The Flavor Path to New Physics: Status and Future Prospects

Claudia Cornella (CERN)

September 23, 2025 || DESY

Setting the stage

Questions I'd like to discuss:

- What does current data tell us about the flavor of physics *beyond* the SM? Connection to the SM flavor puzzle?
- How will this change in the future, with existing and future facilities?
- Which theory challenges *within* the SM do we need to face to profit from the expected experimental precision in flavor-changing processes?

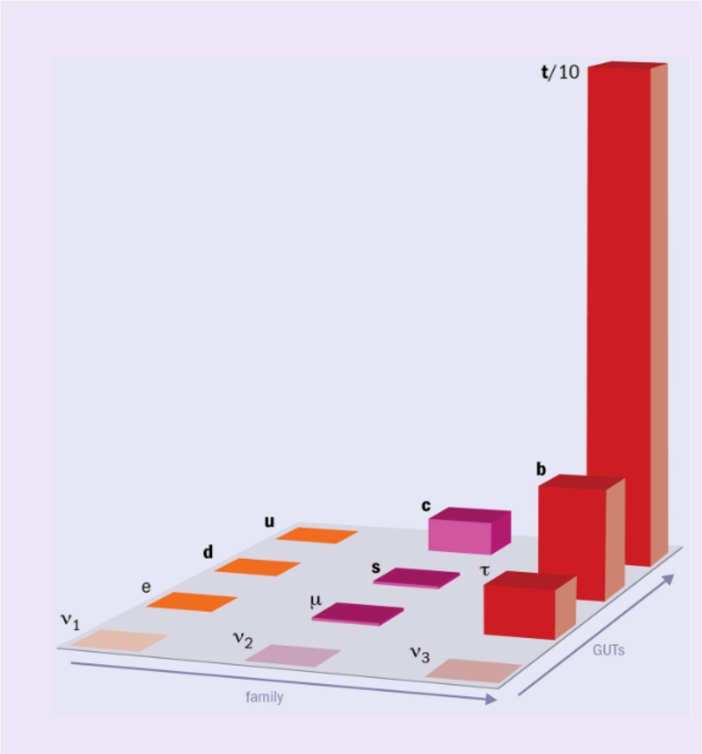
Caveat: I will do so from a specific angle — focus on flavor changing transitions involving quarks & heavy new physics scenarios.

Flavor in the Standard Model: puzzling aspects

SM flavor puzzle = a series of puzzling observations

3 copies x species, identical from the point of view of gauge interactions, yet seen very differently by the Higgs
[and by BSM giving mass to neutrinos]

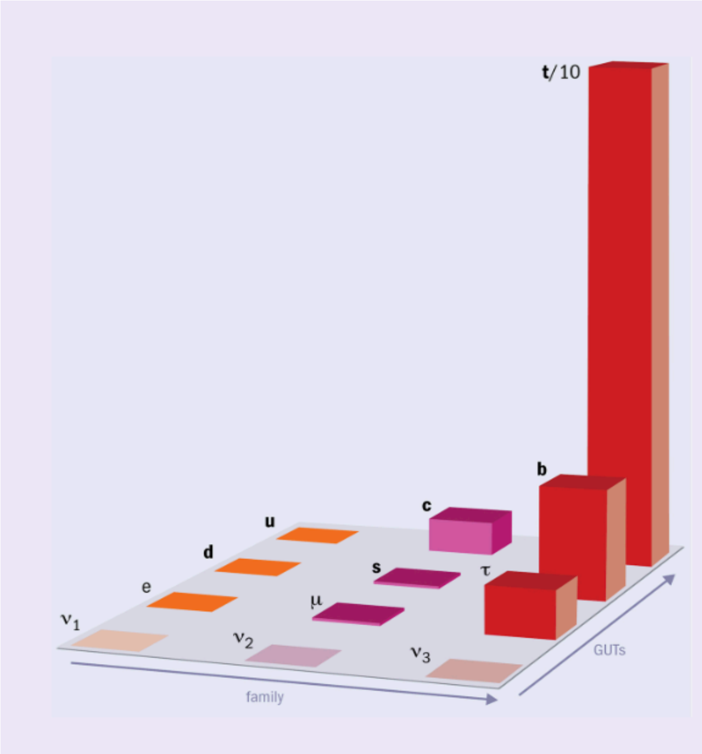
- 12 orders of magnitude from neutrinos to the top mass
- pronounced mass hierarchies for charged fermions
- mixing looks very different in lepton vs quark sector



Flavor in the Standard Model: puzzling aspects

SM flavor puzzle = a series of puzzling observations

3 copies x species, identical from the point of view of gauge interactions, yet seen very differently by the Higgs
[and by BSM giving mass to neutrinos]



- 12 orders of magnitude from neutrinos to the top mass
- pronounced mass hierarchies for charged fermions
- mixing looks very different in lepton vs quark sector

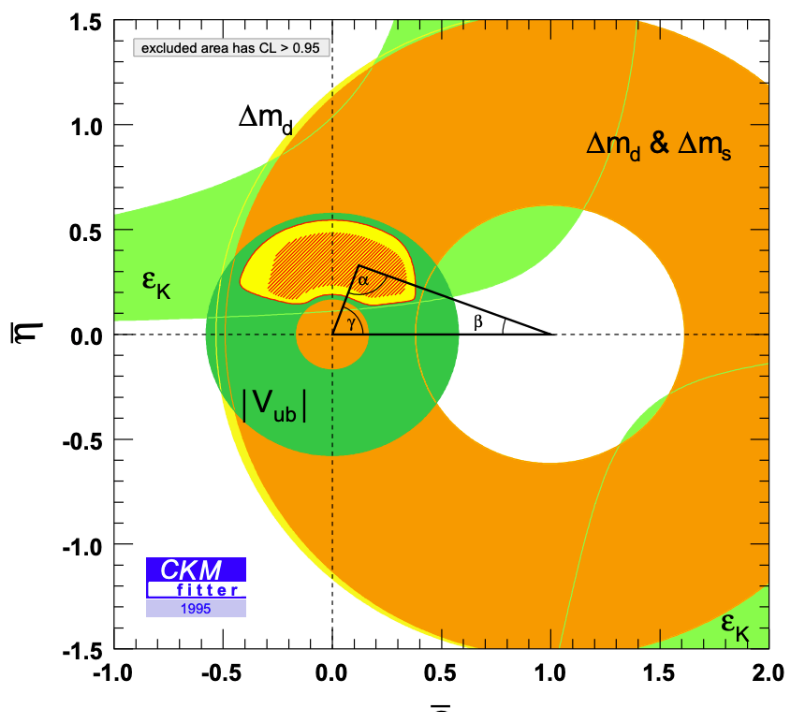
No explanation in the SM: just free parameters "fixed" via measurements. T*echnically natural,* yet suggestive of an organising principle (necessarily) *beyond* the SM.

- Many ideas: Froggatt-Nielsen, Randall-Sundrum, GUTs, Flavor deconstruction…
- Not pointing to specific scales unless linked to other "problems" (hierarchy/gauge coupling unification)

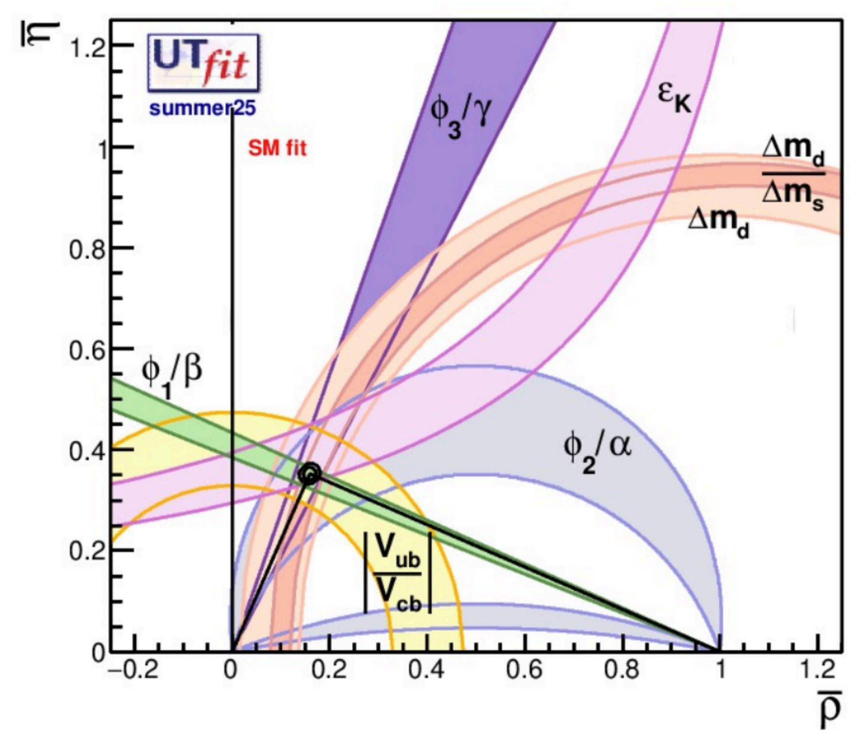
Flavor in the Standard Model: strong predictions

Despite its mysterious origin, the flavor structure of the SM leads to a set of remarkably **successful predictions**:

- absence of charged lepton flavor violation [up to small mν effects]
- lepton flavor universality [up to ml effects]
- suppression of flavor changing neutral currents [GIM + loop]
- unitarity of the CKM



1995



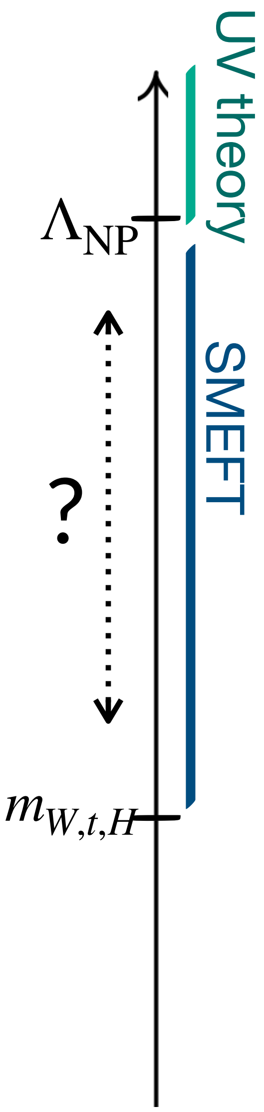
2025

*

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

The scale of New Physics, from theory

We have many more reasons beyond the flavor puzzle to know that BSM exists — yet the absence of direct hints suggests a mass gap. How large? **What is the scale of NP?**



The scale of New Physics, from theory

We have many more reasons beyond the flavor puzzle to know that BSM exists — yet the absence of direct hints suggests a mass gap. How large? **What is the scale of NP?**

Top-down considerations

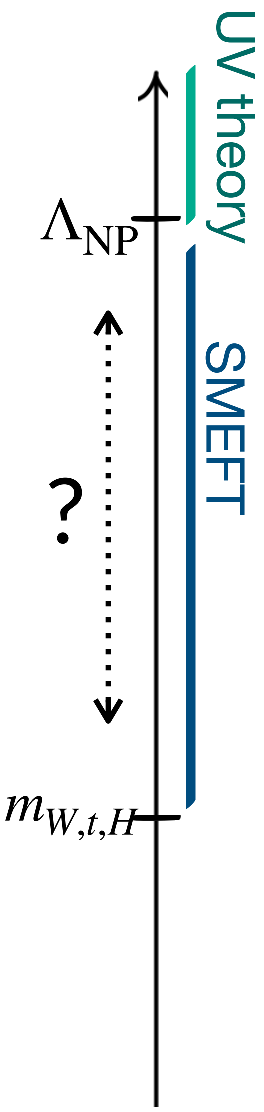
- the main hint for a "low" Λ is a "natural" solution to the hierarchy problem

  Any heavy BSM coupled to the Higgs destabilises m_h

  ⇒Need some NP coupled to Higgs & top at Λ ~TeV to stabilise it.

  In general, these solutions modify the Yukawa sector: necessarily connected to flavor.

- Other challenges (dark matter, dark energy, inflation…) are more difficult to link to a Λ accessible by colliders — *Exception*: the WIMP miracle



The scale of New Physics, from data

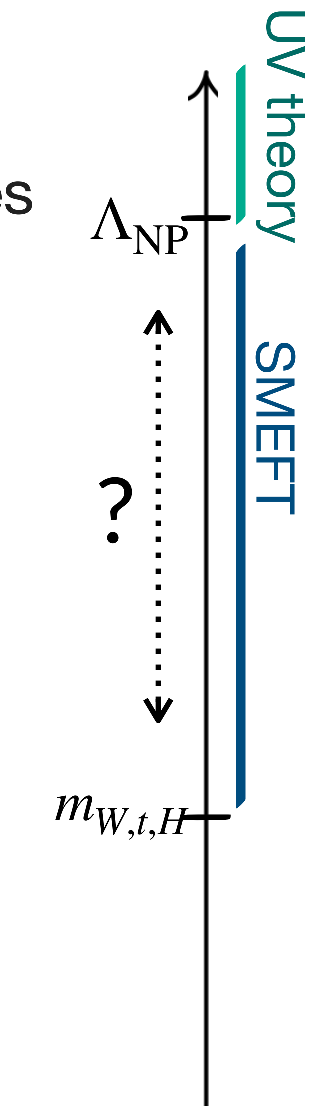
We have many more reasons beyond the flavor puzzle to know that BSM exists — yet the absence of direct hints suggests a mass gap. How large? **What is the scale of NP?**

Bottom-up considerations

- Indirect searches at $E \ll \Lambda$ can pinpoint Λ far beyond directly accessible scales
  many historical precedents: m_c from K mixing, m_t from EWPOs

- best performed with processes that we can predict and measure precisely
  - null tests proton decay (~~U(1)~~$_B$), $0\nu\beta\beta$ (~~U(1)~~$_L$), $\mu \to e\gamma$ ((~~U(1)~~$_{Li}$), LFUV
  - flavor-changing transitions
  - EWPOs

- likely where we'll see the biggest experimental progress in the next 50 yrs
  @ existing & planned facilities: (HL-)LHC, KEK, JPARC…
  @ a future Tera Z factory



The scale of New Physics, from data

- the **SMEFT** is the tool to translate data from different sectors & energy regimes into constraints on heavy new physics. [see E. Vryonidou's talk]

Constraints on WCs can be interpreted as bounds on an effective NP scale:

$$\Lambda^i_{\rm eff} = \frac{\Lambda}{\sqrt{C_i}} \sim \frac{M}{g}$$

The scale of New Physics, from data

- the **SMEFT** is <u>the</u> tool to translate data from different sectors & energy regimes into constraints on heavy new physics. [see E. Vryonidou's talk]

Constraints on WCs can be interpreted as bounds on an effective NP scale:

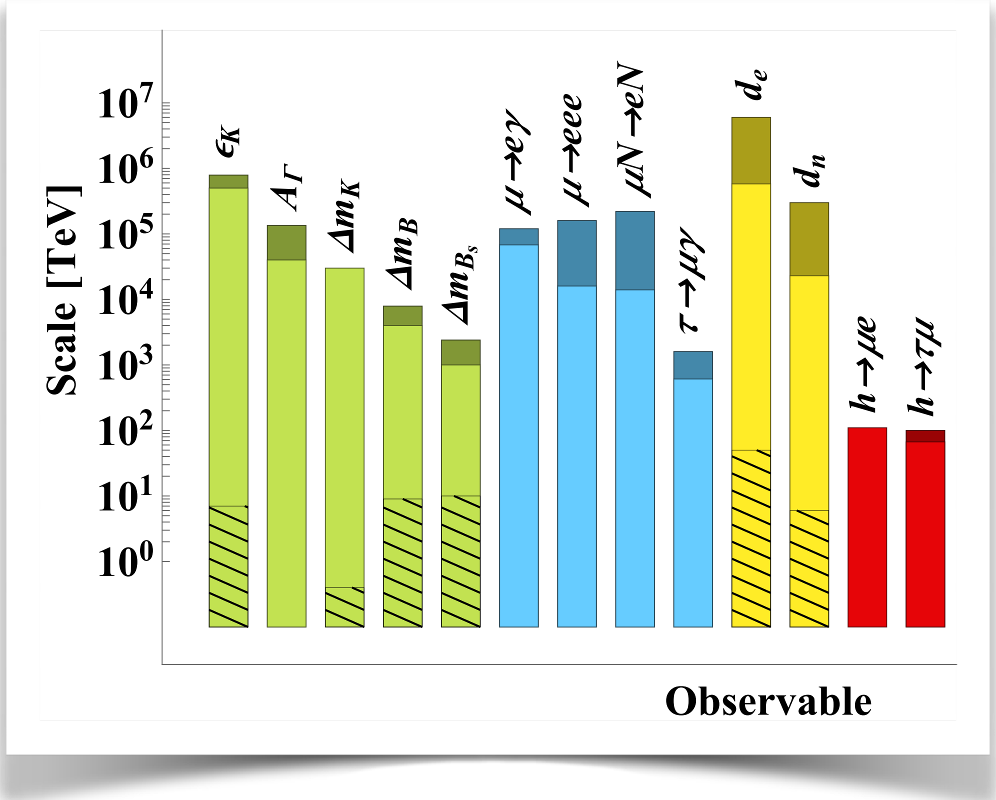
$$\Lambda^i_{\rm eff} = \frac{\Lambda}{\sqrt{C_i}} \sim \frac{M}{g}$$

- When looking at flavor data through this EFT lens, one encounters the well known

New Physics flavor puzzle

nothing forbids bad violations of the SM accidental symmetries, yet we don't see any

$$\Lambda^{\rm FV}_{\rm eff} \gtrsim 10^{4-6}\,{\rm TeV}$$



The scale of New Physics, from flavor data

Two "extreme" options:

New physics is anarchic:

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

- Very heavy, hence untestable
- Higgs stabilised in some other way
  [relaxion, landscape..?]
- unclear how flavor patterns could arise

New physics has a flavor structure:

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

- possibly testable,
- possibly still natural,
- possibly related to the flavor puzzle

The scale of New Physics, from flavor data

Two “extreme” options:

New physics is anarchic:

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

- Very heavy, hence untestable
- Higgs stabilised in some other way
  [relaxion, landscape..?]
- unclear how flavor patterns could arise

New physics has a flavor structure:

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

- possibly testable,
- possibly still natural,
- possibly related to the flavor puzzle

Which one?

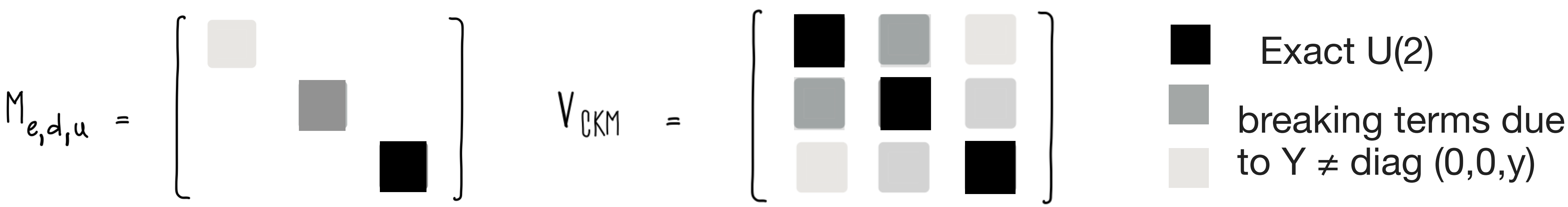
Approximate Flavor Symmetries in the SM and Beyond

Given that we're interested in "reachable" new physics scenarios, we can use the **accidental symmetries of the SM** as guidance.

Approximate Flavor Symmetries in the SM and Beyond

Given that we're interested in "reachable" new physics scenarios, we can use the **accidental symmetries of the SM** as guidance.

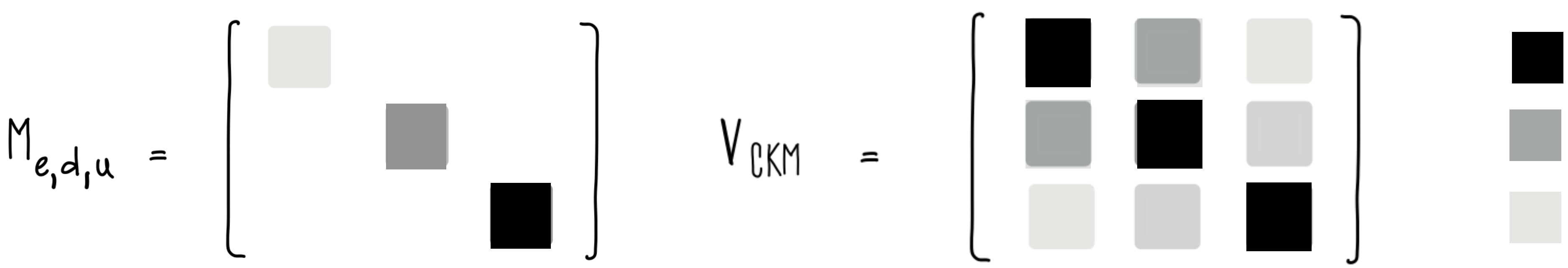
The SM has an approximate $U(2)^5$ flavor symmetry*: [*enlarged to $U(3)^3 \times U(2)_u \times U(2)_q \times U(2)$ when considering only $y_t \neq 0$]



Approximate Flavor Symmetries in the SM and Beyond

Given that we're interested in "reachable" new physics scenarios, we can use the **accidental symmetries of the SM** as guidance.

The SM has an approximate $U(2)^5$ flavor symmetry*: [*enlarged to $U(3)^3 \times U(2)_u \times U(2)_q \times U(2)$ when considering only $y_t \neq 0$]



Exact U(2)

breaking terms due to Y ≠ diag (0,0,y)

Seems to hold also beyond the SM — at least if NP is not too far. In other words,

if there is NP "close by" (< 10^4 TeV), it must respect a U(2)-like structure

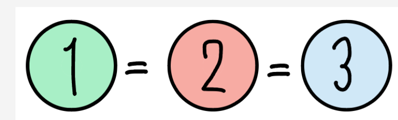
Approximate Flavor Symmetries in the SM and Beyond

This paradigm can host two very different classes of NP models:

Approximate Flavor Symmetries in the SM and Beyond

This paradigm can host two very different classes of NP models:

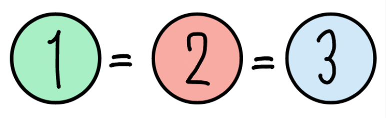
MFV-like ("universal") New Physics



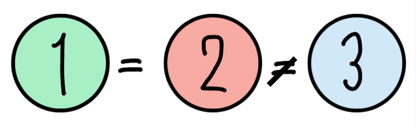
Approximate Flavor Symmetries in the SM and Beyond

This paradigm can host two very different classes of NP models:

MFV-like ("universal") New Physics



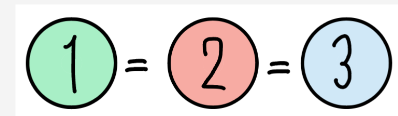
Non-universal (3rd family) New Physics



Approximate Flavor Symmetries in the SM and Beyond

This paradigm can host two very different classes of NP models:

MFV-like ("universal") New Physics

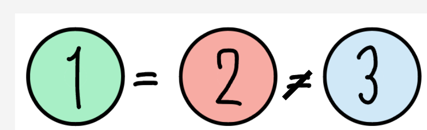


- w/o additional assumptions, $U(2)^n \approx$ MFV:
  - Yukawas *only* sources of flavor violation.
  - describes approximately flavor-universal NP

- CKM-like suppression of FCNCs, but unsuppressed valence-quark couplings

  $\Rightarrow$ high pT data pushes $\Lambda \gtrsim O(10)$ TeV

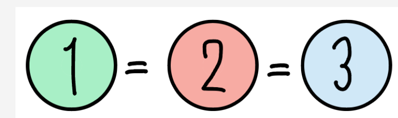
Non-universal (3rd family) New Physics



Approximate Flavor Symmetries in the SM and Beyond

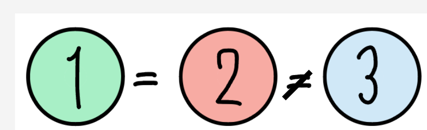
This paradigm can host two very different classes of NP models:

MFV-like (“universal”) New Physics



- w/o additional assumptions, $U(2)^n \approx$ MFV:
  - Yukawas *only* sources of flavor violation.
  - describes approximately flavor-universal NP
- CKM-like suppression of FCNCs, but unsuppressed valence-quark couplings
  $\Rightarrow$ high pT data pushes $\Lambda \gtrsim O(10)$ TeV

Non-universal (3rd family) New Physics

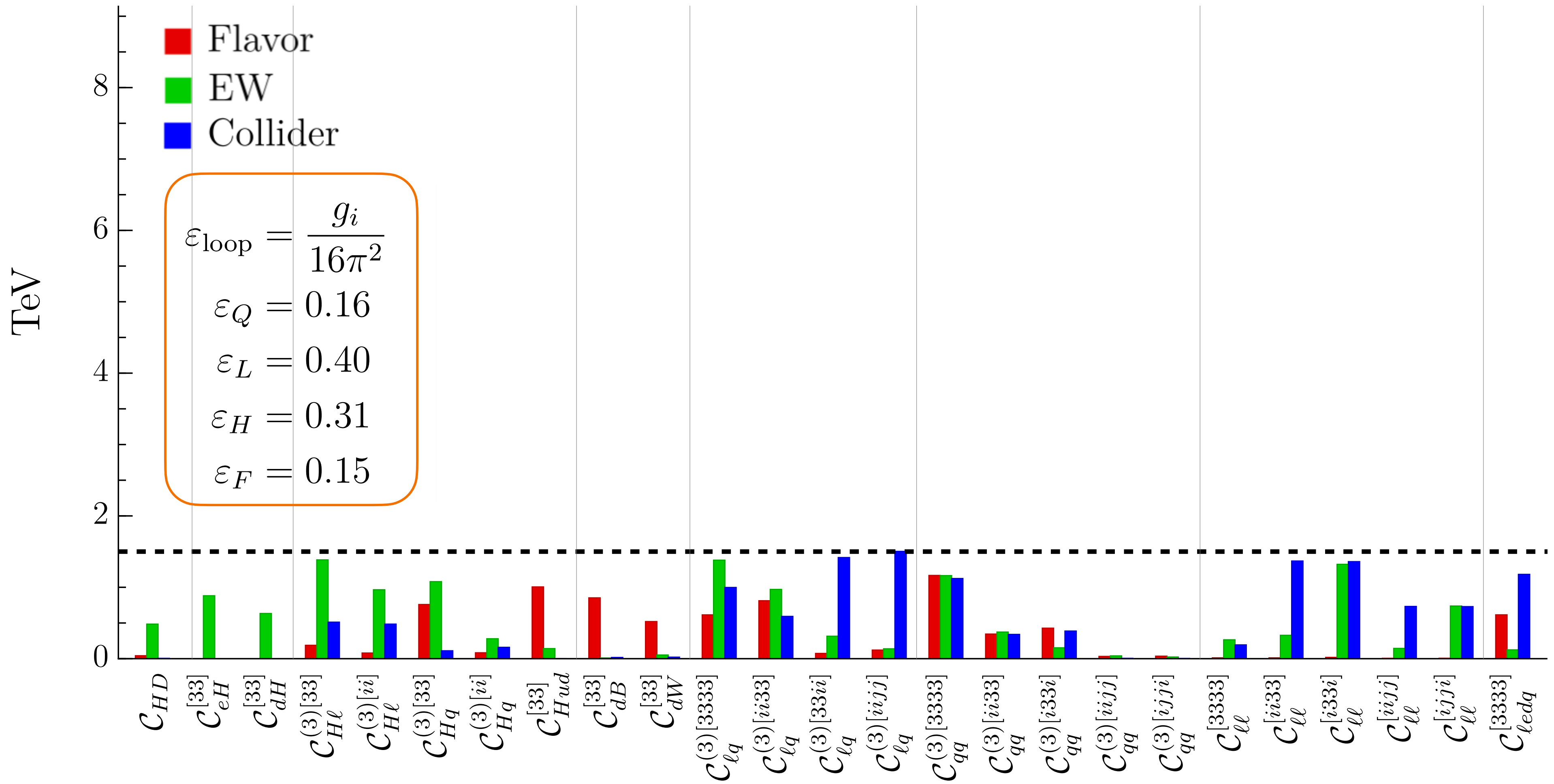


- $U(2)^n$ can host NP coupling dominantly to the 3rd family
- theoretical motivation: possible link to flavor puzzle (and hierarchy problem)
  [as of today, natural solutions to the hierarchy problem require flavor-non-universal NP]
- valence-quark couplings suppressed $\Rightarrow$ high pT bounds relax to $\Lambda \gtrsim O(1)$ TeV

Bounds on Non Universal New Physics

Single operator analysis in **SMEFT + minimally broken U(2)^5**

[= no sources of quark flavour mixing apart from the CKM]



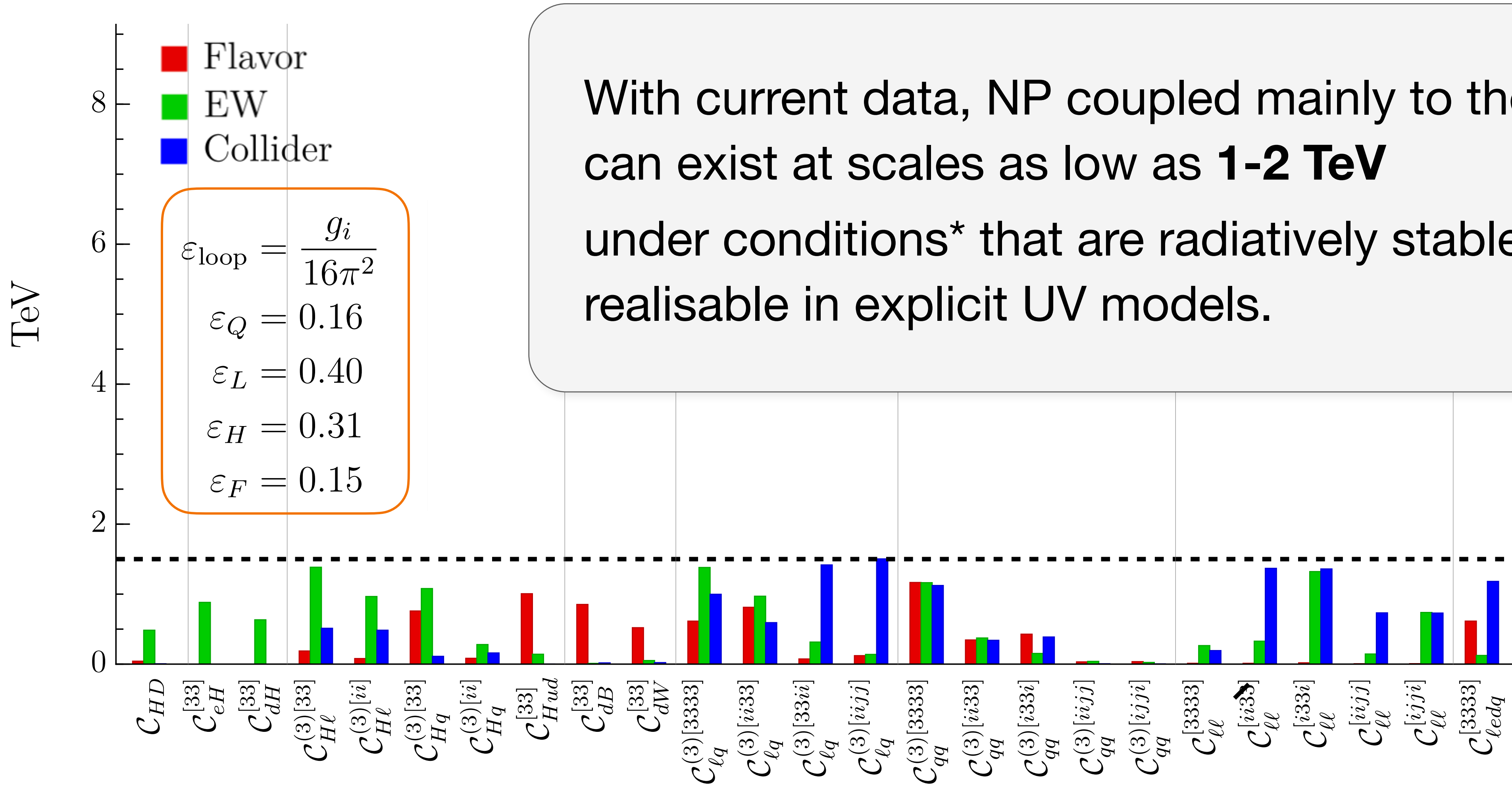
(*) Minimal suppression of NP couplings to light families, Higgs & orientation in flavor space fixed by high-PT, EW and flavor data, respectively.

[Allwicher, CC, Isidori, Stefanek, 2311.00020]

Bounds on Non Universal New Physics

Single operator analysis in **SMEFT + minimally broken U(2)⁵**

[= no sources of quark flavour mixing apart from the CKM]



With current data, NP coupled mainly to the 3rd family can exist at scales as low as **1-2 TeV**

under conditions* that are radiatively stable and realisable in explicit UV models.

(*) Minimal suppression of NP couplings to light families, Higgs & orientation in flavor space fixed by high-PT, EW and flavor data, respectively.

[Allwicher, CC, Isidori, Stefanek, 2311.00020]

On adding flavor to the SMEFT

Why using flavor assumptions in the SMEFT? Don't we lose agnosticity? Yes, but…

- the SMEFT is *not* a model, and fully general != informative
- realistic models populate only some directions → new correlations & stronger bounds
- postulating a flavor structure = studying a *class* of NP models

On adding flavor to the SMEFT

Why using flavor assumptions in the SMEFT? Don't we lose agnosticity? Yes, but…

- the SMEFT is *not* a model, and fully general != informative
- realistic models populate only some directions → new correlations & stronger bounds
- postulating a flavor structure = studying a *class* of NP models

Including flavor data in SMEFT analyses is challenging

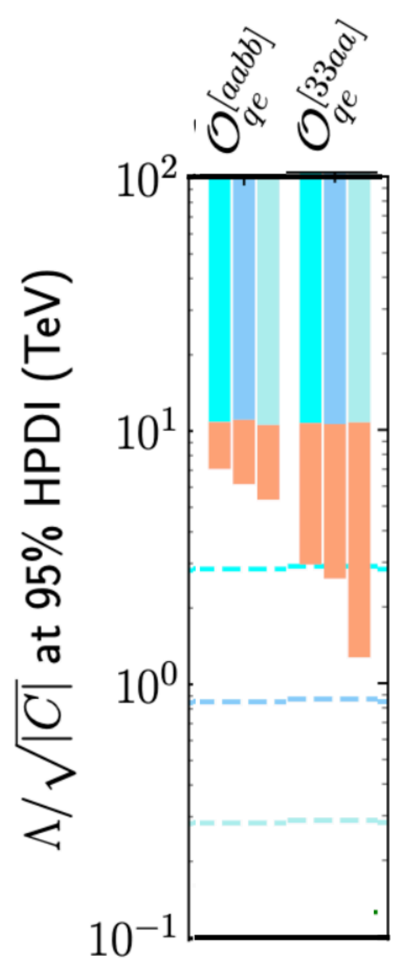
- For EW and collider data, exact flavor symmetries [hence CKM = 1] are enough
- Flavor data requires the inclusion of breaking terms:
  - "mandatory" breakings to reproduce masses + CKM
  - additional non-standard sources of breaking, to be constrained from data
- Ongoing, non-trivial effort [Aoude, Hurth, Renner, Shepherd 2003.05432 Bruggisser, van Dyk, Westhoff 2212.02532 Grundwald, Hiller, Kröninger, Nollen 2304.12837 Allwicher, CC, Isidori, Stefanek 2311.00020 Bartocci, Biekötter, Hurth 2311.04963…]

  First global SMEFT fit with $U(2)^5$ and real CKM [de Blas, Goncalves, Miralles, Reina, Silvestrini, Valli 2507.06191]

On adding flavor to the SMEFT: complementarity

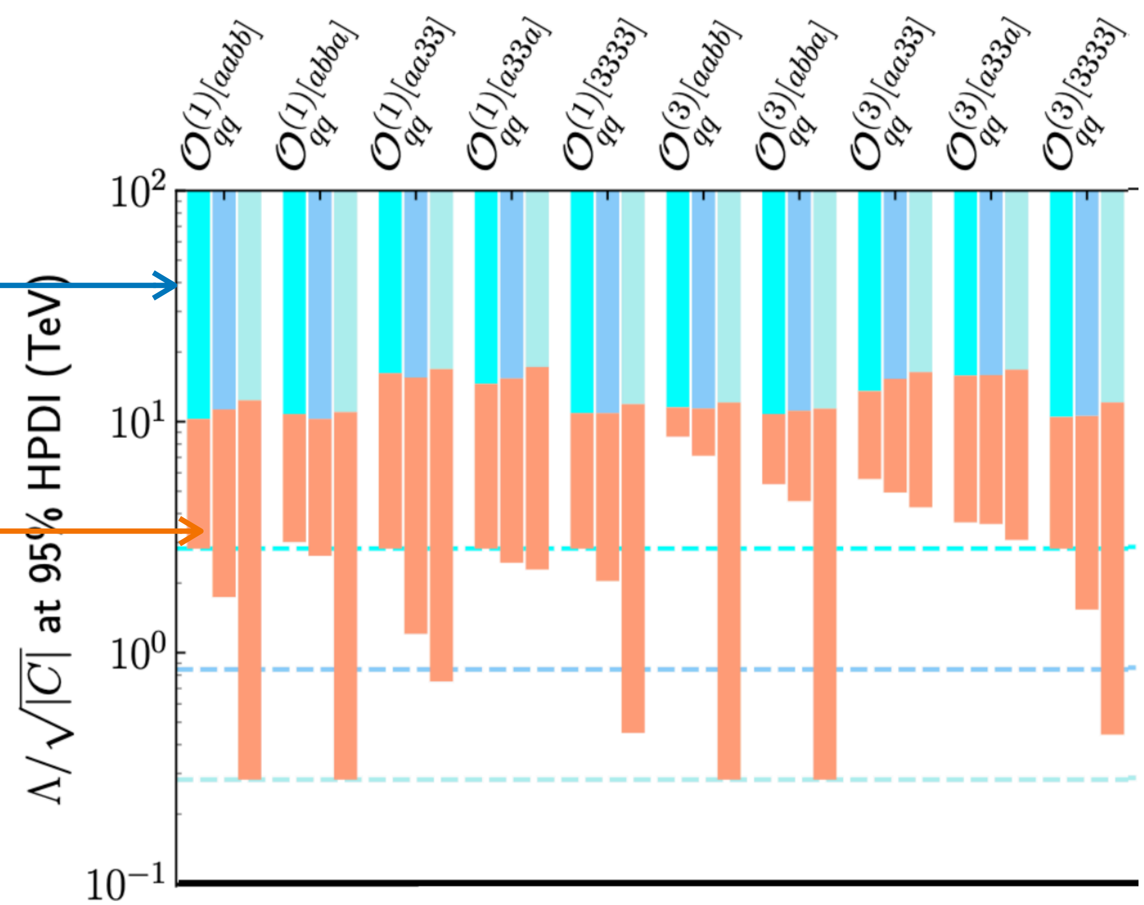
beyond the trivial U(3)⁵ limit, flavour measurements play a crucial role in constraining also flavor-conserving new interactions!

Examples: $B_s \to \mu^+\mu^-$ *for lepton-quark ops* *meson mixing for 4-quark ops.*



Full fit

W/o flavor observables

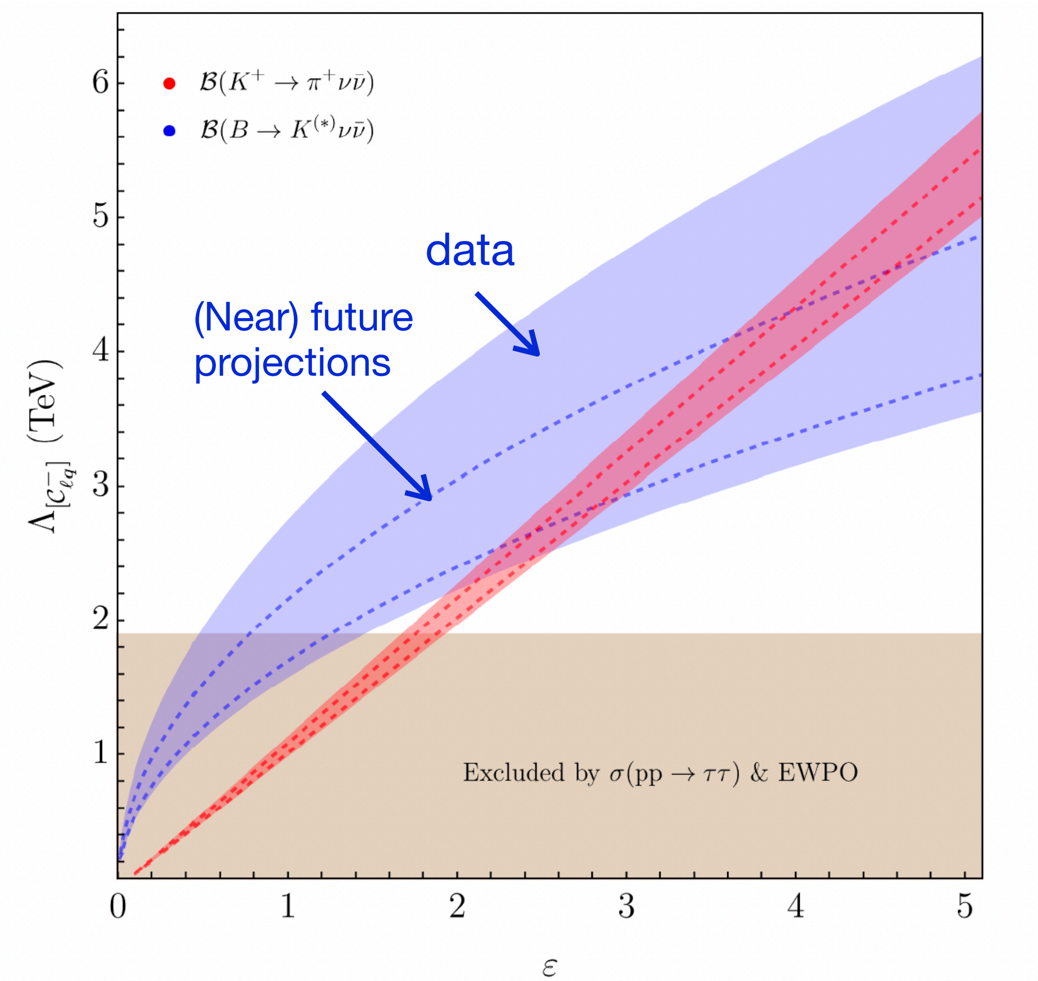


[de Blas, Goncalves, Miralles, Reina, Silvestrini, Valli 2507.06191]

On adding flavor to the SMEFT: unicity

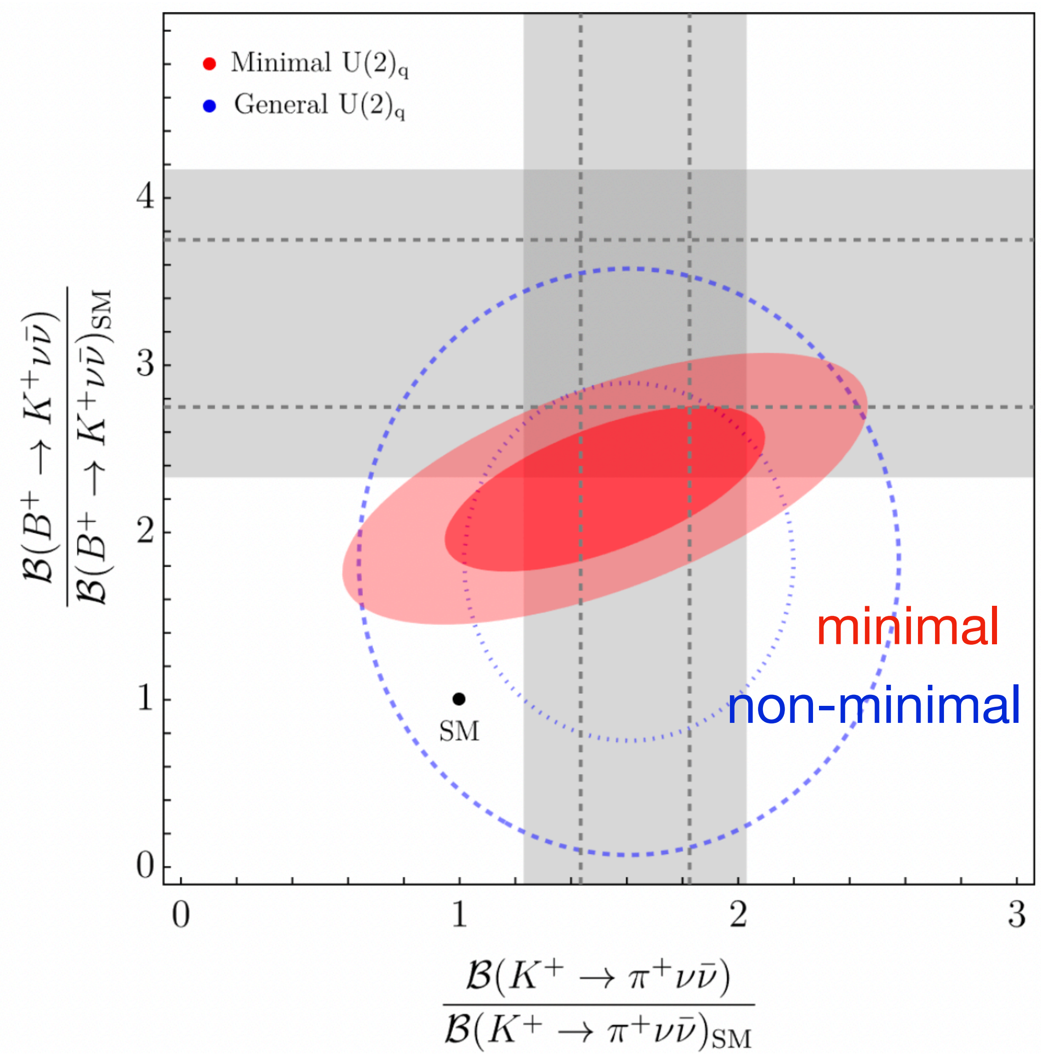
But flavor also provides unique info on the flavor structure of new physics

determine size of breaking terms



e.g. leading $U(2)_q$ breaking can be determined by comparing b→s vs s→d

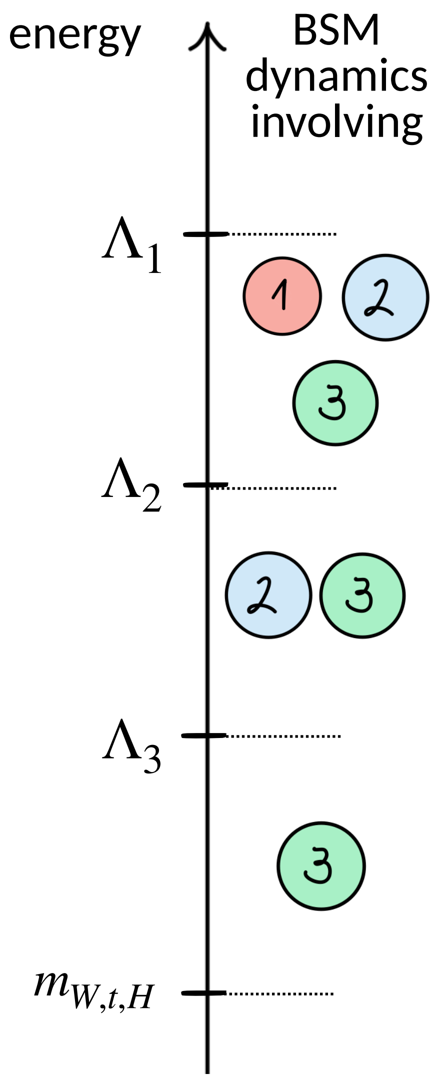
discriminate between breaking patterns via characteristic correlations



[Allwicher, Bordone, Isidori, Piazza, Stanzione, 2410.21444]

Model building for Non Universal New Physics

Key idea: The U(2) symmetry in the Yukawas and in the new physics couplings has the same dynamical origin & is a remnant of a fundamental difference



At high energies, the 3 **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.

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

Model building for Non Universal New Physics

Key idea: The U(2) symmetry in the Yukawas and in the new physics couplings has the same dynamical origin & is a remnant of a fundamental difference

- Explicit realisation via **flavor deconstruction** of the SM gauge group:

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

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

Many examples for G have been studied:

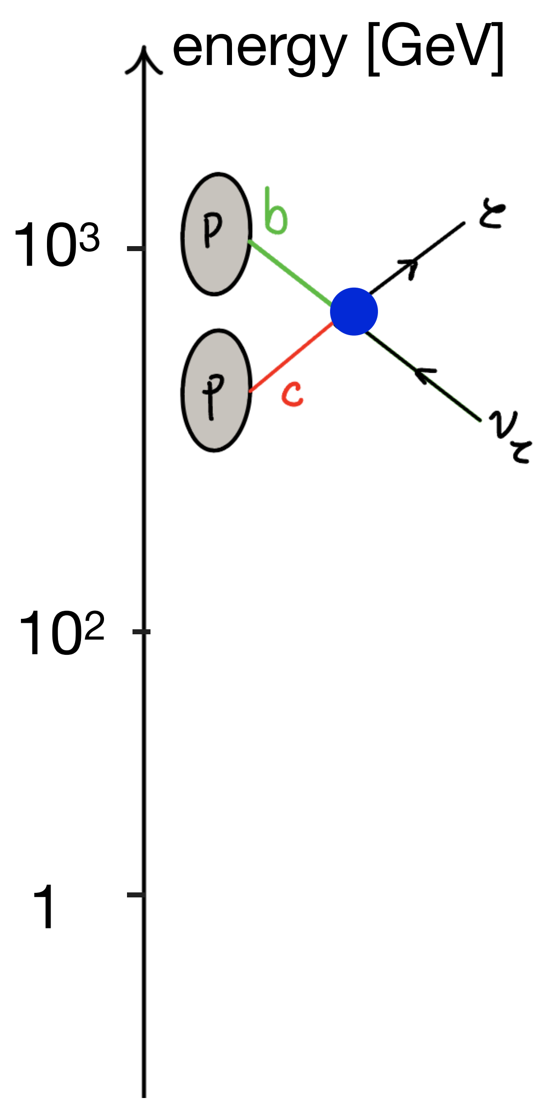
$SU(4)_3 \times SU(3)_{12} \times SU(2)_L \times U(1)'_Y$

$SU(3) \times SU(2)_{L,3} \times SU(2)_{L,12} \times U(1)_Y$

$SU(3) \times SU(2)_L \times U(1)_{Y,3} \times U(1)_{Y,12}$

  - built-in U(2)^5 in the gauge sector; 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 — rich phenomenology for $\Lambda_3 \sim$ TeV
  - same breaking of U(2)^5 generates light Yukawas and couplings of the new gauge bosons to light families

High-energy signatures of 3rd family new physics

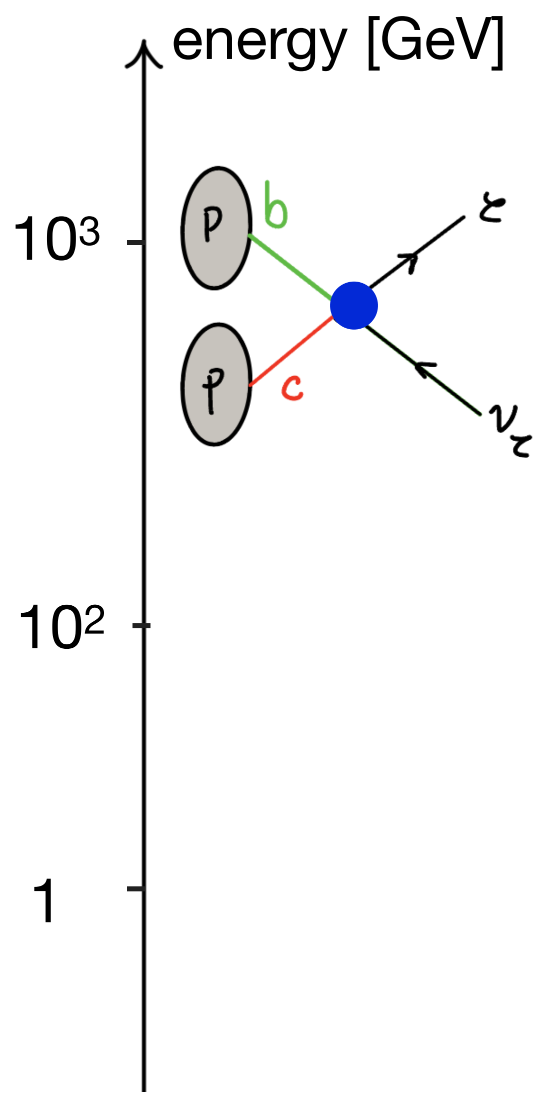


LHC searches [CMS & ATLAS EXPERIMENT] [See talks by T.Vazquez & M. Martinez]

- largest effects in 3rd-family processes:
  - lepton sector: $pp \to t\bar{t}$, $pp \to b\bar{b}\ldots$
  - quark sector: $pp \to \tau\tau$, $pp \to \tau\nu$
  - also LFU, e.g. comparing $pp \to \tau\tau$ to $pp \to \mu\mu$

- energy enhancement in tails helps overcome pdf suppression of heavy flavours in the proton

High-energy signatures of 3rd family new physics



LHC searches [&] [See talks by T.Vazquez & M. Martinez]

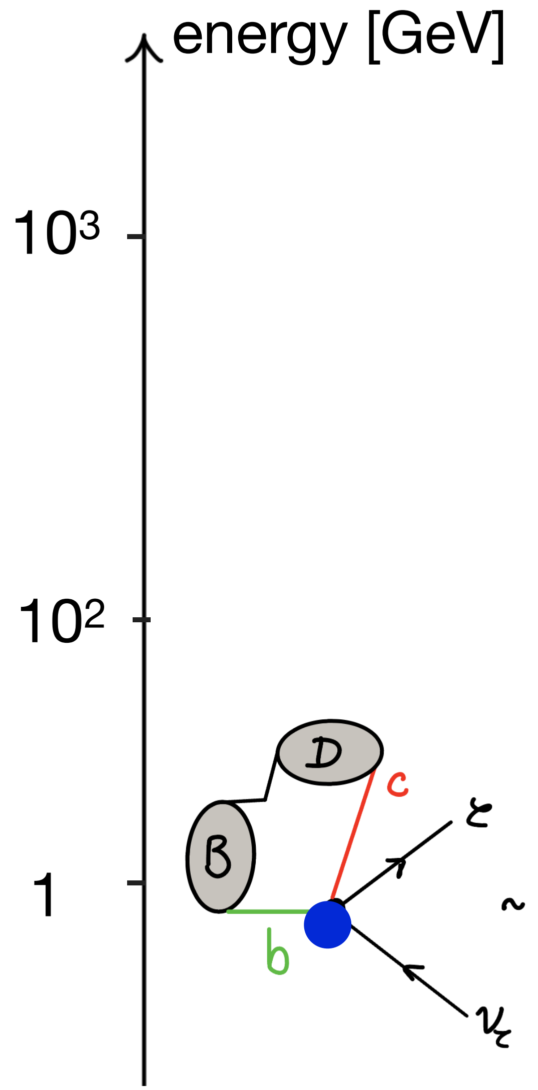
- largest effects in 3rd-family processes:
  - lepton sector: $pp \to t\bar{t}$, $pp \to b\bar{b}\ldots$
  - quark sector: $pp \to \tau\tau$, $pp \to \tau\nu$
  - also LFU, e.g. comparing $pp \to \tau\tau$ to $pp \to \mu\mu$

- energy enhancement in tails helps overcome pdf suppression of heavy flavours in the proton

Status and prospects

- currently, LHC probes scales up to $\sim$ TeV
- HL-LHC: improvement in WCs bounds range from 20% to 4 x for semileptonic operators (factor 2x in the scale)

Low-energy signatures of 3rd family new physics



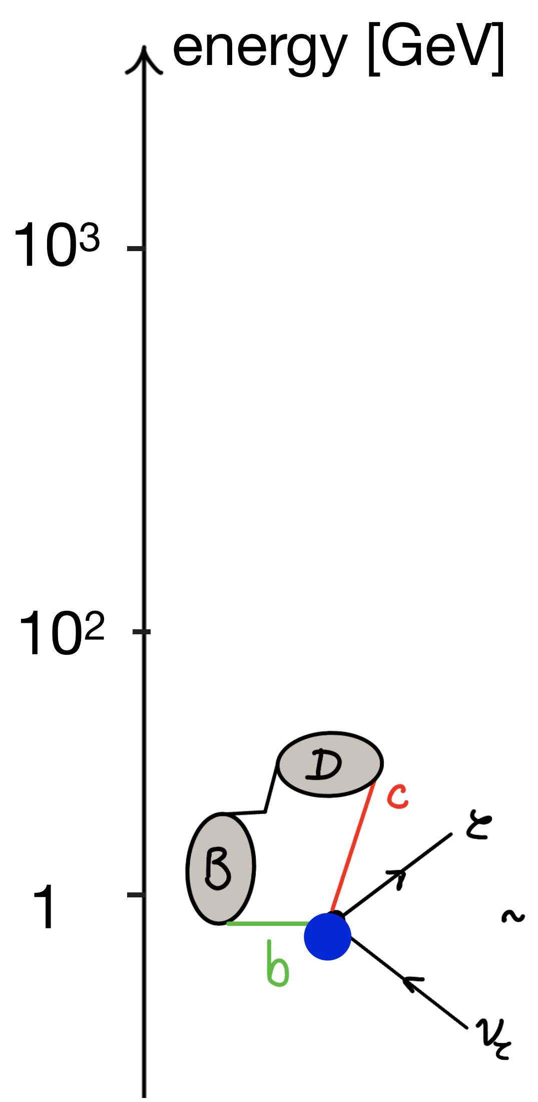
Flavor-changing low-energy probes

- Leading effects in 3 → light transitions: B & τ physics

  e.g. semileptonic 3→2 transitions: $b \to s(d)\ell\ell^{(\prime)},\ b \to s(d)\nu\nu$

  largest effects expected for τ , ν_τ. $b \to c(u)\ell\nu$

Low-energy signatures of 3rd family new physics



Flavor-changing low-energy probes

- Leading effects in 3 → light transitions: B & τ physics

  e.g. semileptonic 3→2 transitions: $b \to s(d)\ell\ell^{(\prime)},\ b \to s(d)\nu\nu$

  largest effects expected for τ, ν_τ. $b \to c(u)\ell\nu$

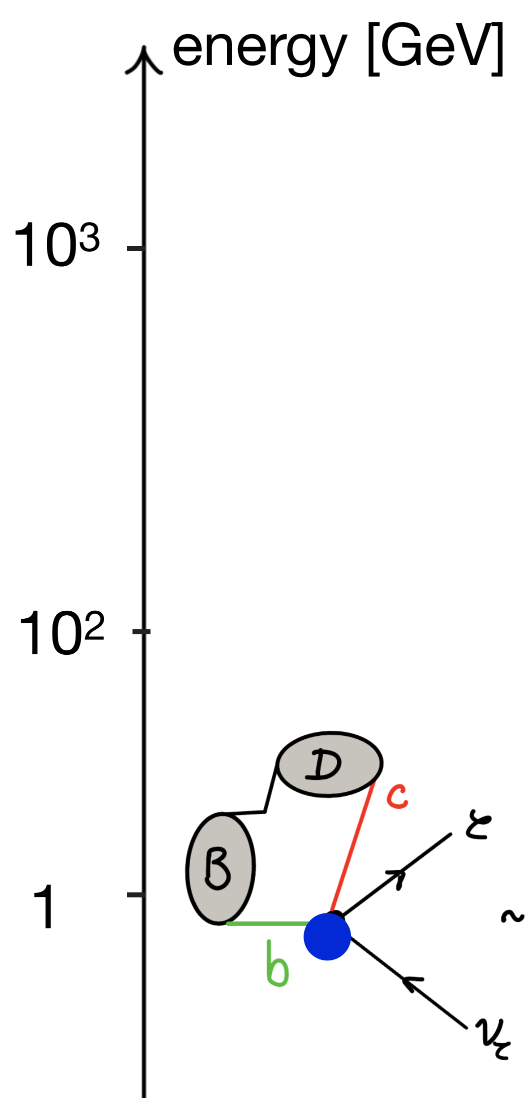
Status & prospects in B physics

Belle II: collected ca. the Babar dataset
many ongoing analyses

LHCb: run 3 ongoing, getting ready for upgrade 2
plenty of data to analyse (many results based on run 1+1/2 run 2)

CMS: very ambitious B-physics program
already delivering competitive results in muonic channels

Low-energy signatures of 3rd family new physics



Flavor-changing low-energy probes

- Leading effects in 3 → light transitions: B & τ physics

  e.g. semileptonic 3→2 transitions: $b \to s(d)\ell\ell^{(\prime)},\ b \to s(d)\nu\nu$

  largest effects expected for τ, ν_τ. $b \to c(u)\ell\nu$

Status & prospects in B physics

- In the next 15 years, LHCb & Belle II should collect ~100x the B mesons they have now.

  This means:
  - CKM matrix elements <1%
  - LFU ratios in SL decays to O(1%) level
  - observe CPV in B_s
  - measure CPV in charm precisely

  Important progress: B_s and D mixing are already leading constraints on flavored heavy NP!

FCNCs with Taus

Probing $b \to s\tau\tau$ directly is experimentally very challenging.

Recently, several remarkable results:

[★ =new world best]

- $\boldsymbol{B^+ \to K^+\tau^+\tau^-}$

  [CKM2025] Belle [711 fb-1] incl. tagging + Belle II [365 fb-1]: BR< 8.7 x 10^{-4} at 90% C.L [★]

- $\boldsymbol{B^0 \to K^{*0}\tau^+\tau^-}$

  [CKM2025] Belle II [365 fb-1]: BR < 1.8 x 10^{-3} at 90% CL

- Other

  [2024] bound on $C_{9\tau}$ from $\tau^+\tau^-$ rescattering in $B^0 \to K^{*0}\mu^+\mu^-$ competitive with direct

  [CKM2025] LHCb [5.4 fb-1]: searches for $B^0 \to K^+\pi^-\tau^+\tau^-$ & $B^0 \to K^+K^-\tau^+\tau^-$ translate in BR < O(10^{-4}) on $B^0 \to K^{*0}\tau^+\tau^-$ and $B_s \to \phi\tau^+\tau^-$ [★]

⇒ we start being sensitive to scenarios with large NP couplings to 3rd family

Limit: even with full LHCb and Belle II datasets, bounds likely to exceed SM (~10^{-7}) by $10^{2\text{-}3}$.

⇒ Will need Tera-Z to go beyond!

FCNCs with Neutrinos

Currently the only measured FCNCs sensitive to NP interacting with 3rd family leptons are the **dineutrino** modes $b \to s\nu\bar{\nu}$ and $s \to d\nu\bar{\nu}$.

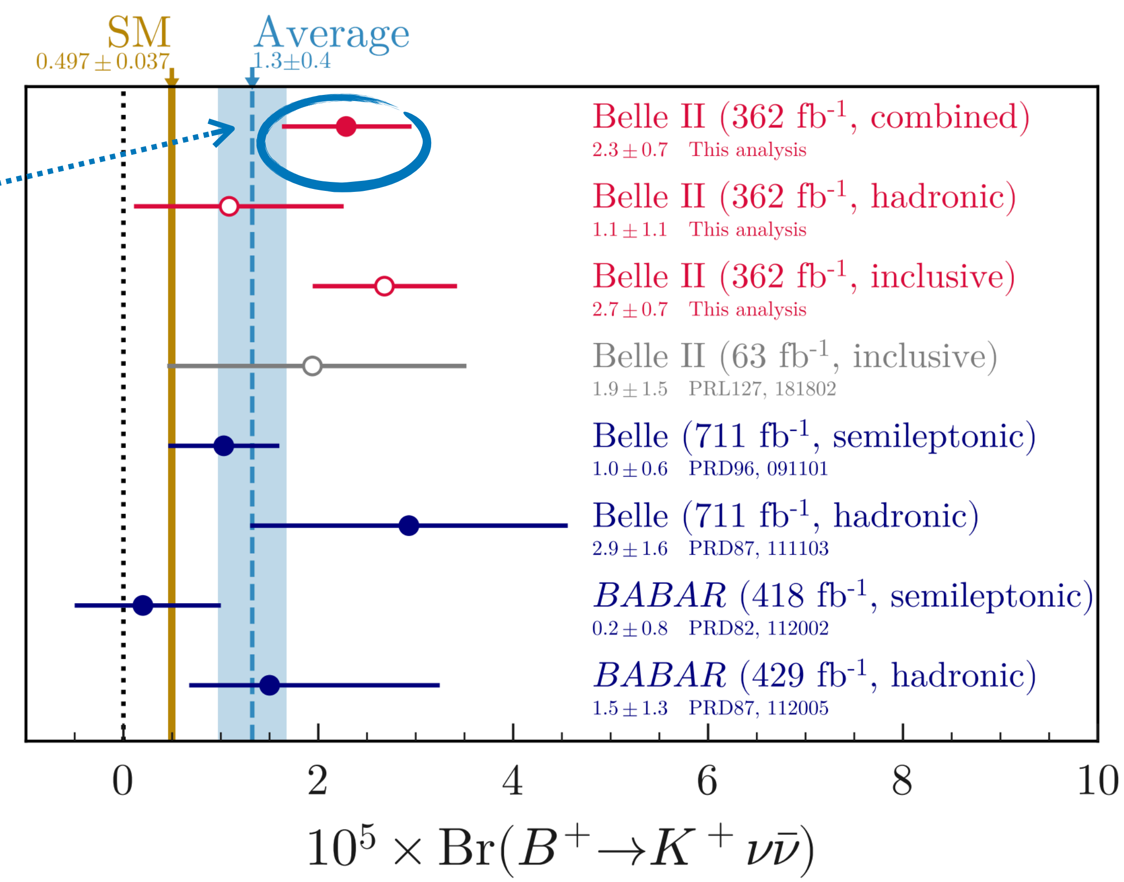
- **Very precise SM prediction:**
  - advantage wrt to dilepton modes: no "charm loop" effects (ν don't couple to γ)
  - theory uncertainty dominated by V_{cb} (&form factors for $B \to K/\pi$).
  - not yet a showstopper, but solving the Vcb puzzle + lattice improvements will be important to exploit future exp. precision

- **Powerful tests** of **NP flavor structure:**
  - all sensitive to leading $U(2)_q$ breaking
  - s →d sensitive also to subleading $U(2)_q$, $U(2)_d$ spurions

FCNCs with Neutrinos

$b \to s\nu\bar{\nu}$

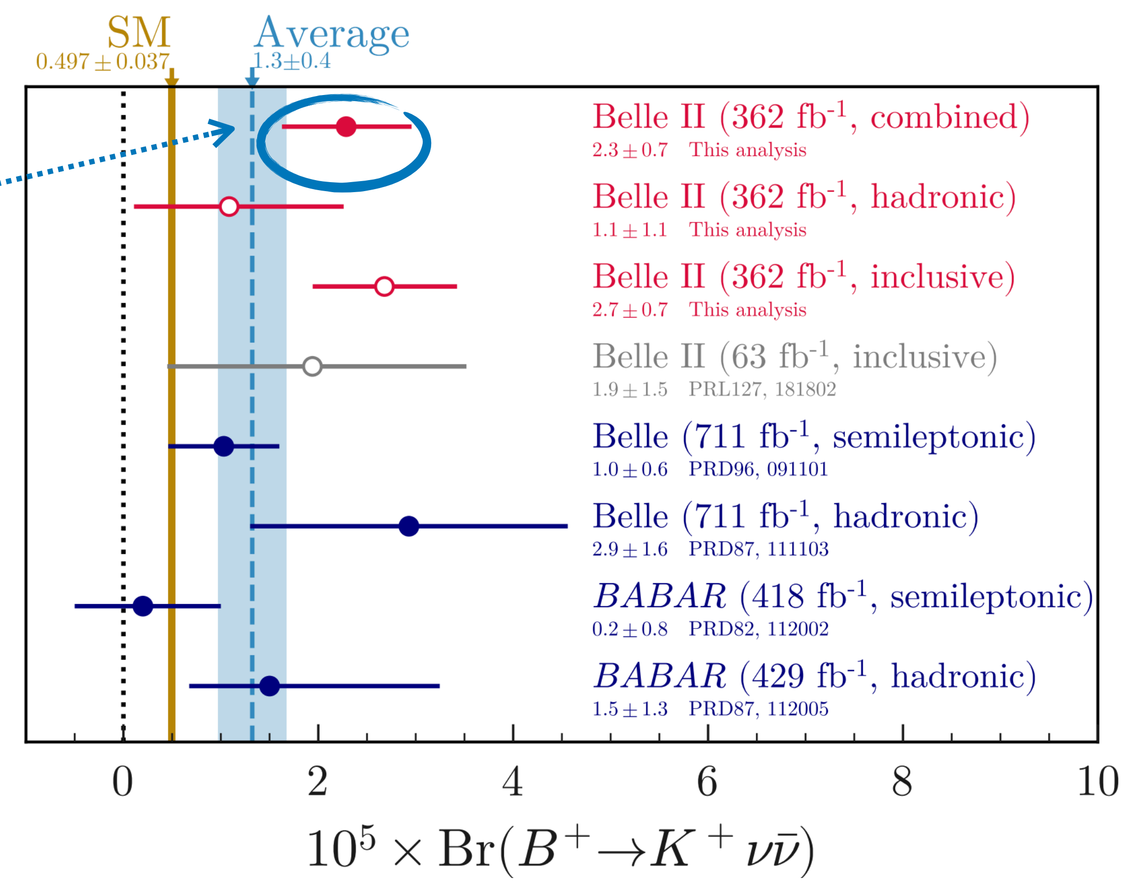
- Belle II [2023]: first evidence for $B^+ \to K^+\nu\bar{\nu}$
- combined result ~**2σ** above SM (**Λ_{eff} ~ 6 TeV**)
- Target: 10% precision @ Belle II
- work ongoing on $K^{*0,+}$ and K_S



FCNCs with Neutrinos

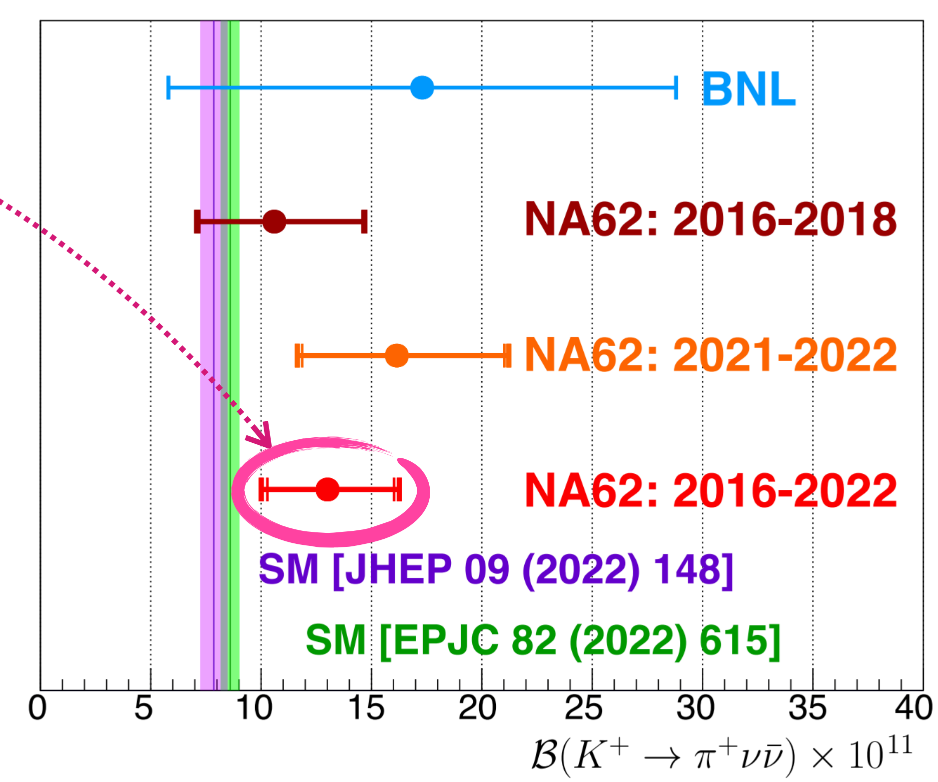
$b \to s\nu\bar{\nu}$

- Belle II [2023]: first evidence for $B^+ \to K^+\nu\bar{\nu}$
- combined result ~2σ above SM (Λ_{eff} ~ 6 TeV)
- Target: 10% precision @ Belle II
- work ongoing on $K^{*0,+}$ and K_S



$s \to d\nu\bar{\nu}$

- Na62 [2024]: first evidence for $K^+ \to \pi^+\nu\bar{\nu}$
- combined result ~2σ above SM (Λ_{eff} ~ 80 TeV)
- Target: 15% precision @Na62 (5% @HIKE†)
- $K_L \to \pi^0\nu\bar{\nu}$: BR_{SM}~ O(10^{-11}), BR_{exp} < O(10^{-9}) [KOTO not competitive with charged mode for NP searches

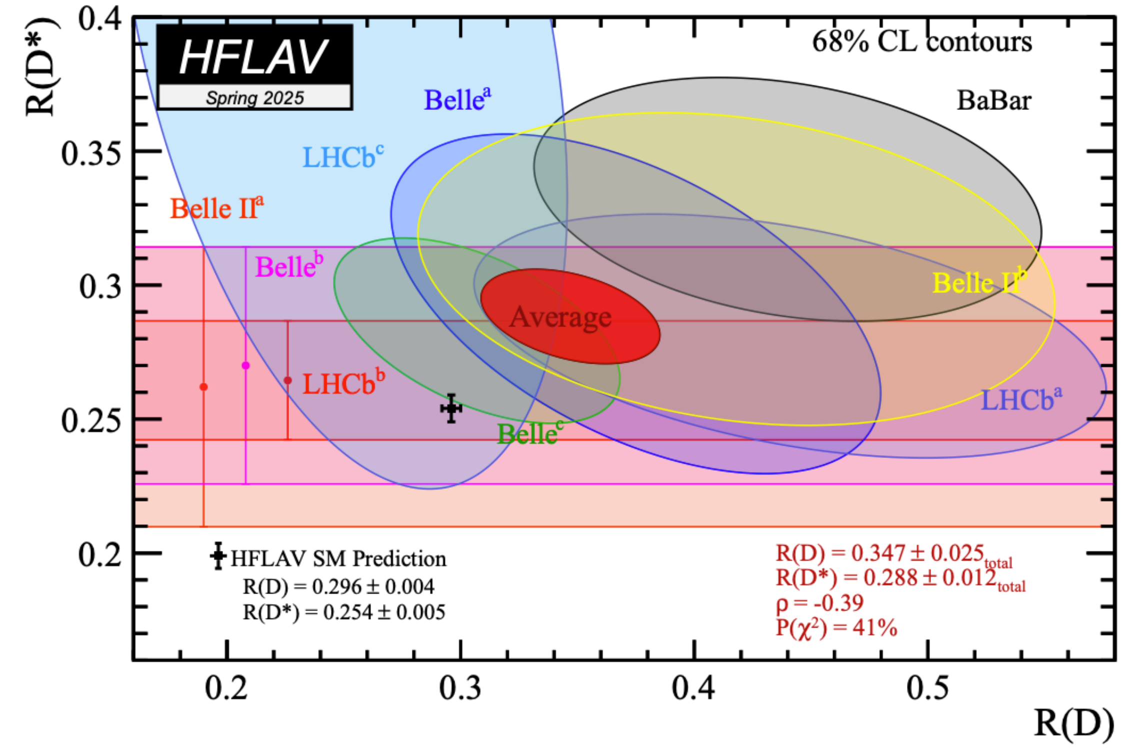


LFUV in $b \to c\ell\nu$

[*w/o the Belle II measurement presented @CKM2025 by I. Tsaklidis, 1.3σ from the HFLAV average displayed here]

15-year old tension far from being settled:

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



~ 10% enhancement due to excess in τ mode
combined* ~**3.8σ** above SM (**Λ_{eff} ~ O(1) TeV**)

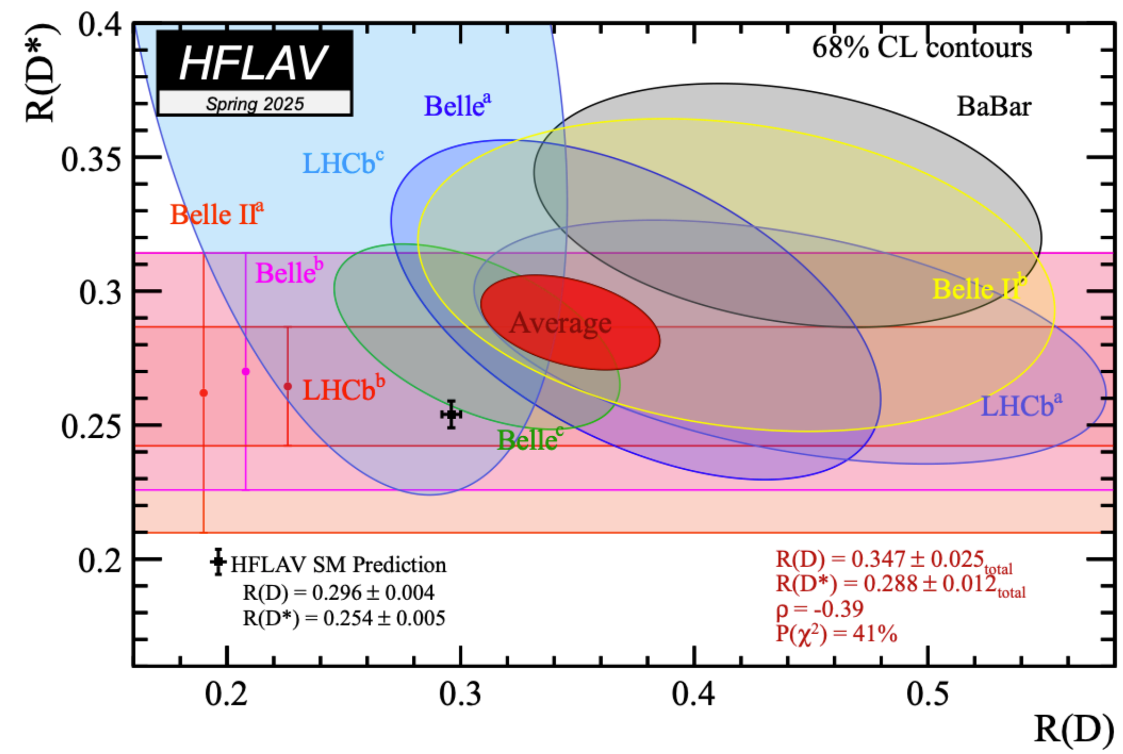
- SM well under control
- Two recent results [2025]: Belle II semil. & hadronic tag
- target for 2040: 1% @ Belle II [50ab^{-1}], 3% @ LHCb[300fb^{-1}]

LFUV in $b \to c\ell\nu$

[*w/o the Belle II measurement presented @CKM2025 by I. Tsaklidis, 1.3σ from the HFLAV average displayed here]

15-year old tension far from being settled:

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



~ 10% enhancement due to excess in τ mode
combined* ~**3.8σ** above SM (**Λ_{eff} ~ O(1) TeV**)

- SM well under control
- Two recent results `[2025]`: Belle II semil. & hadronic tag
- target for 2040: 1% @ Belle II [50ab^{-1}], 3% @ LHCb[300fb^{-1}]

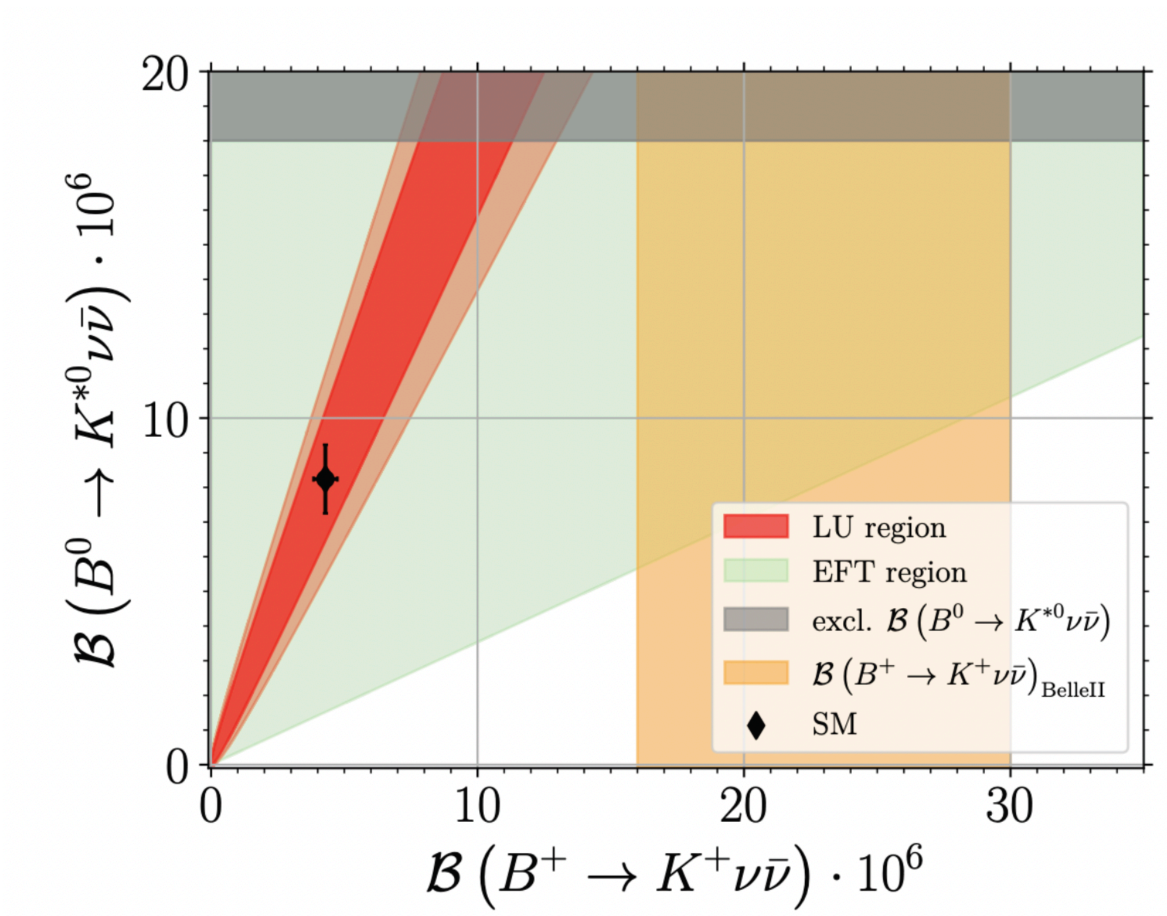
If due to new physics, expect correlated excesses at low and high energies:

- $B \to K\tau\tau$, $B_s \to \tau\tau$ ~O(100) x SM
- distortion of tails in pp → ττ, pp → τ + E_{miss}
  ATLAS/CMS already constrain a relevant portion of parameter space [see talk by T. Vazquez]
- …plus many more more “model dependent” signatures

Hints for New Physics?

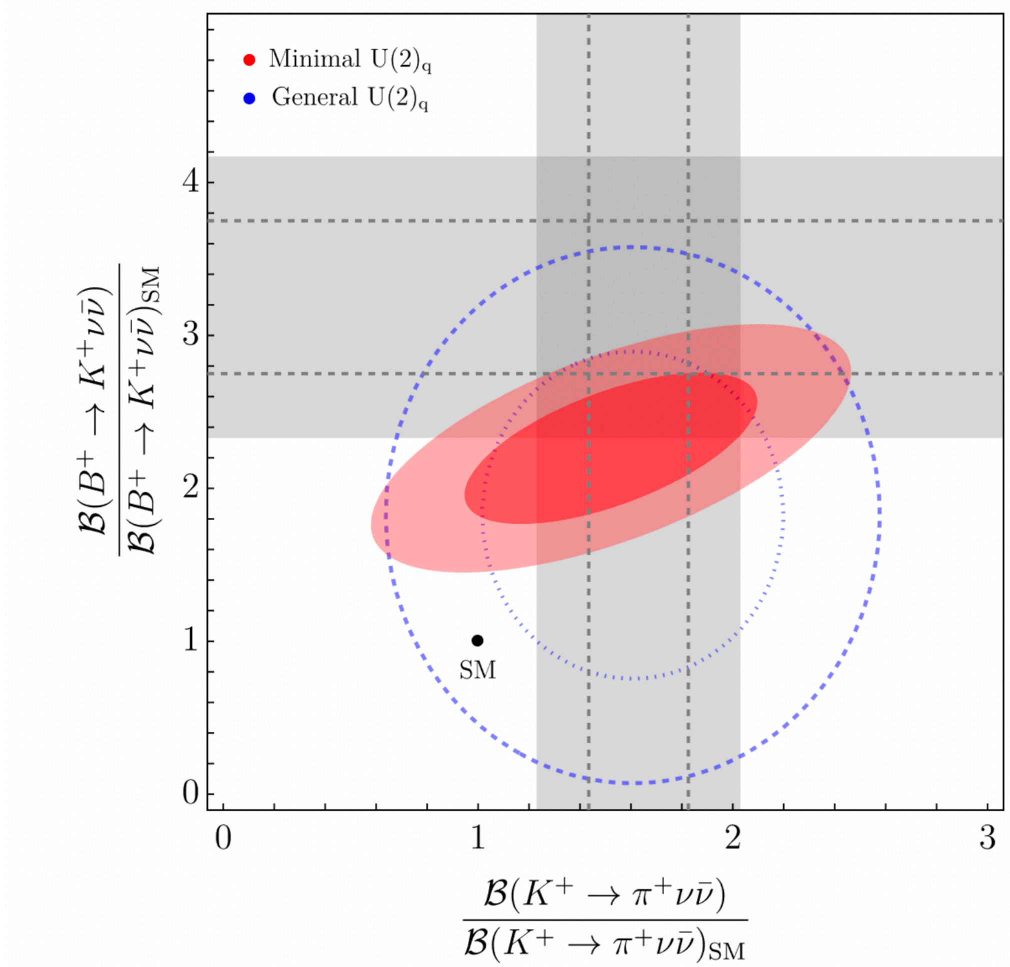
the excess in $B \to K\nu\bar{\nu}$ cannot be due to flavor-universal BSM

[Bause et al 2309.00075
Athron et al 2308.13426]



the excesses in $R_{D^{(*)}}$, $B \to K\nu\bar{\nu}$ and $K \to \pi\nu\bar{\nu}$ are compatible with a U(2)-like flavor structure

[Allwicher et al 2410.21444]



Open problems on the SM side

Several open challenges in deriving SM predictions, mostly due to the non-perturbative nature of QCD at low energy.

A selection within B physics:

- controlling long-distance effects in $b \to s\ell\ell$
- QED effects beyond the pointlike approximation
- discrepancies between inclusive/exclusive determinations of V_{cb} and V_{ub}
- ….many more!

Open problems on the SM side

Several open challenges in deriving SM predictions, mostly due to the non-perturbative nature of QCD at low energy.

A selection within B physics:

- controlling long-distance effects in $b \to s\ell\ell$
- QED effects beyond the pointlike approximation
- discrepancies between inclusive/exclusive determinations of V_{cb} and V_{ub}
- ….many more!

Long vs short-distance effects in $b \to s\ell\ell$

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

universality ratios, differential BRs, angular obs. for many hadrons

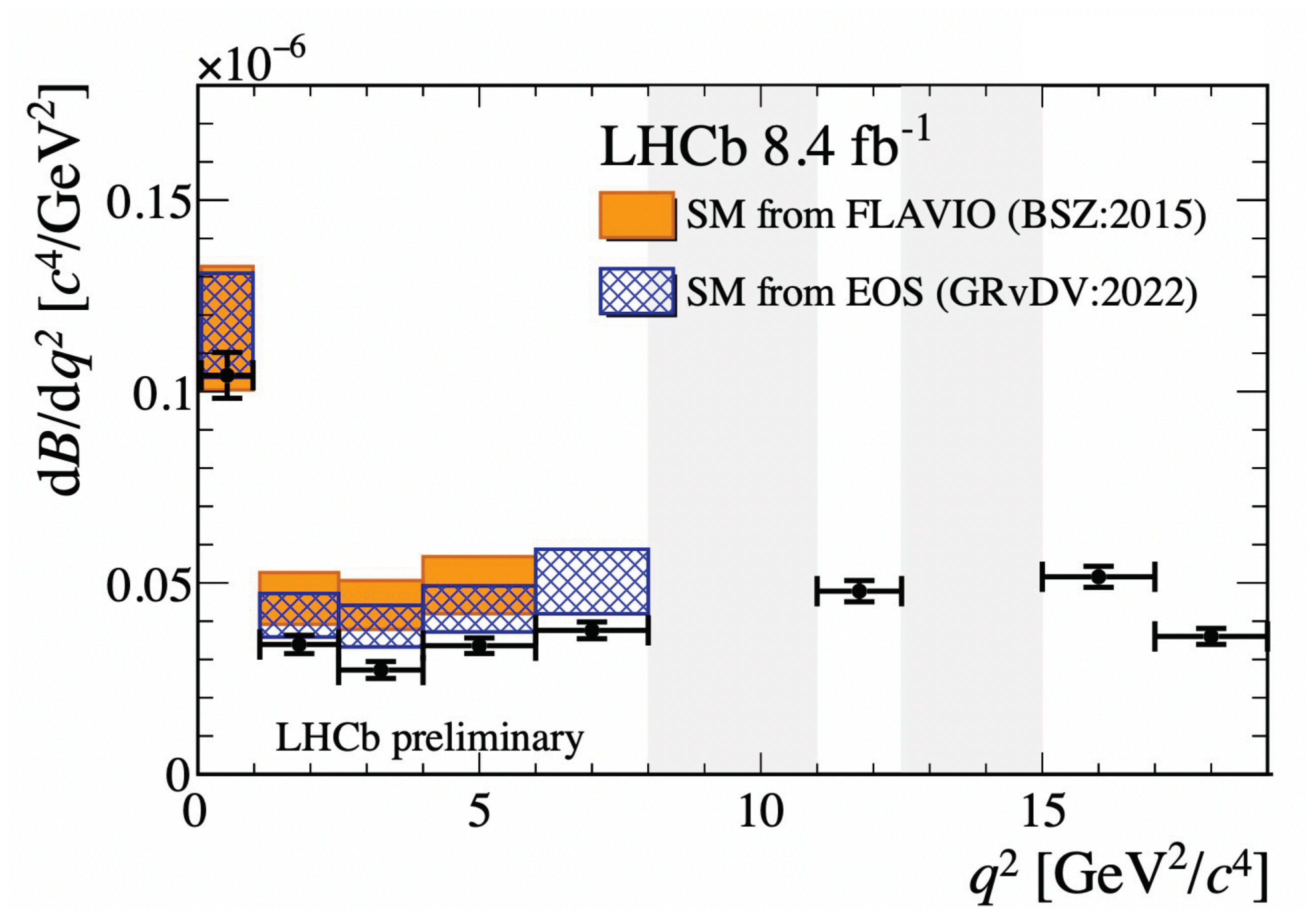
$$\frac{BR(H_b \to H_s \mu^+\mu^-)}{BR(H_b \to H_s e^+e^-)} \qquad \frac{dBR(H_b \to H_s \mu^+\mu^-)}{dq^2} \qquad P_5', \; A_{FB} \ldots$$

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

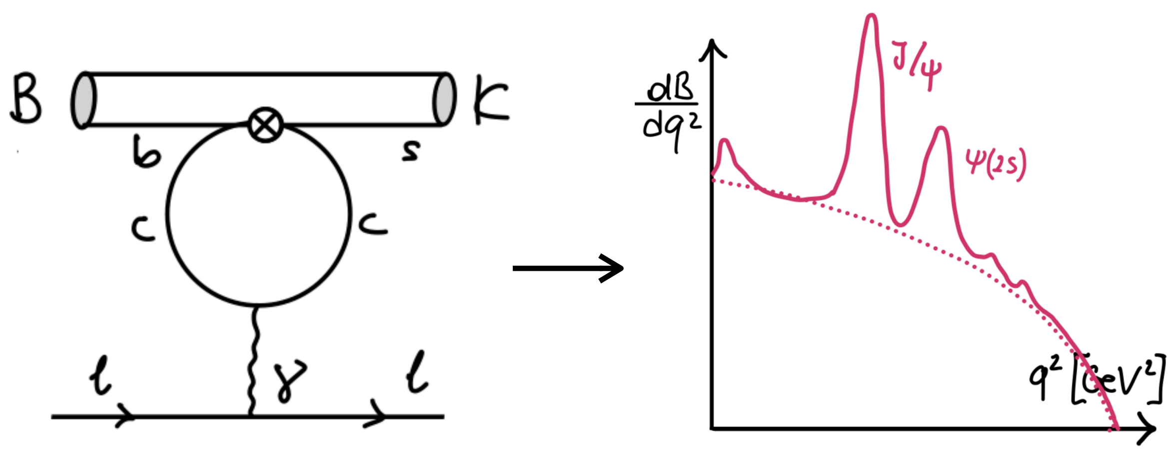
$H_s: K^+, K^0, K^{*+}, K^{*0}, \phi, pK^-$

- μ/e LFU in tested to O(5%), yet persistent tensions in branching fractions and in the $B \to K^*$ angular analysis [LHCb & CMS]

- BSM explanation requires $C_9^U \sim 0.25 C_9^{\rm SM}$ but disentangling NP from hadronic contributions remains difficult



Long vs short-distance effects in $b \to s\ell\ell$



SD+LD; known; parametrized; possibly unaccounted for; what we would like to know

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

long distance
short distance

Big theory & exp. effort to *tame* the "charm loop"

- strategy: parametrize with dispersion relations/z expansion, fit to q^2 spectrum, extract residual amplitude

- This seems independent of q², [LHCb 2405.17347, Bordone, Isidori, Mächler, Tinari 2401.18007,….]
  still extraction of NP limited by control of "flat" LD effects;

  No general consensus (parametrization relies on quark-hadron duality, calculations at fixed q^2 rely on approximations…)

- first lattice study [Frezzotti, Tantalo, Gagliardi, Lubicz, Martinelli 2508.03655]
  — still far from a first-principle calculation, but important "proof of principle"

Structure-dependent QED effects in B decays

Exp. precision headed **towards O(1%)** in several channels — theory must match!

A major challenge in this sense is the proper treatment of QED effects, including those stemming from the composite nature of the B.

In the **standard approach** (e.g. PHOTOS) the B is treated as *point-like*

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

⇒ need to **go beyond** by including *structure-dependent* corrections

Structure-dependent QED effects in B decays

- theoretically **interesting**
  - break naive lepton x hadron factorization
  - require generalized process-dependent hadronic quantities (decay constants, ffs)

Structure-dependent QED effects in B decays

- theoretically **interesting**
  - break naive lepton x hadron factorization
  - require generalized process-dependent hadronic quantities (decay constants, ffs)

- phenomenologically **relevant**
  - can be power-enhanced in some cases (e.g. $B_s \to \mu^+\mu^-$)
  - can induce qualitatively new effects: mimic LFUV, distort distributions, affect differently incl. & excl. decays

Structure-dependent QED effects in B decays

- theoretically **interesting**
  - break naive lepton x hadron factorization
  - require generalized process-dependent hadronic quantities (decay constants, ffs)

- phenomenologically **relevant**
  - can be power-enhanced in some cases (e.g. $B_s \to \mu^+\mu^-$)
  - can induce qualitatively new effects: mimic LFUV, distort distributions, affect differently incl. & excl. decays

- **difficult** to compute
  - not yet accessible on the lattice — though quite some work on light mesons [Di Carlo et al., 1904.08731; 2109.05002; Desiderio et al., 2006.05358;…]
  - can be studied in the continuum using EFT techniques (HQET, SCET) to factorize corrections associated to different scales to achieve QCD x QED factorization
  - recent and active research topic; factorization theorems only for few processes: $B_s \to \mu^+\mu^-,\ B \to \pi K,\ \ B \to D\pi,\ B_s \to \mu^+\mu^-\gamma,\ B \to \mu\nu$

[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]

The simplest B decay, precisely

Why $B \to \ell\nu$?

- would allow for "cleanest" determination of $|V_{ub}|$
- powerful probe of (pseudo)scalar new physics and of LFU in $b \to u$

Why QED?

- Belle II aims for O(5%) in μ,τ modes Tera Z can go down to O(1)%
- $\delta f_B <$ O(1%), hence unknown QED is the next source of uncertainty

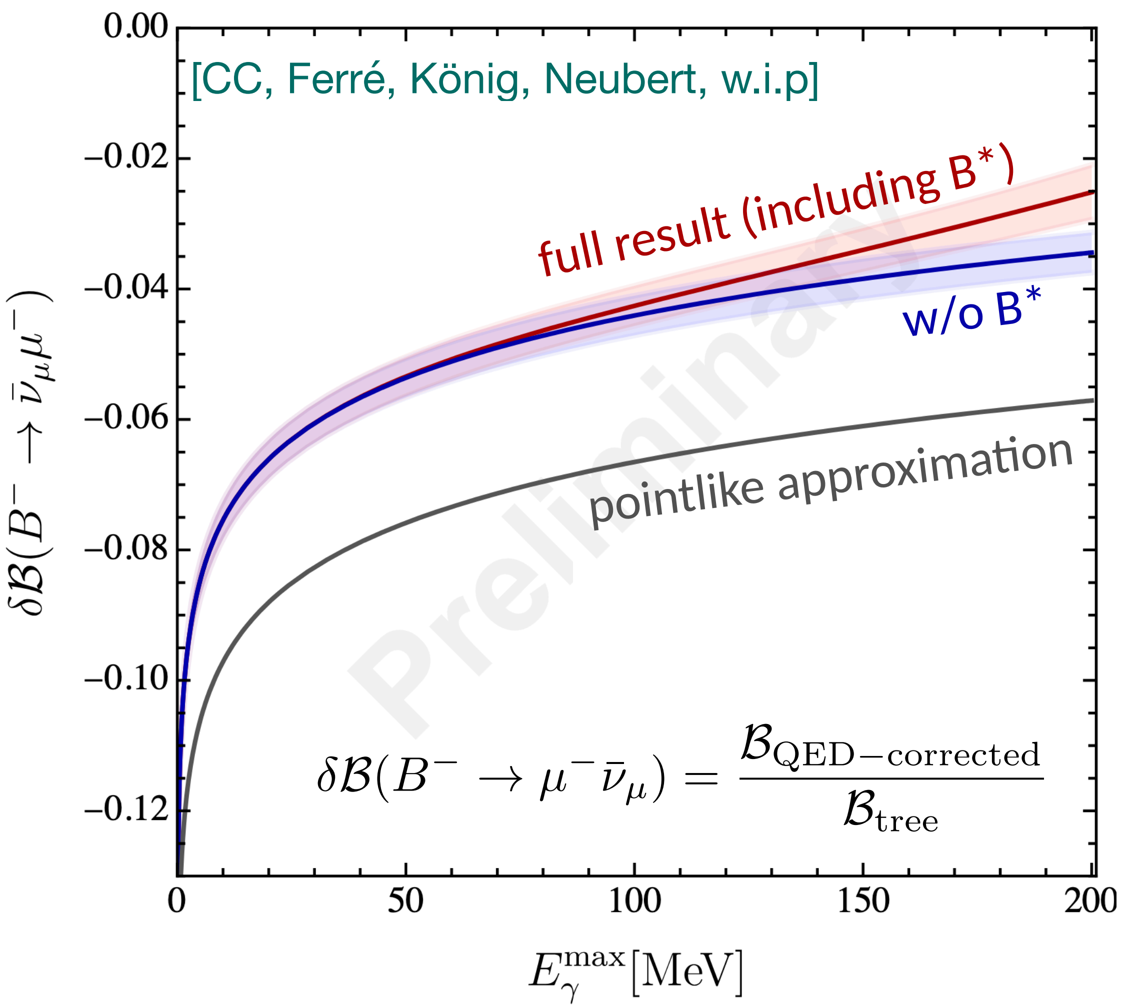
The simplest B decay, precisely

Why $B \to \ell\nu$?

- would allow for “cleanest” determination of $|V_{ub}|$
- powerful probe of (pseudo)scalar new physics and of LFU in $b \to u$

Why QED?

- Belle II aims for O(5%) in μ,τ modes Tera Z can go down to O(1)%
- δf_B < O(1%), hence unknown QED is the next source of uncertainty



Result: structure-dependent effects shift μ channel by ~2% wrt pointlike result

[uncertainty due to unknown QED-induced shift to f_B & LCDAs might be improved with inputs from lattice/LCSR]

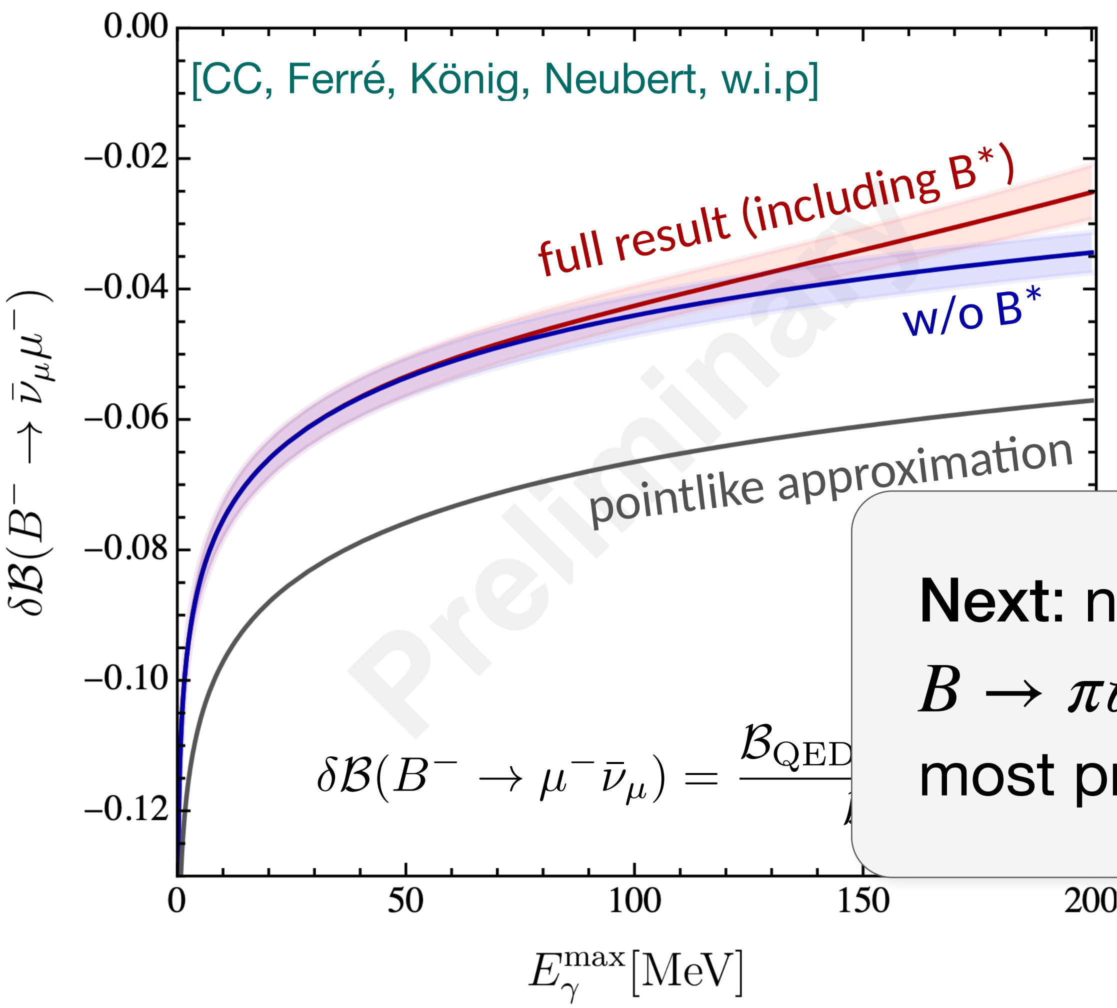
The simplest B decay, precisely

Why $B \to \ell\nu$?

- would allow for "cleanest" determination of $|V_{ub}|$
- powerful probe of (pseudo)scalar new physics and of LFU in $b \to u$

Why QED?

- Belle II aims for O(5%) in μ,τ modes Tera Z can go down to O(1)%
- δf_B < O(1%), hence unknown QED is the next source of uncertainty



Result: structure-dependent effects shift μ channel by ~2% wrt pointlike result

[uncertainty due to unknown QED-induced shift to f_B & LCDAs might be improved with inputs from lattice/LCSR]

Next: need to work towards full assessment of QED for $B \to \pi\ell\nu$ & $B \to D^{(*)}\ell\nu$ — currently "the" channels for most precise excl. determination of V_{ub}, V_{cb}

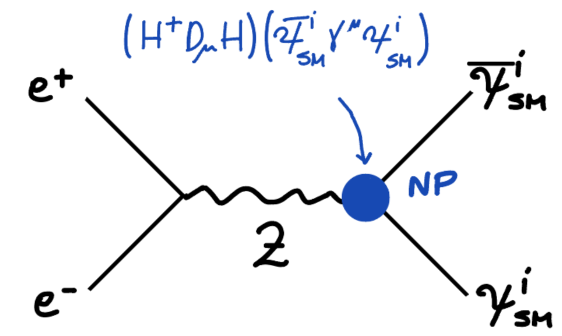
Why Tera-Z can help probe Flavored New Physics

Looking into the future, a Tera-Z facility can help test flavoured NP via the *combination* of its EW precision & flavor program. How?

Why Tera-Z can help probe Flavored New Physics

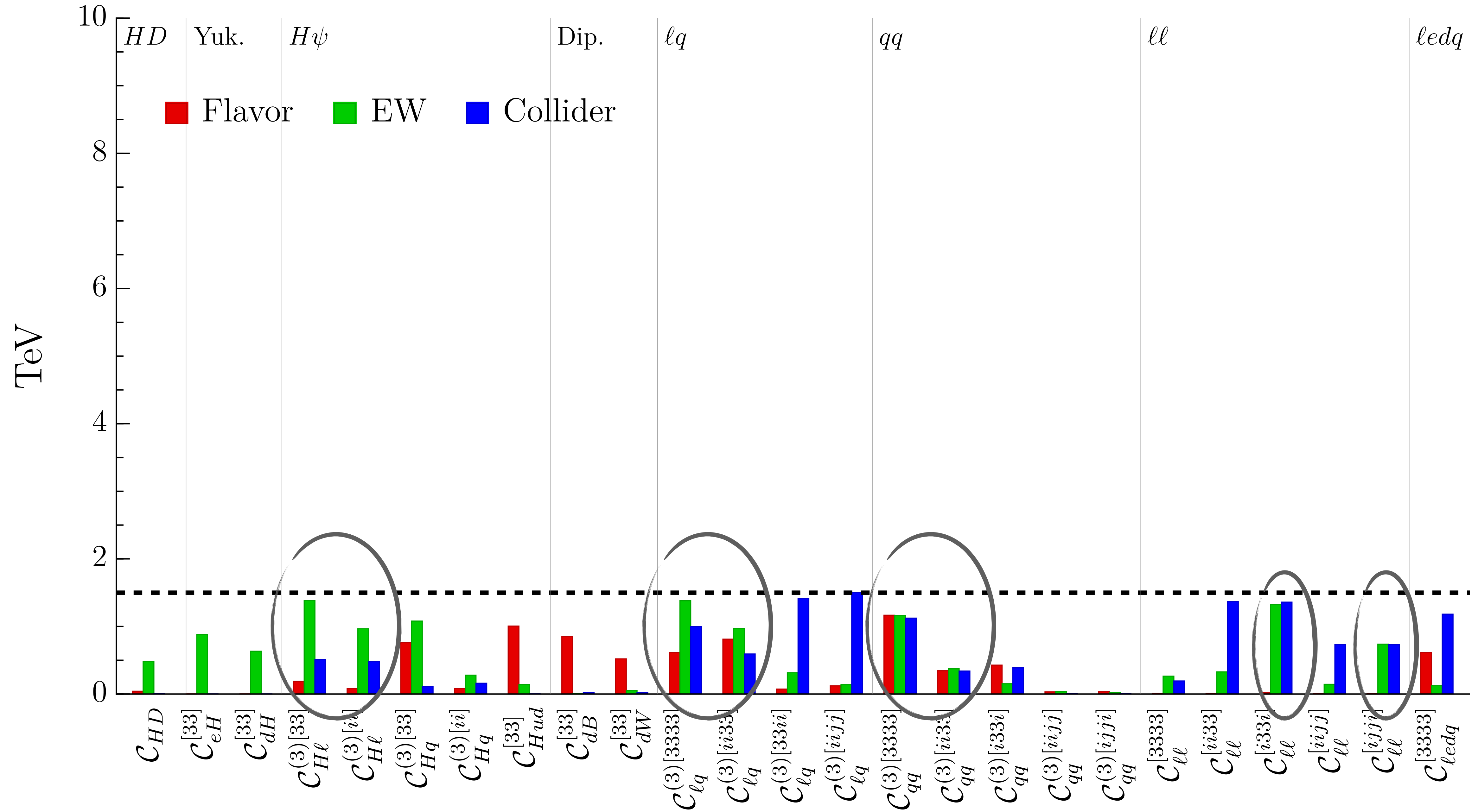
Looking into the future, a Tera-Z facility can help test flavoured NP via the *combination* of its EW precision & flavor program. How?

- **EW precision**
  - 3rd family NP is "protected" against direct searches at the LHC & flavor, but *not* protected vs EWPT - "*everything runs into EW*"
  - At a Z factory, we can use the flavor blindness of SM gauge interactions to probe NP coupled to any generation via EWPT
    ⇒ EWPT are powerful probes of flavor non-universal NP



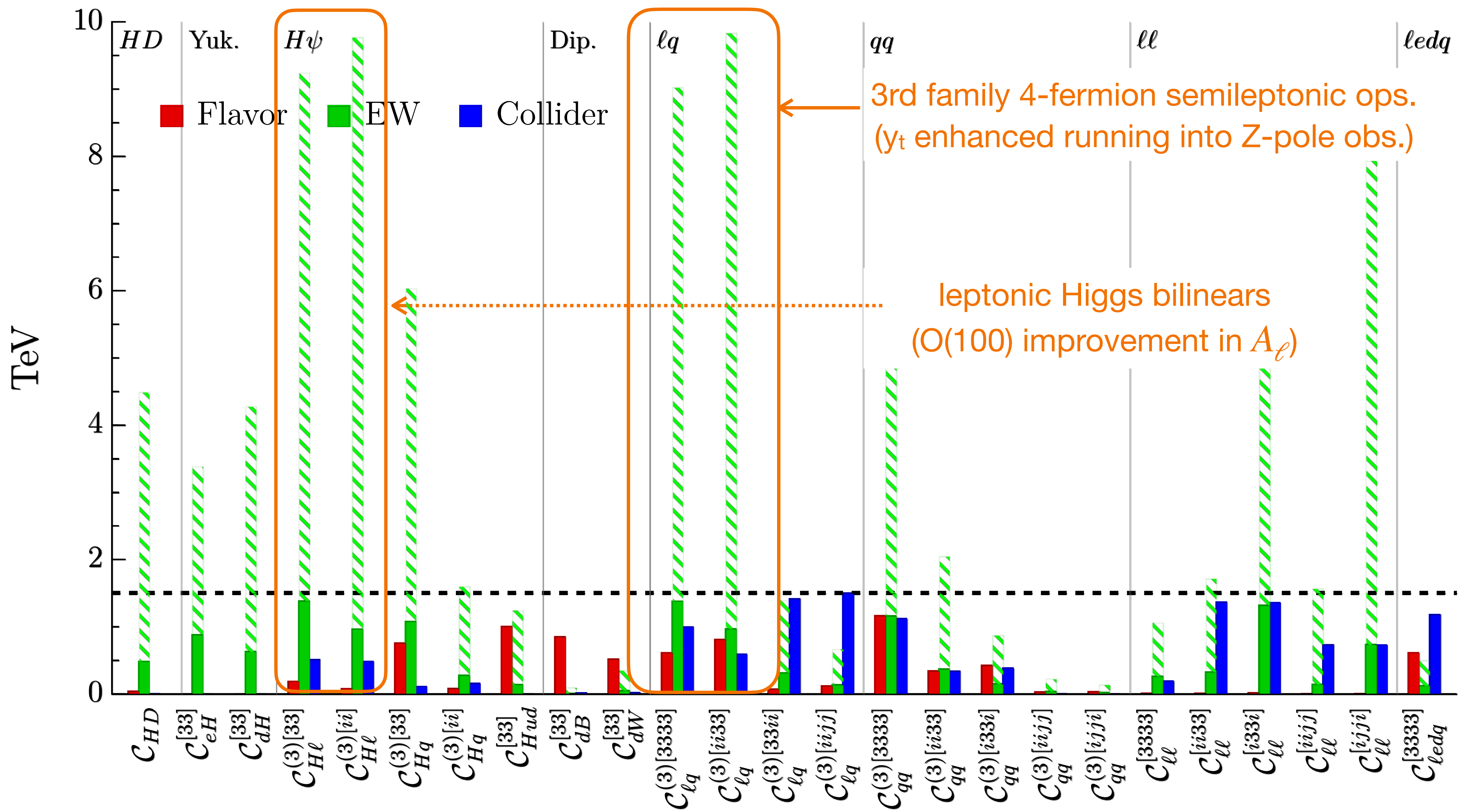
Why Tera-Z can help probe Flavored New Physics

Even now LEP bounds have a strength comparable to current direct searches for operators involving mostly the 3rd generation:



Why Tera-Z can help probe Flavored New Physics

….with $\approx 10^5$ more Z bosons than LEP,
A tera-Z machine in its Z-pole run could probe 3rd-family NP up to ~ 10 TeV!



Why Tera-Z can help probe Flavored New Physics

Looking into the future, a Tera-Z facility can help test flavoured NP via the *combination* of its EW precision & flavor program. How?

- **Flavor**
  - combines the best features of pp colliders and B factories
    high statistics, "closed" kinematics, high boost of b and τ, access to all b hadrons
  - precise measurements of $b \to s\tau\tau$ & $b \to s\nu\nu$, incl. $b \to d$ counterpart
  - test LFU in $\boldsymbol{\tau}$ decays @ $O(10^{-4})$
  - dedicated studies with detector simulation (IDEA baseline) + background modelling available for a few channels, many more under development

[for more on the complementarity of EW&flavor @Tera-Z, see M. Pesut's talk]

Why Tera-Z can help probe Flavored New Physics

Looking into the future, a Tera-Z facility can help test flavoured NP via the *combination* of its EW precision & flavor program. How?

- **Flavor**
  - combines the best features of pp colliders and B factories
    high statistics, "closed" kinematics, high boost of b and τ, access to all b hadrons
  - precise measurements of $b \to s\tau\tau$ & $b \to s\nu\nu$, incl. $b \to d$ counterpart (new frontiers)
  - test LFU in $\boldsymbol{\tau}$ decays @ O(10^{-4})
  - dedicated studies with detector simulation (IDEA baseline) + background modelling available for a few channels, many more under development

[for more on the complementarity of EW&flavor @Tera-Z, see M. Pesut's talk]

Why Tera-Z can help probe Flavored New Physics

Looking into the future, a Tera-Z facility can help test flavoured NP via the *combination* of its EW precision & flavor program. How?

- **Flavor**
  - combines the best features of pp colliders and B factories
    high statistics, "closed" kinematics, high boost of b and τ, access to all b hadrons
  - precise measurements of $b \to s\tau\tau$ & $b \to s\nu\nu$, incl. $b \to d$ counterpart
    new frontiers
    Beyond Belle II: Pushing Precision to O(1%)
  - test LFU in τ decays @ $O(10^{-4})$
  - dedicated studies with detector simulation (IDEA baseline) + background modelling available for a few channels, many more under development

[for more on the complementarity of EW&flavor @Tera-Z, see M. Pesut's talk]

$B \to K^* e^+ e^-$ at FCC-ee

[Bordone, CC, Davighi, 2503.22635]
[Bordone, CC, Davighi, Monteil, in preparation]

- Expectations at FCC-ee:
  - Electron reconstruction as efficient as muons, ~ 80%
  - Statistical error per bin < 1% (half of HL-LHC projections)

- HL-LHC limited by systematics (stat=syst)

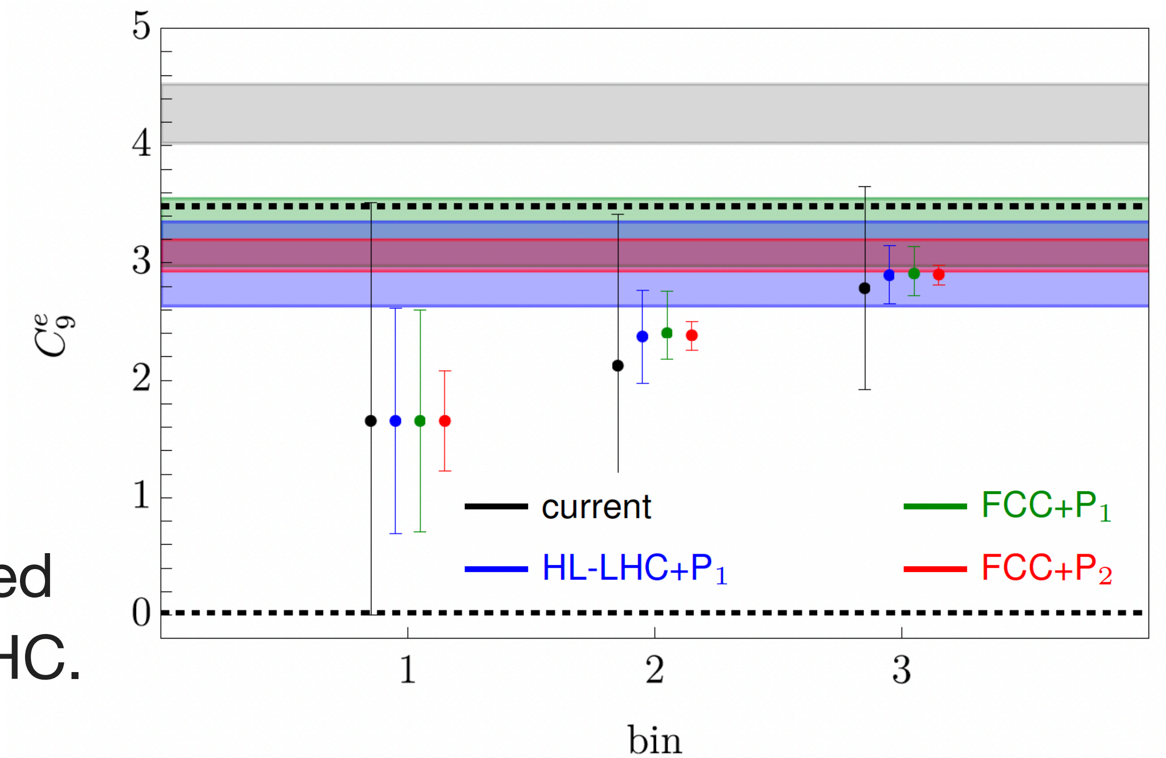
- Two benchmarks on future reduction of theory uncertainties:

$$\mathrm{P}_1 : \sigma_{F_i} \to \sigma_{F_i}/2\,, \qquad \sigma_{C_7^{\rm eff}} \to \sigma_{C_7^{\rm eff}}/2\,, \qquad \frac{\sigma_{V_{cb}}}{V_{cb}} \to 1\%\,,$$

$$\mathrm{P}_2 : \sigma_{F_i} \to \sigma_{F_i}/5\,, \qquad \sigma_{C_7^{\rm eff}} \to \sigma_{C_7^{\rm eff}}/5\,, \qquad \frac{\sigma_{V_{cb}}}{V_{cb}} \to 0.5\%\,.$$

Upshot: FCC-ee statistics can be fully exploited only with P2! Otherwise comparable to HL-LHC.

extracted "C_9^e" [residual amplitude] from binned branching fraction of $B \to K^* e^+ e^-$



Conclusions

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

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.

Looking forward, a tera-Z machine 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

On the theory side, several challenges need to be addressed to take full advantage of mid and long-term experimental advancements.