# *B-physics anomalies: lessons and open issues*

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[ *University of Zürich* ]

- Introduction
- A brief look to the data
- What have we learned?
- A class of UV models addressing the anomalies
- What do we still hope to learn?
- Conclusions

University of Zurich UZH

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## *Introduction*

At the end of 2012, after the discovery of Higgs boson by ATLAS & CMS, and the first evidence of $B_s \to \mu\mu$ by LHCb, if you would we have asked me, "*which are the probability of detecting new-physics signals in semi-leptonic B decays*?" I would have answered: "*very little*" (*as I guess many theory colleagues…*)

Motivating the answer with

- No evidence of New Physics at high-pT
- SM-like Higgs particle

→ "heavy" NP

- No evidence of New Physics in a series of "clean" flavor-changing observables, such as $\Delta F=2$, but also $b \to s\gamma$ & $B_s \to \mu\mu$

→ MFV-like NP

- Difficulty of making precise ("clean") SM tests in processes such as $B \to K^{(*)}ll$

→ LFU tests not considered interesting..

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Motivating the answer with

- No evidence of New Physics at high-pT
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→ "heavy" NP

*not so heavy if coupled to 3rd gen. only*

- No evidence of New Physics in a series of "clean" flavor-changing observables, such as $\Delta F=2$, but also $b \to s\gamma$ & $B_s \to \mu\mu$

→ ~~MFV-like NP~~

*MFV is not the only viable option*

- Difficulty of making precise ("clean") SM tests in processes such as $B \to K^{(*)}ll$

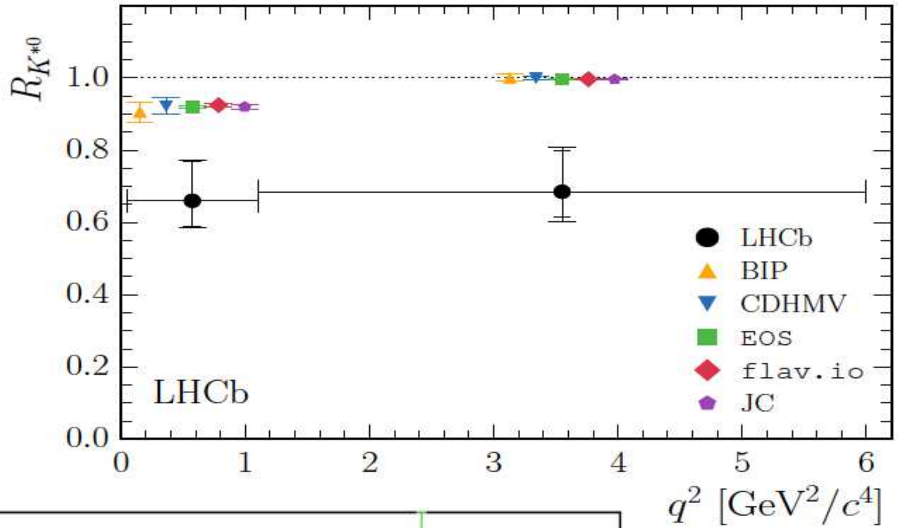
→ ~~LFU tests not considered interesting..~~

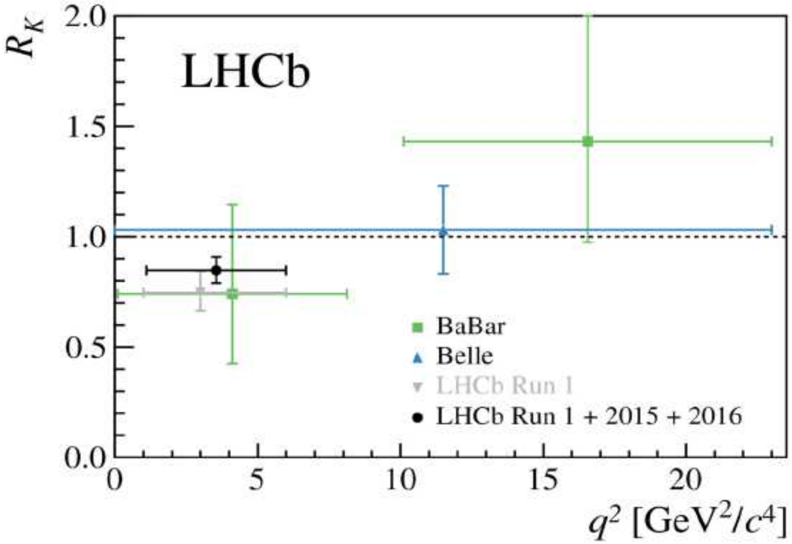
*LFU tests are very interesting !*

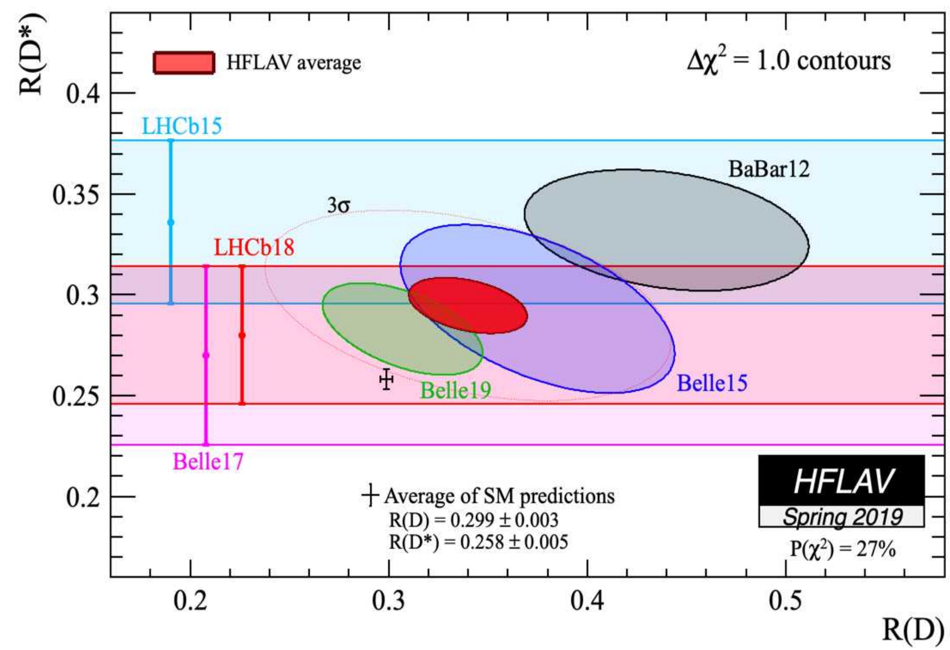
*Already since 2015 I give a completely different answer…!*

Thanks to the B-physics anomalies we have abandoned a few theory prejudices and identified (*partially rediscover*) *very interesting directions in model building*

# A brief look to the data



## *A brief look to the data*

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

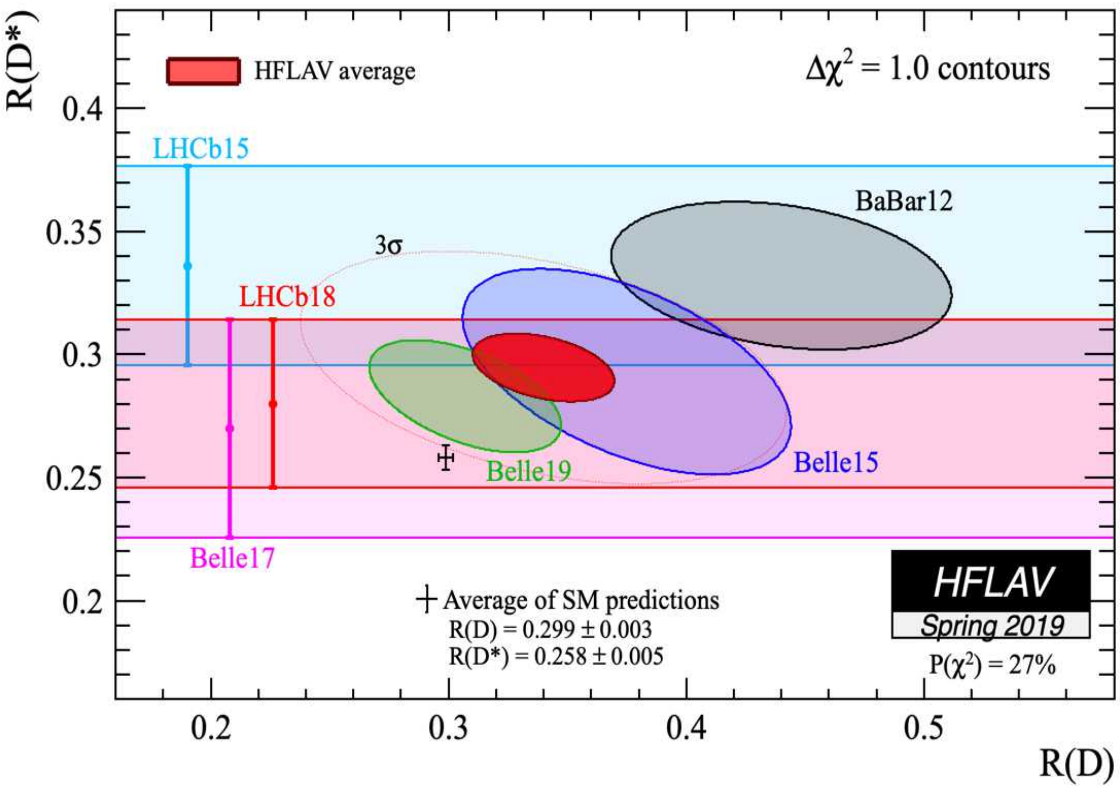
More precisely, we seem to observe a different behavior (*beside pure kinematical effects*) of different lepton species in the following processes:

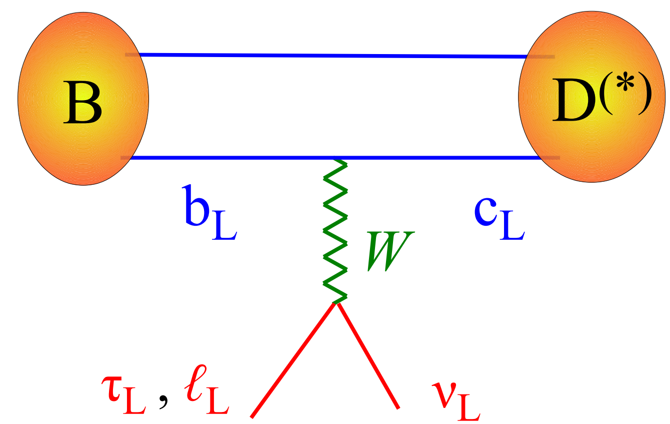
- $b \to c\, l\nu$ (charged currents): $\tau$ vs. light leptons ($\mu$, $e$)
- $b \to s\, l^+l^-$ (neutral currents): $\mu$ vs. $e$

## A brief look to the data

- $b \to c\, l\nu$ (charged currents): $\tau$ vs. light leptons ($\mu$, e)

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})} \qquad X = \text{D or D*}$$




- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)
- SM predictions quite solid: hadronic uncertainties cancel (*to large extent*) in the ratios

## *A brief look to the data*

- b → c $l\nu$ (charged currents): τ vs. light leptons (μ, e)

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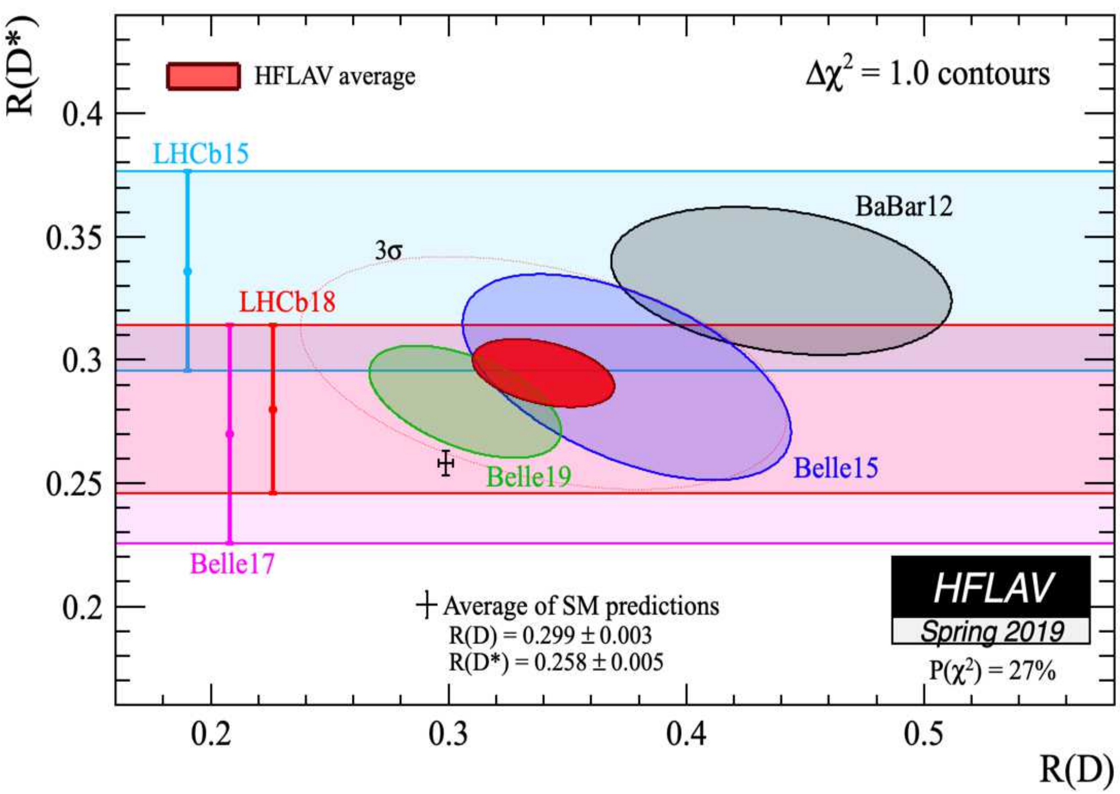
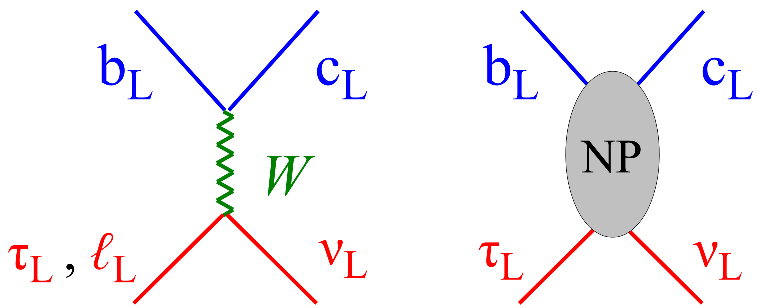



- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)

- Data consistent with a universal enhancement (~20%) of $b_L \to c_L \tau_L \nu_L$

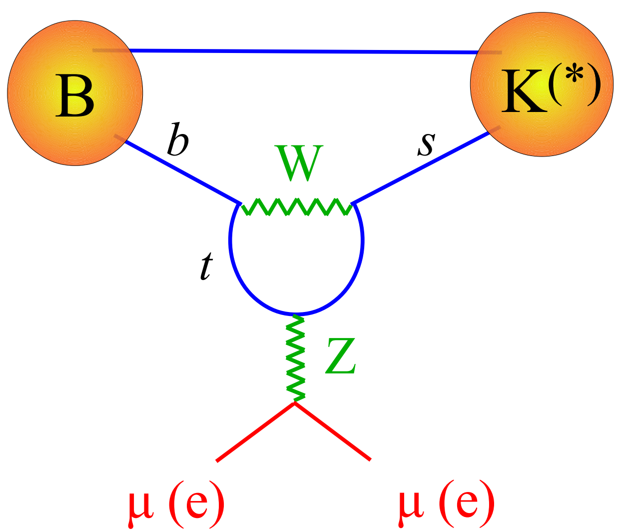
## A brief look to the data

- $b \to s\, l^+ l^-$ (neutral currents)

Starting from 2013, a series of "anomalies" started to appear in exclusive B meson decays of the type $b \to s\, \ell^+\ell^-$ [ $\ell = \mu$, e]:

- $P'_5$ anomaly [$B \to K^* \mu\mu$ angular distribution]
- Smallness of all $B \to H_s\, \mu\mu$ rates [$H_s$=K, $K^*$, $\phi$ (from $B_s$ )]
- LFU ratios ($\mu$ vs. e) in $B \to K^* \ell\ell$ & $B \to K\, \ell\ell$
- Smallness of BR($B_s \to \mu\mu$)

*chronological order*



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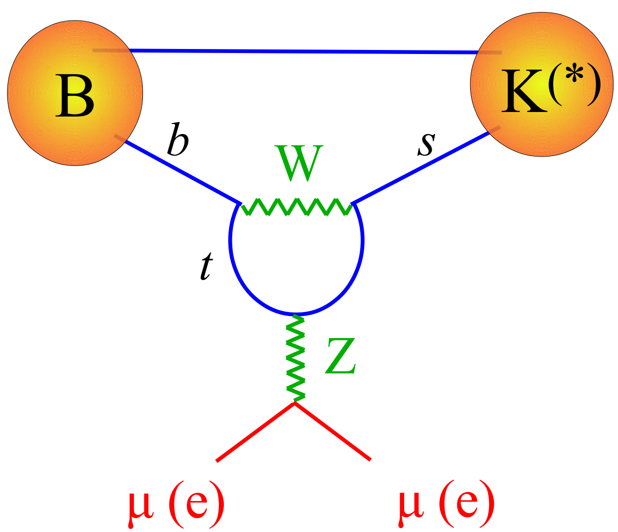
- LFU ratios ($\mu$ vs. e) in $B \to K^*\ell\ell$ & $B \to K\, \ell\ell$ — th. error <1%
- Smallness of BR($B_s \to \mu\mu$) — th. error few %




Some of these observables are affected by irreducible theory errors (*form factors*, *long-distance contributions*) → in the following I will briefly highlight only those with small errors

The striking observation is that the picture of all the data is <u>extremely coherent</u>, pointing to well-defined non-SM effects (of short-distance origin).

## *A brief look to the data*

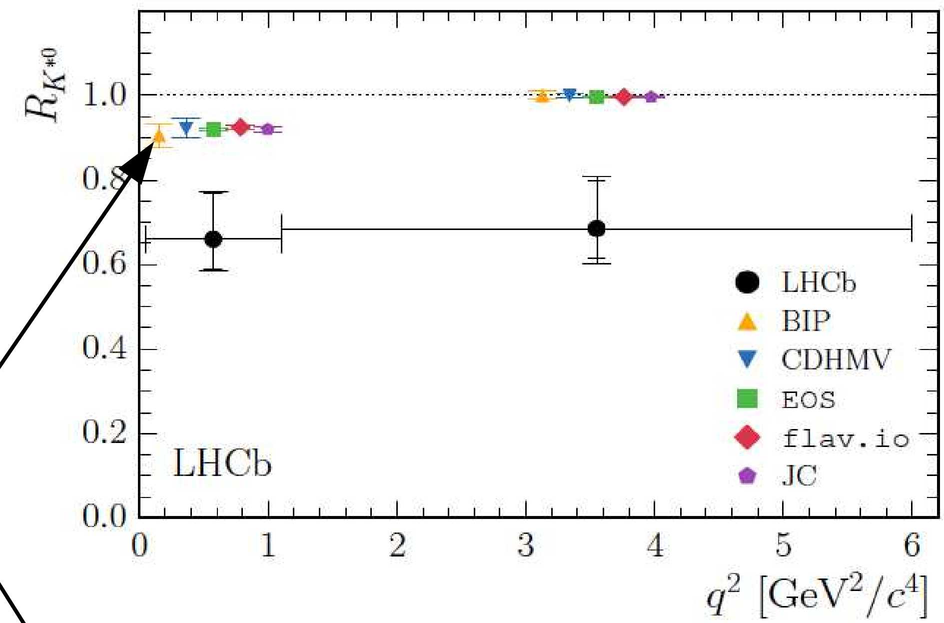
- $b \to s\, l^+l^-$ (neutral currents): $\mu$ vs. $e$

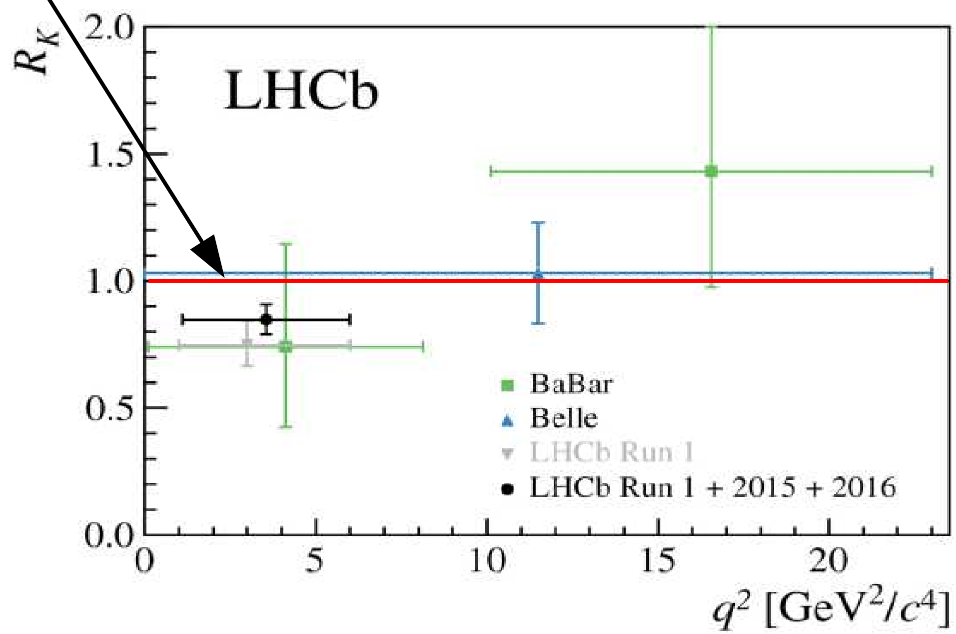
$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)} \qquad (H = K, K^*)$$

SM prediction very robust: $(R_H) = 1$
[*up tiny QED and lepton mass effects*]

Bordone, GI, Pattori '16
GI, Nabeebascus, Zwicky '20

Deviations from the SM predictions ranging from 2.2σ to 2.5σ in each of the 3 bins measured by LHCb

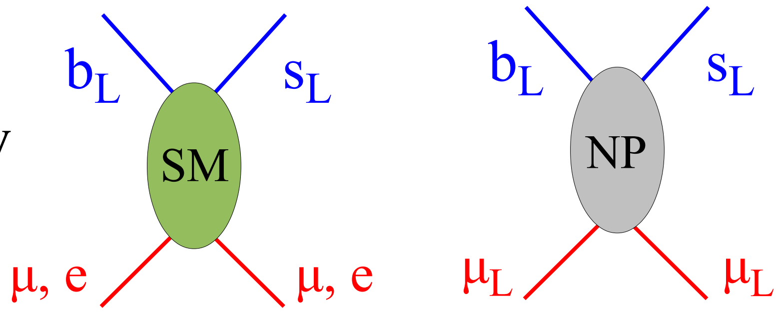


## *A brief look to the data*

- $b \to s\, l^+ l^-$ (neutral currents): $\mu$ vs. e

To a large extent, the LFU breaking effects are described by the same set of Wilson coeff. necessary to describe the BR and angular anomalies if we assume NP only in $b \to s\mu\mu$ and (& not in ee)




The significance of the LFU observables alone has not increased in 2019, but the overall consistency with other data has further increased in 2019-2020, as well as the evidence that the putative NP effects come from a pure left-handed operator

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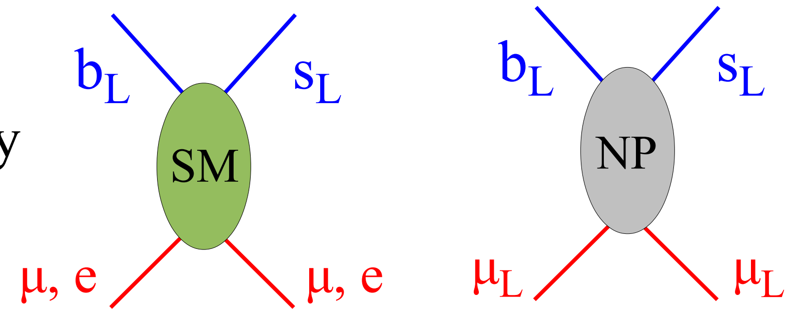
- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e

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- Expected suppression of $BR(B_s \to \mu\mu)$ of ~20% compared to its SM value:

$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$ Beneke *et al.* '19

$$BR(B_s \to \mu\mu)_{exp} = (2.72 \pm 0.34) \times 10^{-9}$$ ATLAS+CMS+LHCb '19

$2.6\sigma$

A super-conservative analysis, taking into account only the observables III. & IV, with a single NP operator, leads to a pull of $\boxed{4.2\sigma}$ compared to the SM.

What have we learned?

## *What have we learned?*

Recent data show some convincing evidences of Lepton Flavor Universality violations in two (*a priori independent*) semi-leptonic decays of the b quark

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

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

*Three main messages for BSM physics*

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

LFU violation & flavor-non-universal interactions

The role of flavor symmetries

The Return of the Leptoquark

## *What have we learned?*

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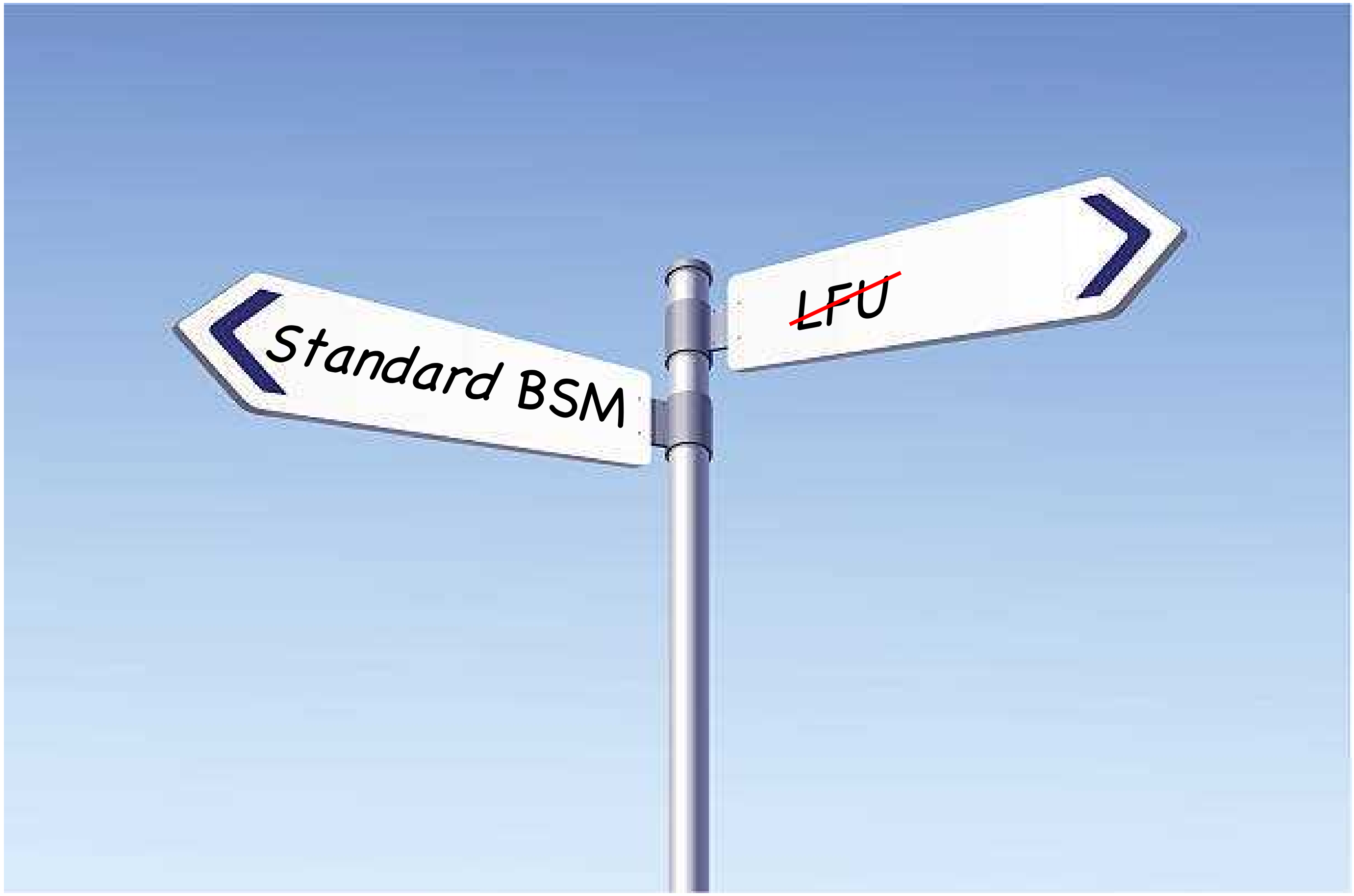

# I. *LFU violation and flavor non-universal interactions*

LFU [= *identical behavior of the 3 charged leptons in the limit where we neglect their masses*] is a consequence of the accidental flavor symmetry of the SM Lagrangian in the limit where we neglect the (small) lepton Yukawa couplings:

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}}(A_{\mathrm{a}}, \psi_{\mathrm{i}}) + \mathscr{L}_{\mathrm{Higgs}}(\mathrm{H}, A_{\mathrm{a}}, \psi_{\mathrm{i}})$$

3 identical replica of the basic fermion family [$\psi = Q_L, u_R, d_R, L_L, e_R$]
in the gauge sector $\Rightarrow$ huge flavor-degeneracy [ $\mathrm{U}(3)_L \times \mathrm{U}(3)_E \times ...$]

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$$\downarrow \text{SM Yukawa}$$

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

No reason to assume it holds beyond the SM...

[*it is not even an exact symmetry of the SM* !]

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No reason to assume it holds beyond the SM...

It has been verified with extremely high accuracy in several systems:

- $Z \to ll$ decays [~ 0.1%]
- $\tau \to l\nu\nu$ decays [~ 0.1%]
- $K \to (\pi) l\nu$ decays [~ 0.1%] & $\pi \to l\nu$ decays [~ 0.01%]

*This is why is often assumed as a "sacred principle"....*

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Still, no deep reason, and no strong experimental tests in semileptonic processes involving 3$^{rd}$ generation quarks, before these recent measurements

*The observed universality, especially for light leptons, could well be only an accidental low-energy property, due to their "weak" coupling to new physics.*

# I. *LFU violation and 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*)

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So far, the vast majority of model-building attempts to extend the SM was based on the following two (*implicit*) hypotheses:

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- Postpone (*ignore*) the flavor problem → ~~The 3 gen. as "identical" copies (*but for Yukawa-type interactions*)~~

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

↓

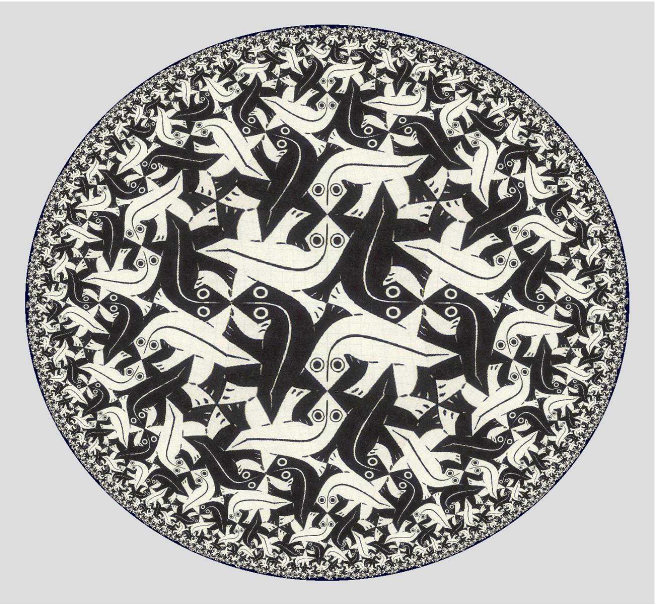
- We should not ignore the flavor problem
  → *new TeV-scale interactions distinguishing the different families*
- A (very) different behavior of the 3 families (with special role for 3$^{rd}$ gen.), may be the key to solve/understand also the gauge hierarchy problem
  → *Higgs mostly coupled to 3$^{rd}$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

## *What have we learned?*

LFU violation & flavor-non-universal interactions

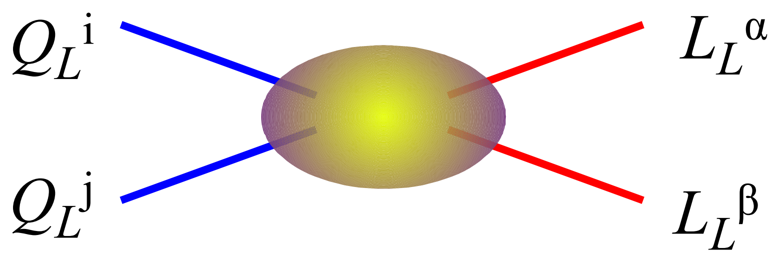
The role of flavor symmetries

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

$$T_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha 3}\times\delta_{3\beta}) \quad + \quad \text{small terms for } 2^{nd}\ (\&\ 1^{st}) \text{ generations} \quad \longrightarrow$$

*Link to pattern of the Yukawa couplings !*

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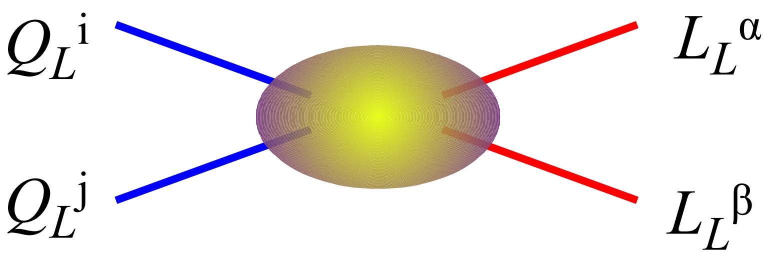


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*Long list of constraints* [FCNCs + semi-leptonic b decays + π, K, τ decays + EWPO]

↓

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 $U(2)^n$

$$\psi = \left[ \begin{array}{c} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \\ \hline \psi_3 \end{array} \right] \begin{array}{l} \longleftarrow \text{light generations (\textit{flavor doublet})} \\ \\ \longleftarrow 3^{rd} \text{ generation (\textit{flavor singlet})} \end{array}$$

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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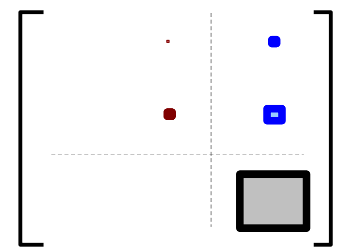
E.g. up-sector: $U(2)_q \times U(2)_u$

$$Y_U = y_t \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \leftarrow U(2)_q \quad \longrightarrow \quad \begin{bmatrix} \Delta & V \\ & 1 \end{bmatrix} \equiv$$



$\uparrow$
$U(2)_u$

*unbroken symmetry*

*after symmetry symmetry*

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

Main idea: the same symmetry-breaking pattern control the mixing $3^{rd} \rightarrow 1^{st}, 2^{nd}$ gen. for the NP responsible for the anomalies

$$|V| \approx |V_{ts}| = 0.04$$
$$|\Delta| \approx y_c = 0.006$$

N.B.: this symmetry & symmetry-breaking pattern was proposed well-before the anomalies appeared [*it is not ambulance chasing...!* ]

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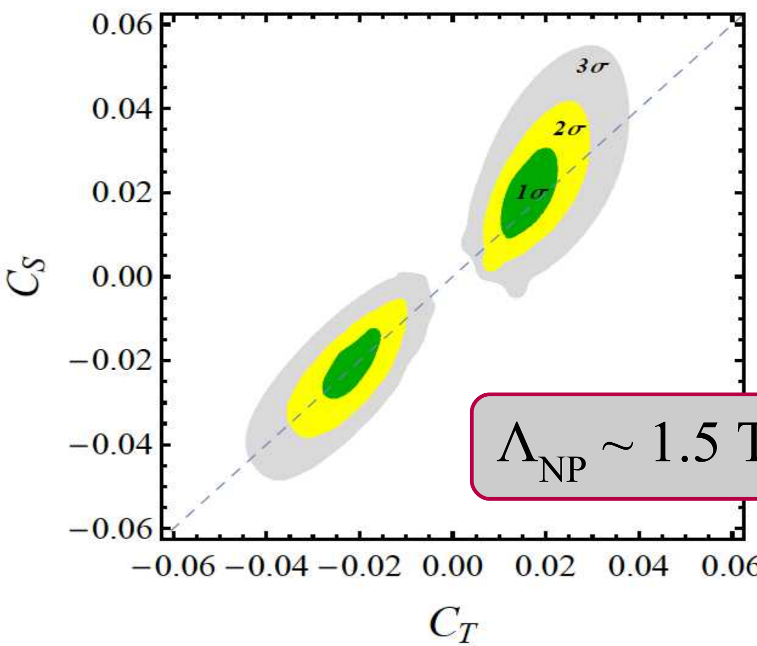
⬇

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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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 $\mu/e$ LFU violation in $\Lambda_b \to pK\ell\ell$, with $R_{pK} \approx R_K$

Fuentes-Martin *et al.* 19
LHCb '19

## *What have we learned?*

LFU violation & flavor-non-universal interactions

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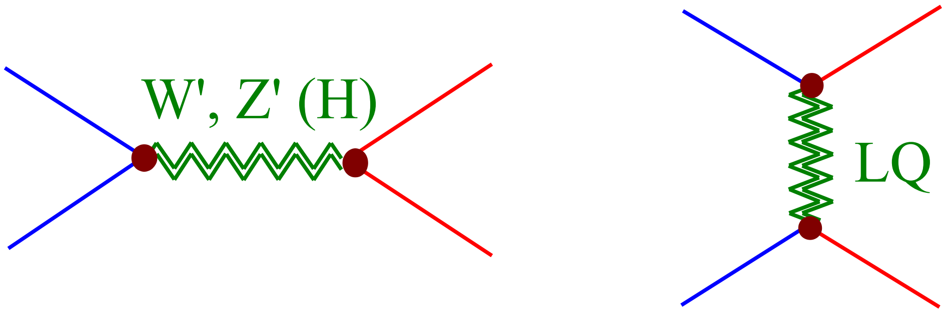
The Return of the Leptoquark

# 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...



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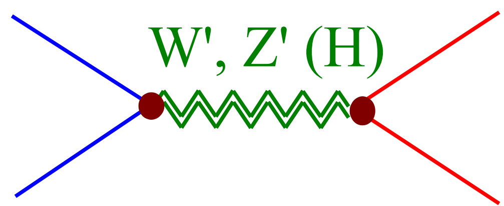
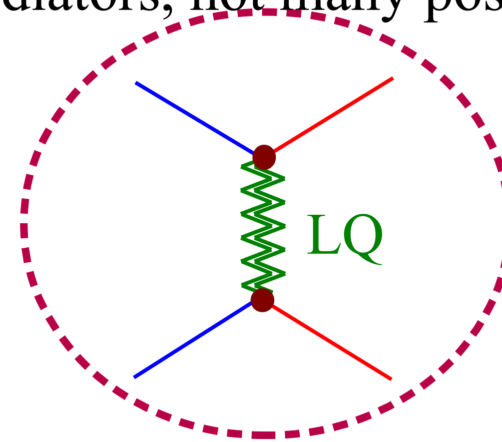
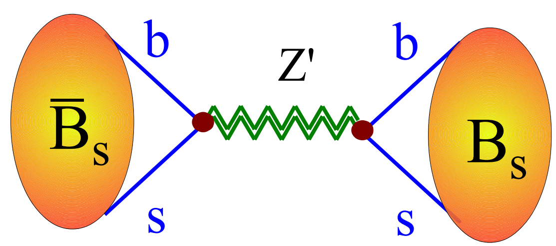
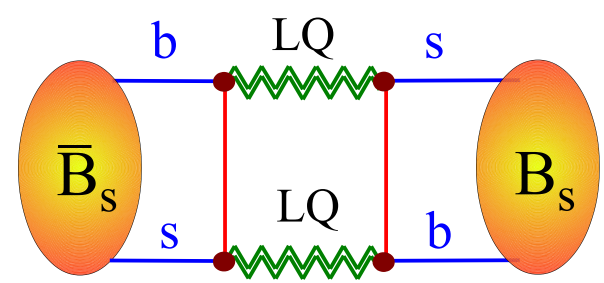



LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

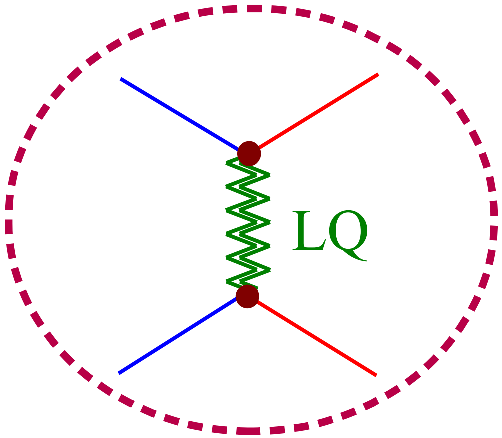
I. $\Delta F=2$ & $\tau \to l\nu\nu$




II. Direct searches: 3rd 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*]

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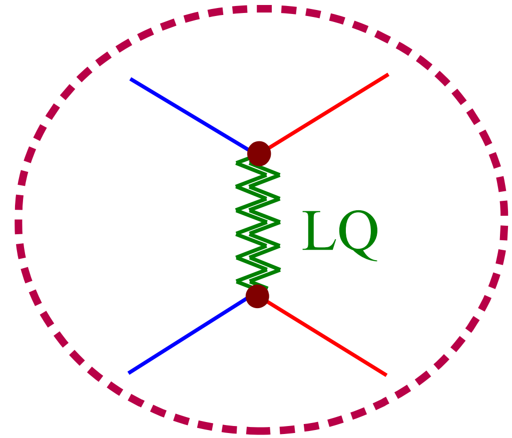


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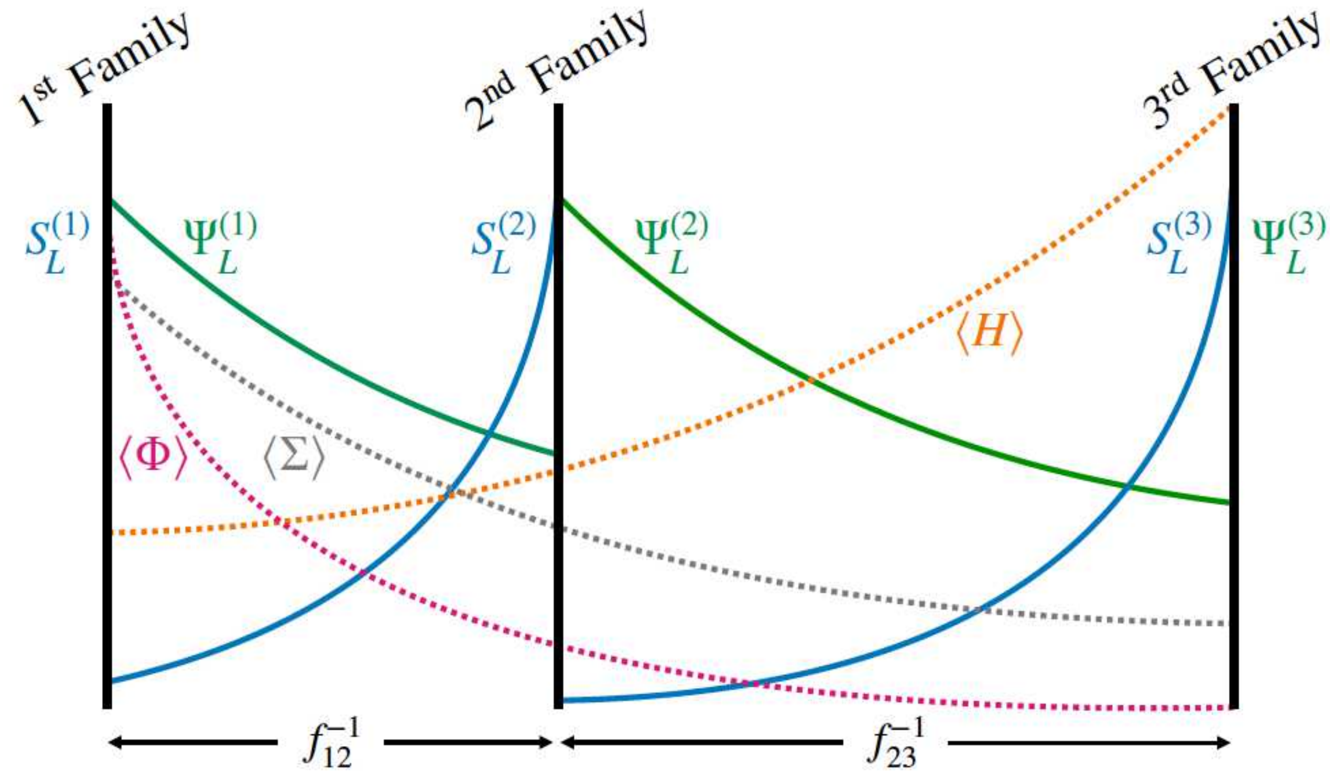
On the other hand, they are a "natural" feature in many SM extensions → "Renaissance" of LQ models (*to explain the anomalies, but not only...*):

- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18
- Scalar LQ from GUTs & ~~R~~ 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

# A class of UV models addressing the anomalies



## A class of UV models addressing 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: $SU(4)\times SU(2)_L\times SU(2)_R$

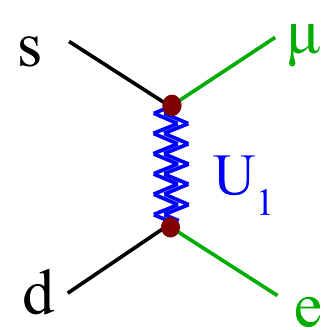
Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix}$ $\begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

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

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

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 $K_L \to \mu e$]

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




Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17
Bordone et al. '17; Fornal, Gadam, Grinstein, '18

## A class of UV models addressing the anomalies

Second observation: we can "protect" the first two families charging under SU(4) only the third generation

PS group: $SU(4) \times SU(2)_L \times SU(2)_R$

- *flavor universality*

Non-universal 4321: $SU(4)_3 \times SU(3)_{1,2} \times SU(2)_L \times SU(2)_R$

[3$^{rd}$ gen.] [light gen.]

- *Accidental* U(2)$^5$ *flavor symm. in the gauge sect.*

SSB

$SU(3)_C \times U(1)_{B-L}$ + LQ [$U_1$] + Z' + G'

[universal]

[non-universal, with $U_1$ coupled only on the 3$^{rd}$ gen.]

Successful and predictive phenomenology, at both low and high energies

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

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UV completions

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

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

Closely connected (but distinct) UV completions addressing the flavor hierarchies

$[\ PS\ ]_{\text{warped-5d}}$ 3-branes

Fuentes-Martin, GI, Pages, Stefanek '20

$SU(4)_3 \times SU(3)' \times SU(2)_L \times SU(2)_R \times G_{HC}$

Fuentes-Martin & Stangl '20

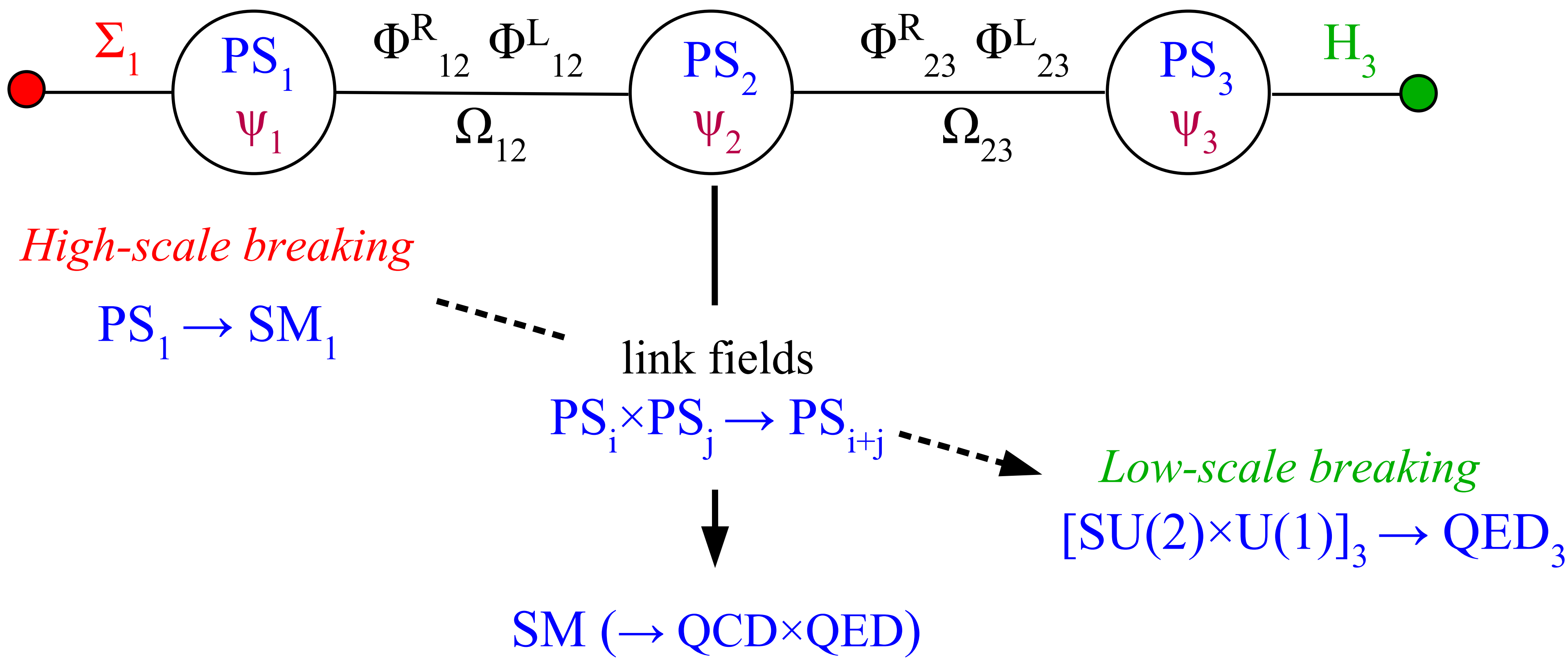
$G_{HC}$= strong dynamics @ few TeV leading to

- SSB of $SU(4) \times SU(3)'$
- Higgs as a pseudo-Goldstone

## A class of UV models addressing the anomalies

- The $PS^3$ set-up

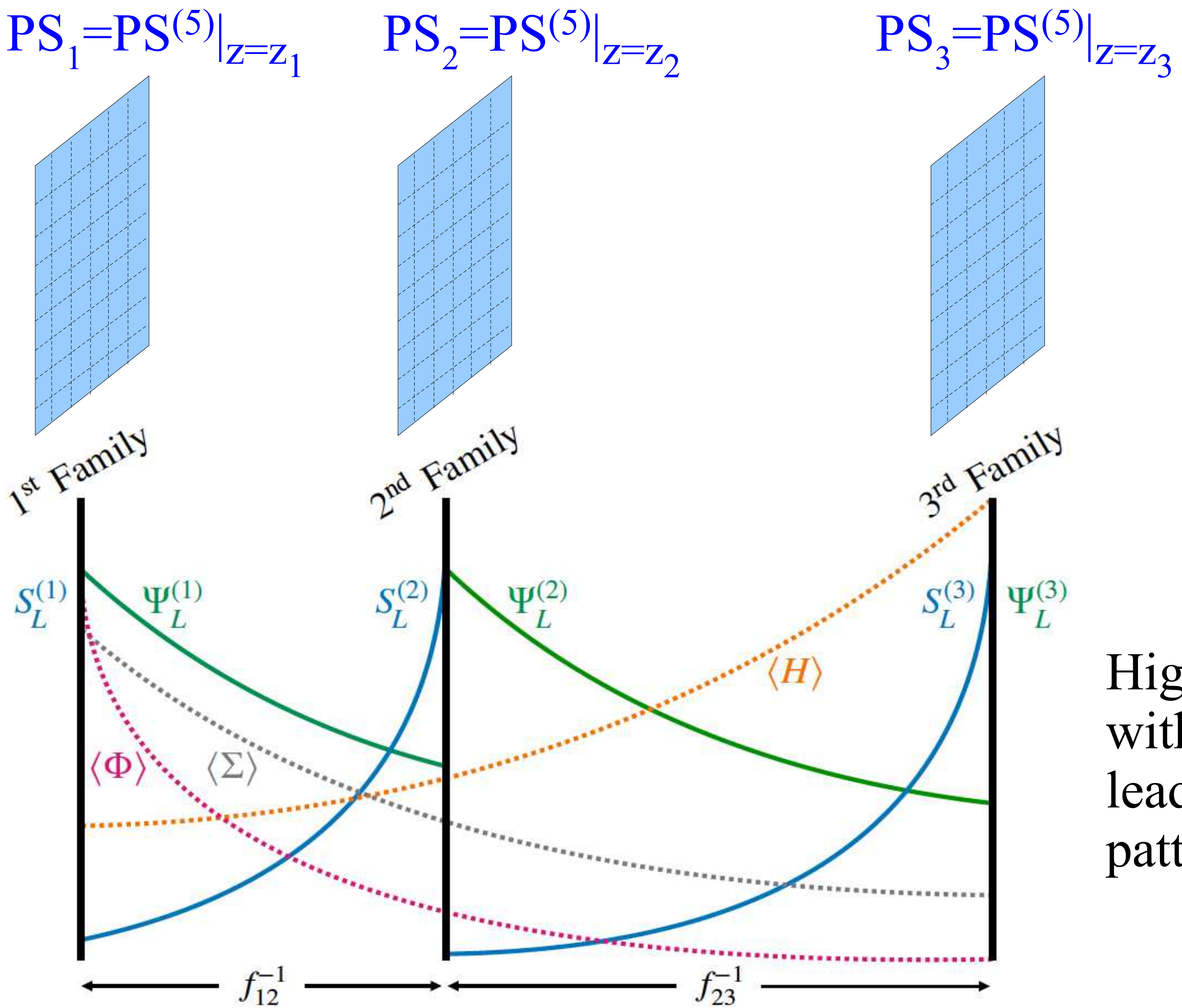
Bordone, Cornella, Fuentes-Martin, GI, '17




- Unification of quarks and leptons [*natural explanation for* $U(1)_Y$ *charges*]
- De-unification (= *flavor deconstruction*) of the gauge symmetry
- Breaking to the diagonal SM group occurs via appropriate "link" fields, responsible also for the generation of the hierarchies in the Yukawa couplings.

## A class of UV models addressing the anomalies

- The PS$^3$ set-up... and its 5D embedding




Flavor ↔ 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

Fuentes-Martin, GI, Pages, Stefanek '20

## *A class of UV models addressing the anomalies*

In all cases collider and low-energy pheno are controlled by the effective 4321 model at the TeV scale

Despite the apparent complexity, the construction is highly constrained

Renormalizable structure achieved with vector-like fermions

| Field | $SU(4)$ | $SU(3)'$ | $SU(2)_L$ | $U(1)'$ |
|---|---|---|---|---|
| $q'^i_L$ | $\mathbf{1}$ | $\mathbf{3}$ | $\mathbf{2}$ | $1/6$ |
| $u'^i_R$ | $\mathbf{1}$ | $\mathbf{3}$ | $\mathbf{1}$ | $2/3$ |
| $d'^i_R$ | $\mathbf{1}$ | $\mathbf{3}$ | $\mathbf{1}$ | $-1/3$ |
| $\ell'^i_L$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ | $-1/2$ |
| $e'^i_R$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $-1$ |
| $\psi'_L$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{2}$ | $0$ |
| $\psi'_u$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{1}$ | $1/2$ |
| $\psi'_d$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{1}$ | $-1/2$ |
| $\chi^i_L$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{2}$ | $0$ |
| $\chi^i_R$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{2}$ | $0$ |
| $H_1$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ | $1/2$ |
| $H_{15}$ | $\mathbf{15}$ | $\mathbf{1}$ | $\mathbf{2}$ | $1/2$ |
| $\Omega_1$ | $\bar{\mathbf{4}}$ | $\mathbf{1}$ | $\mathbf{1}$ | $-1/2$ |
| $\Omega_3$ | $\bar{\mathbf{4}}$ | $\mathbf{3}$ | $\mathbf{1}$ | $1/6$ |
| $\Omega_{15}$ | $\mathbf{15}$ | $\mathbf{1}$ | $\mathbf{1}$ | $0$ |

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

$\psi_3$ $\qquad$ $\psi_{1,2}$

$\langle \Omega\text{'s} \rangle$ $\quad \rightarrow$ LQ [$U_1$] + Z' + G'

[~ 1-5 TeV]

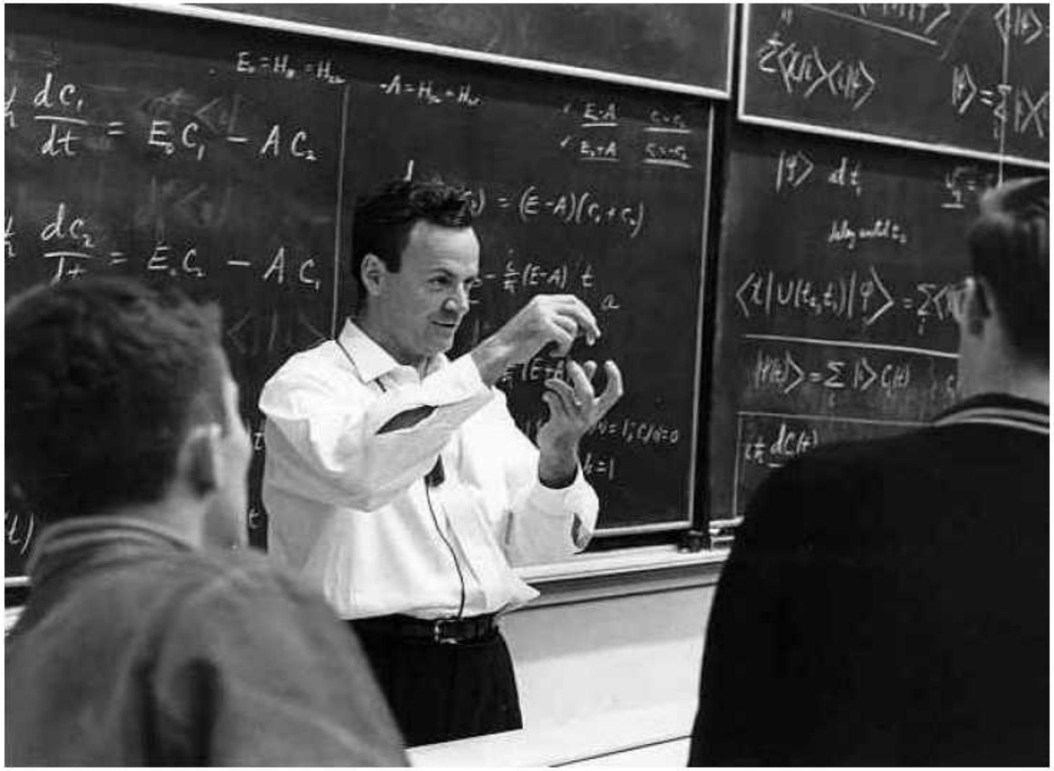
SM

$\psi_{1,2,3}$

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

*consistent with present data*

## What do we still hope to learn?



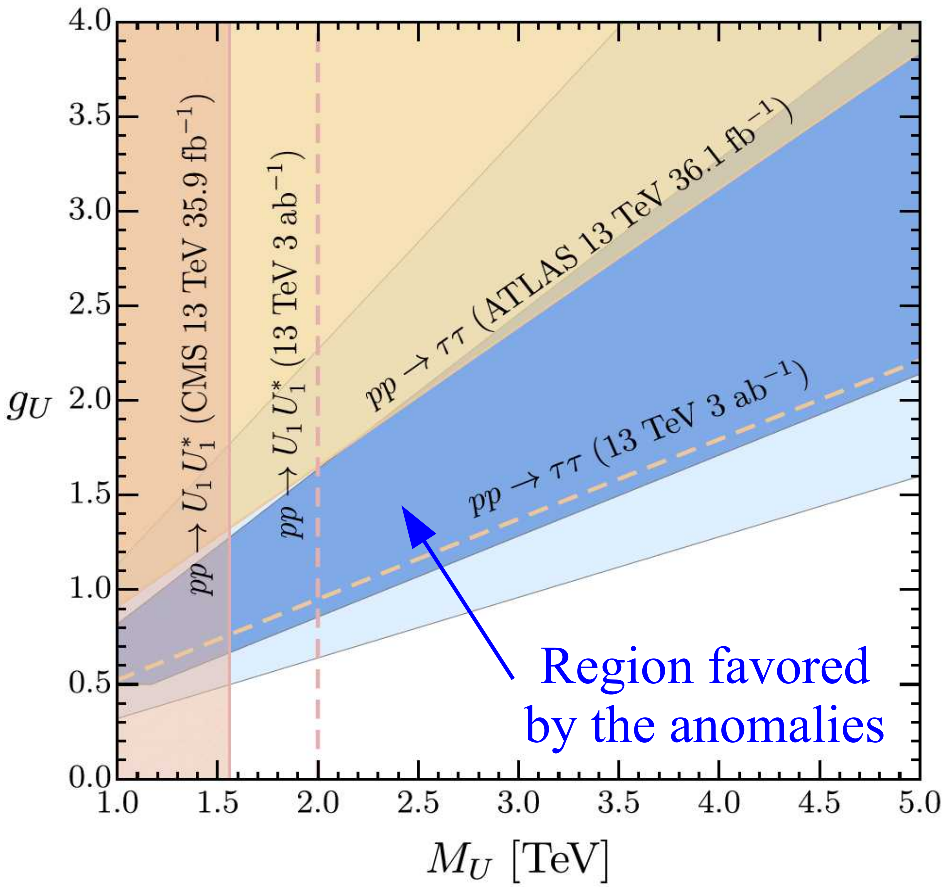
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

## *What do we still hope to learn?*

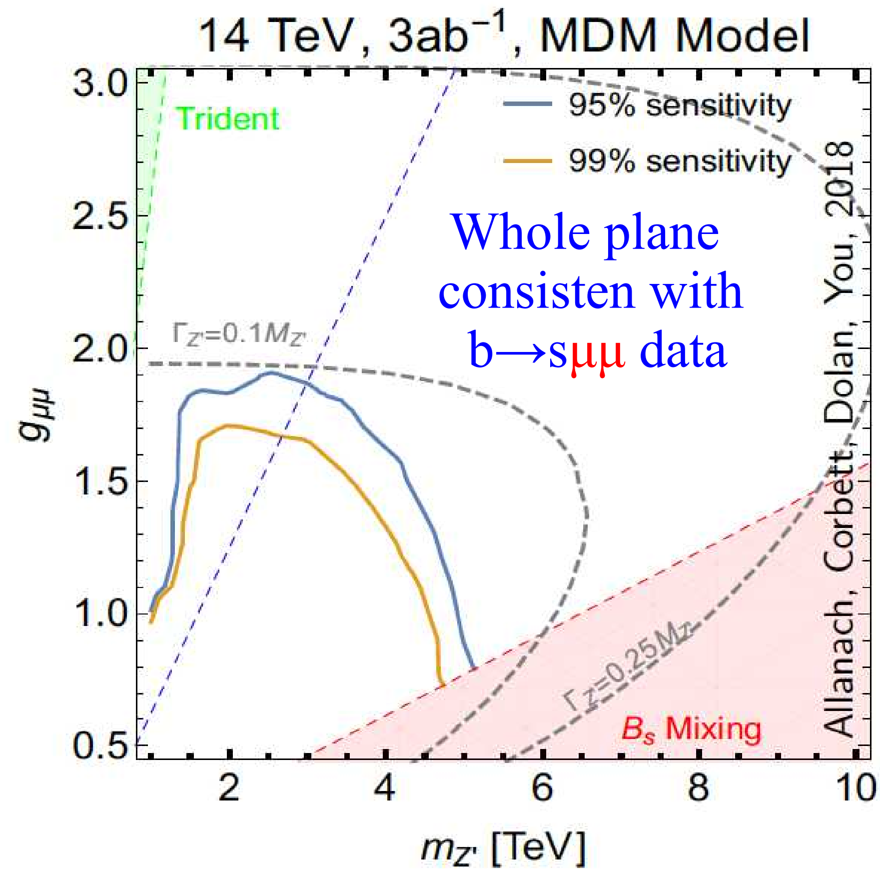
Ideally, to confirm all this... we would need to see a direct signal of the new mediators at high-pT.

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 non-univ. 4321 [Baker *et al.* '19]




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



## *What do we still hope to learn?*

Since a high-energy discovery is not guaranteed in the short term → key role still played by low-energy observables

E.g.: correlations among $b \to s(d)\ell\ell$ within the U(2)-based EFT

| | $\mu\mu$ (ee) | $\tau\tau$ | $\nu\nu$ |
|---|---|---|---|
| $b \to s$ | $R_K$, $R_{K^*}$ <br> *present anomalies* | $B \to K^{(*)} \tau\tau$ <br> ⋮ | $B \to K^{(*)} \nu\nu$ <br> ⋮ |
| $b \to d$ | $B_d \to \mu\mu$ <br> $B \to \pi\, \mu\mu$ <br> $B_s \to K^{(*)} \mu\mu$ <br> ⋮ | $B \to \pi\, \tau\tau$ <br> ⋮ | $B \to \pi\, \nu\nu$ <br> ⋮ |
| $s \to d$ | *long-distance pollution* | *NA* | $K \to \pi\, \nu\nu$ |

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| | μμ (ee) | ττ | νν |
|---|---|---|---|
| $b \to s$ | $R_K$, $R_{K^*}$<br>O(20%) | $B \to K^{(*)}\tau\tau$<br>→ 100×SM | $B \to K^{(*)}\nu\nu$<br>O(1) |
| $b \to d$<br>$R_K$ | $B_d \to \mu\mu$<br>$B \to \pi\mu\mu$<br>$B_s \to K^{(*)}\mu\mu$<br>O(20%) $[R_K=R_\pi]$ | $B \to \pi\tau\tau$<br>→ 100×SM | $B \to \pi\nu\nu$ |
| $s \to d$ | *long-distance pollution* | *NA* | $K \to \pi\nu\nu$<br>O(1) |

$$\boxed{\frac{A(b\to d\ell\ell)_{SM+NP}}{A(b\to s\ell\ell)_{SM+NP}} = \frac{A(b\to d\,\ell\ell)_{SM}}{A(b\to s\,\ell\ell)_{SM}}}$$

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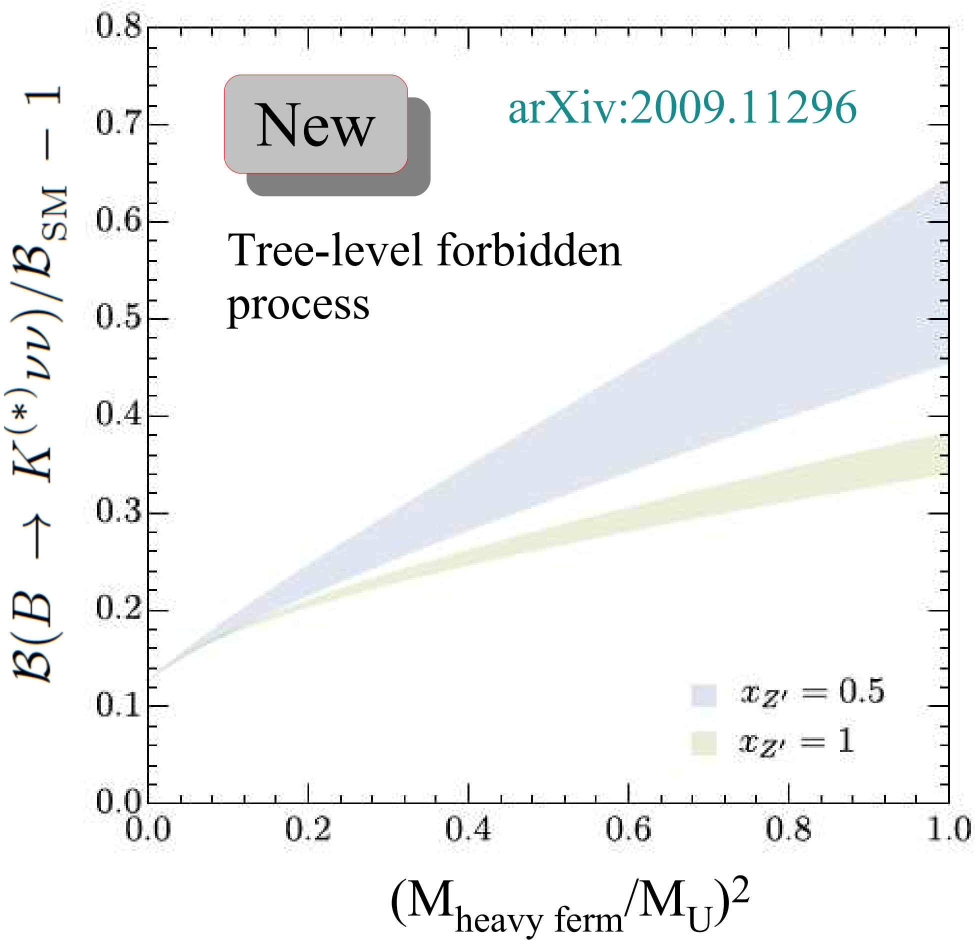


Fuentes-Martin *et al.* '20

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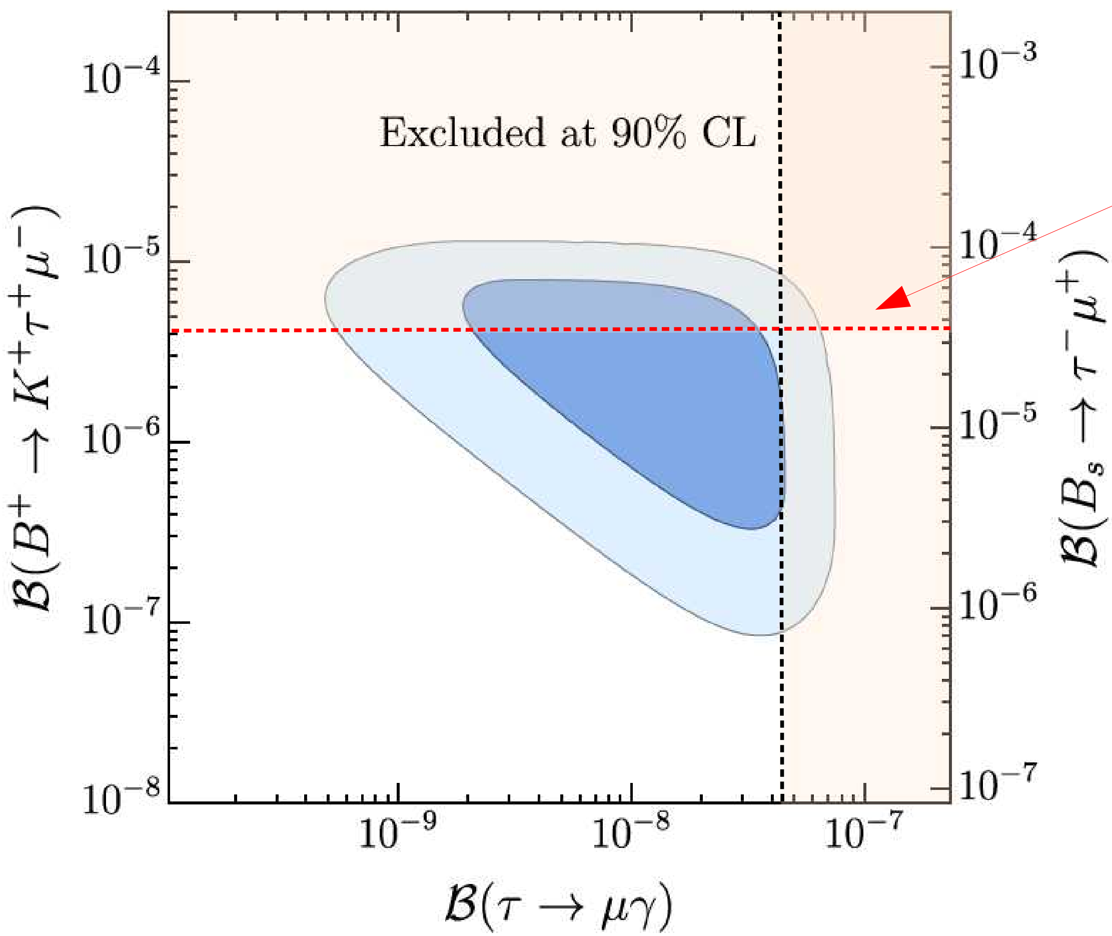
E.g.: LFV rates in the PS$^3$ model




Recent bound by LHCb entering the interesting region of parameter space

More difficult to make precise predictions for μ → e transitions.

But both μ → 3e and $K_L$ → μe could be quite close to their present exp. bounds:

BR(μ → 3e) → few $10^{-14}$

BR($K_L$ → μe) → few $10^{-12}$

## Conclusions

- The "B-physics anomalies" provide a concrete demonstration of the high discovery potential of flavor physics. Even if they will go away, they have been very beneficial in shaking some prejudices in model building and in (re-)opening new interesting directions.

    - If interpreted as NP signals, both set of anomalies are not in contradiction among themselves & with existing low- & high-energy data. Taken together, they point to NP coupled mainly to 3$^{rd}$ generation, with a flavor structure connected to that appearing in the SM Yukawa couplings.

    - Simplified models with LQ states seem to be favored. Among them, the $U_1$ case stands for simplicity & phenomenological success. The $PS^3$ model is an interesting example of (a class of) UV framework(s) which could host it, and could help to shed light on "old" SM problems.

- To understand if any of the two statements above is correct...

… we desperately need more data !!!!!