**Flavor physics**

*old problems, recent hopes and new challenges*

Gino Isidori  
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- An introduction to flavor physics
- Lepton Flavor Universality
- Model building and future prospects
Plan of the lectures:

- An introduction to flavor physics
  - Preface
  - The flavor sector of the Standard Model
  - Properties of the CKM matrix and CKM fits
  - The two flavor puzzles
  - The SM as an effective theory
  - The NP flavor problem
  - MFV and beyond

- Lepton Flavor Universality
- Model building and future prospects
MFV and beyond

SU(3)_Q \times SU(3)_U \times SU(3)_D

Quark Flavor Group
**MFV and beyond**

Current data show no significant deviations from the SM (at the 5%-30% level, depending on the specific amplitude) on $\Delta F = 2$ observables (mass differences and CP-violating phases) → strong bounds on possible BSM contributions:

$$M(B_d - \overline{B_d}) \sim \frac{(y_t^2 V_{tb} V_{td}^*)^2}{16\pi^2 m_t^2} + c_{NP} \frac{1}{\Lambda^2}$$

\[\begin{align*}
\sim 1 & \quad \text{tree/strong + generic flavor} & \Lambda \gtrsim 2 \times 10^4 \text{ TeV} [K] \\
\sim \frac{1}{(16\pi^2)} & \quad \text{loop + generic flavor} & \Lambda \gtrsim 2 \times 10^3 \text{ TeV} [K] \\
\sim (y_t V_{ti} V_{tj}^*)^2 & \quad \text{tree/strong + “alignment”} & \Lambda \gtrsim 5 \text{ TeV} [K & B] \\
\sim (y_t V_{ti} V_{tj}^*)^2/(16\pi^2) & \quad \text{loop + “alignment”} & \Lambda \gtrsim 0.5 \text{ TeV} [K & B]
\end{align*}\]
<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on $\Lambda$ (TeV)</th>
<th>Bounds on $c_{ij}$ ($\Lambda = 1$ TeV)</th>
<th>Observables</th>
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<tbody>
<tr>
<td></td>
<td>Re</td>
<td>Im</td>
<td>Re</td>
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<tr>
<td>$(\bar{c}<em>{L\gamma}^{\mu}d</em>{L})^2$</td>
<td>9.8 $\times 10^2$</td>
<td>1.6 $\times 10^4$</td>
<td>9.0 $\times 10^{-7}$</td>
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<tr>
<td>$(\bar{c}<em>{Rd</em>{L}})(\bar{c}<em>{Ld</em>{R}})$</td>
<td>1.8 $\times 10^4$</td>
<td>3.2 $\times 10^5$</td>
<td>6.9 $\times 10^{-9}$</td>
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<td>$(\bar{c}<em>{L\gamma}^{\mu}u</em>{L})^2$</td>
<td>1.2 $\times 10^3$</td>
<td>2.9 $\times 10^3$</td>
<td>5.6 $\times 10^{-7}$</td>
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<tr>
<td>$(\bar{c}<em>{R\mu L})(\bar{c}</em>{L\mu R})$</td>
<td>6.2 $\times 10^3$</td>
<td>1.5 $\times 10^4$</td>
<td>5.7 $\times 10^{-8}$</td>
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<tr>
<td>$(\bar{b}<em>{L\gamma}^{\mu}d</em>{L})^2$</td>
<td>5.1 $\times 10^2$</td>
<td>9.3 $\times 10^2$</td>
<td>3.3 $\times 10^{-6}$</td>
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<td>$(\bar{b}<em>{Rd</em>{L}})(\bar{b}<em>{Ld</em>{R}})$</td>
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**highly non trivial flavor structure**

**MFV hypothesis**
**MFV and beyond**

The MFV hypothesis is the strongest assumption we can make to impose hierarchical structures also on physics beyond the SM:

- **Flavor symmetry:**
  \[ U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots \]
  (accidental) global symm. of the SM gauge sector
  \[ \rightarrow \text{promoted to basic symm. of the eff. theory} \]

- **Symmetry-breaking terms:**
  \[ Y_D \sim 3_Q \times 3_D \quad Y_U \sim 3_Q \times 3_U \]
  SM Yukawa couplings \[ \rightarrow \text{promoted to unique breaking terms of the flavor symmetry} \]
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  SM Yukawa couplings → promoted to unique breaking terms of the flavor symmetry

**MFV hypothesis:** *Yukawa couplings = unique sources of flavor symmetry breaking*

Automatic GIM & CKM suppression as in the SM
[bounds on NP effective scale of effective operators lowered to ~ TeV]
**MFV and beyond**

The MFV hypothesis is the strongest assumption we can make to impose hierarchical structures also on physics beyond the SM.

**Underlying idea:** the Yukawa couplings are generated at some very heavy (unaccessible) energy scale, and they are the only sources of flavor symmetry breaking accessible at low energies.
**MFV and beyond**

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**Underlying idea:** the Yukawa couplings are generated at some very heavy (unaccessible) energy scale, and they are the only sources of flavor symmetry breaking accessible at low energies.

While this idea can be implemented in explicit NP models (*i.e.* gauge-mediated SUSY breaking) is far from being general...

![Flavor anarchy](MFV)

and it does not address the SM flavor problem (*→* no justification for the observed hierarchies of the SM Yukawa couplings): it is only a (consistent) way to postpone the issue...
**MFV and beyond**

So far, the vast majority of BSM model-building attempts has been based on the following two hypotheses:

- 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) [MFV paradigm]

Under these hypotheses flavor physics is not very exciting (minor role in the search for physics beyond the SM).

Interesting enough, the recent anomalies seem to suggest to abandon these hypotheses, and in particular the MFV paradigm.

As we shall see next, these data seem to point toward non-trivial flavor dynamics not far from the TeV scale, not obviously related to a stabilization of the Higgs sector, but possibly linked to a solution of the SM flavor problem.
Plan of the lectures:

- An introduction to flavor physics
- Lepton Flavor Universality
  - General considerations on LFU
  - LFU tests in $b \to c$ transitions
  - Rare $b \to s$ decays: generalities
  - The $b \to s \ell\ell$ anomalies
  - EFT approaches to the anomalies

- Model building and future prospects
General considerations on LFU

Isidor Issac Rabi
(1898—1988)
General considerations on LFU

In the last few years LHCb, Babar and (to some extent) also Belle reported some “anomalies” (= deviations from SM predictions) in B-meson decays.

Data seem to indicate a different (non-universal) behavior of different lepton species in specific $b$ ($3^{rd}$ 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. $e$
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What is particularly interesting, is that

✱ These anomalies unambiguously point to relatively low NP scales

✱ They are sizable ($\sim$10-20% compared to SM), and they appear in a consistent correlated way in various observables, most of which can be compute with high accuracy ($\sim$1%) within the SM

✱ They are challenging an assumption (Lepton Flavor Universality), that we gave for granted for many years (without many good theoretical reasons...).

Before discussing the precise structure (and the reliability) of these anomalies, it is worth clarifying what we mean by LFU and why it is interesting to test it.
General considerations on LFU

LFU \([= \text{identical behavior of the 3 charged leptons in the limit where we neglect their masses}\)]\) 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 !]
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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\(^{\text{rd}}\) generation quarks, before these recent measurements
Suppose we could test matter only with long wave-length photons...

\[ \gamma \quad U(1)_{Q} \quad e^{+} \quad p^{+} \]

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

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

\[ \gamma, g, W, Z \]
\[ SU(3) \times SU(2) \times U(1) \]

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

\[ e^+, p^+ \]
\[ U(1)_Q \]

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
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\[ SU(3) \times SU(2) \times U(1) \]
\[ e \quad \mu \quad \tau \]

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.

All flavor symmetries could well be only accidental low-energy properties [such as isospin or SU(3) in QCD].
LFU tests in $b \to c$ transitions
**LFU tests in \( b \rightarrow c \) transitions**

The way we test LFU in charged-current \( b \rightarrow c \) transitions is via the ratios

\[
R_{12}(H_c) = \frac{\Gamma(B \rightarrow H_c \ell_1 \nu_1)}{\Gamma(B \rightarrow H_c \ell_2 \nu_2)}
\]

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

We are not able to compute very precisely, separately, numerators and denominators in these ratios because of hadronic uncertainties...

E.g.:

\[
A(B \rightarrow D \ell \nu)_{\text{SM}} = G_{\text{eff}} V_{cb} \langle D \mid b_L \gamma_\mu c_L \mid B \rangle \ell \nu_{\mu \ell}
\]

\[
\rightarrow f_+(q^2) (p_B + p_D)_\mu + f_-(q^2) (p_B - p_D)_\mu
\]

But these uncertainties cancels (to a large extent) in the ratios
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\]

But these uncertainties cancels (to a large extent) in the ratios

Anomalies appeared when comparing \( \tau \) vs. light leptons (\( \mu, e \))
**LFU tests in $b \to c$ transitions**

Test of Lepton Flavor Universality in (charged current) $b \to c$ transitions [$\tau$ vs. light leptons ($\mu$, $e$)]:

![Graph showing LFU tests in $b \to c$ transitions](image)
Test of **Lepton Flavor Universality in** (charged current) $b \rightarrow c$ transitions $[\tau$ vs. light leptons $(\mu, e)]$:
**LFU tests in $b \to c$ transitions**

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Test of Lepton Flavor Universality in (charged current) \( b \rightarrow c \) transitions

[\( \tau \) vs. light leptons (\( \mu, e \))]:

\[
R(H_c) = \frac{\Gamma(B \rightarrow H_c \tau\nu)}{\Gamma(B \rightarrow H_c \ell\nu)}
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\( H_c = D \) 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. \( \rightarrow 3.1\sigma \) excess over SM \((D + D^*)\)
**LFU tests in $b \rightarrow c$ transitions**

Test of Lepton Flavor Universality in (charged current) $b \rightarrow c$ transitions [$\tau$ vs. light leptons ($\mu$, $e$)]:

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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. $\rightarrow 3.1\sigma$ excess over SM ($D + D^*$)

• The two channels are well consistent with a universal enhancement ($\sim 30\%$) of the SM $b_L \rightarrow c_L \tau_L \nu_L$ amplitude
Rare $b \to s$ decays: generalities

\[ B \xrightarrow{W} t \xrightarrow{Z} \mu (e) \quad \text{and} \quad K^{(*)} \xrightarrow{W} s \xrightarrow{Z} \mu (e) \]
Rare $b \rightarrow s$ decays: generalities

The largest (and statistically more significant) set of anomalies is the one extracted from rare decays mediated by $b \rightarrow s \ell^+\ell^-$ amplitudes [$\ell = \mu, e$]:

- $P_5'$ 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 $BR(B_s \rightarrow \mu\mu)$
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$b \to s\ell\ell$ 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

$\to$ detailed discussion needed
The interesting short-distance info is encoded in the $C_i(M_W)$ (initial conditions) of the Wilson coefficients of the FCNC operators.
2\textsuperscript{nd} step: Evolution of $H_{\text{eff}}$ down to low scales using RGE

\begin{equation*}
H_{\text{eff}} = \sum_i C_i(M_W) \, Q_i
\end{equation*}

**Penguin operators:**

\begin{align*}
Q_6 &= \sum_q \left( \bar{b}_L \gamma_{\mu} s_L \right) \bar{q} \gamma^\mu q \\
Q_9 &= \left( \bar{b}_L \gamma_{\mu} s_L \right) \bar{l} \gamma^\mu l \\
Q_{10} &= \left( \bar{b}_L \gamma_{\mu} s_L \right) \bar{l} \gamma^\mu \gamma_5 l
\end{align*}

\begin{equation*}
H_{\text{eff}} = \sum_i C_i(\mu \sim m_b) \, Q_i
\end{equation*}

**Four-quark (tree-level) ops.:**

\begin{align*}
Q_1 &= \left( \bar{b}_L \gamma_{\mu} s_L \right) \left( \bar{c}_L \gamma^\mu c_L \right) \\
Q_2 &= \left( \bar{b}_L \gamma_{\mu} c_L \right) \left( \bar{c}_L \gamma^\mu s_L \right) \\
&\vdots
\end{align*}

**Potential dilution of the interesting short-distance information:**

Mixing of the four-quark $Q_i$ into the FCNC $Q_i$ [perturbative long-distance contribution]

- **Small** in the case of the $Z$ penguin ($Q_{10}$) because of the power-like GIM mechanism [mixing parametrically suppressed by $O(m_c^2/m_t^2)$]
- **Large** for gluon & photon penguins
3\textsuperscript{rd} step: Evaluation of the hadronic matrix elements

\[ A(B \rightarrow f) = \sum_i C_i(\mu) \langle f | Q_i | B \rangle (\mu) \quad [ \mu \sim m_b ] \]

- Hadronic uncertainty due to form factors (as in charged-currents)
- Irreducible th. error due to long-distance effects not included in f.f.

(\textit{charm} threshold → particularly large close to \textbf{cc} resonances)
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- Hadronic uncertainty due to form factors (as in charged-currents)
- Irreducible th. error due to long-distance effects not included in f.f.
  \( (\text{charm threshold} \rightarrow \text{particularly large close to } c\bar{c} \text{ resonances}) \)

Still, we can make precise prediction in appropriate ratios and/or constructing observables insensitive to long-distance effects.

As far as current anomalies are concerned:

- ☀️ \( P'_5 \) 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 \( \text{BR}(B_s \rightarrow \mu\mu) \)

- 😊 th. error very small (\( \leq 1\% \))
- 😊 th. error few %
The $b \rightarrow s \ell\ell$ anomalies
The $b \to s\ell\ell$ anomalies

I. The $P'_5$ anomaly

The $B \to K^*\mu\mu$ differential distribution:

$$\frac{d^4(\Gamma + \Gamma)}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

$$P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$$

observables designed to cancel f.f. dependence in the heavy-quark limit

Descotes-Genon, Matias, Ramon, Virto '12
The $b \to s \ell \ell$ anomalies

I. The $P'_5$ anomaly

The $B \to K^* \mu \mu$ differential distribution:

\[ q^2 \, [\text{GeV}^2/c^4] = m_{\mu \mu}^2 \]
The $b \rightarrow s\ell\ell$ anomalies

I. The $P'_5$ anomaly

The $B \rightarrow K^*\mu\mu$ differential distribution:

![Graph showing differential distribution]

$P'_5 = \frac{\Gamma(B \rightarrow K^*\mu\mu)}{\Gamma(B \rightarrow K^{(*)}\ell\ell)}$
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

[ $H_s = K, K^*, \phi$ (from Bs) ]

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 $C_9$ ($\leftrightarrow$ charm loops) \to significance reduced with conservative estimates of long-distance corrections
The $b \to s \ell\ell$ anomalies

III. The “clean” LFU ratios:

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

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 $b \to s \ell \ell$ 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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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 $\text{BR}(B_s \to \mu\mu)$ by $\sim 20\%$ compared to its SM expectation:

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

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

[LHCb+CMS+ATLAS '19]
**The $b \to s \ell\ell$ anomalies**

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

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 → expected suppression of $\text{BR}(B_s \to \mu\mu)$ by $\sim 20\%$ compared to its SM expectation:

$$\text{IV. } \begin{align*}
\text{BR}(B_s \to \mu\mu)_{\text{SM}} &= (3.57 \pm 0.17) \times 10^{-9} \\
\text{BR}(B_s \to \mu\mu)_{\text{exp}} &= (2.65 \pm 0.43) \times 10^{-9}
\end{align*}$$

[[LHCB+CMS+ATLAS '19]]

A super-conservative analysis, taking into account only the observables III. & IV, with a single NP operator, leads to a pull of $3.2\sigma$ compared to the SM.
The $b \to s \ell \ell$ anomalies

A super-conservative analysis, taking into account only the observables III. & IV, with a single NP operator, leads to a pull of $3.2 \sigma$ 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 → pulls exceeding $5 \sigma$:

Alguero et al. '19

Aebischer et al. '19
EFT approaches to the anomalies
EFT approaches to the anomalies

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

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

- Generic EFT approach – with flavor symmetries
- Simplified Dynamical Models & high-energy signatures
- Possible UV completions

The main guide will be the attempt to describe both LFU effects within the same framework [possibly linking them to the observed pattern of Yukawa couplings] and, while “going up” in energies (and assumptions)

Check the consistency & derive predictions for
- other low-energy observables
- high-pT physics
Anomalies are seen (so far...) only in semi-leptonic (quark×lepton) operators

Data largely favor non-vanishing left-handed current-current operators, although other contributions are also possible

Bhattacharya et al. '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)
EFT approaches to the anomalies

- Anomalies are seen (so far..) only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing left-handed current-current operators, although other contributions are also possible

\[
\frac{F_{ij\alpha\beta}}{\Lambda^2} \bar{Q}_L^i \Gamma Q_L^j \bar{L}_L^\alpha \Gamma L_L^\beta
\]

- Large coupling (competing with SM tree-level ) in bc → l_3 ν_3
- Small non-vanishing coupling (competing with SM FCNC) in bs → l_2 l_2
**EFT approaches to the anomalies**

- Anomalies are seen *(so far...)* only in semi-leptonic *(quark×lepton)* operators
- Data largely favor non-vanishing **left-handed** current-current operators, although other contributions are also possible

\[
Q_L^i \rightarrow L_L^\alpha \rightarrow \frac{F_{ij\alpha\beta}}{\Lambda^2} \bar{Q}_L^i \Gamma Q_L^j \bar{L}_L^\alpha \Gamma L_L^\beta
\]

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

\[
F_{ij\alpha\beta} = (\delta_i^3 \times \delta_j^3) \times (\delta_\alpha^3 \times \delta_\beta^3) + \text{small terms for 2\textsuperscript{nd} (\& 1\textsuperscript{st}) generations}
\]

*Link to pattern of the Yukawa couplings!*
EFT approaches to the anomalies

- Anomalies are seen (so far...) only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing left-handed current-current operators, although other contributions are also possible

\[ Q_L^i \quad L_L^\alpha \quad \frac{F_{ij\alpha\beta}}{\Lambda^2} \quad \bar{Q}_L^i \Gamma Q_L^j \bar{L}_L^\alpha \Gamma L_L^\beta \]

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

E.g:

- Calibbi, Crivellin, Ota, '15 (+many others...)
- Feruglio, Paradisi, Pattori '16

+ many more...
EFT approaches to the anomalies

- Anomalies are seen (so far...) only in semi-leptonic (quark×lepton) operators
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\[
\frac{F_{ij\alpha\beta}}{\Lambda^2} \bar{Q}_L^i \Gamma Q_L^j \bar{L}_L^\alpha \Gamma L_L^\beta
\]

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.

We need to go beyond MFV, but we must somehow retain many of its good phenomenological features...
**EFT-type considerations**

The attempt to link the anomalies to the structure of the Yukawa couplings reinforce the idea of a connection among the two, and points toward NP at the TeV scale → “hint” of a possible connection (*still to be understood...*) to the hierarchy problem

N.B.: such link is lost in high-scale NP models addressing only $R_K$

\[ \Lambda_{|R_D|} < 9 \text{ TeV} \]
\[ \Lambda_{|R_K|} < 84 \text{ TeV} \]

Di Luzio, Nardecchia '17

\[ \text{Hierarchy problem} \]

\[ \text{Yukawa structure} \]
**EFT-type considerations**

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\[
\Delta R_D \sim (3\% - 50\%) \text{ depending on the flavor-breaking structure }
\]
**EFT-type considerations**

Interestingly, present data already provide a (weak) indication of the connection among the two anomalies within a rather general EFT hypothesis.

\[ \bar{Q}_L^2 \Gamma Q_L^2 \bar{L}_L^3 \Gamma L_L^3 \]

non-standard but LF universal contribution to \( C_9 \)

Crivellin, Greub, Muller, Saturnino '19

Aebischer et al. '19