

Decoding flavor hierarchies

[an essential key to physics beyond the SM]

Gino Isidori
[University of Zürich]

- ▶ Introduction
- ▶ The two flavor puzzles
- ▶ Flavor non-universal interactions
- ▶ The B anomalies [*what we learned, what's still left*]
- ▶ Leptoquarks and 4321
- ▶ Conclusions



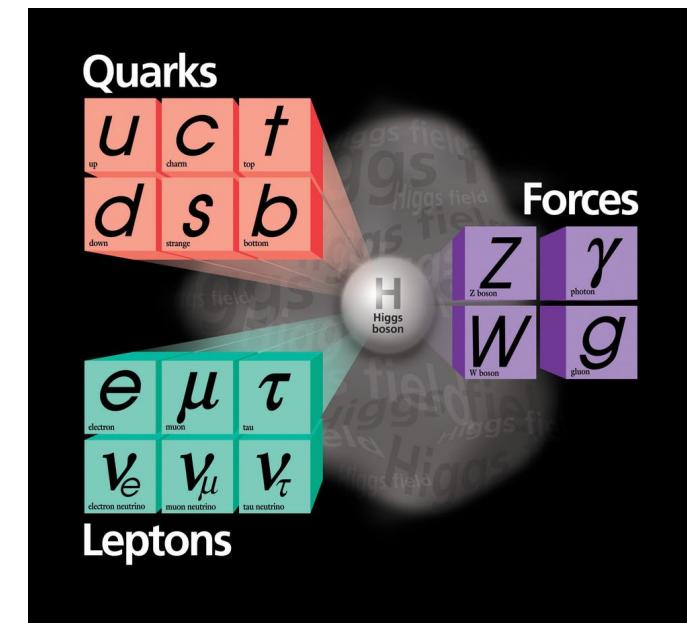
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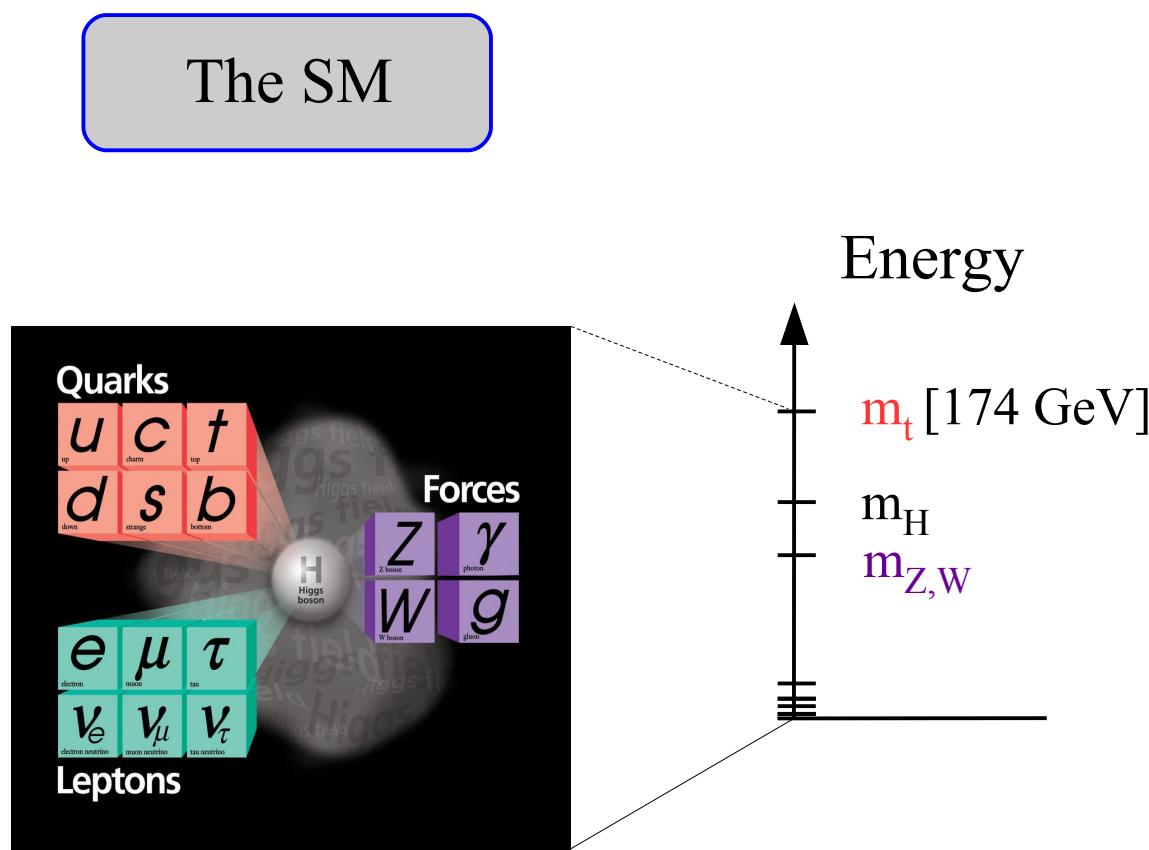
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Introduction



► Introduction

We recently celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).



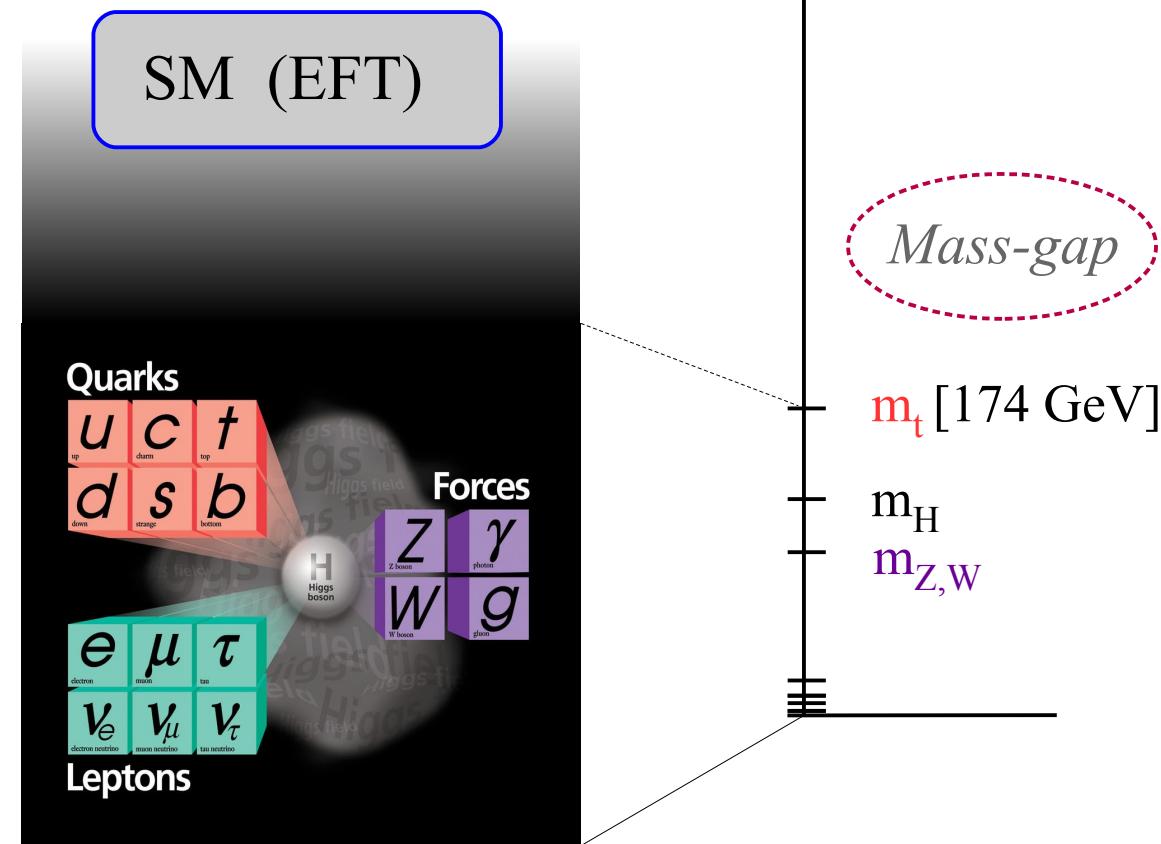
► Introduction

We recently celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

However, as for any QFT, we believe the SM is only an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \dots$$

We identified the *long-range* properties of this EFT



► Introduction

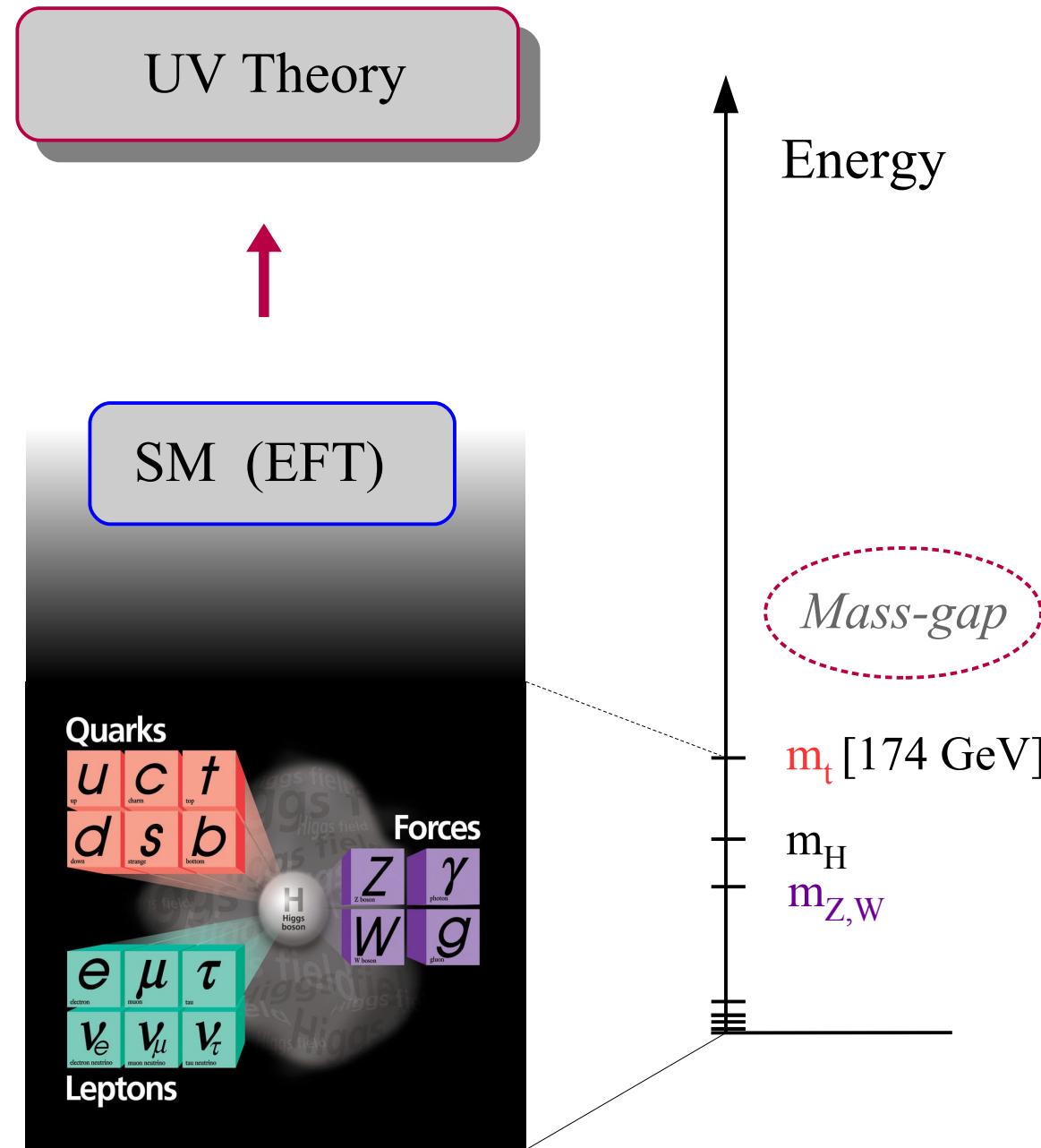
There are several reasons why we think the SM must be extended at high energies:

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:

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problem due to...

→ Instability of the Higgs mass term

→ Ad hoc tuning in the model parameters

→ *Cosmological implementation of the SM*

→ *General problem of any QFT*

...indicating

non-trivial properties of the SM Lagrangian if interpreted as EFT



Useful hints for its UV completion

The two flavor puzzles

$$V_{\text{CKM}} \sim \begin{pmatrix} \text{black} & \text{grey} & \text{light grey} \\ \text{grey} & \text{black} & \text{light grey} \\ \text{light grey} & \text{light grey} & \text{black} \end{pmatrix}$$

► 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?

Historical note: this year is a special anniversary year for flavor physics:

- '60 anniversary of the Cabibbo paper (1963)
- '50 anniversary of the Kobayashi-Maskawa paper (1973)

► 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:

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

The diagram illustrates the CKM matrix, which is a 3x3 unitary matrix representing the Cabibbo-Kobayashi-Maskawa (CKM) mixing. The matrix elements are represented by colored squares: black for zero, gray for small values, and light gray for larger values. A red dashed box highlights the first column of the matrix, corresponding to the Cabibbo angle. The matrix is shown as:

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where the first column is highlighted by a red dashed box. The matrix elements are labeled as follows:

- Top-left element: 0
- Top-middle element: 0
- Top-right element: 0.003
- Middle-left element: 0
- Middle-middle element: 0.04
- Middle-right element: 0.008
- Bottom-left element: 0.008
- Bottom-middle element: 0.04
- Bottom-right element: 0

A large bracket on the left indicates that the first column is approximately equal to the vector $\begin{pmatrix} 0 \\ 0 \\ 0.003 \end{pmatrix}$.

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

► The two flavor puzzles

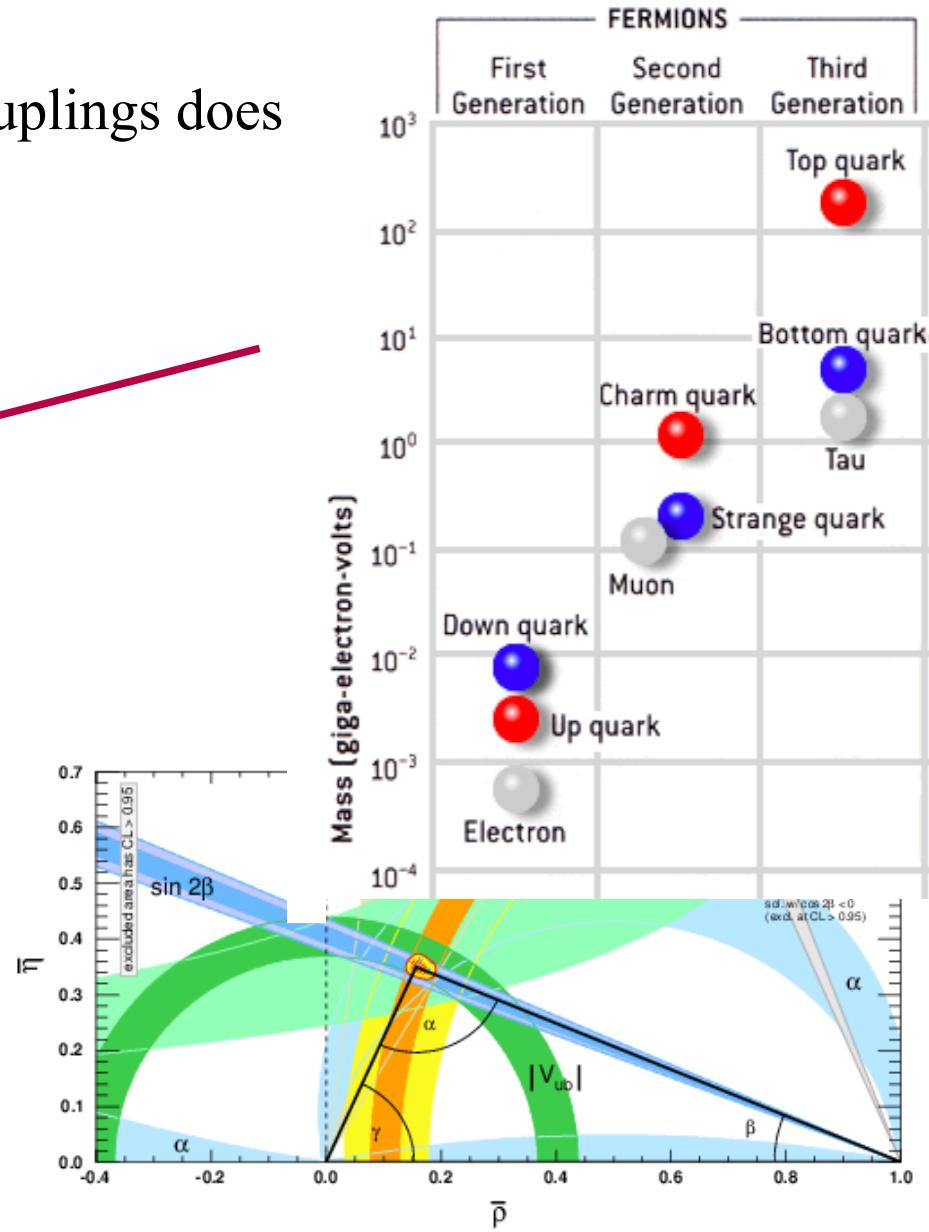
Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

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

$$Y_U \sim \begin{pmatrix} & & \\ & & \\ & & \\ & & \\ & & \end{pmatrix}$$

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

[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:

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

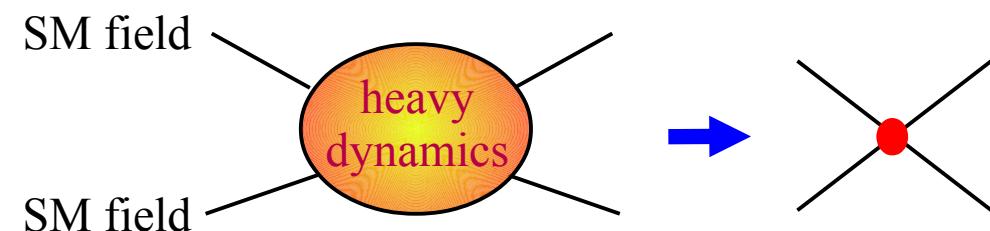
$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d \geq 5}$$

Interactions surviving @ large distances
(operators with $d \leq 4$)

Long-range forces
of the SM particles
+
ground state (Higgs)

Local contact interactions
(operators with $d > 4$)

“Remnant” of the heavy
dynamics at low energies



► The two flavor puzzles

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

Large flavor symmetry

Flavor-degeneracy broken by the Yukawa interaction

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

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

“Peculiar” breaking structure

Exact & approximate (*accidental?*) symmetries

Eg:

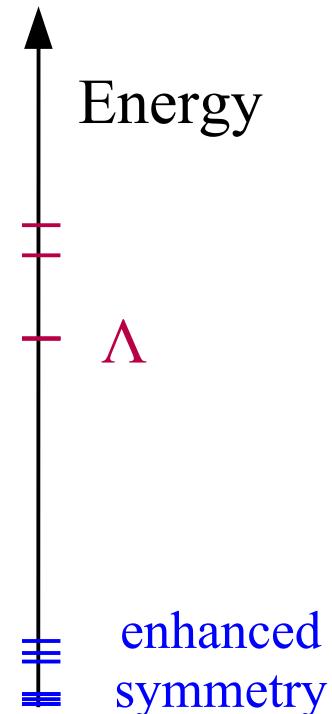
- $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} =$ (individual) Lepton Flavor [*exact symmetry*]
- $m_u \approx m_d \approx 0 \rightarrow$ Isospin symmetry [*approximate symmetry*]

► Accidental symmetries in QFT [a brief detour]

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

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

“Accidental symmetries” are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough “variables” to describe the violation of the symmetry [\sim multipole expansion]



► Accidental symmetries in QFT [a brief detour]

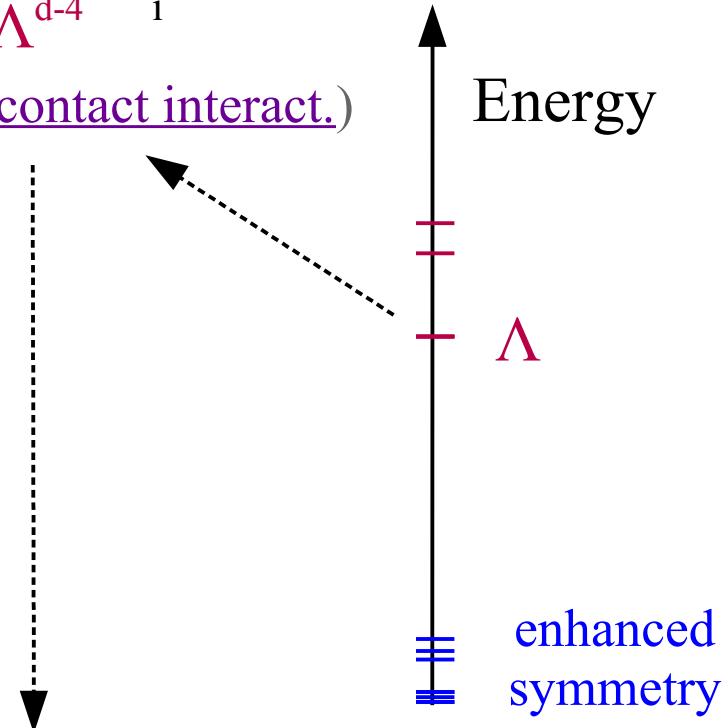
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If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops



Violations of
accidental symmetries

How to explain CP violation in the SM, and the history of the KM mechanism, are a wonderful illustration of this effect

► Accidental symmetries in QFT [a brief detour]

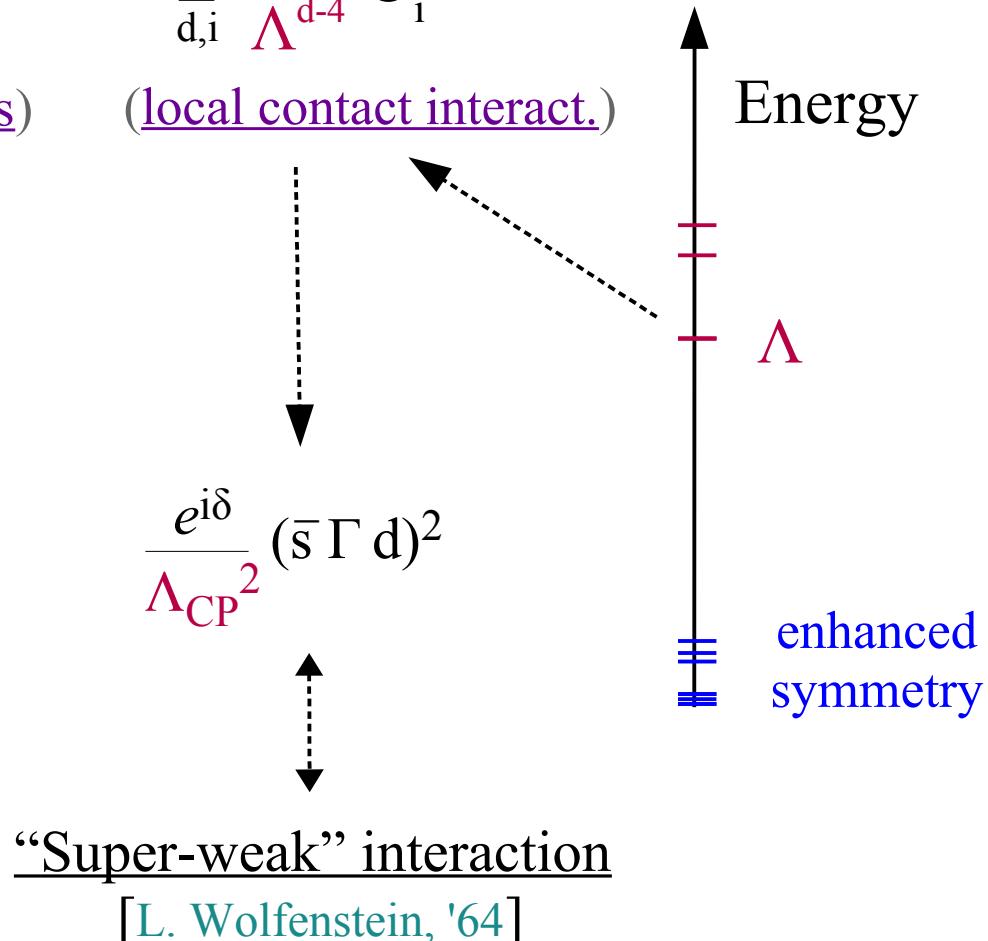
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Back in 1973: SM with 2 generations, as “reference model” → CP violation is an accidental symmetry [KM, '73]

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

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



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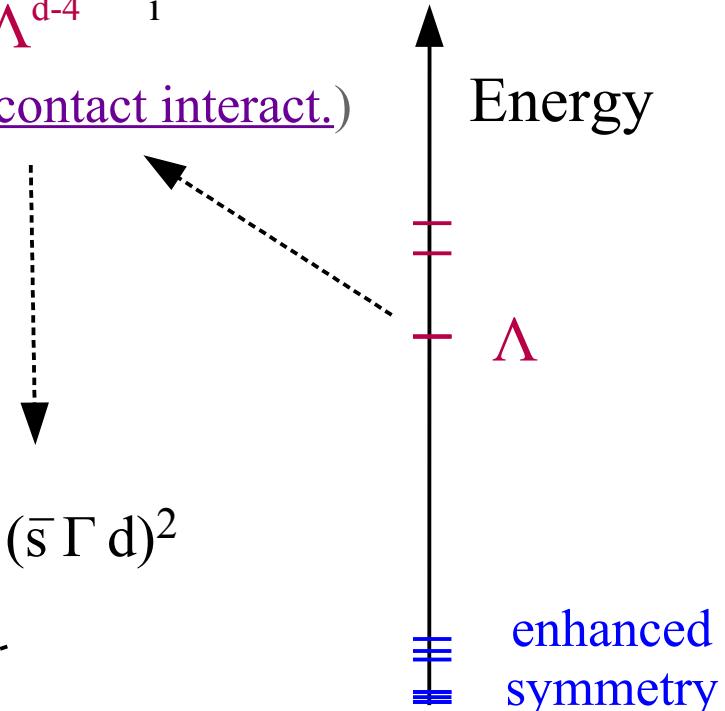
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$$\Lambda_{\text{CP}} \sim 10^4 \text{ TeV}$$

SM-3
[KM, '73]

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

Ellis, Gaillard,
Nanopoulos, '76



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

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

► The two flavor puzzles

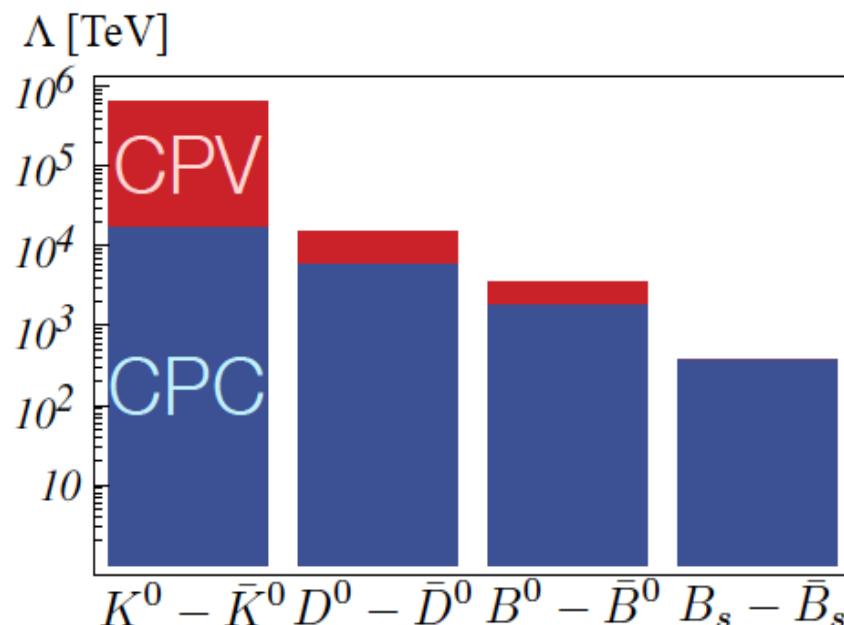
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In principle, we could expect many violations of the accidental symmetries from the heavy dynamics (\rightarrow *new flavor violating effects*). However, beside some anomalies in B-physics, we observe none.



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

The NP Flavor puzzle



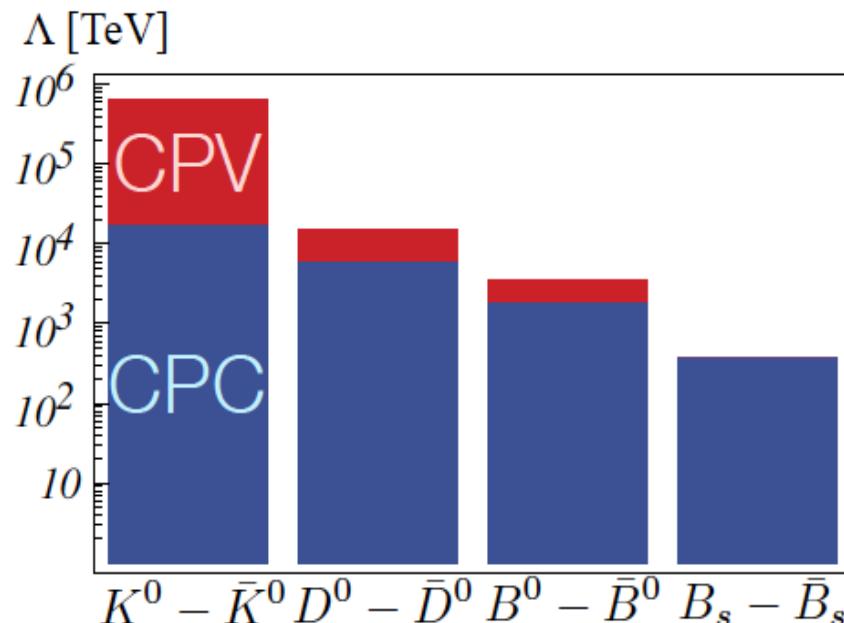
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In principle, we could expect many violations of the accidental symmetries from the heavy dynamics (\rightarrow new flavor violating effects). However, beside some anomalies in B-physics, we observe none.



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



The NP Flavor puzzle

Remember that these high scales can be a “mirage”...

Only unambiguous message:
no large breaking of the approximate
 $U(2)^n$ flavor symmetry
at near-by energy scales

► The two flavor puzzles

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

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.

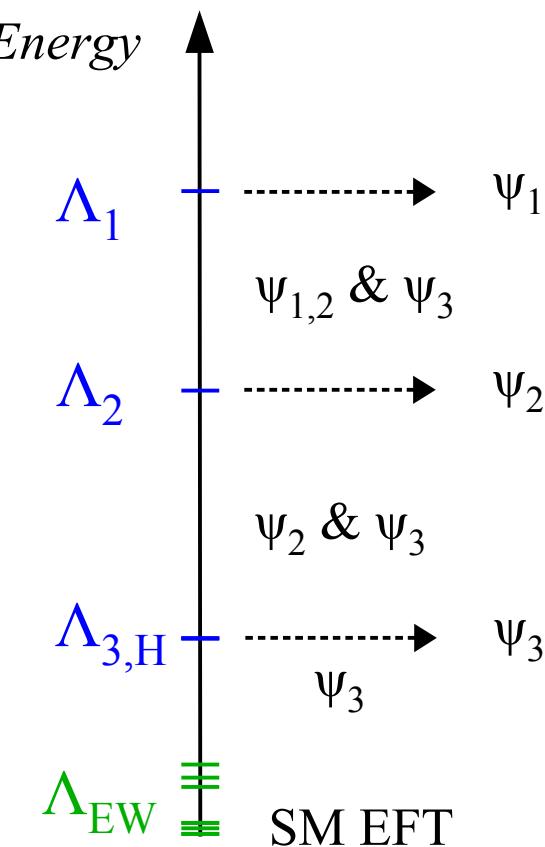


approx. U(2)ⁿ holds
also beyond the SM

The big questions in flavor physics:

- Can we find an explanation for the Yukawa hierarchies?
- If the (residual) flavor symmetries are accidental symmetries, at which scale are they broken? Can be there multiple scales behind the origin of flavor?

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:

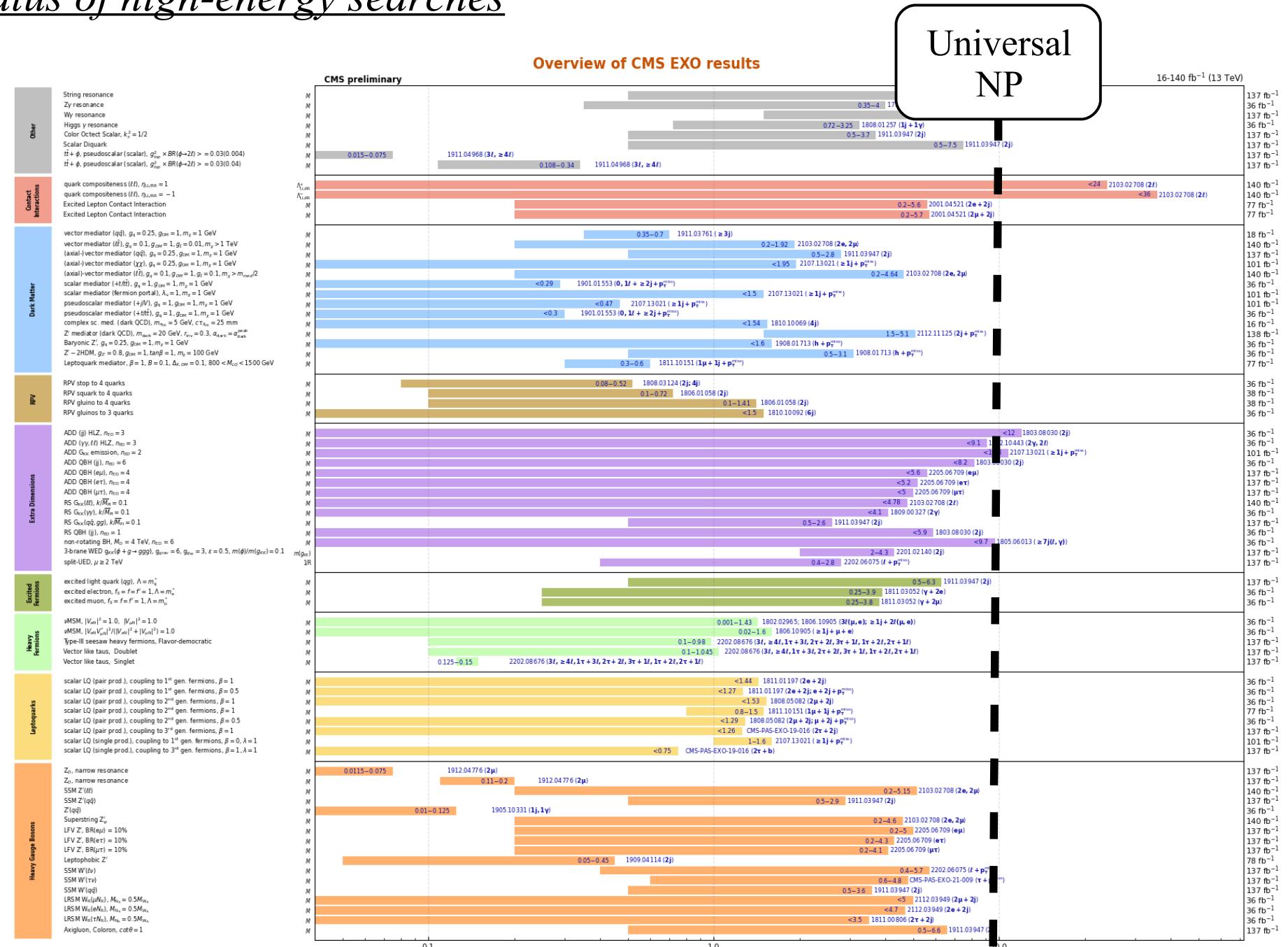
- Concentrate on the Higgs hierarchy problem
 - “Postpone” the flavor problem
-
- *The “MFV paradigm”:*

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

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

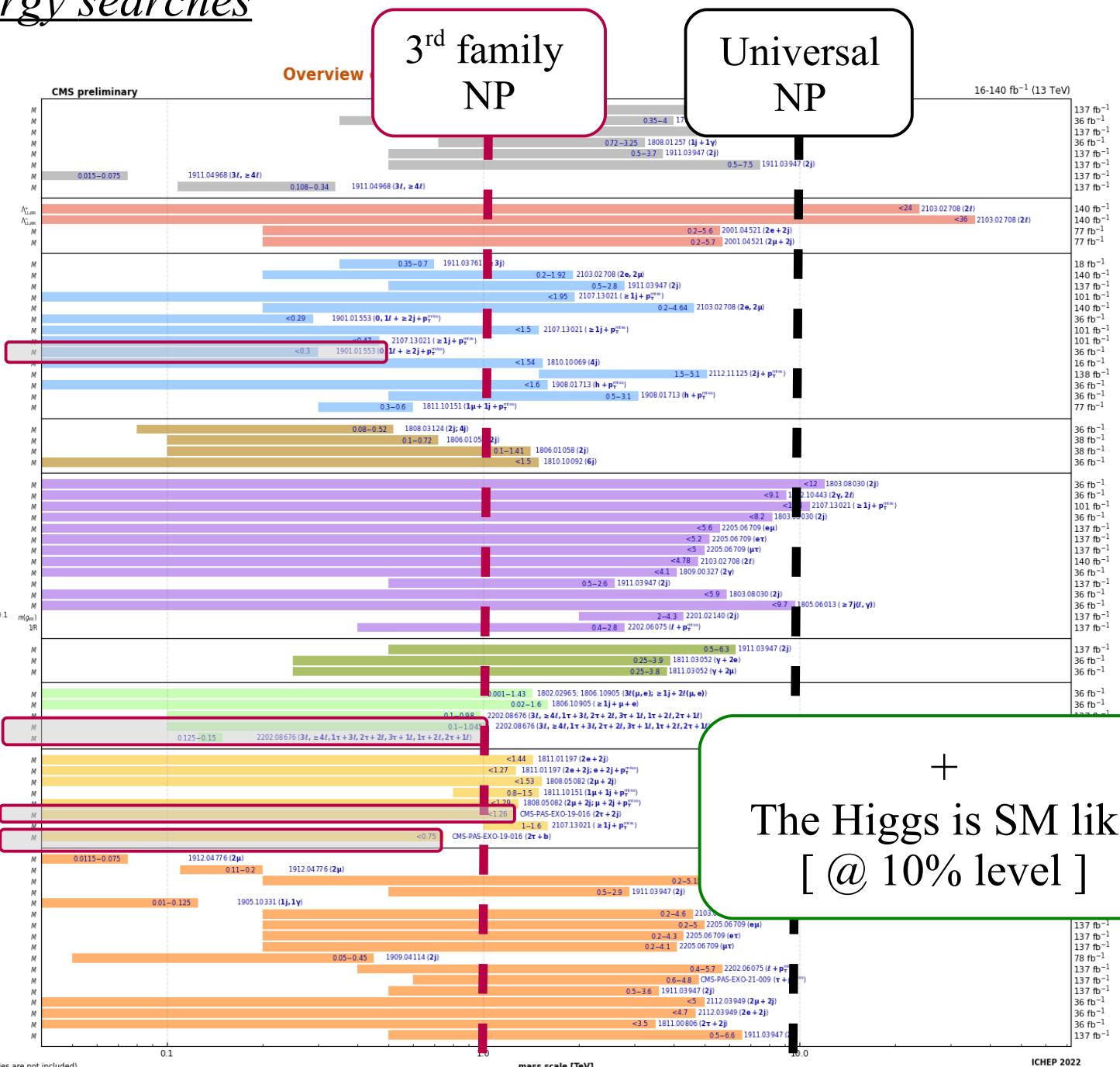
...but it has become a less compelling option
after run-I and run-II results

Status of high-energy searches



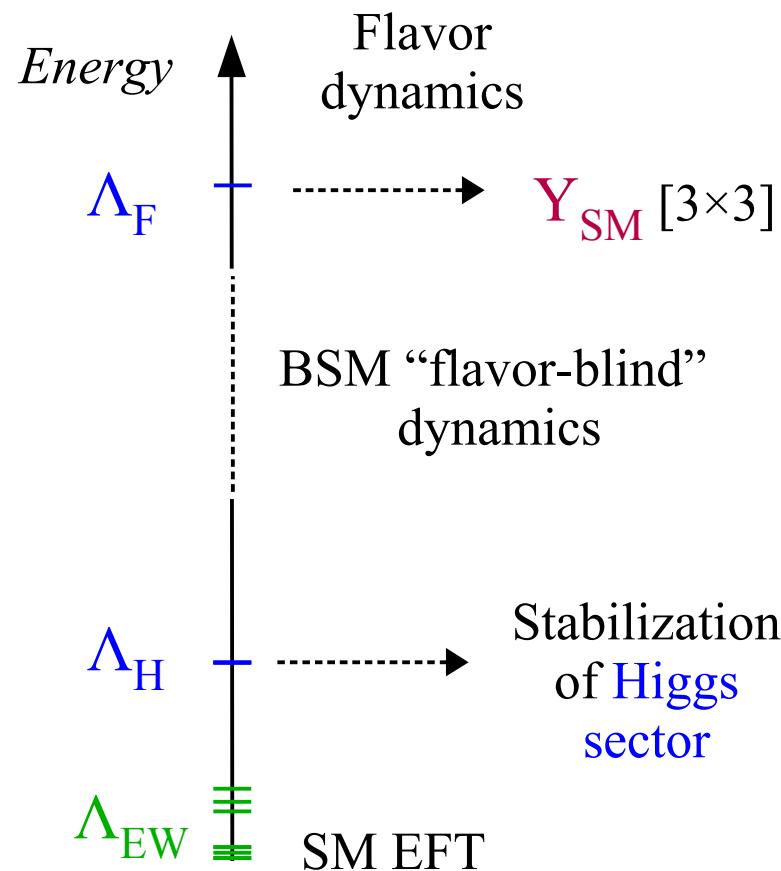
Status of high-energy searches

Other	
String resonance	
Zy resonance	
Wy resonance	
Higgs y resonance	
Color Octet Scalar, $\lambda^2 = 1/2$	
Scalar Diquark	
$t\bar{t} + \phi$, pseudoscalar (scalar), $g_{t\bar{t}\phi}^2 \times BR(\phi \rightarrow 2l) > 0.03$ (0.004)	
$t\bar{t} + \phi$, pseudoscalar (scalar), $g_{t\bar{t}\phi}^2 \times BR(\phi \rightarrow 2l) > 0.03$ (0.04)	
Contact Interactions	
quark compositeness ($U(1)$, $\eta_{L,R} = 1$)	
quark compositeness ($U(1)$, $\eta_{L,R} = -1$)	
Excited Lepton Contact Interaction	
Excited Lepton Contact Interaction	
Dark Matter	
vector mediator ($q\bar{q}$), $g_s = 0.25$, $m_{\phi} = 1$, $m_{\chi} = 1$ GeV	
vector mediator ($t\bar{t}\bar{b}b$), $g_s = 0.1$, $g_{t\bar{t}\phi} = 1$, $g_{\phi} = 0.01$, $m_{\phi} > 1$ TeV	
(axial-)vector mediator ($q\bar{q}$), $g_s = 0.25$, $g_{\phi\chi} = 1$, $m_{\chi} = 1$ GeV	
(axial-)vector mediator ($q\bar{q}$), $g_s = 0.25$, $g_{\phi\chi} = 1$, $m_{\chi} = 1$ GeV	
(axial-)vector mediator ($t\bar{t}\bar{b}b$), $g_s = 0.25$, $g_{\phi\chi} = 1$, $m_{\chi} = 1$ GeV	
scalar mediator (+ $t\bar{t}\bar{b}b$), $g_s = 0.1$, $g_{\phi\chi} = 1$, $m_{\chi} = 1$ GeV	
scalar mediator (+ $t\bar{t}\bar{b}b$), $g_s = 1$, $g_{\phi\chi} = 1$, $m_{\chi} = 1$ GeV	
pseudoscalar mediator (+ $t\bar{t}\bar{b}b$), $g_s = 1$, $g_{\phi\chi} = 1$, $m_{\chi} = 1$ GeV	
pseudoscalar mediator (+ $t\bar{t}\bar{b}b$), $g_s = 1$, $g_{\phi\chi} = 1$, $m_{\chi} = 25$ mm	
complex sc. med. (dark QCD), $m_{\phi} = 5$ GeV, $c_{\phi\chi} = 25$ mm	
Z' mediator (dark QCD), $m_{Z'} = 20$ GeV, $\alpha_{Z'} = 0.3$, $\alpha_{\phi\chi} = \alpha_{\phi\phi}^{Z'}$	
Baryonic Z': $g_s = 0.25$, $g_{\phi\chi} = 1$, $m_{\chi} = 1$ GeV	
Z' – 2HDM, $g_s = 0.25$, $g_{\phi\chi} = 1$, $m_{\chi} = 100$ GeV	
Leptoquark mediator, $\beta = 1$, $B = 0.1$, $\Delta\epsilon_{\text{cor}} = 0.1$, $800 < M_{Q\bar{Q}} < 1500$ GeV	
RPV	
RPV stop to 4 quarks	
RPV squark to 4 quarks	
RPV gluino to 4 quarks	
RPV gluinos to 3 quarks	
Extra Dimensions	
ADD (ij) HLZ, $n_{\text{DO}} = 3$	
ADD (yz) HLZ, $n_{\text{DO}} = 3$	
ADD $G_{\mu\nu}$ emission, $n_{\text{DO}} = 2$	
ADD QBH (ij), $n_{\text{DO}} = 6$	
ADD QBH (ej), $n_{\text{DO}} = 4$	
ADD QBH (er), $n_{\text{DO}} = 4$	
ADD QBH (ur), $n_{\text{DO}} = 4$	
RS $G_{\mu\nu}(ll)$, $kM_{\text{Pl}} = 0.1$	
RS $G_{\mu\nu}(yy)$, $kM_{\text{Pl}} = 0.1$	
RS $G_{\mu\nu}(q\bar{q})$, $kM_{\text{Pl}} = 0.1$	
RS QBH (ij), $n_{\text{DO}} = 1$	
non-rotating BH, $M_0 = 4$ TeV, $n_{\text{DO}} = 6$	
3-brane WED $g_{\phi\chi}(g + ggg)$, $g_{\phi\chi} = 6$, $g_{\phi\phi} = 3$, $\varepsilon = 0.5$, $m(\phi)/m(g_{\phi\chi}) = 0.1$	
split-UED, $\mu \geq 2$ TeV	
Exotic Fermions	
excited light quark ($q\bar{q}$), $\Lambda = m_s^*$	
excited electron, $e = f = 1$, $\Lambda = m_e^*$	
excited muon, $f_3 = f = 1$, $\Lambda = m_\mu^*$	
Heavy Fermions	
vMSM, $ V_{e\mu} ^2 = 1.0$	
vMSM, $ V_{e\mu} ^2/(V_{e\tau} ^2 \cdot V_{\mu\tau} ^2) = 1.0$	
Type-III seesaw heavy fermions, Flavor-democratic	
Vector like tau, Doublet	
Vector like tau, Singlet	
Lighthiggs	
scalar LO (pair prod.), coupling to 1 st gen. fermions, $\beta = 1$	
scalar LO (pair prod.), coupling to 1 st gen. fermions, $\beta = 0.5$	
scalar LO (pair prod.), coupling to 2 nd gen. fermions, $\beta = 1$	
scalar LO (pair prod.), coupling to 2 nd gen. fermions, $\beta = 1$	
scalar LO (pair prod.), coupling to 2 nd gen. fermions, $\beta = 0.5$	
scalar LO (pair prod.), coupling to 3 rd gen. fermions, $\beta = 1$	
scalar LO (single prod.), coupling to 1 st gen. fermions, $\beta = 0$, $\lambda = 1$	
scalar LO (single prod.), coupling to 3 rd gen. fermions, $\beta = 1$, $\lambda = 1$	
Heavy Gauge Bosons	
Z ₀ , narrow resonance	
Z ₀ , narrow resonance	
SSM Z'(ff)	
SSM Z'(q \bar{q})	
Z'(q \bar{q})	
Supersymmetrized Z'	
LFV Z, $BR(e\mu) = 1.0\%$	
LFV Z, $BR(\mu e) = 1.0\%$	
LFV Z, $BR(\mu\tau) = 1.0\%$	
Lepto-phobic Z'	
SSM W'(bb)	
SSM W'(rr)	
SSM W'(gg)	
LHCW W _b (ll χ_1), $M_{\chi_1} = 0.5M_{W_b}$	
LRSW W _b (ll χ_1), $M_{\chi_1} = 0.5M_{W_b}$	
LRSW W _b (ll χ_1), $M_{\chi_1} = 0.5M_{W_b}$	
Axigluon, Coloron, $c\theta\tilde{\theta} = 1$	



► 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** to higher scales



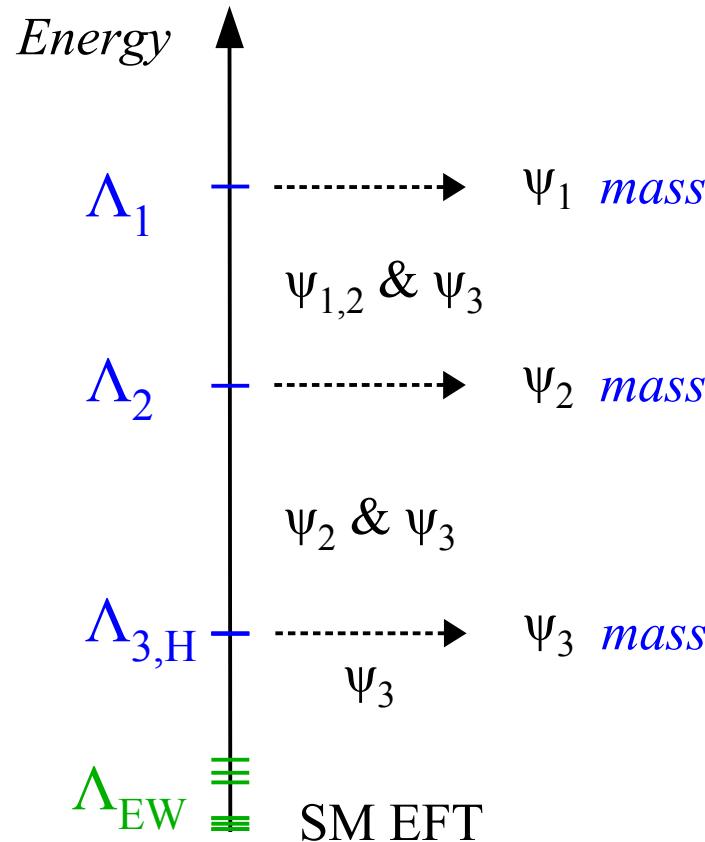
3 gen. = “identical copies”
up to high energies

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



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

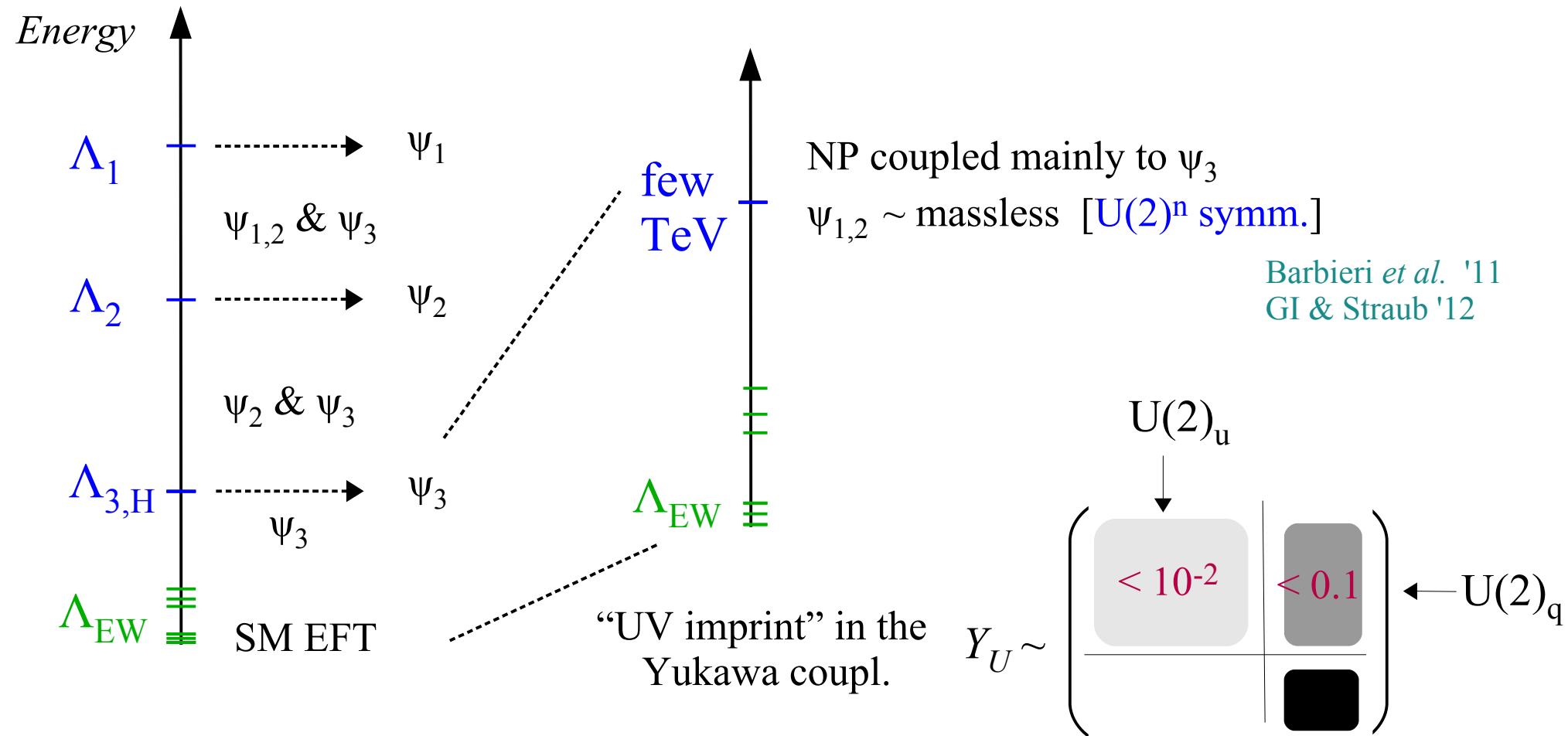
Dvali & Shifman '00
Panico & Pomarol '16
⋮
Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23



3 gen. = “identical copies”
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► Flavor non-universal interactions

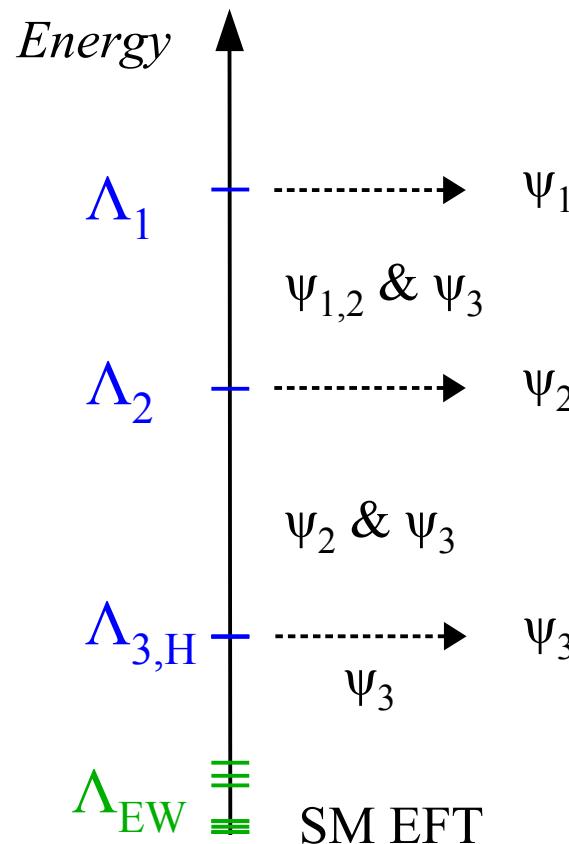
New paradigm to address both the Higgs hierarchy problem and the flavor puzzle:
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Effective organizing principle for the **flavor structure** of the **SMEFT**

► 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

► 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 3rd 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: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

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

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

$$Y \sim \begin{pmatrix} \text{green box} & | & \text{red X} \\ \hline \text{red X} & | & \text{green box} \end{pmatrix}$$

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

$$Y \sim \begin{pmatrix} \text{red X} & | \\ \hline \text{green box} & | \end{pmatrix}$$

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

$$Y \sim \begin{pmatrix} \text{red X} & | \\ \hline | & \text{green box} \end{pmatrix}$$



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

► *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

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

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

UV completion
@ higher E

small impact on δm_h

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

$d > 4$ ops
(@ TeV scale)

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

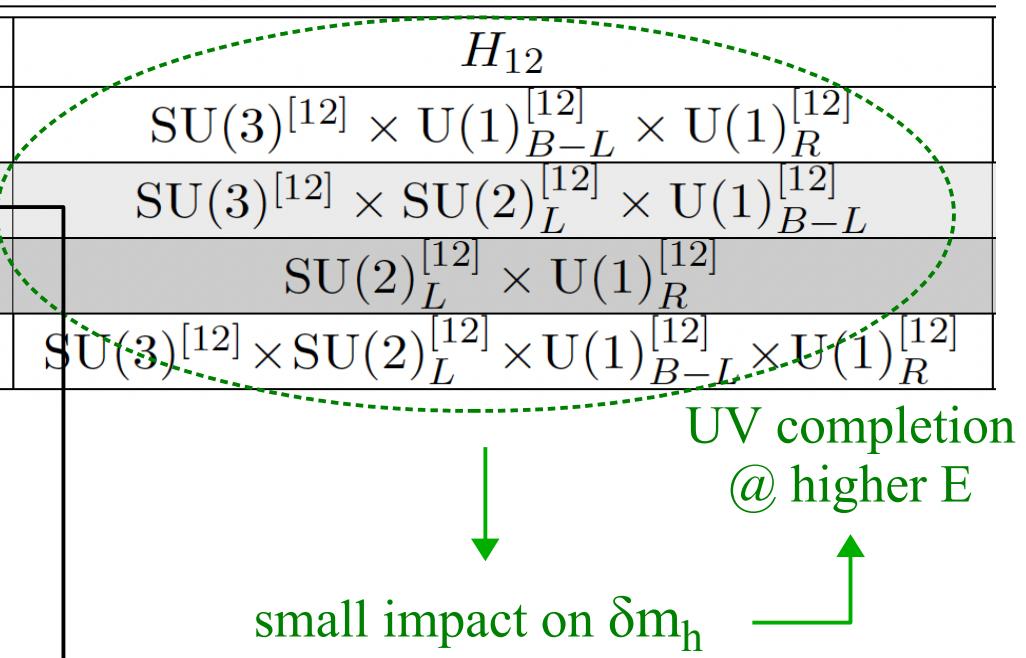
I. + II. + III. + general pheno bounds: two viable TeV-scale options:

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Strongly disfavored by:

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



$$Y \sim \begin{pmatrix} & \\ & \\ \hline & \\ & 1 \end{pmatrix}$$

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

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

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2	$\cancel{SU(2)_R}$	$\cancel{SU(4)}^{[3]} \times \cancel{SU(2)_L}^{[3]}$	$SU(3)^{[12]} \times SU(2)_L^{[12]} \times U(1)_{B-L}^{[12]}$
3	$\cancel{SU(4)}$	$\cancel{SU(2)_L}^{[3]} \times \cancel{SU(2)_R}^{[3]}$	$SU(2)_L^{[12]} \times U(1)_R^{[12]}$
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UV completion
@ higher E

General feature:

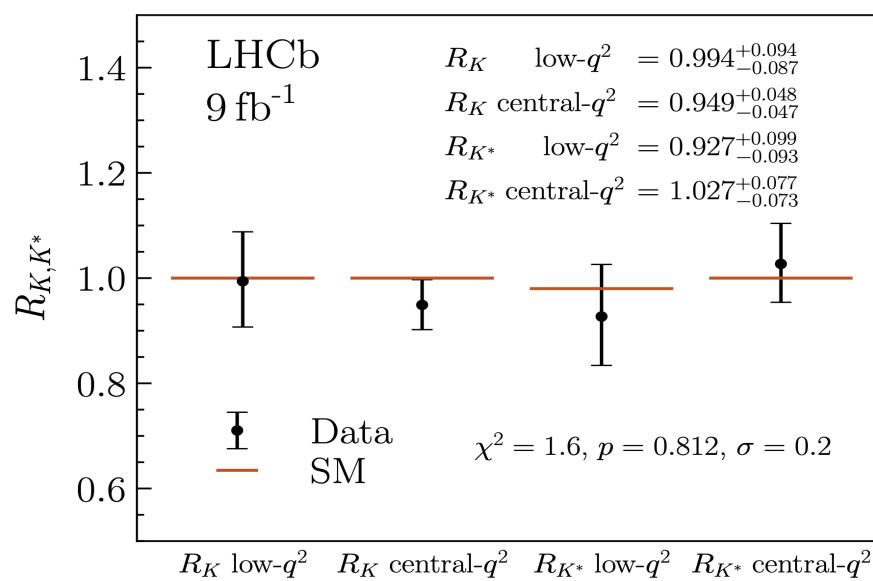
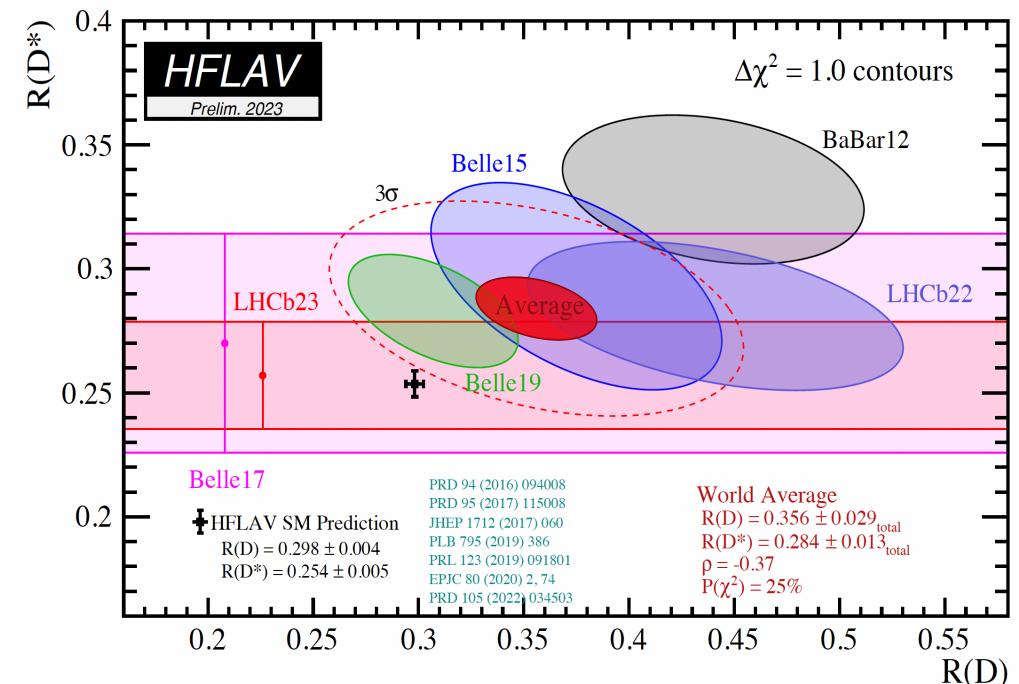
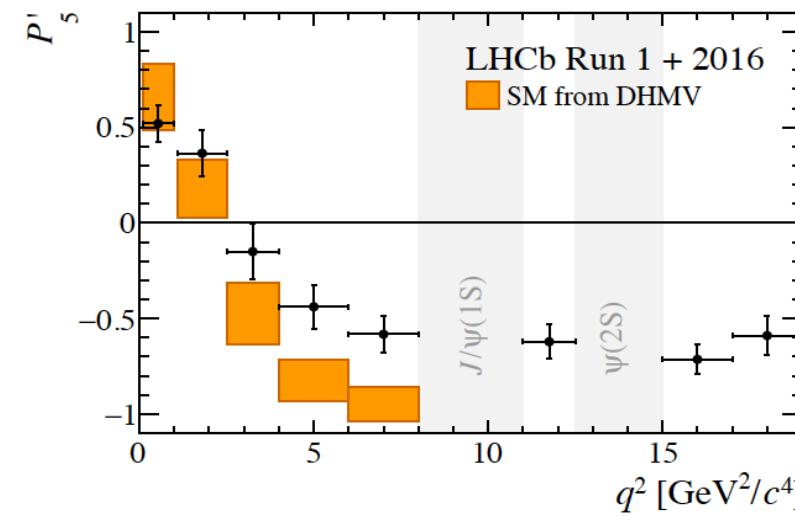
$SU(4)$ group acting on the 3rd family, with low-energy breaking scale to avoid fine-tuning on the Higgs mass:

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

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:

$b \rightarrow c \, l \nu$ (*Charged Currents*)

$b \rightarrow s \, l^+ l^-$ (*Neutral Currents*)

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

► 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:

$b \rightarrow c l\nu$ (*Charged Currents*)

$b \rightarrow s l^+l^-$ (*Neutral Currents*)

The anomalies can be grouped into 3 categories:

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

$b \rightarrow c l\nu$

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

$b \rightarrow s l^+l^-$

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

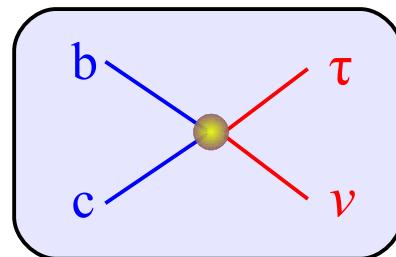
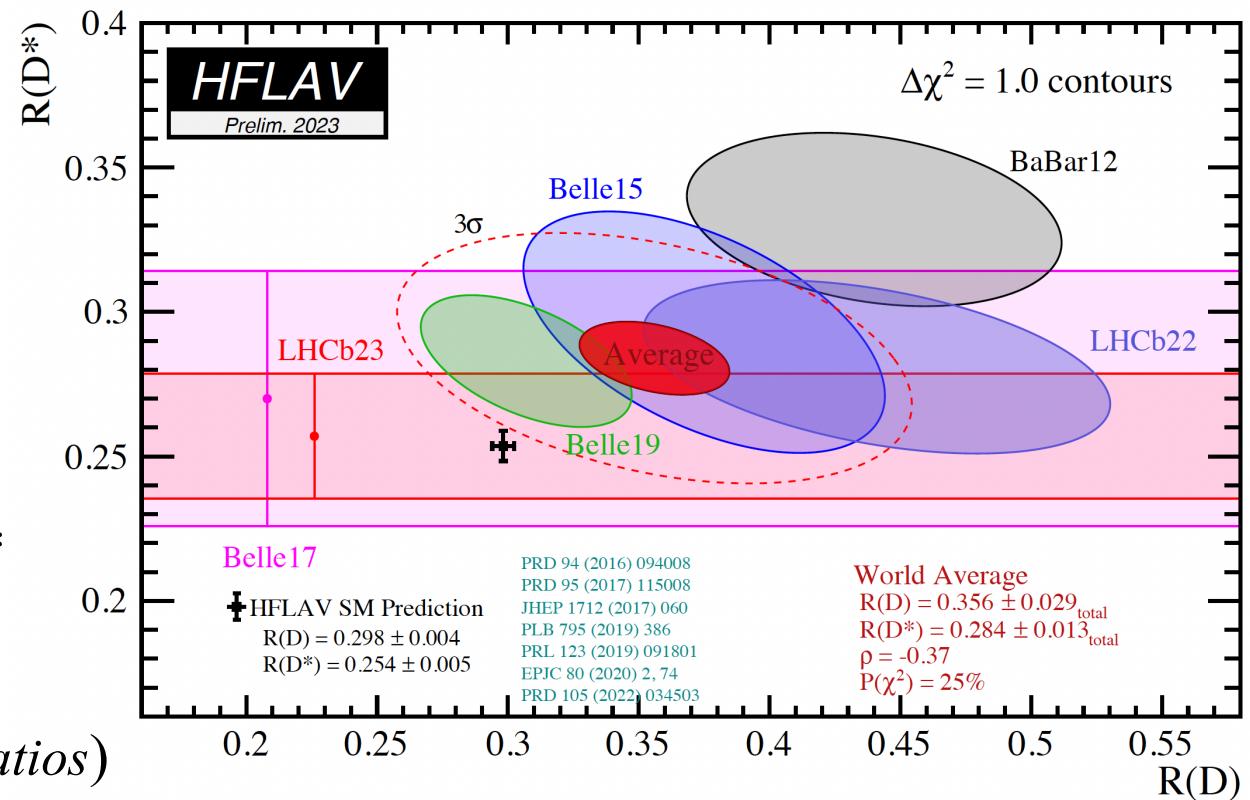
► The B-physics anomalies

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

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

$X = D$ or D^*

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



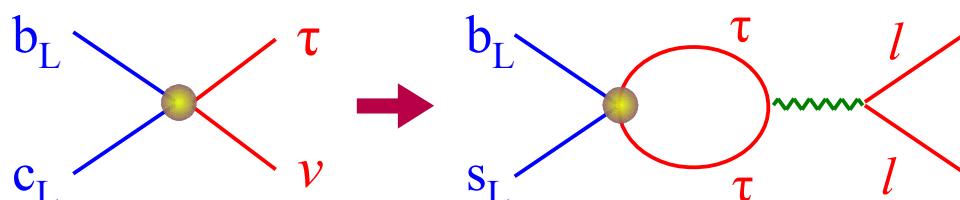
► The B -physics anomalies

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

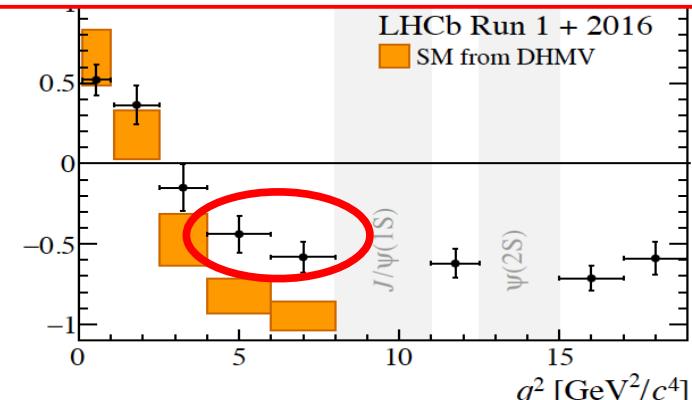
$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell)$$

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

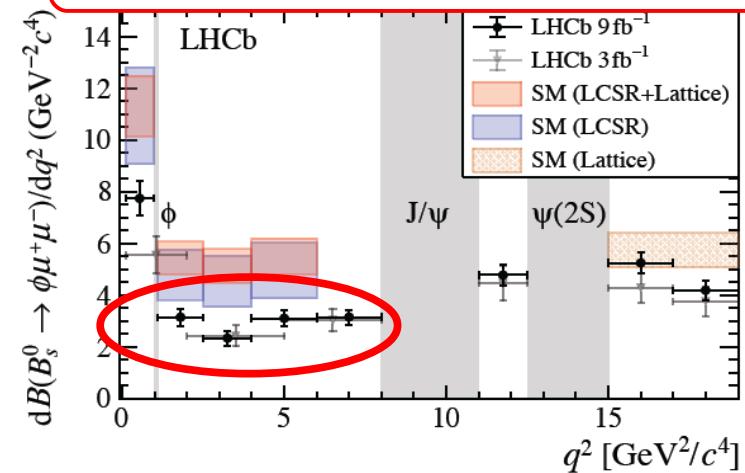
Possible explanation connected to CC
(hence 3rd family LFU violation):



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



$B \rightarrow H \mu\mu$ branching ratios



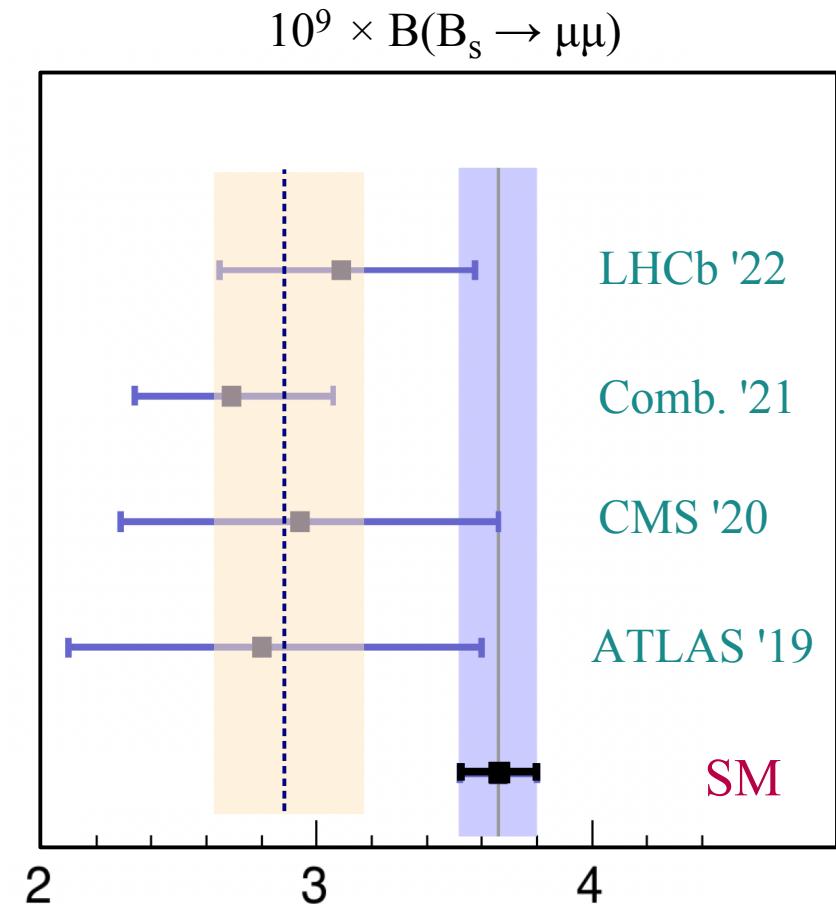
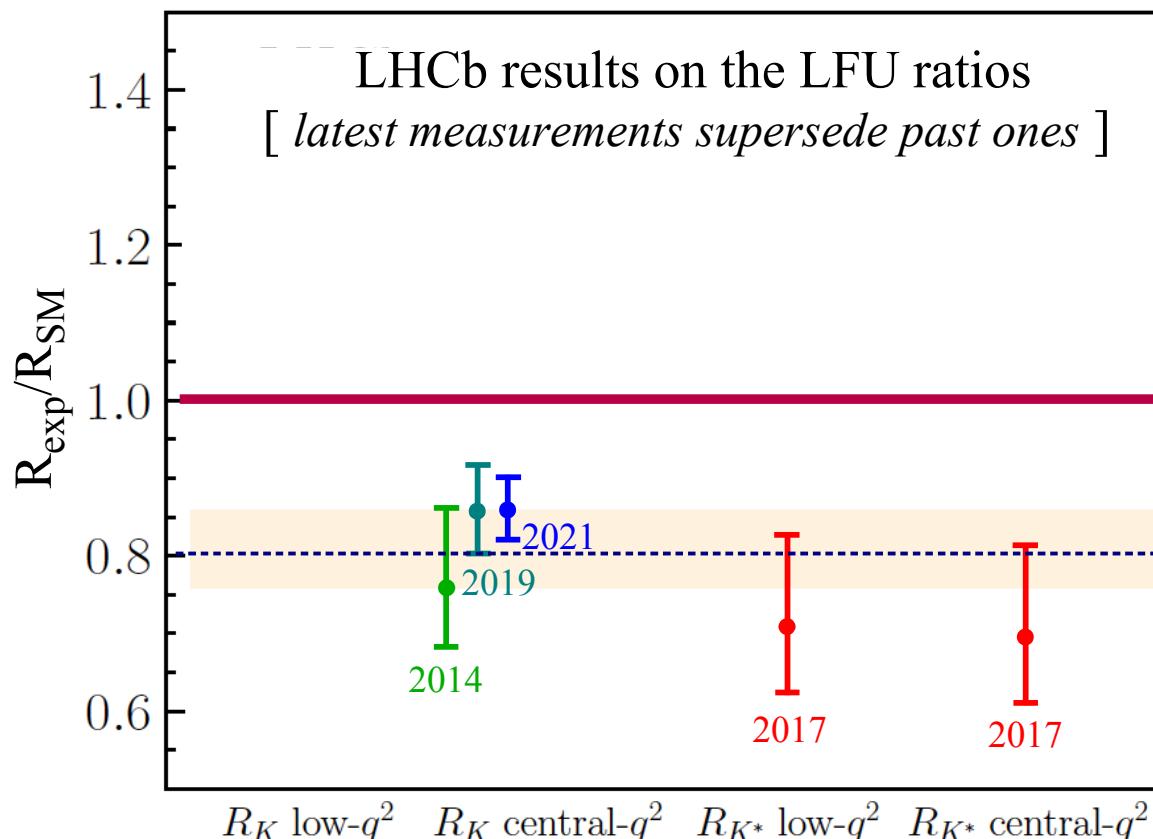
ΔC_9^{Univ}
N.B.: correct sign & size !

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

► The B -physics anomalies

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

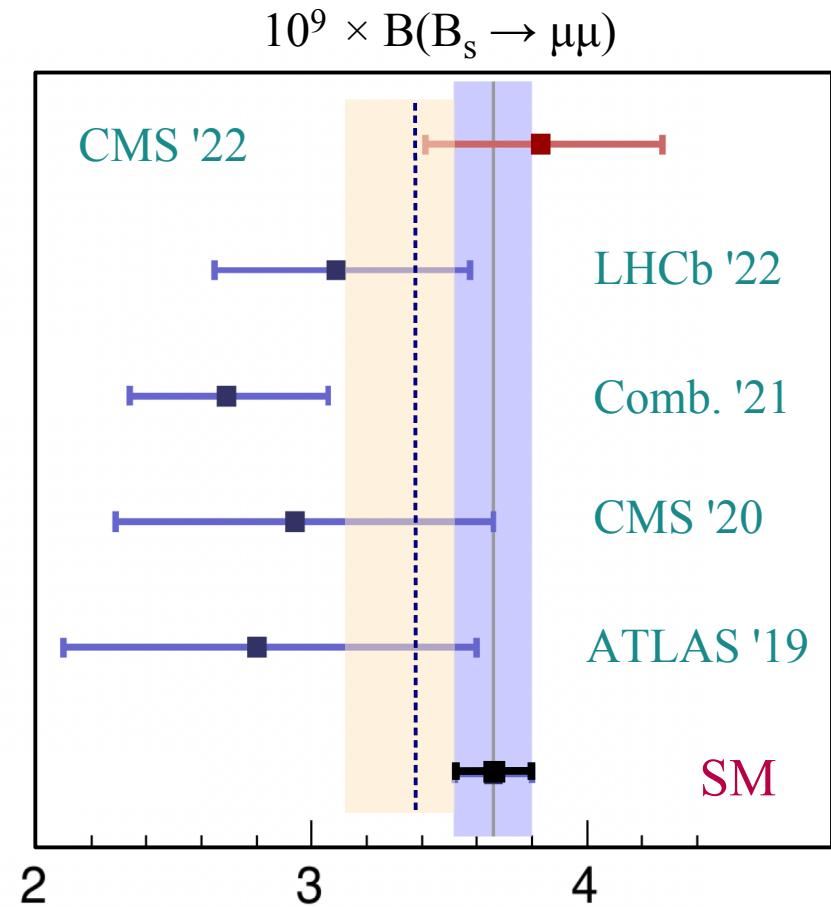
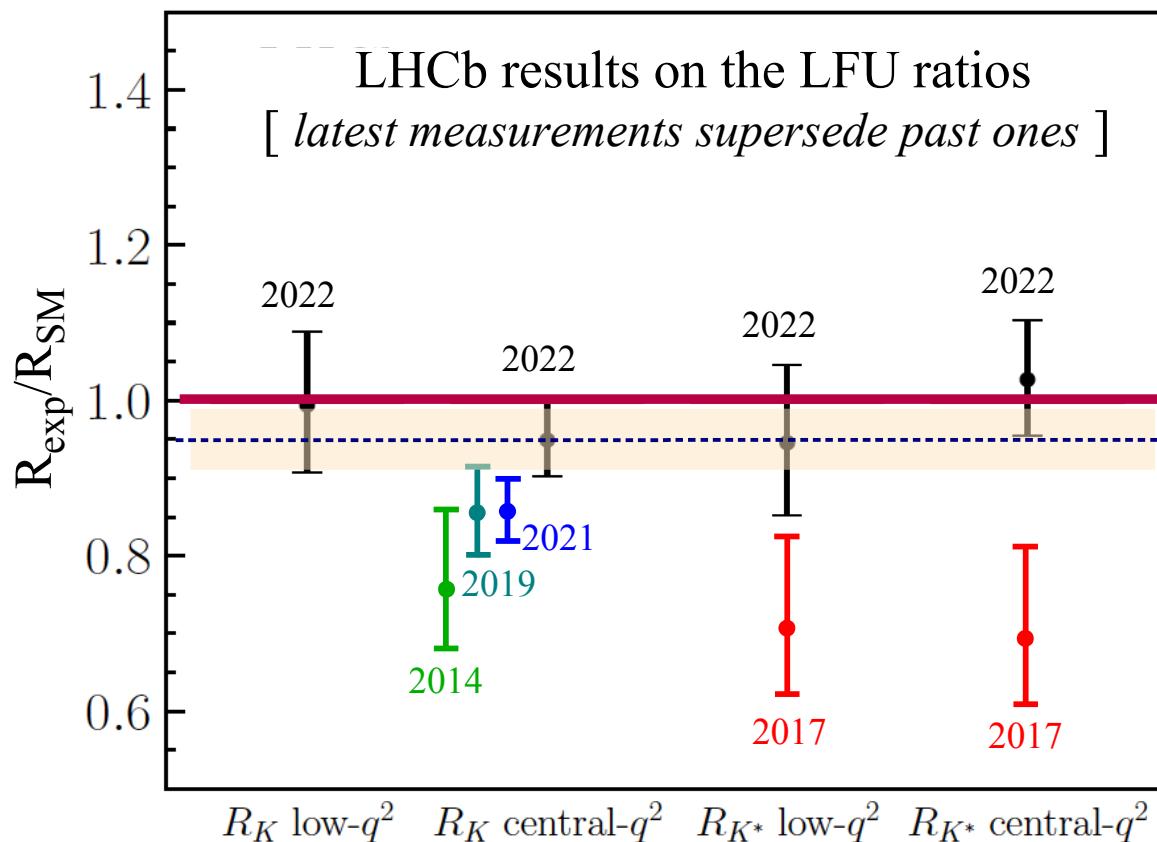
- Clean SM predictions
(*LFU ratios + no long-distance in $B_s \rightarrow \mu\mu$*)
- Highest significance till summer 2022



► The B -physics anomalies

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

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

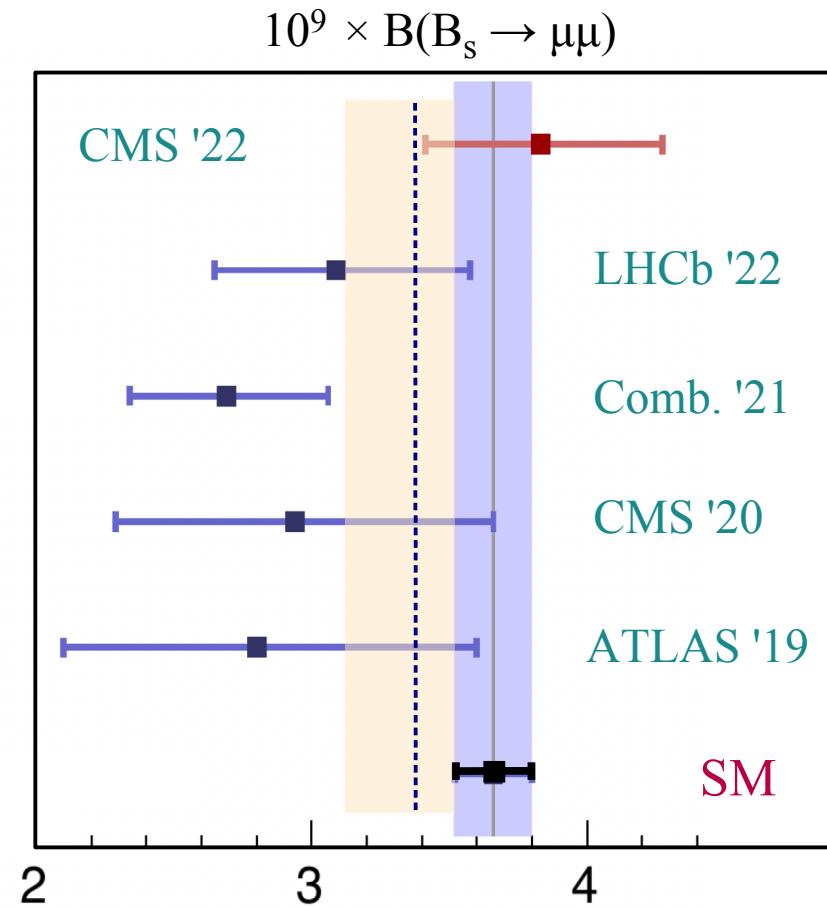
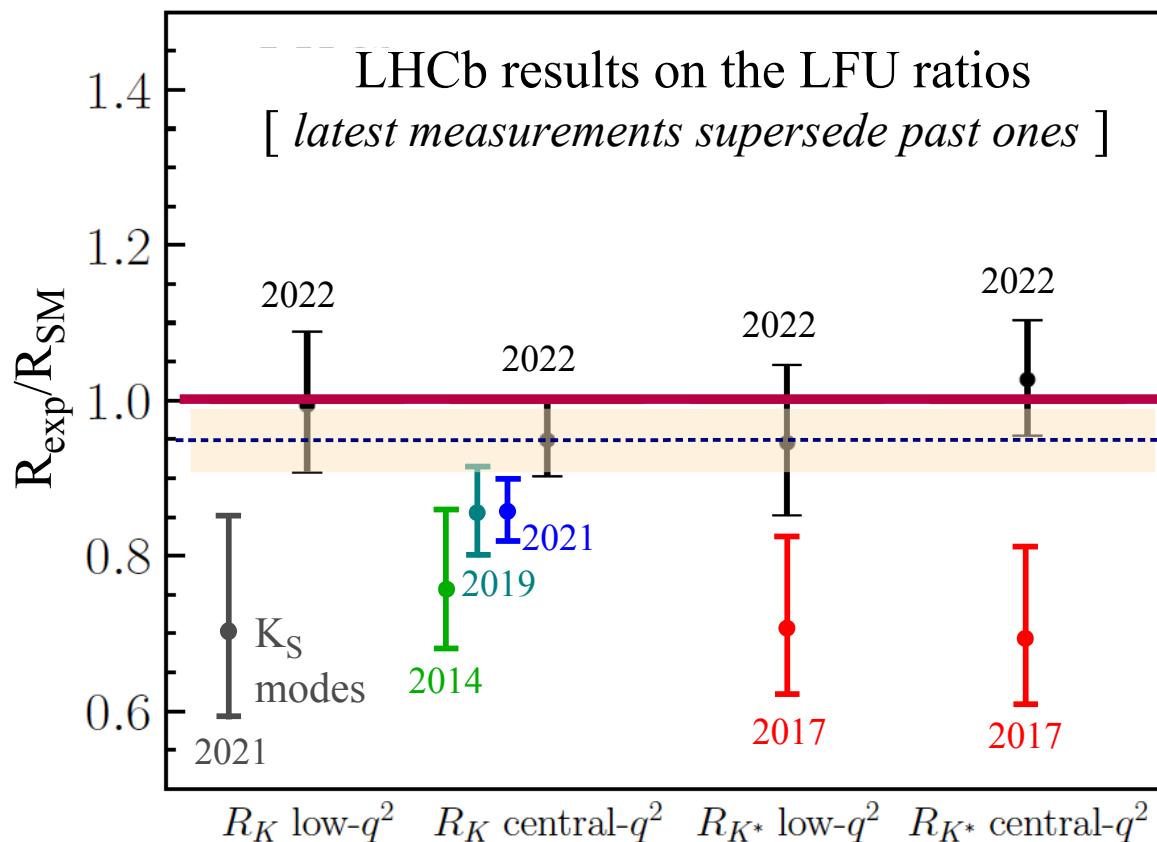


► The B -physics anomalies

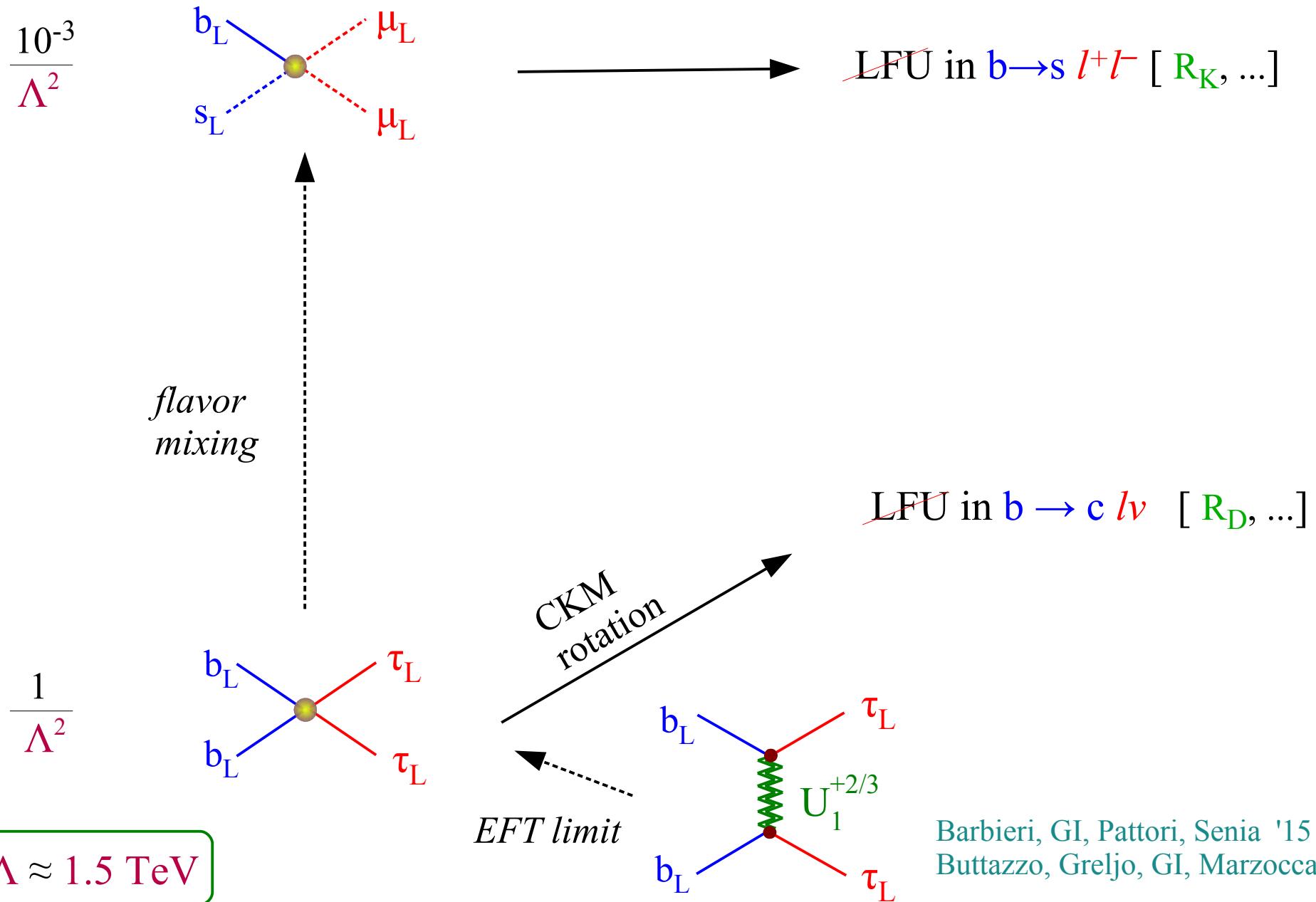
III. ~~LFU~~ anomaly in NC & BR($B_s \rightarrow \mu\mu$)

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

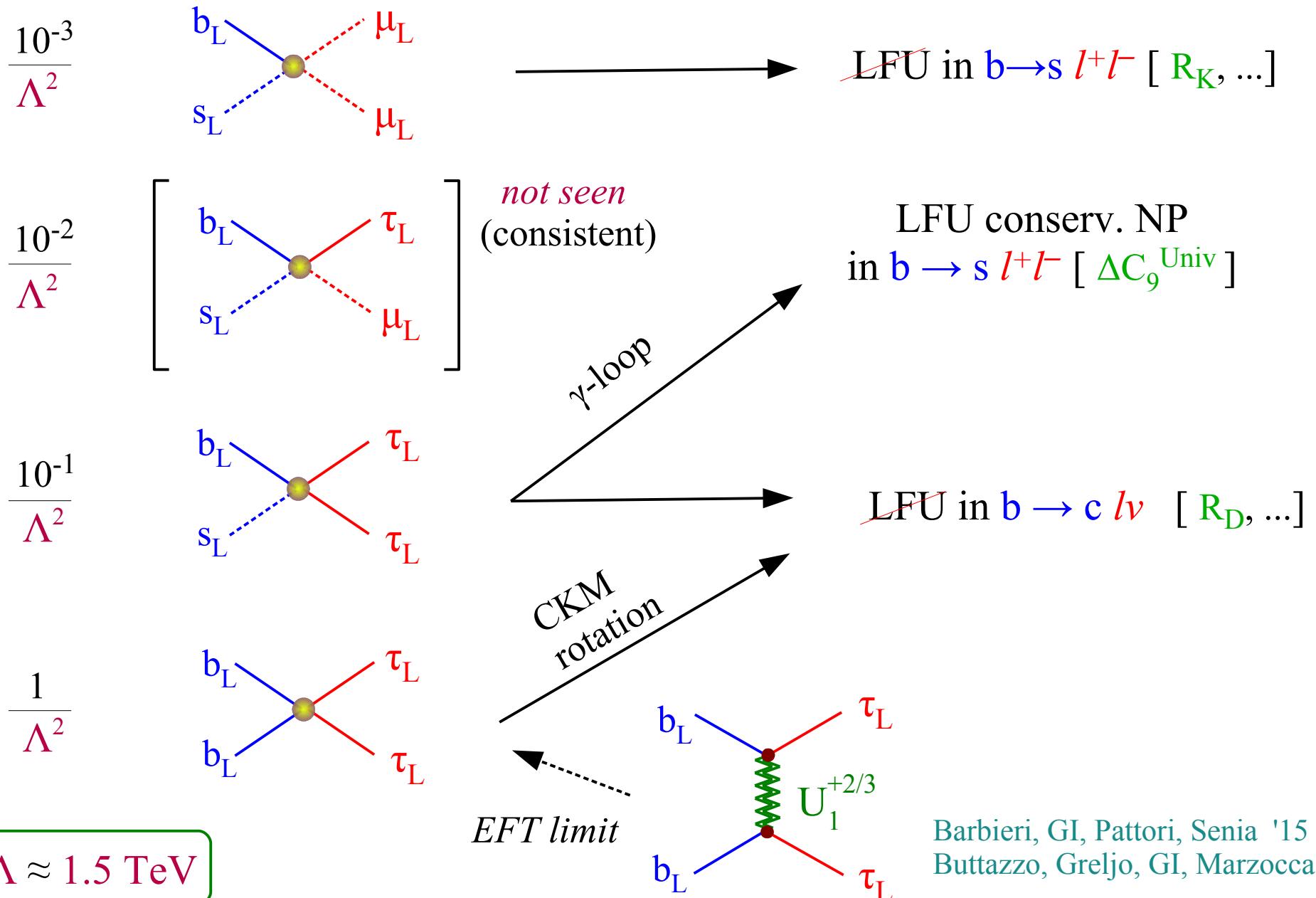
N.B.: While the overall loss of significance is high, the overall implications for the class of NP models I advocate, are modest



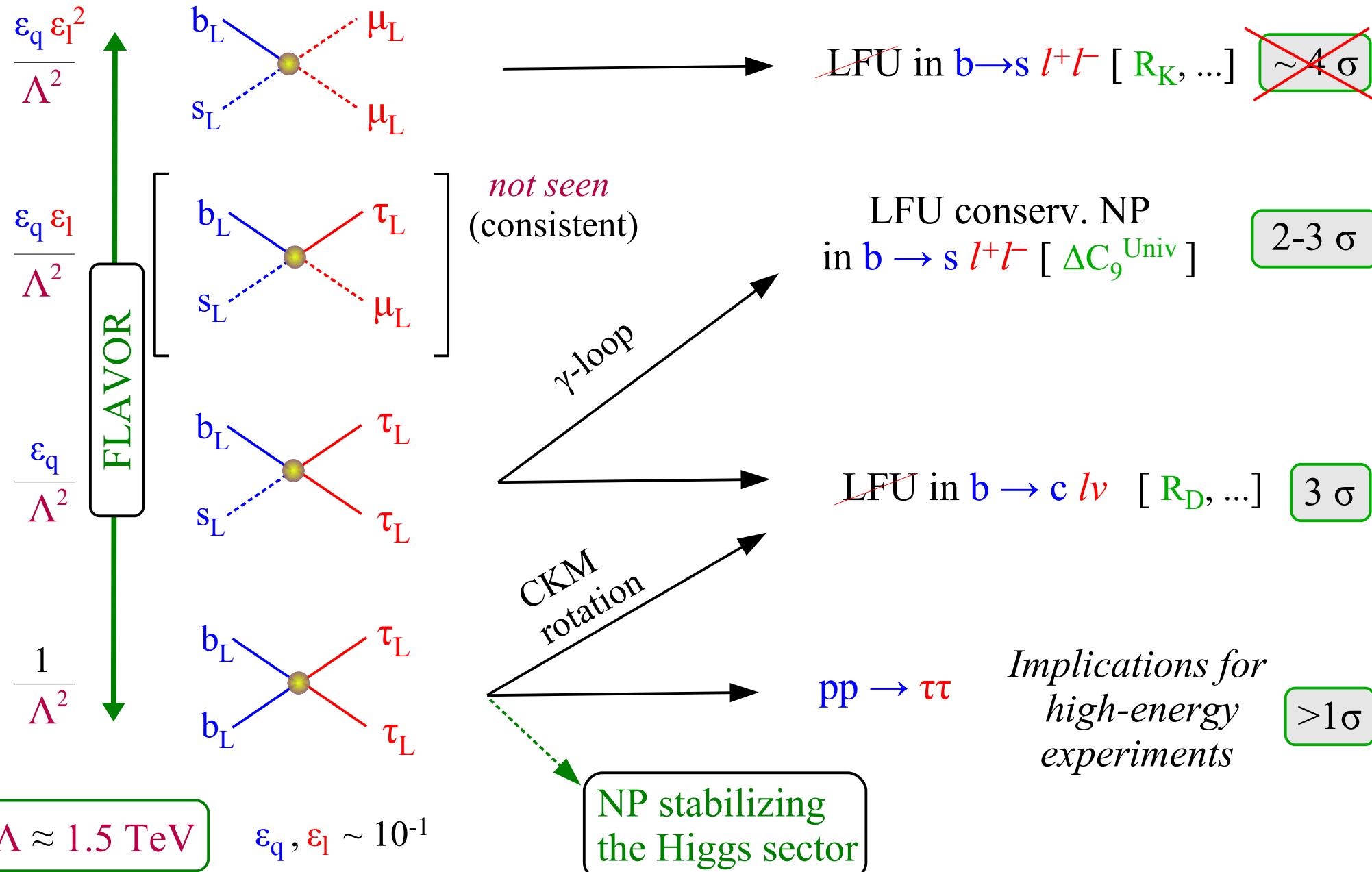
► The B -physics anomalies



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► The B -physics anomalies



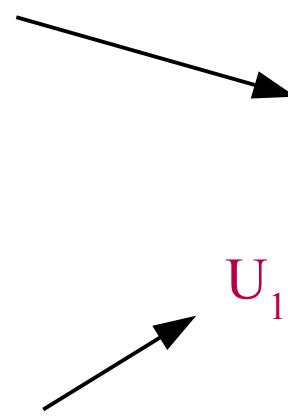
Leptoquarks & 4321

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

► Leptoquarks & 4321

Theory arguments
[flavor hierarchies,
charge quantization]

B-physics anomalies
[mainly CC]



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

minimal choice
[last step of the SSB chain]

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

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

► Leptoquarks & 4321

Theory arguments
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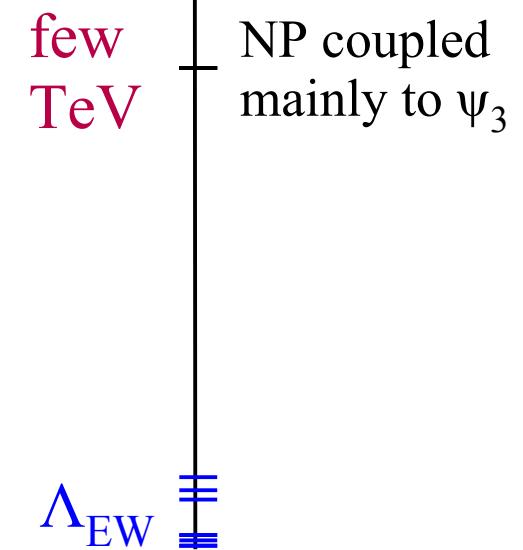
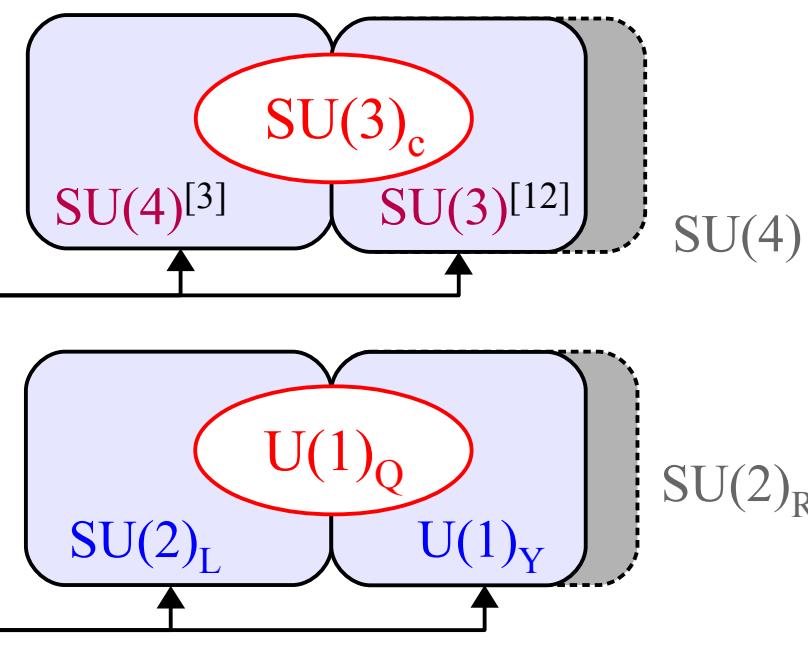
*non universality in
flavor*

chirality

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

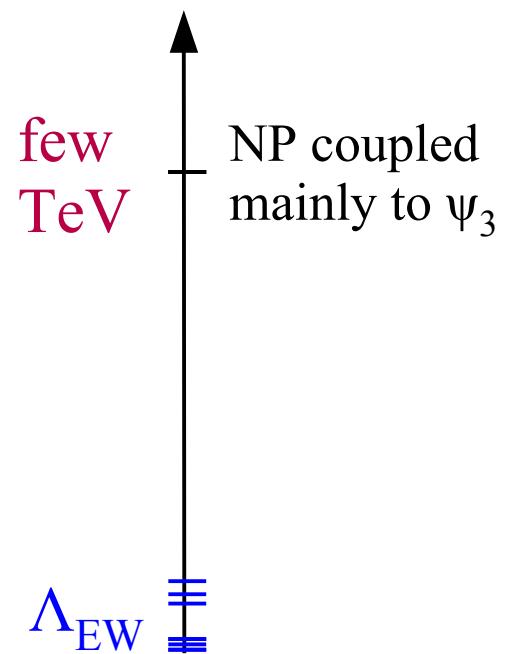
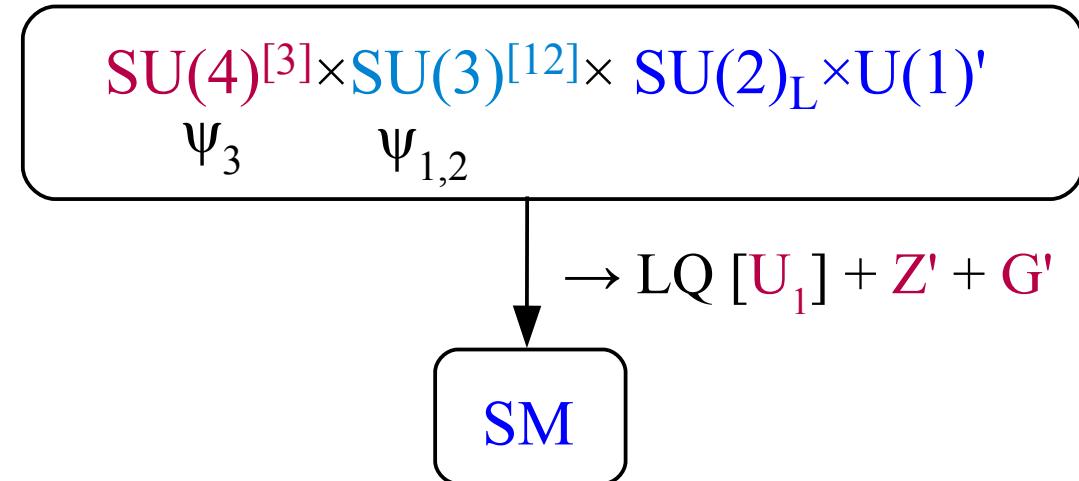
minimal choice
[last step of the SSB chain]

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



► Leptoquarks & 4321

Even in more ambitious UV models,
collider and low-energy pheno are
controlled by the 4321 gauge group
that rules TeV-scale dynamics
→ new heavy mediators [G' & Z']



► Leptoquarks & 4321

Even in more ambitious UV models, collider and low-energy pheno are controlled by the 4321 gauge group that rules TeV-scale dynamics
 → new heavy mediators [G' & Z']

A key role is played by at least one family of
 → vector-like fermions (= fermions with both chiralities having same gauge quantum numbers) that mix with the 3 families of chiral fermions

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

$$\Psi_3 \quad \Psi_{1,2}$$

$$\rightarrow \text{LQ } [\text{U}_1] + \text{Z}' + \text{G}'$$

SM

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

$$\begin{array}{c} \text{---} \\ \text{---} \end{array} \quad \Psi_{1L}$$

$$\begin{array}{c} \text{---} \\ \text{---} \end{array} \quad \Psi_{2L}$$

$$\begin{array}{l} \text{SM} \\ \text{Yukawa} \\ \text{coupling} \end{array} \rightarrow Y \sim \left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right)$$

$$\begin{array}{l} \text{LQ eff.} \\ \text{coupling} \end{array} \rightarrow \beta_L \sim \left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right)$$

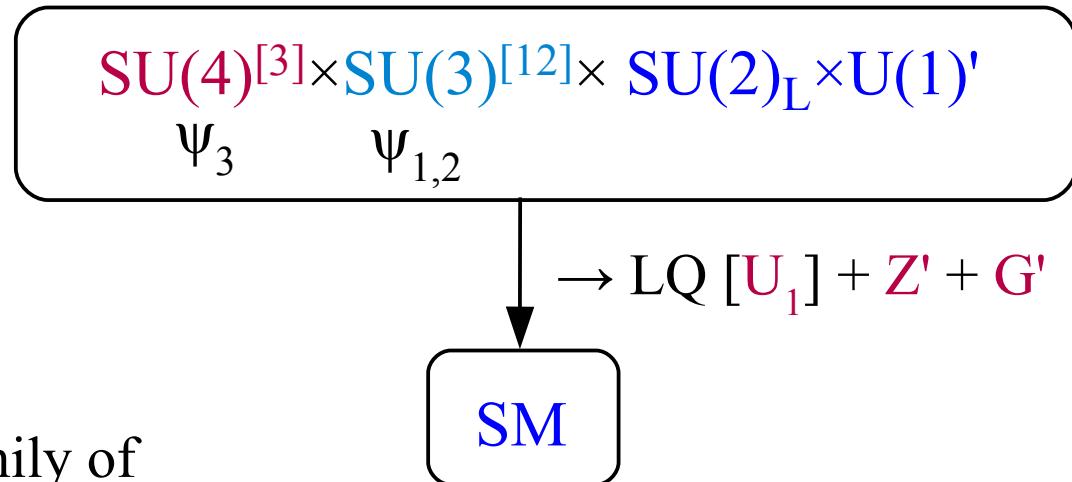
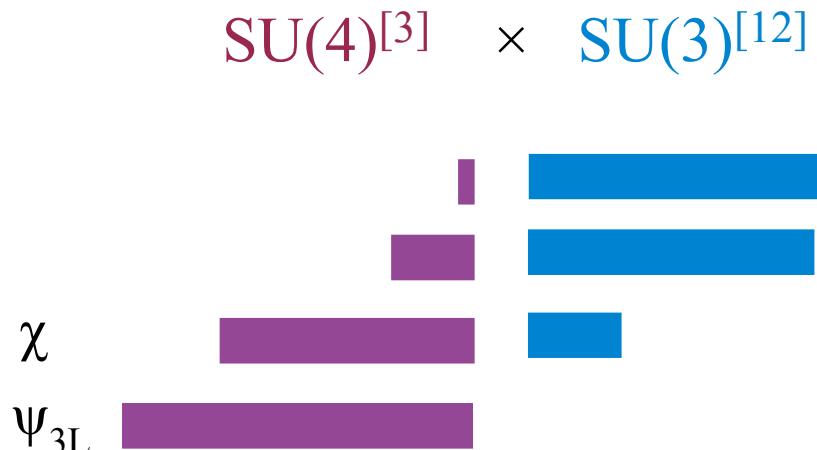
$$\begin{array}{c} \chi \quad \text{---} \\ \Psi_{3L} \quad \text{---} \end{array} \quad (\text{VL fermions})$$

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha) \right] + \text{h.c.}$$

► Leptoquarks & 4321

Even in more ambitious UV models, collider and low-energy pheno are controlled by the 4321 gauge group that rules TeV-scale dynamics
 → new heavy mediators [G' & Z']

A key role is played by at least one family of
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$$Y \sim \begin{pmatrix} & & \\ & & \\ & & \\ & & \end{pmatrix}$$

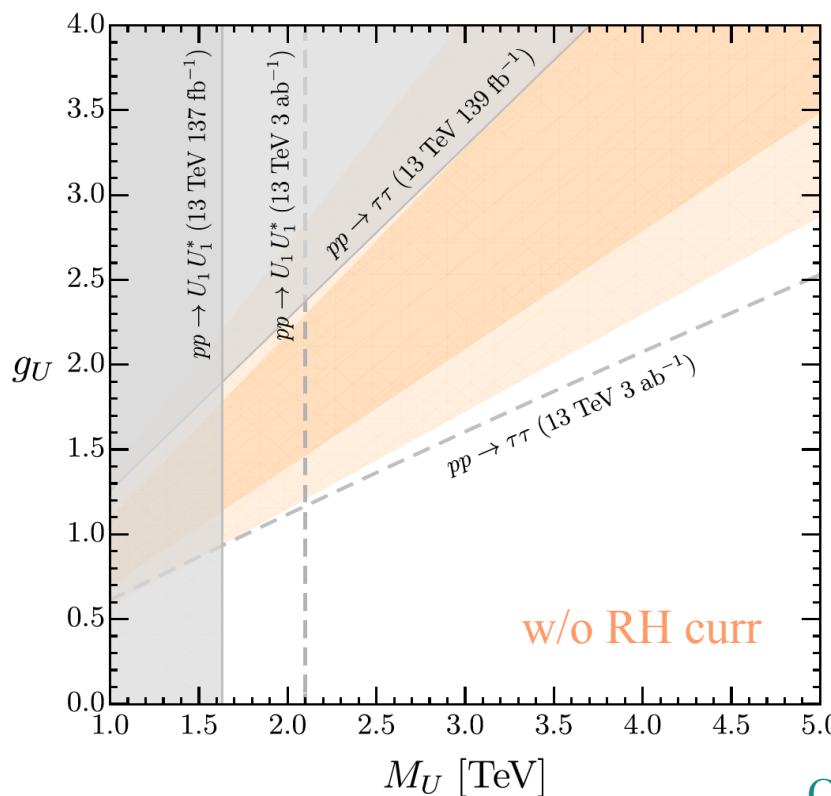
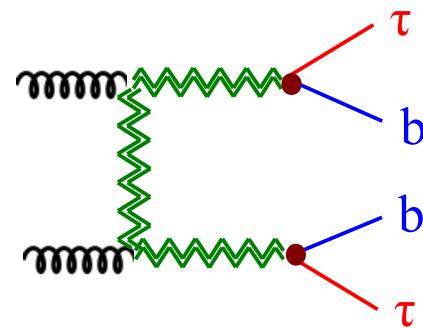
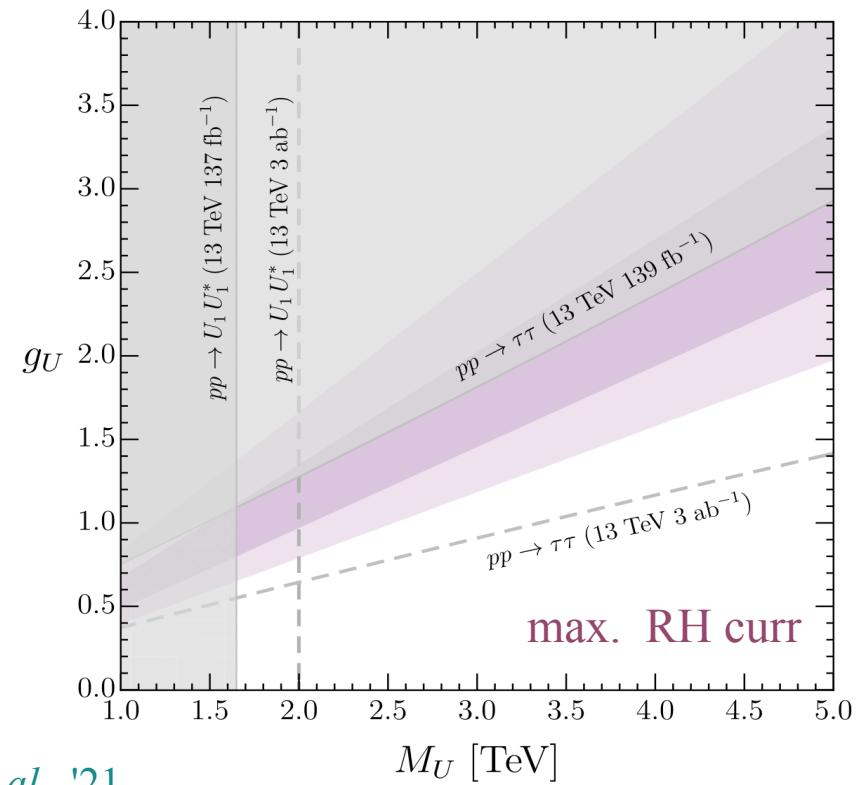
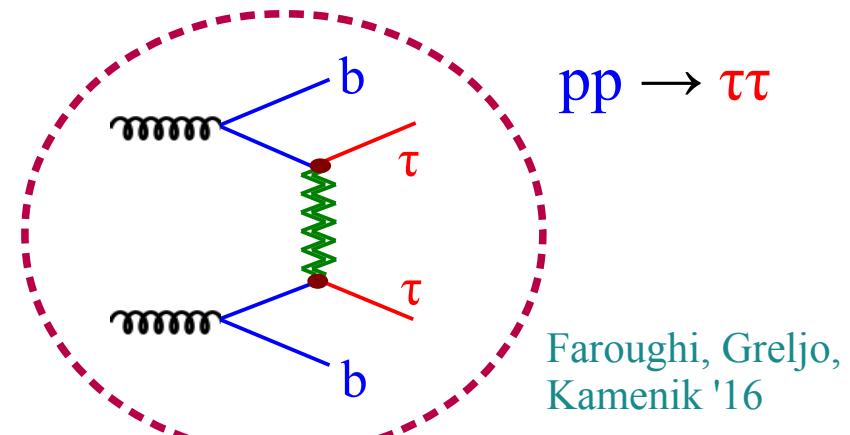
Mass-mixing
after 4321
breaking

$$\beta_L \sim \begin{pmatrix} & & \\ & & \\ & & \\ & & \end{pmatrix}$$

$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha) \right] + \text{h.c.}$

► Leptoquarks & 4321: implications

I The U_1 leptoquark at high energies:

Cornella *et al.* '21

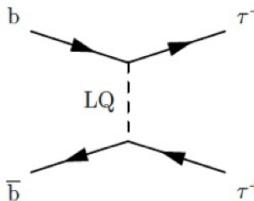
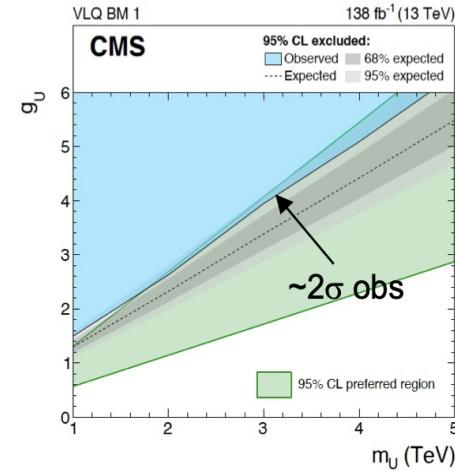
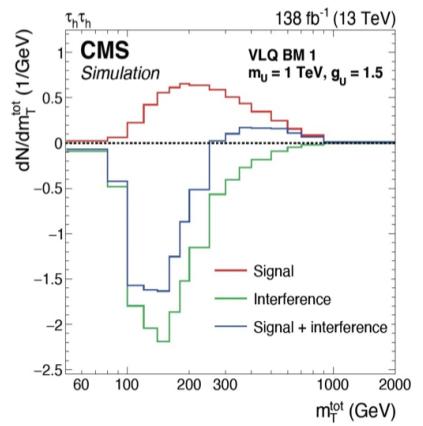
► Leptoquarks & 4321: implications

Aurelio Juste [Moriond EW '23]



LQ-b- τ : Comparison of recent results

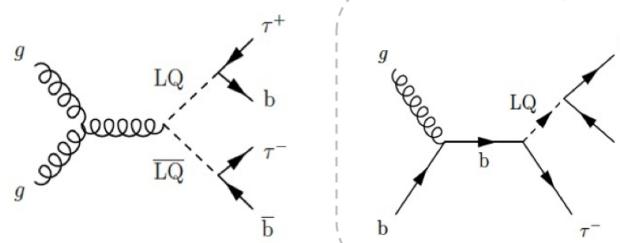
Including interference w/ SM bkg

[CMS-HIG-21-001](#)

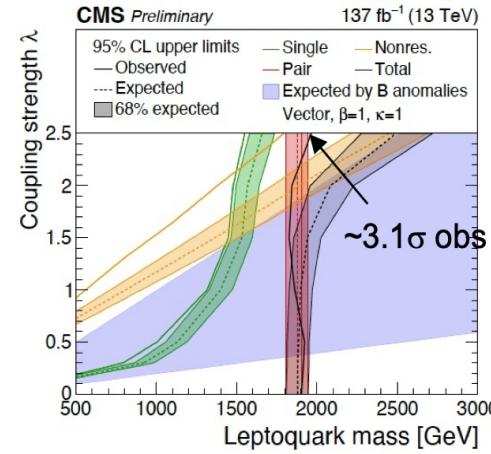
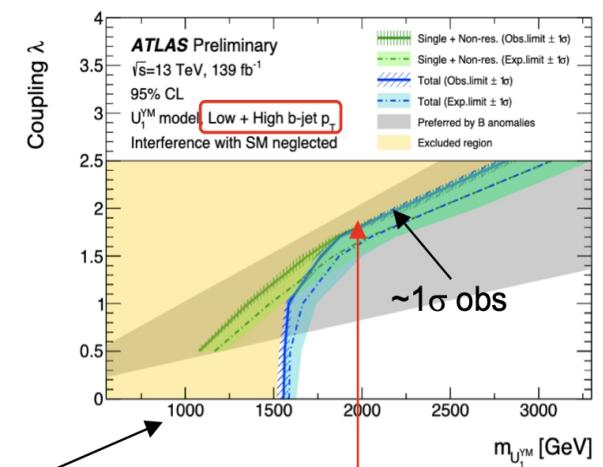
Shown at Moriond EW 2022

Need to clarify interference issue for future interpretations

Neglecting interference w/ SM bkg



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

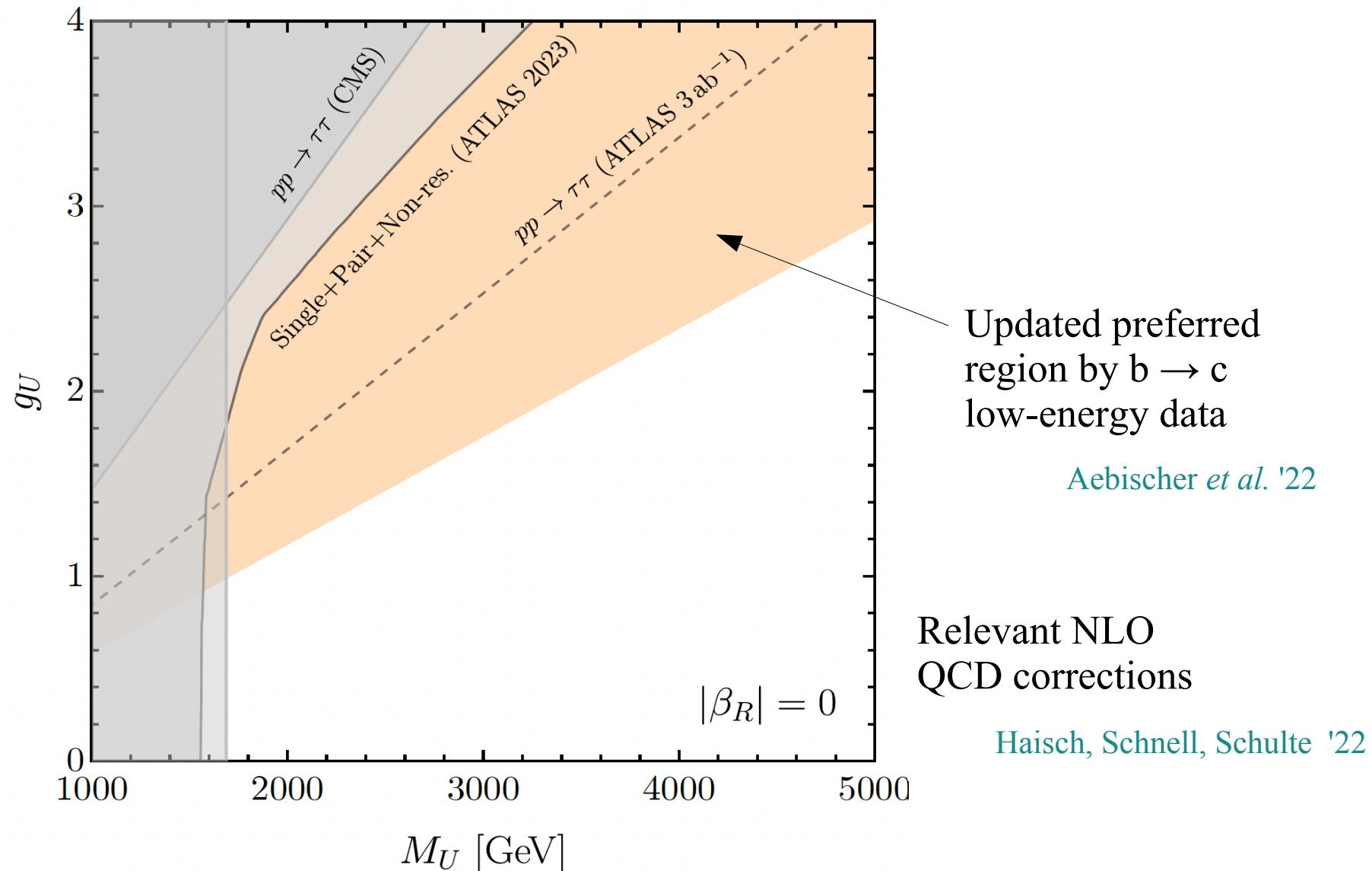
[CMS-PAS-EXO-19-016](#)[EXOT-2022-39](#)

Excludes
CMS' excess

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

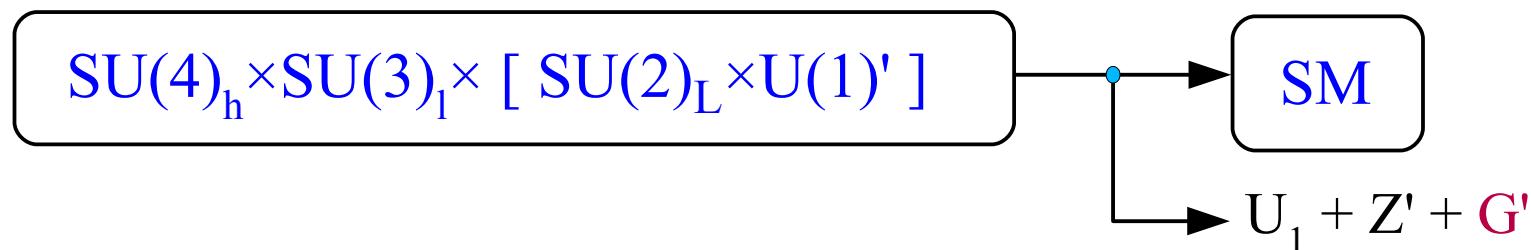
► Leptoquarks & 4321: implications

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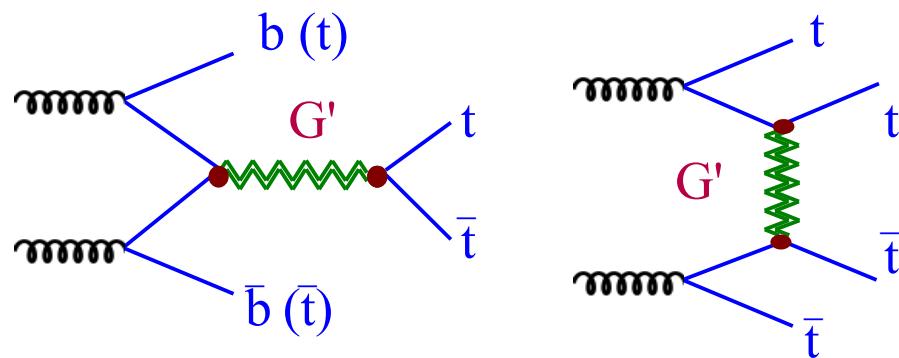


► Leptoquarks & 4321: implications

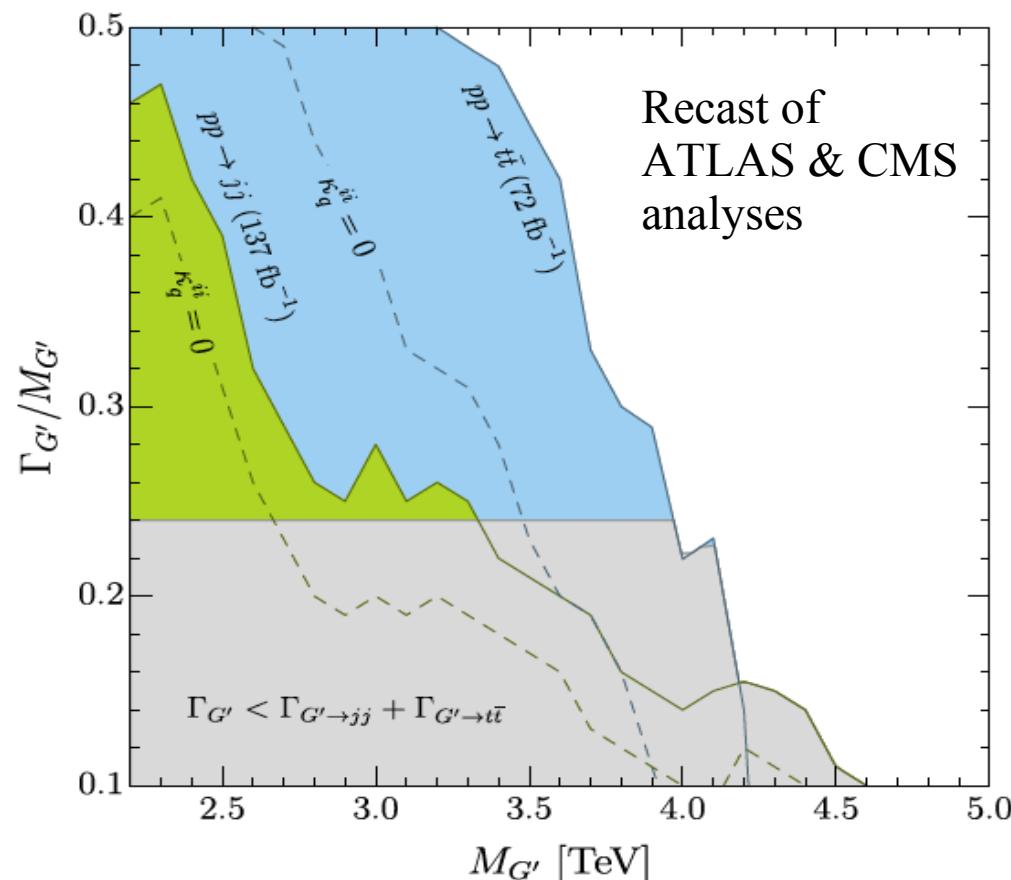
II The other heavy vectors of 4321 (*more model dependent*)



New striking collider signature:
 G' (“coloron”) = heavy color octet,
coupled mainly to 3rd generation quarks



→ strongest constraint on the scale
of the model from $pp \rightarrow \bar{t}t$



► Leptoquarks & 4321: implications

III The vector-like fermions

On general grounds, the vector-like fermions are expected to be lighter than the heavy gauge bosons:

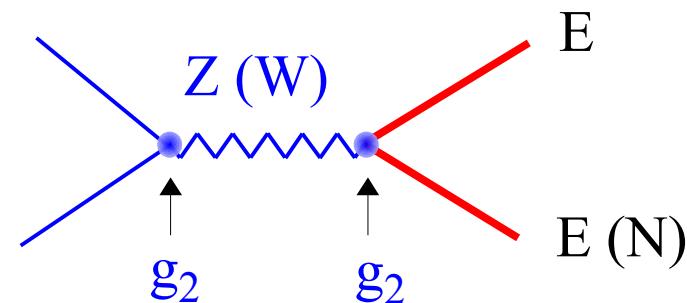
$$M_\chi \lesssim 2 \text{ TeV} \quad M_{U,G',Z'} \sim 2 - 5 \text{ TeV}$$

The lightest vector-like (VL) fermions are the **VL leptons** for which a clear upper bound follows from B_s mixing & R_D :



Di Luzio *et al.* '18

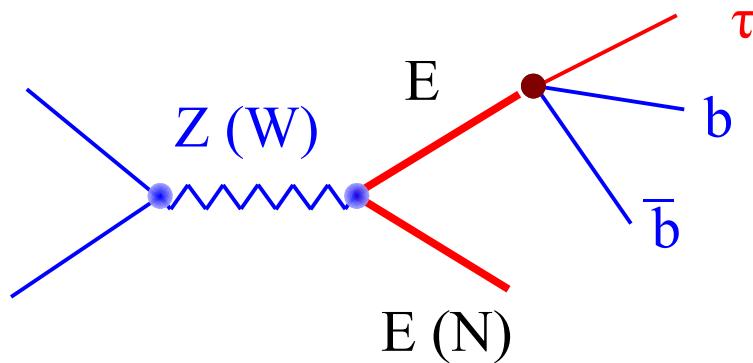
Model-independent production channel:



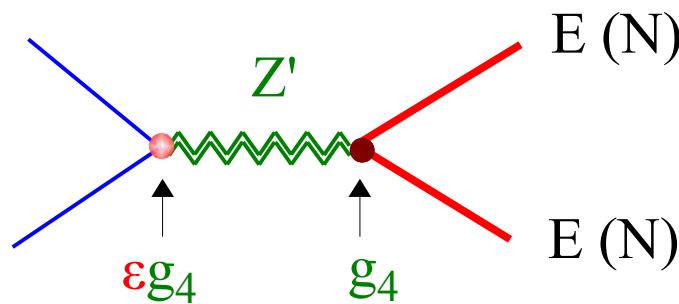
$$\chi_\tau = \begin{bmatrix} N_{L,R} \\ E_{L,R} \end{bmatrix} \quad \begin{array}{l} \text{heavy neutrino} \\ \text{heavy charged lepton} \end{array}$$

► Leptoquarks & 4321: implications

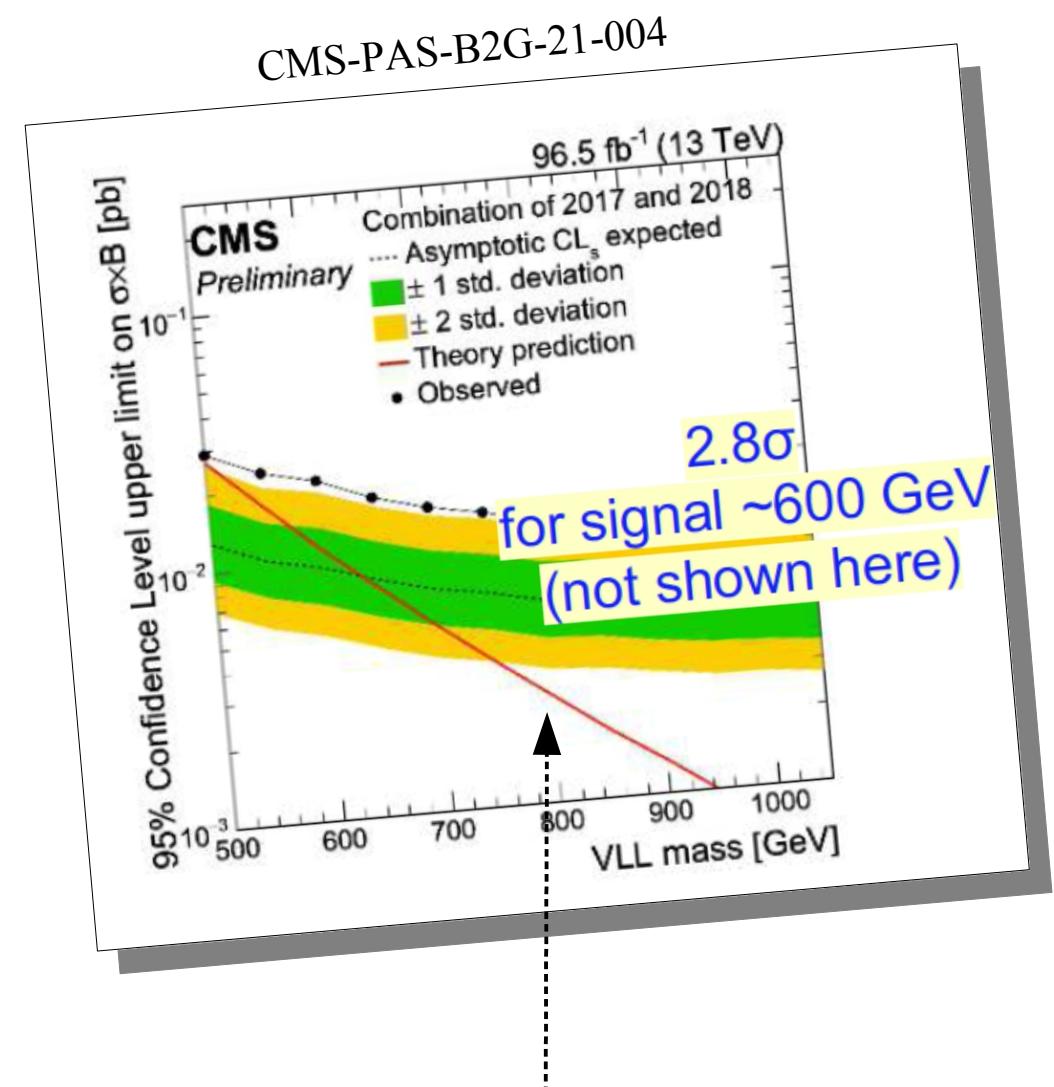
III The vector-like fermions



Additional production via heavy Z' exchange (model-dependent):



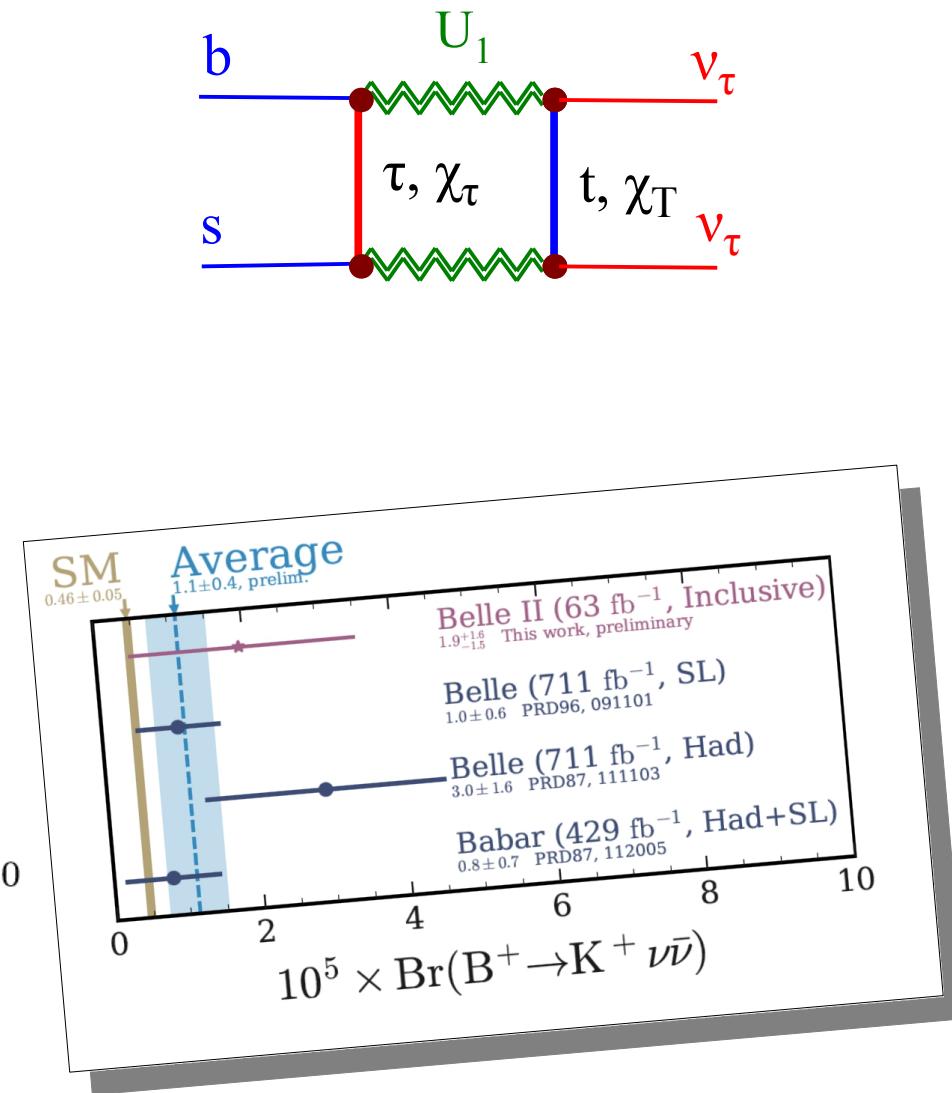
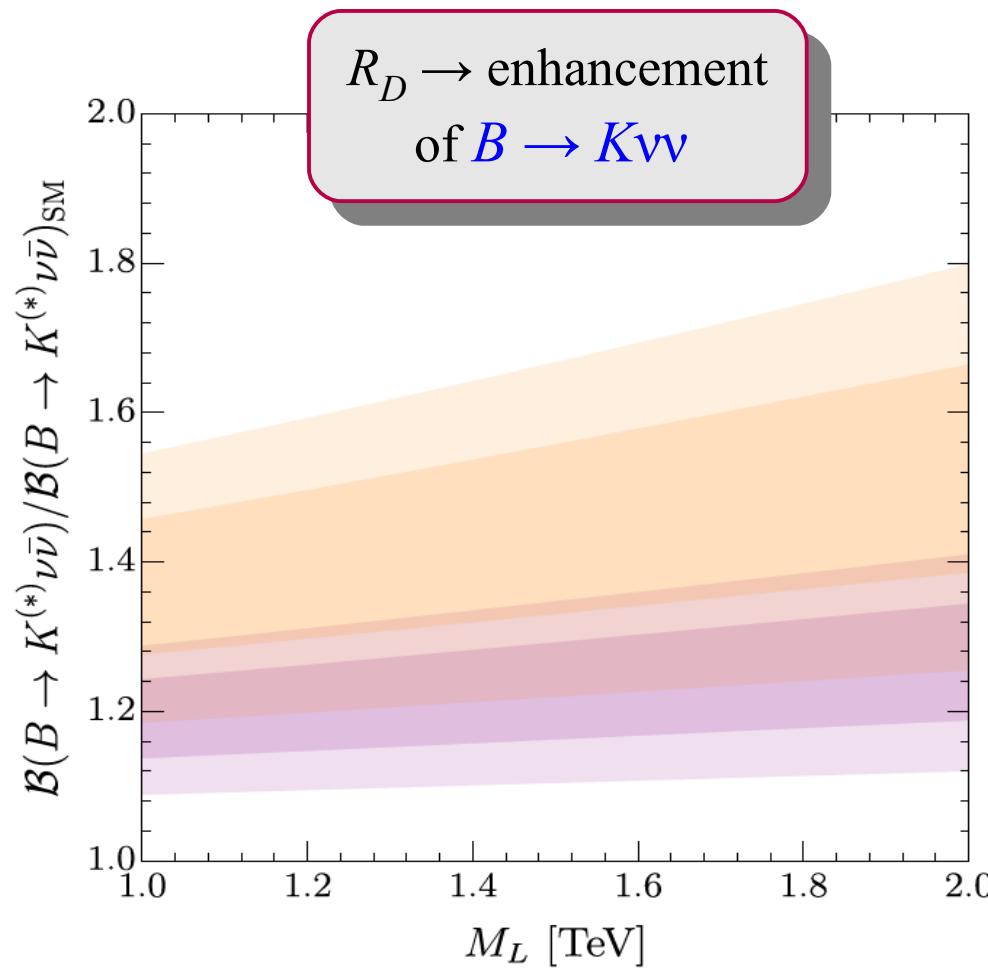
$$\varepsilon = (g_2/g_4)^2 \sim 10\%$$



N.B.: the two amplitudes interfere (for same initial & final state) possibly giving rise to sizable enhancements

► Leptoquarks & 4321: implications

III The vector-like fermions in low-energy observables



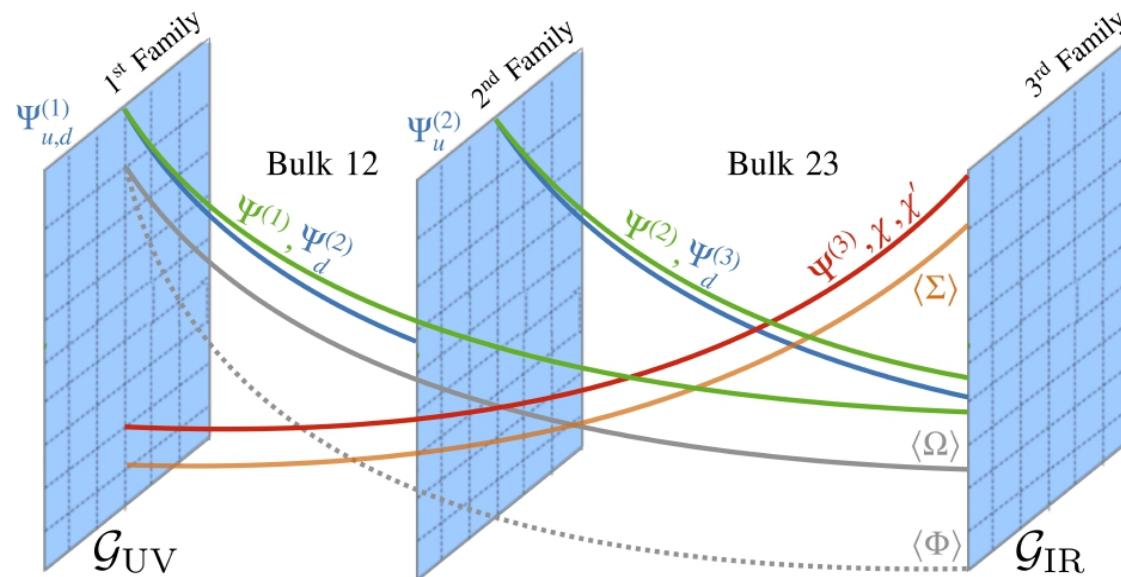
Conclusions

- 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 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 run-3...).



► Leptoquarks & 4321: UV completions

An ambitious attempt to construct a *full theory of flavor* has been obtained embedding (a variation of the) Pati-Salam gauge group into an extra-dimensional construction:



Flavor \leftrightarrow special position
(topological defect) in an extra
(compact) space-like dimension

Dvali & Shifman, '00

Higgs and SU(4)-breaking fields
with oppositely-peaked profiles,
leading to the desired flavor
pattern for masses & anomalies

Bordone, Cornella, GI, Javier-Fuentes '17

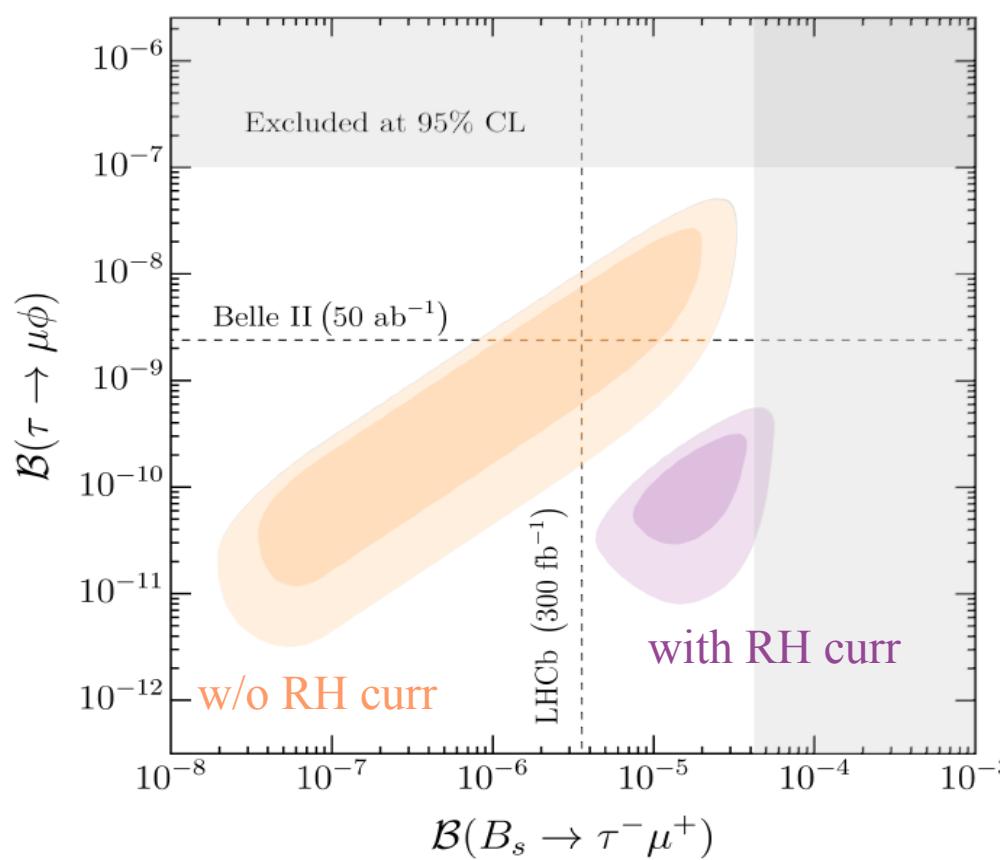
- ★ Anarchic neutrino masses via inverse see-saw mechanism Fuentes-Martin, GI, Pages, Stefanek '22
- ★ “Holographic” Higgs from appropriate choice of bulk/brane gauge symm.
[$G_{\text{bulk-23}} = \text{SU}(4)_3 \times \text{SU}(3)_{1,2} \times \text{U}(1) \times \text{SO}(5)$ $G_{\text{IR}} = \text{SU}(3)_c \times \text{U}(1)_{\text{B-L}} \times \text{SO}(4)$]
- Light Higgs as pseudo Goldstone Fuentes-Martin, Stangl '20
Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

Agashe, Contino, Pomarol '05

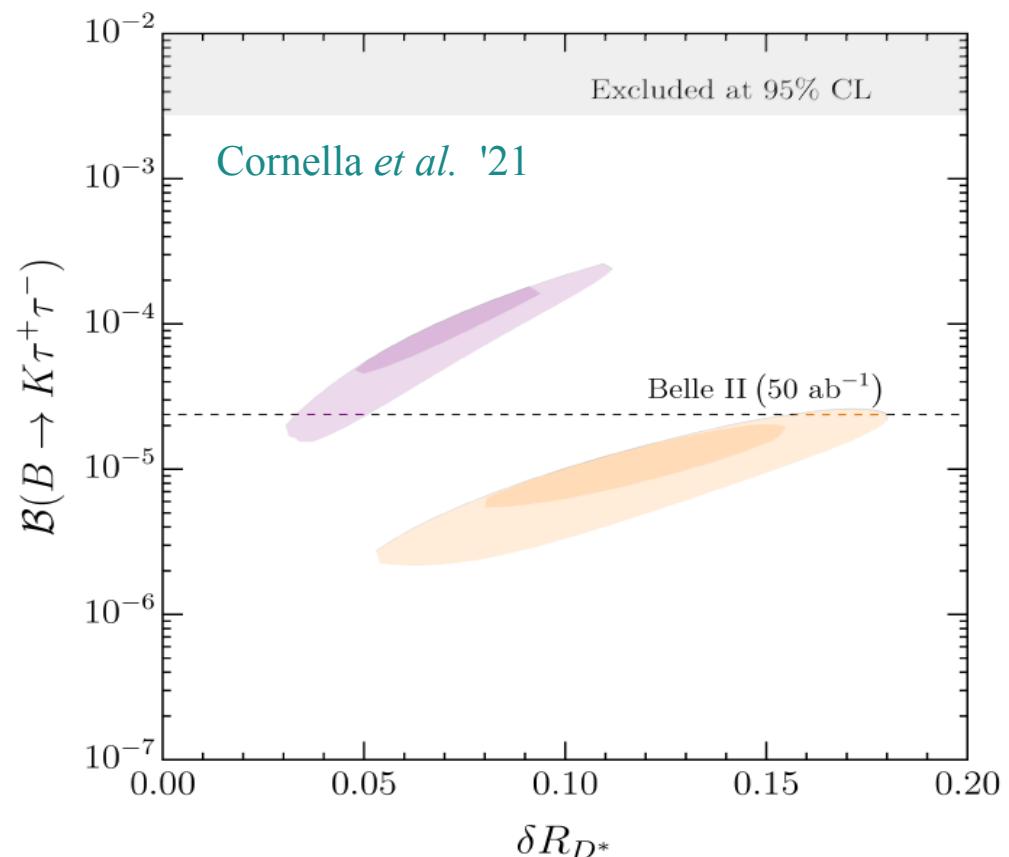
► Leptoquarks & 4321: implications

IV Rare decays of **b** and τ

$\tau \rightarrow \mu$ LFV
(in B and tau decays)

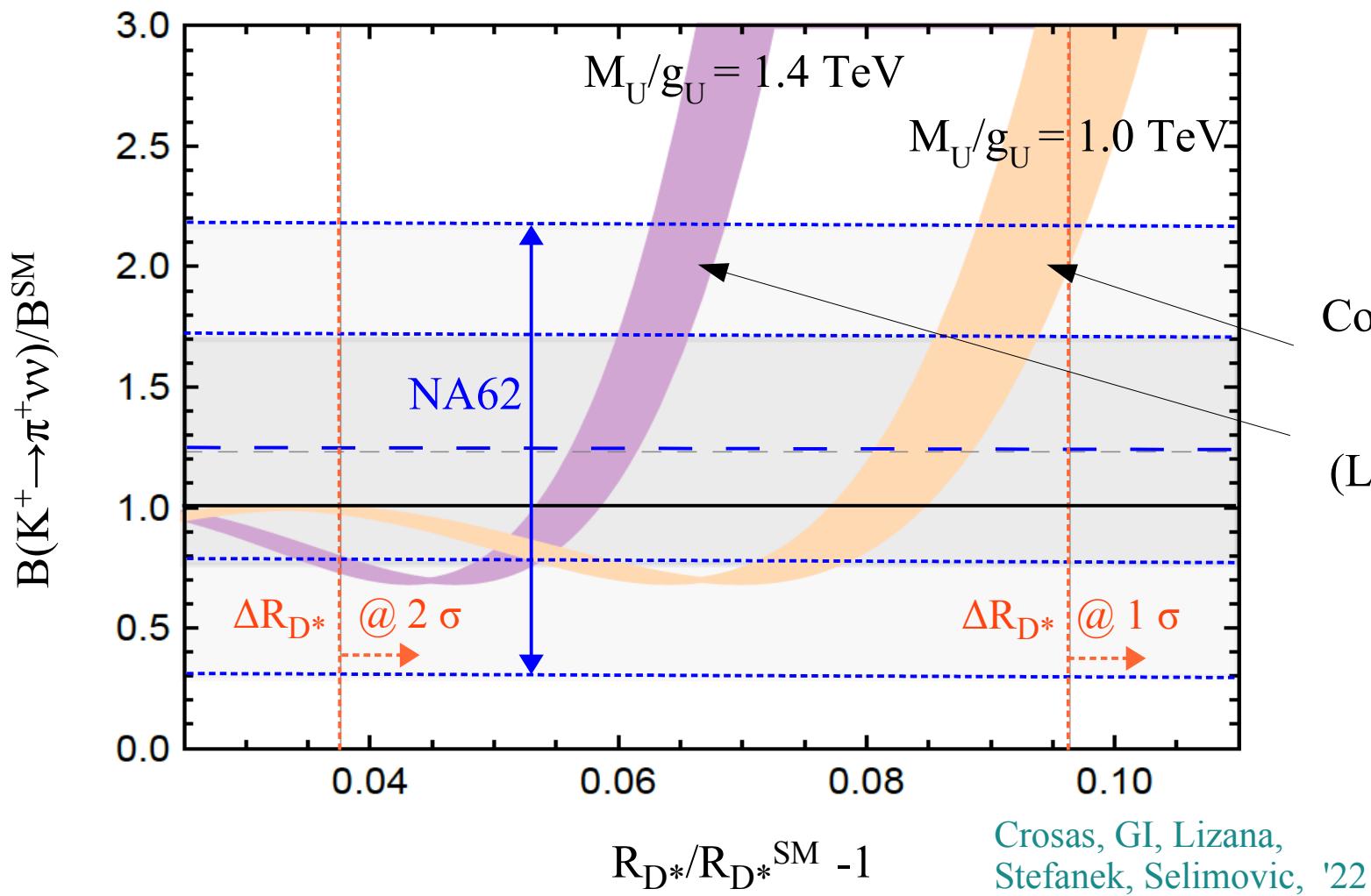


largely enhanced $b \rightarrow s\tau\tau$ rates
(in all channels)



► Leptoquarks & 4321: implications

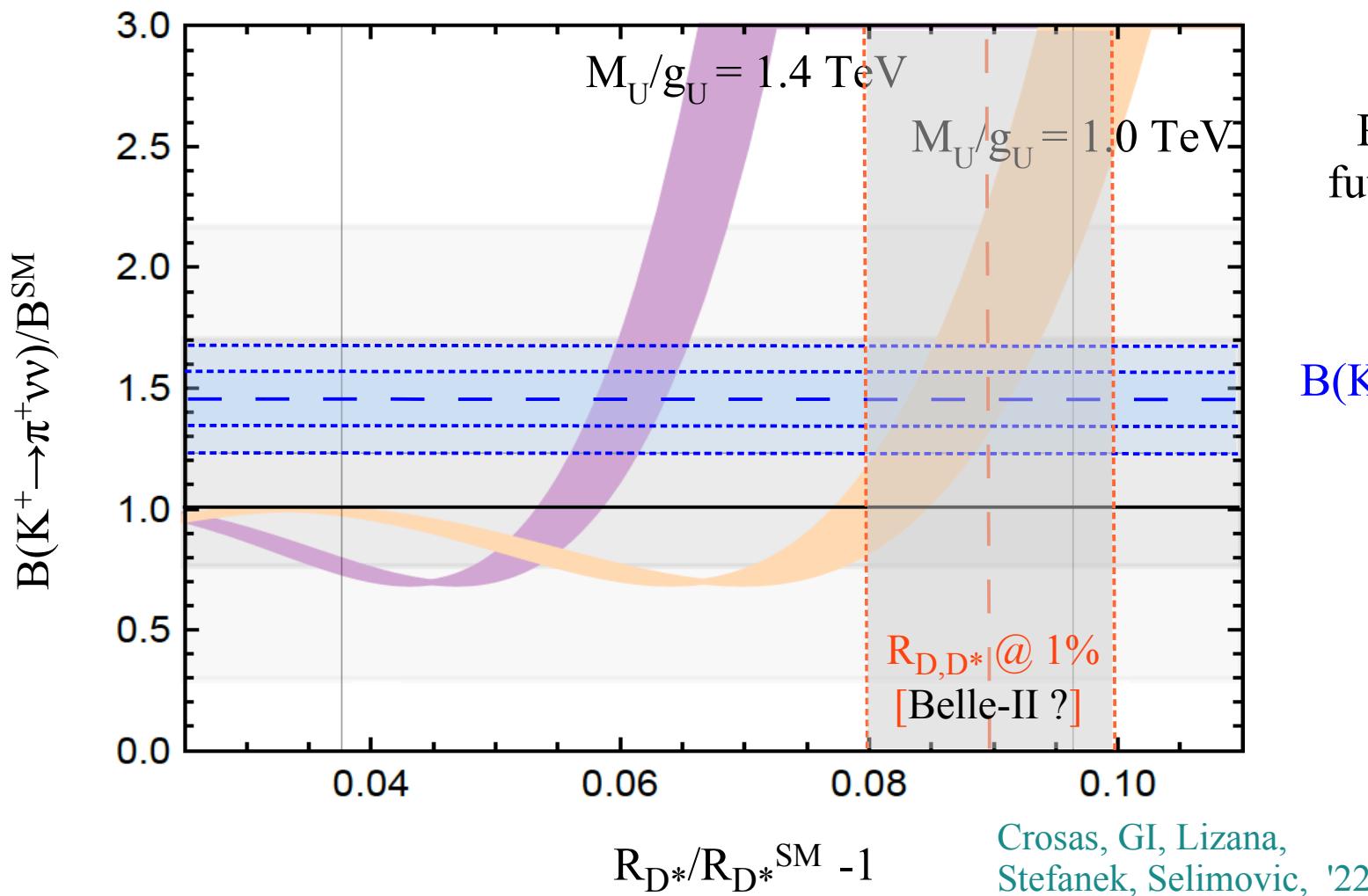
V Last but not least: Kaon Physics



Correlations depending
on high-energy
parameters
(LQ mass & coupling)

► Leptoquarks & 4321: implications

V Last but not least: Kaon Physics



Possible impact of future measurements:

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})/B^{\text{SM}} @ 8\%$
[CERN ?]

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