New physics interpretations to the $R(D)$ and $R(D^*)$ anomalies: a W' boson

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Based on: **C. H. García-Duque, J. H. Muñoz, NQ and E. Rojas, PRD 103, 073003 (2021) [arXiv:2103.00344 [hep-ph]]**

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OUTLINE

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   - Test of LFU in leptonic Υ meson decays
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3. Conclusions

Test of LFU in semileptonic B meson 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.

[Fajfer and Murgui (CHARM 2020)].

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

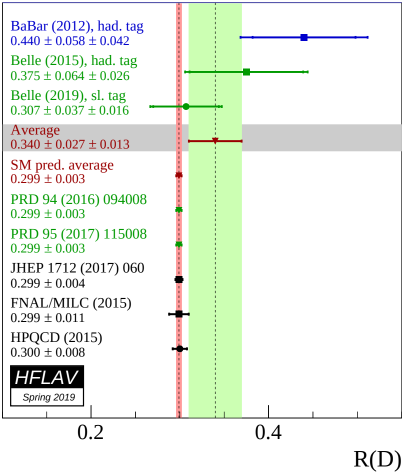
Observable	Measurement	Experiment	SM prediction	Tension
$R(D)$	$0.307 \pm 0.037 \pm 0.016$	Belle-2019	0.299 ± 0.003	0.2σ
	$0.340 \pm 0.027 \pm 0.013$	HFLAV-2019		1.4σ
$R(D^*)$	$0.283 \pm 0.018 \pm 0.014$	Belle-2019	0.258 ± 0.005	1.1σ
	$0.295 \pm 0.011 \pm 0.008$	HFLAV-2019		2.5σ

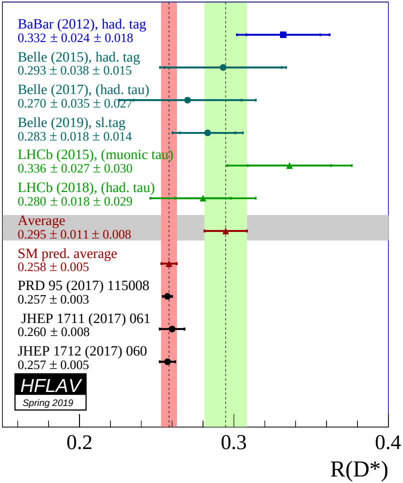
Experimental status on observables related to the charged transition $b \to c\tau\bar{\nu}_\tau$.

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

Test of LFU in semileptonic B meson decays

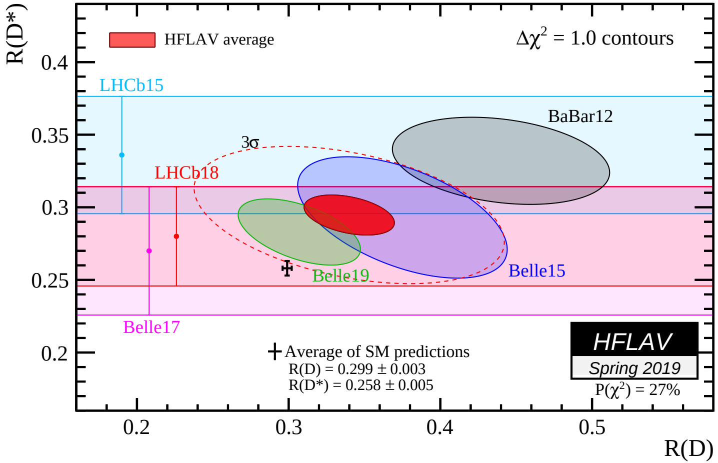
Heavy Flavor Averaging Group (HFLAV) - 2019





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 $R(J/\psi) = \mathrm{BR}(B_c \to J/\psi\tau\bar{\nu}_\tau)/\mathrm{BR}(B_c \to J/\psi\mu\bar{\nu}_\mu)$, and the polarization observables τ lepton polarization $P_\tau(D^*)$ and. D^* longitudinal polarization $F_L(D^*)$ have been observed by the Belle experiment **[Murgui (CHARM 2020)]**.

Observable	Measurement	Experiment	SM prediction	Tension
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	$0.295 \pm 0.011 \pm 0.008$	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
	(large uncertainty!)			
$F_L(D^*)$	$0.60 \pm 0.08 \pm 0.035$	Belle-2019	0.46 ± 0.04	1.6σ
$R(X_c)$	0.223 ± 0.030	PDG	0.216 ± 0.003	0.2σ
$B_c^- \to \tau^-\bar{\nu}_\tau$	$< 10\,\%$		$(2.16 \pm 0.16)\,\%$	

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

[Banerjee (CHARM 2020)].

- 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].

NP explanations to the charged-current $b \to c\tau\bar{\nu}_\tau$ anomalies.

Model-independent approach

Effect of NP operators regarding the most general dimension-six effective Lagrangian contributing to $b \to c\tau\bar{\nu}_\tau$. **[Murgui (CHARM 2020)]**

- 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

C_{V_L}: NP scenarios

- Vector Leptoquarks

Hati, Kriewald, Orloff & Teixeira, 1907.05511; Fornal, Gadam & Grinstein, 1812.01603; Becirevic *et al*, 1806.05689; Yan, Yang & Yuan, 1905.01795; Cornella, Fuentes-Martin & Isidori, 1903.11517

- Extra gauge bosons W'

Gomez, NQ, & Rojas, 1907.08357; He & Valencia, 1711.09525; Boucenna *et al*, 1608.01349; Greljo, Isidori & Marzocca, 1506.01705; Abdullah *et al*, 1805.01869; Greljo, Camalich & Ruiz-Álvarez, 1811.07920

We reanalize the extra gauge boson scenario within the vector triplet model.

Vector Triplet boson model (SM + Extra gauge bosons)

- The SM is extended by including a color-neutral real $SU(2)_L$ triplet of massive vectors W' and Z' that coupled **predominantly** to LH fermions from the **third-generation** [Greljo, Isidori & Marzocca, 1506.01705; Faroughy, Greljo, & Kamenik, 1609.07138]

$$\mathcal{L}^{\mathrm{LH-VB}} = g_b \bar{Q}_3 \frac{\sigma_a}{2} \gamma^\mu W_\mu^a Q_3 + g_\tau \bar{L}_3 \frac{\sigma_a}{2} \gamma^\mu W_\mu^a L_3,$$

  where g_b and g_τ are the corresponding couplings of LH quarks and leptons to vector bosons.
- NP effects are **negligible** for light lepton modes (e or μ).
- After the heavy vector bosons are integrating out, the relevant charged-current and neutral-current operators are given by

$$\begin{aligned} \mathcal{L}_{\mathrm{CC}}(b \to c\tau\bar{\nu}_\tau) &= -\frac{g_b g_\tau}{2M_{W'}^2} V_{cb} (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + \text{ H.c.}, \\ \mathcal{L}_{\mathrm{NC}}(b\bar{b} \to \tau\bar{\tau}) &= -\frac{g_b g_\tau}{4M_{Z'}^2} (\bar{b}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \tau), \end{aligned}$$

- The gauge bosons are (almost) degenerate $M_{W'} \simeq M_{Z'}$ (EW precision data).
- The NP effects are driven by the mass scale of the heavy mediators and the size of couplings g_b and g_τ (we will take these couplings to be real).

Phenomenological analysis of the VTB model

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

- $b \to c\tau\bar{\nu}_\tau$ 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$(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\,\%$.
- R_Υ old data: $R_{\Upsilon(1S)}$ BABAR-10, $R_{\Upsilon(2S)}$ CLEO-07, and $R_{\Upsilon(3S)}$ CLEO-07.
- R_Υ with BABAR-20 data: $R_{\Upsilon(1S)}$ BABAR-10, $R_{\Upsilon(2S)}$ CLEO-07, and $R_{\Upsilon(3S)}$ BABAR-20.
- R_Υ combined data: $R_{\Upsilon(1S)}$ BABAR-10, $R_{\Upsilon(2S)}$ CLEO-07, and $R_{\Upsilon(3S)}$ average.
- 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].

  Belle II-P1: Belle II measurements on $R(D^{(*)})$ keep the central values of Belle combination averages with the projected Belle II sensitivities .
  Belle II-P2: Belle II measurements on $R(D^{(*)})$ are in agreement with the current SM predictions at the 0.1σ level with the projected Belle II sensitivities.
- LHC bounds and prospects at the high-luminosity (HL)-LHC [Marzocca, Min, & Son, 2008.07541; Iguro, Takeuchi, and Watanabe, 2011.02486].

Phenomenological analysis of the VTB model

Fit results for $M_{W'} = 1$ TeV (couplings in the perturbative regime $< \sqrt{4\pi}$)

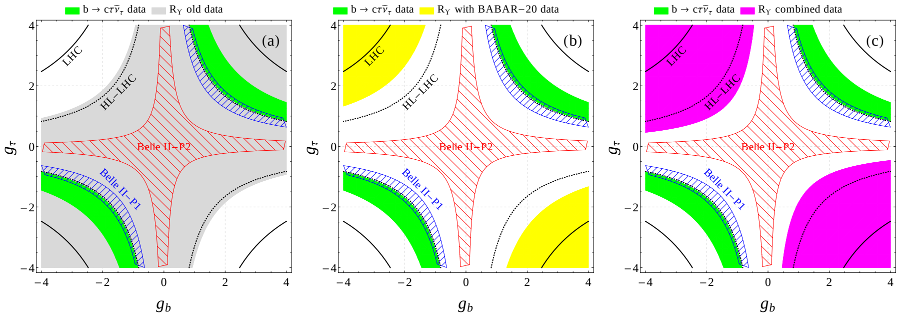
Dataset	(g_b, g_τ)	$\chi^2_{\rm min}/N_{\rm dof}$	p-value (%)	${\rm pull_{SM}}$
$b \to c\tau\bar{\nu}_\tau$	(2.99,1.54)	1.04	39.0	3.72
$b \to c\tau\bar{\nu}_\tau$ + R_Υ old	(3.05,1.52)	0.79	61.3	3.75
$b \to c\tau\bar{\nu}_\tau$ + R_Υ with BABAR-20	(3.27,1.39)	1.20	29.3	3.68
$b \to c\tau\bar{\nu}_\tau$ + R_Υ combined	(3.05,1.52)	1.11	35.3	3.68

BFP values of gauge couplings, $\chi^2_{\rm min}/N_{\rm dof}$, p-value, and ${\rm pull_{SM}} = \sqrt{\chi^2_{\rm SM} - \chi^2_{\rm min}}$ for different datasets of observables.

Our results show that:

- BABAR measurement on $R_{\Upsilon(3S)}$ induces tension in the analysis, causing the quality of the fit to decrease (smaller p-value)
- BABAR's result seems to challenge the VTB model explanation.

Parametric space (g_b, g_τ)



Our results show that:

- BABAR results on $R_{\Upsilon(3S)}$ generates tension; therefore, charged-current and neutral-current data of b-flavored mesons cannot be addressed simultaneously in this model.
- Only relaxing the $R_{\Upsilon(3S)}$ experimental uncertainties to the 2σ level can a common allowed region be obtained.
- Remarkably, the Belle II-P2 scenario would provide stronger bounds on the (g_b, g_τ) plane than prospects at the HL-LHC.

Concluding Remarks

- The charged current $b \to c\tau\bar{\nu}_\tau$ anomalies constitute a tantalizing **window for NP**.
- 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.
- Motivated by the very recent **BABAR measurement on $R_{\Upsilon(3S)}$**, we revisited the **VTB model** proposed as a viable solution to the $b \to c\tau\bar{\nu}_\tau$ anomalies.
- We found that the BABAR measurement of $R_{\Upsilon(3S)}$ is particularly challenging and the 1σ range uncertainties **cannot be explained simultaneously** with charged-current $b \to c\tau\bar{\nu}_\tau$ data.
- The recent BABAR results on $R_{\Upsilon(3S)}$ hint toward a **new anomalous measurement**.
- Future measurements from Belle II (as well as LHCb) will be a matter of importance.

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)**.

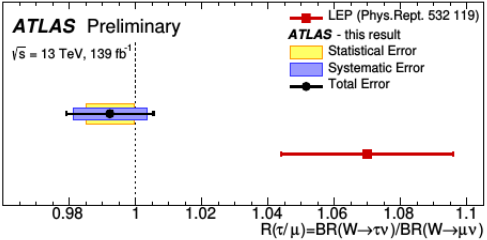
LFU has been tested in:

- W bosons partial decay widths from LEP measurements

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

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

ATLAS-CONF-2020-014



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.