Addressing the B meson anomalies within the minimal U_1 leptoquark model

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Test of LFU in $b \to c\tau\bar{\nu}_\tau$ decays

Recent tests of **lepton flavor universality (LFU)** in B meson decays ($b \to c\tau\bar{\nu}_\tau$), performed by the BABAR, Belle and LHCb experiments, have shown **consistent deviations from the SM predictions**.

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathrm{BR}(B \to D^{(*)}\ell'\bar{\nu}_{\ell'})}, \quad (\ell' = e \text{ or } \mu).$$

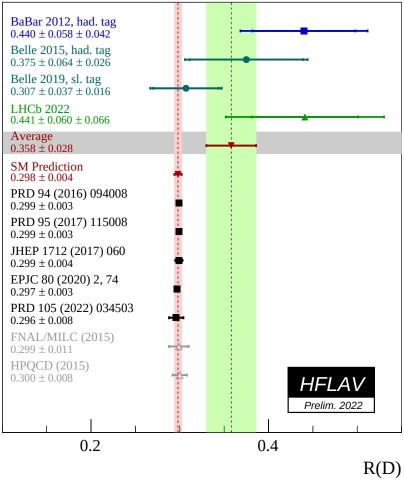
Observable	Measurement	Experiment	SM prediction	Tension
$R(D)$	$0.307 \pm 0.037 \pm 0.016$	Belle-2019	0.298 ± 0.004	0.2σ
	$0.340 \pm 0.027 \pm 0.013$	HFLAV-2019		1.4σ
	$0.441 \pm 0.060 \pm 0.066$	LHCb-2022		1.9σ
	$0.358 \pm 0.025 \pm 0.012$	HFLAV-2022		2.2σ
$R(D^*)$	$0.283 \pm 0.018 \pm 0.014$	Belle-2019	0.254 ± 0.005	1.1σ
	$0.295 \pm 0.011 \pm 0.008$	HFLAV-2019		2.5σ
	$0.281 \pm 0.018 \pm 0.024$	LHCb-2022		1.9σ
	$0.285 \pm 0.010 \pm 0.008$	HFLAV-2022		2.3σ

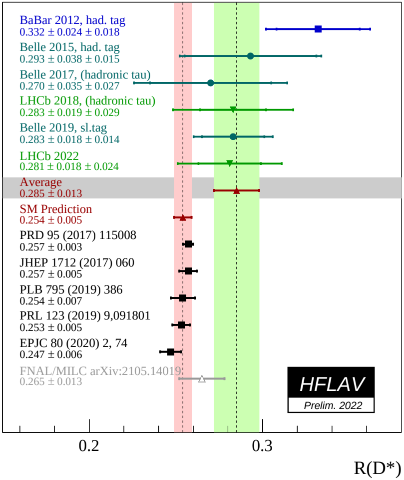
Experimental status on observables related to the charged transition $b \to c\tau\bar{\nu}_\tau$.

$R(D)$ and $R(D^*)$ anomalies!

Test of LFU in semileptonic B meson decays

Heavy Flavor Averaging Group (HFLAV) - 2022





Test of LFU in semileptonic B meson decays

In addition, the LHCb reported a measurement on $R(J/\psi) = \mathrm{BR}(B_c \to J/\psi\tau\bar{\nu}_\tau)/\mathrm{BR}(B_c \to J/\psi\mu\bar{\nu}_\mu)$, and the polarization observables τ lepton polarization $P_\tau(D^*)$ and. D^* longitudinal polarization $F_L(D^*)$ have been observed by the Belle experiment.

Observable	Measurement	Experiment	SM prediction	Tension
$R(D)$	$0.307 \pm 0.037 \pm 0.016$	Belle-2019	0.299 ± 0.003	0.2σ
	$0.340 \pm 0.027 \pm 0.013$	HFLAV-2019		1.4σ
$R(D^*)$	$0.283 \pm 0.018 \pm 0.014$	Belle-2019	0.258 ± 0.005	1.1σ
	$0.295 \pm 0.011 \pm 0.008$	HFLAV-2019		2.5σ
$R(J/\psi)$	$0.71 \pm 0.17 \pm 0.18$	LHCb-2018	0.283 ± 0.048	2.0σ
$P_\tau(D^*)$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$	Belle-2018	-0.497 ± 0.013	0.2σ
$F_L(D^*)$	$0.60 \pm 0.08 \pm 0.035$	Belle-2019	0.46 ± 0.04	1.6σ
$R(X_c)$	0.223 ± 0.030	PDG	0.216 ± 0.003	0.2σ
$R(\Lambda_c)$	0.242 ± 0.076	LHCb-2022	0.324 ± 0.004	1.8σ
$B_c^- \to \tau^-\bar{\nu}_\tau$	$< 10\,\%$		$(2.16 \pm 0.16)\,\%$	

Experimental status on observables related to the charged transition $b \to c\tau\bar{\nu}_\tau$.

charged-current $b \to c\tau\bar{\nu}_\tau$ anomalies!

Test of LFU in leptonic Υ meson decays

- LFU can also be tested through the ratio of leptonic decays of bottomonium meson $\Upsilon(nS)$ [Aloni, Efrati, Grossman, & Nir, 1702.07356].

$$R_{\Upsilon(nS)} \equiv \frac{\mathrm{BR}(\Upsilon(nS) \to \tau^+\tau^-)}{\mathrm{BR}(\Upsilon(nS) \to \ell^+\ell^-)}, \quad (n = 1, 2, 3)$$

Observable	Measurement	Experiment	SM prediction	Tension
$R_{\Upsilon(1S)}$	$1.005 \pm 0.013 \pm 0.022$	BABAR-2010	$0.9924 \pm \mathcal{O}(10^{-5})$	0.5σ
$R_{\Upsilon(2S)}$	$1.04 \pm 0.04 \pm 0.05$	CLEO-2007	$0.9940 \pm \mathcal{O}(10^{-5})$	0.8σ
$R_{\Upsilon(3S)}$	$1.05 \pm 0.08 \pm 0.05$	CLEO-2007	$0.9948 \pm \mathcal{O}(10^{-5})$	0.6σ
	$0.966 \pm 0.008 \pm 0.014$	BABAR-2020		1.8σ
	0.968 ± 0.016	Average		1.7σ

Experimental status on observables related to the neutral transition $b\bar{b} \to \tau^+\tau^-$.

- New physics scenarios aiming to provide an explanation to the LFU violation anomalies in $b \to c\tau\bar{\nu}_\tau$ decays also induce effects in the neutral-current $b\bar{b} \to \tau^+\tau^-$ transition [Faroughy, Greljo, & Kamenik, 1609.07138; Aloni, Efrati, Grossman, & Nir, 1702.07356].

Test of LFU in $b \to s\mu^+\mu^-$ decays

Experimental measurements related to the neutral-current transition $b \to s\mu^+\mu^-$ show deviations respect with the Standard Model (SM) predictions. The ratio of semileptonic decay channels,

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)},$$

provides a test of μ/e lepton flavor universality (LFU) in different dilepton mass-squared range q^2.

- The ratio R_K was first reported in 2014 by the LHCb collaboration **[arXiv:1406.6482]**,

$$R_K^{\mathrm{LHCb-14}} = 0.745^{+0.090}_{-0.074} \pm 0.036, \quad \text{for } q^2 \in [1.0, 6.0]\ \mathrm{GeV}^2,$$

  which deviates from the SM prediction of $R_K^{\mathrm{SM}} \approx 1$ at the level of 2.6σ.

- Recently, the LHCb has released an updated measurement on R_K **[arXiv:2103.11769]**

$$R_K^{\mathrm{LHCb-21}} = 0.846^{+0.044}_{-0.041}, \quad \text{for } q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2,$$

  which is 3.1σ away from the SM predicition.

$b \to s\mu^+\mu^-$ anomalies!

Test of LFU in $b \to s\mu^+\mu^-$ decays

- In 2017, the flavor ratio R_{K^*} was measured by the LHCb Collaboration in the low and central q^2 bins **[arXiv:1705.05802]**,

$$R_{K^*}^{\rm LHCb-17} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03, & \text{for } q^2 \in [0.045, 1.1] \ {\rm GeV}^2, \\ 0.69^{+0.11}_{-0.07} \pm 0.05, & \text{for } q^2 \in [1.1, 6.0] \ {\rm GeV}^2, \end{cases}$$

  respectively. These measurements differ from the SM in the two q^2 regions by $\sim 2.3\sigma$ and $\sim 2.5\sigma$, respectively.
- These discrepancies are reinforced by some anomalous observables (such as angular observables and differential branching fraction) related with $B \to K^*\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ decays

$b \to s\mu^+\mu^-$ anomalies!

NP explanations to the B meson anomalies.

Global analyses

- The global analyses of $b \to s\mu^+\mu^-$ data suggest various new physics solutions [Altmannshofer and Straub, 2103.13370; Carvunis et al 2102.13390; Alguero et al 2104.08921; Geng et al 2103.12738].
- Considering one NP operator or two related operators at a time and assuming new physics only in the muon sector, the $\mathcal{O}_9 = (\bar{s}P_L\gamma_\mu b)(\bar{\mu}\gamma^\mu\mu)$ **operator** as well as a combination of $\mathcal{O}_9$ and $\mathcal{O}_9 = (\bar{s}P_L\gamma_\mu b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$ with $C_9 = -C_{10}$ can account for all $b \to s\mu^+\mu^-$ data.
- These model independent solutions can be realized in several NP models.
- NP arising from **LH vector** C_{V_L} associated with the **operator** $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L\nu_\tau)$ is a preferred solution to address the anomalies, providing a **good fit to the data.**

Murgui, Peñuelas, Jung & Pich, 1904.09311; Mandal, Murgui, Peñuelas, & Pich, 2004.06726; Shi *et al*, 1905.08498; Blanke *et al*, 1905.08253; Bhardam & Ghosh, 1904.10432

We reanalize the single vector leptoquark model as a combined explanation.

(Phenomenological Approach)

U_1 leptoquark model

- The interaction of the $SU(2)_L$ **singlet vector leptoquark** $U_1 \equiv U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$ with the SM fermions can written as [Angelescu *et al*, 1808.08179; 2103.12504]

$$\Delta\mathcal{L}_{U_1} = (x_L^{ij}\,\bar{Q}_{iL}\gamma_\mu L_{jL} + x_R^{ij}\,\bar{d}_{iR}\gamma_\mu \ell_{jR})U_1^\mu,$$

  where quark-lepton flavor couplings x_L and x_R are (in general) complex 3×3 matrices,Q_L and L_L are the LH quark and lepton doublets.

- After integrating out the vector leptoquark U_1, the Lagrangian $\Delta\mathcal{L}_{U_1}$ can generate tree-level contributions to **neutral-current** $b \to s\mu^+\mu^-$ and **charged-current** $b \to c\tau^-\bar{\nu}_\tau$ transitions, as well as **LFV decays** ($B^+ \to K^+\mu^\pm\tau^\mp$, $B_s \to \mu^\pm\tau^\mp$, $\tau \to \mu\phi$, $\Upsilon(nS) \to \mu^\pm\tau^\mp$), and **rare** B **decays** ($B \to K\tau^+\tau^-, B_s \to \tau^+\tau^-$).

- We will consider the flavor structure

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}, \quad x_R = 0.$$

  We neglect RH contributions for simplicity. This is the so-called *minimal* U_1 *model*. [Angelescu *et al*, 1808.08179; 2103.12504].

Phenomenological analysis of the minimal U_1 model

To provide a robust phenomenological study we perform a χ^2 analysis by taking into account the following data:

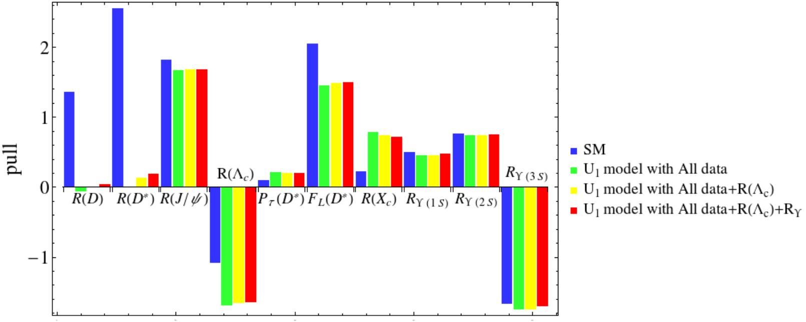
- $b \to s\mu^+\mu^-$ data: $C_9 = -C_{10}$ solution
- $b \to c\tau\bar{\nu}_\tau$ data: $R(D^{(*)})$ (HFLAV 2019 averages), $R(J/\psi)$, $R(X_c)$; the polarizations $P_\tau(D^*), F_L(D^*)$; and the upper limit BR$(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\,\%$.
- $b\bar{b} \to \tau^+\tau^-$ data: bottomonium ratios $R_{\Upsilon(nS)}$
- LFV decays ($B^+ \to K^+\mu^\pm\tau^\mp$, $B_s \to \mu^\pm\tau^\mp$, $\tau \to \mu\phi$, $\Upsilon(nS) \to \mu^\pm\tau^\mp$), and rare B decays $(B \to K\tau^+\tau^-, B_s \to \tau^+\tau^-)$.
- Projected Belle II scenarios (New!): for $50\ \mathrm{ab}^{-1}$ data improvements at the level of $\sim 2-3\,\%$ and $\sim 2\,\%$ will be achieved for the uncertainties (statistical and systematic) of $R(D^*)$ [Belle II Physics Book, 1808.10567].
- LHC bounds: we include the recast of ATLAS and CMS regarding the direct searches and the high$-p_T$ considerations of the $pp \to \ell\bar{\ell}$ differential cross section [Angelescu *et al*, 1808.08179; 2103.12504].

Four free-parameters $(x_L^{s\mu}, x_L^{s\tau}, x_L^{b\mu}, x_L^{b\tau})$ of the U_1 LQ model to be fitted. We fix the LQ mass to the benchmark value of $M_{U_1} = 1.8$ TeV.

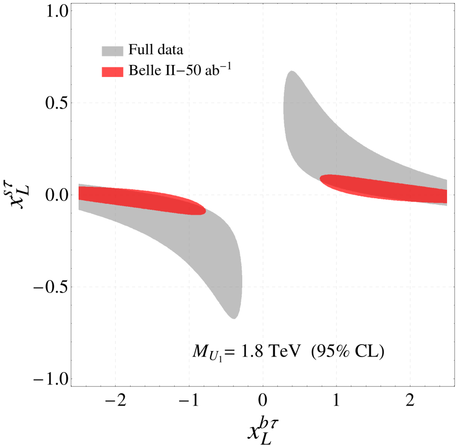
Phenomenological analysis of the minimal U_1 model

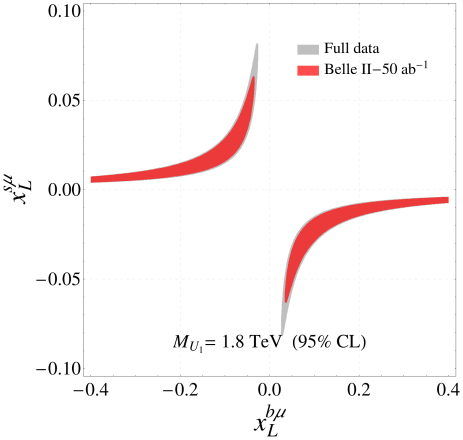
TABLE IV. The 1σ fit results of U_1 LQ couplings, $\chi^2_{\rm min}/N_{\rm dof}$, and $p-$value for different data sets. In all the cases considered, we have used the benchmark mass value of $M_{U_1} = 1.8$ TeV.

Data set	$x_L^{s\mu}$	$x_L^{s\tau}$	$x_L^{b\mu}$	$x_L^{b\tau}$	$\chi^2_{\rm min}/N_{\rm dof}$	$p-$value (%)
All data	$[-0.19, 0.15]$	$[0.08, 0.17]$	$[0.13, 0.18]$	$[1.25, 1.87]$	6.26/15	97.5
All data $+R(\Lambda_c)_{\rm LHCb}$	$[-0.17, 0.14]$	$[0.06, 0.16]$	$[0.14, 0.20]$	$[1.24, 1.88]$	8.93/16	91.6
All data $+R(\Lambda_c)_{\rm Revisited}$	$[-0.18, 0.15]$	$[0.07, 0.16]$	$[0.14, 0.19]$	$[1.24, 1.88]$	7.51/16	96.2
All data $+R(\Lambda_c)_{\rm LHCb} + R_\Upsilon$	$[-0.17, 0.15]$	$[0.06, 0.16]$	$[0.14, 0.19]$	$[1.22, 1.87]$	12.7/21	85.1
All data $+R(\Lambda_c)_{\rm Revisited} + R_\Upsilon$	$[-0.18, 0.15]$	$[0.07, 0.16]$	$[0.14, 0.19]$	$[1.23, 1.86]$	11.3/21	91.2



Parametric space minimal U_1 model





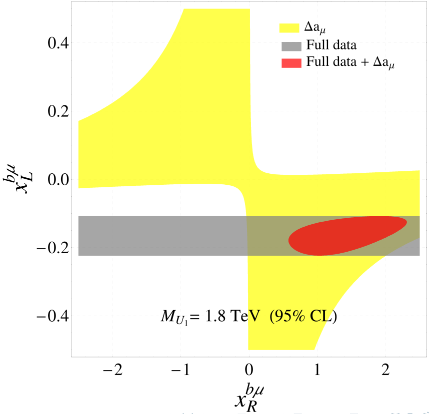
Addressing the $a_\mu = (g-2)_\mu$ anomaly

The combined experimental average (Fermilab (New!) and BNL E821) of the anomalous magnetic moment of the muon, $a_\mu = \frac{1}{2}(g-2)_\mu$

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}.$$

shows a 4.2σ deviation from the SM contribution.

- The minimal U_1 model can contribute at the one-loop level to Δa_μ by economically allowing a single right-handed bottom-muon coupling ($x_R^{b\mu} \neq 0$).
- The B meson anomalies ($b \to c\tau\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$ data) and a_μ can be simultaneously explained within this singlet vector LQ model.



Conclusions

- The minimal U_1 model can **provide a simultaneous explanation** of the B meson anomalies ($b \to c\tau\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$ data).
- Our results showed that the inclusion of the new observables $R(\Lambda_c)$ and $R_{\Upsilon(3S)}$ generates a **non-trivial tension** into the global fit, yielding to a worsening of the goodness of the fit.
- Future measurements from **Belle II** (as well as LHCb) will be a matter of importance to the model.
- Our results might be used as **guide for model builders**.
- By economically extending the minimal U_1 model with the addition of the **right-handed bottom-muon coupling ($x_R^{b\mu} \neq 0$)** with large values, the $(g-2)_\mu$ **anomaly can also be accommodated**.

THANK YOU !

BACK UP

Lepton flavor universality

What is Lepton flavor universality?

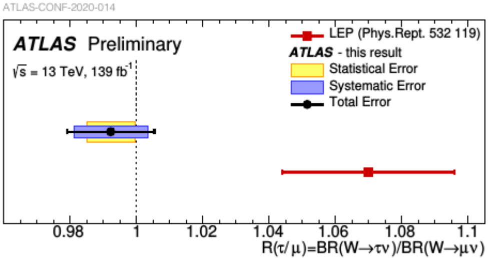
The couplings of the leptons to the gauge bosons W and Z are flavour-independent: the interactions between leptons and gauge bosons are the same for all leptons. This property is called **lepton flavor universality (LFU)**.

LFU has been tested in:

- W bosons partial decay widths from LEP measurements

$$R_W^{\tau/\ell} = \frac{\text{BR}(W \to \tau\bar{\nu}_\tau)}{\text{BR}(W \to \mu\bar{\nu}_\mu)} = 1.070 \pm 0.026 \quad (2.7\sigma) \qquad [R_W^{\tau/\ell}]_{\text{SM}} = 0.999$$

- ATLAS [arXiv:2007.14040] : $R_W^{\tau/\ell} = 0.992 \pm 0.013$ (0.5σ)



Introduction/Motivation

LFU has been tested in:

- W and Z bosons partial decay widths from LEP measurements

$$R_W^{\mu/e} = \frac{\text{BR}(W \to \mu\bar{\nu}_\mu)}{\text{BR}(W \to e\bar{\nu}_e)} = 0.983 \pm 0.018 \qquad [R_W^{\mu/e}]_{\text{SM}} = 1.000$$

$$R_Z^{\mu/e} = \frac{\text{BR}(Z \to \mu\bar{\mu})}{\text{BR}(Z \to e\bar{e})} = 1.0009 \pm 0.0028 \qquad [R_Z^{\mu/e}]_{\text{SM}} = 1.000$$

$$R_Z^{\tau/e} = \frac{\text{BR}(Z \to \tau\bar{\tau})}{\text{BR}(Z \to \mu\bar{\mu})} = 1.0020 \pm 0.0032 \qquad [R_Z^{\tau/e}]_{\text{SM}} = 0.998$$

- Leptonic τ decays pose very stringent constraints on lepton universality [Pich, PPNP 75, 41 (2014)], as well as $P \to \ell\bar{\nu}_\ell$ and $P \to P'\ell\bar{\nu}_\ell$.

$$R_P^{\mu/e} = \frac{\text{BR}(P \to \mu\bar{\nu}_\mu)}{\text{BR}(P \to e\bar{\nu}_e)} \qquad P = \pi, K, D, D_s$$

$$R_P^{\mu/e} = \frac{\text{BR}(P \to P'\mu\bar{\nu}_\mu)}{\text{BR}(P \to P'e\bar{\nu}_e)} \qquad P^{(\prime)} = \pi, K, D, D_s$$

Test μ/e in excellent agreement between SM and experiment.