

Singlet vector leptoquark explanation of the B meson anomalies

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OUTLINE

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

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

[Pompili (COMHEP 6)].

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

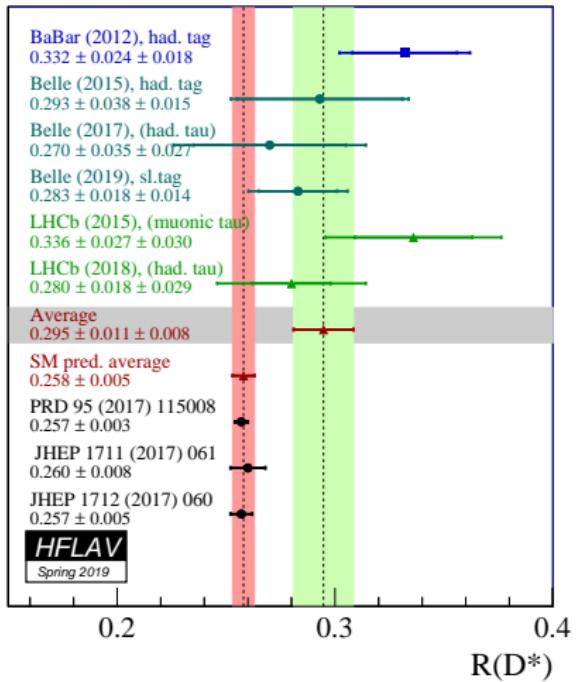
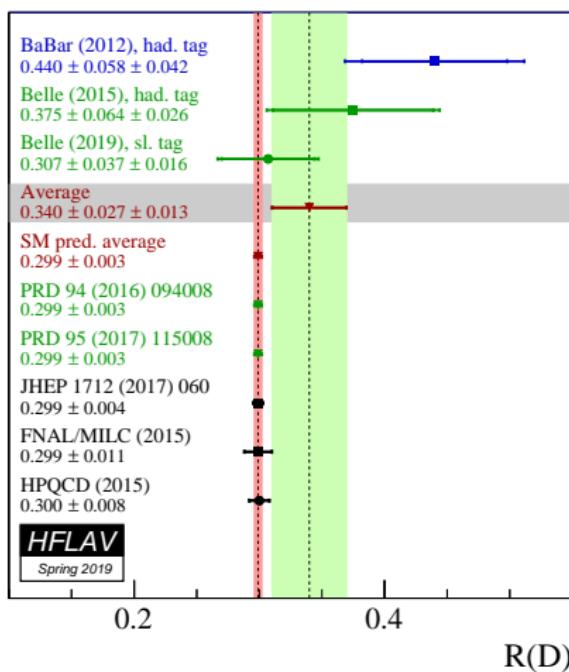
Observable	Measurement	Experiment	SM prediction	Tension
$R(D)$	$0.307 \pm 0.037 \pm 0.016$	Belle-2019	0.299 ± 0.003	0.2σ
	$0.340 \pm 0.027 \pm 0.013$	HFLAV-2019		1.4σ
$R(D^*)$	$0.283 \pm 0.018 \pm 0.014$	Belle-2019	0.258 ± 0.005	1.1σ
	$0.295 \pm 0.011 \pm 0.008$	HFLAV-2019		2.5σ

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

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

Test of LFU in semileptonic B meson decays

Heavy Flavor Averaging Group (HFLAV) - 2019



Test of LFU in semileptonic B meson decays

In addition, the LHCb reported a measurement on $R(J/\psi) = \text{BR}(B_c \rightarrow J/\psi\tau\bar{\nu}_\tau)/\text{BR}(B_c \rightarrow J/\psi\mu\bar{\nu}_\mu)$, 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
$P_\tau(D^*)$	$-0.38 \pm 0.51^{+0.21}_{-0.16}$ <i>(large uncertainty!)</i>	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
$B_c^- \rightarrow \tau^-\bar{\nu}_\tau$	$< 10\%$		$(2.16 \pm 0.16)\%$	

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

charged-current $b \rightarrow c\tau\bar{\nu}_\tau$ 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].

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

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 $b\bar{b} \rightarrow \tau^+ \tau^-$.

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

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

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

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

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

[Pompili (COMHEP 6)].

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

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

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

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

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

which is 3.1σ away from the SM prediction.

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

Test of LFU in $b \rightarrow s\mu^+\mu^-$ 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](#)],

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

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 $B \rightarrow K^*\mu^+\mu^-$ and $B_s \rightarrow \phi\mu^+\mu^-$ decays

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

NP explanations to the B meson anomalies.

Global analyses

- The global analyses of $b \rightarrow s\mu^+\mu^-$ 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 $b \rightarrow s\mu^+\mu^-$ 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 reanalyze the single vector leptoquark model as a combined explanation.

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 be 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** $b \rightarrow s\mu^+\mu^-$ and **charged-current** $b \rightarrow c\tau^-\bar{\nu}_\tau$ transitions, as well as **LFV decays** ($B^+ \rightarrow K^+ \mu^\pm \tau^\mp$, $B_s \rightarrow \mu^\pm \tau^\mp$, $\tau \rightarrow \mu\phi$, $\Upsilon(nS) \rightarrow \mu^\pm \tau^\mp$), and **rare B decays** ($B \rightarrow K\tau^+\tau^-$, $B_s \rightarrow \tau^+\tau^-$).
- 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 U_1 model

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

- $b \rightarrow s\mu^+\mu^-$ data: $C_9 = -C_{10}$ solution
- $b \rightarrow c\tau\bar{\nu}_\tau$ data: $R(D^{(*)})$ (HFLAV 2019 averages), $R(J/\psi)$, $R(X_c)$; the polarizations $P_\tau(D^*)$, $F_L(D^*)$; and the upper limit $\text{BR}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau) < 10\%$.
- $b\bar{b} \rightarrow \tau^+\tau^-$ data: bottomonium ratios $R_{\Upsilon(nS)}$
- LFV decays ($B^+ \rightarrow K^+\mu^\pm\tau^\mp$, $B_s \rightarrow \mu^\pm\tau^\mp$, $\tau \rightarrow \mu\phi$, $\Upsilon(nS) \rightarrow \mu^\pm\tau^\mp$), and rare B decays ($B \rightarrow K\tau^+\tau^-$, $B_s \rightarrow \tau^+\tau^-$).
- Projected Belle II scenarios (New!): for 50 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 $pp \rightarrow \ell\bar{\ell}$ differential cross section [Angelescu et al, 1808.08179; 2103.12504].

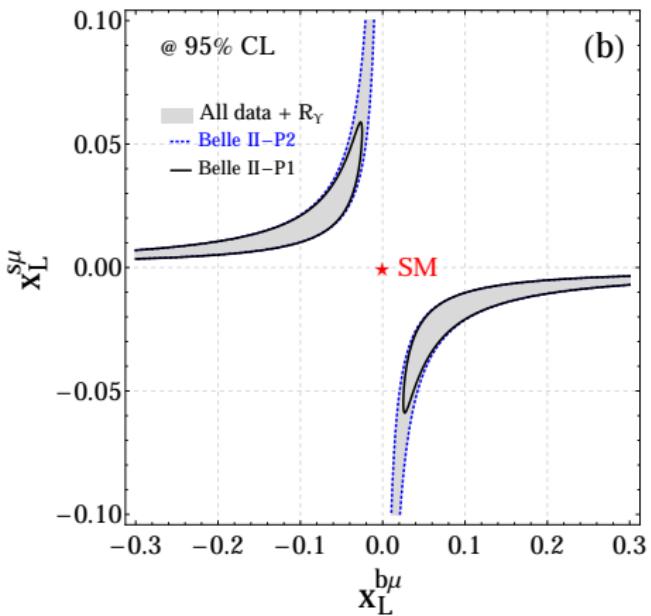
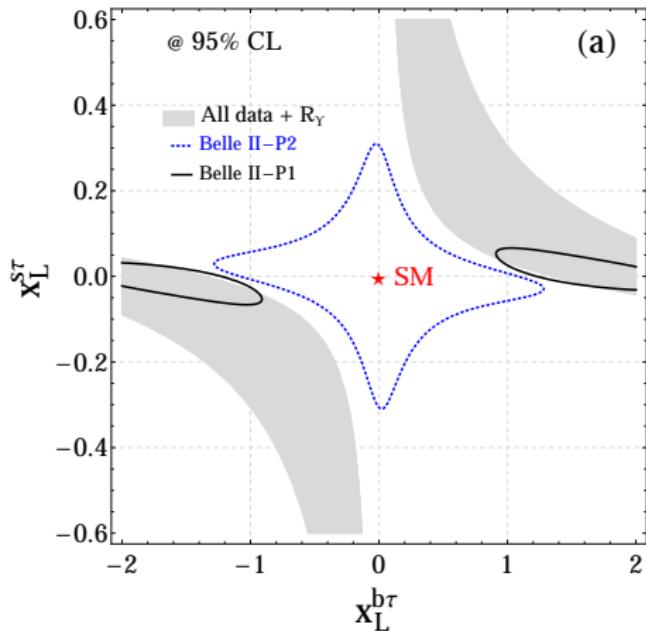
Four free-parameters ($x_L^{s\mu}, x_L^{s\tau}, x_L^{b\mu}, x_L^{b\tau}$) of the U_1 LQ model to be fitted. We fix the LQ mass to the benchmark values of $M_{U_1} = 1.5 \text{ TeV}$ and 2.0 TeV .

Phenomenological analysis of the U_1 model

Fit results

M_{U_1} (TeV)	U_1 LQ couplings	BFP	1σ intervals
1.5	$x_L^{s\mu}$	0.023	[0.019, 0.026]
	$x_L^{s\tau}$	0.26	[0.18, 0.34]
	$x_L^{b\mu}$	-0.070	[-0.080, -0.060]
	$x_L^{b\tau}$	0.73	[0.55, 0.90]
2.0	$x_L^{s\mu}$	0.030	[0.026, 0.034]
	$x_L^{s\tau}$	0.35	[0.25, 0.45]
	$x_L^{b\mu}$	-0.093	[-0.106, -0.079]
	$x_L^{b\tau}$	0.97	[0.73, 1.20]

- We get a minimum of the χ^2 function $\chi^2_{\min} = 9.45$, with a good fit of the data $\chi^2_{\min}/N_{\text{dof}} = 0.68$ corresponding to a p -value = 80 %.

Parametric space U_1 model

Some conclusions

- The vector leptoquark U_1 model can provide a simultaneous explanation of the B meson anomalies ($b \rightarrow c\tau\bar{\nu}_\tau$ and $b \rightarrow s\mu^+\mu^-$ data).
- Future measurements from **Belle II** (as well as LHCb) will be a matter of importance.
- The vector LQ U_1 can contribute at the one-loop level to $(g - 2)_\mu$.

THANK YOU !

BACK UP

Lepton flavor universality

What is Lepton flavor universality?

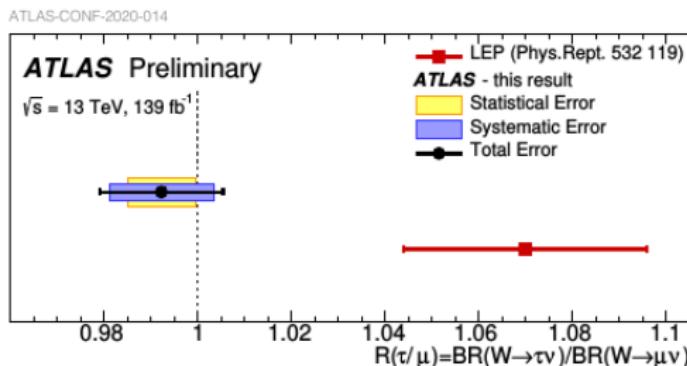
The couplings of the leptons to the gauge bosons W and Z are flavour-independent: the interactions between leptons and gauge bosons are the same for all leptons. This property is called **lepton flavor universality (LFU)**.

LFU has been tested in:

- W bosons partial decay widths from LEP measurements

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

- ATLAS [[arXiv:2007.14040](https://arxiv.org/abs/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

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

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

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

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

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

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

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