b→sll decays as probe of New Physics
[what we learned & what we still hope to learn]

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- Introduction
- A brief look to the data
- What have we learned? [3 general BSM lessons]
- An explicit model to address the anomalies
- What do we still hope to learn?
- Conclusions
Introduction

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Motivating the answer with

- No evidence of New Physics at high-pT
- SM-like Higgs particle
- No evidence of New Physics in a series of “clean” flavor-changing observables, such as $\Delta F=2$, but also $b \rightarrow s\gamma \ & B_s \rightarrow \mu\mu$
- Difficulty of making precise (“clean”) SM tests in $B \rightarrow K(*)\ell\ell$ decays

“heavy” NP

MFV-like NP

LFU tests no so interesting...
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Thanks to the recent $B \rightarrow K(*)ll$ data, we have abandoned a few theory prejudices & identified (partially rediscovered) very interesting directions in model building

not so heavy if coupled to 3rd gen. only

flavor non-universal interactions

LFU tests are very interesting!
A brief look to the data

---

**Graph 1:**
- **LHCb**
- **$R_K$ vs. $q^2 [GeV^2/c^4]$**
- Data points from BaBar, Belle, LHCb Run 1, LHCb Run 1 + 2015 + 2016

**Graph 2:**
- **LHCb**
- **$R_{K^{*0}}$ vs. $q^2 [GeV^2/c^4]$**
- Data points from LHCb, BIP, CDHMV, EOS, flav.io, JC
A brief look to the $b \rightarrow s l l$ anomalies

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

- $P'_{5}$ anomaly [$B \rightarrow K^* \mu\mu$ angular distribution]
- Smallness of all $B \rightarrow H_s \mu\mu$ rates [$H_s = K$, $K^*$, $\phi$ (from $B_s$)]
- LFU ratios ($\mu$ vs. $e$) in $B \rightarrow K^* \ell\ell$ & $B \rightarrow K \ell\ell$
- Smallness of BR($B_s \rightarrow \mu\mu$)

[Diagram showing the decay processes]
**A brief look to the \( b \to s \ell \ell \) anomalies**

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- \( P'_5 \) 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 \( B \to K^*\ell\ell \ & B \to K \ell\ell \) th. error <1%
- Smallness of \( \text{BR}(B_s \to \mu\mu) \) few %

Dealing with exclusive modes, 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

But the striking observation is that the picture of all the data is extremely coherent, pointing to well-defined non-SM effects (of short-distance origin).
A brief look to the $b \to s l l$ anomalies

- The “clean” Lepton Flavor Universality ratios:
  \[
  R_H = \frac{\int d\Gamma(B \to H \mu\mu)}{\int d\Gamma(B \to H \text{ee})} \quad (H= K, K^*)
  \]

SM prediction very robust: $(R_H) = 1$

[up tiny QED and lepton mass effects]

Bordone, GI, Pattori '16

Deviations from the SM predictions ranging from $2.2\sigma$ to $2.5\sigma$ in each of the 3 bins measured by LHCb
To a large extent, these 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 $b \rightarrow s \mu\mu$ and ($\&$ not in $e\rightarrow e\mu\mu$).

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.

\[ R_H = \frac{\int d\Gamma(B \rightarrow H \mu\mu)}{\int d\Gamma(B \rightarrow H ee)} \]
**A brief look to the $b \to sll$ anomalies**

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

  \[
  \text{BR}(B_s \to \mu\mu)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9} \quad \text{Beneke et al. '19} \\
  \text{BR}(B_s \to \mu\mu)_{\text{exp}} = (2.72 \pm 0.34) \times 10^{-9} \quad \text{ATLAS+CMS+LHCb '19}
  \]

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

→ More later today...
What have we learned?
What have we learned?

- The $b \rightarrow sll$ data show a convincing evidence of LFU violation ($\mu$ vs. $e$) in a rare (FCNC) process.
- An independent (slightly less significant, $\sim 3\sigma$) evidence of LFU violation ($\tau$ vs. $\mu$) occurs in charged-current semi-leptonic decays $b \rightarrow c\ell\nu$.

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

- LFU violation & flavor-non-universal interactions
- The role of flavor symmetries
- The Return of the Leptoquark

More tomorrow...
What have we learned?

LFU violation & flavor-non-universal interactions

The role of flavor symmetries

The Return of the Leptoquark
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:

\[
\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}}(A_a, \psi_i) + \mathcal{L}_{\text{Higgs}}(H, A_a, \psi_i)
\]

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 [\(\text{U(3)}_L \times \text{U(3)}_E \times \ldots\)]
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No reason to assume it holds beyond the SM...

[*it is not even an exact symmetry of the SM!*] \(\downarrow\) Yukawa

\[U(1)_e \times U(1)_\mu \times U(1)_\tau\]
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No reason to assume it holds beyond the SM...

However, it has been verified with extremely high accuracy in several systems:

- \(Z \rightarrow ll\) decays \([\sim 0.1\%]\]
- \(\tau \rightarrow l\nu\nu\) decays \([\sim 0.1\%]\]
- \(K \rightarrow (\pi)\nu\) decays \([\sim 0.1\%]\) & \(\pi \rightarrow l\nu\) decays \([\sim 0.01\%]\)

*This is why is often assumed as a “sacred principle”....*

Still, no deep reason, and no strong experimental tests in semileptonic processes involving 3\(^{rd}\) generation quarks, before these recent measurements
I. **LFU violation and flavor non-universal interactions**

LFU becomes a natural possibility when we consider the *flavor universality* of the SM gauge sector as pure *low-energy property*, conceiving underlying interactions which are genuinely *flavor non-universal at high energies*.

We are well aware that the “elementary fields” of QED, namely the Dirac-type elector and the photon are not the elementary constituents of the SM Lagrangian.
I. \textit{LFU violation and flavor non-universal interactions}

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\[
\begin{array}{cccc}
\text{Low energies} & U(1)_Q & \gamma & U(1)_Y \\
\text{High energies} & SU(2)_L & e_{L+R} & e_L \\
\end{array}
\]

An analog phenomenon could occur for both the SM fermions and the SM gauge interactions, in flavor space

\[
\begin{array}{cccc}
\gamma, g, W, Z & SU(3) \times SU(2) \times U(1) & e, \mu, \tau \\
\end{array}
\]

\textit{Flavour universality as the low-energy limit of a UV theory where fundamental interactions acts differently on the different generations [as signaled by their different masses...]}
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An analog phenomenon could occur for both the SM fermions and the SM gauge interactions, in flavor space.

SM fermions = mixture of different UV states is a well explored BSM option [partial compositeness → non-universality related to mass]
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\times lepton) operators
- We definitely need non-vanishing **left-handed** current-current operators although other contributions are also possible

\[
T_{ij\alpha\beta} = (\delta_{i3} \times \delta_{3j}) (\delta_{\alpha3} \times \delta_{3\beta}) + \text{small terms for 2\textsuperscript{nd} (\& 1\textsuperscript{st}) generations}
\]

\[
Q_{L}^{i} \rightarrow L_{L}^{\alpha} \quad Q_{L}^{j} \rightarrow L_{L}^{\beta}
\]

- Large coupling [competing with SM tree-level] in \(bc \rightarrow l_{3} \nu_{3}\) \([R_{D}, R_{D^{*}}]\)
- Small coupling [competing with SM loop-level] in \(bs \rightarrow l_{2} l_{2}\) \([R_{K}, R_{K^{*}}, ...]\)

*Link to pattern of the Yukawa couplings!*
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

![Diagram](image)

Long list of constraints \([\text{FCNCs} + \text{semi-leptonic b decays} + \pi, K, \tau \text{ decays} + \text{EWPO}]\)

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

\[ \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix} \]

light generations (flavor doublet)

3\textsuperscript{rd} generation (flavor singlet)

SM fermion (e.g. q\textsubscript{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\textsuperscript{rd} family
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 $U(2)^n$

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

$Y_U = y_t$

$U(2)_u$

$U(2)_q$

$\Delta$

$V$

$1$

$|V| \approx |V_{ts}| = 0.04$

$|\Delta| \approx y_c = 0.006$

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

*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 × 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

\[ \Lambda_{NP} \sim 1.5 \text{ TeV} \]
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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 → c anomaly

II. Rising “evidence” of LFU contribution to C_9 from ττ loops

III. Evidence of a ~20% suppression of BR(B_s → μμ) [as predicted in 2015...]

IV. First hint of μ/e LFU violation in Λ_b → pKll, with R_pK ≈ R_K

Crivellin et al. '19
Alguero et al. '19
Aebischer et al. '19
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...

\[ W', Z' (H) \]

\[ LQ \]

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.

\[ \Lambda_{\text{eff}} < 9 \text{ TeV} \]
\[ \Lambda_{\text{eff}} < 84 \text{ TeV} \]

Di Luzio, Nardecchia '17

No additional assumptions

Yukawa structure

Hierarchy problem

U(2)^n

few TeV

b → c \( \tau \nu \)

b → s \( \mu \mu \)
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...

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

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

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 \( \mu \) & \( e \) (such as \( K_L \rightarrow \mu e \))
  → avoided with non-trivial flavor structure [e.g. non-univ. interactions]
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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

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

- 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 + ...

- 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:** \( \text{SU(4)} \times \text{SU(2)}_L \times \text{SU(2)}_R \)

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 \(\text{SU(4)} \rightarrow \text{SU(3)}_C \times \text{U(1)}_{B-L}\)

The problem of the “original PS model” are the strong bounds on the LQ couplings to 1\text{st} & 2\text{nd} generations [e.g. \(M > 200\) TeV from \(K_L \rightarrow \mu e\)]

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**

\[
[ \text{PS} ]^3 = [ \text{SU}(4) \times \text{SU}(2)_L \times \text{SU}(2)_R ]^3
\]

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!)

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

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

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

High-scale breaking

$\text{PS}_1 \rightarrow \text{SM}_1$

Low-scale breaking

$[\text{SU}(2) \times \text{U}(1)]_3 \rightarrow \text{QED}_3$

- 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 3$^{\text{rd}}$ gen., as in the flavor-universal “4321” model [Di Luzio, Greljo, Nardecchia, '17]
**The PS$^3$ model**

Below $\sim 100$ TeV
U(2)$^5$ flavor symmetry (but for link fields)

**Leading flavor structure:**

- Yukawa coupling for 3$^{\text{rd}}$ gen. only
- “Light” LQ field (from PS$_3$) coupled only to 3$^{\text{rd}}$ gen.
- U(2)$^5$ symmetry protects flavor-violating effects on light gen.
The PS$^3$ model

Below $\sim 100$ TeV
U(2)$^5$ flavor symmetry
(but for link fields)

Sub-leading Yukawa terms from higher dim ops:

$$Y_U = \begin{bmatrix} \Delta & V \\ y_t & \end{bmatrix}$$

$$\langle \Phi^R_{\ell3} \Phi^L_{\ell3} \rangle \quad \langle \Omega_{\ell3} \rangle \quad (\Lambda_2)^2 \quad \Lambda_2$$

$$\rightarrow W_L' + W_R' [\sim 5-10 \text{ TeV}]$$

$$\rightarrow LQ [U_1] + Z' + G' [\sim 1-5 \text{ TeV}]$$
If you think all this is “too Baroque”...

...we can start here:

4321 (*flavor non-universal*) model:

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 PS$^3$ model**

Present collider and low-energy pheno are all controlled by the last-step in the breaking chain $[4321 \rightarrow \text{SM}]$

Despite the apparent complexity, the construction is highly constrained

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

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<td>1/6</td>
</tr>
<tr>
<td>$\Omega_{15}$</td>
<td>15</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

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

\[ \sim 1-5 \text{ TeV} \]

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

consistent with present data

Greljo, Stefanek, '18; Di Luzio et al. '18
Cornella, Fuentes-Martin, GI, '19
Baker, Fuentes-Martin, GI, König, '19
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 from $b \to s(d)ll$ decays

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 non-univ. 4321 [Baker et al. '19]  
E.g.: $Z'$ for $b\to s\mu\mu$ only [Allanach et al. '19]
- **What do we still hope to learn from \( b \to s(d)ll \) decays**

Since a high-energy discovery is not guaranteed in the short term → key role still played by low-energy observables [with prominent role of \( b \to s(d)ll' \)]:

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

<table>
<thead>
<tr>
<th>( b \to s )</th>
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<tbody>
<tr>
<td>( b \to s )</td>
<td>( R_K, R_{K^*} )</td>
<td>long-distance pollution</td>
</tr>
<tr>
<td>( b \to d )</td>
<td>( B_d \to \mu\mu )</td>
<td>( NA )</td>
</tr>
<tr>
<td>( B \to \pi \mu\mu )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B_s \to K^* \mu\mu )</td>
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<td></td>
</tr>
<tr>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td>( \tau\tau )</td>
<td>( \nu\nu )</td>
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<tr>
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<tr>
<td></td>
<td>$O(20%)$</td>
<td>$\to 100\times SM$</td>
<td>$O(1)$</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>$O(20%)$ $[R_K=R_\pi]$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$s \to d$ | long-distance pollution | $NA$ | $K \to \pi\nu\nu$ |
| $s \to d$ | | | $O(1)$ |

\[
\frac{A(b \to d ll)_{SM+NP}}{A(b \to s ll)_{SM+NP}} = \frac{A(b \to d ll)_{SM}}{A(b \to s ll)_{SM}}
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<td></td>
<td>$B_s \to K^* \mu\mu$</td>
<td>$\rightarrow 100\times SM$</td>
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Since a high-energy discovery is not guaranteed in the short term → key role still played by low-energy observables [ *with prominent role of* \( b \to s(d)ll' \):]

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 \( \mu \to e \) transitions.

But both \( \mu \to 3e \) and \( K_L \to \mu e \) could be quite close to their present exp. bounds:

\[
\text{BR}(\mu \to 3e) \rightarrow \text{few } 10^{-14} \\
\text{BR}(K_L \to \mu e) \rightarrow \text{few } 10^{-12}
\]
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 3rd 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 !!!!!!