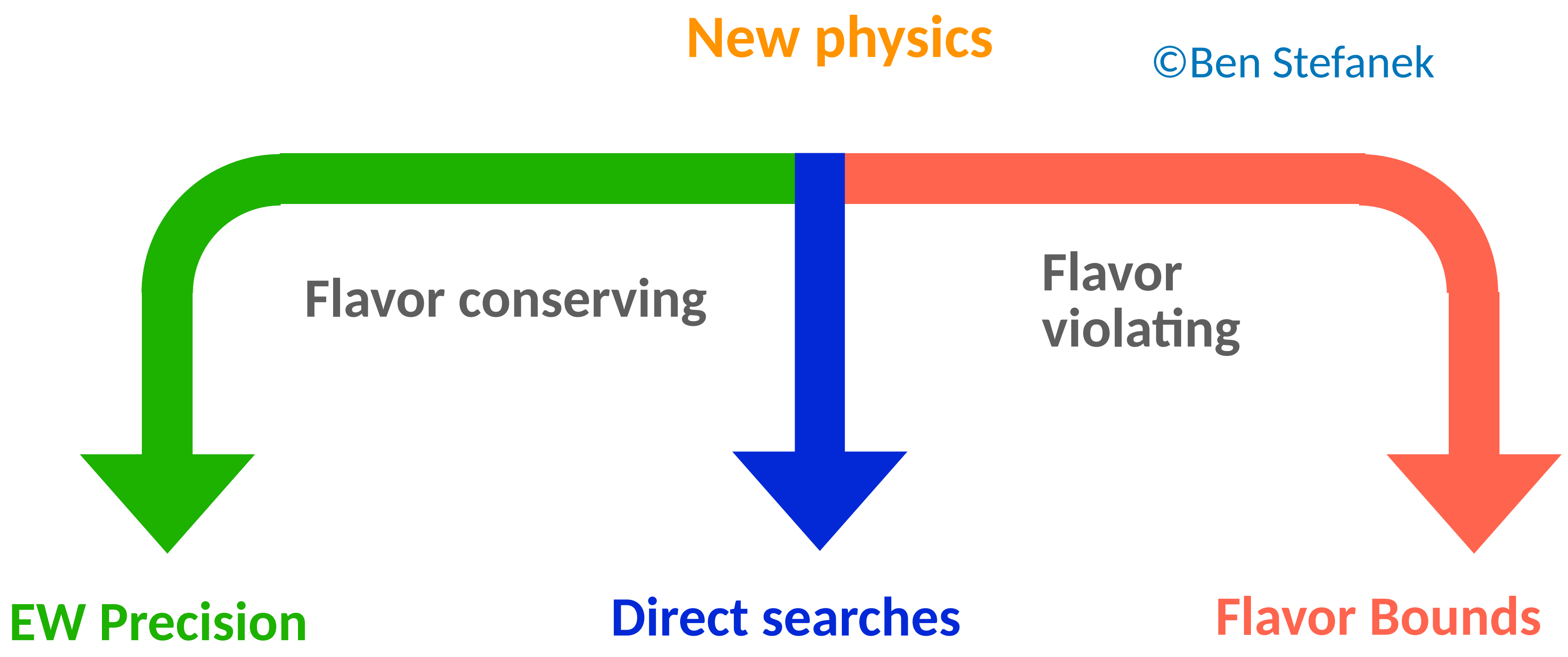
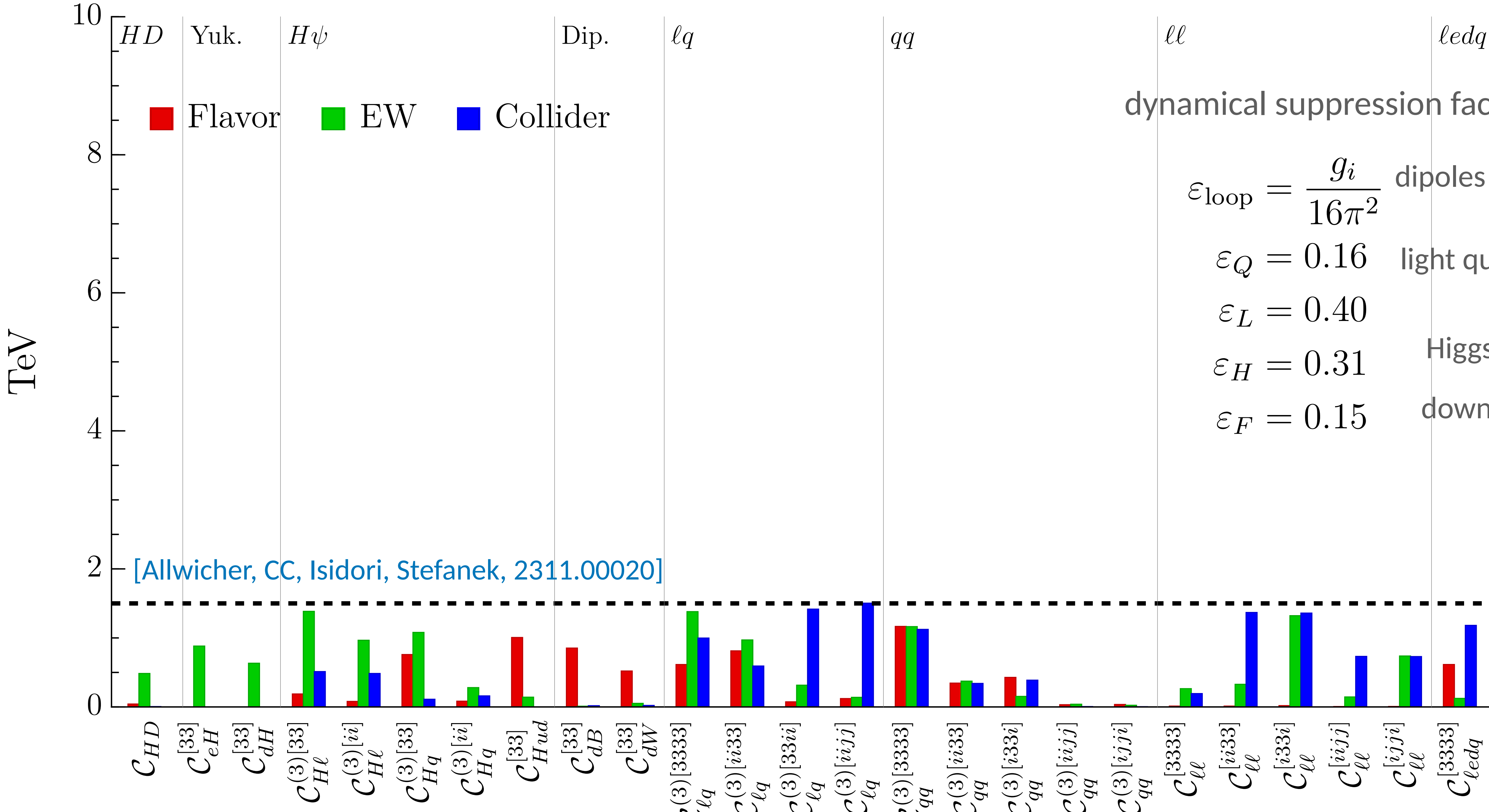
Confronting experiments



Current bounds on flavor-non-universal New Physics

With **current data**, NP mainly coupled to the 3rd family can exist at scales as low as **1-2 TeV**.
Mutatis mutandis, similar results hold in the context of partial compositeness.

[Glioti, Rattazzi, Ricci, Vecchi 2402.09503]



dynamical suppression factors:

$$\varepsilon_{\text{loop}} = \frac{g_i}{16\pi^2}$$ dipoles loop induced

$$\varepsilon_Q = 0.16$$ light quarks & leptons

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$$\varepsilon_H = 0.31$$ Higgs

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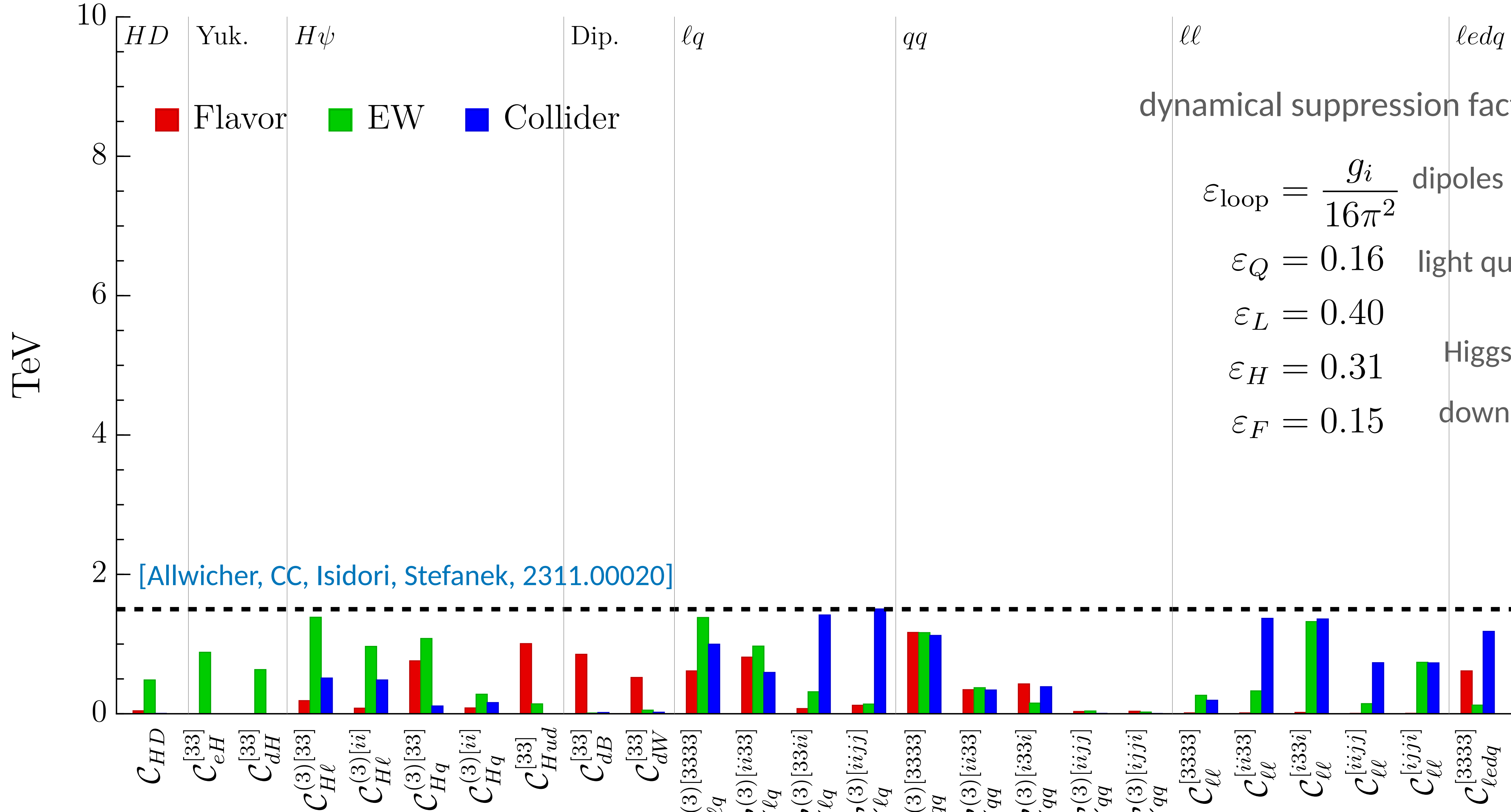
$\Rightarrow$ **3rd family NP is the closest motivated target for experimental exploration.**



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High-pT searches

The largest effect are expected in **3rd-family searches**, taking heavy flavors from the proton.

lepton sector: $pp \to t\bar{t},\ pp \to b\bar{b} \ldots$

quark sector: $pp \to \tau\tau,\ pp \to \tau\nu$

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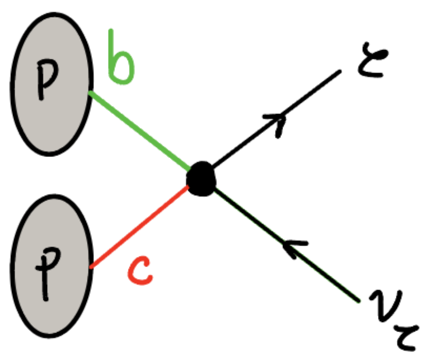
e.g. $pp \to \tau\nu$



$$\frac{\mathscr{L}_{ij} \times |V_{ij}|^2 \times \left(\frac{M_W^2}{\hat{s}} - \epsilon_L\right)^2}{\mathscr{L}_{u\bar{d}+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{M_W^2}{\hat{s}}\right)^2}$$

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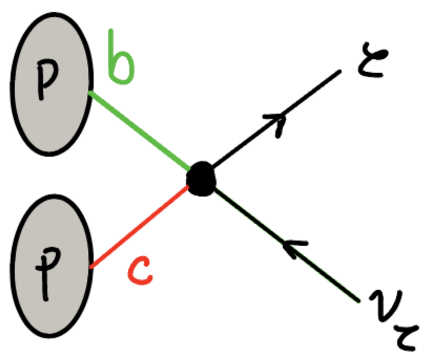

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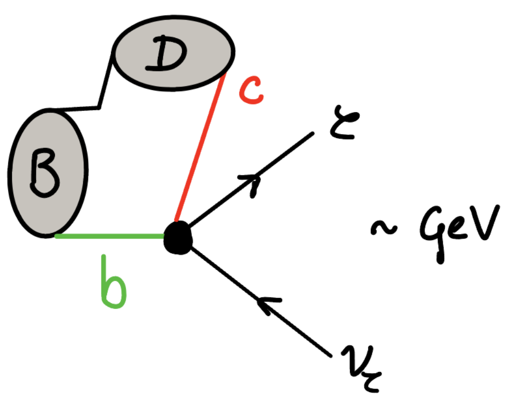

Complementary to low-energy flavor searches: test the same NP in a different energy regime!

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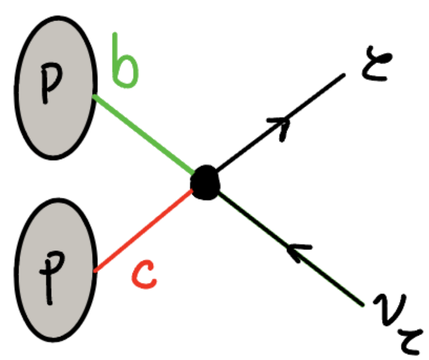

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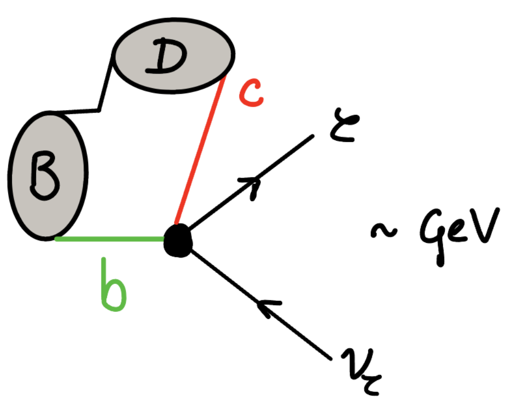

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Important to study also LFV and LFUV, e.g. comparing $pp \to \tau\tau$ to $pp \to \mu\mu$.

[See talks by Kai-Feng Chen]

Indirect searches with B mesons

3 $\to$ light transitions: **B** & **tau** physics

Here focus on **semileptonic** transitions: neutral currents $b \to s(d)\ell\ell^{(\prime)},\ b \to s(d)\nu\nu$

charged currents $b \to c(u)\ell\nu$

Largest effects expected for $\boldsymbol{\tau}, \boldsymbol{\nu_\tau}$.

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- Probing $b \rightarrow s\tau\tau$ directly is experimentally very challenging:

  Even with full LHCb and Belle II dataset, the bounds will exceed the SM by $10^{2\text{-}3}$.

	CURRENT BOUND	PROJECTIONS	SM PREDICTION
$BR(B^+ \rightarrow K^+\tau^+\tau^-)$	$< 2.25 \cdot 10^{-3}$ @ 90% CL Babar	$< 6.5 \cdot 10^{-5}$ @ 90% CL Belle 2 5ab^{-1}	$(1.4 \pm 0.2) \cdot 10^{-7}$
$BR(B_s \rightarrow \tau^+\tau^-)$	$< 6.8 \cdot 10^{-3}$ @ 95% CL LHCb	$< 5 \cdot 10^{-4}$ @ 95% CL LHCb 300 fb^{-1}	$(7.73 \pm 0.49) \cdot 10^{-7}$

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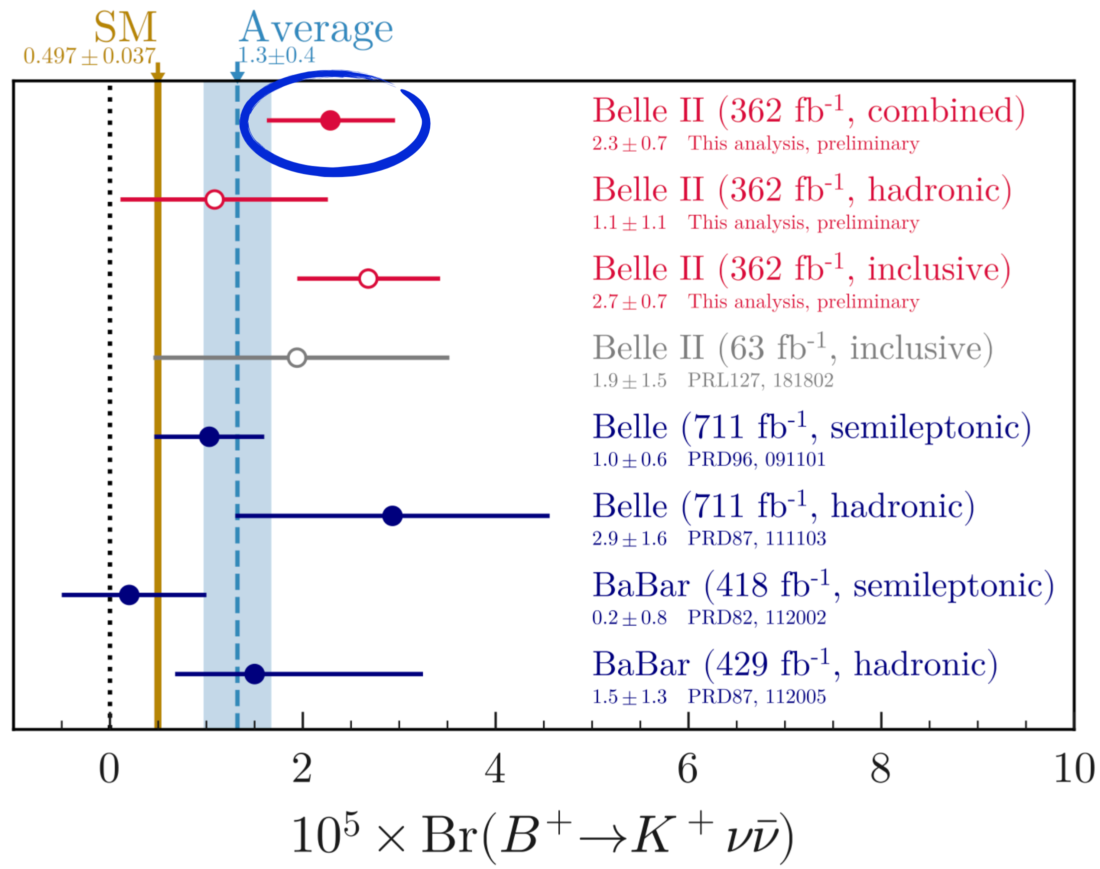
Largest effects expected for τ, ν_τ.

- Currently the **only accessible FCNC** directly sensitive to 3rd generation leptons is $B \to K\nu\bar{\nu}$

  First evidence by Belle II, combined result result 2.7σ above the SM

  Work ongoing on $K^{*0,+}$ and K_S modes.



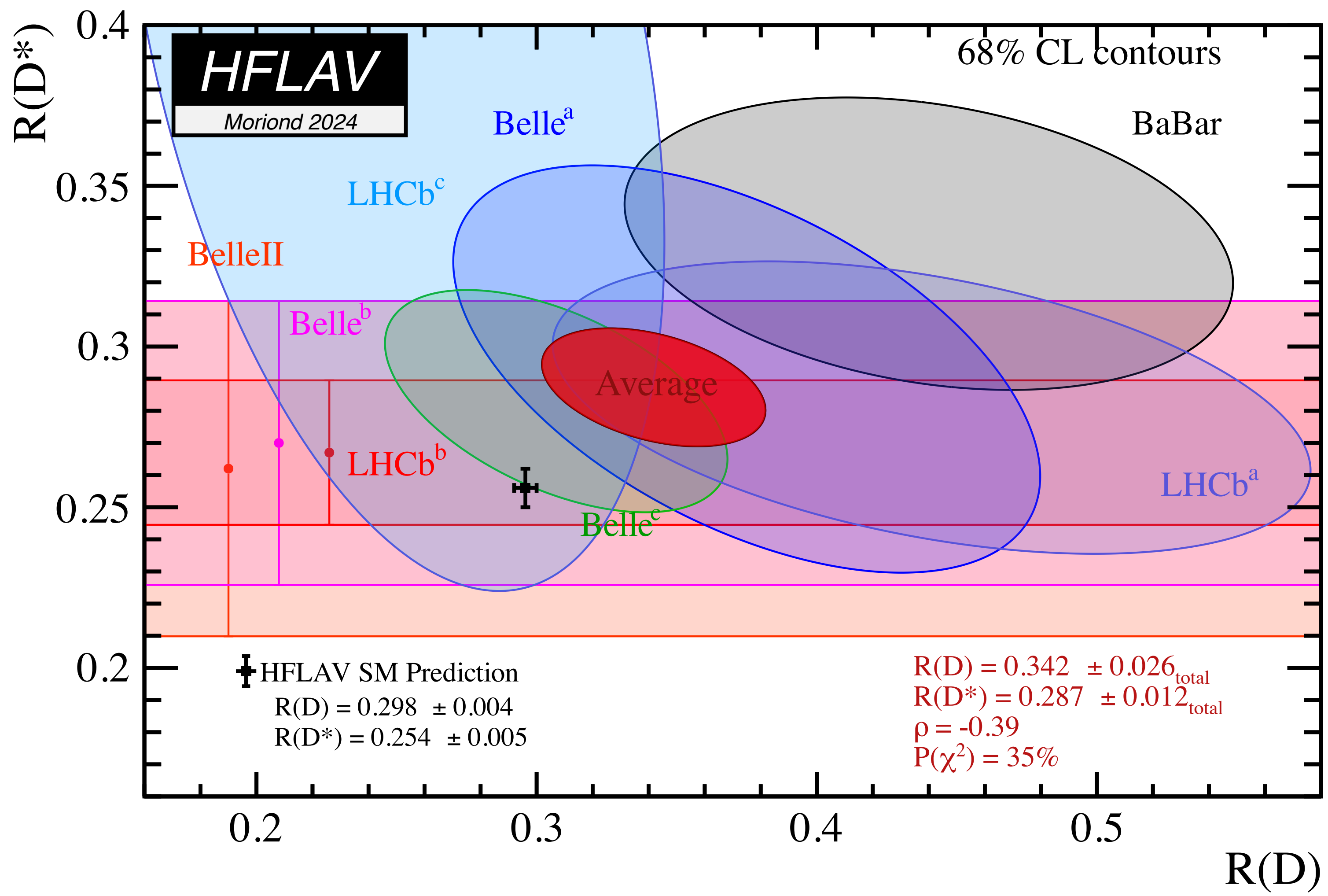
Lepton flavor universality (violation) in $b \to c\ell\nu$

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

$[\ell = e, \mu]$

$\approx 3\,\sigma$ tension w.r.t. SM

$\sim 10\,\%$ enhancement hinting at **excess in** the **tau** mode



[See also talks by Marina Artuso and Eluned Smith]

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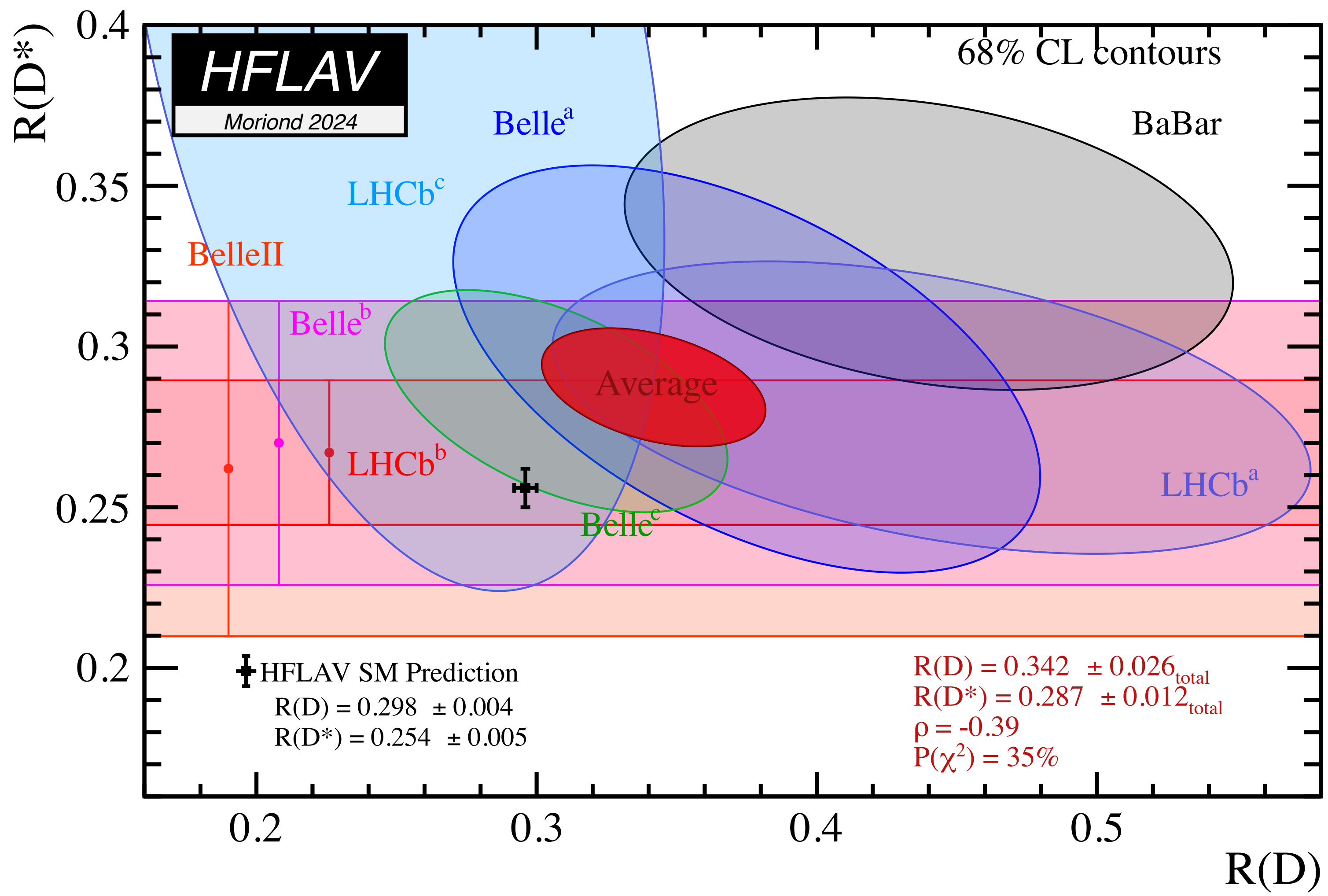

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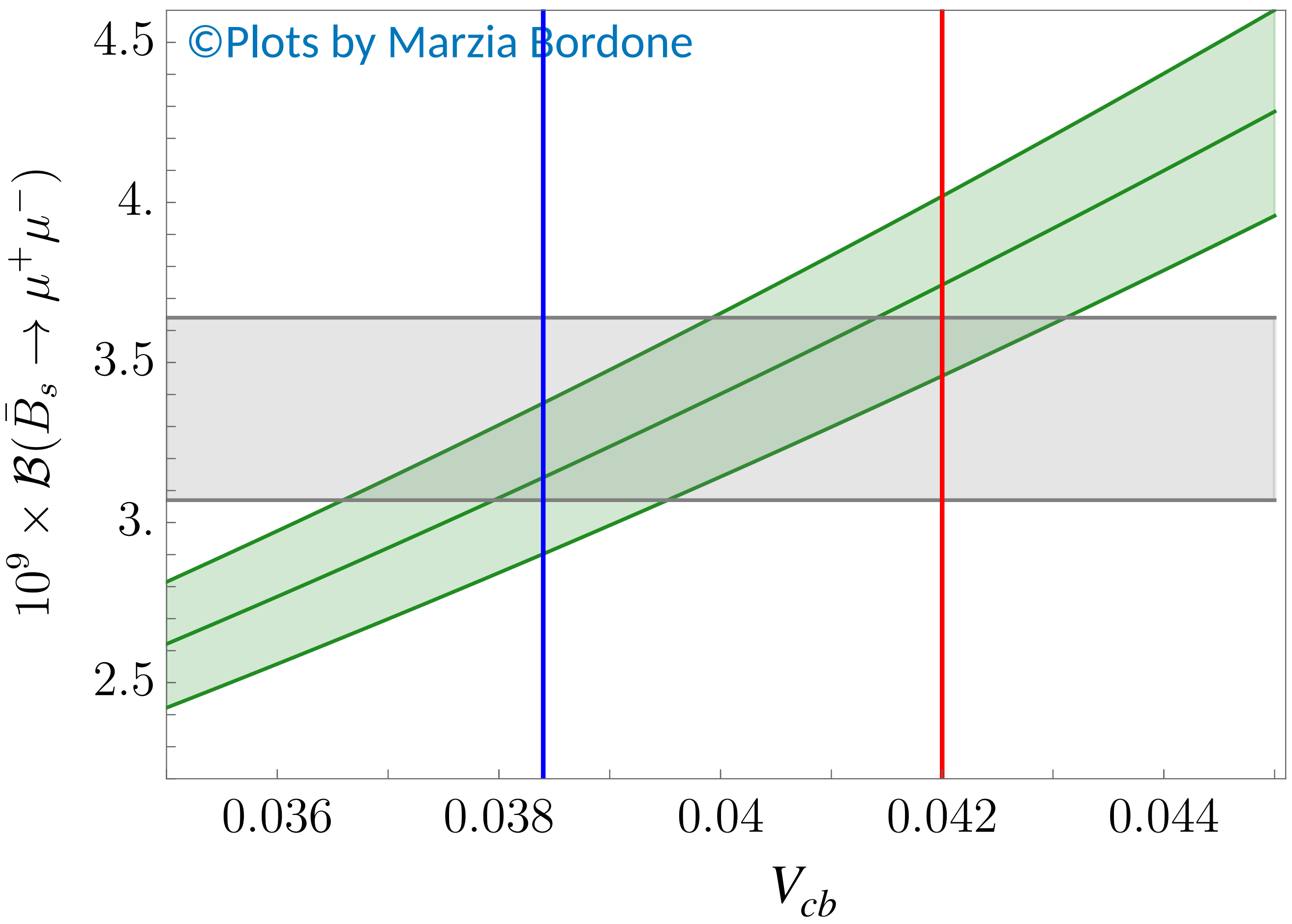
Theoretically clean.

Predictions rely on $B \to D^{(*)}$ form factors: no problem for $B \to D$, on going work to understand some inconsistencies for $B \to D^*$.

The Vcb puzzle



V_{cb} significantly impacts the **prediction** of clean channels, e.g. $B_s \to \mu^+\mu^-$ and $B \to K\nu\bar{\nu}$.

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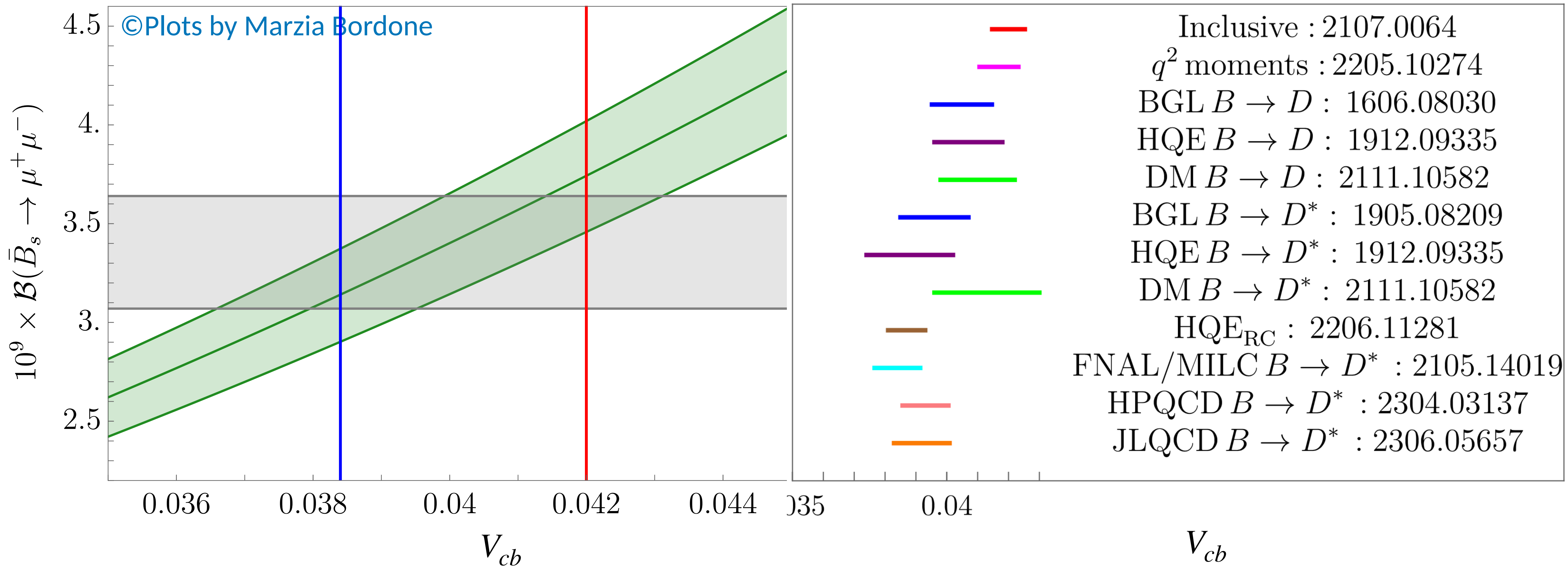

V_{cb} significantly impacts the **prediction** of clean channels, e.g. $B_s \to \mu^+\mu^-$ and $B \to K\nu\bar{\nu}$.

Inclusive and **exclusive** determinations differ by 3 - 4 σ.

- inclusive consistent across various datasets
- less consensus in the exclusive from $B \to D^*$; work in progress to understand the various tensions

$b \to s\mu\mu$

LHC data offer incredible access to the $b \to s\mu\mu$ system:

μ/e **universality ratios,** **differential BRs,** **angular obs.** for **many** different **modes**

$$\frac{BR(H_b \to H_s \mu^+\mu^-)}{BR(H_b \to H_s e^+e^-)}$$

$$\frac{dBR}{dq^2}(H_b \to H_s \mu^+\mu^-)$$

P_5', A_{FB} ...

H_b : B^+, B^0, B_s^0, Λ_b

H_s : K^+, K^0, K^{*+}, K^{*0}, ϕ, pK^-

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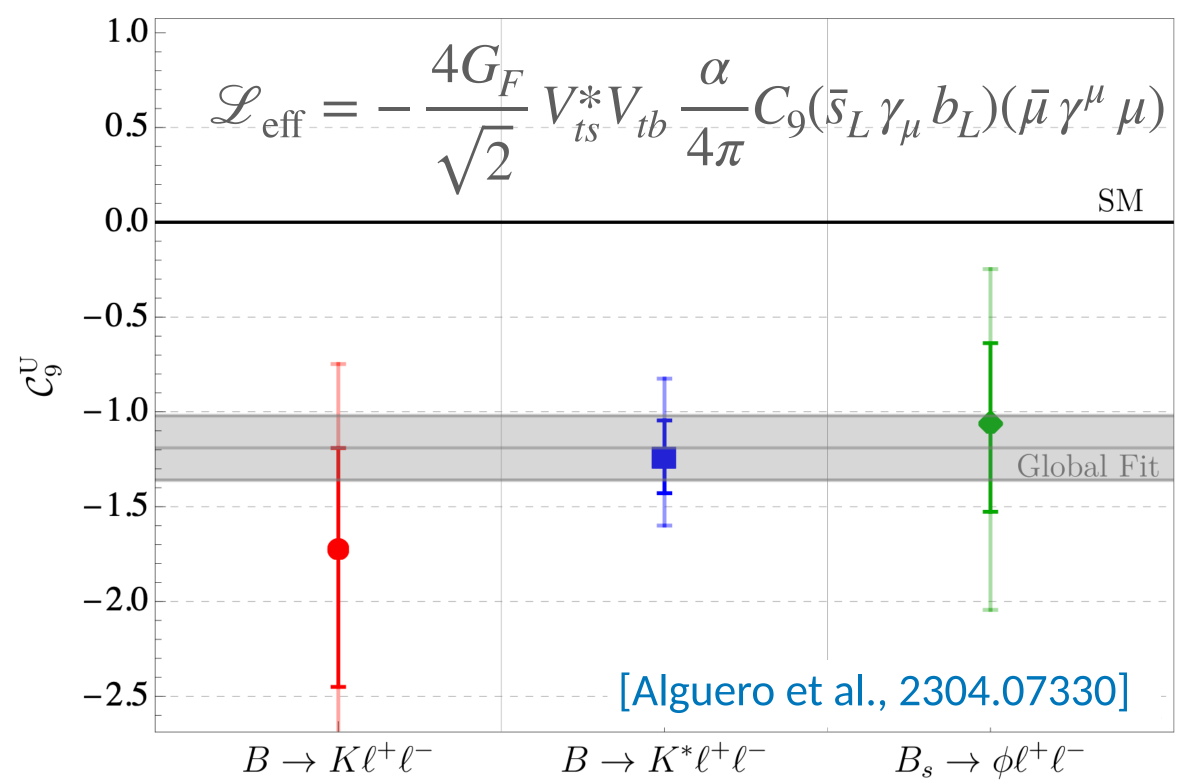
H_b: $B^+, B^0, B_s^0, \Lambda_b$

H_s: $K^+, K^0, K^{*+}, K^{*0}, \phi, pK^-$

Persisting **tensions** in several branching fractions and in the $B \to K^*$ angular analysis.

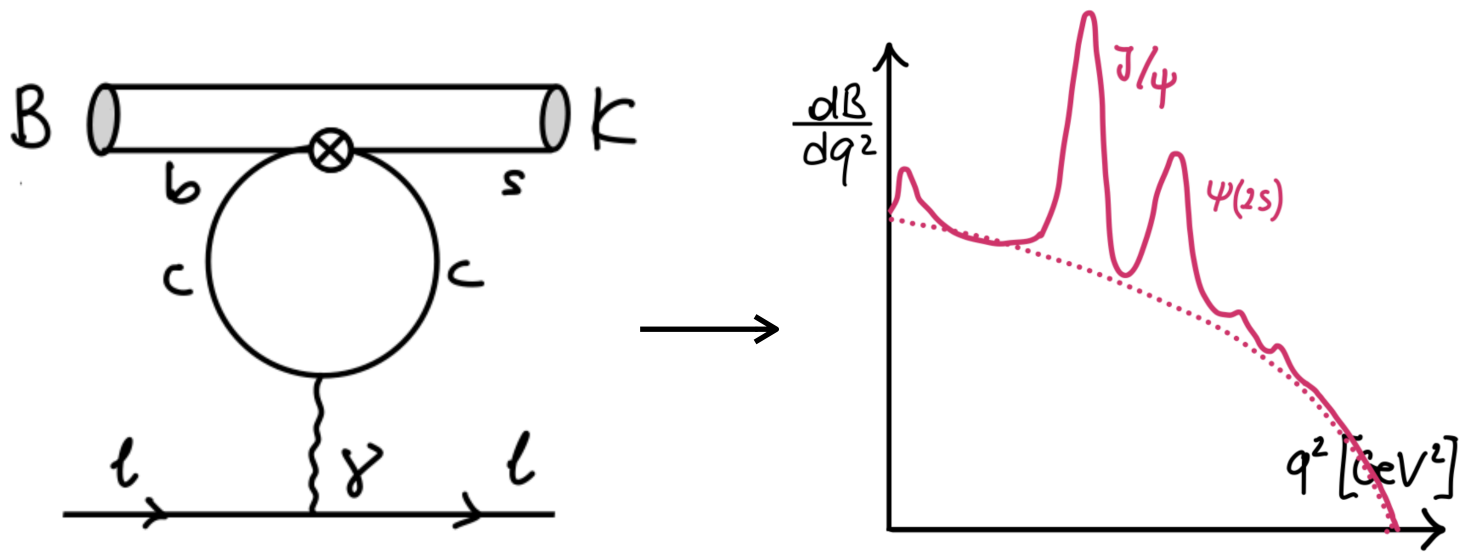
BSM explanation requires $C_9^U \sim 0.25 C_9^{SM}$

NP or underestimated hadronic contribution?



Disentangling long-distance and NP in $b \to s\mu\mu$

[see Eluned Smith's talk]



Ongoing theory and experimental effort to **disentangle long-distance** and **NP**:

- **parametrize** long-distance with dispersion methods/z expansion
- **fit** to q^2 spectrum
- **extract** residual amplitude

SD+LD

known ↑ parametrized ↑ possibly unaccounted for ↑ what we would like to know ↗

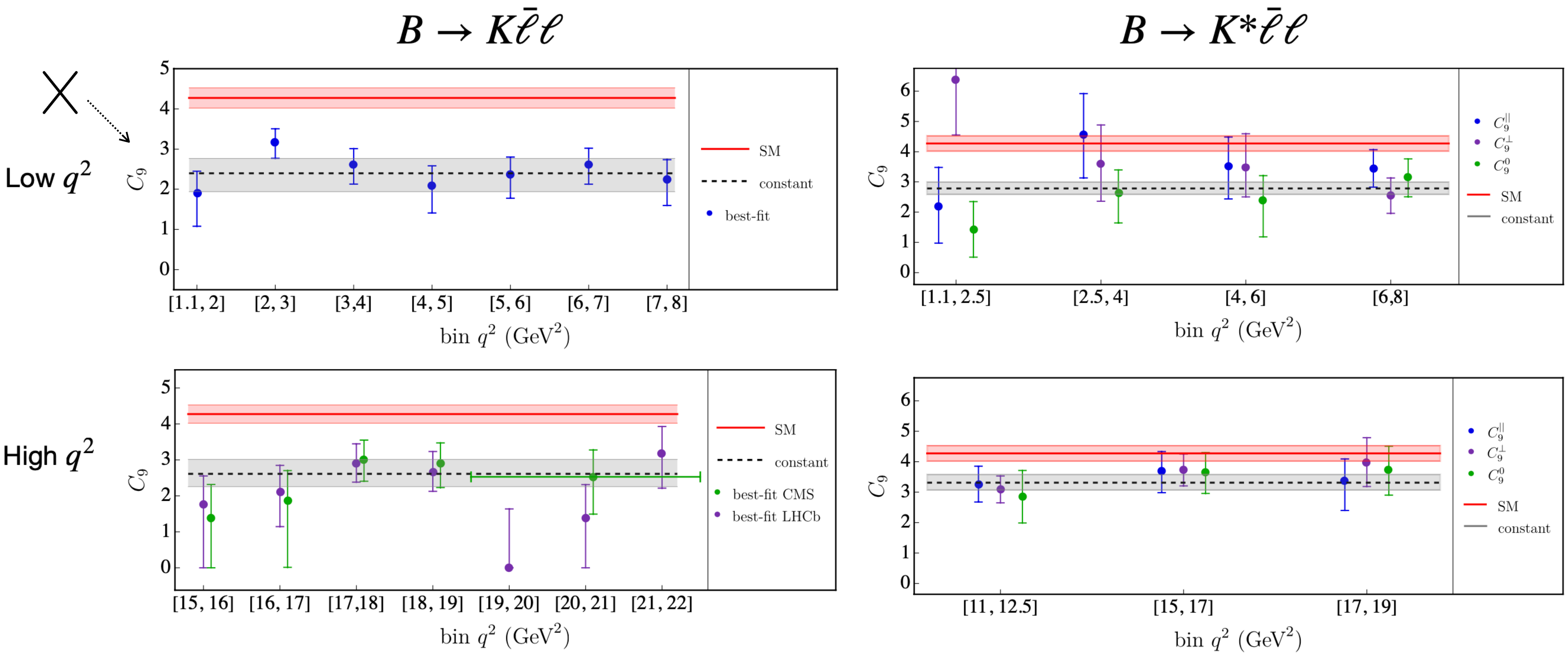
$$C_9(q^2) = C_9^{SM} + Y(q^2) + Y(q^2) + C_9^{NP}$$

$$\underbrace{Y(q^2) + C_9^{NP}}_{X(q^2)}$$

long distance

short distance

Disentangling long-distance QCD and NP in bsll



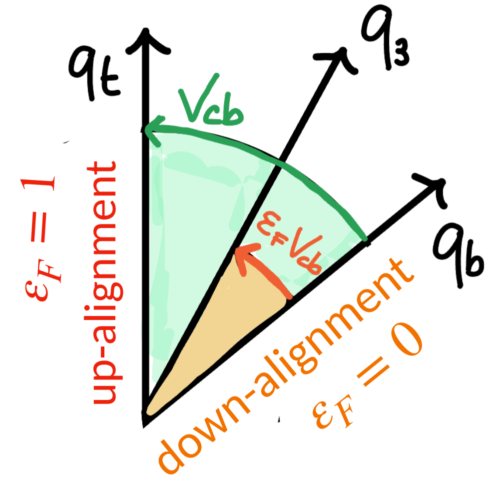
[Bordone, Isidori, Mächler, Tinari 2401.18007]

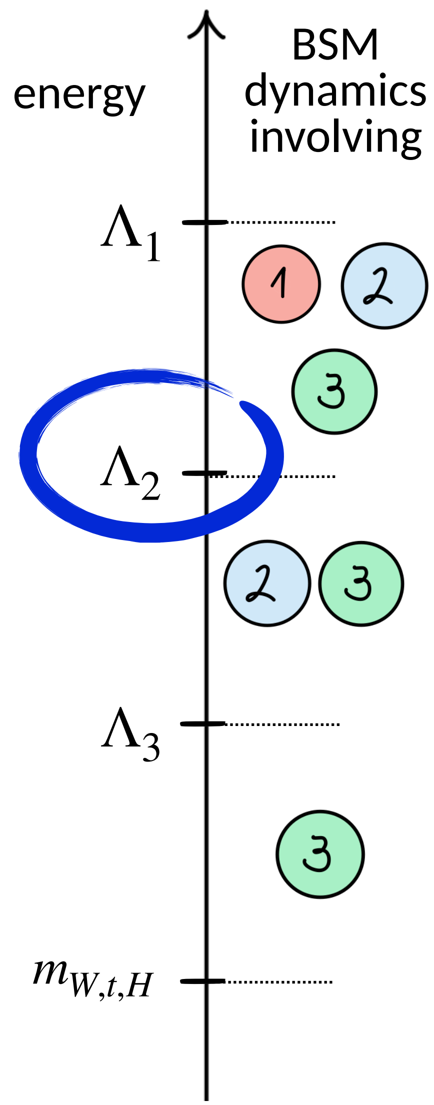
- result seems independent of q² (and λ for K*)
- cannot exclude sizeable long-distance effects with little q² and λ dependence.
  HHChiPT estimate suggests D*Ds/Ds*D*rescattering is too small to mimic $C_9^U \sim 0.25 C_9^{\rm SM}$

Indirect searches with Kaons

Rare kaon decays (s → d FCNCs)

- complementary to b → s in determining the orientation of 3rd family in flavor space
- allow us to probe $U(2)_{q,d}$ breaking in the 21 sector, related to the "next threshold", Λ_2
- For NP modes with a CKM-like structure, typically correlated with $B \to K\nu\bar{\nu}$





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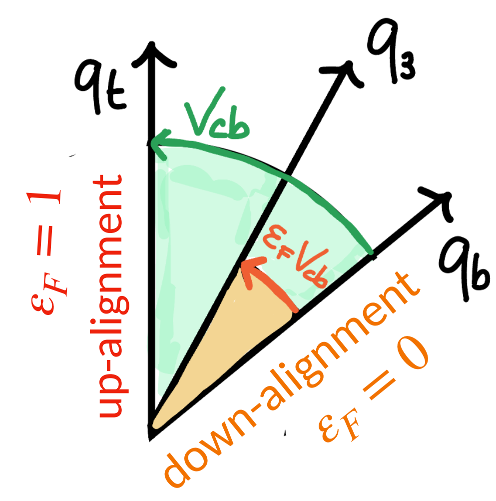
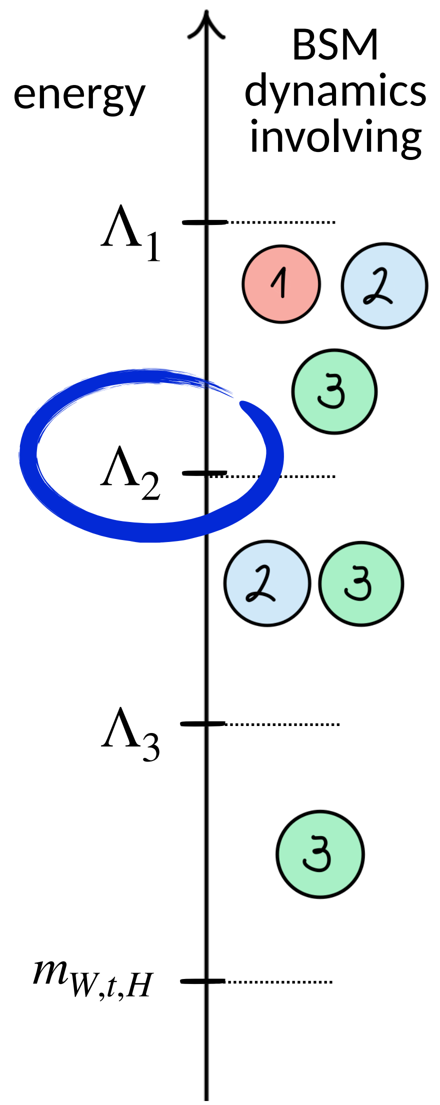


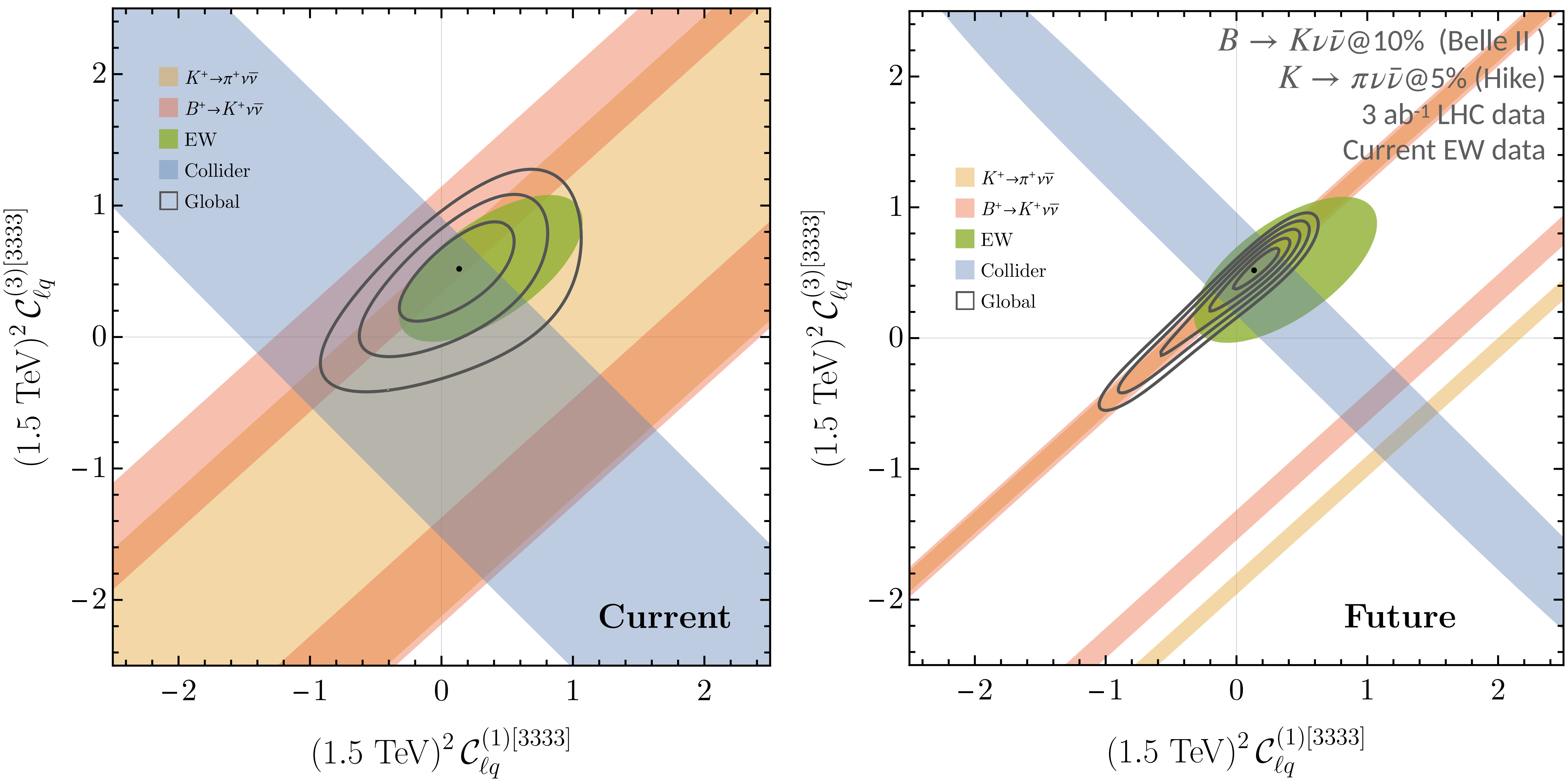


$\boldsymbol{K^+ \to \pi^+ \nu\bar{\nu}}$ is special:

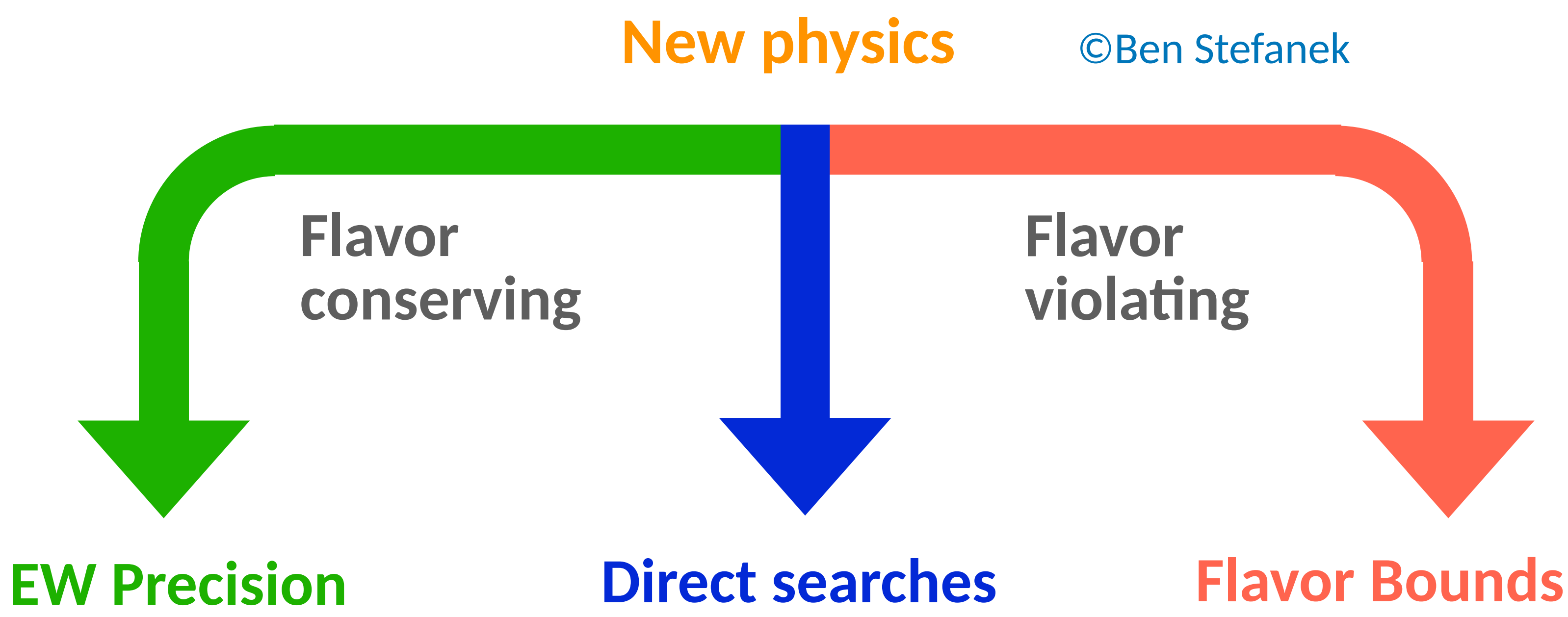
- only rare K decay from which short distance information is accessible
- sole opportunity to get a clean B vs K comparison in the same transition, if similar precision (~10%) is achieved

Combining flavor, collider and electroweak

[Allwicher, CC, Isidori, Stefanek, 2311.00020]

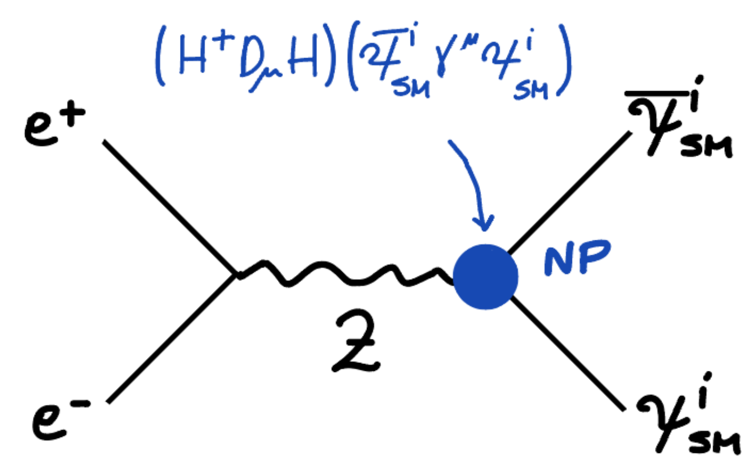


Electroweak Precision as a Flavor Probe



3rd family NP is "**protected**" against direct searches at the LHC & flavor bounds, but not against **EW precision tests**.

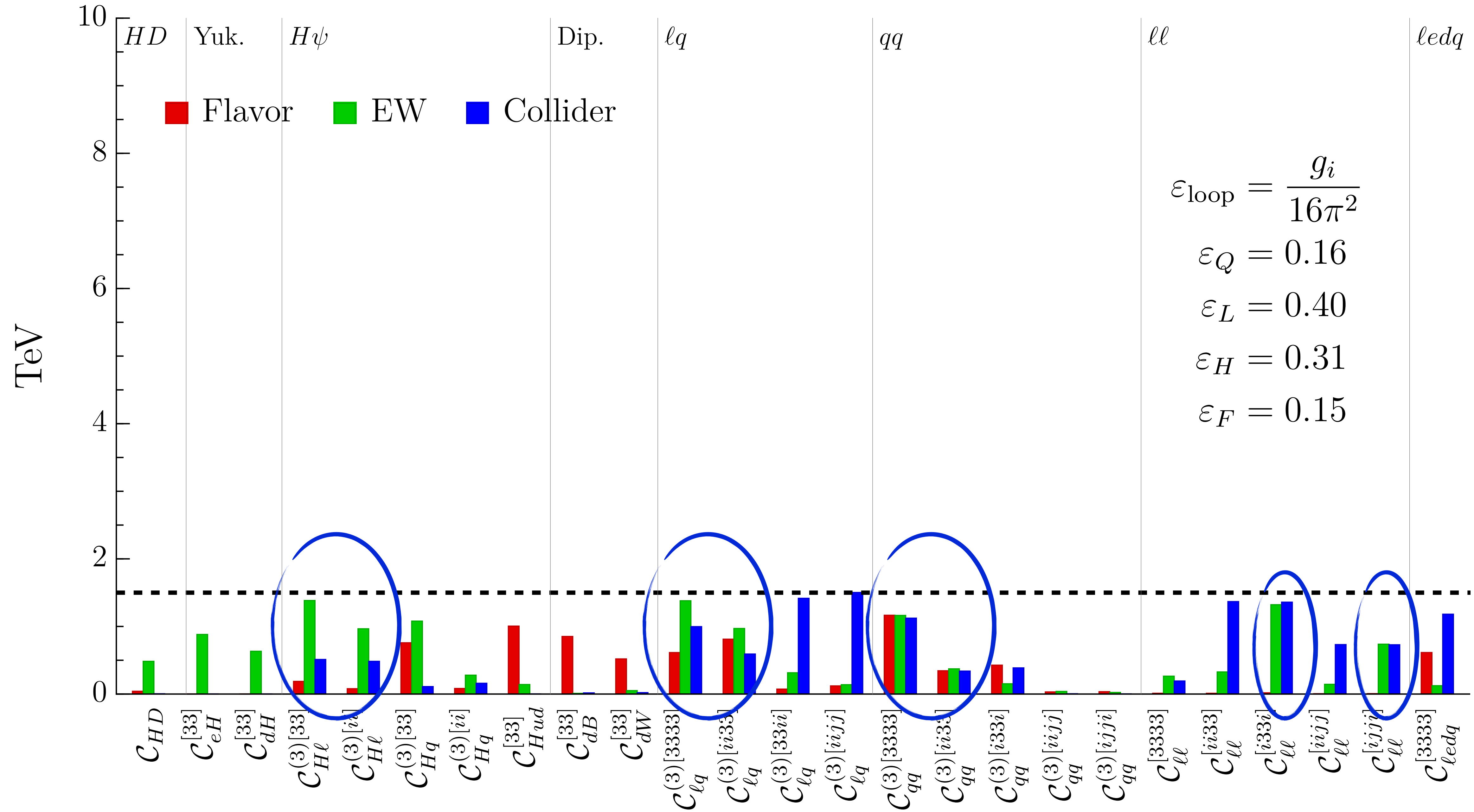
At a Z factory, we can use the flavor blindness of the SM gauge interactions to indirectly probe NP coupled to **any** generation.



⇒ EWPT are powerful probes of flavor non-universality

Perspectives at Tera Z: EW precision tests

⇒ **LEP** bounds have a strength **comparable** to current **direct searches** for operators involving mostly the 3rd generation!



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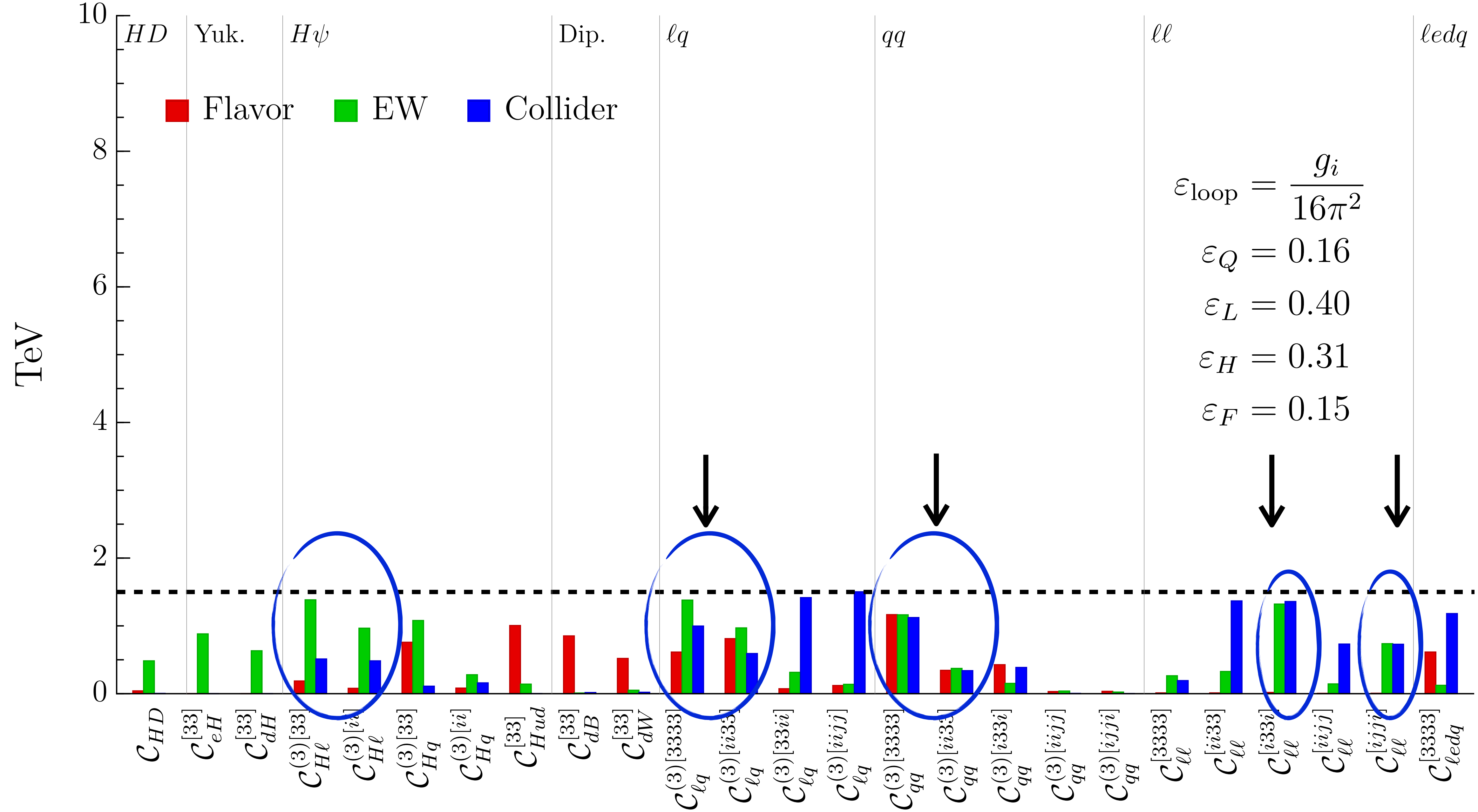
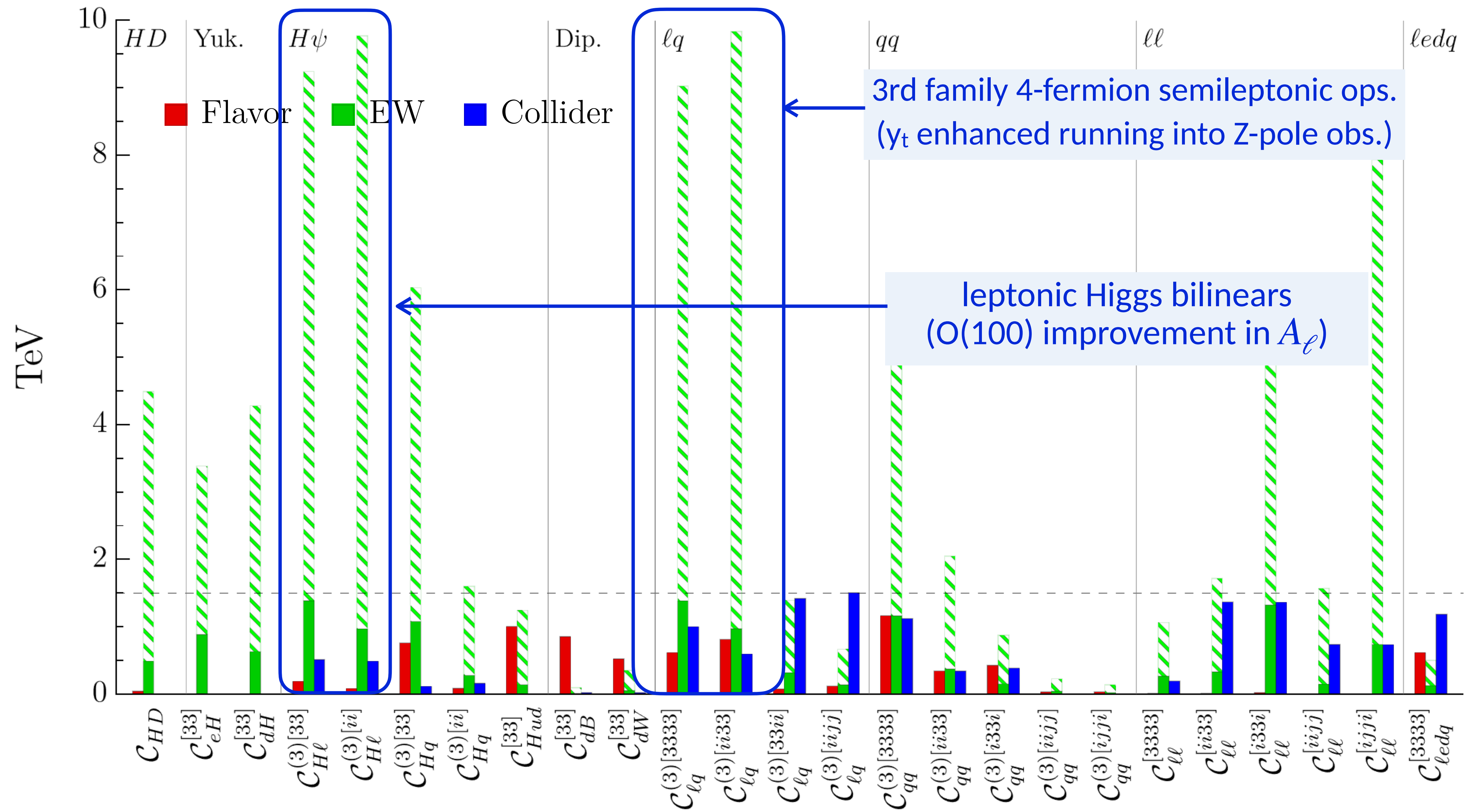


Perspectives at Tera Z: EW precision tests

⇒ **LEP** bounds have a strength **comparable** to current **direct searches** for operators involving mostly the 3rd generation!

With $\approx 10^5$ more Z bosons than LEP, a tera-Z machine could probe 3rd-family NP **up to ~ 10 TeV**!



Perspectives at Tera Z: heavy flavors

A tera-Z machine is a powerful **heavy-flavor factory**. For **FCC-ee:**

Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B_s^0/\overline{B}_s^0$	$B_c^+/\overline{B}_c^-$	$\Lambda_b/\overline{\Lambda}_b$	$c\overline{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

[FCC Snowmass Summary, 2203.06520]

Clean environment and **boosted** topologies are **advantages** with respect to Belle II & LHCb

Will allow for major advancement in B & tau physics. Among others:

- precise measurements of $b \to s\tau\tau$ & $b \to s\nu\nu$, incl. $b \to d$ counterpart
  e.g. $B \to K\tau\tau$: if SM-like, few · 1000 reconstructed decays → O(5%) precision on BR!
- access to heavier b-hadrons: B_c , B_s , Λ_b
- LFU tests in $\boldsymbol{\tau}$ decays at the 10^{-4} level

Conclusions

LHC NP at **TeV scale** requires flavor protection. Models with **NP coupled mostly to the 3rd family** are the **closest target**, and have a strong theoretical motivation.

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Many **signatures** to look for at **existing experiments**:

- direct 3rd family searches
- precision measurements in B, K and tau decays

These are the best path to discovery until the next collider.

Conclusions

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Looking forward, a tera-Z machine like FCC-ee is ideal in testing these scenarios

- unprecedentedly precise **EWPT** that cannot be bypassed by flavor symmetries
- major advancements in **tau** and **B physics**, with access to new channels

If we firmly establish **any** anomaly, it will help design a future hadron collider, potentially creating a no-lose situation for **FCChh**.