Addressing the $R(D)$ and $R(D^*)$ anomalies within a charged scalar boson scenario

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OUTLINE

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Test of lepton universality in semileptonic B meson decays

Recent tests of lepton universality 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 [Ciezarek *et al*, Nature **546**, 227 (2017)].

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

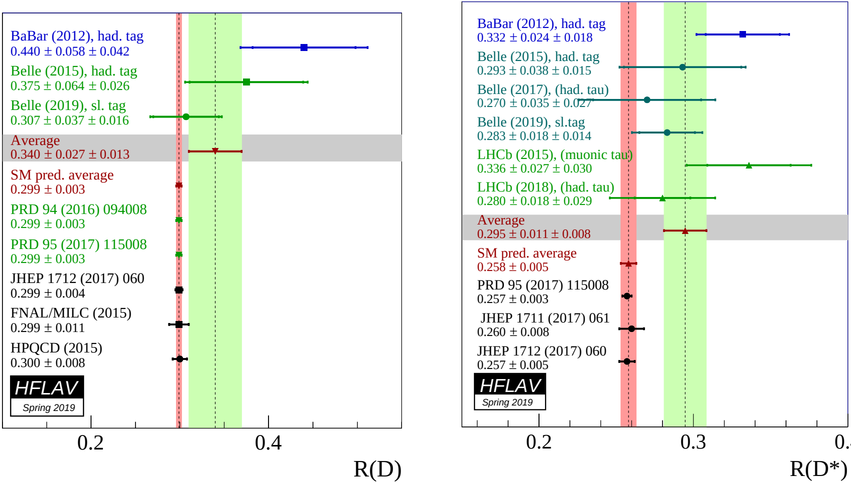
Observable	Measurement	Experiment	SM prediction	Tension
$R(D)$	$0.307 \pm 0.037 \pm 0.016$	Belle-2019	0.299 ± 0.003	0.2σ
	$0.340 \pm 0.027 \pm 0.013$	HFLAV-2019		1.4σ
$R(D^*)$	$0.283 \pm 0.018 \pm 0.014$	Belle-2019	0.258 ± 0.005	1.1σ
	$0.295 \pm 0.011 \pm 0.008$	HFLAV-2019		2.5σ

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

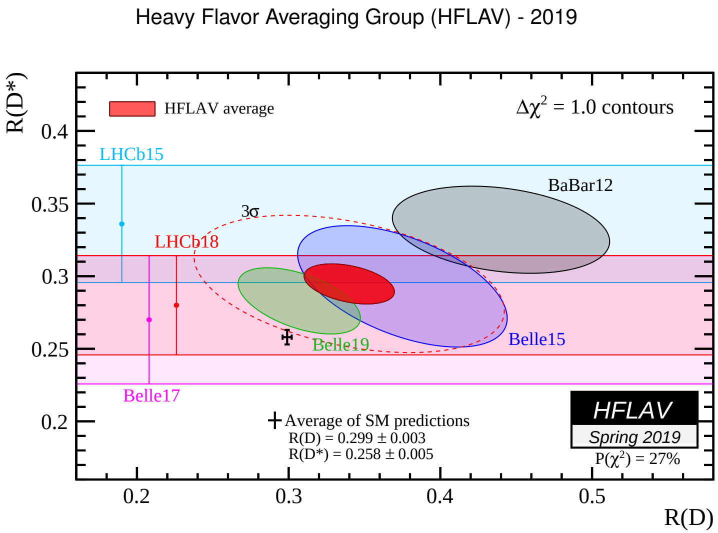
$R(D)$ and $R(D^*)$ anomalies!

Test of lepton universality in semileptonic B meson decays

Heavy Flavor Averaging Group (HFLAV) - 2019



Test of lepton universality in semileptonic B meson decays



Test of lepton universality 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

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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!

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

- Model-independent analyses of the impact of NP effective operators

  Murgui, Peñuelas, Jung & Pich, 1904.09311; Shi *et al*, 1905.08498; Bhardam & Ghosh, 1904.10432
- Charged scalars

  Biswas, Ghosh, Patra & Shaw; Celis, Jung, Li & Pich, 1612.07757; Fraser *et al*, 1805.08189
- Leptoquarks (scalar and vector)

  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
- RPV supersymmetric couplings

  Altmannshofer, Dev & Soni, 1704.06659; Deshpande & He, 1608.04817; Trifinopoulos, 1807.01638
- Extra gauge bosons W'

  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
- Complementary test at the LHC searches of some of these scenarios have been also explored.

We study a Charged Higgs boson ($H^\pm$) contribution within the framework of a generic 2HDM

Charged Higgs boson within the framework of a generic 2HDM

Charged-current $b \to c\tau\bar{\nu}_\tau$ (SM + scalar operators)

In the SM framework, the $b \to c\tau\bar{\nu}_\tau$ quark level processes are mediated by a virtual W boson exchange, which is described by the effective Lagrangian

$$-\mathcal{L}_{\text{eff}}(b \to c\tau\bar{\nu}_\tau)_{\text{SM}} = \frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau), \quad (1)$$

The effective Hamiltonian for the charged-current transition $b \to c\tau\bar{\nu}_\tau$ that includes all the four-fermion scalar operators, considering both left- and right-handed neutrinos, has the following form

$$\begin{aligned} \mathcal{H}_{\text{eff}}(b \to c\tau\bar{\nu}_\tau) \quad = \quad & \frac{4G_F}{\sqrt{2}} V_{cb}^{\text{CKM}} \Big[(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + C_S^{LL} (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau) \\ & + C_S^{RL} (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) + C_S^{LR} (\bar{c} P_L b)(\bar{\tau} P_R \nu_\tau) + C_S^{RR} (\bar{c} P_R b)(\bar{\tau} P_R \nu_\tau) \Big], \end{aligned}$$

where $(C_S^{LL}, C_S^{RL}, C_S^{LR}, C_S^{RR})$ are the Wilson coefficient associated with the NP operators that depend on the choices of the chiral charges.

Charged Higgs Yukawa couplings in the generic 2HDM

The most general Lagrangian for the $b \to c\tau\bar{\nu}_\tau$ transition induced by the Yukawa couplings of a charged scalar boson $H^\pm$ is given by

$$\begin{aligned}\mathcal{L}_{H^\pm}(b \to c\tau\bar{\nu}_\tau) = &- H^+ \left(\bar{c}X^D_{cb}P_R b - \bar{c}X^{U*}_{bc}P_L b + \bar{\nu}_\tau X^E_{\nu_\tau\tau}P_R\tau - \bar{\nu}_\tau X^{N*}_{\tau\nu_\tau}P_L\tau\right) \\ &- H^- \left(\bar{b}X^{D*}_{cb}P_L c - \bar{b}X^U_{bc}P_R c + \bar{\tau}X^{E*}_{\nu_\tau\tau}P_L\nu_\tau - \bar{\tau}X^N_{\tau\nu_\tau}P_R\nu_\tau\right), \end{aligned} \quad (2)$$

where X^U_{bc}, X^D_{cb}, $X^E_{\nu_\tau\tau}$, and $X^N_{\tau\nu_\tau}$ are the Yukawa couplings to the up-quarks, down-quarks, charged leptons and neutrinos. We will use the shorthand notation $X^E_\tau \equiv X^E_{\nu_\tau\tau}$ and $X^N_\tau \equiv X^N_{\tau\nu_\tau}$.

After integrating out $H^\pm$, the scalar WCs are written as

$$C_S^{LL} = +\frac{\sqrt{2}}{4G_F V_{cb}^{\rm CKM}}\frac{(X^{U*}_{bc})(X^{E*}_\tau)}{M^2_{H^\pm}}, \quad C_S^{RL} = -\frac{\sqrt{2}}{4G_F V_{cb}^{\rm CKM}}\frac{(X^D_{cb})(X^{E*}_\tau)}{M^2_{H^\pm}}, \quad (3)$$

$$C_S^{LR} = -\frac{\sqrt{2}}{4G_F V_{cb}^{\rm CKM}}\frac{(X^{U*}_{bc})(X^N_\tau)}{M^2_{H^\pm}}, \quad C_S^{RR} = +\frac{\sqrt{2}}{4G_F V_{cb}^{\rm CKM}}\frac{(X^D_{cb})(X^N_\tau)}{M^2_{H^\pm}}, \quad (4)$$

with $M_{H^\pm}$ being the $H^\pm$ charged scalar boson mass.

The $b \to c\tau\bar{\nu}_\tau$ observables can be expressed in terms of the effective scalar/pseudoscalar contributions, $C_S^{RL} \pm C_S^{LL}$ and $C_S^{LR} \pm C_S^{RR}$, for LH and RH neutrinos.

Phenomenological analysis

To accommodate the $b \to c\tau\bar{\nu}_\tau$ anomalies we perform a χ^2 analysis and consider

- Two different data sets:

  1) Set 1 (S1): $R(D^{(*)})$ HFLAV, $R(J/\psi), F_L(D^*), P_\tau(D^*), R(X_c)$,
  2) Set 2 (S2): $R(D^{(*)})$ Belle combination, $R(J/\psi), F_L(D^*), P_\tau(D^*), R(X_c)$

- Upper bound $\text{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\,\%$ and $30\,\%$.
- Projected Belle II scenarios (New!):

  Belle II-P1: Belle II measurements on $R(D^{(*)})$ keep the central values of Belle combination averages with the projected Belle II sensitivities for $50\ \text{ab}^{-1}$.
  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 for $50\ \text{ab}^{-1}$.

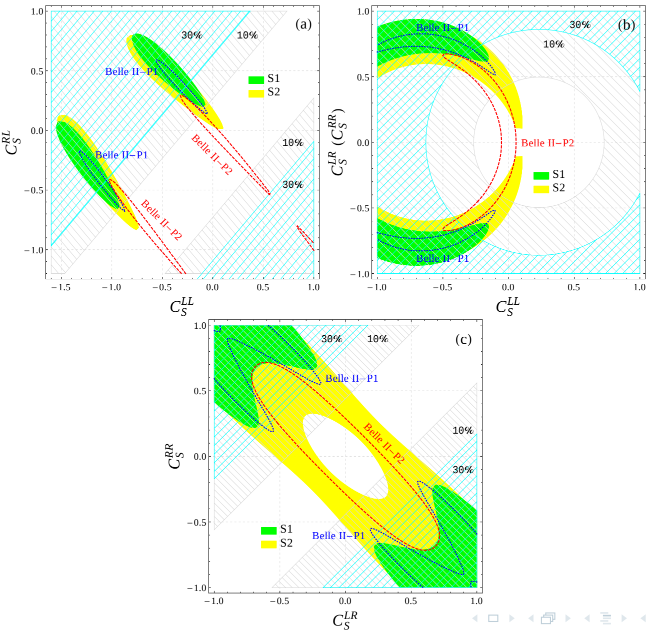
- Charged scalar boson ($H^\pm$) couples only to the bottom-charm quarks and the third generation of leptons τ-ν_τ, i.e., the corresponding Yukawa couplings are differente from zero, while the other ones are taken to be zero.

Two scalar WCs scenarios

Set S1 ($\chi^2_{\rm SM} = 19.1$, p-value$_{\rm SM} = 4.1 \times 10^{-3}$)						
Two scalar WCs	BFP	$\chi^2_{\rm min}$	p-value (%)	pull$_{\rm SM}$	1σ intervals	
(C_S^{LL}, C_S^{RL})	(-1.28,-0.25)	3.45	48.5	3.95	$C_S^{LL} \in [-1.33, -1.22]$	$C_S^{RL} \in [-0.30, -0.18]$
(C_S^{LL}, C_S^{LR})	(-0.91,-0.78)	3.56	46.8	3.94	$C_S^{LL} \in [-1.04, -0.68]$	$C_S^{LR} \in [-0.83, -0.71]$
(C_S^{LL}, C_S^{RR})	(-0.91,-0.78)	3.56	46.8	3.94	$C_S^{LL} \in [-1.04, -0.68]$	$C_S^{RR} \in [-0.83, -0.71]$
(C_S^{LR}, C_S^{RR})	(1.15,-0.82)	3.75	44.1	3.91	$C_S^{LR} \in [1.02, 1.25]$	$C_S^{RR} \in [-1.04, -0.70]$
Set S2 ($\chi^2_{\rm SM} = 11.2$, p-value$_{\rm SM} = 8.1 \times 10^{-2}$)						
Two scalar WCs	BFP	$\chi^2_{\rm min}$	p-value (%)	pull$_{\rm SM}$	1σ intervals	
(C_S^{LL}, C_S^{RL})	(-1.22,-0.21)	3.34	50.3	2.11	$C_S^{LL} \in [-1.29, -1.14]$	$C_S^{RL} \in [-0.30, -0.11]$
(C_S^{LL}, C_S^{LR})	(-0.92,-0.68)	3.40	49.3	2.80	$C_S^{LL} \in [-1.07, -0.55]$	$C_S^{LR} \in [-0.75, -0.59]$
(C_S^{LL}, C_S^{RR})	(-0.92,-0.68)	3.40	49.3	2.80	$C_S^{LL} \in [-1.07, -0.55]$	$C_S^{RR} \in [-0.75, -0.59]$
(C_S^{LR}, C_S^{RR})	(0.95,-0.95)	3.64	45.7	2.76	$C_S^{LR} \in [0.63, 1.18]$	$C_S^{RR} \in [-1.18, -0.63]$

Best-fit point (BFP) values, p-value, $\rm pull_{SM}$, and 1σ allowed intervals by allowing two scalar WCs different from zero to fit the set of observables S1 and S2.

Two scalar WCs scenarios (95 % CL allowed parameter space)

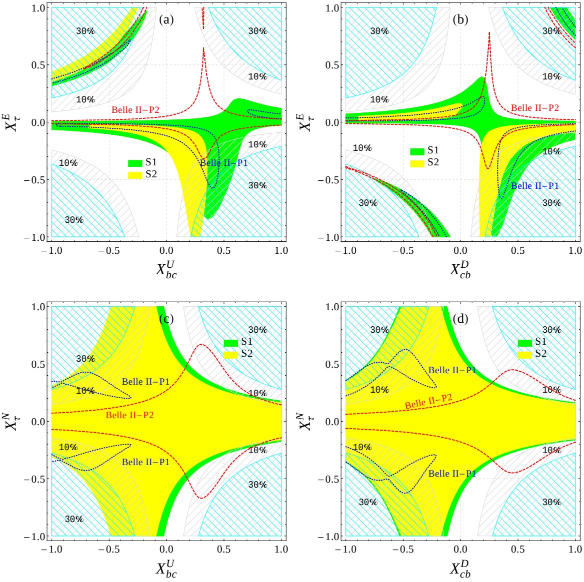


Parametric space of Yukawa couplings

Set S1 ($\chi^2_{\rm SM} = 19.1$, p-value$_{\rm SM} = 7.6 \times 10^{-4}$)			
Yukawa couplings	BFP	p-value (%)	pull$_{\rm SM}$
$(X^U_{bc}, X^D_{cb}, X^E_\tau)$	$(0.33, 0.38, -0.47)$	28.8	2.95
$(X^U_{bc}, X^D_{cb}, X^N_\tau)$	$(-0.35, -0.25, -1.09)$	28.9	2.95
Set S2 ($\chi^2_{\rm SM} = 11.2$, p-value$_{\rm SM} = 2.4 \times 10^{-2}$)			
Yukawa couplings	BFP	p-value (%)	pull$_{\rm SM}$
$(X^U_{bc}, X^D_{cb}, X^E_\tau)$	$(0.23, 0.25, -0.64)$	28.4	1.56
$(X^U_{bc}, X^D_{cb}, X^N_\tau)$	$(-0.38, 0.31, -0.90)$	27.7	1.54

Projections Belle II-P1 and Belle-P2 of the 1σ allowed intervals for two scalar WCs different from zero. Best-fit point (BFP) values, p-value, $\mathrm{pull_{SM}}$, and 1σ allowed intervals by allowing two scalar WCs different from zero to fit the set of observables S1 and S2

Parametric space of Yukawa couplings (95 % CL)

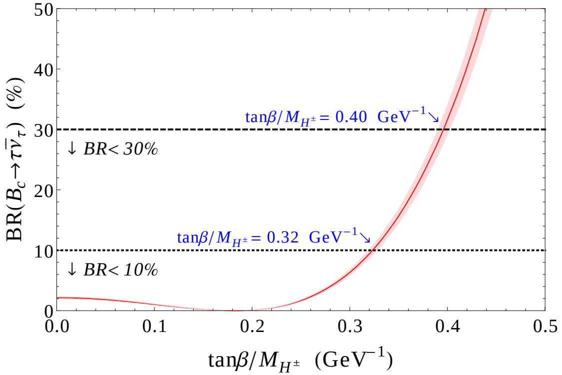


Reexamining the explanation from 2HDM of Type II

- The 2HDM of Type II provides one of the simplest scenarios with charged scalar bosons ($H^\pm$). Within this framework, the NP effects of a charged Higgs boson depend on the mass of charged scalar boson $M_{H^\pm}$ and $\tan\beta$.
- According to the BABAR results (2012 and 2013), the 2HDM of Type II cannot explain simultaneously the $R(D^{(*)})$ discrepancies. Since then (and to date), the 2HDM of Type II interpretation was ruled out and 2HDM models with a more generic flavor structure were considered in the literature.
- Given the current experimental situation on the $R(D^{(*)})$ anomalies, HFLAV-2019 and Belle combination, and the Belle II future sensitivity, we reexamine whether the 2HDM of Type II is still ruled out (or not) as an explanation to the $R(D^{(*)})$ anomalies.

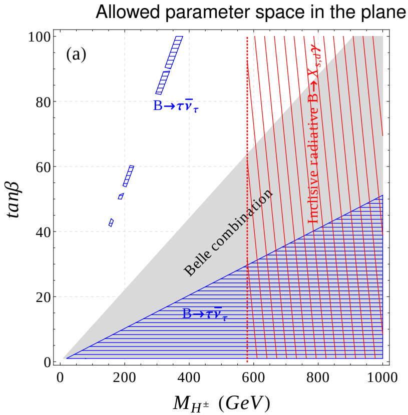
Constraints on $\tan\beta/M_{H^\pm}$ from the upper limits $\mathrm{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)$

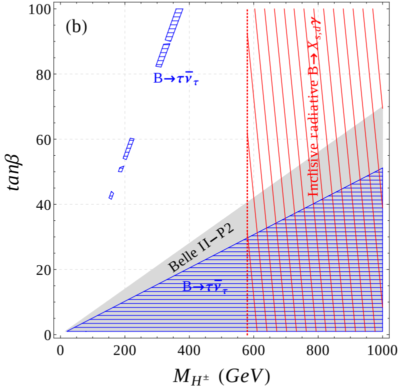
$\mathrm{BR}(B_c^- \to \tau^-\bar{\nu}_\tau)$ in the 2HDM of type II as a function of $\tan\beta/M_{H^\pm}$ (red solid line).



- For $\mathrm{BR}(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\,\%$ $(30\,\%)$, we get the strong bounds $\tan\beta/M_{H^\pm} < 0.40$ (0.32).
- Large values of $\tan\beta/M_{H^\pm}$ are excluded.

Allowed parameter space $(M_{H^\pm}, \tan\beta)$





- it is possible to get a large region on the parameter space $(M_{H^\pm}, \tan\beta)$ to account for a joint explanation to the $R(D)$ and $R(D^*)$ anomalies.
- The projection Belle II-P2 suggests that the 2HDM of Type II would be no longer disfavored.

Concluding Remarks

- The charged current anomalies in B meson decays constitute a tantalizing window for NP.
- We addressed the $b \to c\tau\bar{\nu}_\tau$ anomalies within a Charged Higgs boson within the framework of a generic 2HDM.
- Robust analysis. All $b \to c\tau\bar{\nu}_\tau$ observables: ratios $R(D)$ and $R(D^{(*)})$ plus $R(J/\psi)$, $R(X_c)$, polarizations $P_\tau(D^*), F_L(D^*)$, BR$(B_c^- \to \tau^-\bar{\nu}_\tau) < 10\,\%$, Belle II prospects (New!).
- Our results imply that current experimental $b \to c\tau\bar{\nu}_\tau$ data favors these interpretations (interestingly, charged scalar boson with RH neutrinos).
- There are good prospects that the 2HDM of Type II explanation will rise from the ashes (simple and viable solution).
- Stay tuned to future measurements from Belle II (as well as LHCb).

THANK YOU !

BACK UP

Lepton universality

What is Lepton 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 universality**.

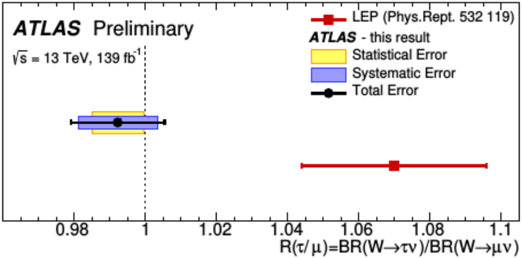
Lepton universality has been tested in:

- 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)

ATLAS-CONF-2020-014



Introduction/Motivation

Lepton universality 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.