Flavor physics: a lighthouse for navigating the hazy BSM seas

Gino Isidori
[*University of Zürich*]

- The two flavor puzzles
- Flavor non-universal interactions [*flavor deconstruction*]
- Status of the B anomalies [*what we learned, what's left*]
- Future prospects in flavor physics

University of Zurich UZH

European Research Council
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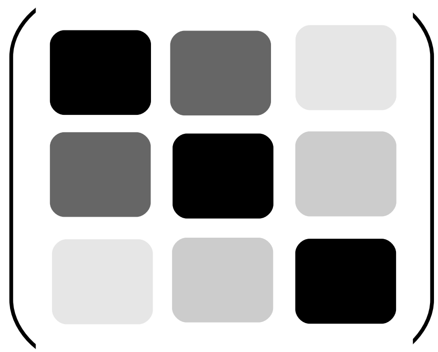
The two flavor puzzles

$V_{\mathrm{CKM}} \sim$ 

The two flavor puzzles

There are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

→ Is there a deeper explanation for this peculiar structures?

II. If the SM is only an effective theory, valid below an ultraviolet cut-off , why we do not see any deviation from the SM predictions in the (suppressed) flavor changing processes? [*NP flavor puzzle*]

→ Which is the flavor structure of physics beyond the SM?

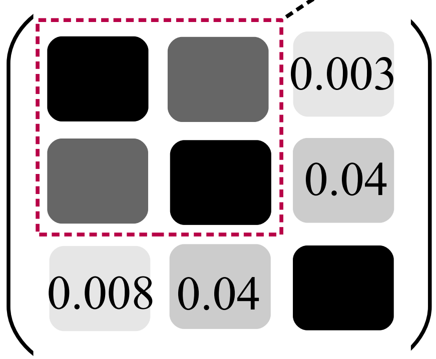
The two flavor puzzles

There are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental:

unitarity violation of the 2×2 (light) block below 10^{-3} !

$V_{\rm CKM} \sim$



N.B.: Despite the very good knowledge we have nowadays about the CKM matrix, we are <u>not able to detect the presence of the 3rd family</u> by looking only at the 2×2 block (*as one naively would have expected...*)

▶ The two flavor puzzles

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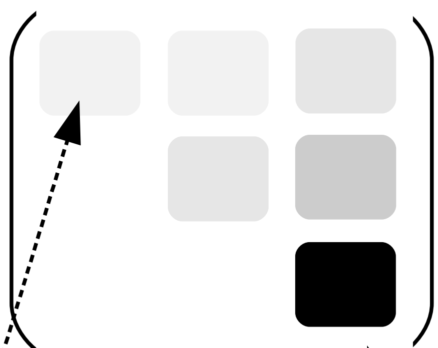
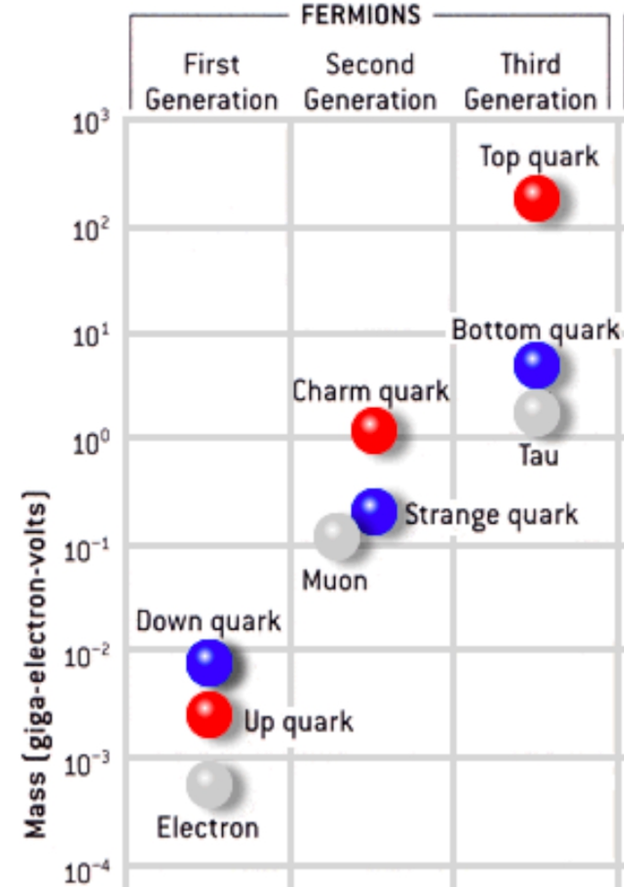
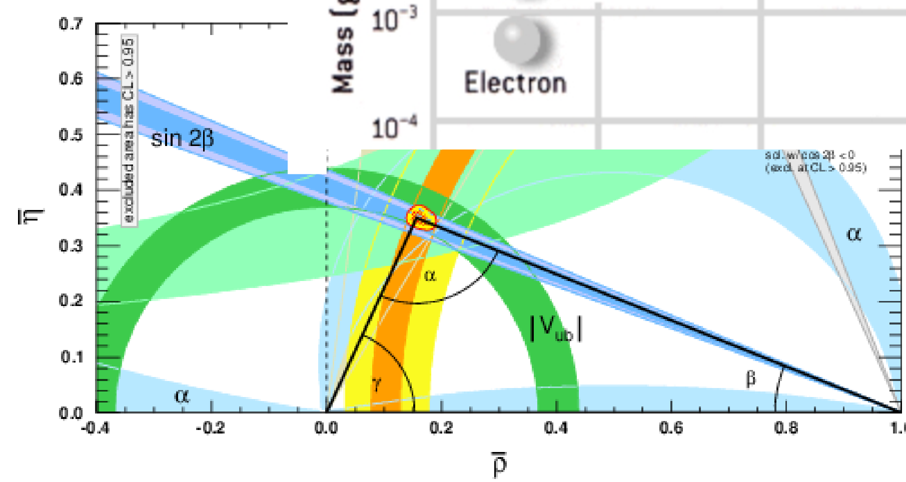
I. The observed pattern of SM Yukawa couplings does not look accidental:

$Y_U \sim$ 





$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5} \qquad y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$

[Y_U in the basis where Y_D is diagonal]

The two flavor puzzles

There are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental:

What we observe is an approximate $U(2)^n$ symmetry acting on the light families

$$\begin{array}{cc} & U(2)_u \\ Y_U \sim & \begin{pmatrix} \multicolumn{2}{c}{< 0.01} & 0.003 \\ & & 0.04 \\ & & \boxed{1} \end{pmatrix} \end{array} \quad \leftarrow U(2)_q$$

$$\bar{Q}_L \, Y_U \, U_R \, H$$

The two flavor puzzles

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Neglecting entries < 0.01 [@ the EW scale]:

$$Y_U \sim \left(\begin{array}{c:c} & 0.04 \\ \hdashline & \boxed{1} \end{array}\right) \qquad Y_D \sim \left(\begin{array}{c:c} & \\ \hdashline & 0.02 \end{array}\right) \qquad Y_E \sim \left(\begin{array}{c:c} & \\ \hdashline & 0.01 \end{array}\right)$$

For $Y_{D,E}$ we could extend $U(2)_{d,e,l}$ to $U(3)_{d,e,l}$

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For $Y_{D,E}$ we could extend $U(2)_{d,e,l}$ to $U(3)_{d,e,l}$

However, beside the overall normalization, in all cases there is a strong hierarchical structure: $U(3) \to U(2)\times U(1)$

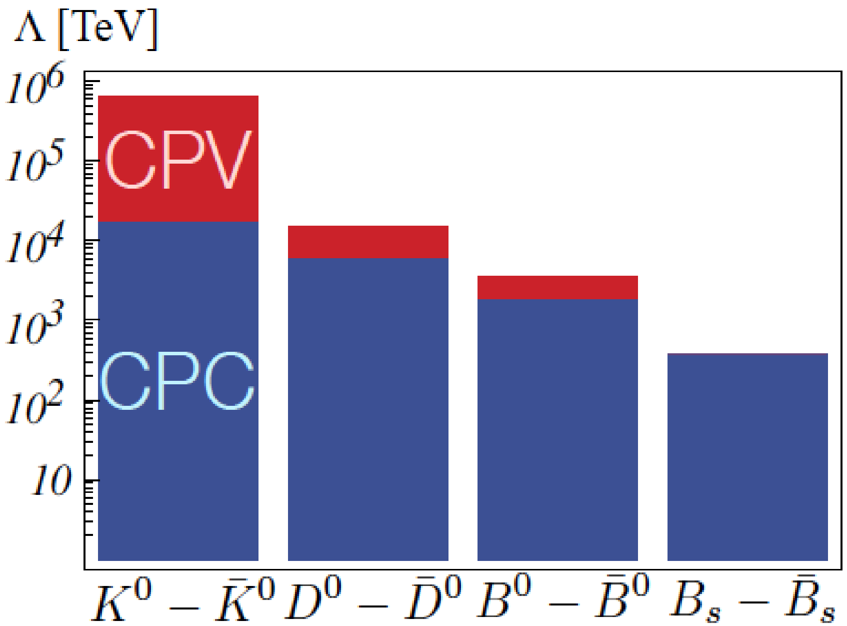
The two flavor puzzles

There are two (long-standing) open issues in flavor physics:

II. Why we do not see any deviation from the SM predictions in the (suppressed) flavor changing processes?

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

Stringent bounds on the scale of possible new flavor non-universal interactions:



These (*over-emphasized*) high scales can be a "mirage"...

The only unambiguous message is:

No large breaking of the approximate $U(2)^n$ flavor symmetry at near-by energy scales

Accidental symmetries in QFT

$$\mathscr{L}_{\cancel{\text{SM-EFT}}\ [\text{SM-2}]\text{-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

(long-distance interactions) (local contact interact.)

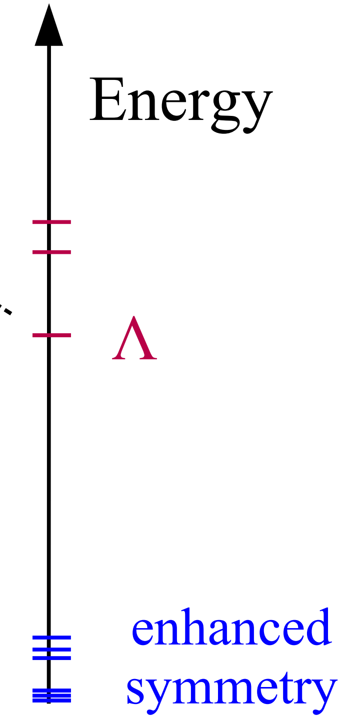
Back in 1973: SM with 2 generations, as "reference model" → CP violation is an accidental symmetry [KM, '73]

But CP violation is observed in K mixing [→ remnant of "heavy NP"]

$$\Lambda_{CP} \sim 10^4 \text{ TeV}$$

$$\frac{e^{i\delta}}{\Lambda_{CP}^2} (\bar{s}\,\Gamma\, d)^2$$

"Super-weak" interaction
[L. Wolfenstein, '64]



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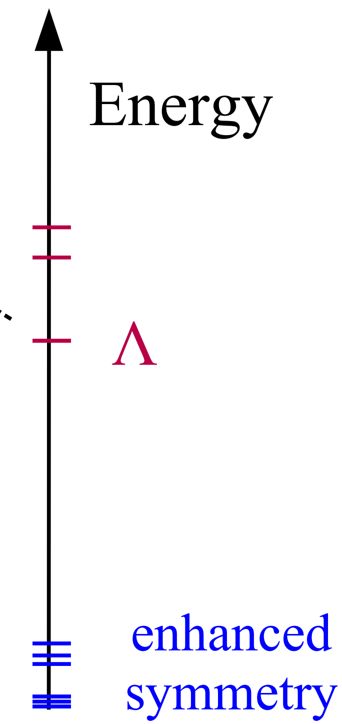

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$$\Lambda_{CP} \sim 10^4\ \text{TeV}$$

SM-3
[KM, '73]

$$\frac{1}{\Lambda_{CP}^2} \sim \frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2}$$

Ellis, Gaillard, Nanopulos, '76

Key message: beware of seemingly high scales in EFT approaches: they can be a "mirage"...

The two flavor puzzles

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

Flavor-degeneracy:
$U(3)^5$ symmetry

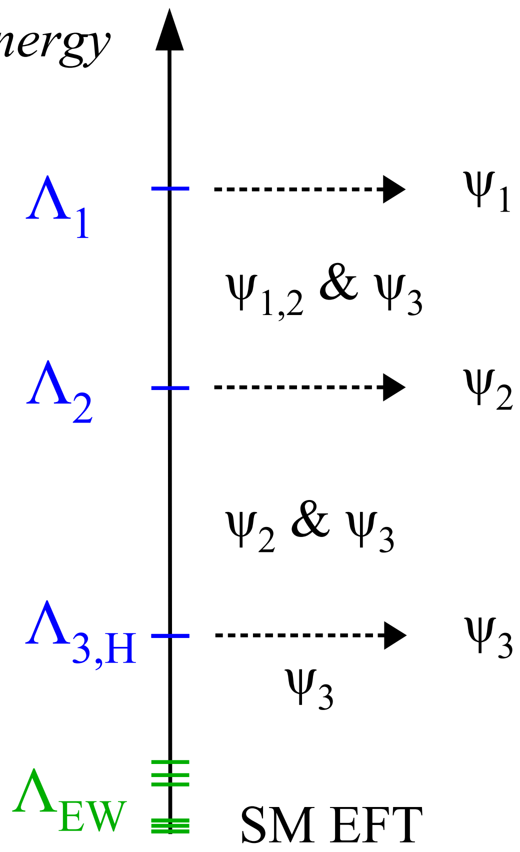
Yukawa couplings:
$U(3)^5 \rightarrow \sim U(2)^n$
peculiar breaking of the flavor symm.

Stringent bounds on generic flavor-violating ops.
$\updownarrow$
approx. $U(2)^n$ holds also beyond the SM

The big questions in flavor physics:

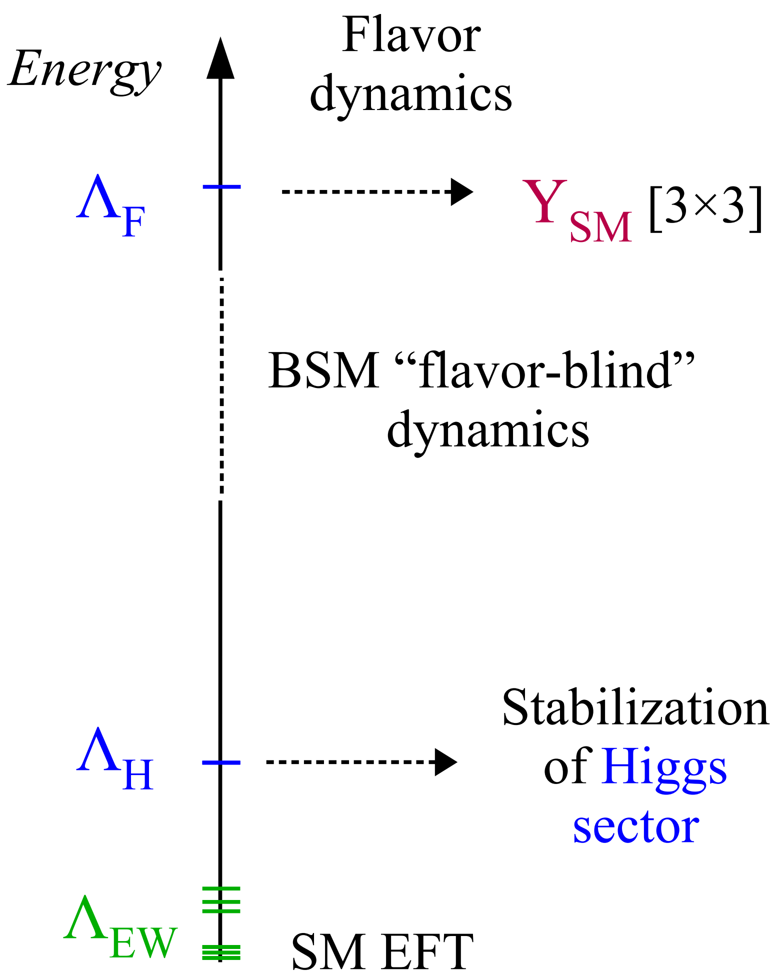
- Can we find an explanation for the Yukawa hierarchies?
- Are the approximate flavor symmetries accidental symmetries (*in QFT sense*)? If so, at which scale(s) do they appear, and at which scale(s) are they broken?

Flavor non-universal interactions



Flavor non-universal interactions

For a long time, the vast majority of model-building attempts to extend the SM was based on the *implicit* hypotheses of *flavor-universal* New Physics



- Concentrate on the Higgs hierarchy problem
- Postpone the flavor problem to higher scales

⇕

The "MFV paradigm"
+
"Horizontal" flavor symm. @ high scales

3 gen. = "identical copies" up to high energies

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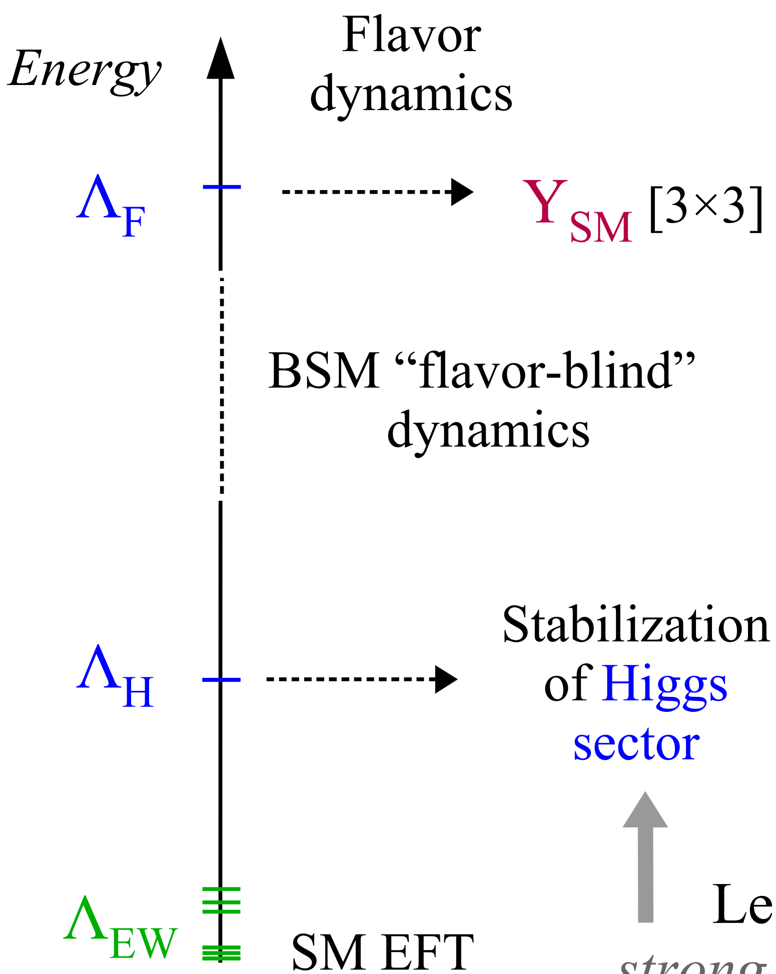

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The "MFV paradigm"
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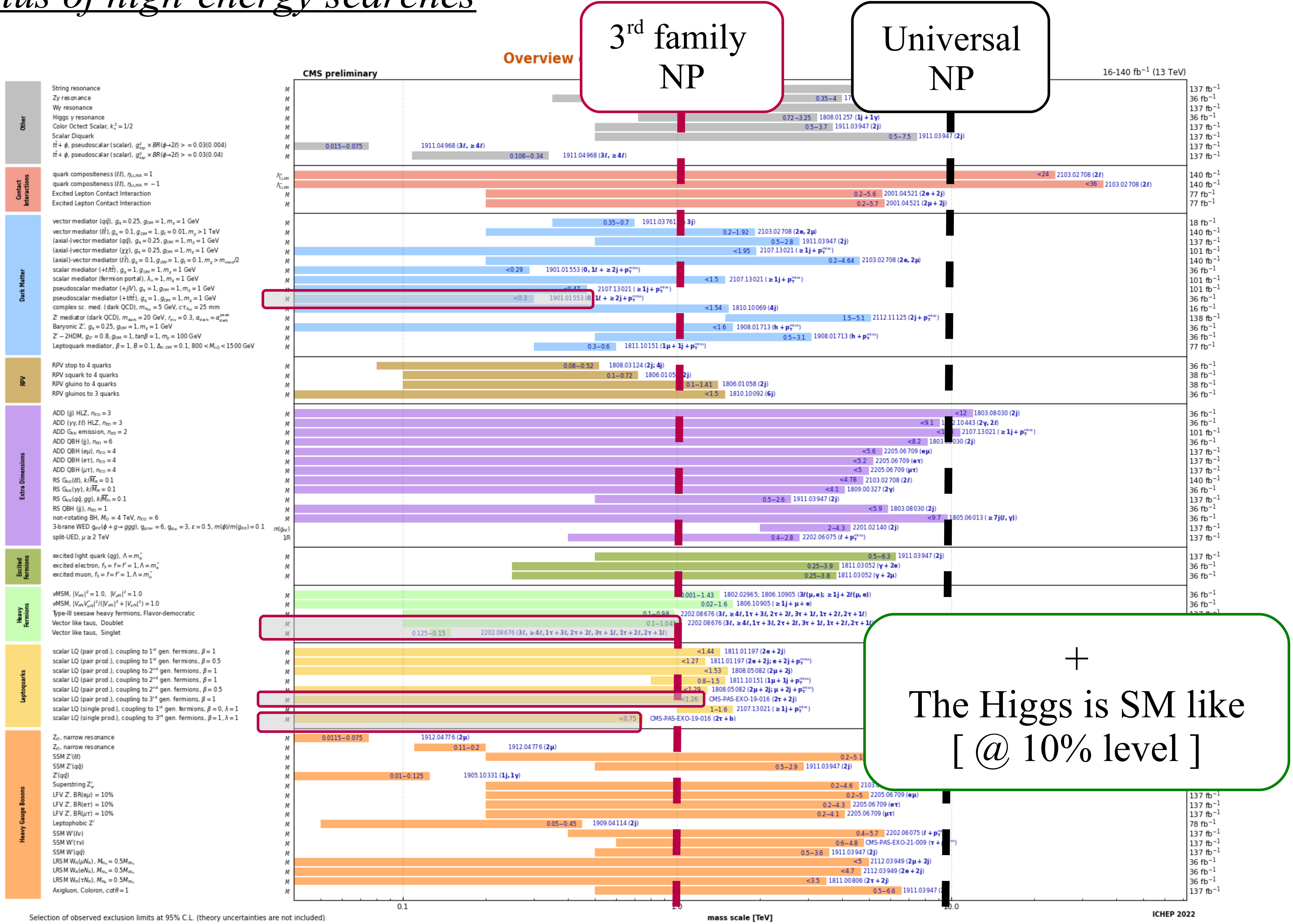
Less compelling after LHC results (run I+II):
strong bounds on NP coupled universally to all families
worsening of the Higgs hierarchy problem

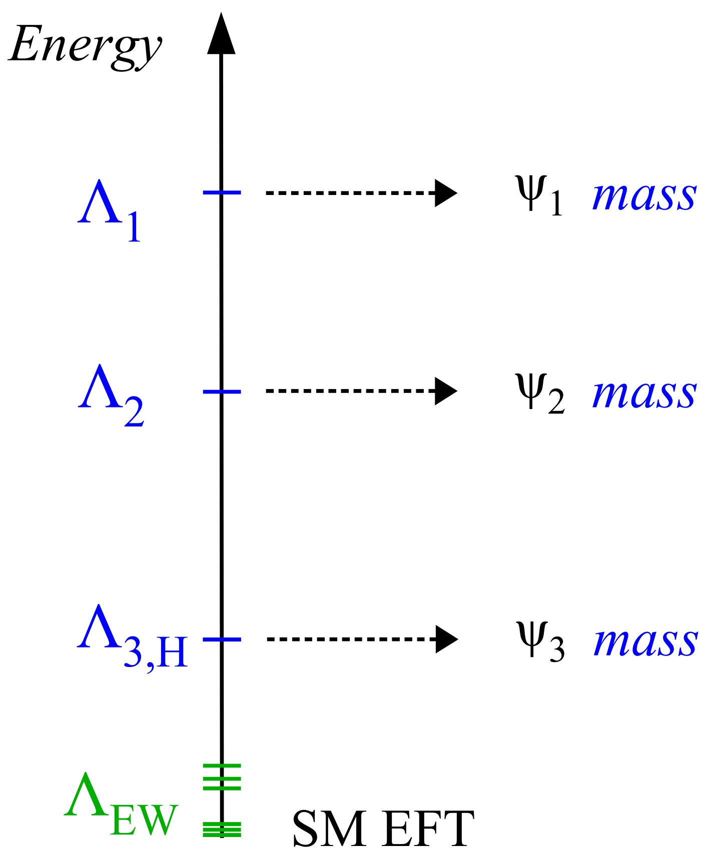
Status of high-energy searches



Flavor non-universal interactions

A more efficient paradigm to address both flavor puzzles (I+II), & *possibly* the Higgs hierarchy, is a *multi-scale* UV with *flavor non-universal* interactions

Dvali & Shifman '00
Panico & Pomarol '16
⋮
Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23



Main idea:

Flavor deconstruction of the SM gauge symm. already at the TeV scale → flavor hierarchies emerge as accidental symmetries

1st & 2nd gen. have small masses (& small coupling to NP) because they are coupled to NP at heavier scales

⬇

~~3 gen. = "identical copies" up to high energies~~

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Arkani-Hamed, Cohen, Georgi '01
Craig, Green, Katz, '11
...

⋆ *Flavor deconstruction* of the SM gauge symmetries:

$$G_{SM}^{[3]} \times G_{SM}^{[12]} \rightarrow G_{SM}$$

[*last step @ ~ TeV scale*]

A more intricate "weaving" vs.

- *"vertical" group containing* G_{SM}

$\times$

- *"horizontal" flavor symmetry*

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Some notable points:

✔ This symmetry breaking pattern is very general:
any scalar rep. (provided $R_{[3]}$, $R_{[12]} \neq 1$) breaks to the diagonal subgroup
→ flavor universality emerges "naturally" at low energies

Craig, Garcia-Garcia, Sutherland '17

✔ Flavor hierarchies obtained without the need of peculiar choices for the "flavor charges" [e.g. U(1) charges as in Froggatt & Nielsen]

Flavor non-universal interactions

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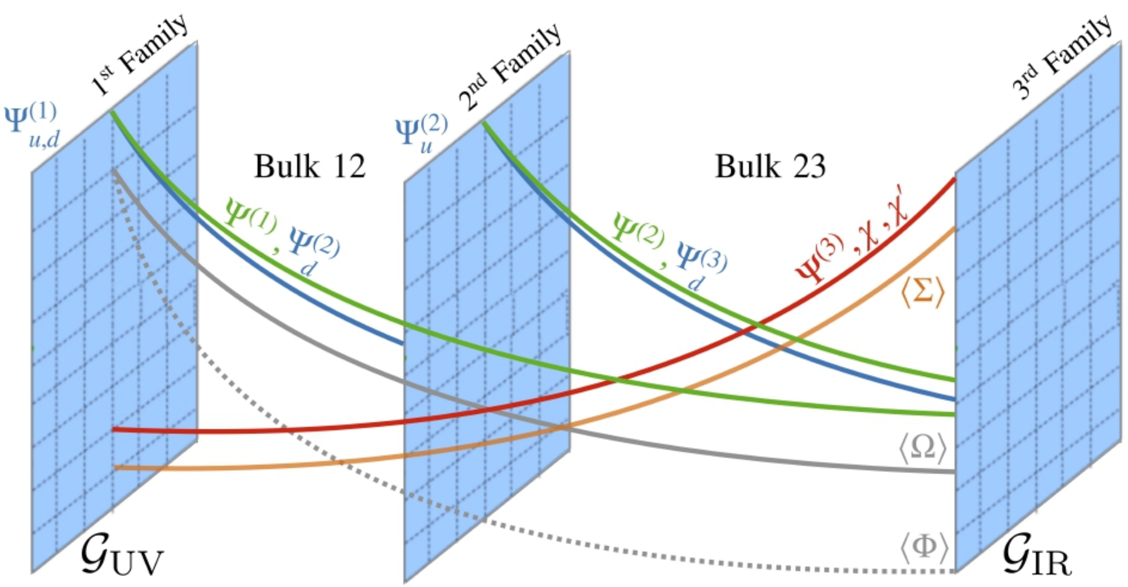
Looking more into the UV, this picture could arise from an extra-dimensional construction:



Flavor ↔ special position (*topological defect*) in an extra (compact) space-like dimension

Dvali & Shifman, '00

- Flavor hierarchies related to brane distances
- "Holographic" Higgs from appropriate choice of bulk/brane gauge symmetries
- Anarchic neutrino masses via inverse see-saw mechanism

Fuentes-Martin, Stangl '20
Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

Flavor non-universal interactions

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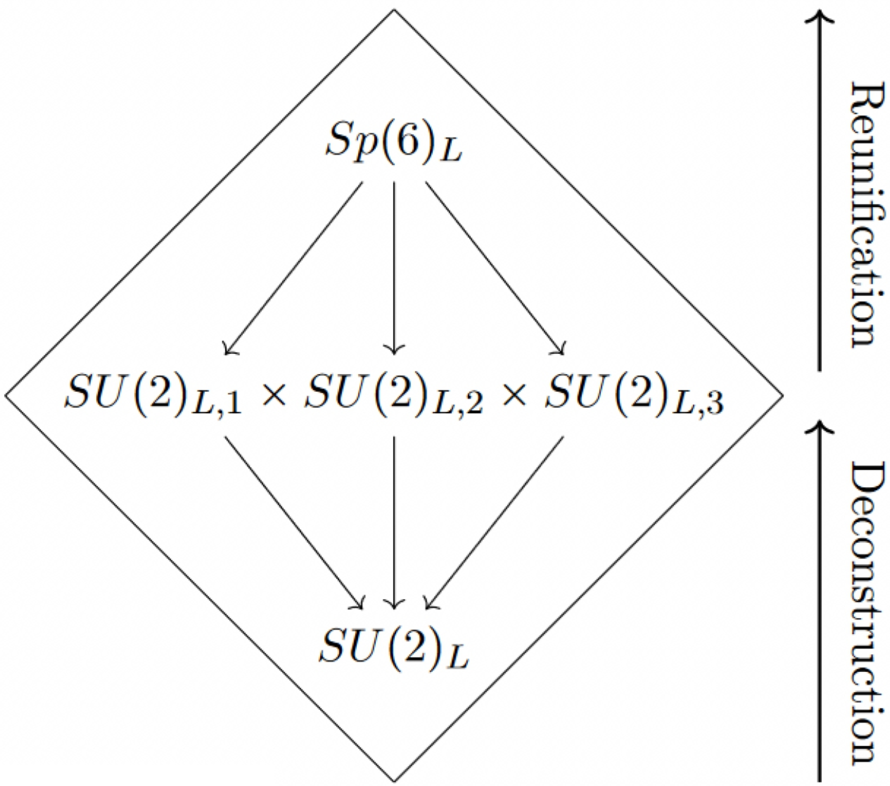
Looking more into the UV, this picture could arise from an extra-dimensional construction, or as limit of larger unified gauge groups.

E.g.: "electroweak-flavor" unification [Davighi & Tooby-Smith '22]:



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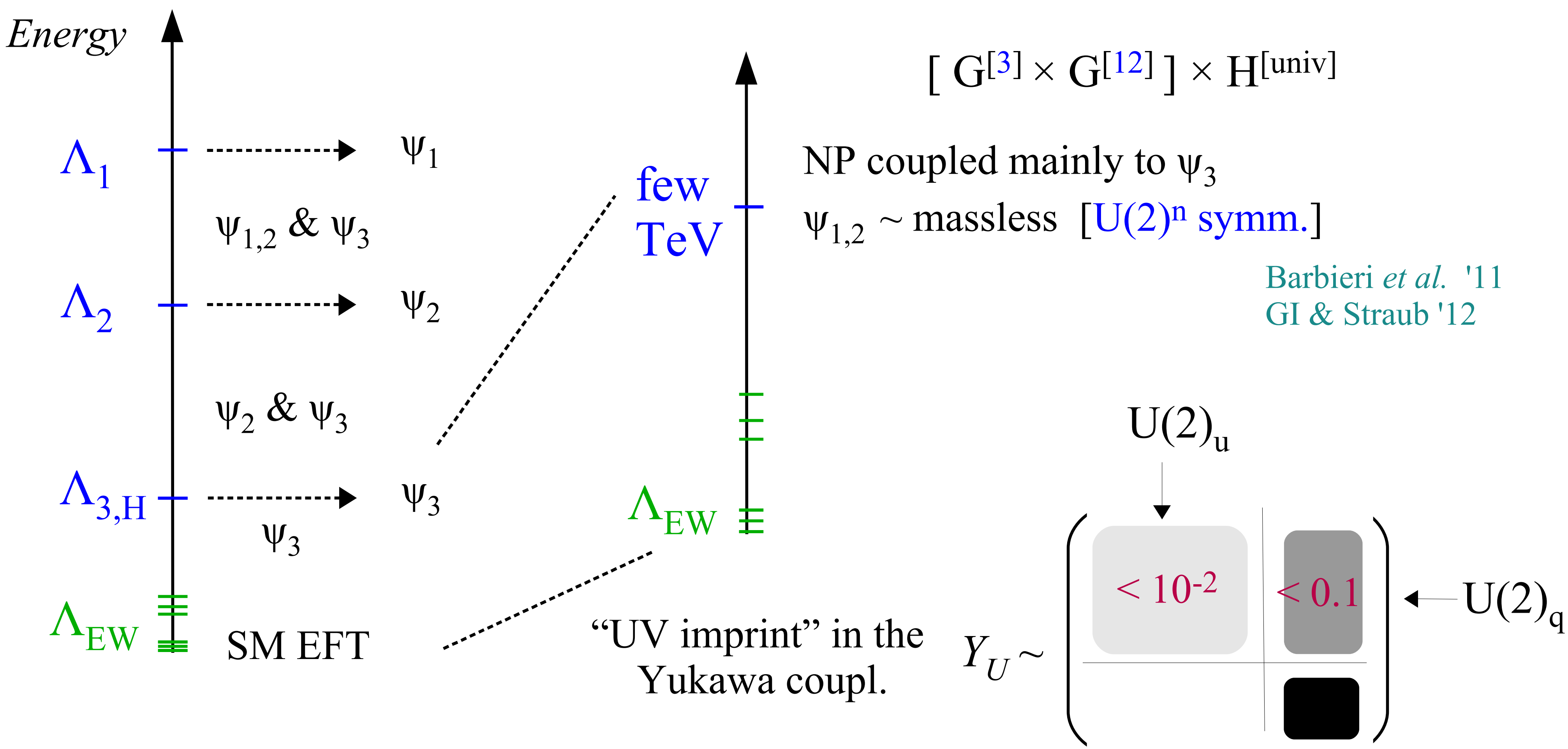


Effective organizing principle for the flavor structure of the SMEFT

▸ *Flavor hierarchies from gauge non-universality* [a brief detour]

To understand which are the viable options for TeV-scale dynamics, we recently analysed all the extensions of the SM gauge group compatible with the following three general assumptions:

Davighi & G.I. '23

I. Obtain the $U(2)^n$ flavor symmetry as accidental symmetry of the (non- universal) gauge sector

II. Elementary Higgs up to (at least) the TeV scale → New states should preserve Higgs-mass stability → NP coupled to 3rd generation should occur at the TeV scale

III. Explain charge-quantization → Semi-simple embedding in the UV [i.e. no U(1) groups in the UV]

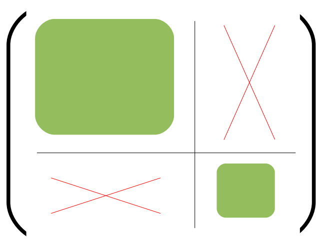
Flavor hierarchies from gauge non-universality [a brief detour]

I. $U(2)^n$ flavor symmetry as accidental symmetry of the gauge sector.

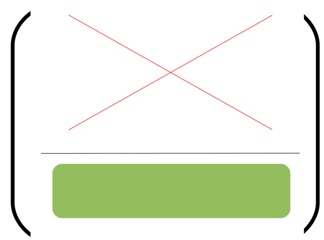
- Classify the allowed Yukawa structures under a flavor-deconstruction of three basic factors characterizing the SM fermions and the EW gauge group: $SU(2)_L \times U(1)_R \times U(1)_{B-L}$

$$\overline{\psi}_L\, Y\, \psi_R\, H$$

$U(1)_{B-L}^{[3]} \times U(1)_{B-L}^{[12]}$

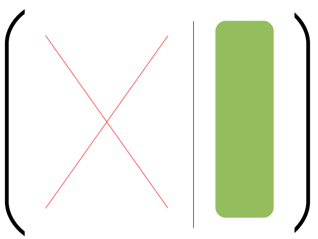
$Y \sim$ 

$SU(2)_L^{[3]} \times SU(2)_L^{[12]}$

$Y \sim$ 

H charged under $SU(2)_L^{[3]}$

$U(1)_R^{[3]} \times U(1)_R^{[12]}$

$Y \sim$ 

H charged under $U(1)_R^{[3]}$

$\Downarrow$

- Deconstructing <u>any pair of the three</u> (or all of them) leads to the desired $U(2)^n$ flavor symmetry

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I. $U(2)^n$ flavor symmetry as accidental symmetry of the gauge sector.

- Classify the allowed Yukawa structures under a flavor-deconstruction of three basic factors characterizing the SM fermions and the EW gauge group: $SU(2)_L \times U(1)_R \times U(1)_{B-L}$

- Deconstructing any pair of the three (or all of them) leads to the desired $U(2)^n$ flavor symmetry:
  - ✓ Part of the EW group necessarily need to be deconstructed

- Minimal choice represented by SM hypercharge [$Y=T^3_R+(B-L)/2$]. However, $U(1)^{[3]}_Y \times U(1)^{[2]}_Y \times U(1)^{[1]}_Y$ has two drawbacks:
  - ✗ No immediate semi-simple embedding
  - ✗ Same deconstruction mechanism protecting both mixing & light masses → not vey efficient in suppressing flavor bounds

Navarro & King '23
Davighi & Stefanek '23

▶ *Flavor hierarchies from gauge non-universality* [a brief detour]

II.+III. Explain charge-quantization → Semi-simple embedding in the UV

But new states should preserve Higgs-mass stability → NP coupled to 3rd generation should occur at the TeV scale

↓

Semi-simple embeddings of the SM have been classified and there are very few possibilities, all featuring one of the possible 3 basic options:

Allanach, Gripaios, Tooby-Smith '23

- SU(4)×SU(2)×SU(2) [Pati & Salam '74]
- SU(5) [Georgi & Glashow, '74]
- SO(10) [Georgi '75, Fritzsch & Minkowski '75]

↓

Proton stability → only the Pati-Salam option is possible at low scales

$$SU(3)_c \times U(1)_{B-L} \hookrightarrow SU(4) \sim \left[\begin{array}{c|c} SU(3)_c & 0 \\ \hline 0 & 0 \end{array}\right] \left[\begin{array}{c|c} 0 & LQ \\ \hline LQ & 0 \end{array}\right] \left[\begin{array}{c|c} 1/3 & 0 \\ \hline 0 & -1 \end{array}\right]$$

▸ *Flavor hierarchies from gauge non-universality* [a brief detour]

I. + II. + III. : four basic options:

TeV-scale gauge group: $G_U \times G_3 \times H_{12}$			
	G_U	G_3	H_{12}
1	$\mathrm{SU}(2)_L$	$\mathrm{SU}(4)^{[3]} \times \mathrm{SU}(2)_R^{[3]}$	$\mathrm{SU}(3)^{[12]} \times \mathrm{U}(1)_{B-L}^{[12]} \times \mathrm{U}(1)_R^{[12]}$
2	$\mathrm{SU}(2)_R$	$\mathrm{SU}(4)^{[3]} \times \mathrm{SU}(2)_L^{[3]}$	$\mathrm{SU}(3)^{[12]} \times \mathrm{SU}(2)_L^{[12]} \times \mathrm{U}(1)_{B-L}^{[12]}$
3	$\mathrm{SU}(4)$	$\mathrm{SU}(2)_L^{[3]} \times \mathrm{SU}(2)_R^{[3]}$	$\mathrm{SU}(2)_L^{[12]} \times \mathrm{U}(1)_R^{[12]}$
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Higgs & 3rd gen. fields
charged only under these groups

UV completion
@ higher E

small impact on δm_h

Allwicher, GI, Thomsen '20
Davighi, G.I., Pesut '22
Davighi & G.I. '23

$$Y \sim \left(\begin{array}{c|c} & \\ \hline & 1 \end{array}\right)$$

d > 4 ops
(@ TeV scale)

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UV completion @ higher E

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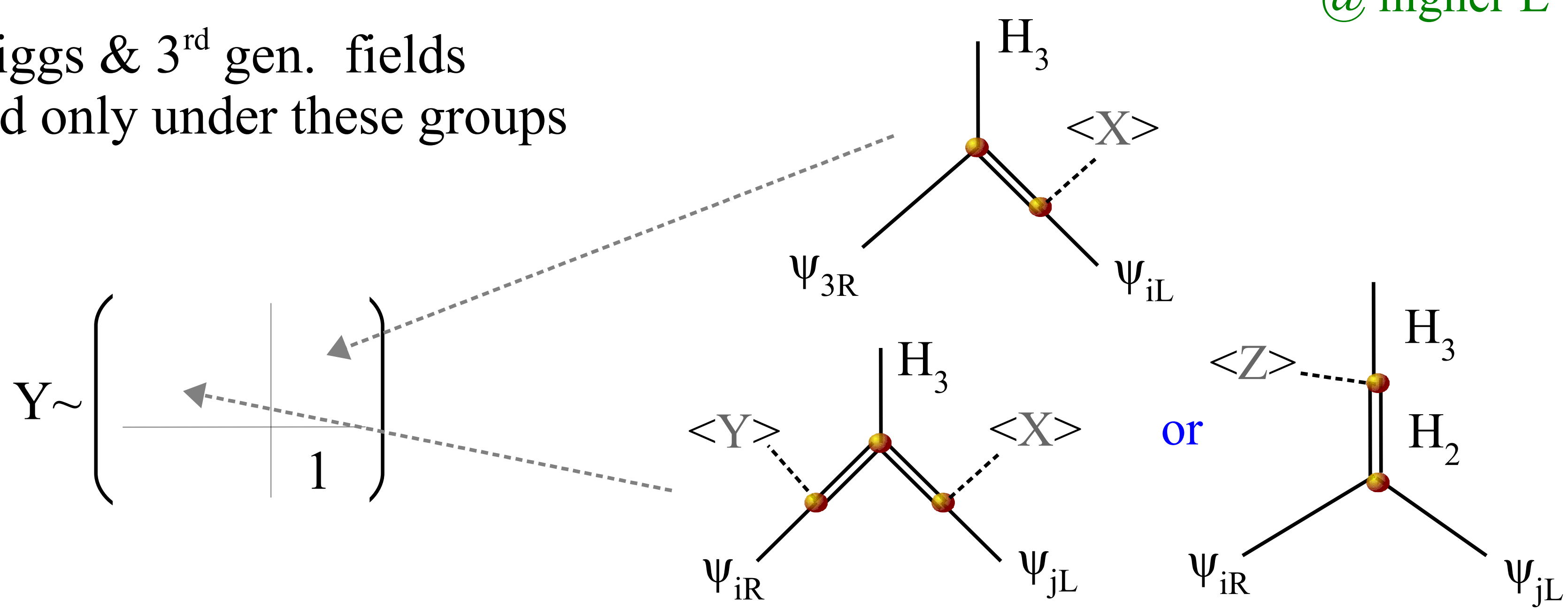

Flavor hierarchies from gauge non-universality [a brief detour]

I. + II. + III. + general pheno bounds: two viable TeV-scale options:

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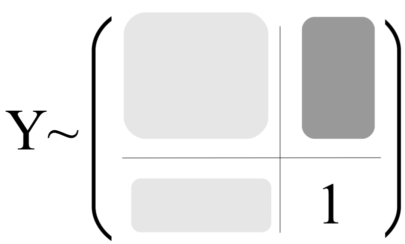
UV completion @ higher E

Strongly disfavored by:

- $K_L \to \mu e$
- RH mixing



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4	$\emptyset$	$\mathrm{SU}(4)^{[3]} \times \mathrm{SU}(2)_L^{[3]} \times \mathrm{SU}(2)_R^{[3]}$	$\mathrm{SU}(3)^{[12]} \times \mathrm{SU}(2)_L^{[12]} \times \mathrm{U}(1)_{B-L}^{[12]} \times \mathrm{U}(1)_R^{[12]}$

UV completion
@ higher E

General feature:

SU(4) group acting on the 3rd family,
with low-energy breaking scale to avoid fine-tuning on the Higgs mass:

$$\delta m_h^2/m_h^2 < 1 \quad \rightarrow \quad \Lambda_U = M_U/g_U \lesssim 5 \text{ TeV}$$

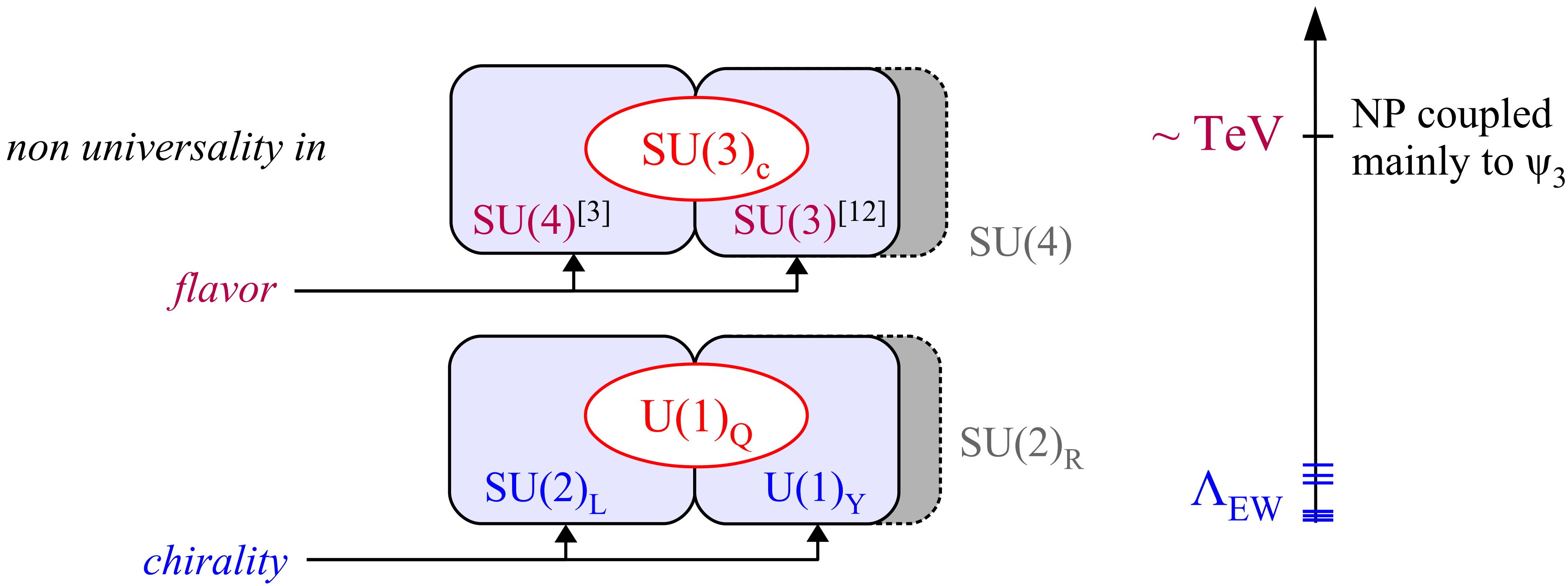
Flavor hierarchies from gauge non-universality [a brief detour]

This connects with the class of consistent TeV-scale models proposed to address the B-physics anomalies...

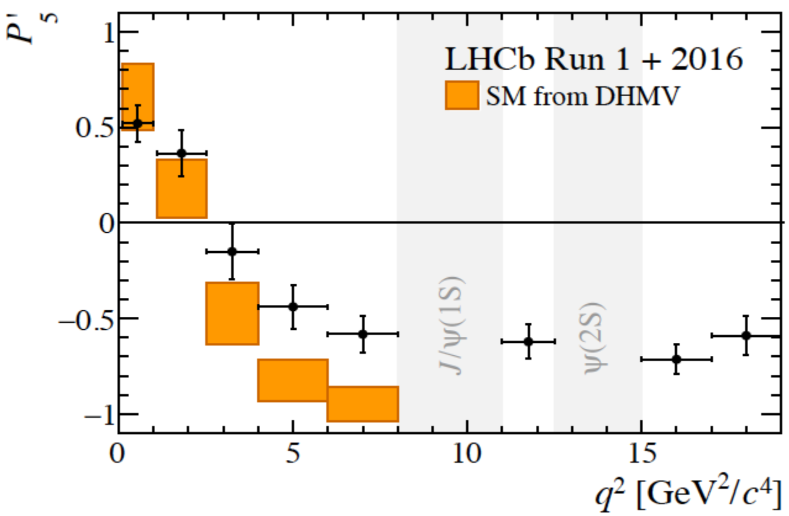
$$\mathrm{SU}(4)^{[3]}\times \mathrm{SU}(3)^{[12]}\times \mathrm{SU}(2)_L\times \mathrm{U}(1)'$$

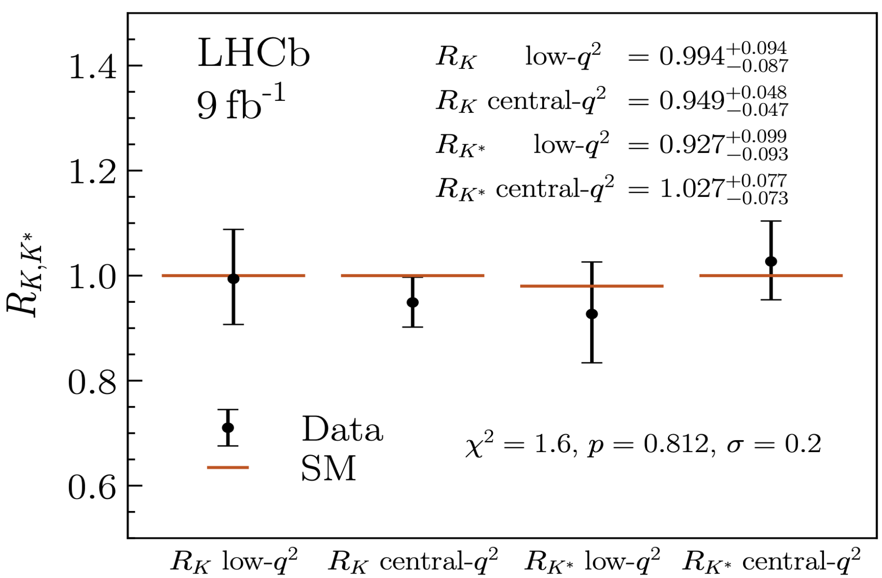
$$\Big\downarrow \;\; \to \mathrm{LQ}\ [U_1] + Z' + G'$$

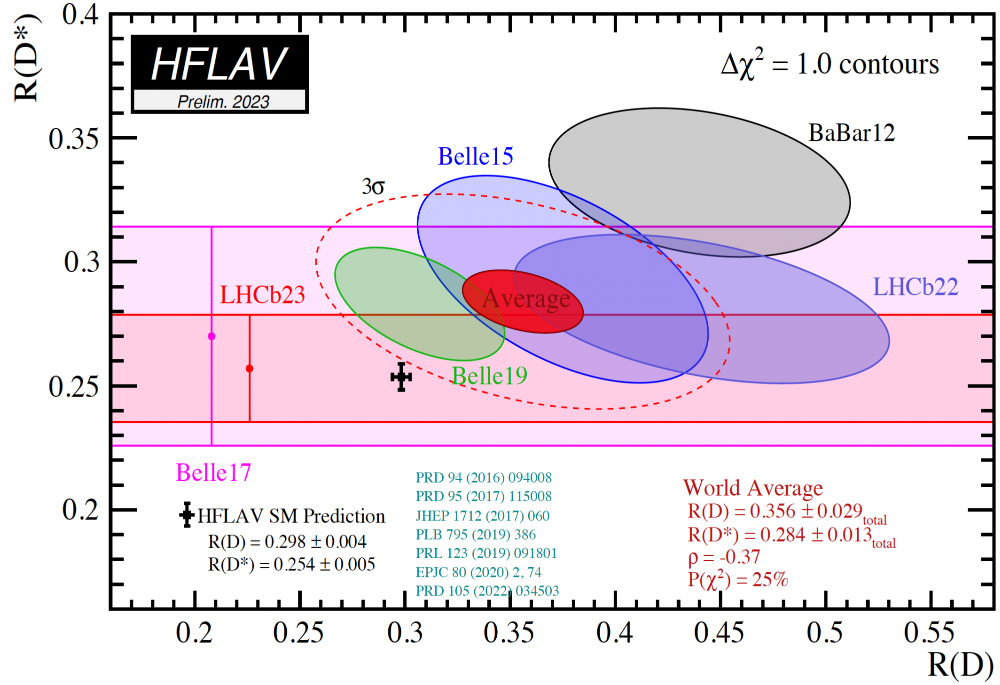
$$\mathrm{SM}$$



The B-physics anomalies







The B-physics anomalies

From 2013 results in (various) semi-leptonic B decays started to exhibit tensions with the SM predictions. Several exclusive channels are involved, but they are all sensitive only to the following two classes of partonic transitions:

$b \to c\, l\nu$ (*Charged Currents*) $b \to s\, l^+ l^-$ (*Neutral Currents*)

Most of the anomalies are connected to a possible breaking of Lepton Flavor Universality = <u>accidental symmetry</u> of the SM Lagrangian in the limit where we neglect the lepton Yukawa couplings

Even if the significance went down recently (*not completely...*), worth to discuss as example of consistent TeV-scale (new) physics that could be revealed by precision flavor experiments

The B-physics anomalies

From 2013 results in (various) semi-leptonic B decays started to exhibit tensions with the SM predictions. Several exclusive channels are involved, but they are all sensitive only to the following two classes of partonic transitions:

$b \to c\, l\nu$ (*Charged Currents*) $b \to s\, l^+l^-$ (*Neutral Currents*)

The anomalies can be grouped into 3 categories:

I. ~~LFU~~ anomaly in CC [τ vs. (μ, e)] — $b \to c\, l\nu$

II. ΔC_9 (*lepton-universal*) anomaly in NC modes

III. ~~LFU~~ anomaly in NC [μ vs. e] & BR($B_s \to \mu\mu$)

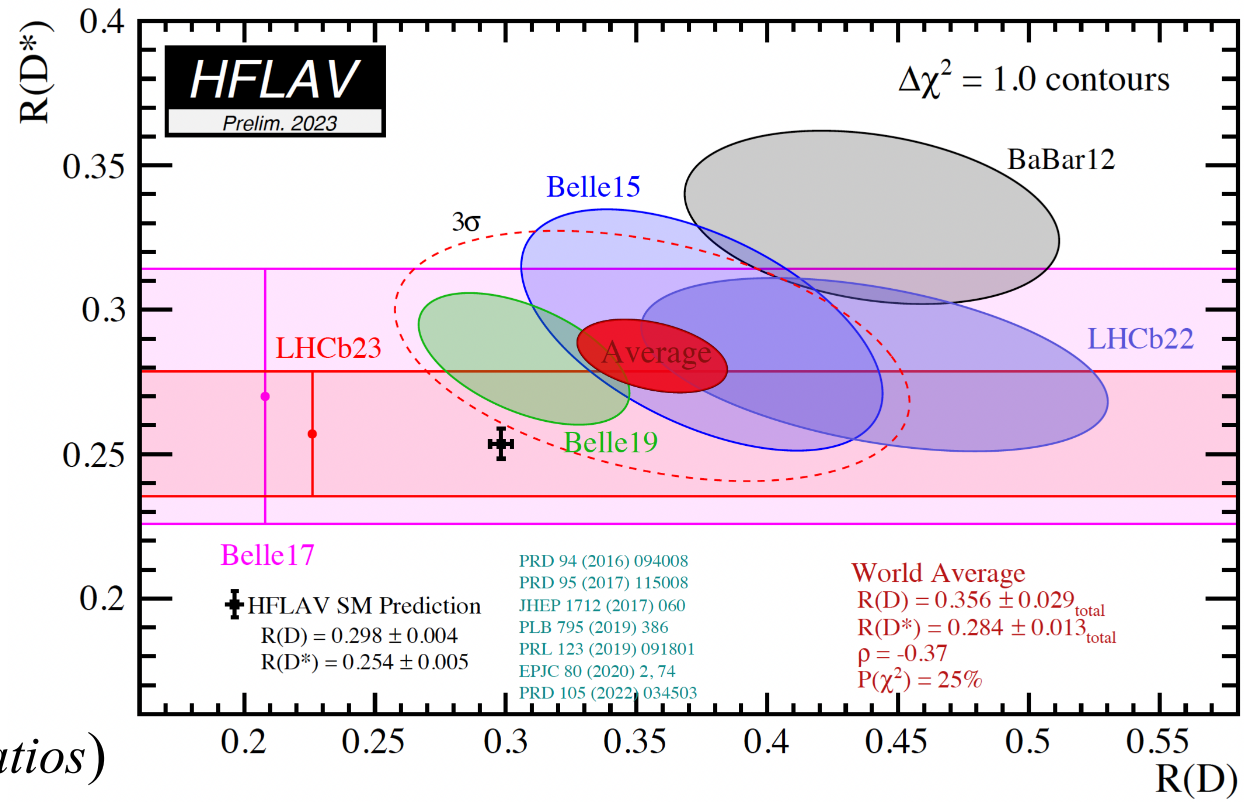
(II. and III.) — $b \to s\, l^+l^-$

The B-physics anomalies

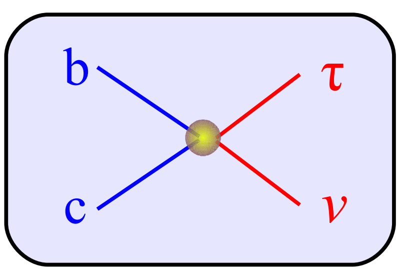
I. ~~LFU~~ anomaly in CC
[τ vs. (μ, e)]

$$R(X) = \frac{\Gamma(B \to X\,\tau\nu)}{\Gamma(B \to X\,l\nu)}$$

X = D or D*



- Clean SM predictions
  (*uncertainties cancel in the ratios*)
- 3.0σ excess over SM
- Compete with SM @ tree-level → *low scale of NP*



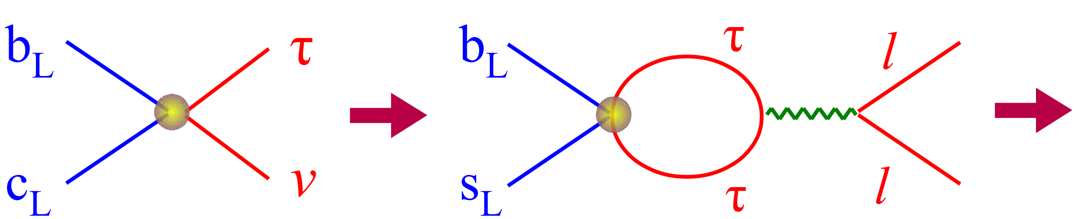
The B-physics anomalies

II. ΔC_9 (*lepton-universal*) anomaly in NC modes

$$\mathcal{O}_9^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

- Possible contamination from SM long-distance (*charming penguins*)
- All attempts to compute the effect agree on ~ 3σ deviation from SM
- Compete with SM @ loop-level

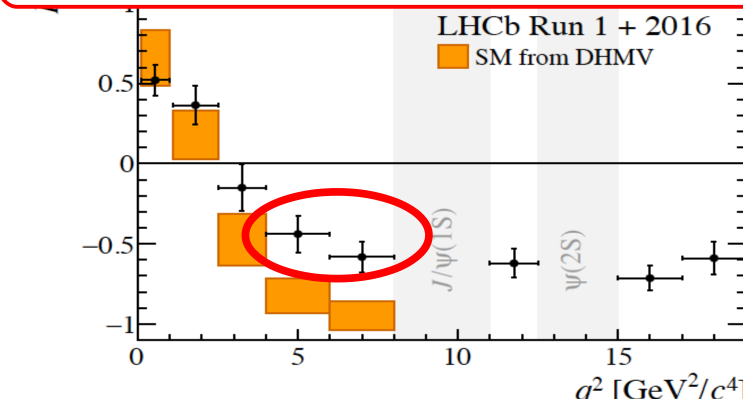
Possible explanation connected to CC (hence 3rd family LFU violation):



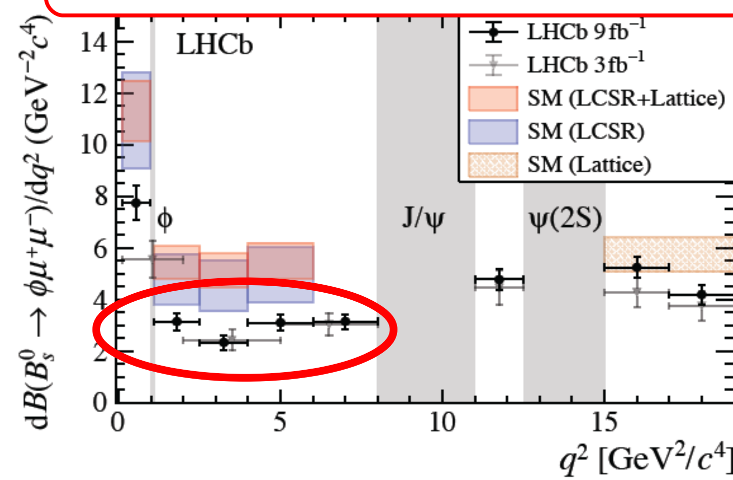
$\Delta C_9^{\mathrm{Univ}}$

N.B.: correct sign & size !

B → K*μμ angular distribution



B → H μμ branching ratios

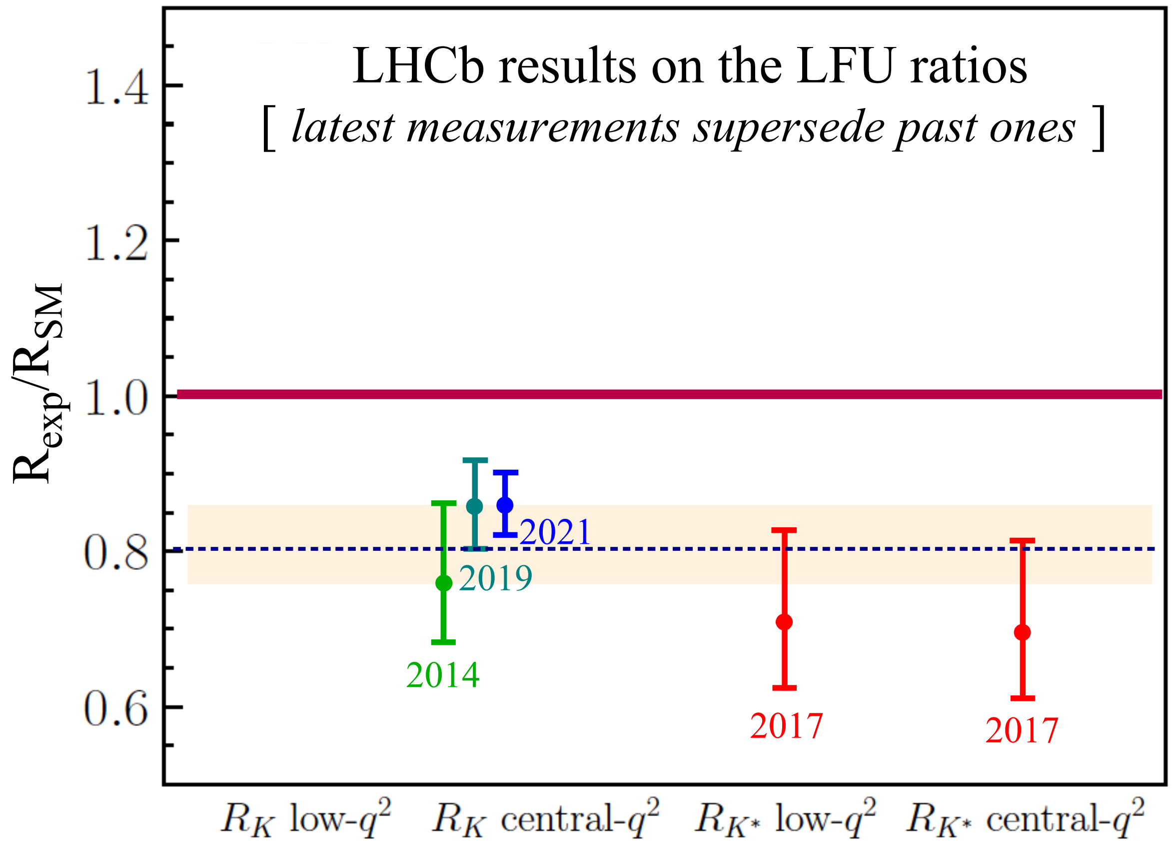


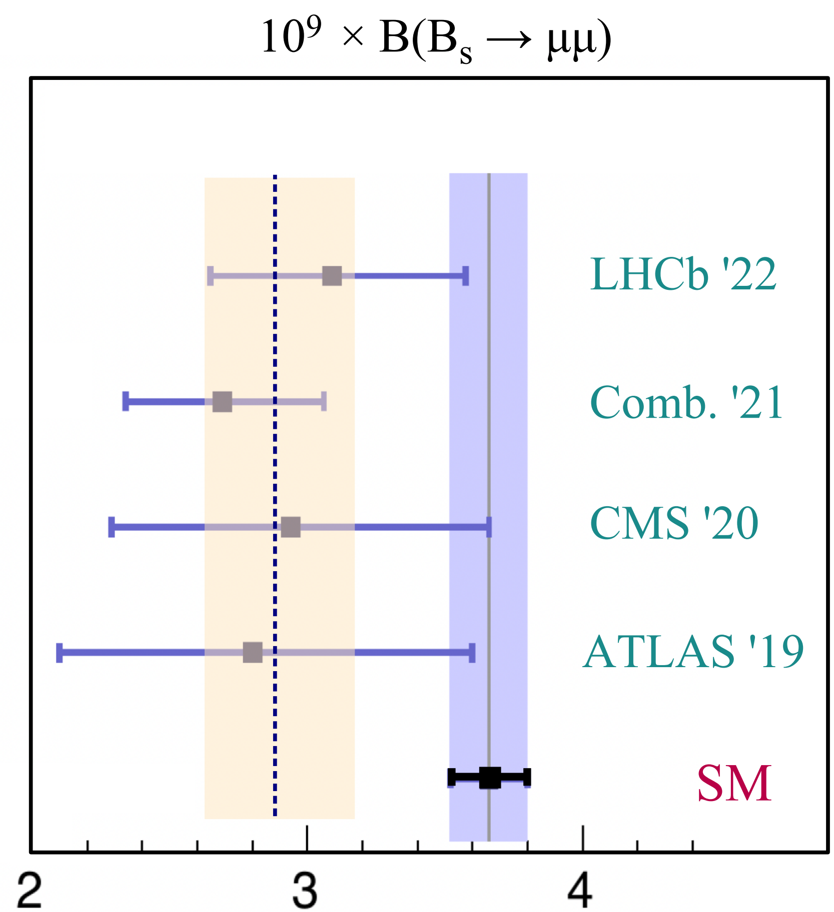
Bobeth & Haisch '11
Crivellin *et al.* '18
Alguero *et al.* '18

▶ *The B-physics anomalies*

III. ~~LFU~~ anomaly in NC [μ vs. e] & BR($B_s \to \mu\mu$)

- Clean SM predictions
  (*LFU ratios + no long-distance in* $B_s \to \mu\mu$)
- Highest significance till summer 2022





The B-physics anomalies

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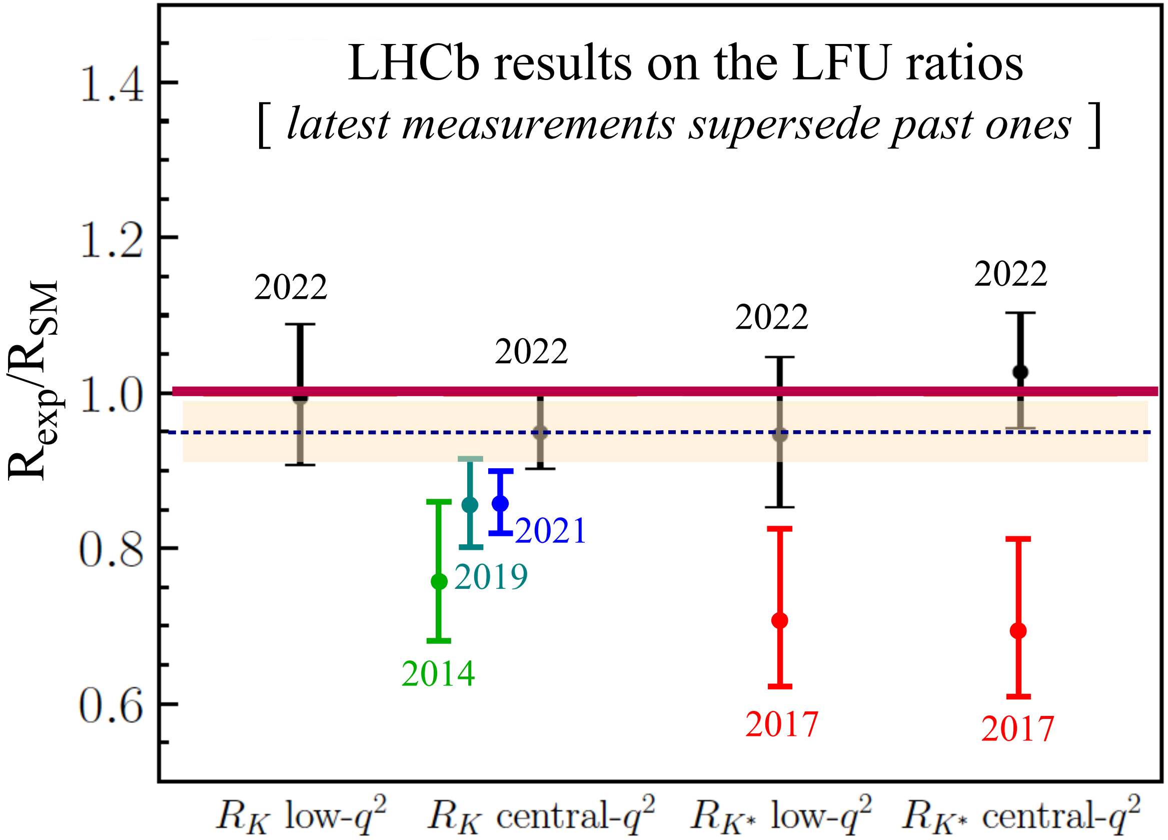
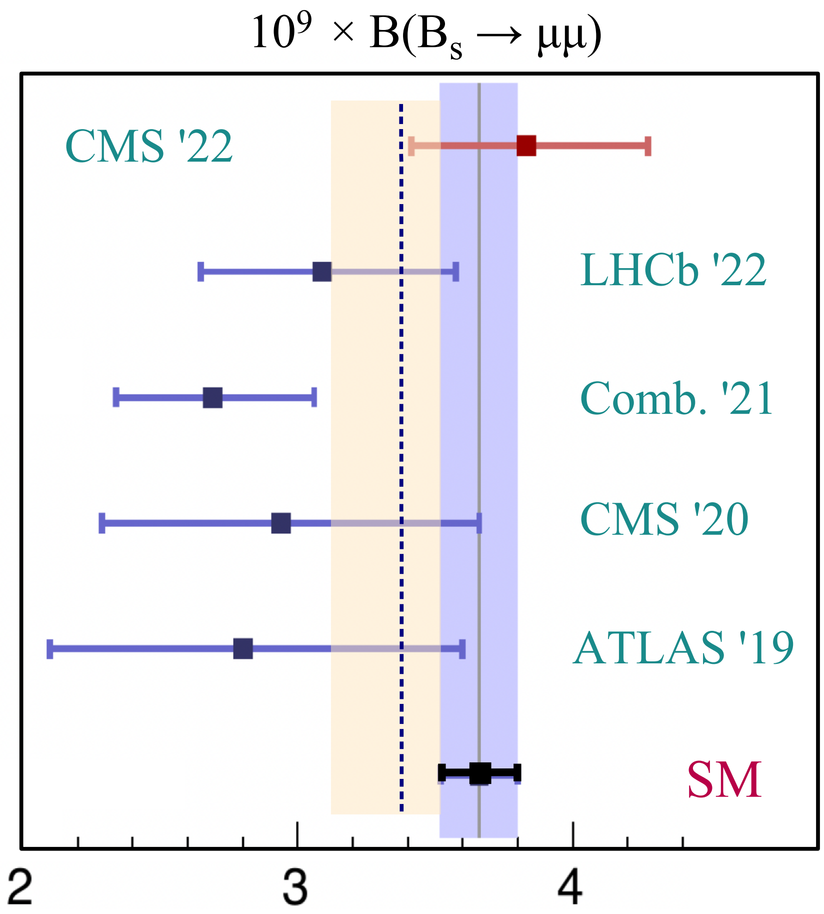


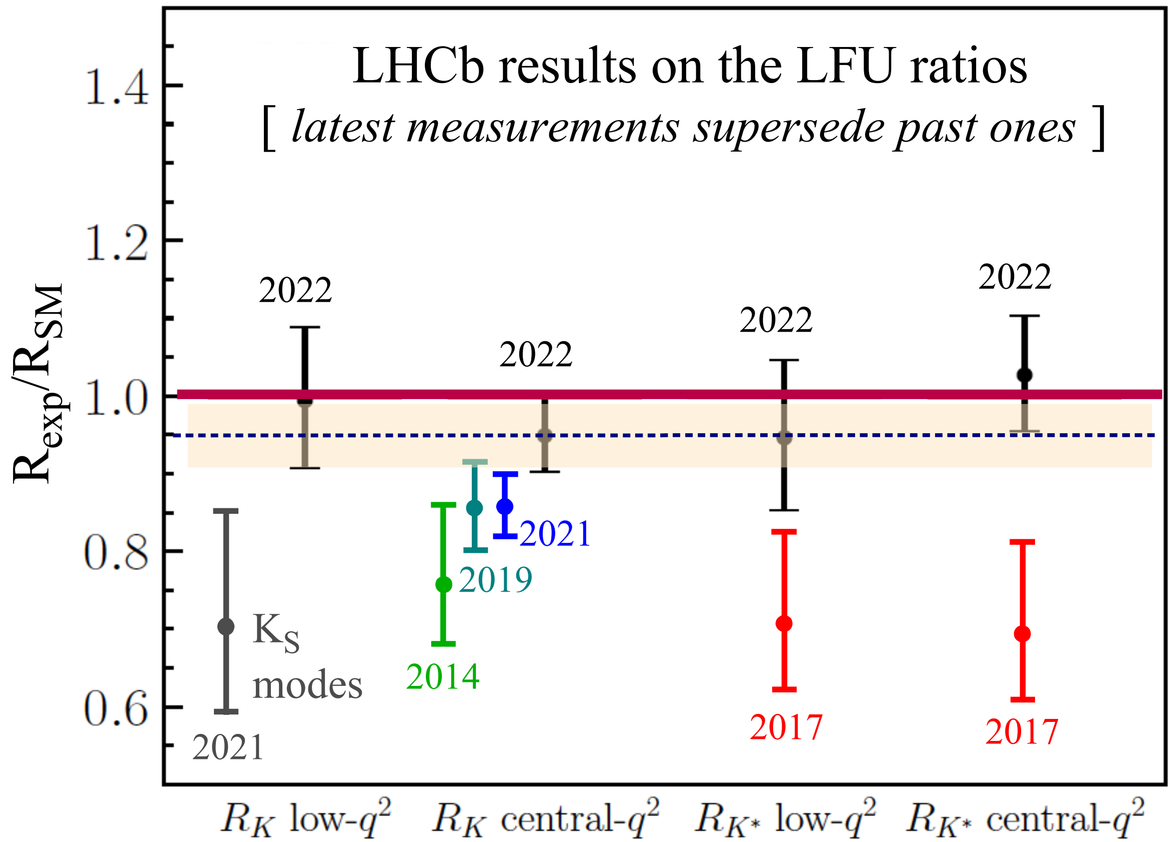


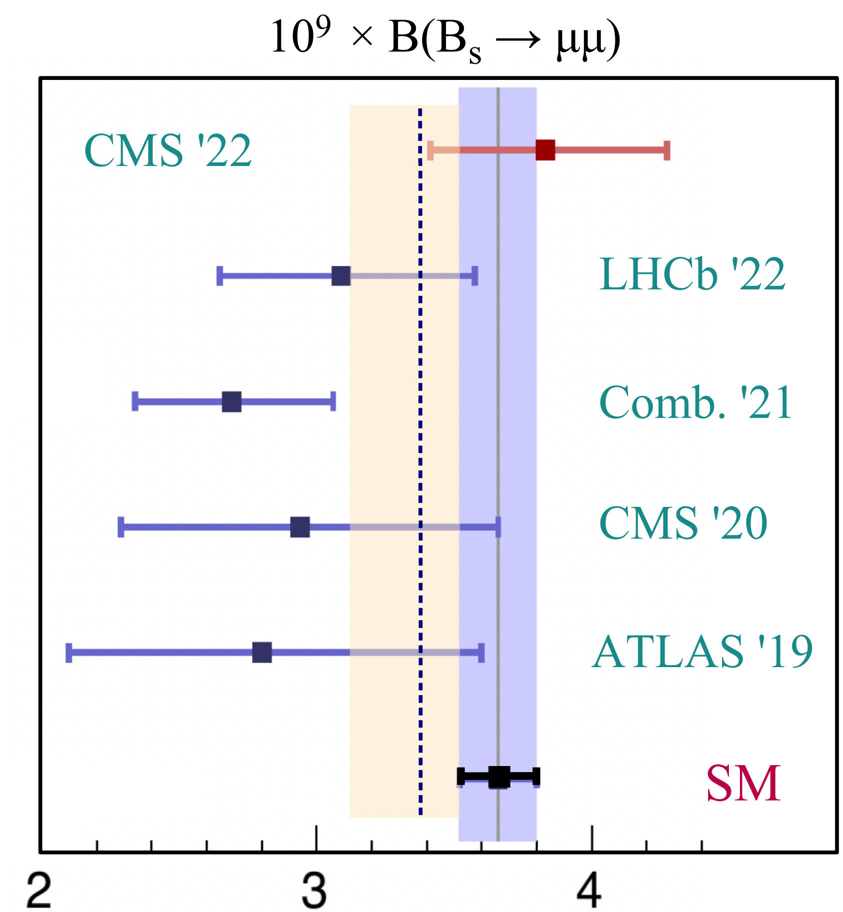
The B-physics anomalies

III. ~~LFU~~ anomaly in NC & BR($B_s \to \mu\mu$)

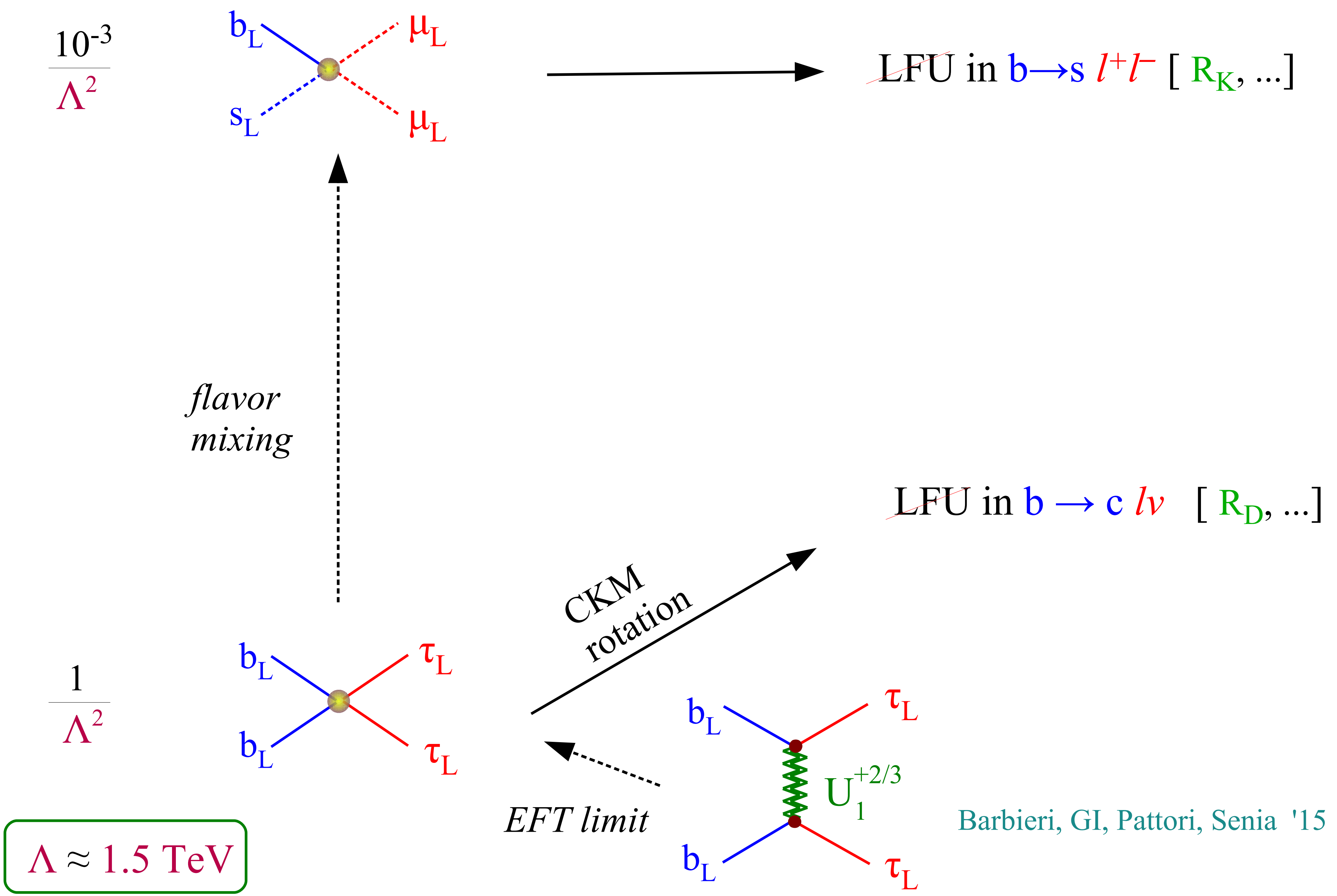
- Clean SM predictions
  (*LFU ratios + no long-distance in* $B_s \to \mu\mu$)
- ~~Highest significance till summer 2022~~

N.B.: *While the overall loss of significance is high, the overall implications for the class of NP models I advocate, are modest*

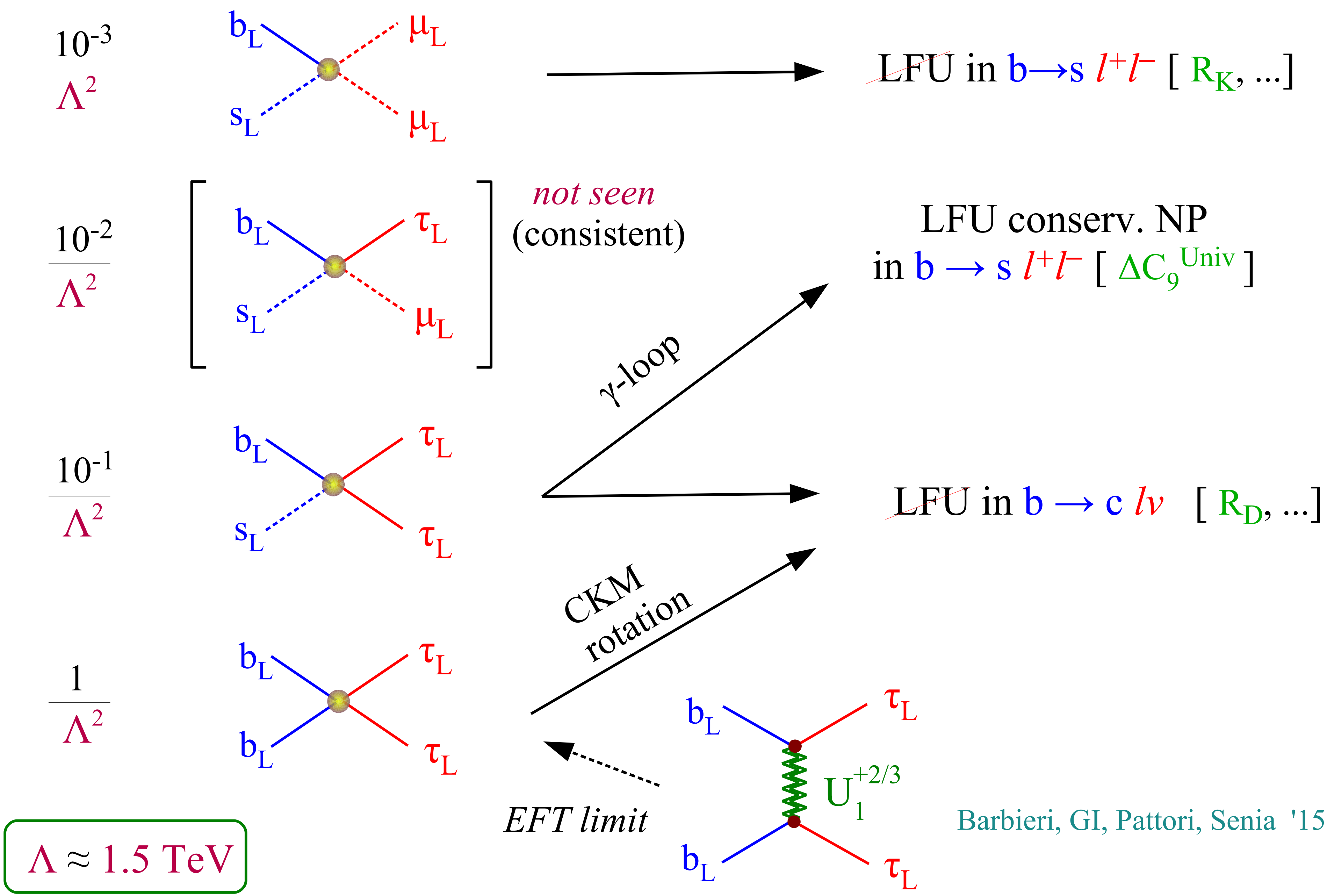




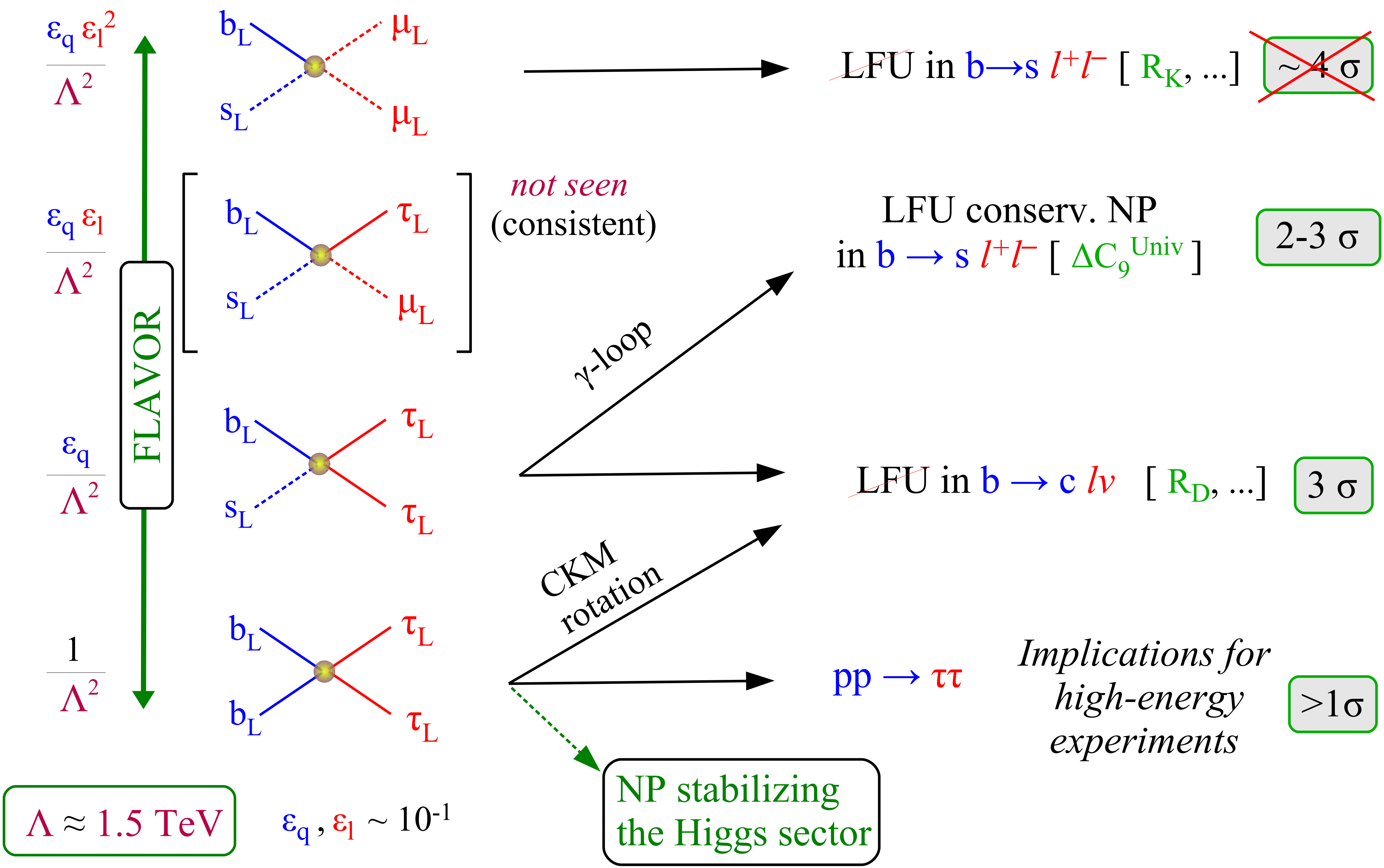
The B-physics anomalies



The B-physics anomalies

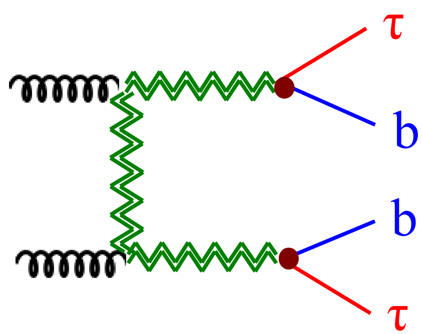


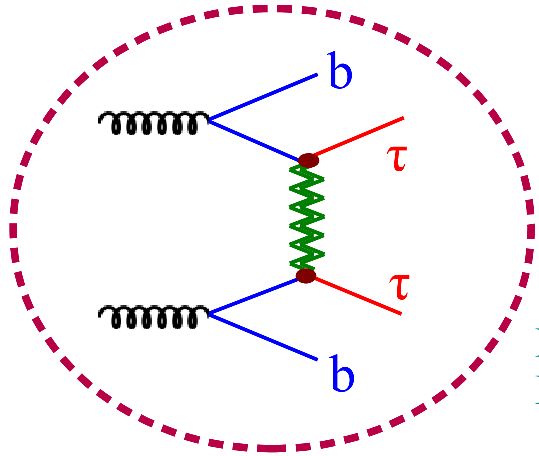
The B-physics anomalies



The B-physics anomalies

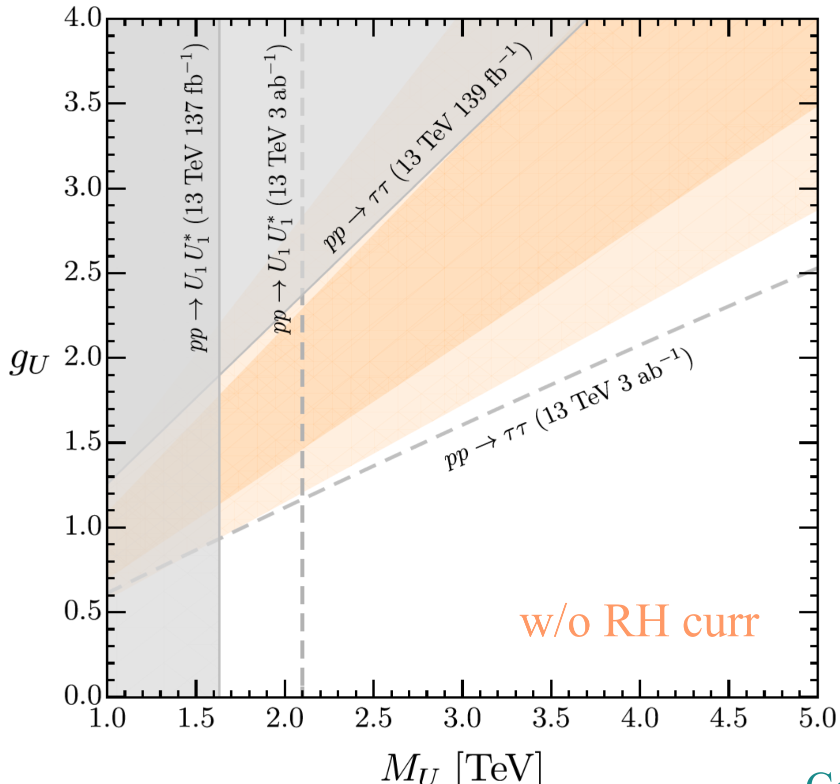
The U_1 leptoquark at high energies:

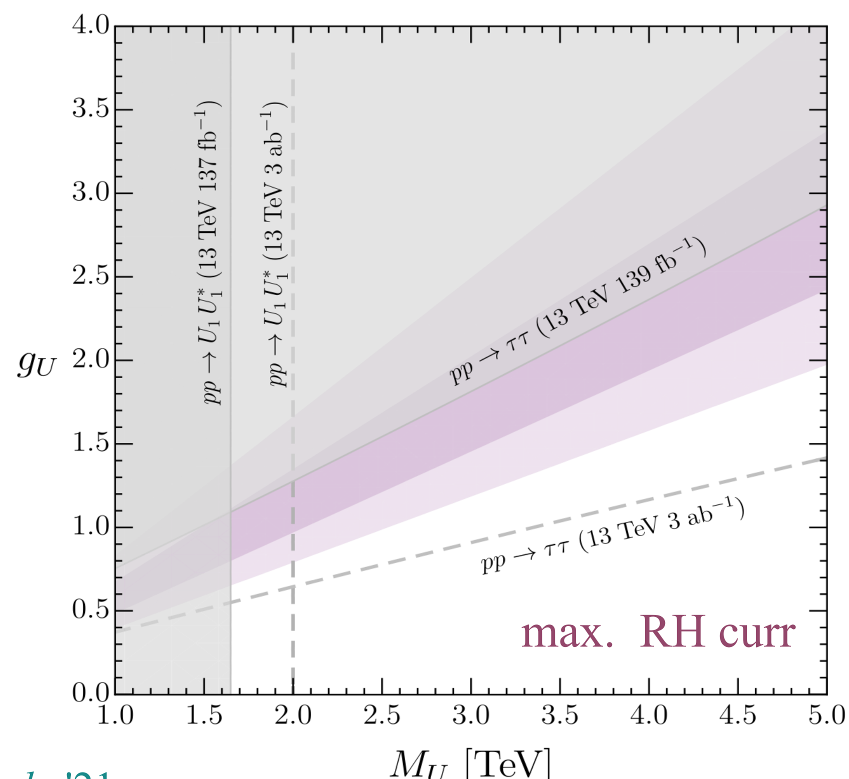




$pp \to \tau\tau$

Faroughi, Greljo, Kamenik '16





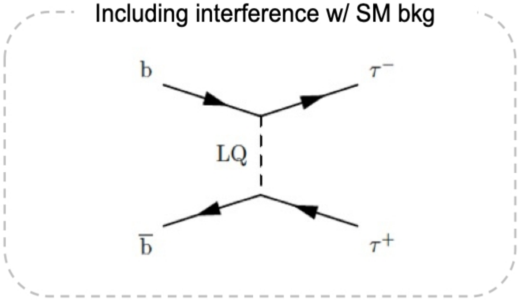
Cornella *et al.* '21

The B-physics anomalies

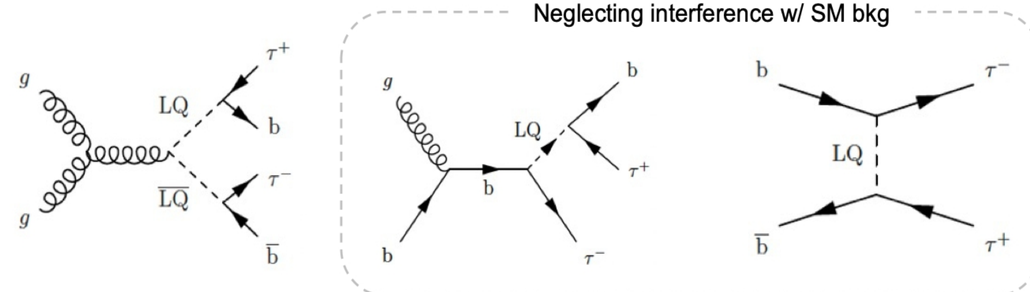
Aurelio Juste [*Moriond EW* '23]

LQ-b-τ: Comparison of recent results

Including interference w/ SM bkg

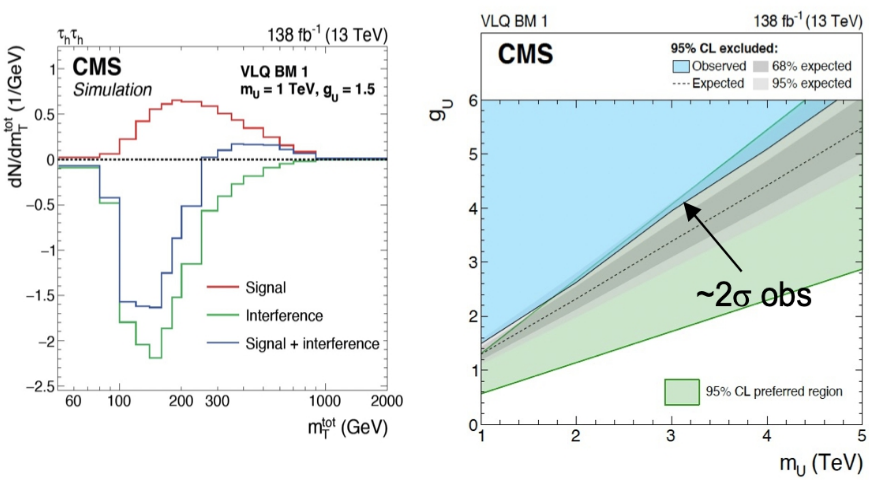


Neglecting interference w/ SM bkg



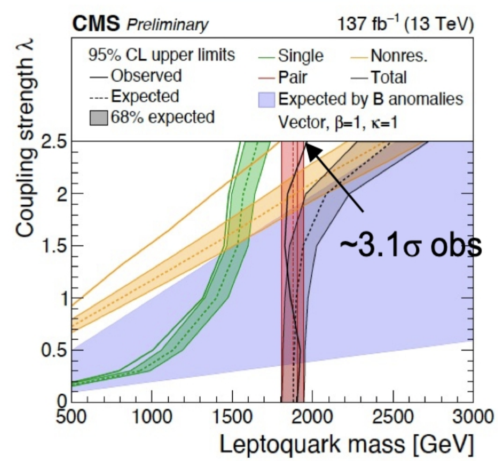
Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

CMS-HIG-21-001

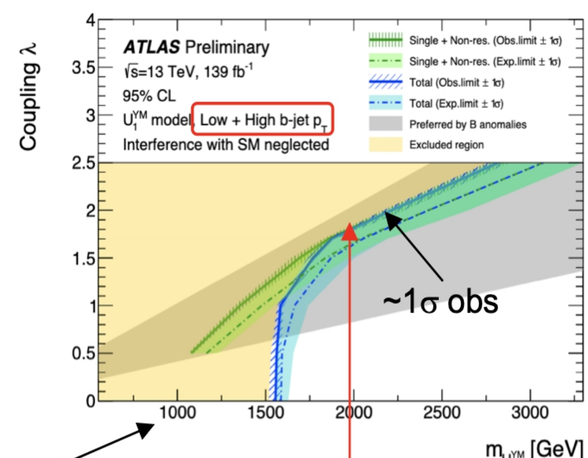


Shown at Moriond EW 2022

CMS-PAS-EXO-19-016



EXOT-2022-39



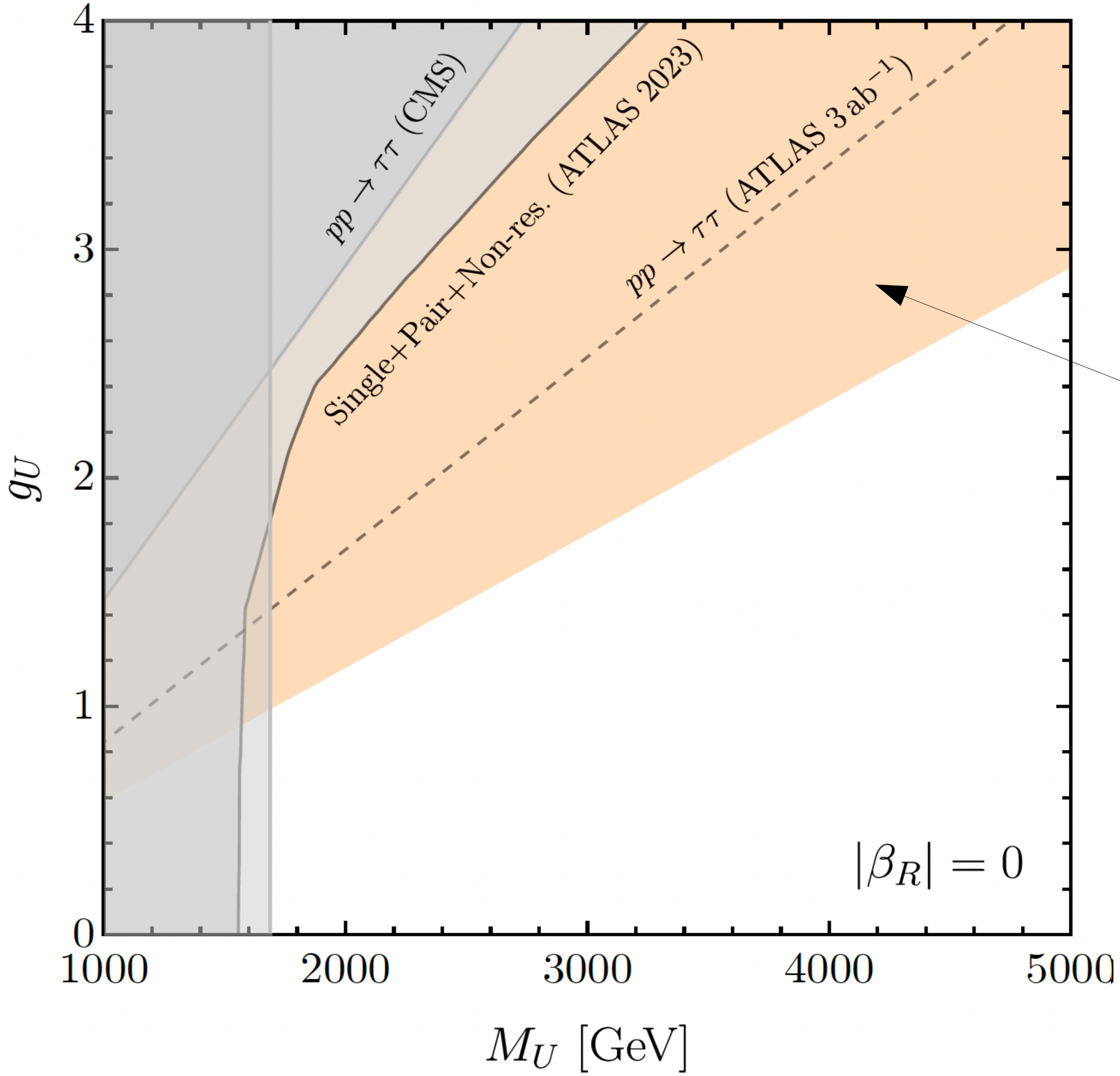
Large improvement in sensitivity when adding low b-jet p_T category

Excludes CMS' excess

Need to clarify interference issue for future interpretations

The B-physics anomalies

The U_1 leptoquark at high energies:



Updated preferred region by b → c low-energy data

Aebischer, GI, Pesut, Stefanek, Wilsch, 23

Relevant NLO QCD corrections

Haisch, Schnell, Schulte '22

Future prospects

Future prospects

In the next ~ 10 years we can expect significant progress in flavor physics from more than one experiment:

- LHCb-II [b & c physics @ hadron collider]: ~ 10 × present statistics
- Belle-II [b & t physics @ e+e-]: ~ 10 × statistics of Belle-I
- NA62 / HIKE [$K \to \pi\nu\nu$]: ~ 3 / 30 × present statistics
- $\mu \to e$ [$\mu \to 3e$ (PSI) + $\mu N \to eN$ (FNAL)]: ~ 1000 × present sensitivity

→ Increase in NP sensitivity significantly higher vs. direct searches

$$A(\psi_i \to \psi_j + X) = A_0 \left[1 + \frac{c_{NP}\, m_W^2}{c_{SM}\, \Lambda^2} \right]$$

Future prospects

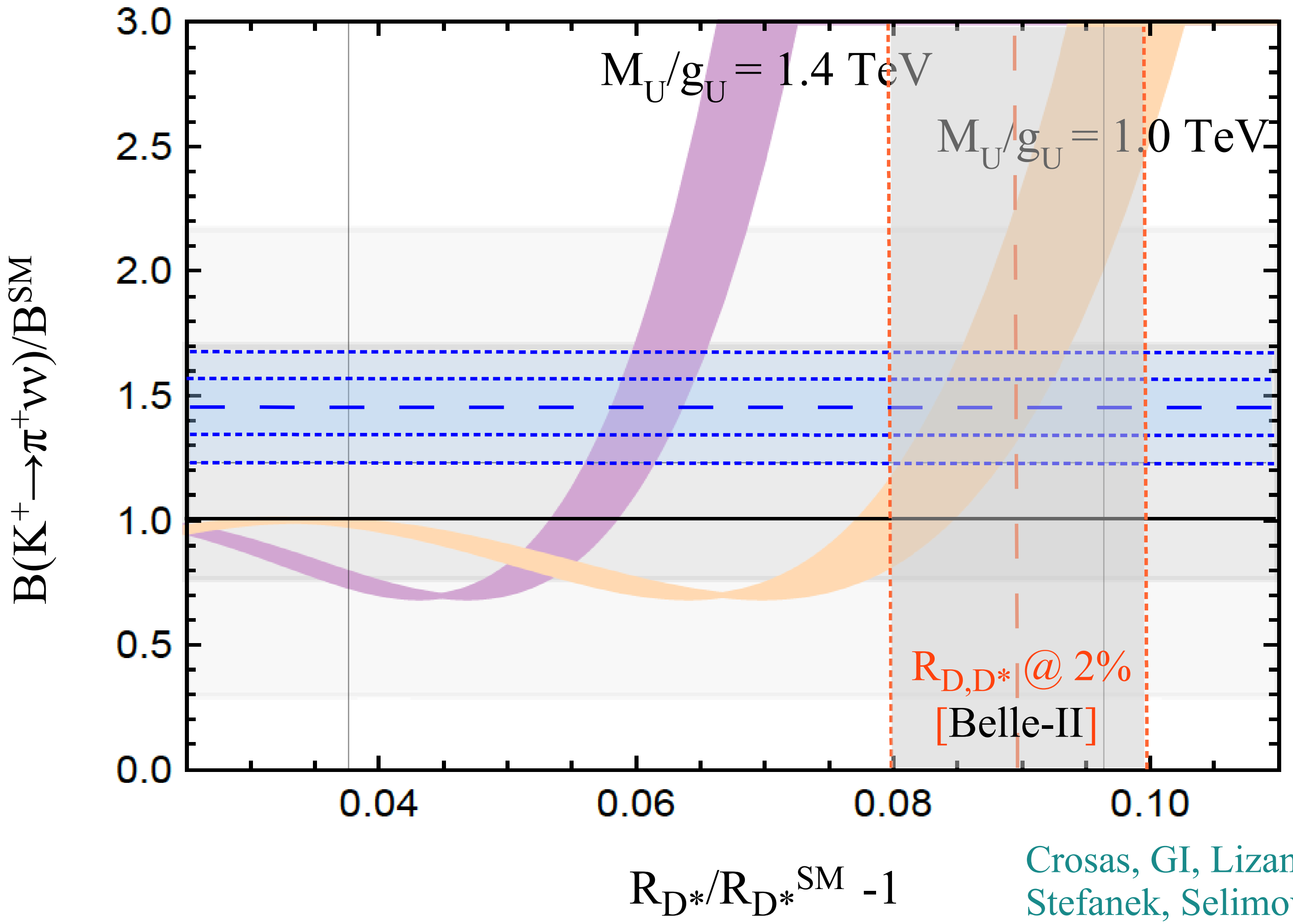
What can we expect

I. Modest improvements [*up to ~ 1/2 on the amplitude*]:
- $B_{s,d}$ mixing & $B(b \to s\gamma) \to$ dominated by th. errors

II. Significant improvements:
- LFU tests in neutral currents [R_K,...]: ~ (5-10)% → ~ (2-3) %
- LFU tests in charged currents [R_D,...]: ~ (5-10)% → ~ (2-3) %
- $B(K \to \pi\nu\nu)$ & $B(B \to K\nu\nu)$ @ 10% level

Future prospects

E.g.: Correlation between $B(K^+\to\pi^+\nu\nu)$ & $R_{D,D*}$ in models addressing current charged-current anomalies:



Possible impact of future measurements:

$B(K^+\to\pi^+\nu\nu)/B^{SM}$ @ 8%
[HIKE]

Crosas, GI, Lizana, Stefanek, Selimovic, '22

Future prospects

What can we expect

I. Modest improvements [*up to ~ 1/2 on the amplitude*]:
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- $B(K \to \pi\nu\nu)$ & $B(B \to K\nu\nu)$ @ 10% level

III. Expected largest improvements:
- LFV in B decays, especially $b \to s + \tau\mu$
- LFV in τ decays
- FCNC of type $b \to s + \tau\tau$

Conclusions

- Flavor physics represents one the most intriguing aspects of the SM and, at the same time, a great opportunity to investigate the nature of physics beyond the SM.

- The idea of a *multi-scale construction & flavor deconstruction* has several appealing aspects: model-building direction largely unexplored so far, that could help shedding light not only on the origin of the flavor hierarchies, but also on the EW hierarchy problem.

- The model-building efforts along this direction, triggered by the B-physics anomalies are still very motivated (*independently of the anomalies fate*).

- If the these ideas corrects, new non-standard effects could emerge soon both at low and at high energies and (some of the) anomalies could just be the first hint...