New Prospects for BSM Physics

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- Introduction [Flavor vs. Hierarchy problems in the SM-EFT]
- LFU anomalies & Flavor symmetries [The U(2)^n case]
- Simplified models: The Return of the Leptoquark
- Non-universal gauge interactions [The PS^3 hypothesis]
- Conclusions
Introduction

All microscopic phenomena seem to be well described by a remarkably simple Theory (that we continue to call “model” only for historical reasons...).

However, this Theory has some deep unsolved problems:

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

The Standard Model (SM) should be regarded 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

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**Introduction**

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*problem due to...*

- Instability of the Higgs mass term
- Ad hoc tuning in the model parameters

*...indicating*

Non-trivial properties of the SM Lagrangian if interpreted as EFT

Useful hints for its UV completion
Integrate out the high-energy modes

low-energy “projection”
loss of information about nature & properties of the high-energy modes

Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution [\textit{\sim 35 years from the Fermi Theory to the GSW model...}]
Integrate out the high-energy modes

UV Theory

low-energy “projection”

loss of information about nature & properties of the high-energy modes

SM EFT

Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution [~ 35 years from the Fermi Theory to the GSW model...]

- The light fields appearing in the EFT are often superposition of the fundamental fields [N.B.: true also for weak theories & gauge fields: $A_\mu = c_0 B_\mu + s_0 W_\mu$]

- Many global symmetries of the EFT could by accidental low-energy properties

- The most interesting hints on UV dynamics comes from un-natural features of the EFT...
Hierarchy vs. Flavor problem in the SM EFT

“trivial” low-energy projection

\[ \mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yuk}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d \geq 5} \]

Structure fully dictated by
- Number of light fields
- Their charges under long-range interactions

Contains only “natural” O(1) couplings
**Hierarchy vs. Flavor problem in the SM EFT**

\[
\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yuk}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}
\]

- **Hierarchy problem** (II vs. I): \( m_\phi \ll \Lambda_{t,W,H} \)
- **SM Flavor problem** (III): \( y_e \ll y_t \) [N.B.: 5 orders of magnitude !]
- **NP Flavor problem** (IV vs. I): \( m_\phi \ll \Lambda_{CP,F} \)

Non-trivial UV imprints

\[
\begin{align*}
\text{I} & : m_\phi^2 H^2 \\
\text{III} & : y_{ij} \psi_i \psi_j H
\end{align*}
\]

\[
\begin{align*}
\Lambda_{t,W,H} & > \text{(few) TeV} \quad \text{II} \\
\Lambda_{CP,F} & > 10^{2-4} \text{ TeV} \quad \text{IV} \\
\Lambda_L & \sim 10^{14} \text{ TeV} \\
\Lambda_B & > 10^{15} \text{ TeV}
\end{align*}
\]
**Hierarchy vs. Flavor problem in the SM EFT**

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1. **I** \( m_\phi^2 H^2 \)
2. **II** \( \Lambda_{t,W,H} > (\text{few}) \text{ TeV} \)
3. **III** \( y_{ij} \psi_i \psi_j H \)
4. **IV** \( \Lambda_{\text{CP,F}} > 10^{2-4} \text{ TeV} \)

The **MFV “solution”** (popular in the *pre-LHC era*):

- The genuine hierarchy problem is not too severe \( \rightarrow \) expect NP at TeV scale
- Postpone the solution of III to very high scale, and assume no other sources of flavor-breaking at low-energies \( \rightarrow \) TeV scale NP is flavor-blind

*Try to separate the two problems & postpone the Flavor one*
**Hierarchy vs. Flavor problem in the SM EFT**

\[ \mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yuk}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d \geq 5} \]

1. \( m_\phi^2 H^2 \)  
2. \( y_{ij} \psi_i \psi_j H \)
3. Non-trivial UV imprints
4. \( \Lambda_{t,W,H} > \text{(few) TeV} \)
5. \( \Lambda_{\text{CP,F}} > 10^{2-4} \text{ TeV} \)

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

- The genuine hierarchy problem is already too severe \( \rightarrow \) **give up on it...** (at least at the EFT level)
- Push the scale of NP to very high scale, so there is no NP flavor problem

---

*Ignore both the Hierarchy & the SM Flavor problems*
**Hierarchy vs. Flavor problem in the SM EFT**

\[
\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yuk}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}
\]

- **I**: \(m_\phi^2 H^2\)
- **II**: \(\Lambda_{t,W,H} > \text{(few) TeV}\)
- **III**: \(\Lambda_{\text{CP},\text{F}} > 10^{-4} \text{ TeV}\)
- **IV**: Non-trivial UV imprints

The path of **flavor non-universal interactions** (not so popular *yet*...):
- The hierarchical structure of the SM Yukawa couplings is a clear indication that all the new degrees of freedom are coupled in a non-universal way to SM fermion families \(\rightarrow\) expect TeV scale NP coupled mainly to 3\(^{\text{rd}}\) gen.
- Genuine hierarchy problem less severe for NP coupled mainly to 3\(^{\text{rd}}\) gen.

*We should not give up & should not try to separate the two problems*
**Hierarchy vs. Flavor problem in the SM EFT**

In the low-energy limit of the SM (= QED\times QCD) we observe perfect universality of LH and RH gauge couplings. However, we know this is a low-energy artifact:

Similarly, the apparent flavor symmetry of the SM could well be only an accidental low-energy property...
Hierarchy vs. Flavor problem in the SM EFT

\[ \mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{yuk}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_{i}^{d\geq 5} \]

Non-trivial UV imprints

- \( \Lambda_{t, W, H} > (\text{few}) \text{ TeV} \)
- \( \Lambda_{\text{LFU}} \sim \text{few TeV} \)
- \( \Lambda_{\text{CP, F}} > 10^{2-4} \text{ TeV} \)

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

- The hierarchical structure of the SM Yukawa coupl. is a clear indication that all the new degrees of freedom are coupled in a non-universal way to SM fermion families → expect TeV scale NP coupled mainly to 3\textsuperscript{rd} gen.

This is the path that seems to be indicated by the recent hints of Lepton Flavor non Universality in semi-leptonic B decays
LFU anomalies & Flavor symmetries
**On the LFU anomalies**

Recent data show some **convincing** evidences of Lepton Flavor Universality violations

- **b → c charged currents**: τ vs. light leptons (μ, e) \([R_D, R_{D*}]\)
- **b → s neutral currents**: μ vs. e \([R_K, R_{K*} (+ P_5 \text{ et al.})]\)

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

*I made statements of this type back in 2015... Since then the evidence for the anomalies has significantly increased.*

*This winter we have seen a first small decrease of the significance of some the anomalies; however, the overall picture has not changed. Actually, I dare to say it has become even more consistent...*
On the LFU anomalies

- 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

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

- 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 \(bs \rightarrow l_2 l_2\) [\(R_K, R_{K*}, \ldots\)]

Link to pattern of the Yukawa couplings!
On the LFU anomalies

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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
**LFU anomalies & 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 chiral flavor symmetry of the type $U(2)^n$

\[ U(2)^n \supset U(2)_q \times U(2)_l \]

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

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

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11
**LFU anomalies & the U(2)^n flavor symmetry**

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

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

\[
\begin{bmatrix}
\Delta & V \\
\hline
1 & \phantom{1}
\end{bmatrix} \equiv \begin{bmatrix}
\cdot & \cdot \\
\cdot & \cdot \\
\cdot & \cdot
\end{bmatrix}
\]

\( U(2)_u \) \quad unbroken symmetry

\( \Delta V \equiv \) after symmetry symmetry

\( |V| \approx |V_{ts}| = 0.04 \)

\( |
\Delta| \approx y_c = 0.006 \)

Main idea: the same symmetry-breaking pattern control the mixing 3\(^{rd}\) → 1\(^{st}\), 2\(^{nd}\) 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...! ]
**LFU anomalies & 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 *chiral* flavor symmetry of the type U(2)^n

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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New data make this picture even more consistent:

I. Higher NP scale given smaller central value of b → c anomaly

II. Rising “evidence” of LFU contribution to C_9, naturally expected in this framework:

Alguero *et al.* '19
Aebischer *et al.* '19

Crivellin, Greub, Muller, Saturnino '19
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II. Rising “evidence” of LFU contribution to C_9.

III. Rising “evidence” of a suppression of BR(B_s \(\to\) μμ), naturally expected by \(\Delta C_9 = -\Delta C_{10}\)

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

Greljo, GI, Marzocca, '15
**LFU anomalies & the $U(2)^n$ flavor symmetry**

A nice virtue of the EFT approach with flavor symmetries is the predictive power. Clear example in semileptonic charged-currents (*only 2 effective parameters, even dropping the assumption of pure LH couplings*):

\[ C_S^c = C_S^u \]

\[ C_V^c = C_V^u \]

\[ B(B_s \to \tau \tau) \]

90% CL excluded

\[ B(B \to \tau \nu) \]

\[ \beta_R = 0 \]

\[ \beta_R = -1 \]

\[ R_D^\tau \]

\[ \Delta P_L^{D^*} \]

\[ \Delta P_{\tau}^{D^*} \]

\[ \Delta R_D - \Delta R_{D^*} \]

Fuentes-Martin, GI, Pages, Yamamoto, '19
Simplified models: the return of the Leptoquark
**General considerations**

Which tree-level mediators can generate the effective operators required for a successful EFT fit? Not many possibilities...

![Diagram of W', Z' (H) and LQ](image)

**N.B.:** Given the effective low-scale of NP, we are naturally lead to simplified models with tree-level leading mediators

These simplified models are not meant to be complete UV models, but rather a “tool” to connect

- low- vs. high-energy phenomenology,
- disconnected sectors of the EFT (e.g. semi-leptonic vs. ΔF=2 ops.)
**General considerations**

Which tree-level mediators can generate the effective operators required for a successful EFT fit? 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: 3rd gen. LQ are also in better shape as far as direct searches are concerned (contrary to $Z'$...).
**General considerations**

Which LQ explain which anomaly?

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<tr>
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Angelescu, Becirevic, DAF, Sumensari [1808.08179]

There is one clear winner [$U_1$]...

$\Lambda_{NP} \sim 1.5$ TeV
General considerations

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There is one clear winner [$U_1$]...

...but the single-mediator case is definitely an over simplification [as we learned in the last ~ 2 years...]

3 interesting options:

- $U_1 + \text{colorless-vectors}$
  - Being a massive vector, $U_1$ requires an appropriate UV compl. $\rightarrow$ always accompanied by (at least) a $Z'$
  - Alonso, Grinstein, Camalich '15
  - Barbieri, GI, Pattori, Senia '15
  - + wide literature

- $S_1 \& S_3$
  - Good option for the EFT “pure-LH” solution
  - Crivellin, Muller, Ota '17
  - Buttazzo et al. '17
  - Marzocca '18

- $R_2 \& S_3$
  - GUT-inspired option for EFT solution including also RH currents
  - Becirevic et al. '18
A “consistent” simplified model for the $U_1$

- Initial attempts focused on LQ with few, purely LH couplings. However, the quantum numbers of the $U_1$ allow both RH and LH currents.
- A consistent reduction in the number of free parameters is achieved with the help of the flavor symmetry:

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ \beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha) \right] + h.c.$$
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\]

The presence of the (motivated) extra coupling leads to a series of interesting effects at both low- and high-energies: 

- $b \rightarrow s\tau\mu$ [tree]
- $b \rightarrow s\tau\tau$ [tree]
- $\tau \rightarrow \mu X$ [loop]

+ many other effects

[ EPWO, LFU in $\tau$'s...]

Bordone, Cornella, Fuentes-Martin, GI, '18
Cornella, Fuentes-Martin, GI, '19
A “consistent” simplified model for the $U_1$

The presence of RH couplings leads to significant differences at high-$p_T$:

![Graph showing regions favored by anomalies](image-url)
A “consistent” simplified model for the $U_1$

Probably the most striking signature of large RH couplings is the (unavoidable) large enhancement of $B(B \to \tau\tau)$ & $B(B \to \tau\mu)$:
Non-universal gauge interactions & the $PS^3$ hypothesis
Toward a UV completion: the PS$^3$ hypothesis

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 the anomalies:

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

Fermions in SU(4):

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

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 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \rightarrow \mu e$]

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]
The PS$^3$ model

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

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

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

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

SM

IR

Q$_i$, u$_i$, d$_i$, L$_i$, e$_i$

Key advantages:
- Light LQ coupled mainly to 3$^{rd}$ gen.
- Accidental U(2)$^5$ flavor symmetry
- Natural structure of SM Yukawa couplings
The PS$^3$ model

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

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 allows us to derive precise low-energy phenomenological signatures (4D renormalizable gauge model).
The PS³ model

High-scale breaking
PS₁ → SM₁

Low-scale breaking
[SU(2)×U(1)]₃ → QED₃

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

The 2-3 breaking gives a TeV-scale LQ [+ Z' & G'] coupled mainly to 3rd gen., as in the “4321” model [Di Luzio, Greljo, Nardecchia, '17]
The $\text{PS}^3$ model

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

Leading flavor structure:

- Yukawa coupling for 3$^\text{rd}$ gen. only
- “Light” LQ field (from $\text{PS}_3$) coupled only to 3$^\text{rd}$ gen.
- $\text{U}(2)^5$ 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:

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

\[
\langle \Phi_{\ell_3}^R \Phi_{\ell_3}^L \rangle \quad \langle \Omega_{\ell_3} \rangle \\
(\Lambda_{23})^2 \quad \Lambda_{23}
\]

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

\[
\rightarrow LQ [U_1] + Z' + G' [\sim 1-5 \text{ TeV}]
\]
Present collider and low-energy pheno
are 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

\[
\begin{array}{c|c|c|c|c}
\text{Field} & SU(4) & SU(3) & SU(2)_L & U(1)' \\
\hline
q^i_L & 1 & 3 & 2 & 1/6 \\
u^R_R & 1 & 3 & 1 & 2/3 \\
d^R_R & 1 & 3 & 1 & -1/3 \\
\ell^R_R & 1 & 1 & 2 & -1/2 \\
e^R_R & 1 & 1 & 1 & -1 \\
\psi^i_L & 4 & 1 & 2 & 0 \\
\psi^i_u & 4 & 1 & 1 & 1/2 \\
\psi^i_d & 4 & 1 & 1 & -1/2 \\
\chi^i_L & 4 & 1 & 2 & 0 \\
\chi^i_R & 4 & 1 & 2 & 0 \\
H_1 & 1 & 1 & 2 & 1/2 \\
H_{15} & 15 & 1 & 2 & 1/2 \\
\Omega_1 & 4 & 1 & 1 & -1/2 \\
\Omega_3 & 4 & 3 & 1 & 1/6 \\
\Omega_{15} & 15 & 1 & 1 & 0 \\
\end{array}
\]

\[
\begin{align*}
\text{SU}(4) \times \text{SU}(3)^{1+2} \times \left[ \text{SU}(2)_L \times U(1)' \right] \\
\Psi_3 & \Psi_{1,2} \\
\langle \Omega's \rangle & \rightarrow \text{LQ} [U_1] + Z' + G' \\
[\sim 1-5 \text{ TeV}] \\
\text{SM} & \Psi_{1,2,3}
\end{align*}
\]

We can reproduce all the positive
features the simplified model +
Calculability of \(\Delta F=2\) processes
[in agreement with present data in
large area of param. space]

Greljo, Stefanek, '18; Di Luzio et al. '18;
Cornella, Fuentes-Martin, GI, '19
The PS$^3$ model

A key difference between the simplified model and this complete UV model is the high-pT phenomenology, which now involves more states.

The bounds on the coloron are less relevant in PS$^3$ vs. the case of a pure LH coupled $U_1$. 

The diagram shows:
- The cross symbolizes the production of $pp \to tt$.
- The blue triangle represents the same $U_1$ contribution to $R_D$.
- The $G'$ bounds from $pp \to tt$.
Conclusions

- The recent LFU anomalies provide a concrete demonstration of the high discovery potential of indirect NP searches. 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 (class of) UV framework(s) which could host it, and could help to shed light on Flavor & Hierarchy problems.

\[ \text{\ldots a lot of fun ahead of us !} \]
[both on the exp. / pheno / model-building point of view]
On the LFU anomalies

Recent data show some convincing evidences of Lepton Flavor Universality violations

- $b \to c$ charged currents: $\tau$ vs. light leptons ($\mu$, $e$) [R$_D$, R$_{D*}$]
- $b \to s$ neutral currents: $\mu$ vs. $e$ [R$_K$, R$_{K*}$ (+ P$_5$ et al.)]

Several results by different exps. all central values above the SM → combined deviation $> 3\sigma$

- Data can be explained by NP contributing only to $b_L \to c_L \tau_L \nu_L$
  (but other amplitudes possible...)

G. Isidori – New prospects for BSM physics
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- $b \rightarrow s$ neutral currents: $\mu$ vs. e [$R_K$, $R_{K*}$ (+ $P_5$ et al.) ]

Non-trivial fit of several observables indicating NP of short-distance origin [3.8σ significance from LFU ratios only]

- Data can be explained by NP contributing only to $b_L \rightarrow s_L \mu L \mu L$
  (but other amplitudes possible.... & in this case definitely welcome)
Symmetry breaking pattern in $PS^3$

High-scale $[\sim 10^3 \text{ TeV}]$
“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 PS³**

- \( \Sigma_1 \) \( \rightarrow \) \( \langle \Sigma_1 \rangle \)
- \( \Lambda_1 > E > \Lambda_{12} \)

- \( \Phi_{12}^L \sim (1,2,1)_1 \times (1,2,1)_2 \)
  \( \rightarrow \) \( \text{VEV} \rightarrow \text{SU}(2)_L^{1+2} \)

- \( \Phi_{12}^R \sim (1,1,2)_1 \times (1,1,2)_2 \)
  \( \rightarrow \) \( \text{VEV} \rightarrow \text{SU}(2)_R^{1+2} \)

- \( \Omega_{12} \sim (4,2,1)_1 \times (4,2,1) \)
  \( \rightarrow \) \( \text{VEV} \rightarrow \text{SU}(4)_{1+2} \) \& \( \text{SU}(2)_L^{1+2} \)

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

\( \text{U}(2)^5 \) flavor symmetry (but for link Yuk. coupl.)
The largest (and statistically more significant) set of anomalies is the one extracted from rare decays mediated by $b \rightarrow s \ell^+\ell^-$ amplitudes [$\ell = \mu, e$]:

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

$b \rightarrow s\ell\ell$ transitions are Flavor Channning Neutral Current amplitudes

- **No SM tree-level contribution**
- **Strong suppression within the SM because of CKM hierarchy**
- **Sizable theory uncertainties**
  
  *(in some observables)*
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- LFU ratios ($\mu$ vs. $e$) in $B \to K^*\ell\ell$ & $B \to K \ell\ell$
- Smallness of $\text{BR}(B_s \to \mu\mu)$

$$\begin{align*}
\smiley &= \text{th. error very small (} \lesssim 1\%\text{)} \\
\frowny &= \text{th. error few } \% 
\end{align*}$$

Charm contributions (pert. + non-pert.) can induce only lepton-universal corrections to $C_9$ (not to $C_{10}$)

Generally they lead to non-local effects ($\leftrightarrow$ non-trivial $q^2$ dependence)
The $b \rightarrow s\ell\ell$ anomalies

I. The $P'_5$ anomaly

The $B \rightarrow K^{*}\mu\mu$ differential distribution:
The $B \to s\ell\ell$ anomalies

I. The $P'_5$ anomaly [$B \to K^*\mu\mu$ differential distribution]

II. The smallness of $d\Gamma(B \to H_s\mu\mu)$ in several modes
   \[ H_s = K, \ K^*, \ \phi \ (\text{from } B_s) \]

Pro NP:
Reduced tension in all the observable -in all bins- with a unique fit of non-standard $C_i(M_W) \to$ compatible with effect of short-distance origin
[non-trivial: $O(100)$ observ. few Wilson coeff.]

Against NP:
Non-standard effect mainly driven by $C_9 \ (\leftrightarrow \text{charm loops})$
$\to$ significance reduced with conservative estimates of long-distance corrections
The $b \to s \ell \ell$ anomalies

III. The “clean” LFU ratios:

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

Deviations from the (precise & reliable) SM predictions ranging from 2.2$\sigma$ to 2.5$\sigma$ in each of the 3 bins measured by LHCb
The $b \rightarrow s \ell\ell$ anomalies

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**The $b \to s\ell\ell$ anomalies**

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What is particularly remarkable is that both these LFU breaking effects & the anomalies (I.+II.) are well described by the same set of Wilson coeff. assuming NP only in $b\to s\mu\mu$ and (\& not in ee)
The $b \to s \ell \ell$ anomalies

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What is particularly remarkable is that both these LFU breaking effects & the anomalies (I.+II.) are well described by the same set of Wilson coeff. assuming NP only in $b \to s \mu\mu$ and (& not in $ee$)

Despite the significance has not increased with the release of new data in 2019, the overall consistency has further increased, as well as the evidence that the putative NP effects come from a pure left-handed operator $\to$ expected suppression of BR($B_s \to \mu\mu$) by $\sim 20\%$ compared to its SM expectation:

$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$
$$BR(B_s \to \mu\mu)_{exp} = (2.72 \pm 0.34) \times 10^{-9}$$

[\text{LHCb+CMS+ATLAS '19}]

A 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.
The $b \to s\ell\ell$ anomalies

A 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 sophisticated analyses, taking into account all observables, with state-of-the-art estimates of hadronic form factors + realistic (but somehow model-dependent) estimates of long-distance effects → pull exceeding $5\sigma$:

![Graph showing the parameters $C_{9\mu} = -C_{10\mu}$ and $\Delta C_{3\mu}$ with contours for different values of $R_K$ and $R_{K^*}$ for $b \to s\mu\mu$.]