Hints of physics beyond the Standard Model in the Flavor Sector

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- Introduction [Flavor Physics within and beyond the SM]
- On the recent “anomalies” in B-physics
- Bottom-up approaches to describe the anomalies
- Speculations on UV completions
- Possible future implications
- Conclusions
Introduction

The Standard Model has proven to be successful over an unprecedented range of energies. However, despite all its phenomenological successes, this Theory has some deep unsolved problems (hierarchy problem, flavor pattern, dark-matter, U(1) charges,...)

The SM should be regarded as an effective theory, i.e. the limit –in the accessible range of energies and effective couplings– of a more fundamental theory, with new degrees of freedom
\textbf{Introduction}

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\textit{“Common lore”} (I):

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

Understanding what \textbf{stabilizes the Higgs sector} \textit{(hierarchy problem)} is the natural “avenue” to discover New Physics
**Introduction**

The Standard Model has proven to be successful over an unprecedented range of energies. However, despite all its phenomenological successes, this Theory has some deep unsolved problems (*hierarchy problem*, flavor pattern, dark-matter, U(1) charges,...)

The SM should be regarded as an effective theory, i.e. the limit –in the accessible range of energies and effective couplings– of a more fundamental theory, with new degrees of freedom.

*But we must admit that, so far, we have very little clues about the validity range of this effective theory...*

We need to search for New Physics with a broad spectrum perspective.

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- Probe physics at energy scales not directly accessible at accelerators

Key (unique) role of **Flavor Physics**
The Flavor structure of the SM

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

3 identical replica of the basic fermion family
[\psi = Q_L, u_R, d_R, L_L, e_R] ⇒ huge flavor-degeneracy [U(3)^5 symmetry]
The Flavor structure of the SM

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3 identical replica of the basic fermion family
\[ [\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow \text{huge flavor-degeneracy} \]

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

\[ \bar{L}_L^i Y^i_L e_R^k \phi + \text{h.c.} \rightarrow \bar{l}_L^i M_{L}^{ii} l_R^i + \ldots \]
\[ \bar{Q}_L^i Y_D^{ik} d_R^k \phi + \text{h.c.} \rightarrow \bar{d}_L^i M_D^{ik} d_R^k + \ldots \]
\[ \bar{Q}_L^i Y_U^{ik} u_R^k \phi_c + \text{h.c.} \rightarrow \bar{u}_L^i M_U^{ik} u_R^k + \ldots \]
Altogether, the SM flavor (Yukawa) sector is characterized by 13 parameters:

\[
\begin{pmatrix}
3 & \text{lepton masses} \\
6 & \text{quark masses} \\
3+1 & \text{CKM parameters}
\end{pmatrix}
\]

Which do not look at all accidental...

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

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

....and which are determined with high accuracy
The Flavor structure of the SM and beyond...

The key question we try to address by continuing doing high-precision measurements of flavor-changing processes of quarks & charged-leptons is:

Are there other sources of flavor symmetry breaking [beside the SM Yukawas]?

So far everything seems to fit well with the SM→ Strong limits on NP

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{1}{\Lambda^2} \mathcal{O}_{\text{eff}} \]

“Common lore” (II):

The flavor structures are generated at some very heavy energy scale

→ No chance to probe their dynamical origin
This point of view is challenged by the recent “anomalies” in B physics, i.e. the observation of a different (non-universal) behavior of different lepton species in specific semi-leptonic processes:

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

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

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...)

**Interesting shift of paradigm**
(in flavor physics, but possibly also beyond)
**A digression on LFU**

Let's go back ~ 100 years, and suppose we can test matter only with long wavelength photons...

$$\gamma$$

$U(1)_{Q}$

$\bullet$  
$\bullet$  
$e^+$  
$p^+$

These two particles seem to be "identical copies" but for their mass ...
A digression on LFU

Let's go back ~ 100 years, and suppose we can test matter only with long wavelength photons...

γ
U(1)Q

These two particles seems to be “identical copies” but for their mass ...

e^+ p^+

That's exactly the same (misleading) argument we use to infer LFU...

γ, g, W, Z
SU(3)×SU(2)×U(1)

e μ τ

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
A digression 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)

---

**“Common lore” (I)**

**“Common lore” (II)**

\[ W, Z + H \]

large (*more interesting...*)

small (*less interesting...*)
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- 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 3\textsuperscript{rd} gen.) may be the key to solve/understand also the gauge hierarchy problem

\[ W, Z + H \]

\[ \text{large (more interesting...)} \]
\[ \text{small (less interesting...)} \]

\[ 3\text{rd} \]
\[ \text{NP} \]

\[ 3\text{rd} \]

\[ \text{small (less interesting...)} \]
\[ \text{large (more interesting...)} \]
A digression on LFU

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- We should not ignore the flavor problem \(\rightarrow\) new (non-Yukawa) interactions at the TeV scale distinguishing the different families
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And if we are lucky... these anomalies may help us to shed light on another key problem of the SM that we have postponed (somehow forgotten...) for a long time:

- The quantization of U(1) charges and the possible (natural...) quark-lepton unification
On the recent B-physics anomalies

\[ R(D) = 0.300(8) \text{ HPQCD (2015)} \]
\[ R(D) = 0.299(11) \text{ FNAL/MILC (2015)} \]
\[ R(D^*) = 0.252(3) \text{ S. Fajfer et al. (2012)} \]
Test of Lepton Flavor Universality in charged currents [τ vs. light leptons (μ, e) ]:

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

$$X = D \text{ or } D^*$$

- **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
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- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM \((D + D^*)\)
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- **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. → \(3.6–3.9\sigma\) 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
Anomalies in $B \rightarrow K^{(*)} \mu\mu$ / ee [LHCb]

* The largest anomaly is the one [observed in 2013 and confirmed with higher statistics in 2015] in the $P_5'$ [$B \rightarrow K^{*}\mu\mu$] angular distribution.

* Less significant correlated anomalies present also in other $B \rightarrow K^{*}\mu\mu$ obs. and also in other $b\rightarrow s\mu\mu$ channels [→ overall smallness of all $BR(B \rightarrow \text{Hadron} + \mu\mu)$]

N.B.: $b \rightarrow s ll$ transitions are Flavor Channing Neutral Current amplitudes

- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Sizable hadronic uncertainties in the rates
Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

- The largest anomaly is the one in the $P_5^{'} [B \to K^{*}\mu\mu]$ angular distribution.
- Less significant correlated anomalies present also in other $B \to K^{*}\mu\mu$ obs.
- But also in this case the most interesting effects are the deviations from the SM in appropriate $\mu/e$ “clean” LFU 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)
**Anomalies in $B \to K^{(*)} \mu\mu / ee$ [LHCb]**

- The largest anomaly is the one in the $P_5'$ [$B \to K^*\mu\mu$] angular distribution.
- Less significant correlated anomalies present also in other $B \to K^*\mu\mu$ obs.
- Most interesting deviations from the SM in the $\mu/e$ "clean" LFU ratios.

- 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 largely favored
- Helicity structure on the lepton side less clear
Bottom-up approaches to describe the anomalies
[from EFT to simplified models]
Bottom-up approaches to describe the anomalies

These recent results have stimulated a lot of theoretical activity (not particularly instructive to discuss all NP proposals...)

What I will discuss next is a bottom-up approach made of three main steps:

- **Generic EFT approach**
- **Simplified Dynamical Models**
- **High-energy behavior and UV completion**

The main guide will be the attempt to describe both LFU effects within the same framework and, while “going up” in energies (and assumptions), check the consistency with
  - other low-energy data
  - high-pT physics
**EFT-type considerations**

- Anomalies are seen only in semi-leptonic \((\text{quark} \times \text{lepton})\) operators.
- Data largely favor non-vanishing \textit{left-handed} current-current operators \[\text{the Fermi-like } \text{SU}(2)_L \text{ triplet contributes to both charged & neutral curr.},\]
  although other contributions are also possible.

\[\begin{align*}
&Q_L & L_L \\
&Q_L & L_L \\
\end{align*}\]

Bhattacharya \textit{et al.} '14  
Alonso, Grinstein, Camalich '15  
Greljo, GI, Marzocca '15  
(+many others...)

\[\text{G. Isidori – Hints of physics beyond the SM in the Flavor Sector} \quad \text{PSI, 26}^{\text{th}} \text{ Apr. 2018}\]
**EFT-type considerations**

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

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

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

Link to pattern of the Yukawa couplings!
**EFT-type considerations**

- Anomalies are seen only in semi-leptonic (quark × lepton) operators.
- Data largely favor non-vanishing left-handed current-current operators \([\text{the Fermi-like } SU(2)_L \text{ triplet contributes to both charged & neutral curr.}],\) although other contributions are also possible.

Two classes of (tree-level) mediators, giving rise to different correlations among the anomalies, other low-energy observables, and high-\(p_T\) physics.
EFT-type considerations

Three main problems identified in the recent literature (driven mainly by $R_D$...):

I. high-$p_T$ constraints

![Diagram of high-$p_T$ constraints]

[low naïve EFT scale: $\Lambda \sim 700$ GeV]

Faroughy, Greljo, Kamenik '16

II. radiative constraints

![Diagram of radiative constraints]

Feruglio, Paradisi, Pattori '16

III. flavor bounds

![Diagram of flavor bounds]

Greljo, GI, Marzocca '15
Calibbi, Crivellin, Ota, '15
(+many others...)
EFT-type considerations [The U(2)^n flavor symmetry]

A solution to all these “combination” problems + natural link with the origin of the Yukawa couplings, is provided by a suitable EFT based on the hypothesis of an approximate U(2)_q × U(2)_l flavor symmetry.
**EFT-type considerations** [The \( U(2)^n \) flavor symmetry]

A solution to all these “combination” problems + natural link with the origin of the Yukawa couplings, is provided by a suitable EFT based on the hypothesis of an approximate \( U(2)_q \times U(2)_l \) flavor symmetry.

A brief detour: \( U(2)^n \) flavor symmetries (acting on light generations)

Quark sector: \( U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d \)

\[
Y_U = y_t \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{U}(2)_q
\]

\[\uparrow\text{unbroken symmetry}\]

\[\text{U}(2)_u\]

\[\mathcal{L}_{\text{Yukawa}} = Q_L^i Y_U^{ij} U_R^j \phi + \ldots\]

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

The exact symmetry limit is good starting point for the SM spectrum (\( m_u = m_d = m_s = m_c = 0, V_{\text{CKM}} = 1 \))
**EFT-type considerations** [The $U(2)^n$ flavor symmetry]

A solution to all these “combination” problems + natural link with the origin of the Yukawa couplings, is provided by a suitable EFT based on the hypothesis of an approximate $U(2)_q \times U(2)_l$ flavor symmetry.

- A brief detour: $U(2)^n$ flavor symmetries (acting on light generations)

Quark sector: $U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d$

$$\begin{align*}
Y_U &= y_t \\
\begin{bmatrix}
0 & 0 \\
0 & 1
\end{bmatrix}
\end{align*}$$

unbroken symmetry

$$\begin{align*}
\begin{bmatrix}
0 & V \\
0 & 1
\end{bmatrix}
\end{align*}$$

leading breaking

$$\begin{align*}
\begin{bmatrix}
\Delta & V \\
0 & 1
\end{bmatrix}
\end{align*}$$

final breaking

**Minimal breaking to reproduce SM Yukawa couplings:**

- The assumption of a single leading breaking ensures an effective protection of FCNCs → consistency with CKM fits
- Large NP effects possible for 3rd generation

| $|V|$ | $|V_{ts}|$ = 0.04 |
| $|\Delta| \approx y_c = 0.006$ |
EFT-type considerations [ “The Zurich's guide” ]

A solution to all these “combination” problems + natural link with the origin of the Yukawa couplings, is provided by a suitable EFT based on the hypothesis of an approximate $U(2)^q \times U(2)^l$ flavor symmetry

- NP in left-handed operators only
- Leading NP effects in 3rd generation only
- Light generation couplings controlled by $U(2)^q \times U(2)^l$ flavor symmetry
  minimally broken (→ link to SM Yuk. coupl.)

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2} \lambda_{\alpha \beta}^q \lambda_{\alpha \beta}^l \left[ C_T (\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j) (\bar{L}_L^\alpha \gamma_\mu \sigma^a L_L^\beta) + C_S (\bar{Q}_L^i \gamma_\mu Q_L^j) (\bar{L}_L^\alpha \gamma_\mu L_L^\beta) \right]
\]

four free parameters...

\[
\begin{bmatrix}
C_T, C_S \\
\lambda_{bs} = O(V_{cb}) \\
\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)
\end{bmatrix}
\]

...and a long list of constraints

[ FCNC and CC semi-leptonic processes, tau decays, EWPO ]
EFT-type considerations [“The Zurich's guide”]

Excellent fit to both anomalies, passing all existing constraints with no fine tuning

Key features compared to previous analyses:

- SU(2)$_L$ singlet & triplet operators
- Flavor symmetry
- Deviation from “pure-mixing”
- O($V_{cb}$) misalignment to $b$-quark mass basis

$\Lambda_{NP}$ raised to $\sim 1.5$ TeV
EFT-type considerations [“The Zurich's guide”]

Excellent fit to both anomalies, passing all existing constraints with no fine tuning

- The virtue of this EFT approach is the demonstration that is possible to find a “combined” (motivated) explanation of the two set of anomalies. Very useful in identifying implications in other low-energy measurements [→ more later...]

- The EFT solution is not unique [e.g. sub-leading RH currents can be added], but large variations are possible only if the $R_{D}$ anom. goes away completely
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'
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: \( B' \) \( W' \)

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

The \( U_1 \) 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: $B'$ $W'$

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

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

Two main approaches

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

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

- Vector LQ (or W',Z') as techni-fermion resonances
  Barbieri et al. '15, Buttazzo et al. '16
  Barbieri, Murphy, Senia, '17
  Blanke, Crivellin, '17

- W', Z' as Kaluza-Klein excitations
  [e.g. from warped extra dim.]
  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17

Perturbative
TeV-scale dynamics
[renormalizable models]

- Renormalizable models with scalar mediators [LQ, but also RPV-SUSY]
  Hiller & Schmaltz, '14
  Becirevic et al. '16, Fajfer et al. '15-'17
  Dorsner et al. '17
  Crivellin, Muller, Ota '17
  Altmannshofer, Dev, Soni, '17
  + ...

- Gauge models
  Cline, Camalich '17
  Calibbi, Crivellin, Li, '17
  Assad, Fornal, Grinstein, '17
  Di Luzio, Greljo, Nardecchia, '17
  Bordone, Cornella, Fuentes-Martin, GI, '17
  + ...
Speculations on UV completions

In the following I will concentrate on one (class of) option(s), among the gauge models, that I find particularly interesting.

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

- Scalar LQ as PNG
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- Vector LQ (or $W',Z'$) as techni-fermion resonances
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Perturbative TeV-scale dynamics [renormalizable models]

- Renormalizable models with scalar mediators [$LQ$, but also RPV-SUSY]
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  Dorsner et al. '17
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  Cline, Camanich '17
  Calibbi, Crivellin, Li, '17
  Assad, Fornal, Grinstein, '17
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  + ...

Gauge models
Speculations on UV completions

In the following I will concentrate on one (class of) option(s), among the gauge models, that I find particularly interesting.

The starting observation is that the Pati-Salam model [proposed in 1974 to unify quark and lepton quantum numbers], predicts a massive vector LQ with the correct quantum numbers

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

<table>
<thead>
<tr>
<th>Fermions in SU(4):</th>
<th>LQ ( [U_1] ) from SU(4) → SU(3)_c</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q^\alpha_L )</td>
<td>( Q^\alpha_R )</td>
</tr>
<tr>
<td>( Q^\beta_L )</td>
<td>( Q^\beta_R )</td>
</tr>
<tr>
<td>( Q^\gamma_L )</td>
<td>( Q^\gamma_R )</td>
</tr>
<tr>
<td>( L_L )</td>
<td>( L_R )</td>
</tr>
</tbody>
</table>

The problem of the “original PS model” are the strong bounds on the LQ couplings to 1\textsuperscript{st} & 2\textsuperscript{nd} generations [e.g. \( M > 100 \text{ TeV} \) from \( K_L \to \mu e \)].

Interesting recent attempts to solve this problem adding extra fermions and/or modifying the gauge group [Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17]
**A more ambitious attempt...**

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

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

*A three site gauge model for flavor hierarchies and flavor anomalies*

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

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

A three site gauge model for flavor hierarchies and flavor anomalies

Bordone, Cornella, Fuentes-Martin, GI, '17
A more ambitious attempt...

High-scale [~ 10^3 TeV] “vertical” breaking [PS → SM]

PS_1 [ SU(4)_1 × SU(2)_R^1 ]

→

SM_1 [ SU(3)_1 × U(1)_Y^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^{rd} gen.

[similar to “4321” but “natural” flavor structure: no ad-hoc mixing with vector-like quarks]
A more ambitious attempt...

Below \( \sim 100 \) TeV

\( \text{U}(2)^5 \) flavor symmetry
(but for link fields)

**Leading flavor structure:**

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

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

Sub-leading Yukawa terms from higher dim ops:

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

\[
\langle \Phi_{\ell 3}^R \Phi_{\ell 3}^L \rangle \\
(\Lambda_{23})^2
\]

\[
\langle \Omega_{\ell 3} \rangle \\
\Lambda_{23}
\]

→ \( W_L' + W_R' \) [~ 5-10 TeV]

→ \( LQ \) \([U_1] + Z' + G' \) [~ 1-2 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:

\[
\begin{align*}
SU(4)_3 \times SU(3)_{1+2} \times [SU(2)_L \times U(1)'] \\
\psi_3 & \quad \psi_{1,2} \\
\langle \Omega_{\ell_3} \rangle & \rightarrow LQ [U_1] + Z' + G' \\
& [\sim 1-3 \text{ TeV}] \\
\text{SM} & \\
\psi_{1,2,3}
\end{align*}
\]

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

Key difference to all existing pheno models: unsuppressed $b_R\tau_R$ coupling of the LQ
**A more ambitious attempt...**

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)*

- $\Delta F=2$ constraints imply 5-10% alignment to $d$-quark mass basis
Possible future implications

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

[attributed to Niels Bohr]
Implications for low-energy measurements

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
### Implications for low-energy measurements

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 → s</td>
<td>R_K, R_{K^*}</td>
<td>B → K(*) ττ</td>
<td>B → K(*) νν</td>
<td>B → K τμ</td>
<td>B → K μe</td>
</tr>
<tr>
<td></td>
<td>O(20%)</td>
<td>→ 100×SM</td>
<td>O(1)</td>
<td>→ ~10⁻⁶</td>
<td>???</td>
</tr>
<tr>
<td>b → d</td>
<td>B_d → μμ</td>
<td>B → π ττ</td>
<td>B → π νν</td>
<td>B → π τμ</td>
<td>B → π μe</td>
</tr>
<tr>
<td></td>
<td>O(20%) [R_K=R_π]</td>
<td>→ 100×SM</td>
<td>O(1)</td>
<td>→ ~10⁻⁷</td>
<td>???</td>
</tr>
<tr>
<td>s → d</td>
<td>long-distance pollution</td>
<td>NA</td>
<td>K → π νν</td>
<td>NA</td>
<td>K → μe</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>O(1)</td>
<td></td>
<td>???</td>
</tr>
</tbody>
</table>
Implications for low-energy measurements

The low-energy observables with large uncertainties are those mediated by four-quark or four-leptons effective operators (**larger model-dependence in connecting them to the semi-leptonic operators, hence to the anomalies**)

However, in many explicit constructions, the effects are close to present bounds:

- **Meson mixing**
  - O(1-10%) deviations from SM in $\Delta M_{Bs}$ & $\Delta M_{Bd}$
  - O(0.1%) CPV violation D-D mixing

- **$\tau$ decays**
  - $\tau \rightarrow 3\mu$ can be close to exp. bound ($BR \sim 10^{-10}$)

- **$\mu \rightarrow e$**
  - No firm prediction (**1st family mixing → work in prog...**), but potentially very interesting, with non-trivial interplay between $\mu \rightarrow 3e$ [*tree-level $Z'$*] & $\mu \rightarrow e\gamma$ [*LQ loop*]
Some general considerations:

Independently of the details of the UV models, the anomalies (and particularly $R_{D(*)}$) 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 3\textsuperscript{rd} generation (→ *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

In particular, 3rd gen. LQ are (still...) in rather good shape also as far as direct searches are concerned:
**Implications for high-$p_T$ physics**

Pair vs. Single scalar LQ production @CMS:

![Graph showing the difficult "Coloron" signal](image)

- **CMS Preliminary**
- **Observed**
- **Expected ± 1 σ**
- **Preferred by B-anomaly ± 1 σ**
- **Excluded by pp → LQ$_s$LQ$_s$**

**Scalar LQ**
- $\beta = 1$

**Leptoquark mass (GeV)**

**The difficult “Coloron” signal:**

- **$pp \rightarrow jj$ @ 13 TeV, 37 fb$^{-1}$**
- **ATLAS observed**
- **ATLAS Bckg fit**
- **$M_{G'} = 1.9$ TeV, $\Gamma_{G'}$ (25%)**
- **$M_{G'} = 2.5$ TeV, $\Gamma_{G'}$ (43%)**
- **$M_{G'} = 2.2$ TeV, $\Gamma_{G'}$ (34%)**

A. Greljo, talk at LHCb- Implications ’17
Conclusions
If these LFU anomalies were confirmed, it would be a fantastic discovery, with far-reaching implications...
Conclusions

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

- 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 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 for these models naturally imply a much richer spectrum of states at the TeV scale (and possibly above...).

- The PS³ model I have presented is particularly interesting as example of the shift of paradigm that these anomalies could imply. But of many points (and possible variations) remains to be clarified/explored...

↓

A lot of fun ahead of us...
(both on the exp., the pheno, and model-building point of view)
Symmetry breaking pattern in $PS^3$

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

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

$SM_1$ [$SU(3)_1 \times U(1)^Y_1$]
**Symmetry breaking pattern in PS³**

\[ \Lambda_1 > E > \Lambda_{12} \]

\[ \Lambda_{12} > E > \Lambda_{23} \]

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

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

(but for link Yuk. coupl.)

\[ \Phi_{\text{L}12} \sim (1,2,1)_1 \times (1,2,1)_2 \]

\[ \Phi_{\text{R}12} \sim (1,1,2)_1 \times (1,1,2)_2 \]

\[ \Omega_{12} \sim (4,2,1)_1 \times (4,2,1)_2 \]

\[ \text{VEV} \rightarrow \text{SU}(2)^{\text{L}}_{1+2} \]

\[ \text{VEV} \rightarrow \text{SU}(2)^{\text{R}}_{1+2} \]

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

- The largest anomaly is the one \textit{[obs. in 2013 and confirmed with higher stat. in 2015]} in the $P_5'$ \([B \rightarrow K^*\mu\mu]\) angular distribution.
- Less significant correlated anomalies present also in other $B \rightarrow K^*\mu\mu$ observables and also in other $b\rightarrow s\mu\mu$ channels \textit{[overall smallness of all BR(B \rightarrow \text{Hadron} + \mu\mu)]}

**Pro NP:**
- Reduced tension in all the observables with a unique fit of non-standard $C_i(M_W)$

**Against NP:**
- Main effect in $P_5'$ not far from $cc$ threshold
- “NP” mainly in $C_9 (\leftrightarrow \text{charm})$
- Significance reduced with conservative estimates of non-factorizable corrections

\textit{Jaeger et al. '12, Hambrock et al. '13, Hiller & Zwicky '13, Ciuchini at al. '15, ...}
Anomalies in $B \to K^{(*)} \mu\mu / ee$ [LHCb]

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

\[ \mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \]
\[ \mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \]

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

$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9}$
$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

LHCb + CMS
Pro NP:
- 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
Anomalies in $B \to K^*(\mu\mu / ee)$ [LHCb]

- But also in this case the most interesting effects are the deviations from the SM in appropriate $\mu/e$ “clean” LFU ratios:

$$R_{K^*} = \frac{\int d\Gamma(B^0 \to K^*\mu\mu)}{\int d\Gamma(B^0 \to K^*ee)}$$