Physics Landscape with Focus on Flavor

Gino Isidori
[*University of Zürich*]

I
- Introduction
- The flavor problem

II
- On the recent "anomalies" in B-physics
  - What have we learned (*3 general lessons*) ?
  - An explicit model to address the anomalies
  - What more do we hope to learn ?
- Conclusions

University of Zurich[UZH]

European Research Council
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Introduction

(*almost...*) all microscopic phenomena we observe in Nature seems to be well described by the SM, a simple and elegant Theory that we continue to call “model” only for historical reasons...

However, despite all its phenomenological successes, the SM has some deep unsolved problems (*hierarchy problem*, *flavor problem*, *neutrino masses, dark-matter, dark energy, inflation…*)

⬇

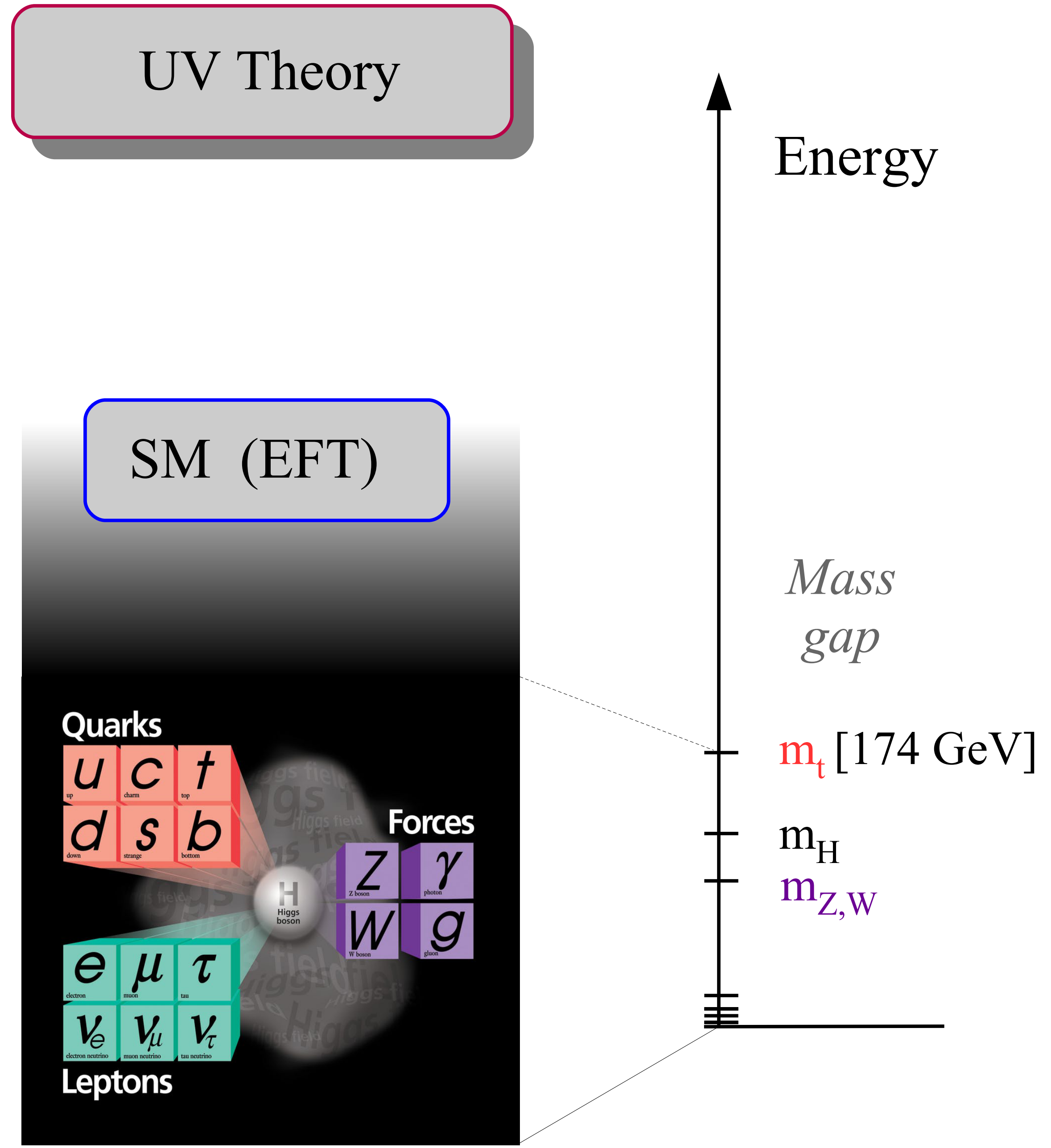
The Standard Model should be regarded as an
Effective Field Theory (*EFT*)

i.e. the limit (*in the range of energies and effective couplings so far probed*)
of a more fundamental theory
with new degrees of freedom

Introduction

What we know after the first phase of the LHC is that:

- The Higgs boson is SM-like and is "light" (*completion of the SM spectrum*)
- There is a mass-gap above the SM spectrum



Introduction

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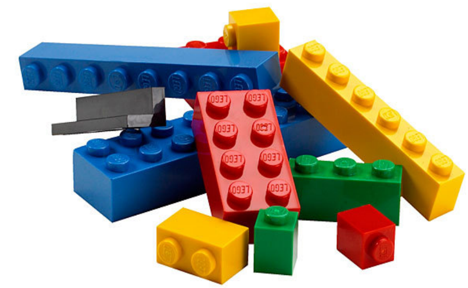
We identified the *"light"* ↔ *"large"* pieces of our *"construction game"* & their long-range interactions →

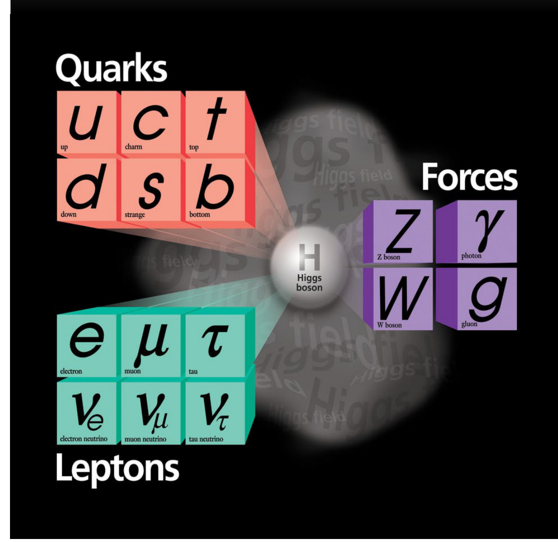
UV Theory

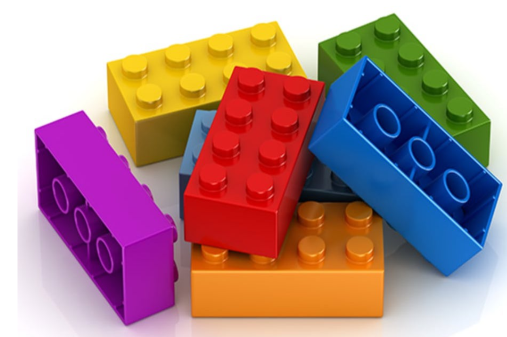
$E \sim L^{-1}$



↑ ?

SM (EFT)





Introduction

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- The Higgs boson is SM-like and is "light" (*completion of the SM spectrum*)
- There is a mass-gap above the SM spectrum

Reconstructing the UV theory from its low-energy limit is a very difficult problem with <u>no unique solution</u>

[*It took more than 35 years to go from the Fermi Theory to the SM…*]

UV Theory

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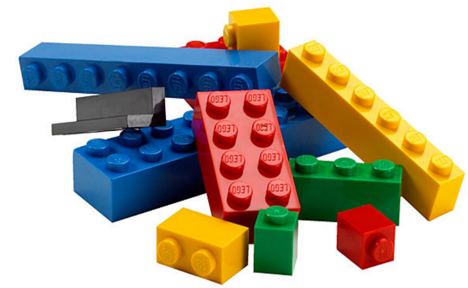

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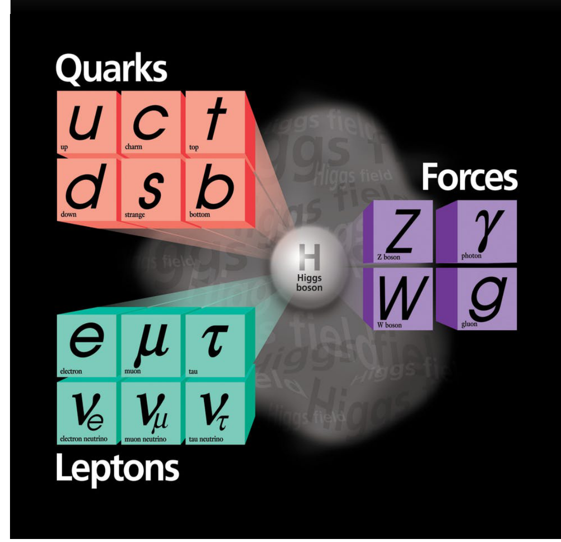

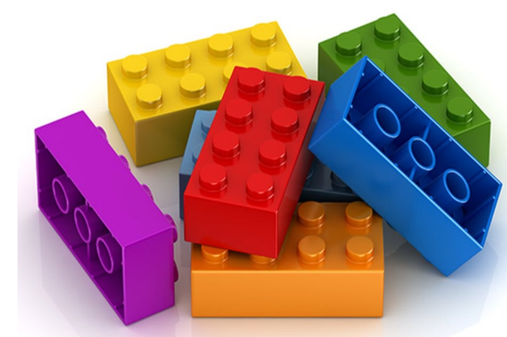

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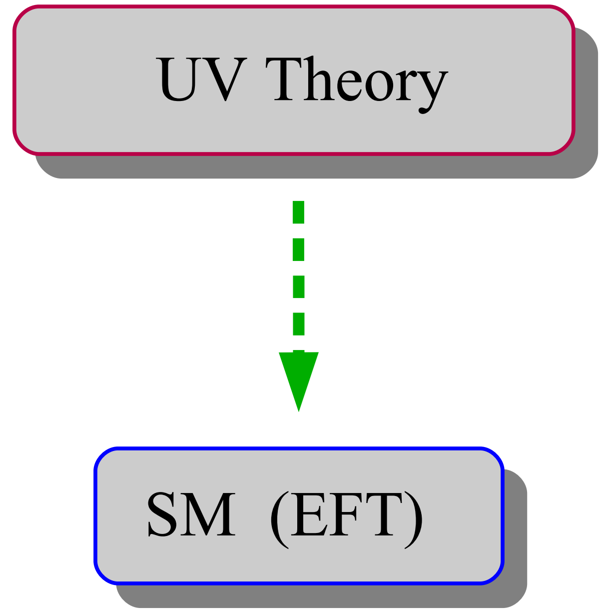
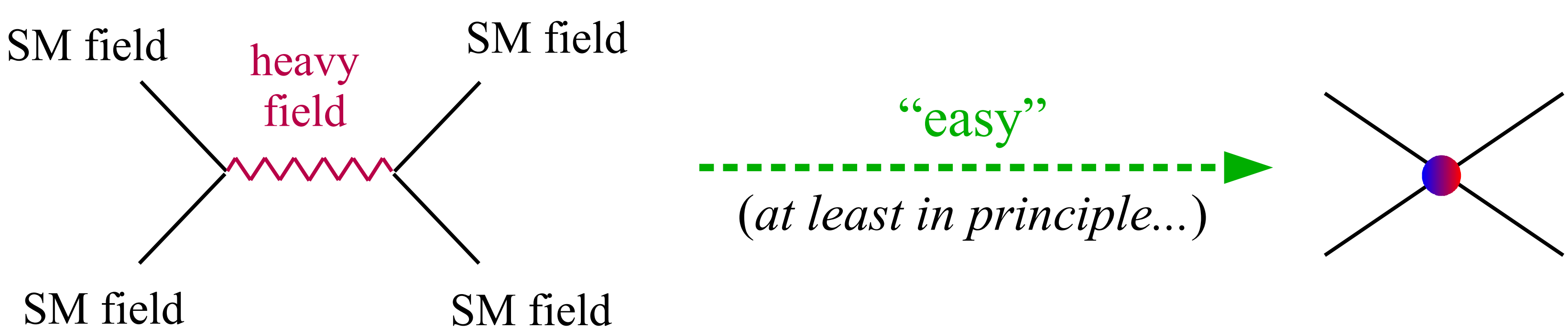


low-energy "projection"

"integrate out" the heavy degrees of freedom



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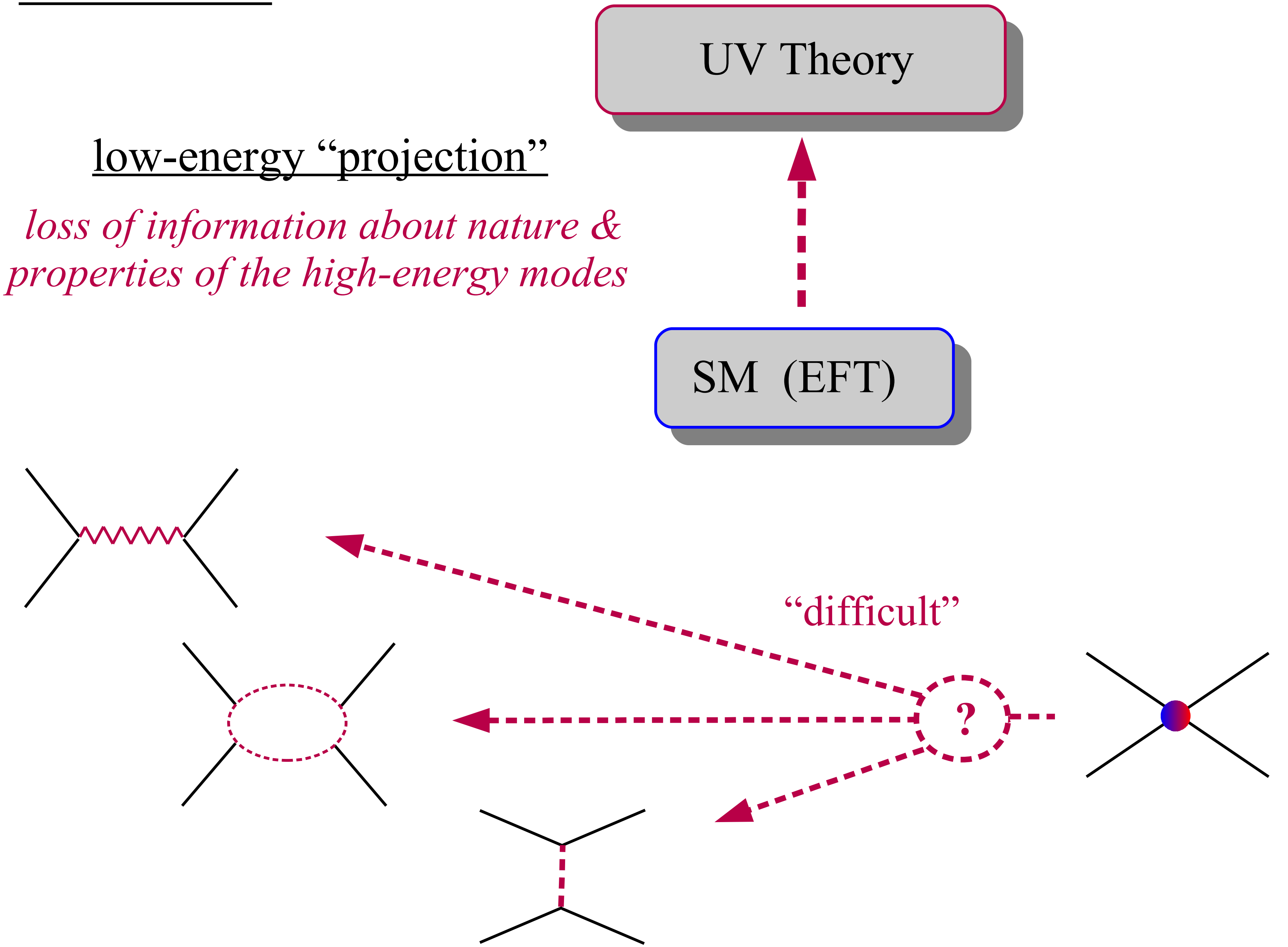
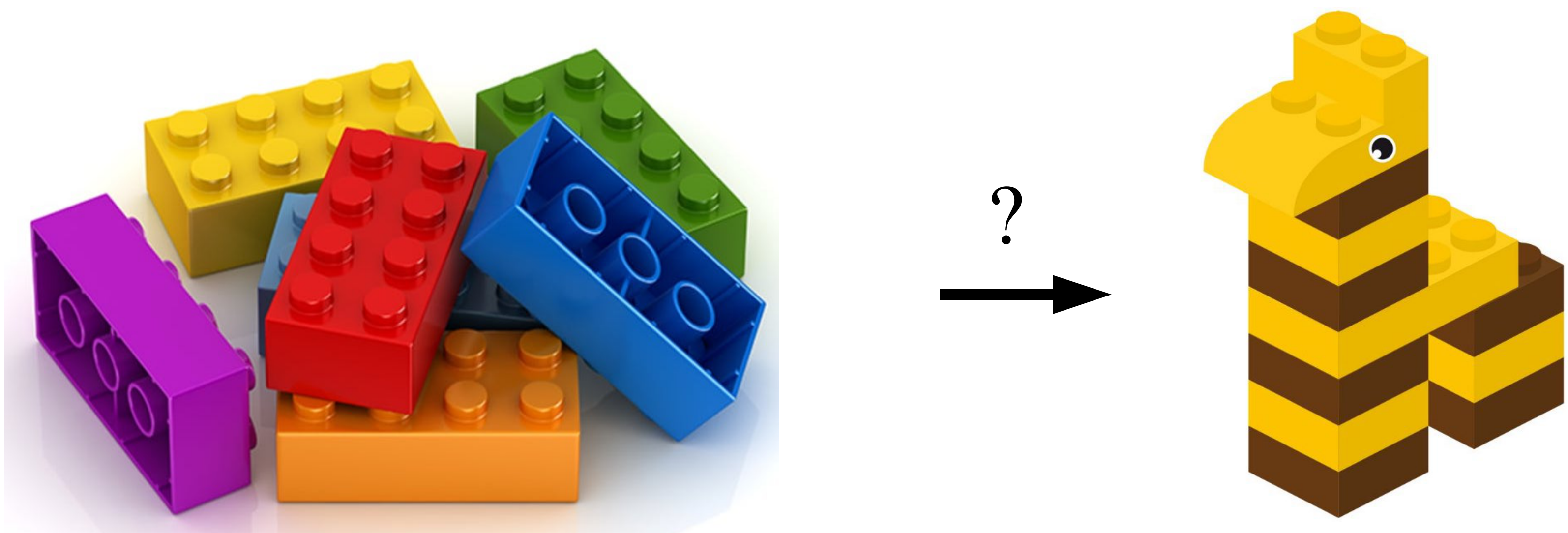


Introduction

The most interesting hints toward UV dynamics come from problems of the SM and, in particular, by the *un-natural features* of the SM-EFT...



Introduction

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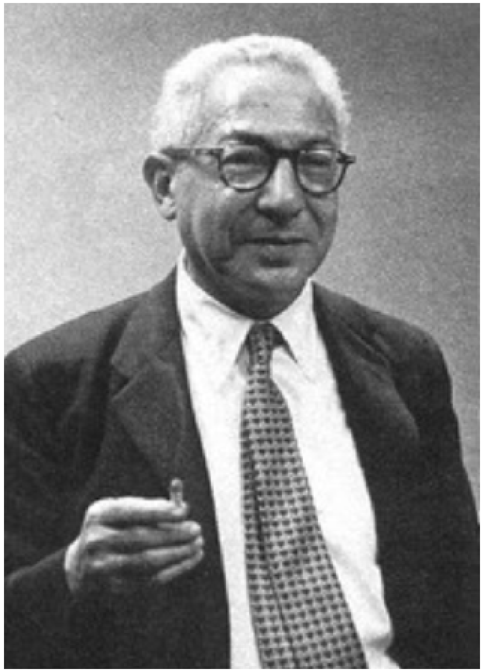
	problem due to...	
I. Electroweak hierarchy problem	*Instability of the Higgs mass under quantum corrections*	Two un-natural (*correlated ?*) features of the SM-EFT
II. Flavor problem(s)	*Un-natural tuning of the couplings to describe fermion masses*	

As I will argue in the rest of this talk, it is worth trying to "attack" these two problems together

- Theoretical motivation already from a closer inspection of the SM-EFT
- Phenomenological motivation from recent data in B physics

The Flavor Problem



Isidor Issac Rabi

(1898—1988)

The Flavor Problem

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

Flavor degeneracy

Within the SM, the flavor-degeneracy is broken only by the Yukawa interaction:

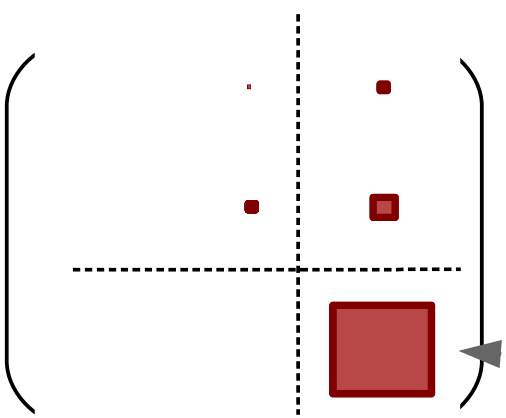
$$y_{ij}\, \psi_i \psi_j\, H \rightarrow m_{ij}\, \psi_i \psi_j$$

The vast majority of SM couplings are the entries of the Yukawa couplings, which span 5 orders of magnitude & do not appear at all accidental:

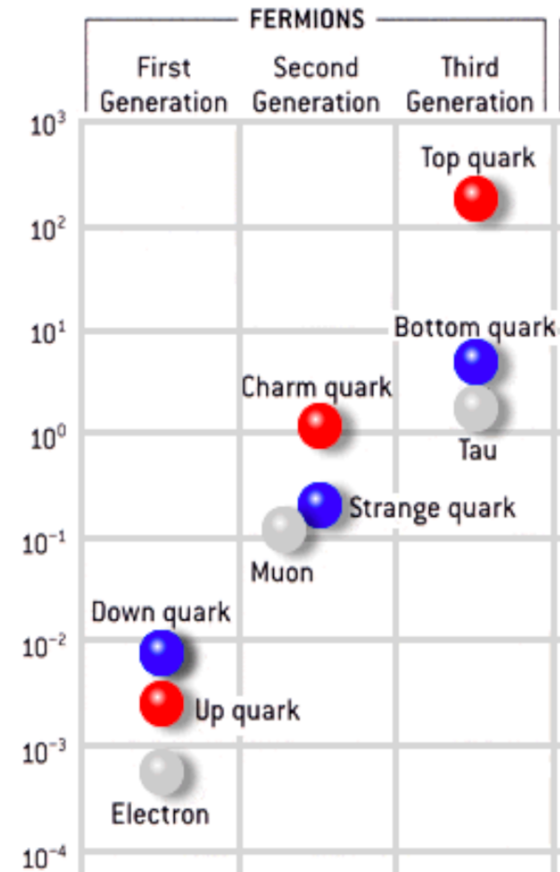
The SM Flavor problem

E.g.:

$Y_U \sim$



$$y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$



The Flavor Problem

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

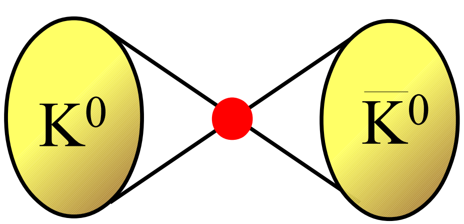
Most general description of the heavy dynamics, as long as we do not have enough energy to directly excite it

In principle, we could expect many other sources of flavor non-degeneracy from the heavy dynamics

However (beside the *anomalies* in B-meson decays → *more later...*), we observe none

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

E.g.:



$$\frac{1}{\Lambda^2}(\bar{\psi}_i \psi_j)^2$$

The Flavor Problem

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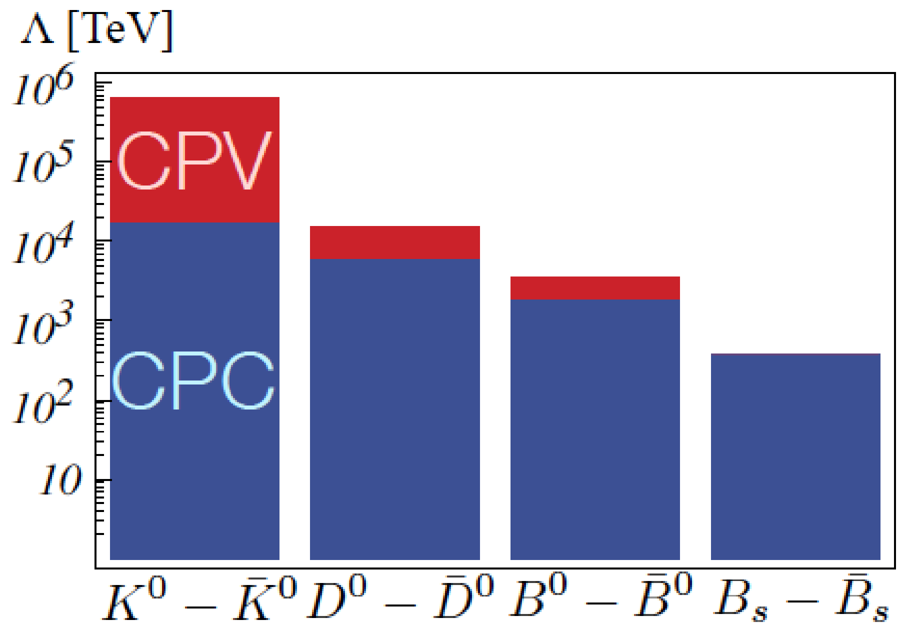


The NP Flavor problem

Strong tension with a natural solution of the EW hierarchy problem

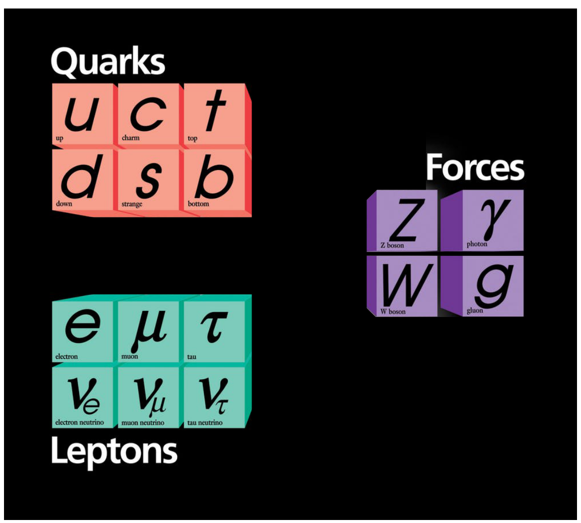
The Flavor Problem

Summarizing….

Non-trivial UV imprints

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

"trivial" low-energy projection



UV Theory

↓

SM (EFT)

Structure fully dictated by

- Number of light fields
- Their charges under long-range interactions

The Flavor Problem

Summarizing....

Non-trivial UV imprints

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq5}$$

I $m_\phi^2 H^2$

III $y_{ij} \psi_i \psi_j H$

II $\Lambda_{EW} >$ (few) TeV

IV $\Lambda_{Flavor} > 10^2 - 10^5$ TeV

- Hierarchy problem (I. vs. II): Why m_ϕ (125 GeV) $\ll \Lambda_{EW}$?
- SM Flavor problem (III): Why y_e ($\sim 10^{-5}$) $\ll y_t$ (~ 1) ?
- NP Flavor problem (I. vs. IV): Why m_ϕ (125 GeV) $\ll \Lambda_{Flavor}$?

The Flavor Problem

Non-trivial UV imprints

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

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IV Λ_{Flavor} > 10^2-10^5 TeV

These problems have been with us since a long time... and we tried to solve them in different ways:

The Minimal Flavor Violation "solution" (popular in the *pre-LHC era*):

- New physics is flavor blind + the (genuine) hierarchy problem is not too severe → expect NP around the TeV scale

Try to separate the two problems & postpone the Flavor one

The Flavor Problem

Non-trivial UV imprints

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The Minimal Flavor Violation "solution" (~~popular~~ *un-popular* in the ~~*pre*~~ *post*-*LHC era*):

- Expect NP around the TeV scale: *No signals of NP up to rather high energy scales, especially if NP is coupled universally....*

The anthropic/landscape idea (popular in the *post LHC run-I era*):

- The genuine hierarchy problem is already too severe → accept fine-tuning & give up on solving both problems (at least at the EFT level)

I don't like it !

The Flavor Problem

Non-trivial UV imprints

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

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These problems have been with us since a long time... and we tried to solve them in different ways:

The path of flavor non-universal interactions (not so popular *yet*...):

- The hierarchical structure of the SM Yukawa coupl. is a clear indication that all the new degrees of freedom are coupled in a non-universal way to SM fermion families → expect TeV scale NP coupled mainly to 3rd gen.
- Genuine hierarchy problem less severe for NP coupled mainly to 3rd gen.

We should not give up & should not try to separate the two problems

The Flavor Problem

Non-trivial UV imprints

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

I $m_\phi^2 H^2$ III $y_{ij}\, \psi_i \psi_j H$

Λ_{EW} > (few) TeV

Λ_{LFU} ~ few TeV

Λ_{Flavor} > 10^2-10^5 TeV

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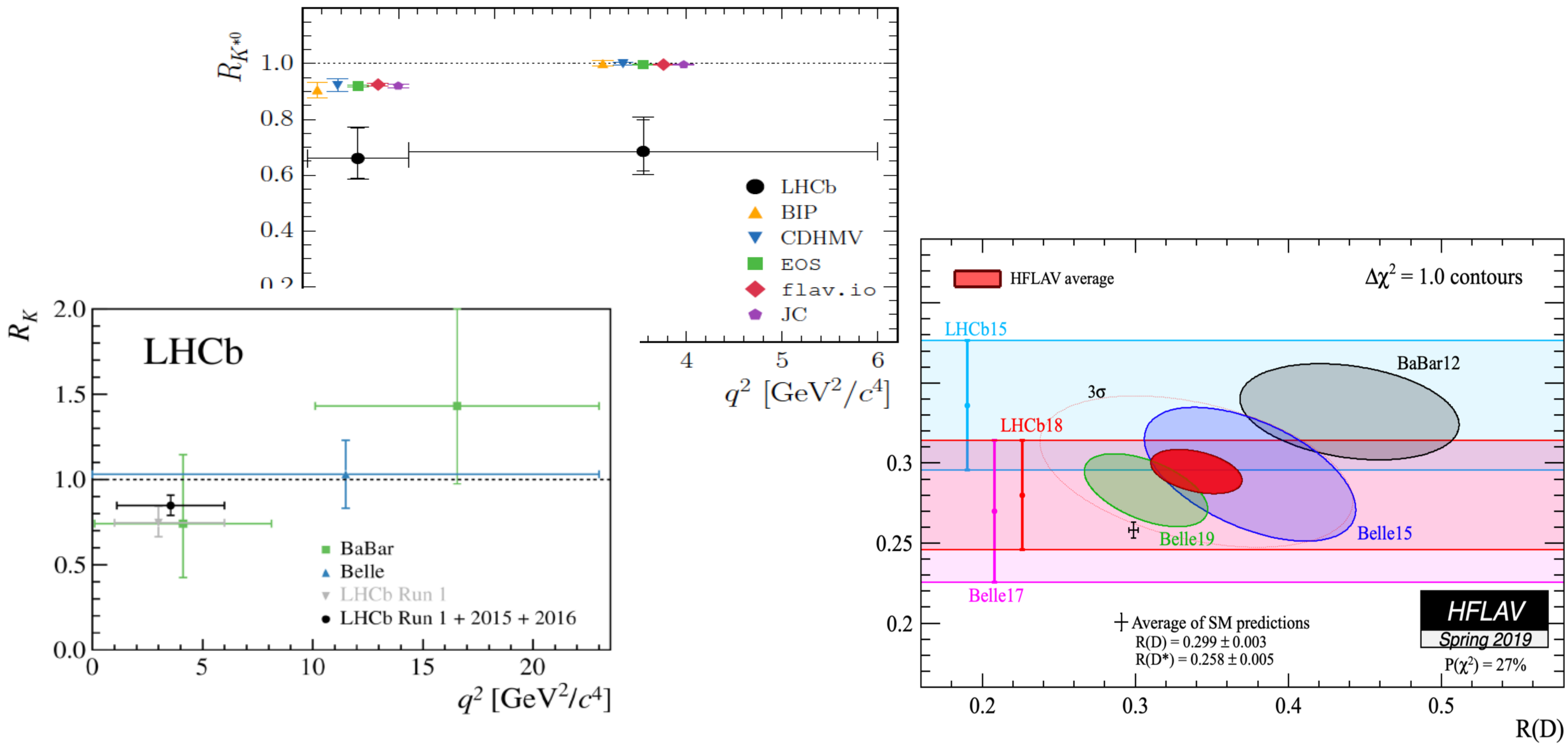
This is the path that seems to be indicated by the recent hints of Lepton Flavor non Universality in semi-leptonic B decays

On the recent LFU anomalies in B decays



On the recent LFU anomalies in B decays

Recent data show some convincing evidences of Lepton Flavor Universality violations in semi-leptonic decays of the b quark.

More precisely, we seem to observe a different behavior (*beside pure kinematical effects*) of different lepton species in the following processes:

- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)
- $b \to s\, l^+l^-$ (neutral currents): μ vs. e

IF taken together... this is probably the largest "coherent" set of deviations from the SM we have ever seen...

→ Hope some more news in the next days !!!

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- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)
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What is particularly interesting, is that these anomalies are challenging an assumption (LFU), that we gave for granted for many years (*without many good theoretical reasons...*)

Three main messages for BSM physics

(*that remains valid/interesting even if (some of) the anomalies will go away*)

↓

Flavor-non-universal interactions

The role of flavor symmetries

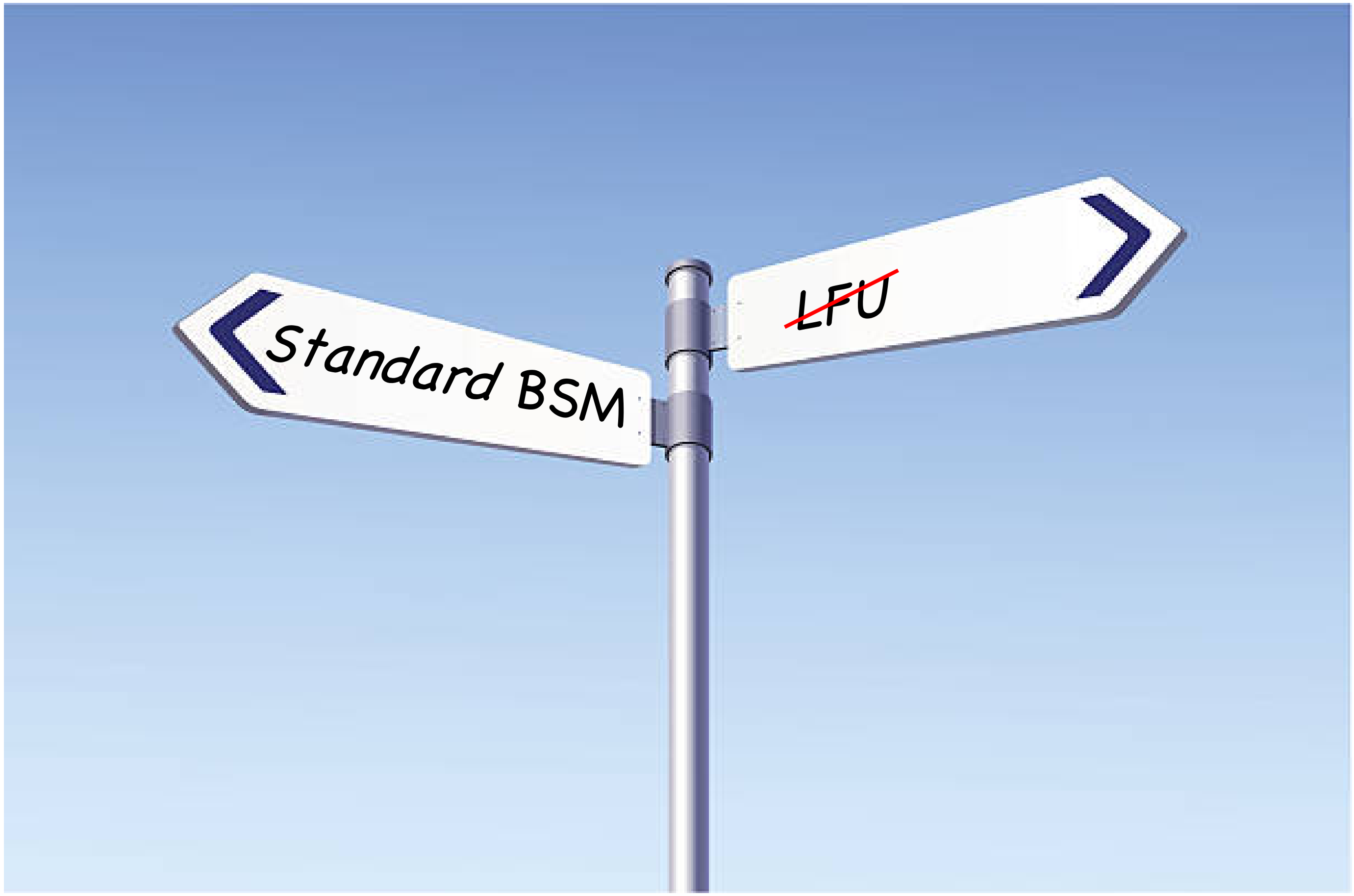
The Return of the Leptoquark

▶ *What have we learned?*

Flavor-non-universal interactions

The role of flavor symmetries

The Return of the Leptoquark



I. *Flavor non-universal interactions*

So far, 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 (*ignore*) the flavor problem ➡ The 3 gen. as "identical" copies (*but for Yukawa-type interactions*)

I. *Flavor non-universal interactions*

So far, 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
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The recent flavor anomalies seem to suggest a new avenue in BSM approaches:

The universality of SM gauge interactions is only a low-energy property

⬇

- We should not ignore the flavor problem
  → *new TeV-scale interactions distinguishing the different families*
- A (very) different behavior of the 3 families (with special role for 3rd gen.), may be the key to solve/understand also the gauge hierarchy problem
  → *Higgs mostly coupled to 3rd gen.*
  → *TeV-scale NP mainly coupled to 3rd gen. could have escaped direct searches*

What have we learned?

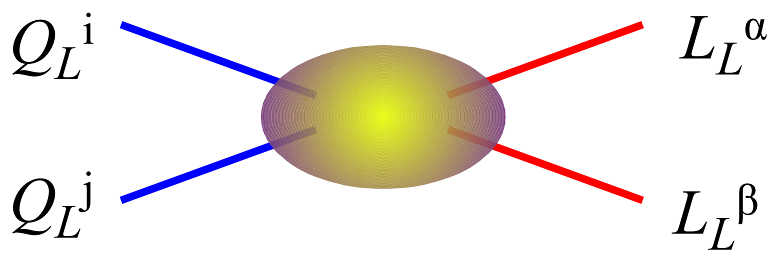
LFU violation & flavor-non-universal interactions

The role of flavor symmetries

The Return of the Leptoquark

II. *The role of flavor symmetries*

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- We definitely need non-vanishing left-handed current-current operators although other contributions are also possible



Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- Large coupling [*competing with SM tree-level*] in bc → $l_3\,\nu_3$ [R_D, R_{D*}]
- Small coupling [*competing with SM loop-level*] in bs → $l_2\ l_2$ [R_K, R_{K*}, ...]

↓

$T_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha3}\times\delta_{3\beta})$ + small terms for 2nd (& 1st) generations → *Link to pattern of the Yukawa couplings !*

II. The role of flavor symmetries

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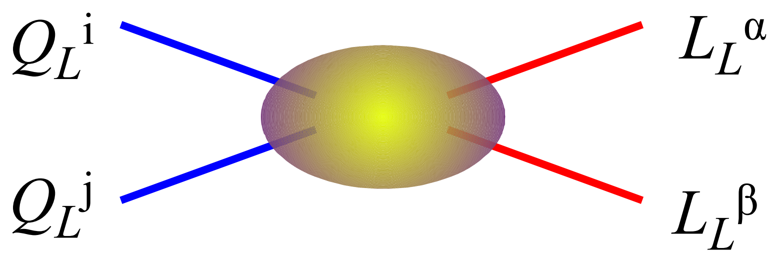

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Long list of constraints [FCNCs + semi-leptonic b decays + π, K, τ decays + EWPO]

↓

Essential role of *flavor symmetries*, not only to explain the pattern of the anomalies, but also to “protect” against too large effects in other low-energy observables

II. *The role of flavor symmetries*

A very good candidate to address both these issues (link with the origin of the Yukawa couplings + compatibility with other low-energy data) is a chiral flavor symmetry of the type $U(2)^n$

$$\psi = \begin{bmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \\ \psi_3 \end{bmatrix}$$

$\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$ ← light generations (*flavor doublet*)

ψ_3 ← 3^{rd} generation (*flavor singlet*)

ψ ↑ SM fermion (e.g. q_L)

….with suitable (small) symmetry-breaking terms, related to the structures observed in the SM Yukawa couplings

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

NB: This flavor symmetry does not need to be a "fundamental" symmetry, it could well be an "accidental" symmetry, resulting from non-universal interactions that distinguish the 3^{rd} family

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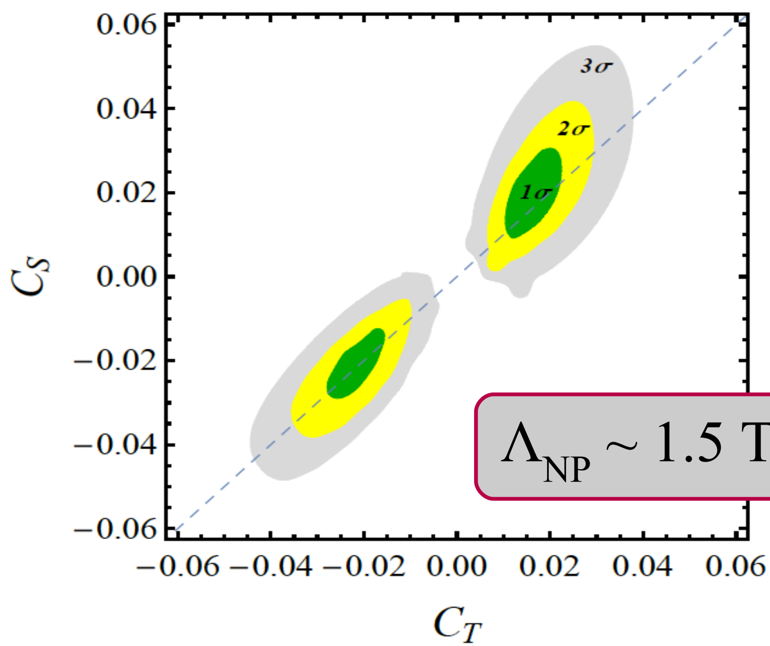
↓

An EFT based on the following two hypothesis:

- $U(2)_q \times U(2)_l$ chiral flavor symmetry
- NP in left-handed semi-leptonic operators only [*at the high-scale*]

provides an excellent fit to the data

Buttazzo, Greljo, GI, Marzocca, '17



$\Lambda_{NP} \sim 1.5$ TeV

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- NP in left-handed semi-leptonic operators only [*at the high-scale*]

provides an excellent fit to the data

N.B.: This set-up was proposed in 2015 and refined in 2017.

Data from 2019 and 2020 have made this picture more consistent:

I. Higher NP scale given smaller central value of the $b \to c$ anomaly

II. Rising "evidence" of LFU contribution to C_9 from $\tau\tau$ loops — Crivellin *et al.* '19, Alguero *et al.* '19, Aebischer *et al.* '19

III. Evidence of a ~20% suppression of $BR(B_s \to \mu\mu)$ [as predicted in 2015...]

IV. First hint of μ/e LFU violation in $\Lambda_b \to pKll$, with $R_{pK} \approx R_K$ — Fuentes-Martin *et al.* 19, LHCb '19

What have we learned?

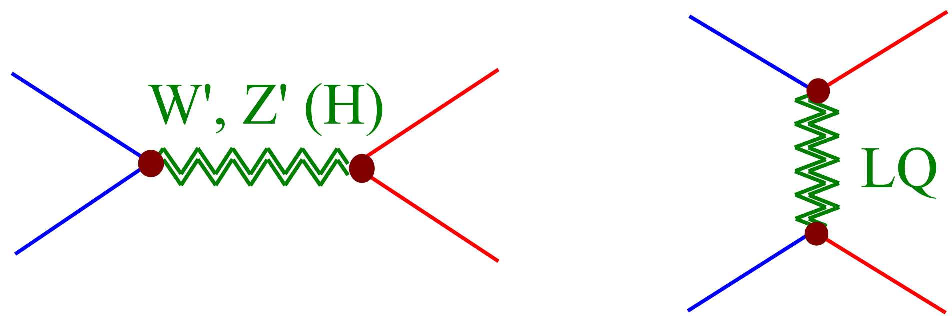
LFU violation & flavor-non-universal interactions

The role of flavor symmetries

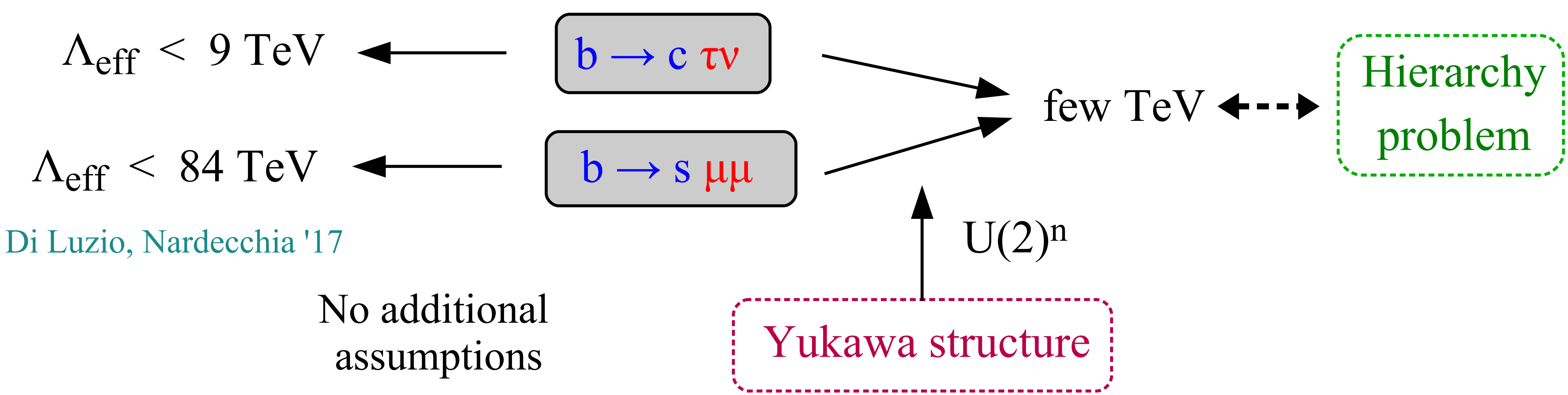
The Return of the Leptoquark

III. *The return of the Leptoquark*

Which mediators can generate the effective operators required for by the EFT fit?
If we restrict the attention to tree-level mediators, not many possibilities...



N.B.: The choice of a tree-level mediator is compelling only if we are interested into a combined fit of the anomalies (→ low scale) effective low-scale of NP.



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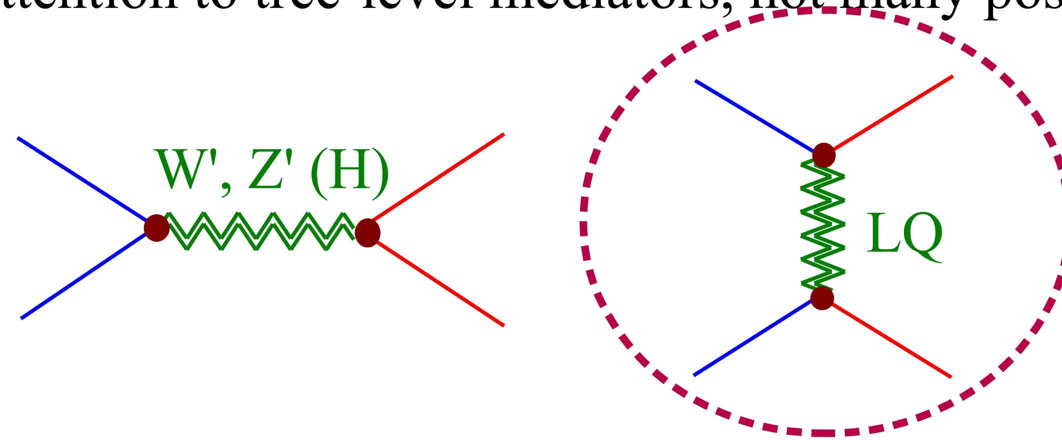
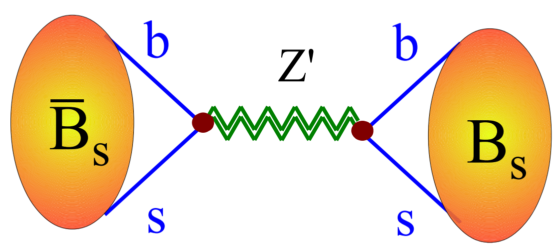
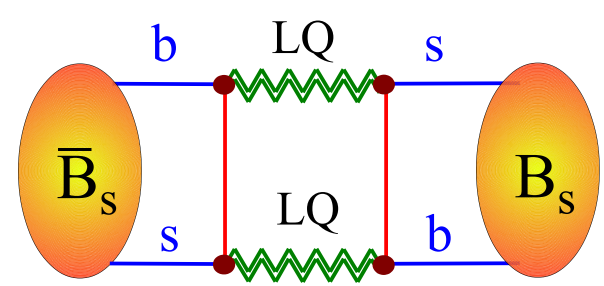


LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

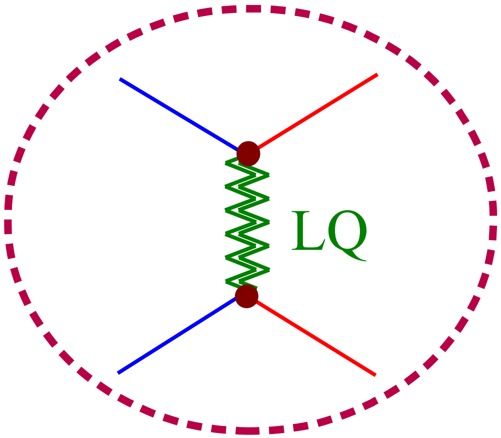
I. $\Delta F=2$ & $\tau \to l\nu\nu$





II. Direct searches: 3[rd] gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'...*).

III. *The return of the Leptoquark*

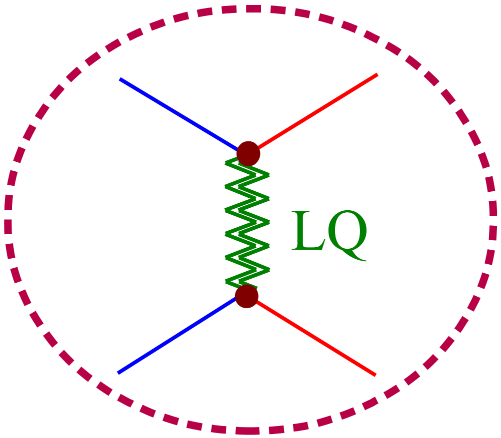


Leptoquarks suffered of an (*undeserved*) "bad reputation" for two main reasons:

- Could mediate proton decay → not a general feature of the LQ: it depends on the model...! [*e.g. not the case in the Pati-Salam model*]

- Severe bounds from processes involving μ & e (such as $K_L \to \mu e$) → avoided with non-trivial flavor structure [*e.g. non-univ. interactions*]

III. *The return of the Leptoquark*



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- Could mediate proton decay → not a general feature of the LQ: it depends on the model...! [*e.g. not the case in the Pati-Salam model*]

- Severe bounds from processes involving μ & e (such as $K_L \to \mu e$) → avoided with non-trivial flavor structure [*e.g. non-univ. interactions*]

On the other hand, they are a "natural" feature in many SM extensions → "Renaissance" of LQ models (*to explain the anomalies, but not only...*):

- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18

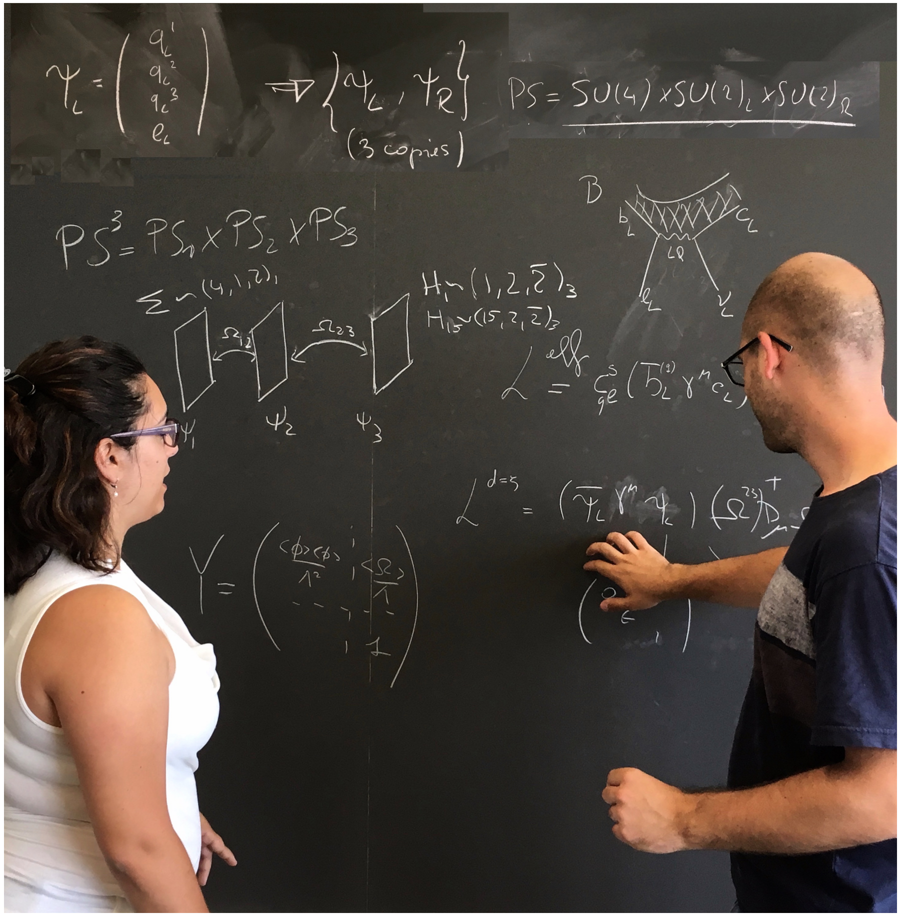
- Scalar LQ from GUTs & R̸ SUSY
  Hiller & Schmaltz, '14; Becirevic *et al.* '16, Fajfer *et al.* '15-'17; Dorsner *et al.* '17; Crivellin *et al.* '17; Altmannshofer *et al.* '17 Trifinopoulos '18, Becirevic *et al.* '18 + ...

- Vector LQ in GUT gauge models
  Assad *et al.* '17
  Di Luzio *et al.* '17
  Bordone et *al.* '17
  + ...

- Vector LQ as techni-fermion resonances
  Barbieri *et al.* '15; Buttazzo *et al.* '16, Barbieri, Murphy, Senia, '17

- LQ as Kaluza-Klein excit.
  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17
  Blanke, Crivellin, '18

An explicit model to address the anomalies



▶ *An explicit (class of) model(s) to address the anomalies*

Starting observation: the gauge theory proposed in the 70's to unify quarks and leptons by Pati & Salam predicts a massive vector LQ with the correct quantum numbers to fit both the anomalies:

Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

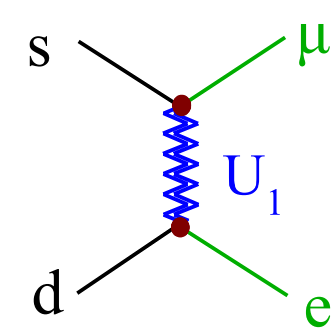
Fermions in SU(4):

$$\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$$

Main Pati-Salam idea:
Lepton number as "the 4th color"

The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_C\times U(1)_{B-L}$

The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]



Interesting attempts to solve this problem adding extra fermions and/or modifying the gauge group

Calibbi, Crivellin, Li, '17;
Di Luzio, Greljo, Nardecchia, '17
Fornal, Gadam, Grinstein, '18

The PS^3 *model*

$$[\ PS\ ]^3 = [\ SU(4)\times SU(2)_L \times SU(2)_R\ ]^3$$

Bordone, Cornella, Fuentes-Martin, GI, '17

Main idea: at high energies the 3 families are charged under 3 independent gauge groups (*gauge bosons carry a flavor index !*)

UV

PS_1 $\psi_1^{L,R}$ PS_2 $\psi_2^{L,R}$ PS_3 $\psi_3^{L,R}$

Unification of quarks and leptons [natural explanation for $U(1)_Y$ charges]

"De-unification" (= *flavor deconstruction*) of the gauge symmetry

SM

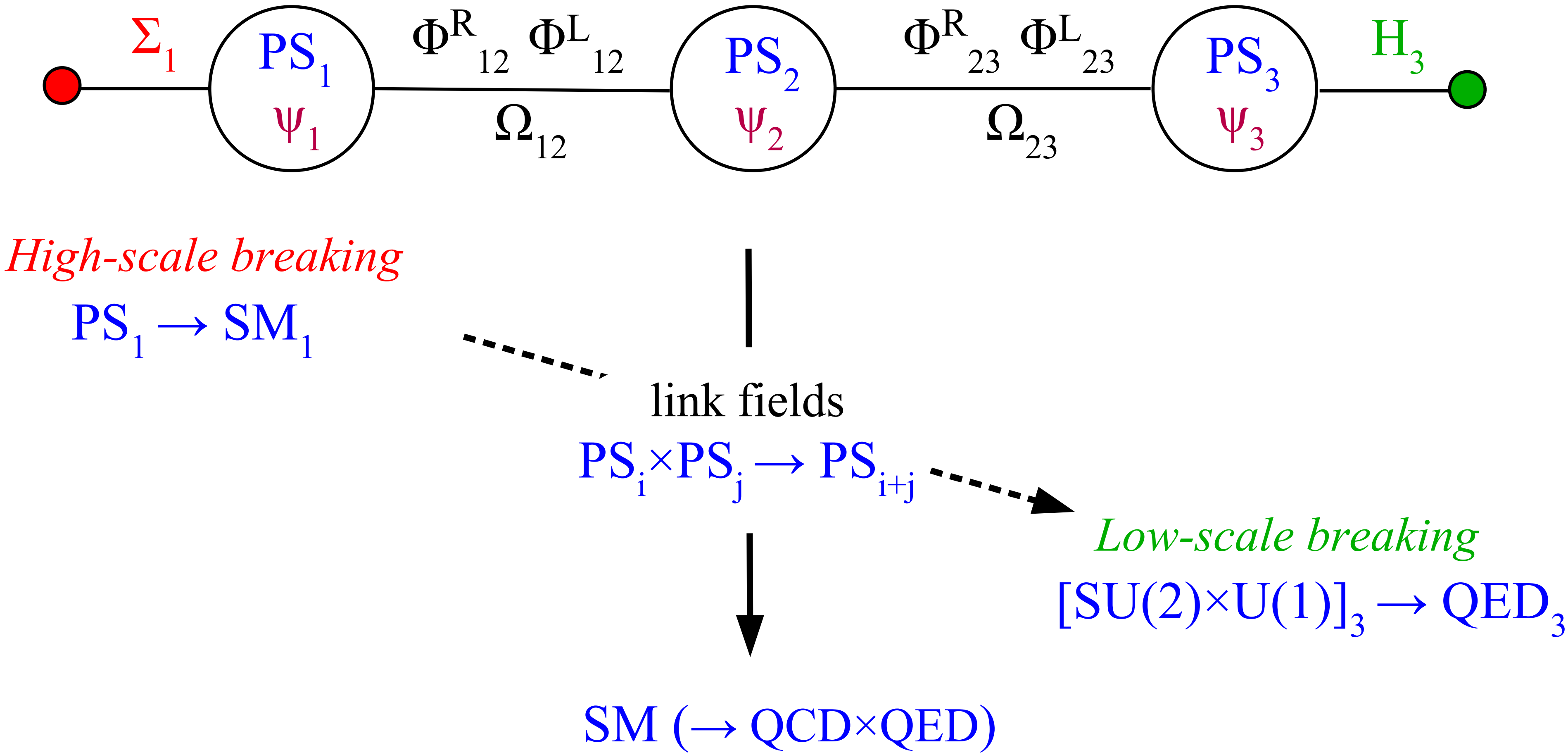
IR

Q_i, u_i, d_i, L_i, e_i

Key advantages:

- Light LQ coupled mainly to 3rd gen.
- Accidental $U(2)^5$ flavor symmetry
- Natural structure of SM Yukawa couplings
- Justification of the whole construction in terms of extra dim.

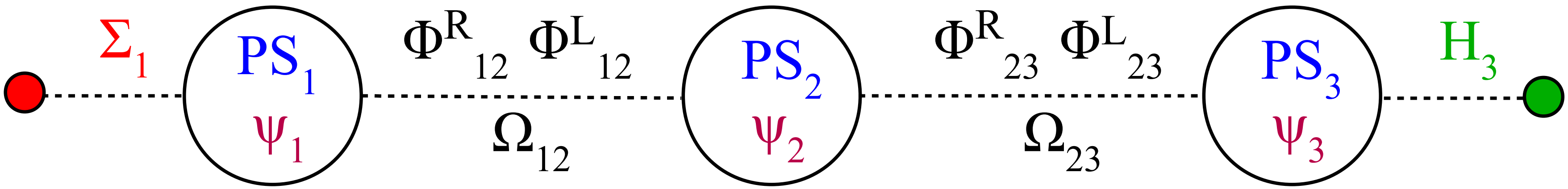
▶ *The* PS^3 *model*



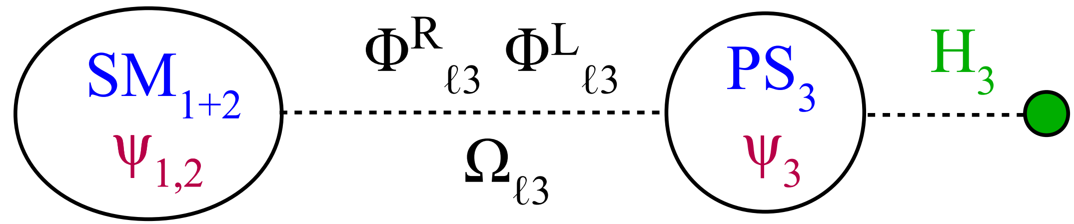
- The breaking to the diagonal SM group occurs via appropriate "link" fields, responsible also for the generation of the hierarchy in the Yukawa couplings.

- The 2-3 breaking gives a TeV-scale LQ [+ Z' & G'] coupled mainly to 3rd gen., as in the flavor-universal "4321" model [Di Luzio, Greljo, Nardecchia, '17]

The PS^3 *model*

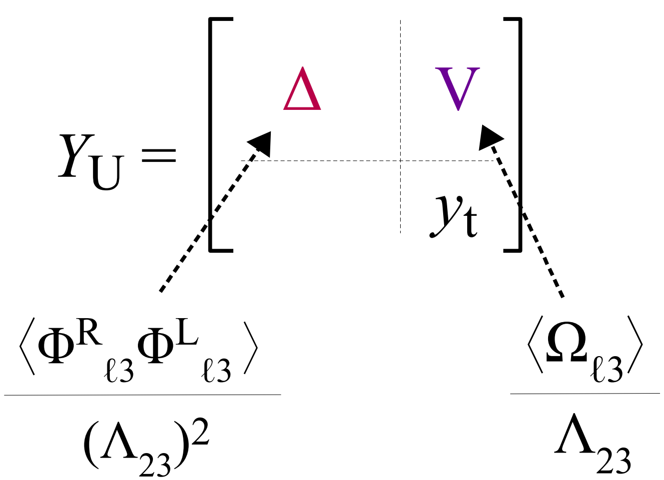


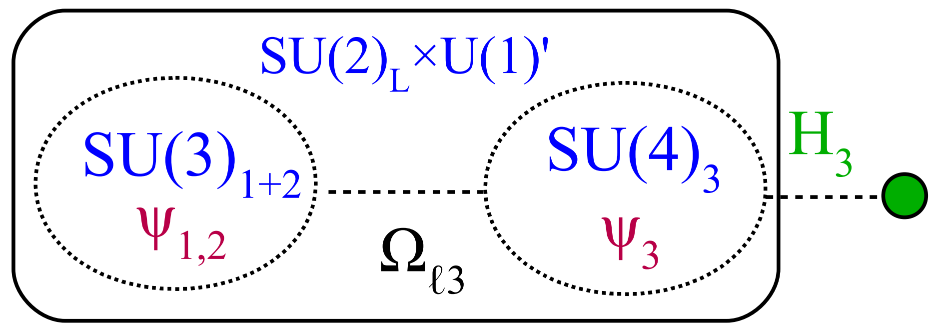
Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields) →



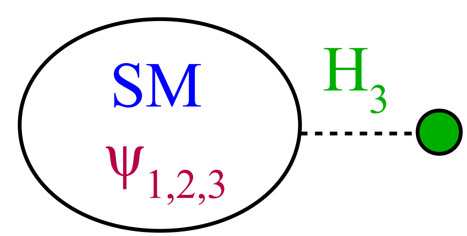
→ $W_L' + W_R'$ [~ 5-10 TeV]

Sub-leading Yukawa terms from higher dim ops:

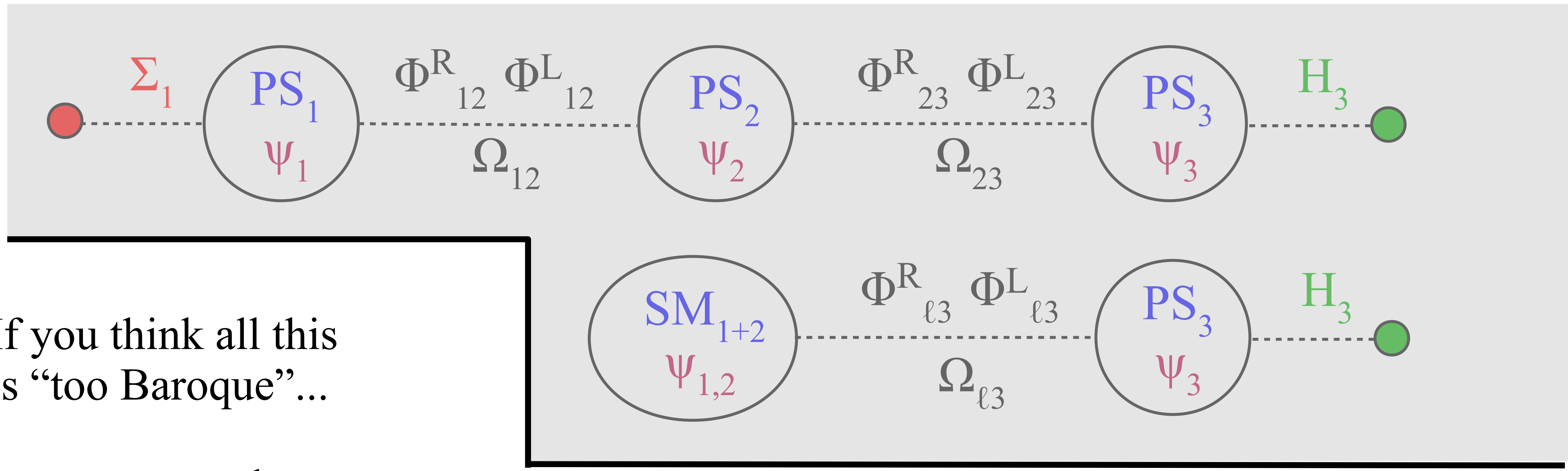




→ LQ [U_1] + Z' + G' [~ 1-5 TeV]

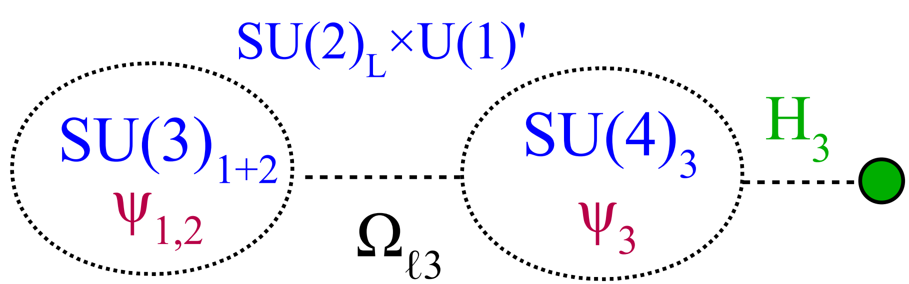


▶ *The wider class of "4321" models*



If you think all this is "too Baroque"...

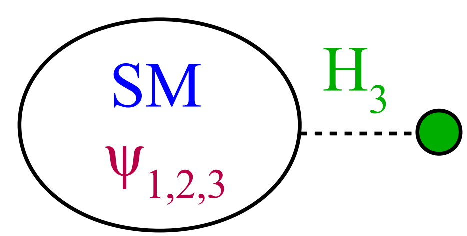
...we can start here:
4321 (*flavor non-universal*) model:



→ LQ [U_1] + Z' + G' [~ 1-5 TeV]

Interesting recent construction leading to the same "low-energy" structure based on new strong dynamics @ few TeV

→ *key feature*: Higgs as a pseudo-Goldstone



Fuentes-Martin & Stangl '20

The wider class of "4321" models

Present collider and low-energy pheno are all controlled by the last-step in the breaking chain [4321 → SM]

Despite the apparent complexity, the construction is highly constrained

Renormalizable structure (no d>5 ops) achieved with vector-like fermions

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	**1**	**3**	**2**	1/6
$u_R'^i$	**1**	**3**	**1**	2/3
$d_R'^i$	**1**	**3**	**1**	−1/3
$\ell_L'^i$	**1**	**1**	**2**	−1/2
$e_R'^i$	**1**	**1**	**1**	−1
ψ_L'	**4**	**1**	**2**	0
ψ_u'	**4**	**1**	**1**	1/2
ψ_d'	**4**	**1**	**1**	−1/2
χ_L^i	**4**	**1**	**2**	0
χ_R^i	**4**	**1**	**2**	0
H_1	**1**	**1**	**2**	1/2
H_{15}	**15**	**1**	**2**	1/2
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	−1/2
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6
Ω_{15}	**15**	**1**	**1**	0

$SU(4)_3 \times SU(3)_{1+2} \times [\, SU(2)_L \times U(1)' \,]$

ψ_3 $\psi_{1,2}$

$\langle \Omega\text{'s} \rangle$ → LQ [U_1] + Z' + G' [~ 1-5 TeV]

SM

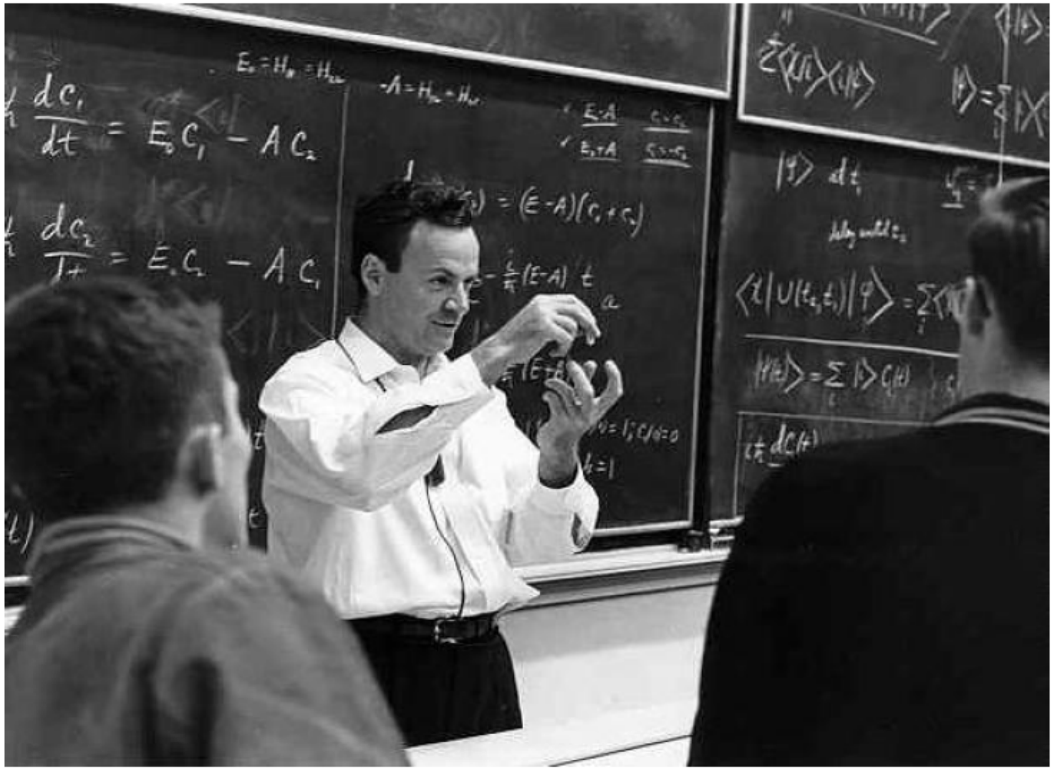
$\psi_{1,2,3}$

- Positive features the EFT reproduced
- Calculability of $\Delta F=2$ processes
- Precise predictions for high-pT data

Consistent with present data both at low and high energies

Greljo, Stefanek, '18; Di Luzio *et al.* '17 & '18; Cornella *et al.*, '19; Baker, Fuentes-Martin, GI, König, '19, Fuentes-Martin, GI, König, Selimovic '20

What more do we hope to learn?



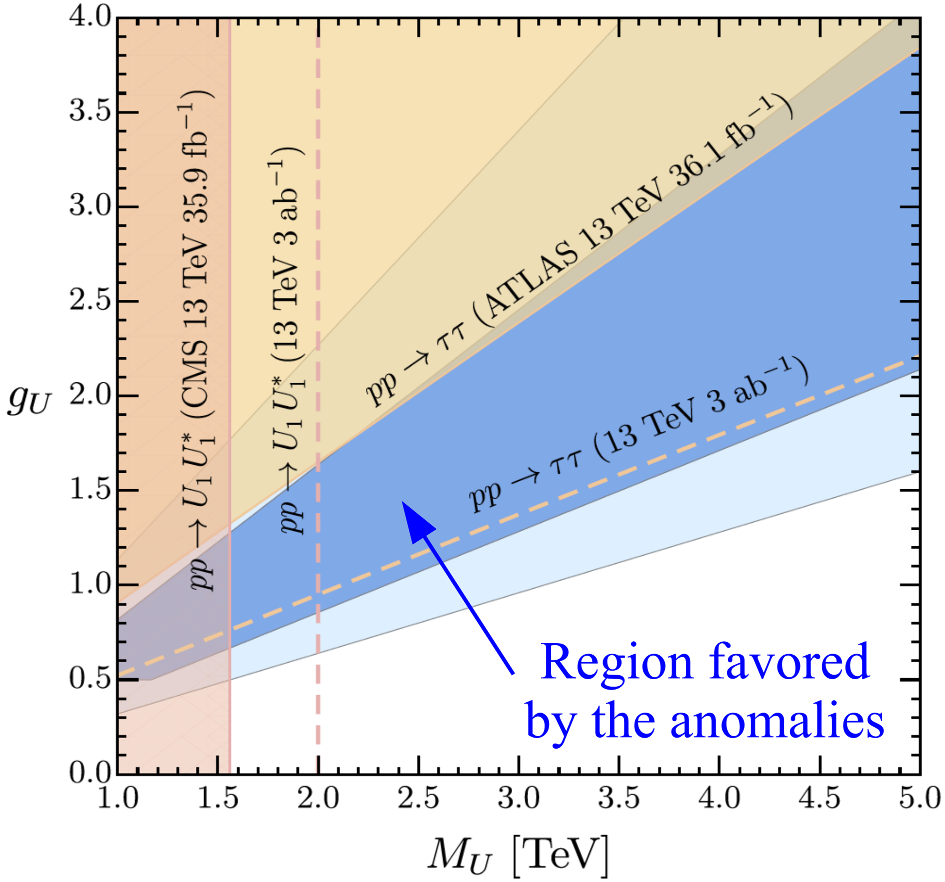
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

What more do we hope to learn?

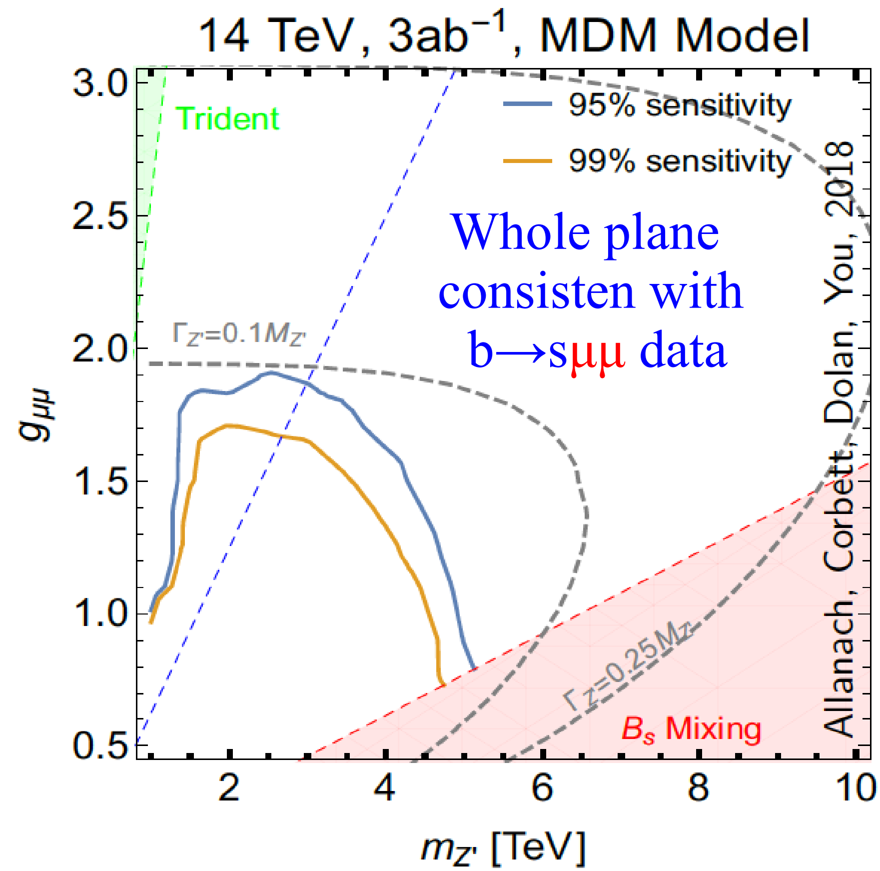
Ideally, to confirm all this... we would like to see a direct signal of the new mediators at high-pT.

But a high-energy discovery is not guaranteed in the short term [*even in the optimistic case of a combined explanation of the anomalies*]

E.g.: U_1 in 4321 models [Baker *et al.* '19]



E.g.: Z' for b→sμμ only [Allanach *et al.* '19]



What more do we hope to learn?

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But a high-energy discovery is not guaranteed in the short term [*even in the optimistic case of a combined explanation of the anomalies*]

In the short (?) term, the role of low-energy observables is potentially more interesting → many visible BSM effects expected, by consistency, virtually in all the models addressing the anomalies

Main message: "super-reach" program for LHCb & Belle-II and other low-energy facilities

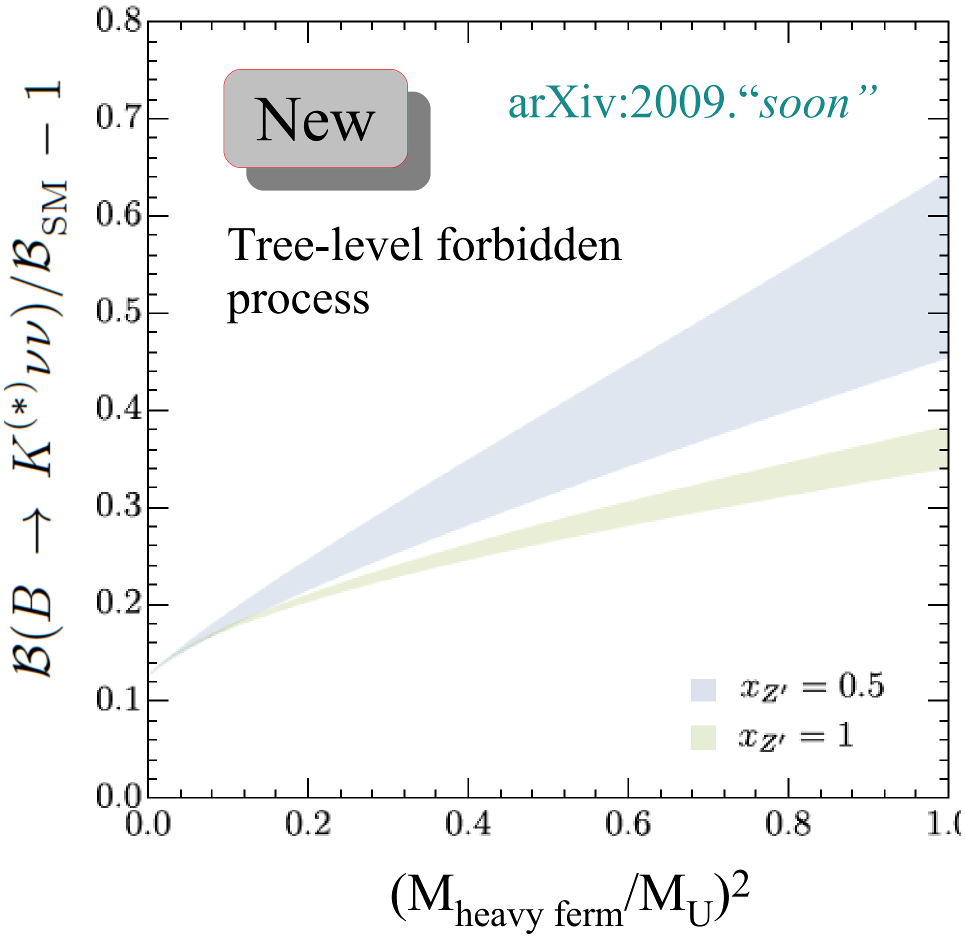
- This program is essential to determine the flavor structure of the new sector
- Correlations among low-energy obs. can be studied by means of EFT *and already with low-energy data we could rule-out many models...*

What more do we hope to learn?

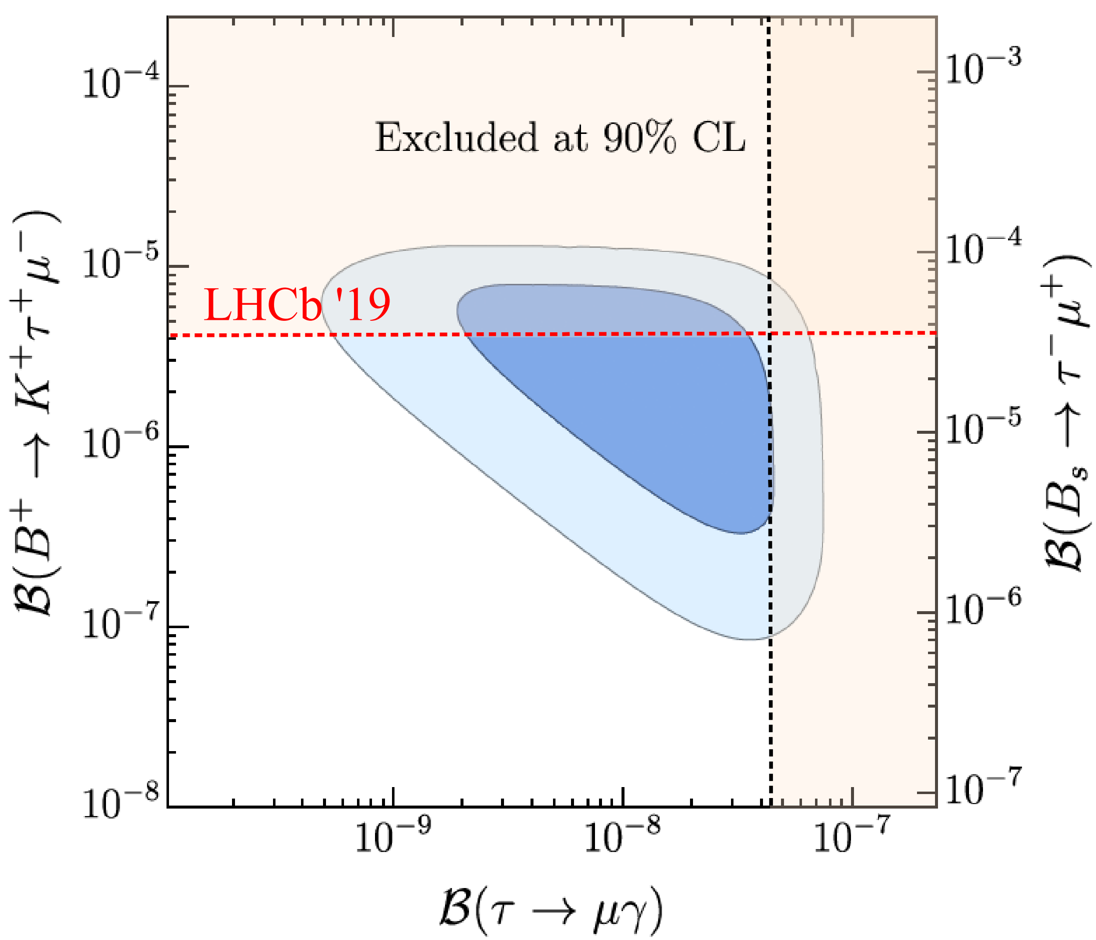
Main message: "super-reach" program for LHCb & Belle-II and other low-energy facilities.

Two examples –in 4321 modes– of observables relevant to both LHCb & Belle-II:

I) $B \to K^{(*)}\nu\nu$ [Fuentes-Martin *et al.* '20]



II) LFV in B & τ decays [Cornella *et al.* '19]



Conclusions

- Flavor physics remains somehow a mystery [*who ordered the muon?*]: we do not have yet clear answers for the two (*SM* & *NP*) *flavor puzzles.* But flavor physics is also a great opportunity to understand what's beyond the SM

- So far, most attempts in model-building tried to "postpone" the solution of the flavor problems to high-energy scales. This has not been very successful, and is not what the SM-EFT suggests.

- The recent LFU anomalies, *albeit not statistically compelling yet*, provide a clear phenomenological indication of non-trivial flavor dynamics around the TeV scale.

- These anomalies are not in contradiction with existing low- & high-energy data and, taken together, they point out to a well-defined structure of New Physics coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings.

⬇

A lot of fun ahead of us...

(both on the exp., the pheno, and the model-building point of view)