Search of new physics through flavor physics observables

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neutrinos, dark matter & dark energy physics

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The Standard Model

- Gauge sector of the SM entirely **fixed by symmetry**:

  $\Rightarrow$ Only a handful of parameters.

  $\Rightarrow$ Theory renormalizable and verified at the loop-level (oblique parameters).

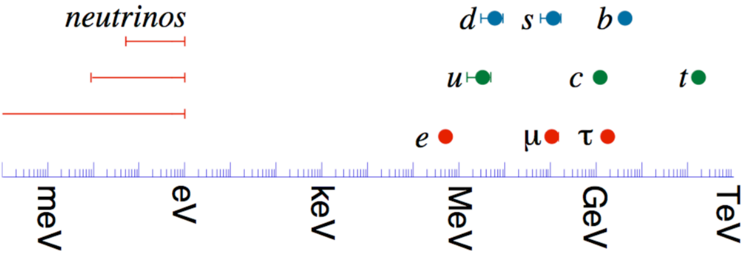
- Flavor sector **not fixed by symmetry** :

  $\Rightarrow$ 13 free parameters (masses and quark mixing) – fixed by data.

$$\mathcal{L}_Y = -Y_\ell\,\bar{L}\,\Phi\,\ell_R - Y_d\,\bar{Q}\,\Phi\,d_R - Y_u\,\bar{Q}\,\tilde{\Phi}\,u_R + \text{h.c.}$$

  $\Rightarrow$ These (many) parameters exhibit a hierarchial structure we do not understand.

- Striking hierarchy ⇒ **Flavor theory**?
- Quarks and leptons mix in completely different ways.



“Who ordered that?”

Motivation

- Assumption in the SM: the couplings of quarks and leptons with the gauge bosons are flavor universal by construction *(up to fermion mass effects)*.

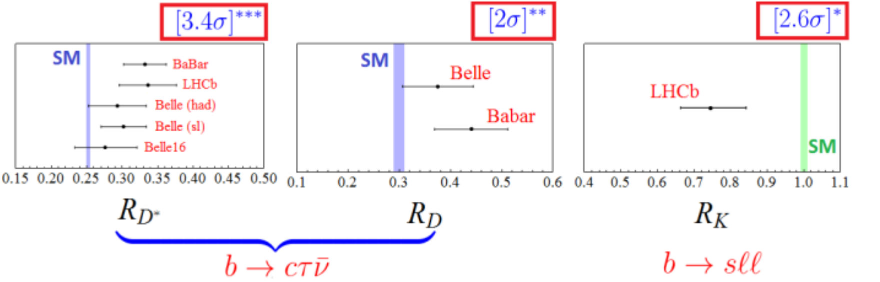
- A few cracks [$\approx 2 - 3\sigma$] appeared recently in B-meson decays

  $\Rightarrow$ Violation of **L**epton **F**lavor **U**niversality (LFU)?

  $\Rightarrow$ To explain those observations *(in both tree-level and loop induced decays)*, one needs to go beyond the SM.

LFUV in B Decays [pre-2017]

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}, \qquad R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)}\Bigg|_{q^2\in[1,6]\ \mathrm{GeV}^2}$$

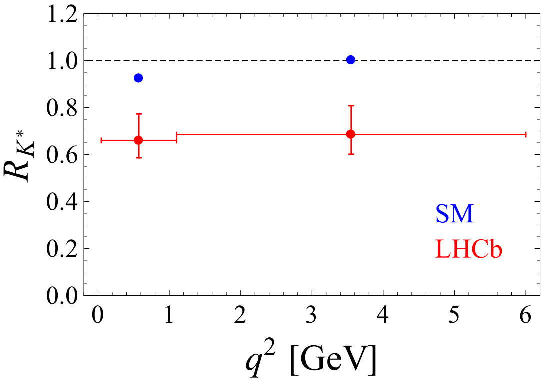


- NEW (FPCP17): LHCb, $R_{D^*} = 0.285(35)$.
- NEW: LHCb, $R_{J/\Psi} = 0.71(17)(18)$. Larger than th. predictions (?)

$$R_{K^*} = \left.\frac{\mathcal{B}(B \to K^* \mu\mu)}{\mathcal{B}(B \to K^* ee)}\right|_{q^2 \in [q^2_{\rm min}, q^2_{\rm max}]}$$

[LHCb, 1705.05802]

- **New results** in two bins of q^2: [$\approx 2.5\sigma$]



TASK:

Using a large ensemble of flavor physics observables as constraints (such as $Z \to \ell\ell$, $W \to \ell\nu$, $B_s \to \mu\mu$ ...), we would like to build a model of New Physics that can explain the so-called B-physics anomalies.

$\Rightarrow$ This is a very difficult problem to solve because of the large amount of experimental constraints!

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⇒ This is a very difficult problem to solve because of the large amount of experimental constraints!

An important part of my thesis was dedicated to this issue.

⇒ I showed that extending the Higgs sector is not enough.

[P. Arnan, D. Bečirević, F. Mescia, OS. 2017]

⇒ Instead, the scenarios involving a leptoquark (LQ) boson can do the job. Here I **focus on $\mathbf{R_K}$ and $\mathbf{R_{K^*}}$**.

[D. Bečirević, S. Fajfer, N. Košnik, OS. 2016]

[D. Bečirević, OS. 2017]

The standard strategy of introducing a low-energy LQ boson cannot provide a tree-level solution to R_K and R_{K^*} without causing other problems *(e.g., proton stability and/or flavor constraints)*.

c.f. [D. Bečirević, N. Košnik, OS, R. Zukanovich. 2016]

[B. Fornal, B. Grinstein. 2017]

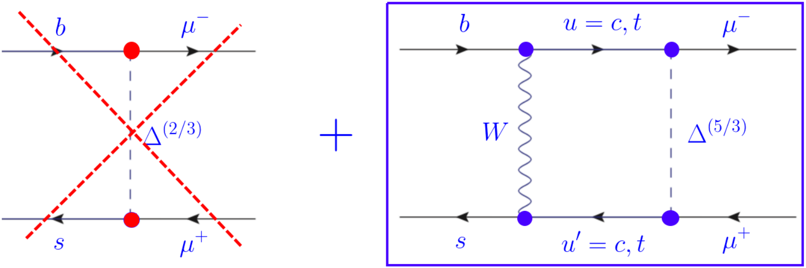
The only scalar LQ which does not disturb the proton stability predicts $R_{K^{(*)}}^{\mathrm{NP}} > R_{K^{(*)}}^{\mathrm{SM}}$, *in disagreement* with the LHCb findings.

I showed that a peculiar choice of the Yukawa couplings can circumvent this problem and explain R_K and R_{K^*} via loops:

[D. Bečirević, OS. 2017]

$$\mathcal{L}_\Delta = (g_R)_{ij}\,\bar{Q}_i \boldsymbol{\Delta} \ell_{Rj} + (g_L)_{ij}\,\bar{u}_{Ri} \widetilde{\boldsymbol{\Delta}}^\dagger L_j + \text{h.c.}, \qquad \Delta = (\mathbf{3},\mathbf{2})_{7/6}$$

$\Rightarrow$ We take $g_R = 0$ and $g_L \neq 0$.



$\Rightarrow$ This provides a viable explanation which can be **tested experimentally**, e.g. through the direct searches at the LHC.

Perspectives

- We are entering a precision era of flavor physics: maturity of LQCD and unprecedented precision in flavor experiments.
- Collective effort in flavor experiments is/will be a guide to theory: *NA62, BES-III and LHCb*, and the forthcoming *Belle-II, KOTO*, $(g-2)_\mu$, *Mu2E*...
- Interesting hints of LFU violation in $R_{K^{(*)}}$ and $R_{D^{(*)}}$:

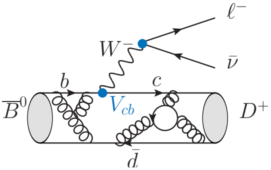
  $\Rightarrow$ Use the experimental data to build a model of NP and verify its validity in direct searches!
- Higgs Flavor Era around the corner?

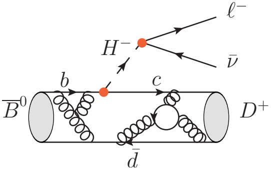
Thank you!

Back-up

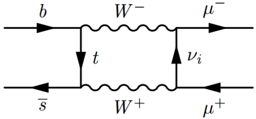
Precision flavor physics: search of deviations w.r.t. the SM predictions

- Flavor changing charged currents: e.g. $b \to c\tau\nu$





- Flavor changing neutral currents: e.g. $b \to s\ell\ell$



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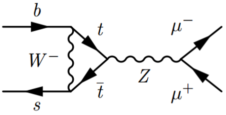


$+ \ldots$

  - Possible mostly due to the maturity of LQCD in determining the relevant *hadronic matrix elements (form factors, decay constants, bag parameters)*.
  - Particularly interesting due to the deviations from LFU observed in B-meson decays: $B \to D^{(*)}\ell\bar{\nu}$ $(\ell = e, \mu, \tau)$ and $B \to K^{(*)}\ell\ell$ $(\ell = e, \mu)$.

$\Rightarrow$ Focus on NP couplings to muons only

[couplings to electrons are also possible, cf. Hiller, Schmaltz 2014]

$SU(3)_c \times SU(2)_L \times U(1)_Y$: **N.B.** $Q = Y + T_3$.

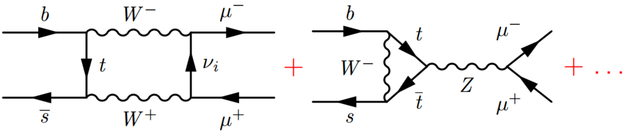
	BNC	Interaction	WC	$R_K/R_K^{\rm SM}$	$R_{K^*}/R_{K^*}^{\rm SM}$
$(\bar{3},1)_{4/3}$	✗	$\overline{d_R^C}\boldsymbol{\Delta}\ell_R$	$(C_9)' = (C_{10})'$	$\approx \mathbf{1}$	$\approx \mathbf{1}$
$(3,2)_{7/6}$	✓	$\overline{Q}\boldsymbol{\Delta}\ell_R$	$C_9 = C_{10}$	$> \mathbf{1}$	$> \mathbf{1}$
$(3,2)_{1/6}$	✓	$\overline{d_R}\widetilde{\boldsymbol{\Delta}}^\dagger L$	$(C_9)' = -(C_{10})'$	$< \mathbf{1}$	$> \mathbf{1}$
$(\bar{3},3)_{1/3}$	✗	$\overline{Q^C} i\tau_2 \boldsymbol{\tau}\cdot\boldsymbol{\Delta} L$	$C_9 = -C_{10}$	$< \mathbf{1}$	$< \mathbf{1}$

$\Rightarrow$ No fully viable model. Triplet can be used, but further symmetries are needed to forbid **proton decay** (see [Dorsner et al. 2017] for a GUT mechanism).

LFU violation

(i) $b \to s\mu^+\mu^-$

- FCNC process:



- Form-factor errors cancel out in the ratio ⇒ **Extremely clean prediction**.

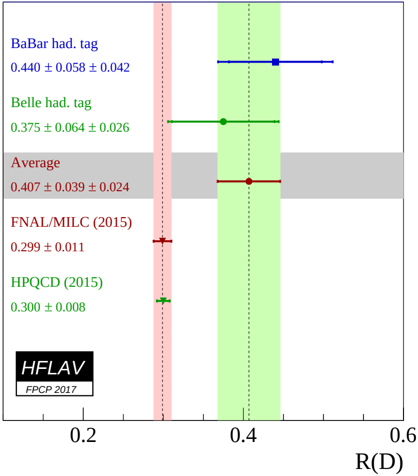
$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu\mu)}{\mathcal{B}(B^+ \to K^+ ee)}\bigg|_{q^2 \in [1,6]\,\mathrm{GeV}^2} \overset{\mathrm{SM}}{=} 1.00(1)$$

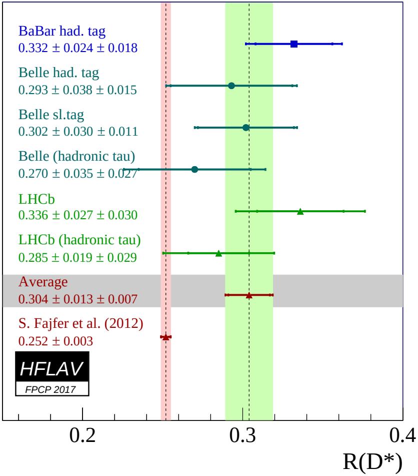
[Bordone et al. 2016]

- 2.6σ **deviation** observed by LHCb:

$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

- 2.5σ **deviation** in two bins for $B \to K^*\mu\mu$: $[0.045, 1.1]$ and $[1.1, 6]$ GeV^2.

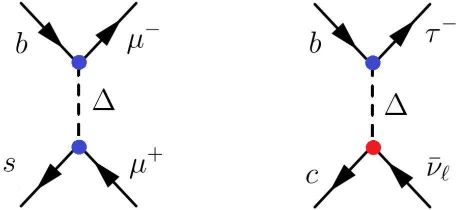




- 3.9σ combined deviation from the SM [theory error under control?]
- 2.2σ deviation if only R_D is considered.
- 2σ deviation in $R_{J/\Psi}$?

We can also explain R_D if a new ingredient is added to the model $\boldsymbol{\Delta^{1/6} = (3,2)_{1/6}}$: three light RH neutrinos ν_R.

$$\mathcal{L}_Y = \boldsymbol{Y^L_{ij}} \bar{L}_i \widetilde{\Delta}^{(1/6)} d_{Rj} + \boldsymbol{Y^R_{ij}} \bar{Q}_i \Delta^{(1/6)} \nu_{Rj} + \text{h.c.}$$



For $b \to c\tau\bar{\nu}$ $\Rightarrow$ $|\mathcal{M}(B \to D^{(*)}\ell\nu)|^2 = |\mathcal{M}_{\text{SM}}|^2 + |\mathcal{M}_{\text{NP}}|^2$.

Naturally generates $\boldsymbol{R^{\text{NP}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}}$ if $|Y^L_{b\tau}| \gtrsim |Y^L_{b\mu}|$.

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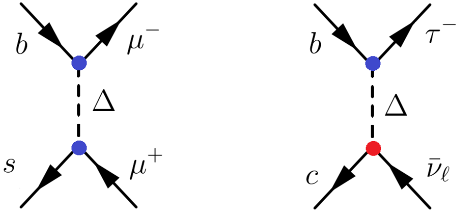

- Passed all flavor tests: $\mathcal{B}(B_s \to \mu^+\mu^-)$, $\mathcal{B}(B \to K\mu\mu)_{\text{high } q^2}$, Δm_{B_s}, $\mathcal{B}(B \to \tau\bar{\nu})$, $\mathcal{B}(D_s \to \tau\bar{\nu})$, $\mathcal{B}(B \to K\nu\bar{\nu})$, $\mathcal{B}(B \to K\mu\tau)$ etc.
- Many experimental signatures for LHCb and Belle-2.

If the LFUV takes place at scales well above EWSB, then use OPE:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots} \Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \Big) \right]$$

- Operators relevant to $b \to s\ell\ell$ are

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma^5 \ell),$$
$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell), \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell),$$
$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \qquad \ldots$$

- To explain $R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$, one needs effective coefficients C_9, C_{10}.