Old and recent puzzles in Flavor Physics

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- Introduction [Open problems, common lore, recent hopes]
- Bottom-up approaches to describe the anomalies
- Speculations on UV completions
- Possible future implications
- Conclusions
**Introduction**

Despite all its phenomenological successes, the Standard Model has some deep unsolved problems:

- Electroweak hierarchy problem
- Flavor puzzle
- Neutrino masses
- U(1) charges
- Dark-matter
- Dark-energy
- Inflation
- Quantum gravity

Indeed we usually regard it as an effective theory, 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

Despite all its phenomenological successes, the Standard Model has some deep unsolved problems:

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<td>Electroweak hierarchy problem</td>
<td>Instability of the Higgs mass term</td>
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Introduction

Despite all its phenomenological successes, the Standard Model has some deep unsolved problems:

**Electroweak hierarchy problem**

→ Instability of the Higgs mass term

→ New dynamics close to the Fermi scale (~ 1 TeV)

"Common lore" (I): 

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

Understanding what stabilizes the Higgs sector (EW hierarchy problem) is the natural "main avenue" to discover New Physics
Introduction

This “main avenue” has led to very appealing BMS constructions that, however, so far do not find experimental confirmation (making these theories less and less appealing...) → worth to explore new directions.

- Electroweak hierarchy problem
- Flavor puzzle
  - Neutrino masses
  - U(1) charges
- Dark-matter
- Dark-energy
- Inflation
- Quantum gravity

A direction which seems to be suggested by recent low-energy data (‘flavor anomalies’ …)

If correct... → very important implications for addressing also the other problems
**Introduction [the flavor structure of the SM]**

The SM flavor sector (= the Yukawa sector) contains a large number of free parameters (fermion masses & mixing angles), which do not look at all accidental...

\[ Y_U \sim \begin{pmatrix} \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots \end{pmatrix} \]

\[ y_t = \frac{\sqrt{2} m_t}{\langle H \rangle} \approx 1 \]

The “old” flavor puzzle...
**Introduction** [the flavor structure of the SM & beyond...]

"Common lore" (II):

The flavor structures are generated at some very heavy energy scale → No chance to probe their dynamical origin

This idea is supported by a series of precision measurement of rare flavor-violating processes which show no deviations from the SM:

\[
\frac{1}{\Lambda^2} \left( \overline{\psi}_i \psi_j \right)^2
\]

Since so far (almost) everything fits well with the SM→ Strong limits on NP
Introduction [the flavor structure of the SM & beyond...]

"Common lore" (II) :

The flavor structures are generated at some very heavy energy scale $\rightarrow$ No chance to probe their dynamical origin

This idea is supported by a series of precision measurement of rare flavor-violating processes which show no deviations from the SM:

There is a flaw in the argument.... bounds above few TeV are misleading!
Introduction [the flavor structure of the SM & beyond...]

The point of view that non-trivial flavor dynamics cannot be probed at low energies is challenged by a series of recent “anomalies” in B physics: the observation of a different (non-universal) behavior of different lepton species in specific in $b \, (3^{rd}\ \text{gen.)} \rightarrow \, c,s \, (2^{nd})$ semi-leptonic processes:

- $b \rightarrow c$ charged currents: $\tau$ vs. light leptons ($\mu$, $e$)
- $b \rightarrow s$ neutral currents: $\mu$ vs. $e$

IF taken together... this is probably the largest “coherent” set of NP effects in present data...

The “new” flavor puzzle...
**Introduction** [the recent hopes... (I) \( b \to c \ell \nu \)]

Test of LFU in charged currents [\( \tau \) vs. light leptons (\( \mu, e \))]:

\[
R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}
\]

\( X = D \) or \( D^* \)

- SM prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in \( R(X) \) expected only from phase-space differences
- Consistent results by 3 different exps. \( \rightarrow 3.6\text{–}3.9\sigma \) excess over SM (\( D + D^* \))
- The two channels are well consistent with a universal enhancement (~30%) of the SM \( b_L \to c_L \tau_L \nu_L \) amplitude
Introduction [the recent hopes... (I) b → c lv ]

Test of LFU in charged currents
[τ vs. light leptons (μ, e)]:

- **BaBar had. tag**
  - 0.440 ± 0.058 ± 0.042
- **Belle had. tag**
  - 0.375 ± 0.064 ± 0.026
- **Average**
  - 0.407 ± 0.039 ± 0.024
- **SM Pred. average**
  - 0.299 ± 0.003
- **PRD 94 (2016) 094008**
  - 0.299 ± 0.003
- **PRD 95 (2017) 115008**
  - 0.299 ± 0.003
- **JHEP 1712 (2017) 060**
  - 0.299 ± 0.004
- **FNAL/MILC (2015)**
  - 0.299 ± 0.011
- **HPQCD (2015)**
  - 0.300 ± 0.008

- **BaBar had. tag**
  - 0.332 ± 0.024 ± 0.018
- **Belle had. tag**
  - 0.293 ± 0.038 ± 0.015
- **Belle sl.tag**
  - 0.302 ± 0.030 ± 0.011
- **Belle hadronic tau**
  - 0.270 ± 0.035 ± 0.027
- **LHCb muonic tau**
  - 0.336 ± 0.027 ± 0.030
- **LHCb hadronic tau**
  - 0.291 ± 0.019 ± 0.029
- **Average**
  - 0.306 ± 0.013 ± 0.007
- **SM Pred. average**
  - 0.258 ± 0.005
- **PRD 95 (2017) 115008**
  - 0.257 ± 0.003
- **JHEP 1711 (2017) 061**
  - 0.260 ± 0.008
- **JHEP 1712 (2017) 060**
  - 0.257 ± 0.005
Various (non-LFU) anomalies, from angular distributions and BR's. Most notably: theoretically clean deviations from the SM in LFU $\mu/e$ ratios:

$$R_H = \frac{\int d\Gamma(B \to H \mu\mu)}{\int d\Gamma(B \to H ee)}$$

$$R_K [1-6 \text{ GeV}^2] = 0.75 \pm 0.09$$

LHCb '14 (vs. $1.00 \pm 0.01$ SM)

Overall significance $\sim 3.8\sigma$

(LFU ratios only)

All effects (LFU + non-LFU) well described by NP of short-distance origin only in $b \to s \mu\mu$ and (& not in $ee$)

Descotes-Genon, Matias, Virto '13, '15; Capdevila et al. '17; D'Amico et al. '17; Altmannshofer & Straub '13, '15, Ciuchini et al. '17; Hurth et al. '16, '17, Many others...
**Introduction** [the flavor structure of the SM & beyond...]

The point of view that non-trivial flavor dynamics cannot be probed at low energies is challenged by a series of recent “anomalies” in B physics: the observation of a different (non-universal) behavior of different lepton species in specific in $b \rightarrow c,s$ (2\textsuperscript{nd}) semi-leptonic processes:

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What is particularly interesting, is that these anomalies are challenging an assumption (Lepton Flavor Universality), that we gave for granted for many years (without many good theoretical reasons...)

\[ \text{Interesting shift of paradigm} \]
\[ \text{in flavor physics, but possibly also beyond} \]
Suppose we could test matter only with long wave-length photons...

We would conclude that these two particles are “identical copies” but for their mass ...
Introduction [General considerations on LFU]

Suppose we could test matter only with long wave-length photons...

\[ \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \]

\[ \gamma, \text{e}^+, \text{p}^+ \]

We would conclude that these two particles are “identical copies” but for their mass ... 

\[ \gamma, g, W, Z \]

\[ \text{e}, \text{\mu}, \text{\tau} \]

These three (families) of particles seems to be “identical copies” but for their mass ...

The SM quantum numbers of the three families could be an “accidental” low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass
Introduction [General considerations on LFU]

Along the same line...

\[
\begin{align*}
\text{Low energies} & \quad \text{High energies} \\
\gamma & \quad \text{U(1)}_Q \\
& \quad \text{e}_L \quad \text{e}_R \\
& \quad \text{SU(2)}_L \\
& \quad \text{e}_L \quad \text{e}_R
\end{align*}
\]
Introduction [General considerations on LFU]

Along the same line...

\[ \text{Low energies} \quad U(1)_Q \quad \gamma \quad e_L \quad e_R \quad \text{SU}(2)_L \]

\[ \text{High energies} \quad U(1)_Y \quad e_L \quad e_R \]

\[ \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \quad \gamma, g, W, Z \quad \text{e, } \mu, \tau \]

The apparent flavor symmetry of the SM could well be only an accidental low-energy property, such as isospin or SU(3) in QCD...
Introduction [General considerations on LFU]

So far, the vast majority of BSM model-building attempts

- Concentrate only on the Higgs hierarchy problem
- Postpone (ignore) the flavor problem, implicitly assuming the 3 families are “identical” copies (but for Yukawa-type interactions)

The recent flavor anomalies seem to suggest a shift of paradigm:

- **We should not ignore the flavor problem** [→ new (non-Yukawa) interactions at the TeV scale 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
Introduction [General considerations on LFU]

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And, if we are lucky... these anomalies may help us to find new ways to achieve quark-lepton unification [→ natural explanation for the U(1) charges]
Bottom-up approaches to describe the anomalies
**Effective Field Theory considerations**

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing left-handed current-current operators [Fermi-like effective theory], although other contributions are also possible
**Effective Field Theory considerations**

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing *left-handed* current-current operators [*Fermi-like effective theory*], although other contributions are also possible

\[
Q_L^i \quad L_L^\alpha \\
Q_L^j \quad L_L^\beta
\]

- Large coupling (competing with SM tree-level) in \( bc \rightarrow l_3 \nu_3 \)
- Small non-vanishing coupling (competing with SM FCNC) in \( bs \rightarrow l_2 l_2 \)

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

*Link to pattern of the Yukawa couplings!*
**Effective Field Theory considerations**

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- Data largely favor non-vanishing left-handed current-current operators [Fermi-like effective theory], although other contributions are also possible

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Q_L^i \quad L_L^\alpha \\
Q_L^j \quad L_L^\beta
\]

→ Long list of constraints from other low-energy processes

E.g:

- \(\tau\rightarrow\mu\nu\nu\) by Calibbi, Crivellin, Ota '15
- \(B_s\rightarrow B_s\) by Feruglio, Paradisi, Pattori '16
- \(K\rightarrow\mu\nu\nu\) by Calibbi, Crivellin, Ota '15

+ many more...
**Effective Field Theory considerations**

- Anomalies are seen only in semi-leptonic (quark×lepton) operators.
- Data largely favor non-vanishing **left-handed** current-current operators [**Fermi-like effective theory**], although other contributions are also possible.

\[
Q_L^i \quad L_L^\alpha \\
Q_L^j \quad L_L^\beta
\]

→ **Long list of constraints** from other low-energy processes

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.
**EFT-type considerations** [The $U(2)^n$ flavor symmetry]

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 flavor symmetry of the type

\[ G_{\text{flav}} \supseteq U(2)_q \times U(2)_l \]

\[ Q_L^i \quad L_L^\alpha \]
\[ Q_L^j \quad L_L^\beta \]

i.e. a (chiral flavor) symmetry acting only on the two “light” generations inspired by the structure observed in the Yukawa couplings:

\[ \mathcal{L}_Y = Q_L^i Y^i_U U_R^j \phi \]

\[ Y_U = y_t \]
\[ \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \]

\[ U(2)_q \]
\[ \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix} \equiv \begin{bmatrix} \cdot & \cdot \\ \cdot & \cdot \end{bmatrix} \]

unbroken symmetry  
breaking terms
Adopting the $U(2)_q \times U(2)_l$ symmetry, with Yukawa-type breaking pattern, as guiding principle for the EFT describing the anomalies, leads to a good fit to all available data:

\[ \Lambda_{NP} \sim 1.5 \text{ TeV} \]

Buttazzo Greljo, GI, Marzocca '17

The virtue of this EFT analysis is the demonstration that is possible to find a “combined” (motivated) explanation of the two set of anomalies.
Simplified dynamical models [“The Return of the LeptoQuark”...]

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options (for the combined explanation):

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<th>SU(2)$_L$</th>
<th>singlet</th>
<th>triplet</th>
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<td>Vector LQ:</td>
<td>$U_1$</td>
<td>$U_3$</td>
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<td>Scalar LQ:</td>
<td>$S_1$</td>
<td>$S_3$</td>
</tr>
<tr>
<td>Colorless vector:</td>
<td>$B'$</td>
<td>$W'$</td>
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W', Z' (H)

Lepto-Quark
**Simplified dynamical models** [“The Return of the LeptoQuark”...]

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options (for the combined explanation):

- **SU(2)\(_L\)** singlet triplet
  - **Vector LQ:** \(\text{U}_1\) \(\text{U}_3\)
  - **Scalar LQ:** \(\text{S}_1\) \(\text{S}_3\)
  - **Colorless vector:** \(\text{B}'\) \(\text{W}'\)

The \(\text{U}_1\) option fits quite nicely... but of course models with more than one mediators are possible
**Simplified dynamical models** [“The Return of the LeptoQuark”...]

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options (for the combined explanation):

- **SU(2)$_L$**
  - singlet
  - triplet

Vector LQ: $U_1$, $U_3$

Scalar LQ: $S_1$, $S_3$

Colorless vector: $B'$, $W'$

Most important: LQ (both scalar and vectors) have an additional clear advantage concerning constraints from non-semileptonic processes:

Similarly, 3rd gen. LQ are in very good shape also as far as direct searches are concerned (contrary to $Z'$...):
Speculations on UV completions

\[
PS_1 = PS^{(5)}|_{z=z_1} \quad PS_2 = PS^{(5)}|_{z=z_2} \quad PS_3 = PS^{(5)}|_{z=z_3}
\]

\[
\psi^L,R_1 \quad \psi^L,R_2 \quad \psi^L,R_3
\]
Speculations on UV completions

Two main approaches

Non-perturbative
TeV-scale dynamics
[non-renormalizable models]

Perturbative
TeV-scale dynamics
[renormalizable models]

Long list of interesting attempts in the recent literature, not worth (and practically impossible) to cover them all.

In the following I will now concentrate on one (class of) option(s) that I find particularly interesting.
Speculations on UV completions

Starting observation: a 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 the anomalies (best single mediator):

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

Fermions in SU(4):

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

Main Pati-Salam idea:

Lepton number as “the 4th color”

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

\[
\text{SU}(4) \sim \begin{bmatrix}
\text{SU}(3)_C & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
0 & LQ \\
LQ & \frac{1}{3}
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & -1
\end{bmatrix}
\]
Speculations on UV completions

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

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 \( K_L \rightarrow \mu e \)]

→ we must go beyond the original model
**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

SM

- Light LQ coupled mainly to 3rd gen.
- Accidental U(2)$^5$ flavor symmetry
- Natural structure of SM Yukawa couplings

IR

Q$_i$, u$_i$, d$_i$, L$_i$, e$_i$
The PS³ model

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

PS₁ = PS(5)|_{z=z₁} \quad \text{PS}_2 = \text{PS}(5)|_{z=z₂} \quad \text{PS}_3 = \text{PS}(5)|_{z=z₃}

Unification
of quarks and leptons

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

This construction can find a “natural” justification in the context of models with extra space-time dimensions

The 4D description is apparently more complex, but it allow us to derive precise low-energy phenomenological signatures (4D renormalizable gauge model)
The \( \text{PS}^3 \) model

\[ \Sigma_1 \xrightarrow{\Phi^{R/L}_{12}} \Phi^R_{12} \xrightarrow{\Omega_{12}} \Phi^L_{12} \xrightarrow{\Omega_{23}} \Phi^R_{23} \xrightarrow{\Omega_{23}} \Phi^L_{23} \xrightarrow{\Omega_{23}} H_3 \]

High-scale \([\sim 10^3 \text{ TeV}]\)
“vertical” breaking

\( \text{PS}_1 \rightarrow \text{SM}_1 \)

link fields

\( \text{PS}_i \times \text{PS}_j \rightarrow \text{PS}_{i+j} \)

Low-scale “vertical” Breaking \([\text{EWSB}]\)

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

\( \text{SM} (\rightarrow \text{QCD} \times \text{QED}) \)

\( \text{PS}_i \)

\( \Psi_1 \)

\( \Psi_2 \)

\( \Psi_3 \)

\( \text{H}_3 \)

\( \text{Su}_1 \)

\( \Phi^R_{12} \)

\( \Phi^L_{12} \)

\( \Omega_{12} \)

\( \Phi^R_{23} \)

\( \Phi^L_{23} \)

\( \Omega_{23} \)

\( \text{SM} (\rightarrow \text{QCD} \times \text{QED}) \)

\( \text{PS}_1 \rightarrow \text{SM}_1 \)

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.
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$^3_3$) coupled only to 3$^{\text{rd}}$ gen.
- U(2)$^5$ symmetry protects flavor-violating effects on light gen.
**The \( \text{PS}^3 \) model**

\[
\begin{align*}
\Sigma_1 & \quad \text{PS}_1 \quad \Phi^R_{12} \quad \Phi^L_{12} \quad \Omega_{12} \\
\psi_1 & \quad \text{PS}_2 \quad \Phi^R_{23} \quad \Phi^L_{23} \quad \Omega_{23} \\
\psi_2 & \quad \text{PS}_3 \quad \Omega_{23} \quad \psi_3 \\
& \quad H_3
\end{align*}
\]

Below \( \sim 100 \text{ TeV} \)

U(2)^5 flavor symmetry

(but for link fields)

\[ \text{SU}(2)^5 \Rightarrow \text{SU}(3)_{1+2} \quad \Phi^R_{\ell 3} \quad \Phi^L_{\ell 3} \quad \Omega_{\ell 3} \]

\[ \text{PS}_3 \quad \Omega_{\ell 3} \quad \psi_3 \]

\[ \rightarrow \text{W}_L' + \text{W}_R' [\sim 5-10 \text{ TeV}] \]

Sub-leading Yukawa terms

from higher dim ops:

\[ Y_U = \begin{bmatrix} \Delta & V \\ y_t & \sqrt{\frac{\langle \Phi^R_{\ell 3} \Phi^L_{\ell 3} \rangle}{(\Lambda_{23})^2}} & \langle \Omega_{\ell 3} \rangle \frac{\Lambda_{23}}{\Lambda_{23}} \end{bmatrix} \]

\[ \rightarrow \text{LQ} [U_1] + Z' + G' [\sim 1-2 \text{ TeV}] \]
Collider phenomenology and flavor anomalies are controlled by the last-but one step in the breaking chain. Despite the apparent complexity, the construction is highly constrained:

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

Quark flavor structure determined up to an angle (\( \rightarrow \) degree of alignment to d-quark mass basis)

Key difference to all existing pheno models: unsuppressed \( b_R - \tau_R \) coupling of the LQ
The PS$^3$ model

Collider phenomenology and flavor anomalies are controlled by the last-but-one step in the breaking chain.

Despite the apparent complexity, the construction is highly constrained.

The fit to low-energy data is very good (although slightly smaller NP effects in $R_D$, mainly because of radiative constraints).
Possible future implications

“It is very difficult to make predictions, especially about the future”

[attributed to Niels Bohr]
**Implications for low-energy flavor physics**

If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

**Main message:** “super-reach” flavor program for LHCb, but also other flavor physics facilities (Belle-II, Kaons, CLFV)

- 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...*
### Implications for low-energy flavor physics

If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables.

E.g.: **correlations among down-type FCNCs** [using the results of $U(2)$-based EFT]:

<table>
<thead>
<tr>
<th></th>
<th>μμ (ee)</th>
<th>ττ</th>
<th>νν</th>
<th>τμ</th>
<th>μe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to s$</td>
<td>$R_K, R_{K^*}$</td>
<td>$B \to K^{(*)}\tau\tau$</td>
<td>$B \to K^{(*)}\nu\nu$</td>
<td>$B \to K\tau\mu$</td>
<td>$B \to K\mu\nu$</td>
</tr>
<tr>
<td></td>
<td>$O(20%)$</td>
<td>$\to 100\times\text{SM}$</td>
<td>$O(1)$</td>
<td>$\to \sim 10^{-5}$</td>
<td>$???$</td>
</tr>
<tr>
<td>$b \to d$</td>
<td>$B_d \to \mu\mu$</td>
<td>$B \to \pi\tau\tau$</td>
<td>$B \to \pi\nu\nu$</td>
<td>$B \to \pi\tau\mu$</td>
<td>$B \to \pi\mu\nu$</td>
</tr>
<tr>
<td></td>
<td>$O(20%)$ [R$<em>K$=R$</em>\pi$]</td>
<td>$\to 100\times\text{SM}$</td>
<td>$O(1)$</td>
<td>$\to \sim 10^{-7}$</td>
<td>$???$</td>
</tr>
<tr>
<td>$s \to d$</td>
<td><strong>long-distance pollution</strong></td>
<td>$NA$</td>
<td>$K \to \pi\nu\nu$</td>
<td>$NA$</td>
<td>$K \to \mu\nu$</td>
</tr>
<tr>
<td></td>
<td>$O(1)$</td>
<td>$???$</td>
<td>$???$</td>
<td>$???$</td>
<td>$???$</td>
</tr>
</tbody>
</table>
**Implications for low-energy flavor physics**

E.g: expectation of LFV processes in the PS$^3$ model:

\[
\left( \frac{\Delta R_D}{0.2} \right)^2 \left( \frac{\Delta R_K}{0.3} \right)^2 \approx 3 \left[ \frac{\mathcal{B}(B \to K^{+}\mu^{-})}{3 \times 10^{-5}} \right] \left[ \frac{\mathcal{B}(\tau \to \mu\gamma)}{5 \times 10^{-8}} \right] \approx \left[ \frac{\mathcal{B}(B_s \to \tau^{\pm}\mu^{\mp})}{2 \times 10^{-4}} \right] \left[ \frac{\mathcal{B}(\tau \to \mu\gamma)}{5 \times 10^{-8}} \right]
\]
Implications for high-$p_T$ physics

Some general considerations:

Independently of the details of the UV models, the anomalies (and particularly the $b \to c$ one) point to NP in the ball-park of direct searches @ LHC

This NP could have escaped detection so far only under specific circumstances (that are fulfilled by the proposed UV completions...):

- Coupled mainly to 3rd generation ($\to$ no large coupl. to proton valence quarks)
- No narrow peaks in dilepton pairs (including tau pairs)

Significant room for improvement for the corresponding searches @ HL-LHC
But only HE-LHC would be able to rule out all reasonable models
**Implications for high-$p_T$ physics**

Some general considerations:

Independently of the details of the UV models, the anomalies (and particularly the $b \rightarrow c$ one) point to **NP in the ball-park of direct searches @ LHC**

Most interesting signatures:

- **unambiguous** (model-independent) prediction of large $pp \rightarrow \tau \tau$ & $pp \rightarrow \tau \nu$, which is quite close to present sensitivity

- models predicting companions of the LQ coupled to 3$^{rd}$ gen. quark currents (such as $Z'$ or “heavy gluons”) lead to large $pp \rightarrow \text{tt}$, which starts to be in tension with present data
Implications for high-$p_T$ physics

E.g.: 3$^\text{rd}$ generation Pair vs. Single scalar LQ production @CMS:
Implications for high-$p_T$ physics

E.g.: $pp \rightarrow \tau\tau$ from t-channel exchange LQ production
(re-interpretation of ATLAS & CMS $\tau\tau$ resonance search)

Buttazzo et al. '17

$|g_U|$ vs. $M_U$ (TeV)

$pp \rightarrow \tau^+ \tau^-$ 300 fb$^{-1}$

$pp \rightarrow \tau^+ \tau^-$ [1609.07138]

Vector LQ

$pp \rightarrow \tau^+ \tau^-$ 12.9 fb$^{-1}$

$pp \rightarrow \tau^+ \tau^-$ 20 fb$^{-1}$

$pp \rightarrow \tau^+ \tau^-$ ATLAS 8 TeV 20 fb$^{-1}$

$pp \rightarrow \tau^+ \tau^-$ CMS 13 TeV 12.9 fb$^{-1}$
**Implications for high-$p_T$ physics**

In specific models, such as the PS$^3$, the TeV-scale phenomenology involve (several) additional states not directly involved in the anomalies.

E.g.: The “Coloron” (= “heavy gluon” coupled preferably to 3$^{rd}$ generation) in $pp \rightarrow tt$
Conclusions

- If these LFU anomalies are confirmed, it would be a fantastic discovery, with far-reaching implications.

- If interpreted as NP signals, both sets of anomalies are not in contradiction among themselves & with existing low- & high-energy data. Taken together, they point out 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. However, realistic UV completions for these models naturally imply a much richer spectrum of states at the TeV scale (and possibly above...) → nearby signatures at high-pT.

- The PS^3 model I have presented is an interesting example of the change of paradigm in model building that these anomalies could imply. But many points/possible-variations remains to be clarified/explored...

\[ \downarrow \]

\textit{A lot of fun ahead of us...} (both on the exp., the pheno, and model-building point of view)
G. Isidori – Old and recent puzzles in Flavor Physics

KEK-PH 2018, December 2018
Symmetry breaking pattern in $PS^3$

High-scale [$\sim 10^3$ TeV]
“vertical” breaking [$PS \rightarrow SM$]

$PS_1$ [$SU(4)_1 \times SU(2)^R_1$]

$SM_1$ [$SU(3)_1 \times U(1)^Y_1$]
Symmetry breaking pattern in $\text{PS}^3$

$\Sigma_1$

$\text{PS}_1$

$\psi_1$

$\langle \Sigma_1 \rangle$

$\Lambda_1 > E > \Lambda_{12}$

$\text{SM}_1$

$\Phi_{12}^{L,R}$

$\langle \Phi_{12}^{L,R} \rangle$

$\Omega_{12}$

$\langle \Omega_{12} \rangle$

$\Lambda_{12} > E > \Lambda_{23}$

$\text{SM}_{1+2}$

$\psi_{1,2}$

Below $\sim 100$ TeV

$\text{U}(2)^5$ flavor symmetry

(but for link Yuk. coupl.)

$\text{PS}_2$

$\psi_2$

$\text{PS}_3$

$\psi_3$

$H_3$

$\text{SM}_{1+2}$

$\psi_{1,2}$

$\Phi_{12}^L \sim (1,2,1)_1 \times (1,2,1)_2$

$\Phi_{12}^R \sim (1,1,2)_1 \times (1,1,2)_2$

$\Omega_{12} \sim (4,2,1)_1 \times (4,2,1)$

VEV $\rightarrow$ $\text{SU}(2)^L_{1+2}$

VEV $\rightarrow$ $\text{SU}(2)^R_{1+2}$

VEV $\rightarrow$ $\text{SU}(4)_{1+2}$ & $\text{SU}(2)^L_{1+2}$
Anomalies in $B \to K^{(*)} \mu\mu / ee$ [LHCb]

Several groups performed global fits of all the available $b \to s \ell\ell$ observables

No consensus on the significance of the non-LFU observables, but full agreement on the main aspects:

- All effects well described by NP of short-distance origin only in $b \to s \mu\mu$ and (& not in $ee$)
- LH structure on the quark side:

$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Descotes-Genon, Matias, Virto '13, '15
Capdevila et al. '17; D'Amico et al. '17
Altmannshofer & Straub '13, '15
Ciuchini et al. '17; Hurth et al. '16, '17
Many others...
Anomalies in $B \rightarrow K^{(*)} \mu\mu / ee$ \([\text{LHCb}]\)

Several groups performed global fits of all the available $b \rightarrow sll$ observables

No consensus on the significance of the non-LFU observables, but full agreement on the main aspects:

Consistency with smallness of $\text{BR}(B_s \rightarrow \mu\mu)$ for $C_9 = -C_{10}$

$\text{BR}(B_s \rightarrow \mu\mu)_\text{SM} = (3.57 \pm 0.17) \times 10^{-9}$

$\text{BR}(B_s \rightarrow \mu\mu)_\text{exp} = (2.65 \pm 0.43) \times 10^{-9}$

Naïve average of LHCb + CMS + ATLAS ('18)

Descotes-Genon, Matias, Virto '13, '15
Capdevila et al. '17; D'Amico et al. '17
Altmannshofer & Straub '13, '15
Ciuchini et al. '17; Hurth et al. '16, '17
Many others...
Anomalies in $B \rightarrow K^{(*)} \mu\mu / ee$ [LHCb]

- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients

More precise data on the $q^2=m_{\mu\mu}$ distribution can help to distinguish NP vs. SM

Descotes-Genon, Matias, Virto '15