Flavor non-universal gauge interactions

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- Introduction
- The two flavor puzzles
- Flavor non-universal interactions
- The B anomalies [*what we learned, what's left*]
- Leptoquarks & 4321
- Few words on this special occasion

University of Zurich UZH

European Research Council
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Introduction

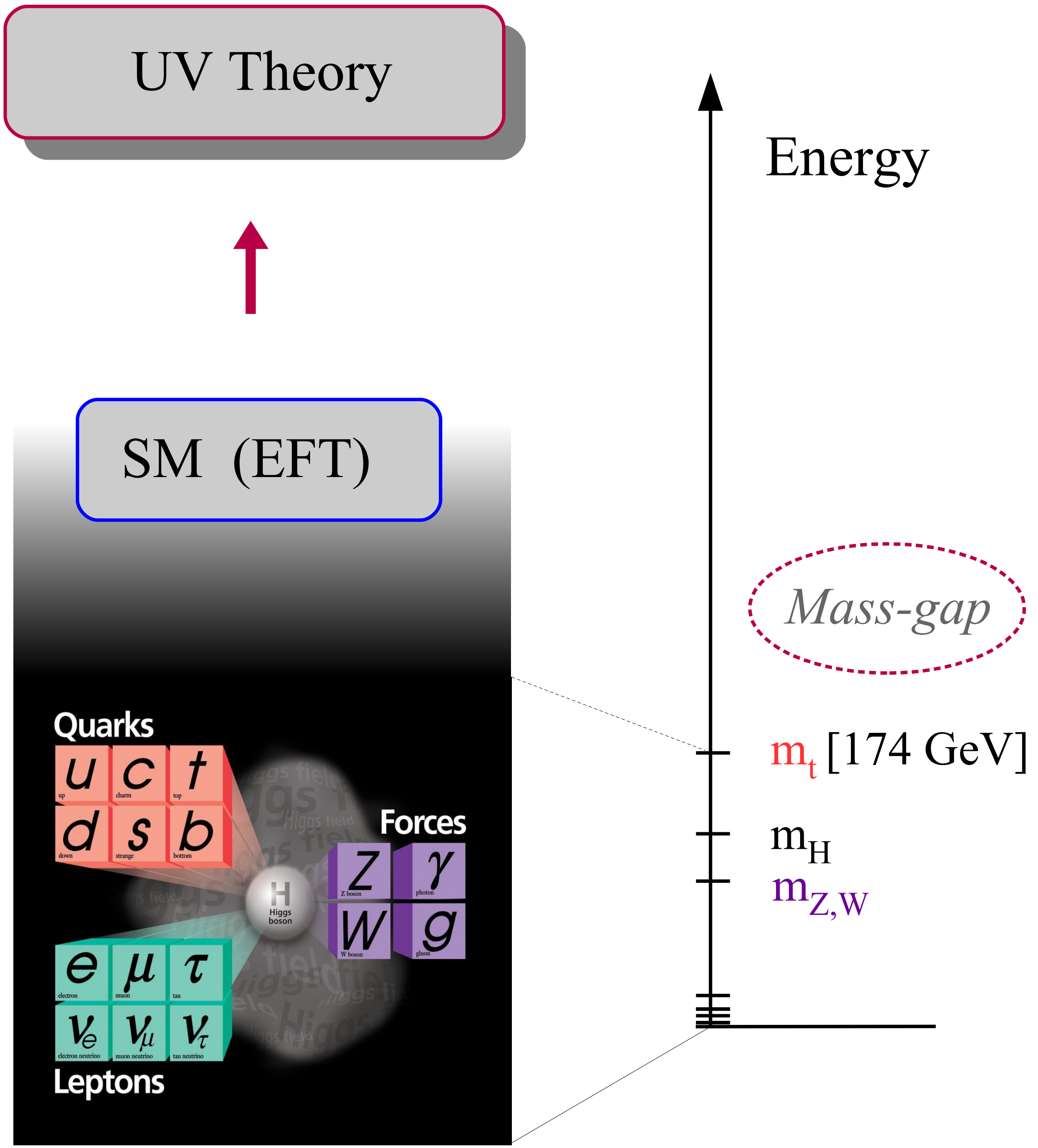
There are several reasons why we think the SM must be extended at high energies:

Electroweak hierarchy problem

Flavor puzzle
U(1) charges
Neutrino masses

Dark-matter
Dark-energy
Inflation

Quantum gravity

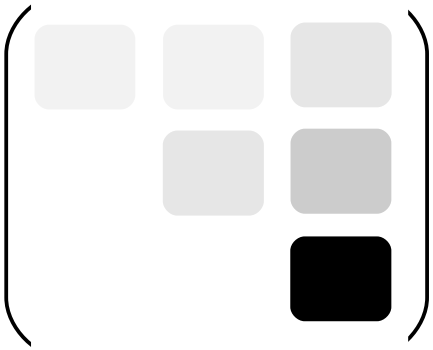


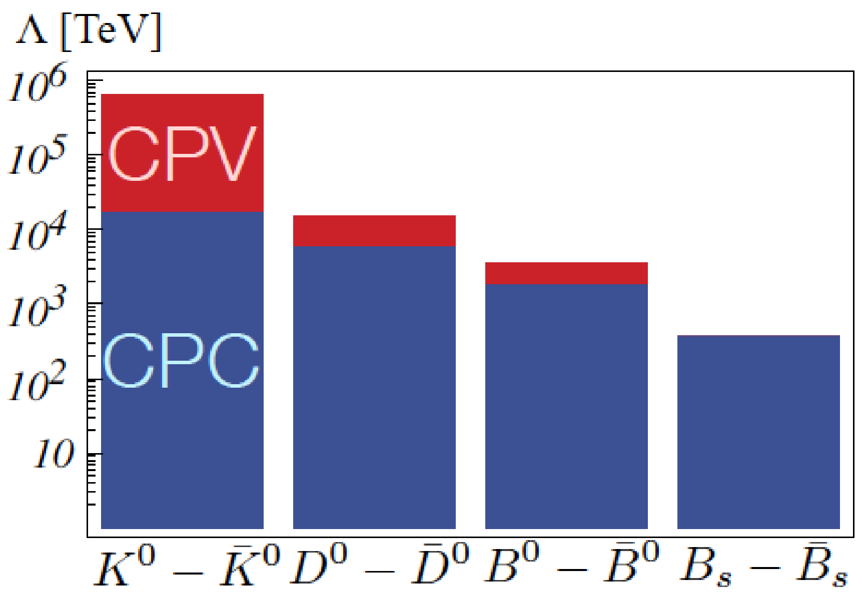
Introduction

There are several reasons why we think the SM must be extended at high energies:

	problem due to...	*...indicating*
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*	non-trivial properties of the SM Lagrangian if interpreted as EFT
Flavor puzzle U(1) charges Neutrino masses	→ *Ad hoc tuning in the model parameters*	↓
Dark-matter Dark-energy Inflation	→ *Cosmological implementation of the SM*	Useful hints for its UV completion
Quantum gravity	→ *General problem of any QFT*	

The two flavor puzzles

$Y_U \sim$ 

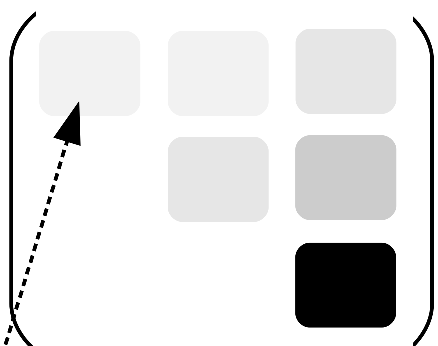


The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

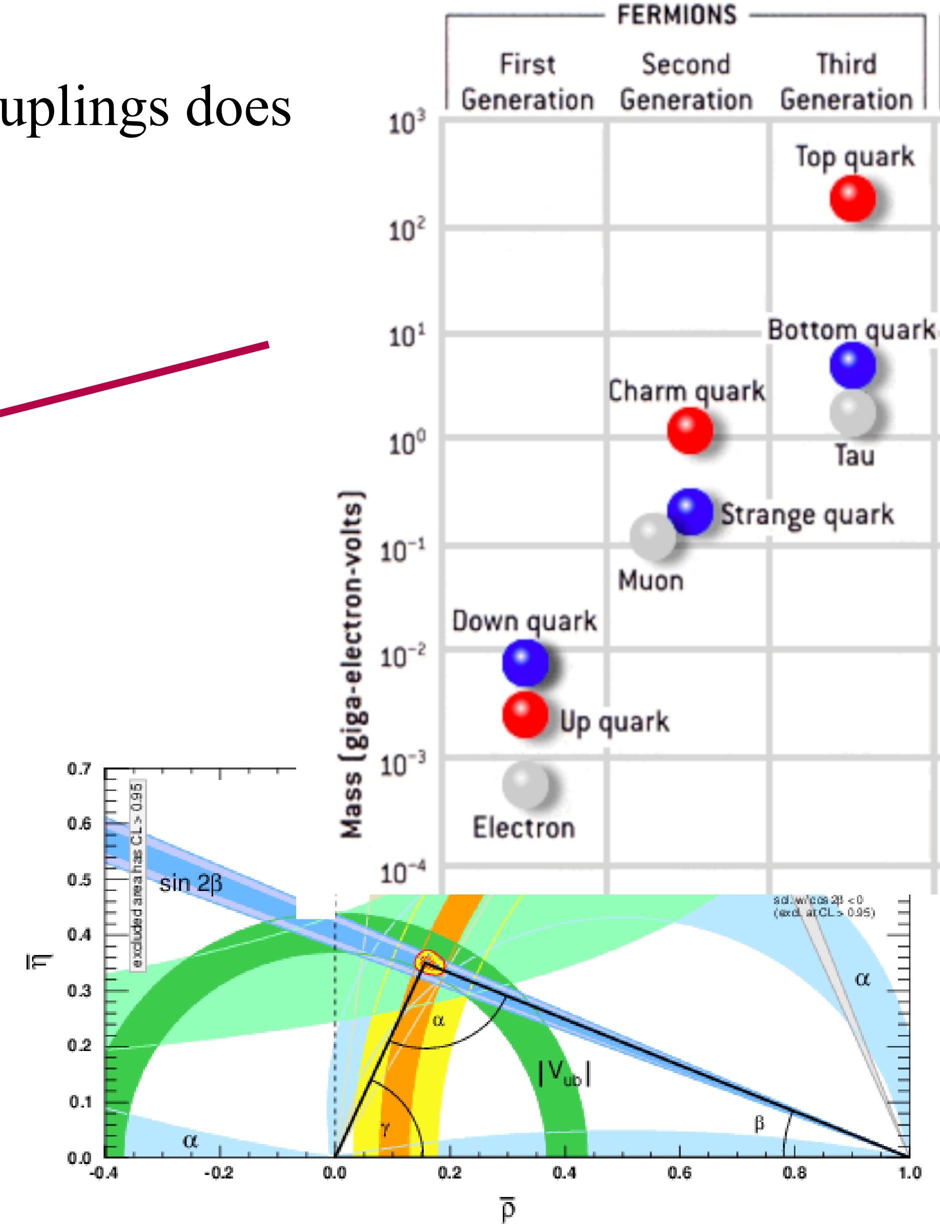
I. The observed pattern of SM Yukawa couplings does not look accidental:

$Y_U \sim$



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

[Y_U in the basis where Y_D is diagonal]



The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

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

$$Y_U \sim \begin{array}{c} \overbrace{\qquad\qquad\quad}^{U(2)_u} \qquad\quad \\ \left(\begin{array}{cc|c} \multicolumn{2}{c|}{< 0.01} & 0.003 \\ & & 0.04 \\ \hline & & 1 \end{array}\right) \end{array} \begin{array}{l} \left.\begin{array}{c} \\ \\ \end{array}\right] \leftarrow U(2)_q \\ \\ \end{array} \qquad \bar{Q}_L\, Y_U\, U_R\, H$$

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

The two flavor puzzles

Even forgetting current anomalies, 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? What constraints these observations imply on physics beyond the SM? [*NP flavor puzzle*]

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

The two flavor puzzles

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

Large flavor symmetry

Three identical replica of the basic fermion family [$U(3)^5$ symmetry]

Flavor-degeneracy broken by the Yukawa interaction

$$y_{ij}\, \psi_L^{\ i}\, \psi_R^{\ j}\, H \;\rightarrow\; m_{ij}\, \psi_L^{\ i}\, \psi_R^{\ j}$$

"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

Eg:

- $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\mu}$ = (individual) Lepton Flavor [*exact symmetry*]
- $m_u \approx m_d \approx 0 \;\rightarrow$ Isospin symmetry [*approximate symmetry*]

The two flavor puzzles

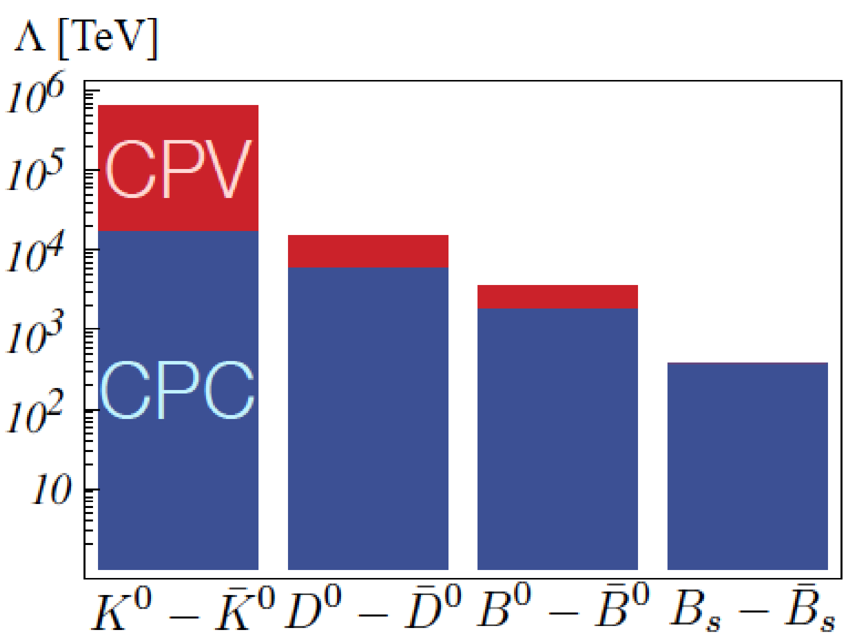
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

In principle, we could expect many violations of the accidental symmetries from the heavy dynamics (→ *new flavor violating effects*). However, beside some anomalies in B-physics, we observe none.

↓

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

The NP Flavor puzzle



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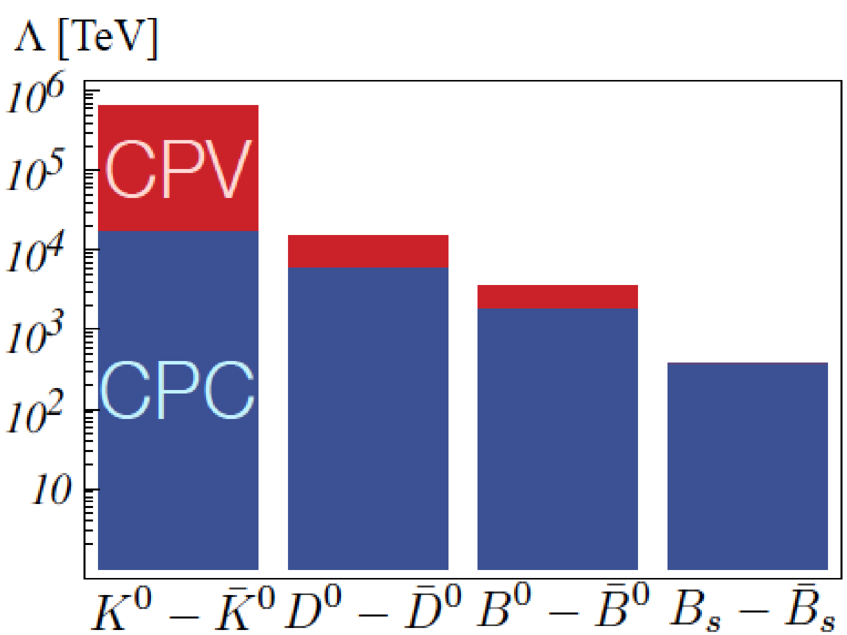
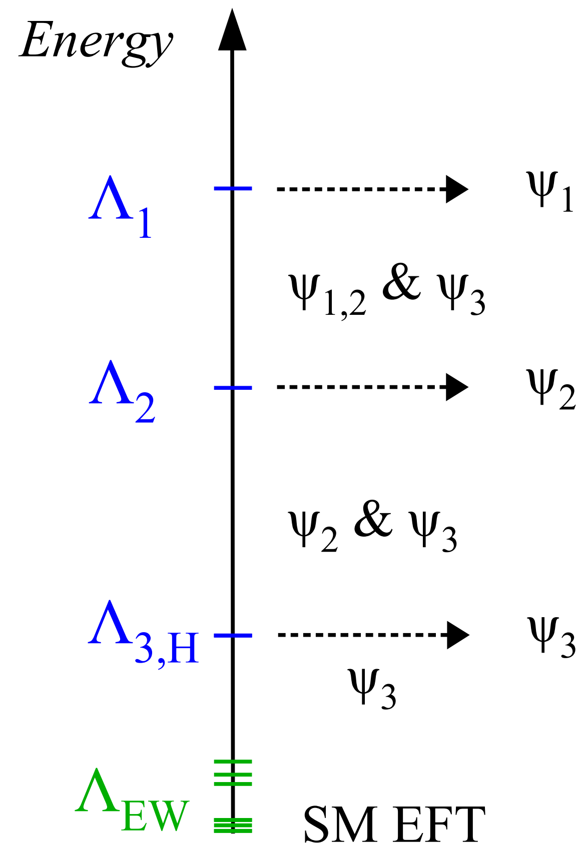


N.B: These high scales can be a "mirage" (= *artifact of the accidental symmetry*).

The only unambiguous message of these bounds is:

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

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 following two (*implicit*) hypotheses:

- Concentrate on the Higgs hierarchy problem
- "Postpone" the flavor problem

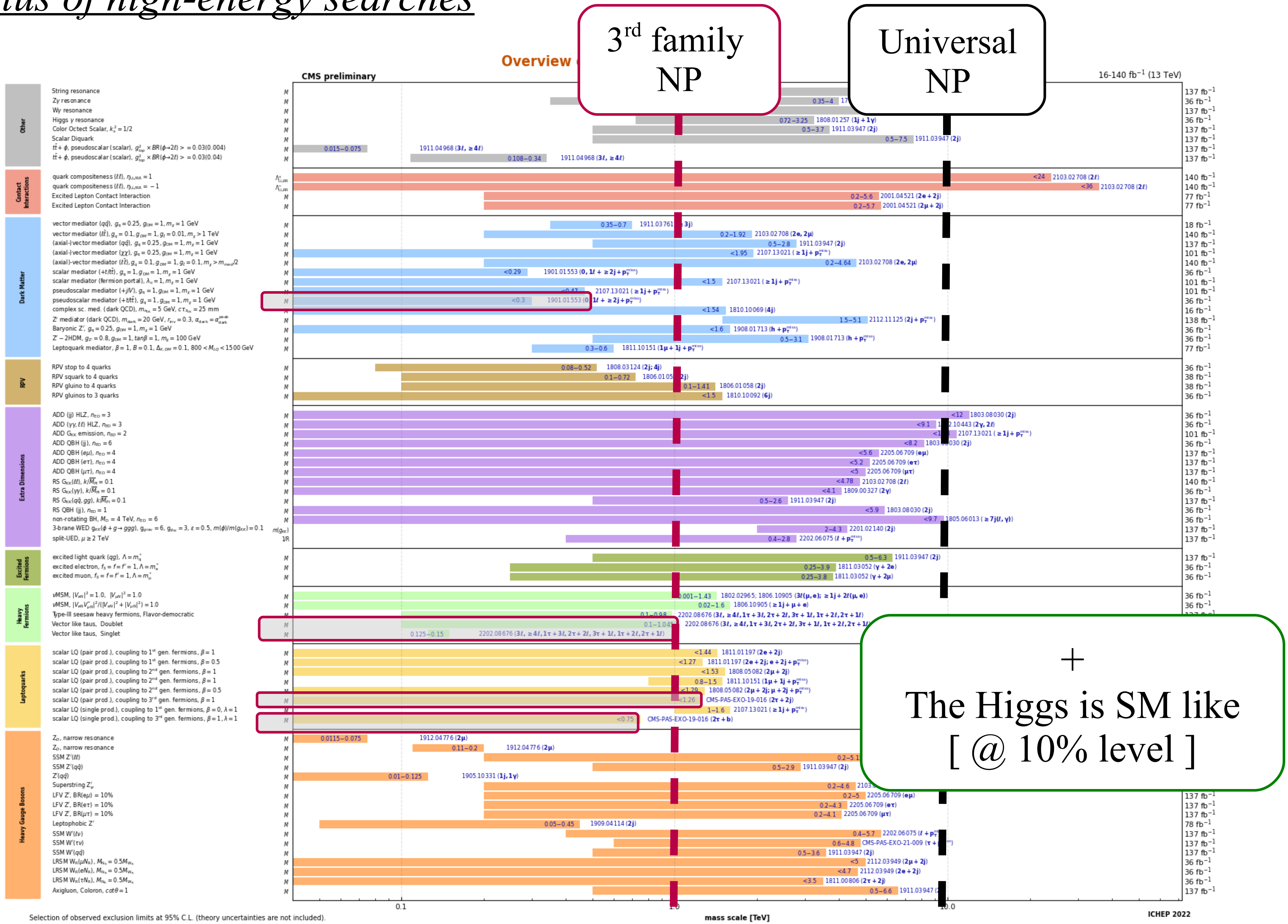
➔ *The "MFV paradigm"*:

"Protect" the Higgs sector with (TeV-scale) flavor-universal NP (*supersymmetry or Higgs compositness*), deferring the solution of the flavor problem to higher scales

This was a very motivated possibility in the pre-LHC era...

...but it has become a less compelling option after run-I and run-II results

Status of high-energy searches



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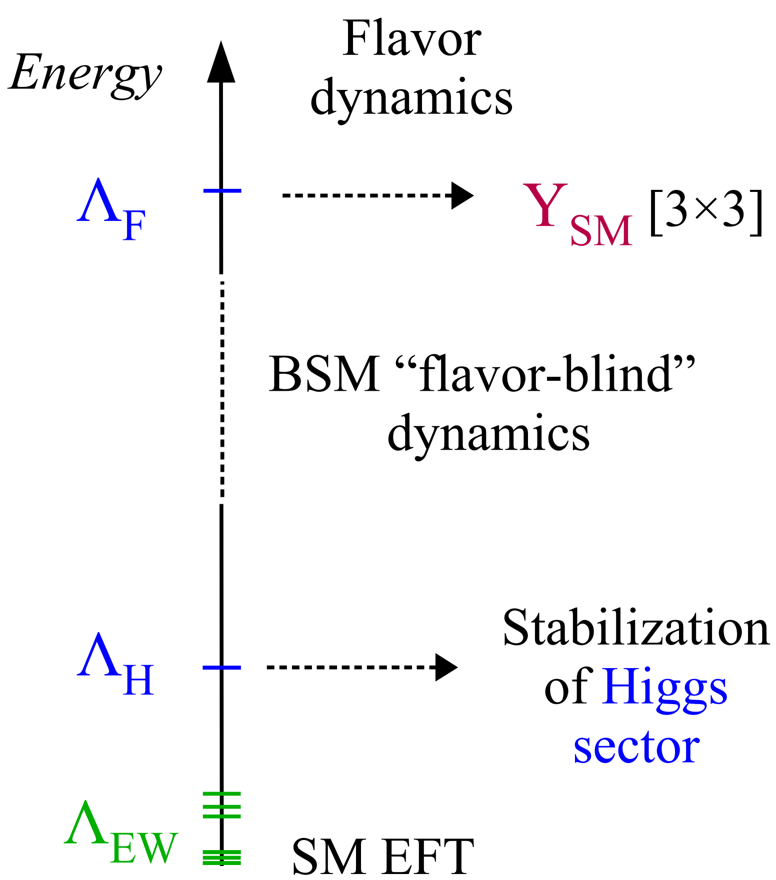


- Concentrate on the Higgs hierarchy problem
- Postpone the flavor problem to higher scales

↓

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

Less compelling after the LHC results:

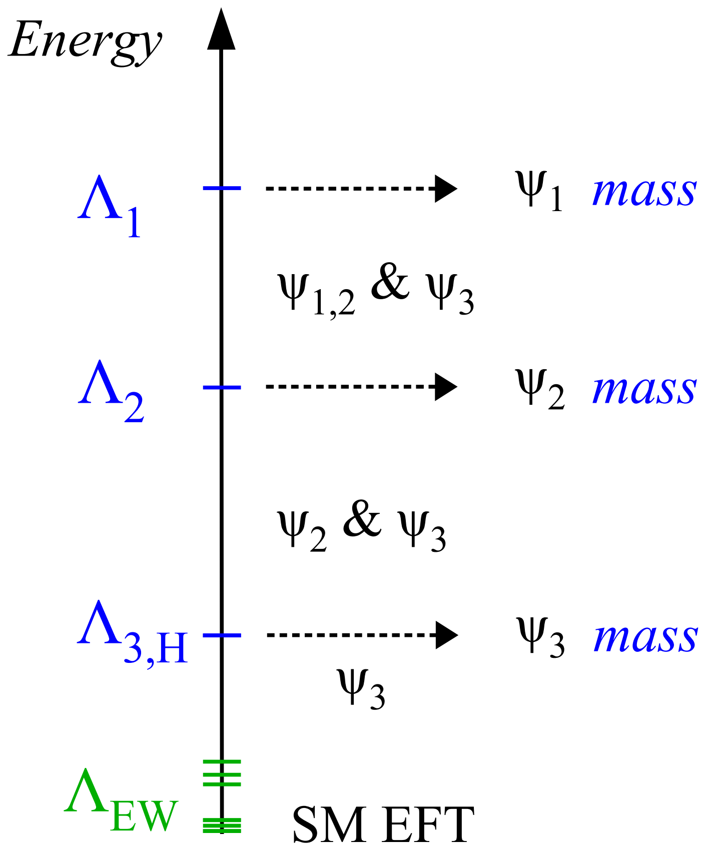
No clear sign of NP from direct searches

strong bounds on NP ***coupled universally*** *to all families*

worsening of the Higgs hierarchy problem

Flavor non-universal interactions

New paradigm to address both the Higgs hierarchy problem and the flavor puzzle: *multi-scale* UV completion 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:

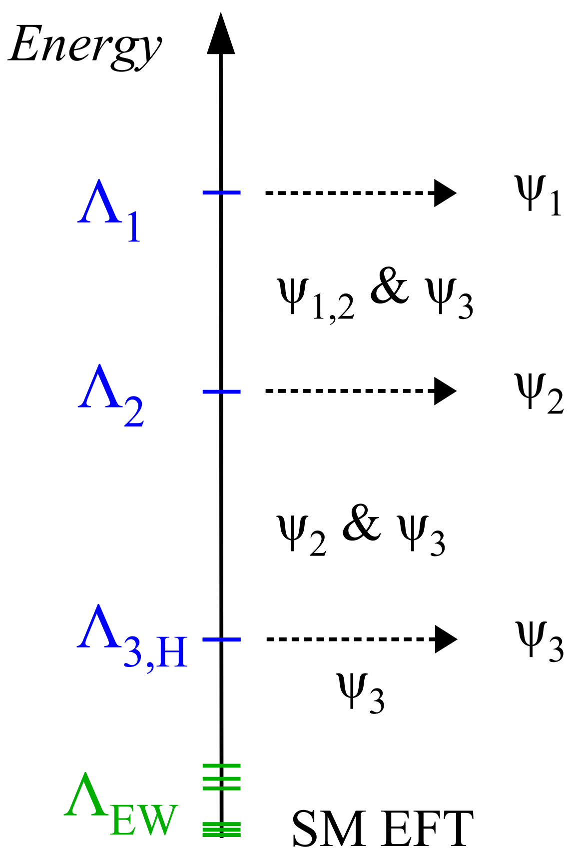
- Flavor non-universal interactions already at the TeV scale:
- 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

⬇

~~3 gen. = “identical copies” up to high energies~~

Flavor non-universal interactions

New paradigm to address both the Higgs hierarchy problem and the flavor puzzle: *multi-scale* UV completion with *flavor non-universal* interactions



A renewed phenomenological interest in this type of approach has been triggered by the B-physics anomalies (*hinting to violations of lepton flavor universality, mainly in 3rd gen.*)

But the construction has an intrinsic, more general, interest:

- ✔ Explain the origin of the flavor hierarchies
- ✔ Allow TeV-scale NP coupled (mainly) to 3rd gen. → Higgs sector stabilization

Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23

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

- Obtain the $U(2)^n$ flavor symmetry as accidental symmetry of the (non-universal) gauge sector
- Elementary Higgs up to (at least) the TeV scale → New states should preserve Higgs-mass stability → NP coupled to 3^{rd} generation should occur at the TeV scale
- Explain charge-quantization → Semi-simple embedding in the UV [i.e. no U(1) groups in the UV]

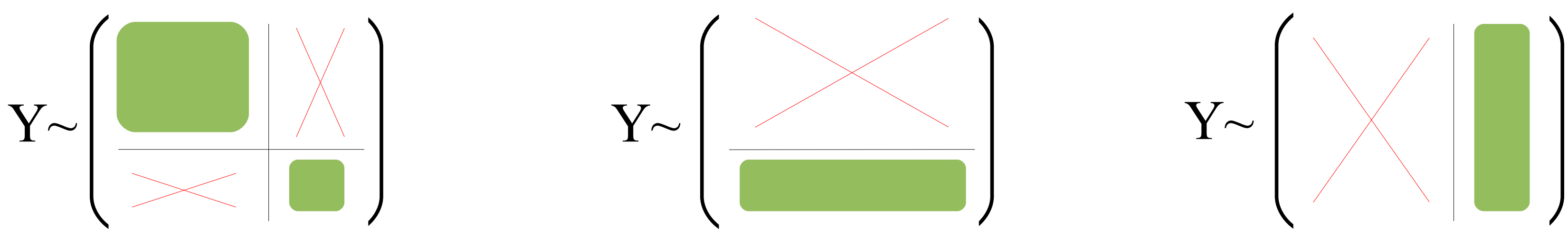
Flavor hierarchies from gauge non-universality [a brief detour]

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: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

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

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



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

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

II. 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

↓

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

Higgs & 3rd gen. fields
charged only under these groups

small impact on δm_h

UV completion
@ higher E

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

d > 4 ops
(@ TeV scale)

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

I. + II. + III. + general pheno bounds: two viable TeV-scale 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	$\cancel{\mathrm{SU}(2)_R}$	$\cancel{\mathrm{SU}(4)^{[3]} \times \mathrm{SU}(2)_L^{[3]}}$	$\mathrm{SU}(3)^{[12]} \times \mathrm{SU}(2)_L^{[12]} \times \mathrm{U}(1)_{B-L}^{[12]}$
3	$\cancel{\mathrm{SU}(4)}$	$\cancel{\mathrm{SU}(2)_L^{[3]} \times \mathrm{SU}(2)_R^{[3]}}$	$\mathrm{SU}(2)_L^{[12]} \times \mathrm{U}(1)_R^{[12]}$
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

$\downarrow$

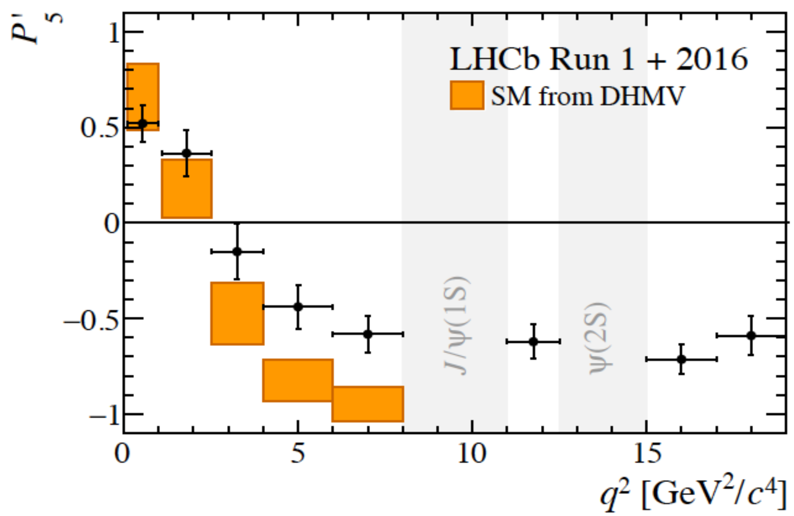
General feature:
SU(4) group acting on the 3rd family, with low-energy breaking scale to avoid fine-tuning on the Higgs mass:

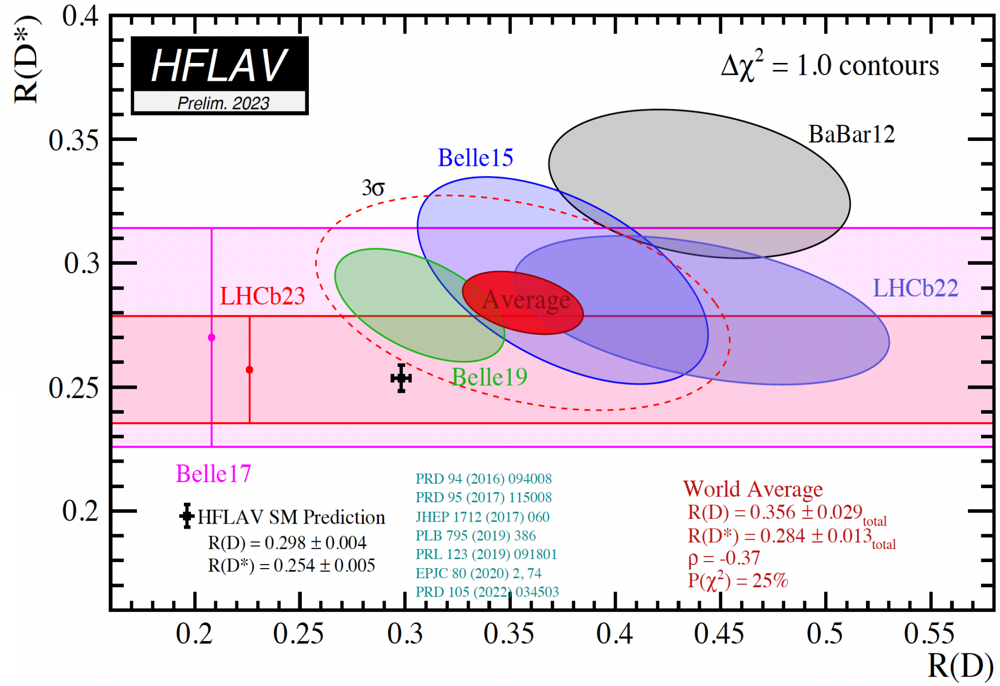
$$\delta m_h^2/m_h^2 < 1 \quad \rightarrow \quad \Lambda_U = M_U/g_U \lesssim 5\ \mathrm{TeV}$$

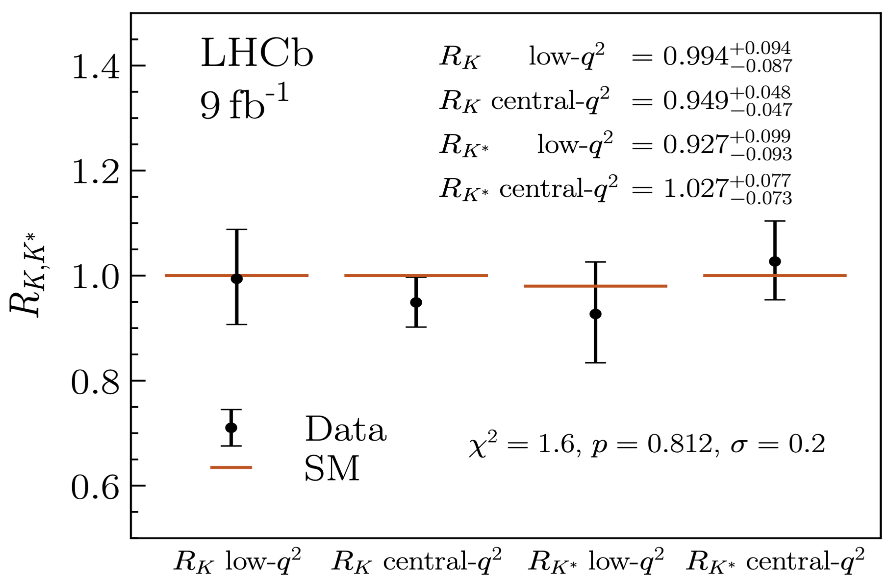
Davighi & G.I. '23

Using only general naturalness arguments (on both flavor & Higgs sectors) we are led to the hypothesis of a low-scale flavor non-universal LQ

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*)

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. → $b \to s\, l^+l^-$

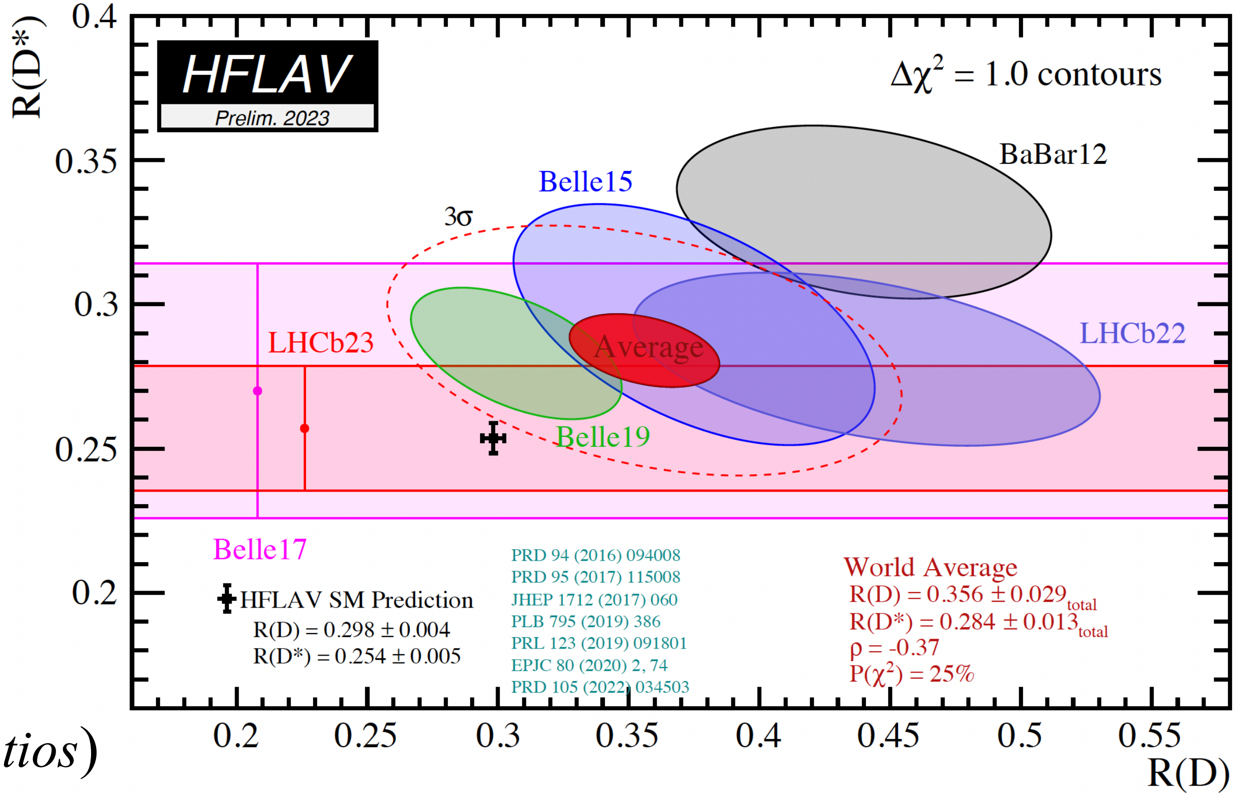
LFU = Lepton Flavor Universality = accidental symmetry of the SM Lagrangian

The B-physics anomalies

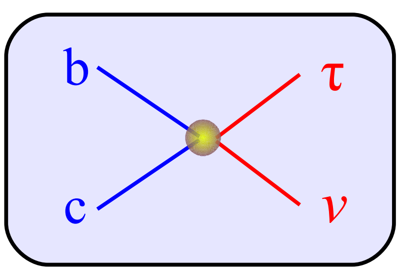
I. ~~LFU~~ anomaly in CC
[τ vs. (μ, e)]

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

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*



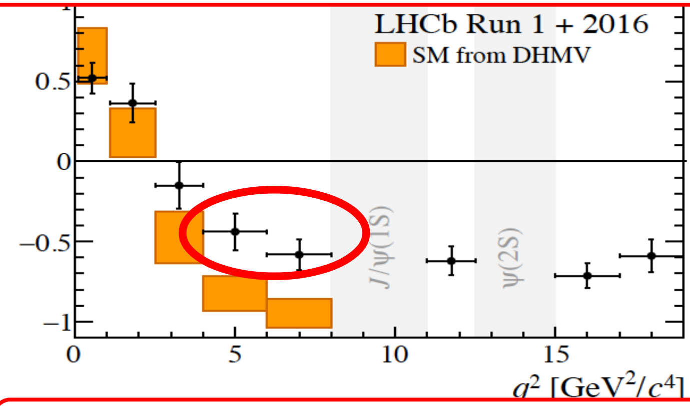
The B-physics anomalies

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

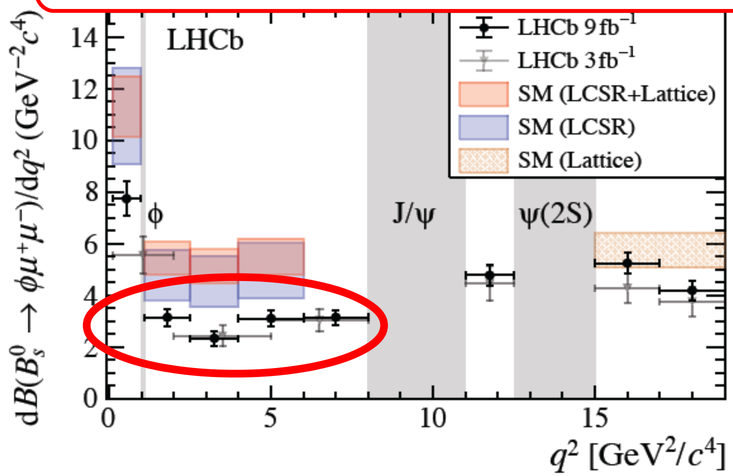
$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

- 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

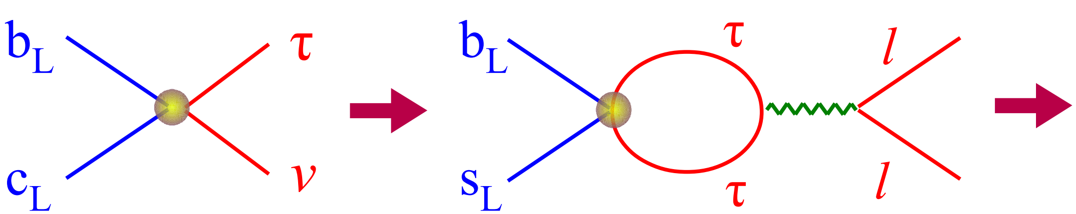
$B \to K^* \mu\mu$ angular distribution



$B \to H \mu\mu$ branching ratios



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



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

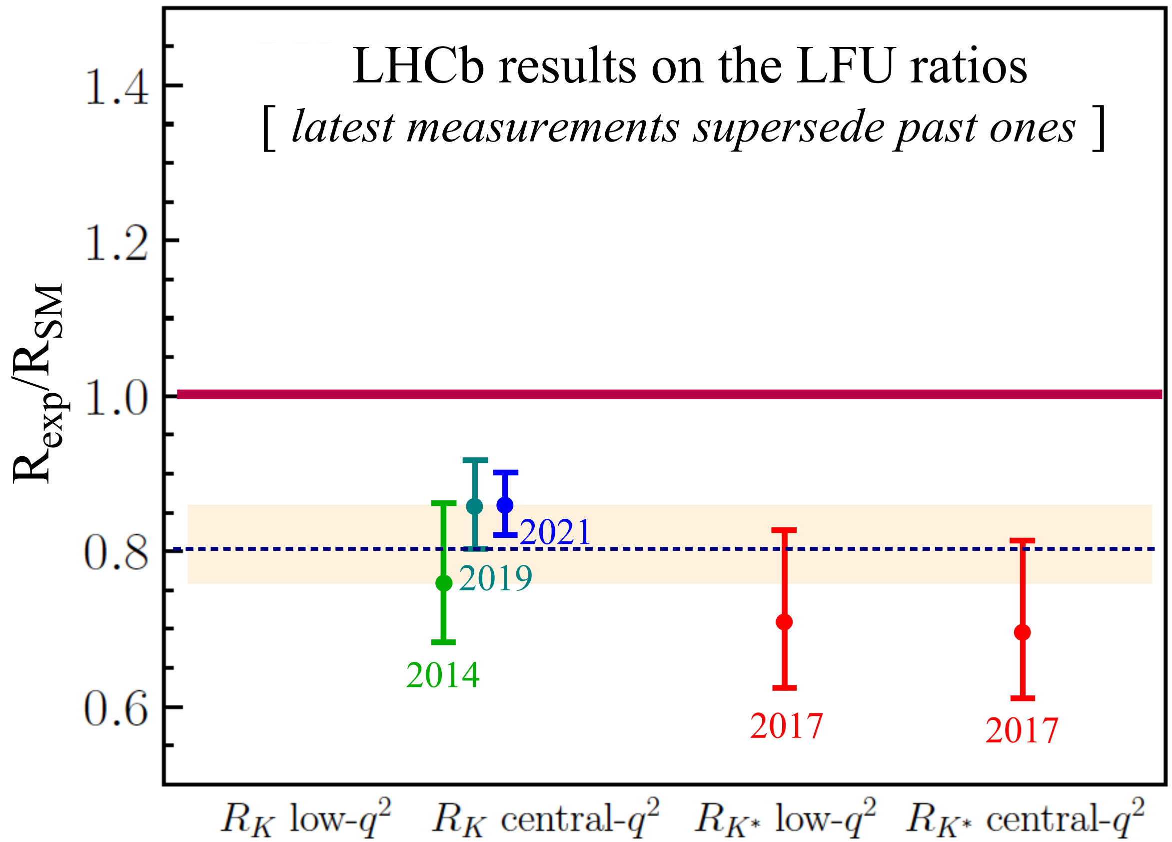
N.B.: correct sign & size !

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

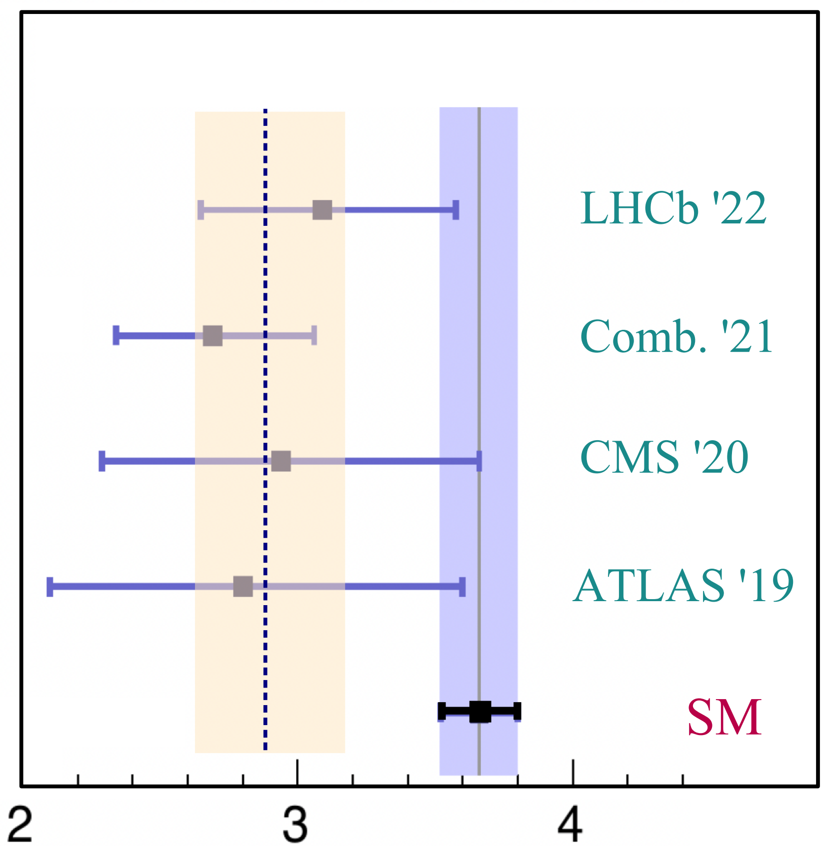
The B-physics anomalies

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



$10^9 \times B(B_s \to \mu\mu)$

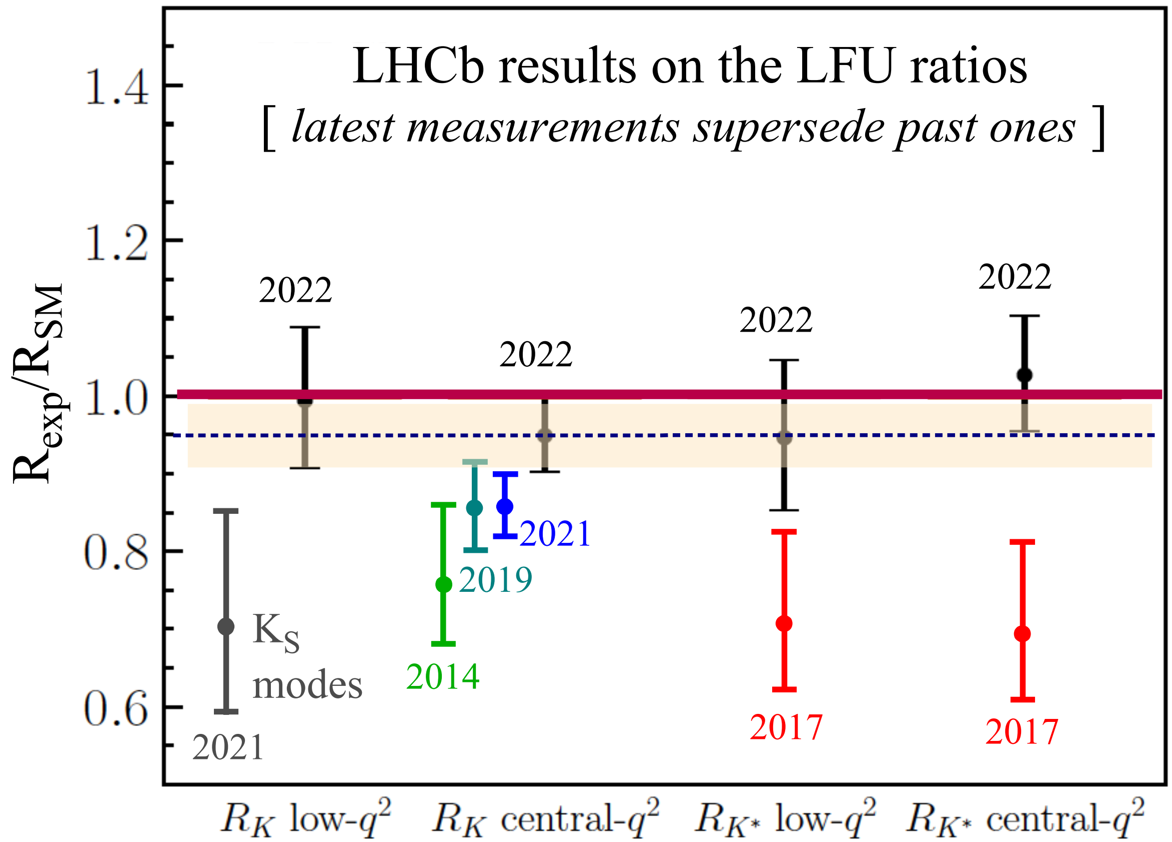


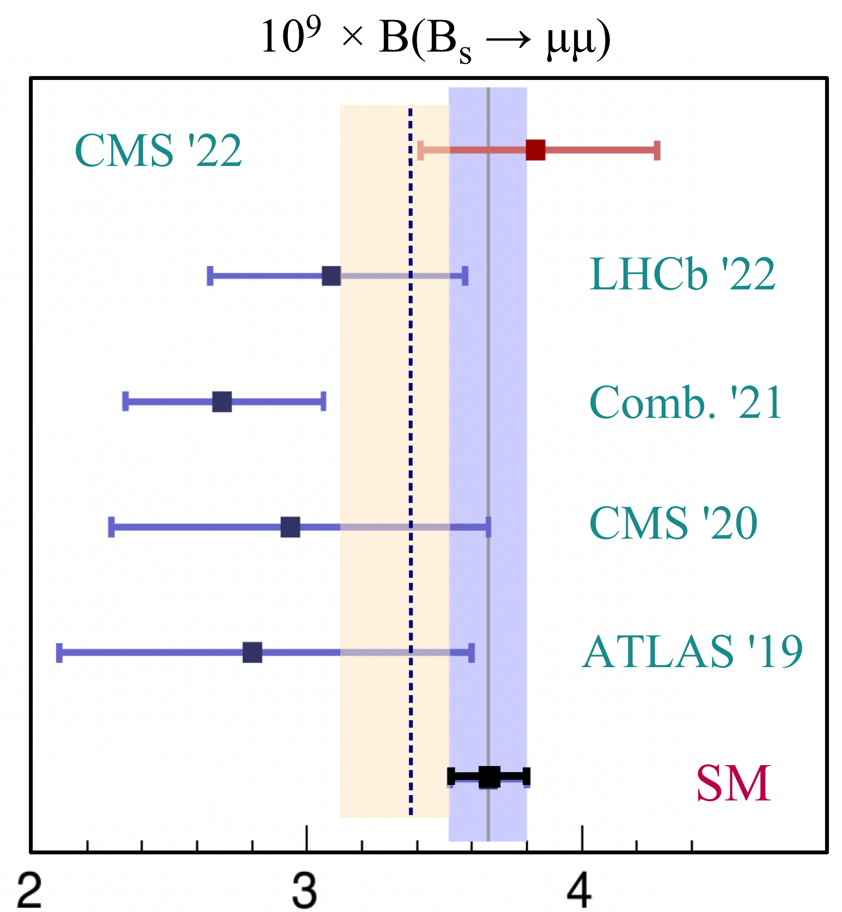
The B-physics anomalies

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*





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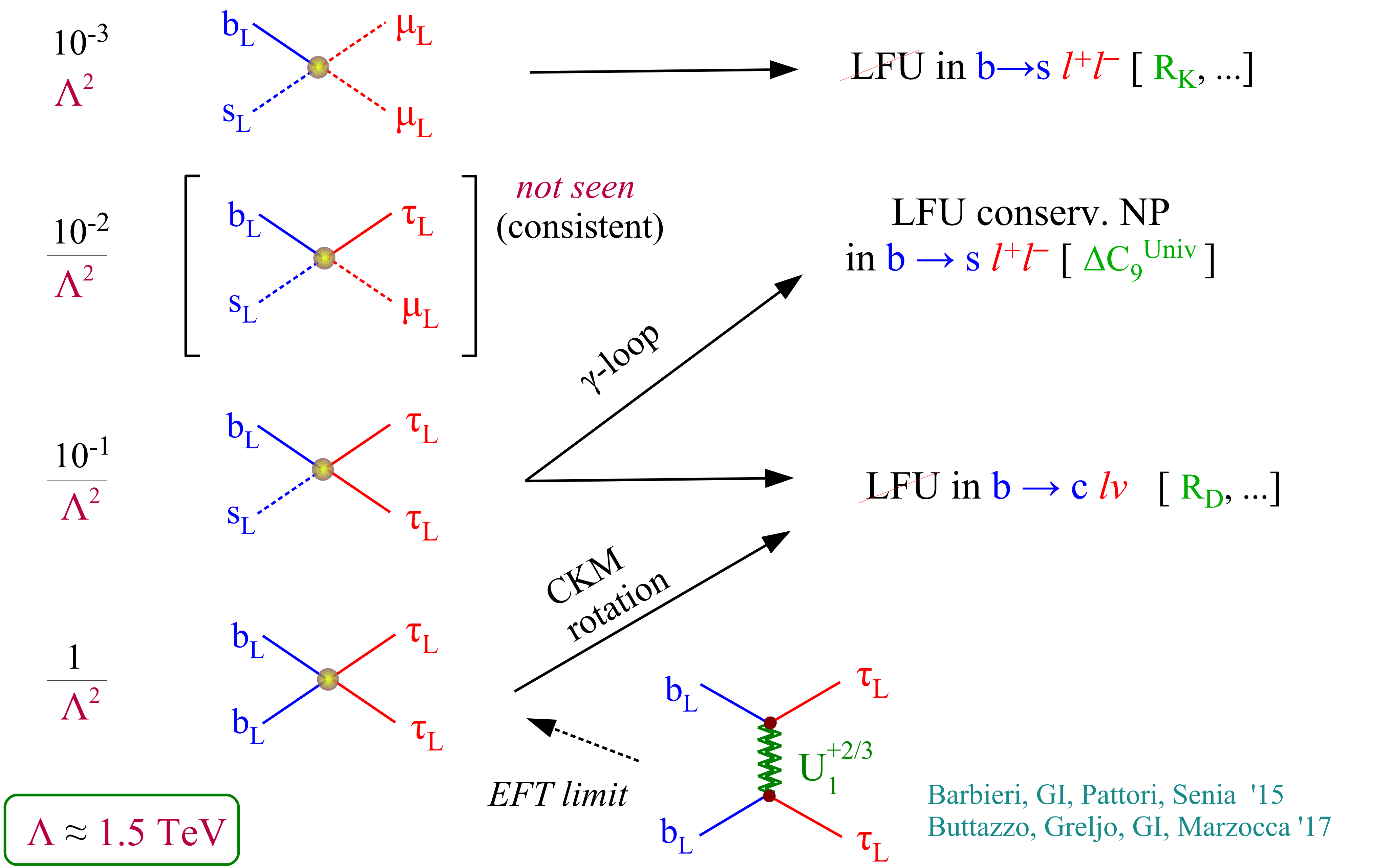

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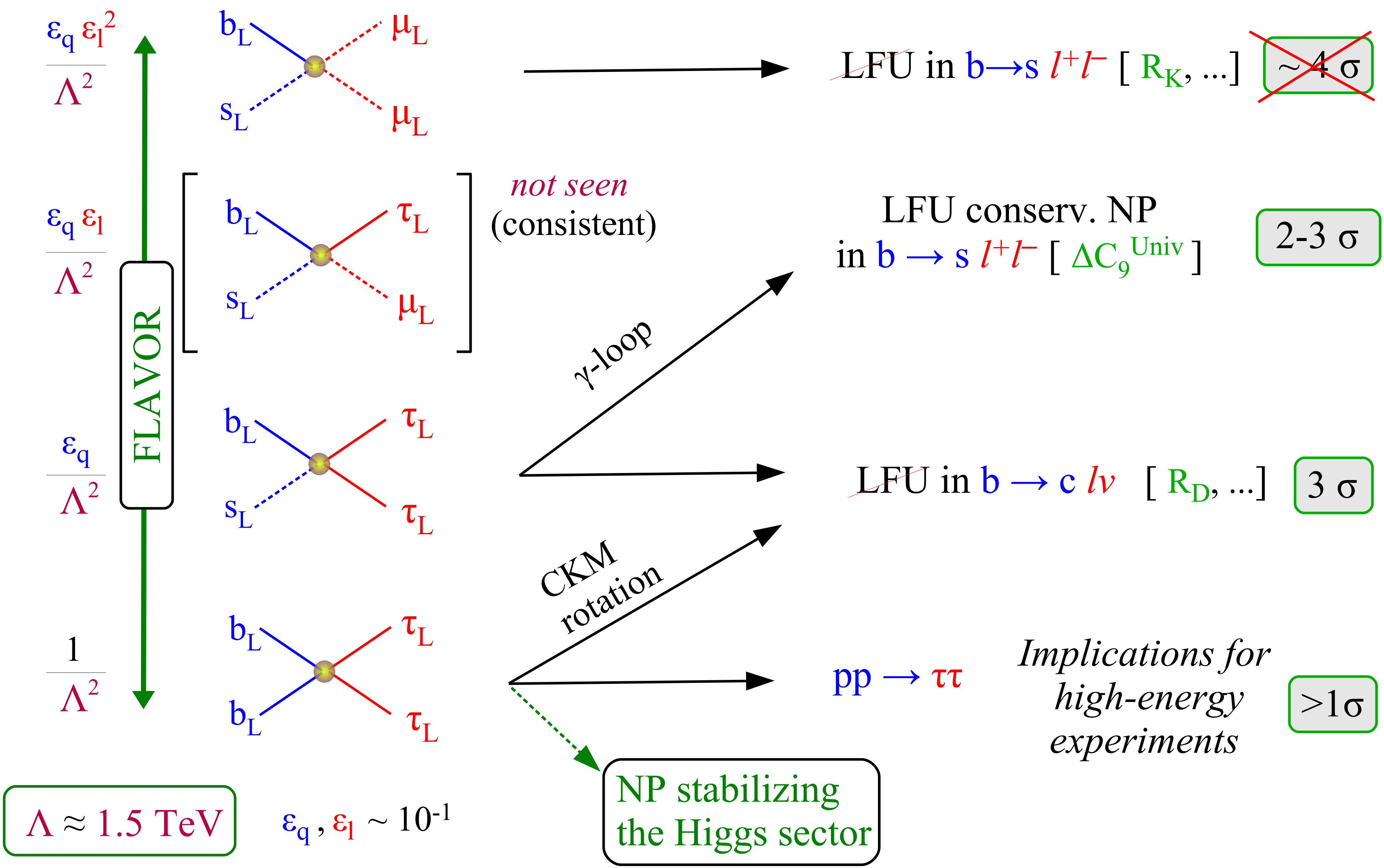

Leptoquarks & 4321

$$\begin{bmatrix} Q^{\alpha} \\ Q^{\beta} \\ Q^{\gamma} \\ L \end{bmatrix}$$

Leptoquarks & 4321

Theory arguments
[flavor hierarchies,
charge quantization]

$SU(4)^{[3]} \times SU(3)^{[12]} \times G_{EW}$

U_1

minimal choice
[*last step of the SSB chain*]

B-physics anomalies
[mainly CC]

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

Di Luzio, Greljo, Nardecchia, '17
Bordone, Cornella, Fuentes-M, GI '17
Greljo & Stefanek, '18

Leptoquarks & 4321

Theory arguments
[flavor hierarchies,
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$SU(4)^{[3]} \times SU(3)^{[12]} \times G_{EW}$

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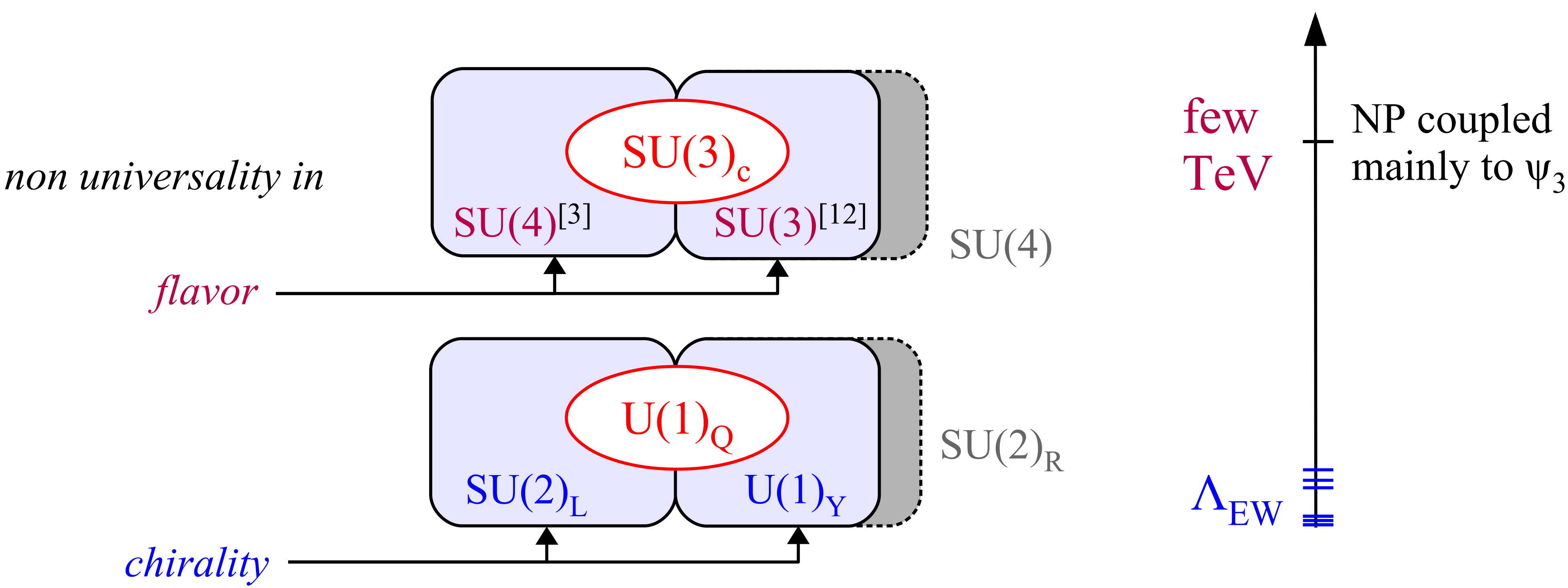
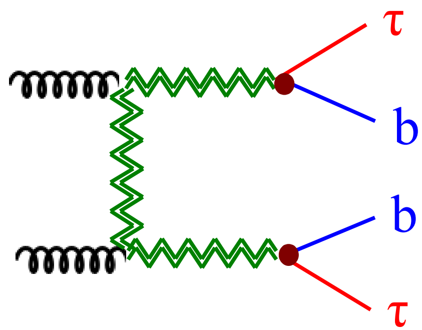
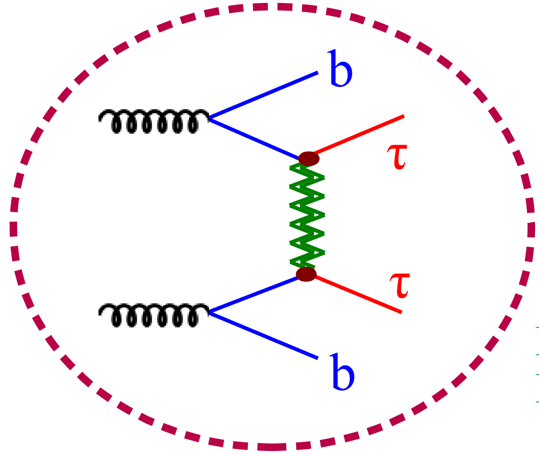


▶ *Leptoquarks & 4321: implications*

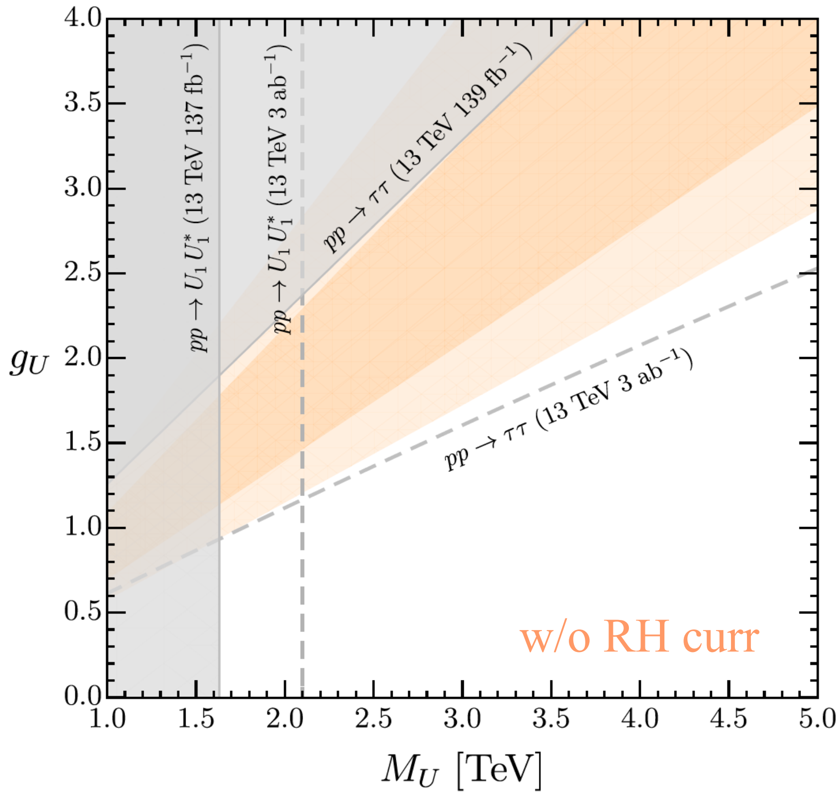
The U_1 leptoquark at high energies:

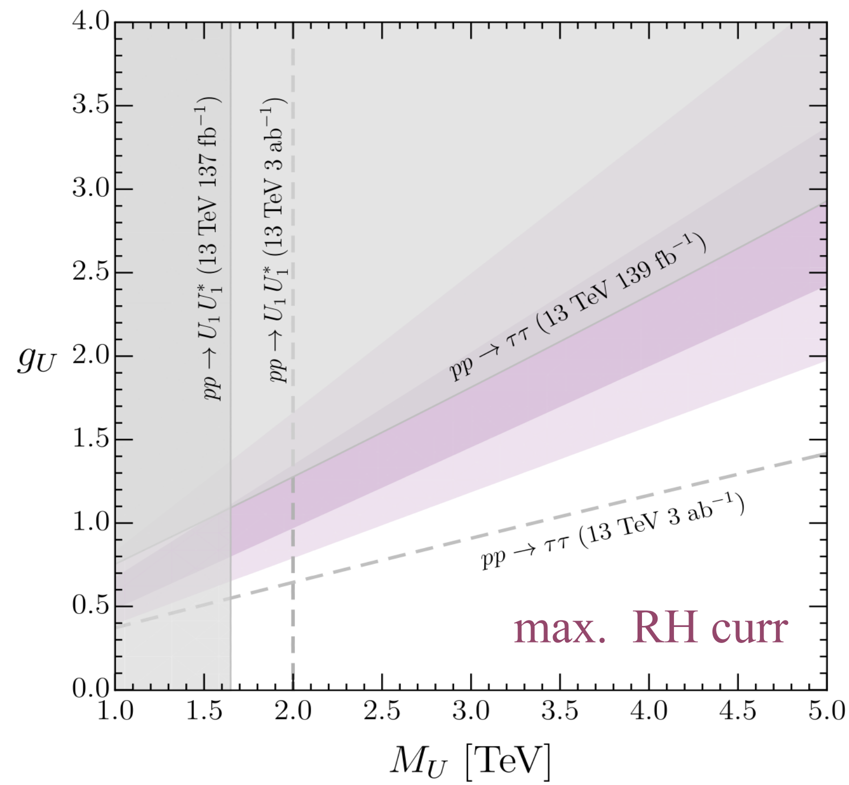




$pp \to \tau\tau$

Faroughi, Greljo, Kamenik '16





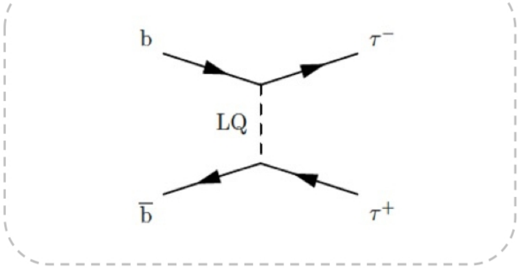
Cornella, Faroughi, Fuentes-Martin, GI, Neubert, '21

▶ *Leptoquarks & 4321: implications*

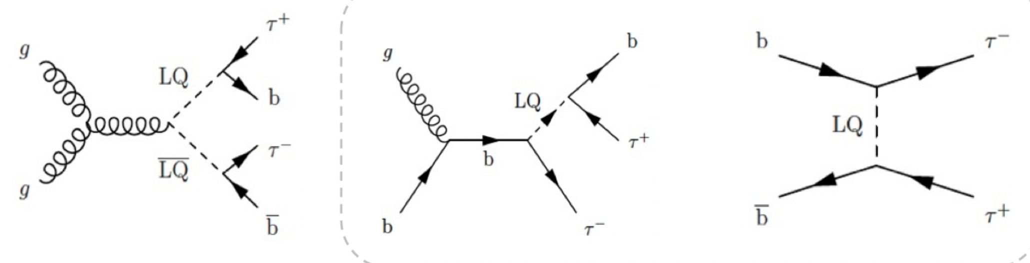
Aurelio Juste [*Moriond EW* '23]

LQ-b-τ: Comparison of recent results

Including interference w/ SM bkg

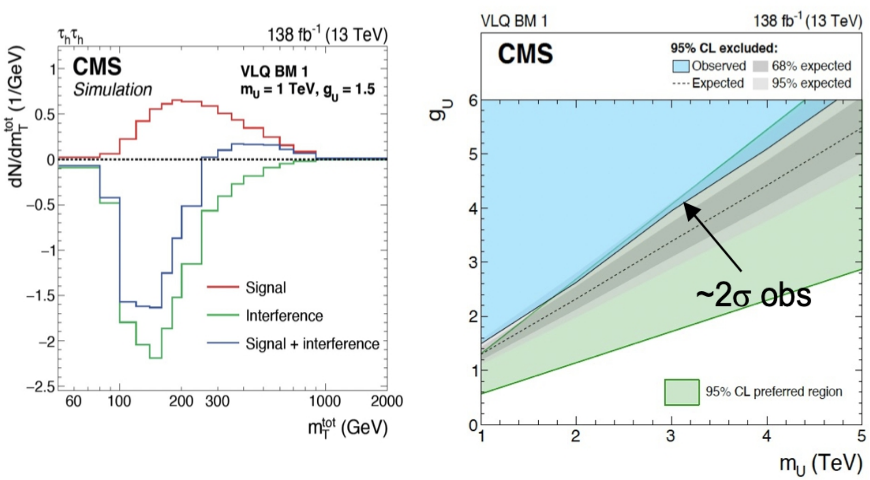


Neglecting interference w/ SM bkg

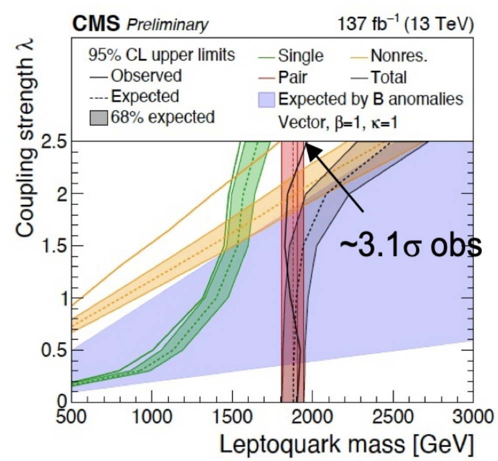


Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

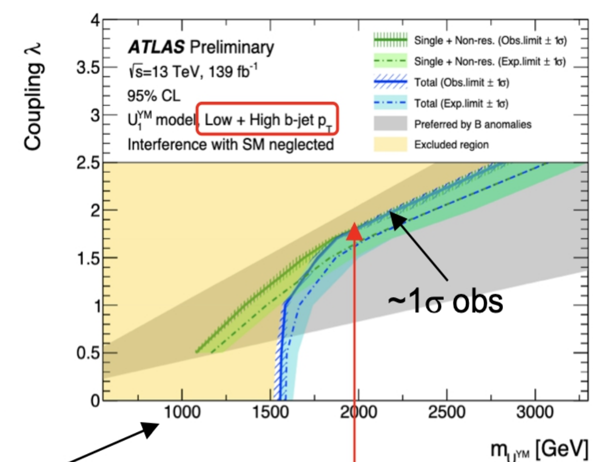
CMS-HIG-21-001



CMS-PAS-EXO-19-016



EXOT-2022-39



Shown at Moriond EW 2022

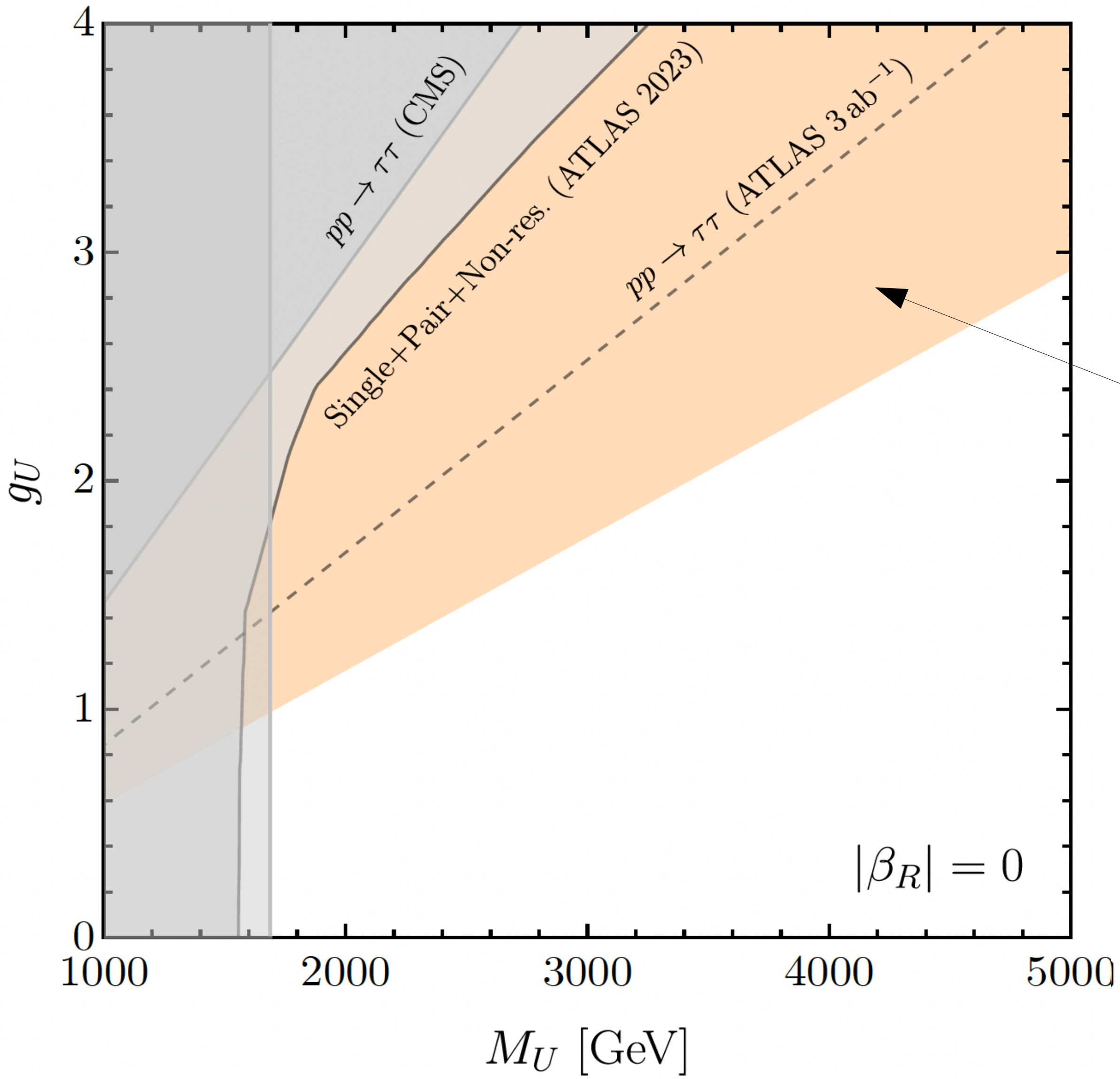
Large improvement in sensitivity when adding low b-jet p_T category

Excludes CMS' excess

Need to clarify interference issue for future interpretations

Leptoquarks & 4321: implications

The U_1 leptoquark at high energies:



Updated preferred region by b → c low-energy data

Aebischer *et al.* '22

Relevant NLO QCD corrections

Haisch, Schnell, Schulte '22

Some concluding remarks

- The idea of a *multi-scale construction at the origin of the flavor hierarchies* has several appealing aspects. Key observation: non-universal gauge interactions at the TeV scale, involving mainly the 3rd family, offer a new way to look at the EW hierarchy problem (and the absence of direct signals of NP so far).

- The model-building efforts along this direction, triggered by the B anomalies, are still very motivated and mildly affected by the recent change in low-energy data.

- If these ideas corrects, new non-standard effects should emerge soon both at low and at high energies (→ very interesting opportunities for LHC @ run-3...).

A few words on this special occasion

As we all know, time is relative...

In my "rest frame", what matters these days is that it is ~26 years that I know Matthias !

Closing Plenary Session, 20 March 1997

- **Transparencies for Francois LeDiberder: Group 12a -- CP Violation in Neutral B Decays, Summary**
- **Transparencies for Amarjit Soni: Group 12a -- Penguins + Direct CP Violation**
- **Transparencies for Gloria Vuagnin: Group 12b -- sin(2 beta), Recent Developments**
- **Transparencies for Paul Dauncey: Group 3 -- Extraction of Gamma**
- **Transparencies for Mattias Neubert: Group 4 -- V_ub, V_cb Extraction**
- **Transparencies for Antonio Masiero: Group 5 -- Rare B Decays**
- **Transparencies for Joe Izen: Group 7 -- Other Non-CP B Physics**
- **Transparencies for Pat Burchat: Group 8 -- Charm, Tau, QCD and 2-Photon Physics**
- **Transparencies for Gerald Eigen: Global Fit of CKM Parameters**

K – MESON CONFERENCE
Princeton-Pennsylvania Accelerator
November 3rd and 4th, 1967

No pictures from that workshop (*sorry...*) but some beautiful slides are still available...

Determination of $|V_{cb}|$

- recoil spectrum of D^* mesons in $B \to D^* \ell \bar\nu$ decays:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3}\,[\text{kin. factors}]\,|V_{cb}|^2\,\mathcal{F}^2(w)$$

with:

$$w = v_B \cdot v_{D^*} = \frac{E_{D^*}}{m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2\,m_B\,m_{D^*}}$$

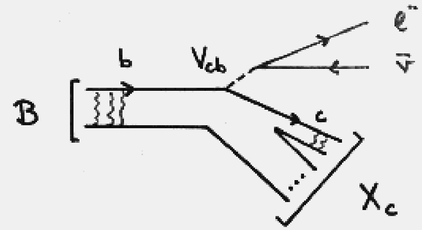
$\mathcal{F}(w)$ = hadronic form factor

= IWF + sym.-breaking corrections

→ measure $|V_{cb}|\,\mathcal{F}(w)$ as function of w

→ extract $|V_{cb}|$ from extrapolation to $w=1$, where heavy quark symmetry helps to calculate $\mathcal{F}(1)$ with high accuracy

2. $|V_{cb}|$ from inclusive semileptonic decays



(Luke, Savage
Bigi, Uraltsev
Ball, Nierste
Ball, Beneke, Braun)

$$\Gamma(B\to X_c e\bar\nu) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2\left\{\left(1+\frac{\lambda_1+3\lambda_2}{2m_b^2}\right) f\!\left(\frac{m_c}{m_b}\right) - \frac{6\lambda_2}{m_b^2}\left(1-\frac{m_c^2}{m_b^2}\right)^4 + \frac{\alpha_s(M)}{\pi}\, g\!\left(\frac{m_c}{m_b}\right) + \dots\right\}$$

Nonperturbative corrections:

$$\left.\begin{aligned} -\lambda_1 &= (0.4 \pm 0.2)\ \text{GeV}^2 \\ \lambda_2 &= 0.12\ \text{GeV}^2 \end{aligned}\right\} \Rightarrow \begin{aligned} &-(4.2 \pm 0.5)\,\% \\ &\text{reduction of rate} \end{aligned}$$

→ negligible uncertainty:

$$\left(\frac{\delta\Gamma}{\Gamma}\right)_{np} \approx 1\,\%$$

Over all these years Matthias has been for me (*and I guess for many others*...), a remarkable example to follow (*a "guide"*), given his outstanding scientific accomplishments

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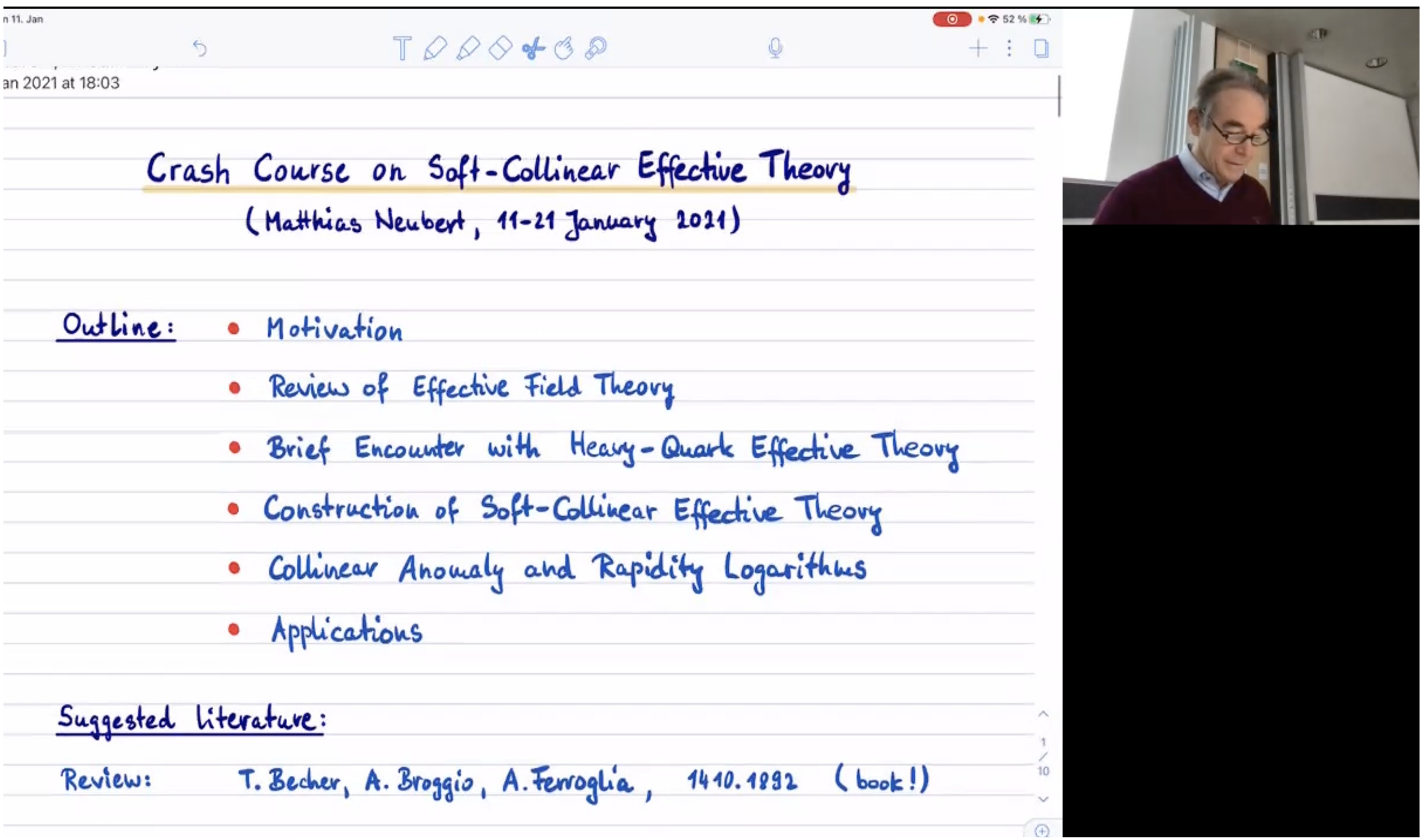
Pictures from a special sabbatical year…



Over all these years Matthias has been for me (*and I guess for many others…*), a remarkable example to follow (*a "guide"*), given his outstanding scientific accomplishments and, more generally, his enthusiasm & passion for research & training (→ *MITP best example*)

Pictures from a special sabbatical year… [Courtesy of Julie Pages]

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Pictures from a special sabbatical year... [Courtesy of Julie Pages]

Over all these years Matthias has been for me (*and I guess for many others…*), a remarkable example to follow (*a "guide"*), given his outstanding scientific accomplishments and, more generally, his enthusiasm & passion for research & training (→ *MITP best example*)

But, <u>most importantly</u>, he has became a very good friend, to whom I wish all the best !