NP effects in $\Lambda_b \to \Lambda_c^{(*)}$ semileptonic decays.

Neus Penalva[1,*], *Eliecer* Hernández[2], and *Juan* Nieves[1]

[1]Instituto de Física Corpuscular (centro mixto CSIC-UV), Institutos de Investigación de Paternam C/Catedrático Beltrán 2, E-46980 Paterna, València, Spain

[2]Departamento de Física Fundamental e IUFFyM, Universidad de Salamanca , Plaza de la Merced s/n, E-37008 Salamanca, Spain

Abstract. In the context of lepton flavor universality violation (LFUV) studies, we study different observables related to the $b \to c\tau\bar{\nu}_\tau$ semileptonic decays. These observables are expected to help in distinguishing between different New Physics (NP) scenarios. Since the τ lepton is very short-lived, we consider three subsequent τ-decay modes, two hadronic $\pi\nu_\tau$ and $\rho\nu_\tau$ and one leptonic $\mu\bar{\nu}_\mu\nu_\tau$. This approach enables the differential decay width to be written in terms of visible (experimentally accessible) variables of the massive particle created in the τ decay. We present numerical results for the observables that can be accessed through the visible kinematics for the $\Lambda_b \to \Lambda_c$ and the $\Lambda_b \to \Lambda_c^*(2595)$ transitions. This work is based on Refs.[1–3].

1 Motivation

This work is motivated by the latest $\mathcal{R}_{\Lambda_c}$ result from LHCb [4] and other observables measured, such as $\mathcal{R}_{H_c} = \dfrac{\Gamma(H_b \to H_c\tau\bar{\nu}_\tau)}{\Gamma(H_b \to H_c\ell\bar{\nu}_\ell)}$, the averaged tau-polarization asymmetry $P_\tau(D^*)$ and the longitudinal D^* polarization $F_L^{D^*}$. Although some of them are compatible with the Standard model (SM) within errors, all together point to possible new physics (NP) effects [5]. As these discrepancies have been seen in decays where the out-going lepton is a τ^- particle, it is believed that these NP effects only affect the 3th quark and lepton generations.

For studying the NP effects, we use the most general Hamiltonian including effects from light right-handed neutrinos eq. (1) [6].

$$H_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1 + \underbrace{C^V_{LL})O^V_{LL} + C^V_{RL}O^V_{RL}}_{\rm (axial-)vector} + \underbrace{C^T_{LL}O^T_{LL}}_{\rm tensor} + \underbrace{C^S_{LL}O^S_{LL} + C^S_{RL}O^S_{RL}}_{\rm (pseudo-)scalar} + \underbrace{C^V_{LR}O^V_{LR} + C^V_{RR}O^V_{RR}}_{\rm (axial-)vector\ RH\ \nu's} + \underbrace{C^S_{LR}O^S_{LR} + C^S_{RR}O^S_{RR} + C^T_{RR}O^T_{RR}}_{\rm (pseudo-)scalar/tensor\ RH\ \nu's}\Big] + h.c., \tag{1}$$

The Wilson coefficients ($C^{V,S,T}_{L,R}$) parameterize the deviations from SM and are fitted to experimental anomalies in $\bar{B}$ meson decays. Hence all different NP models give the same results for $R_{D^{(*)}}$ and in this work we look for other observables that could distinguish among NP models/fits. For the predictions showed here we will use Fits 6 and 7 from ref. [7] and scenario 7a from ref. [6]. In Fits 6 and 7 there are effects coming only from left-handed neutrinos while scenario 7a includes right-handed ν's effects. Here, we will show a summary of the results for $\Lambda_b \to \Lambda_c, \Lambda_b \to \Lambda_c^*(2595)$ and $\Lambda_b \to \Lambda_c^*(2625)$ published in refs. [2, 3].

All the physics in the decays is encoded in the Wilson coefficients and the 10 independent functions of ω that can be seen in table 1 [1]. In the first row, we can see the observables accessible through the decay involving unpolarized τ^-'s that correspond with the angular asymmetries. The measuring of the spin and spin-angular asymmetries of the second and third rows requires the knowledge of the τ^- polarization. Moreover, the two observables in the last row are only different from zero when some of the Wilson coefficients are complex. The ones that have been measured in some of the decays are the forward-backward asymmetry ($A_{\rm FB}$), the integrated longitudinal polarization ($\langle P_L^{\rm CM}\rangle$) and the unpolarized decay width $\left(\dfrac{d\Gamma_{\rm SL}}{d\omega} \propto n_0\right)$.

2 Final state visible kinematics

One of the problems for measuring these observables is that τ^- particles decay very fast and must be reconstructed from one of its many decay channels. All of them involve at least one neutrino that cannot be measured. Therefore, to avoid having to reconstruct the τ energy and direc-

	observables
unpolarized τ^-	n_0, $A_{\rm FB}$, A_Q
polarized τ^-	$\langle P_L^{\rm CM}\rangle$, $\langle P_T^{\rm CM}\rangle$, Z_L, Z_Q, $Z_\perp$
complex WC's	$\langle P_{TT}\rangle$, Z_T

Table 1: Observables that contain all physics of the decay

*e-mail: neuspe@ific.uv.es

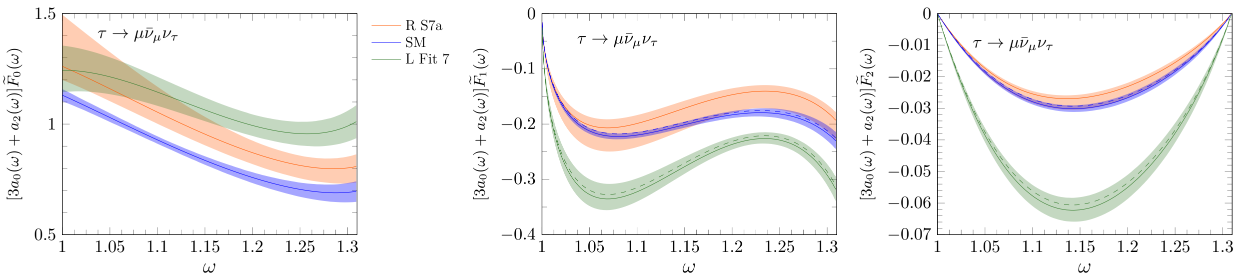

Figure 1: $n_0\tilde{F}^{\mu\bar{\nu}_\mu}_{0,1,2}(\omega)$ for $\Lambda_b \to \Lambda_c$ decay in SM and different NP fits.

tion, we propose using variables related to its visible decay products.

The starting point for our work is the triple differential decay rate of eq. (2), where ξ_d is related to the energy of the charged particle coming from the τ^- decay and θ_d is the angle that is formed by the same particle and the out-going hadron directions. To obtain the expression in eq. (2), we have used the zero width approximation for the τ decay [1, 8].

$$\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d} = \mathcal{B}_d \frac{d\Gamma_{\rm SL}}{d\omega}\Big\{F_0^d(\omega,\xi_d)+ F_1^d(\omega,\xi_d)\cos\theta_d + F_2^d(\omega,\xi_d)P_2(\cos\theta_d)\Big\}, \qquad (2)$$

where

$$\begin{aligned} F_0(\omega,\xi_d) &= C_n(\omega,\xi_d) + C_{P_L}(\omega,\xi_d)\langle P_L^{\rm CM}\rangle \\ F_1(\omega,\xi_d) &= C_{A_{FB}}(\omega,\xi_d)A_{FB} + C_{Z_L}(\omega,\xi_d)Z_L \\ &\quad + C_{P_T}(\omega,\xi_d)\langle P_T^{\rm CM}\rangle \\ F_2(\omega,\xi_d) &= C_{A_Q}(\omega,\xi_d)A_Q + C_{Z_Q}(\omega,\xi_d)Z_Q \\ &\quad + C_{Z_\perp}(\omega,\xi_d)Z_\perp. \end{aligned} \qquad (3)$$

All the asymmetries, except the CP-violating ones, can be obtained from this differential decay rate taking into account that the $C_i(\omega,\xi_d)$ functions that enter in $F_{0,1,2}$ are kinematical factors that can be computed analytically and depend on the τ decay mode ($d = \pi, \rho, \mu$) (see appendix G of [1]).

This triple differential decay rate can be difficult to measure and we could be interested in increasing statistics by integrating over some of the variables. Integrating over the energy and angle of the $\tau-$decay massive product gives us back the unpolarized differential decay width. In the following, we will study how much information is kept in the angular and the energy distributions.

3 Angular distributions

We start by integrating the energy of the τ-decay massive product eq. (6). The new $\widetilde{F}_i$ functions are obtained from the previous F_i after integrating over the energy. As the only part that depends on the energy are the $C_i(\omega,\xi_d)$ analytic kinematical factors, we still have access to some observables [2].

$$\frac{d^2\Gamma_d}{d\omega d\cos\theta_d} = \mathcal{B}_d \frac{d\Gamma_{\rm SL}}{d\omega}\Big[\widetilde{F}_0^d(\omega) + \widetilde{F}_1^d(\omega)\cos\theta_d + \widetilde{F}_2^d(\omega)P_2(\cos\theta_d)\Big], \qquad (4)$$

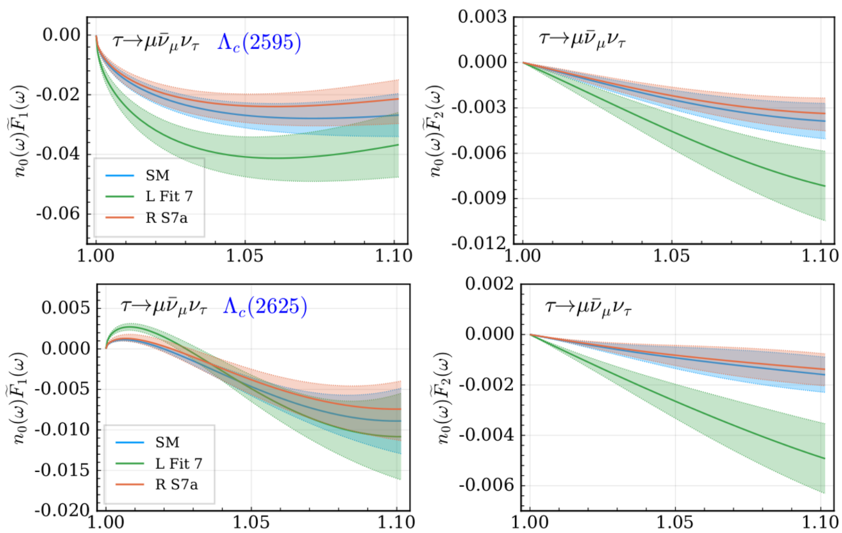

Figure 2: $n_0\tilde{F}^{\mu\bar{\nu}_\mu}_{1,2}(\omega)$ for $\Lambda_b \to \Lambda_c^*(2595)$ and $\Lambda_b \to \Lambda_c^*(2625)$ decays in SM and different NP fits.

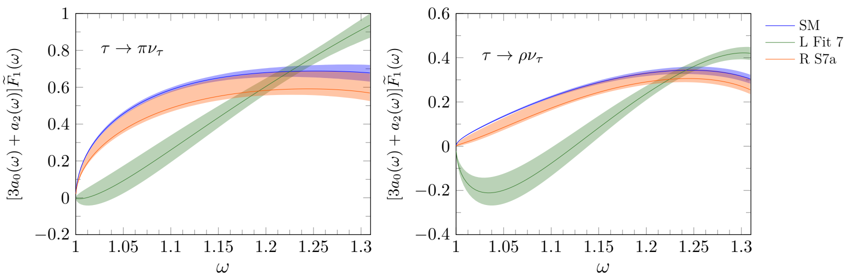

Figure 3: $n_0 \widetilde{F}_1^{\pi(\rho)}(\omega)$ for $\Lambda_b \to \Lambda_c$ decays.

For all τ-decay modes, $\widetilde{F}_0 = \frac{1}{2}$ and thus the information in $\langle P_L^{\rm CM} \rangle$ is lost [2]. In figs. 1 and 2 we show these $\widetilde{F}_i$ functions for the leptonic decay mode of the τ particle. In all cases, Fit 7 can be easily distinguished from the other NP models, except where the form factor errors for $\Lambda_b \to \Lambda_c^*$ decays are still too big. We also can see in the plot of fig. 1 that the limit for a massless μ (dashed line) works fine for all cases. The previous results can be compared also with the hadronic modes for the τ decay. In fig. 3, we show $\widetilde{F}_1$ for the hadron modes of the tau decay and it can be seen that the shape is different from that of the leptonic mode. That can be explained when comparing analytically the $C_i(\omega, \xi_d)$ in the π-massless and μ-massless limit. By doing this, we find an extra factor 3 in the spin and spin-angular asymmetries, as it is seen at eq. (5), that give us more discriminating power in the hadronic decay [2].

$$C^{\pi}_{A_{FB},A_Q}(\omega) = C^{\mu\bar{\nu}_\mu}_{A_{FB},A_Q}(\omega) + O(y^2),$$
$$C^{\pi}_{P_T,Z_L,Z_Q,Z_\perp}(\omega) = -3\, C^{\mu\bar{\nu}_\mu}_{P_T,Z_i}(\omega) + O(y^2) \qquad (5)$$

The next step is integrating over ω to get the angular distribution (eq. (6)). The predictions are shown in fig. 4 for the three τ-decay modes discussed here. Because of that extra factor 3, it is easier to distinguish among models in the hadronic τ-decay.

$$\frac{d\Gamma_d}{d\cos\theta_d} = \mathcal{B}_d \Gamma_{\rm SL} \left[\frac{1}{2} + \widehat{F}_1^d \cos\theta_d + \widehat{F}_2^d\, P_2(\cos\theta_d) \right]. \qquad (6)$$

4 Energy distributions

To obtain the energy distributions, we come back to eq. (2) and integrate over the angle this time. Now, all the information, except the one from F_0, disappear [2]. That allows us to extract $\langle P_L^{\rm CM} \rangle(\omega)$. That observable, integrated over ω, has been measured by the Belle collaboration in the context of $B \to D^*$ decays [9]. We show in fig. 5 its dependence on ω for the $\Lambda_b \to \Lambda_c^{(*)}$. As before, we can see that Fit 7 can be easily distinguished in all Λ_b decays.

Finally, we integrate over ω, to get[1]:

$$\hat{F}_0^d(E_d) = \frac{1}{\Gamma_{\rm SL}} \int_1^{\omega_{\rm sup}(E_d)} \frac{1}{\gamma} \frac{d\Gamma_{\rm SL}}{d\omega} \Big\{ C_n^d(\omega, E_d) + C_{P_L}^d(\omega, E_d) \langle P_L^{\rm CM} \rangle(\omega) \Big\}\, d\omega, \qquad (7)$$

where $\hat{F}_0$ is the normalized energy distribution. $\langle P_L^{\rm CM} \rangle$ does not contribute to the normalization of $\hat{F}_0$ but it affects its shape as seen in fig. 6. Again, we see more discriminating power for the hadronic τ-decay modes.

5 Conclusions

In conclusion, we have seen that using visible final-state kinematics helps to avoid using τ variables that are difficult to reconstruct. With this approach, we can obtain all the observables except the CP-violating ones. Moreover, one can increase statistics by integrating in some of the variables. In the energy distribution we keep the $\langle P_L^{\rm CM} \rangle$ information and the angular distribution includes all other angular-spin asymmetries. $\frac{d\Gamma}{d\cos\theta_d}$, $\frac{d\Gamma}{dE_d}$ and $\frac{d\Gamma}{d\omega}$ are also useful and give complementary information. Finally, we have seen (through eq. (5) and figs. 3, 4 and 6) that the hadronic τ-decay modes have more discriminating power.

[1] We make the change $E_d = \xi_d$ and exchange the integration order of ω and ξ_d. The details of this computation are in ref. [2])

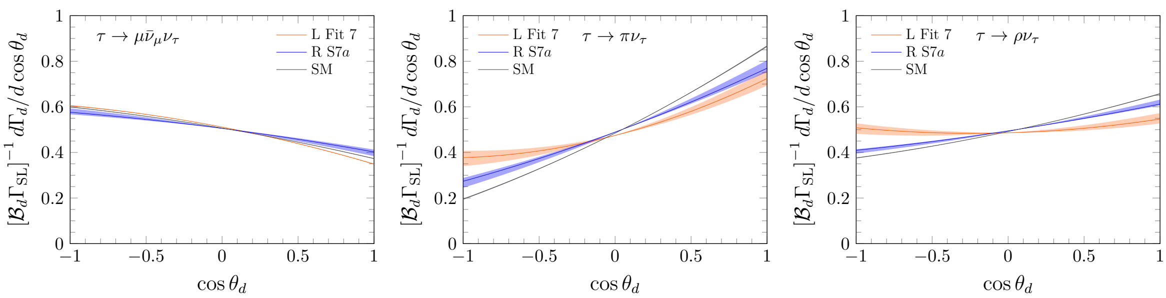

Figure 4: Angular $d\Gamma/d\cos\theta_d$ distribution for the $\Lambda_b \to \Lambda_c$ decays. Same NP scenarios as before.

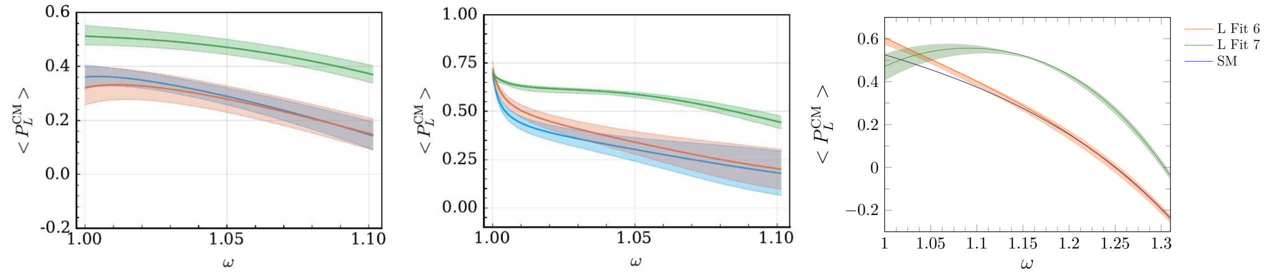

Figure 5: $\langle P_L^{\rm CM}\rangle$ for the $\Lambda_b \to \Lambda_c^*(2595)$, $\Lambda_b \to \Lambda_c^*(2625)$ and $\Lambda_b \to \Lambda_c$ decays.

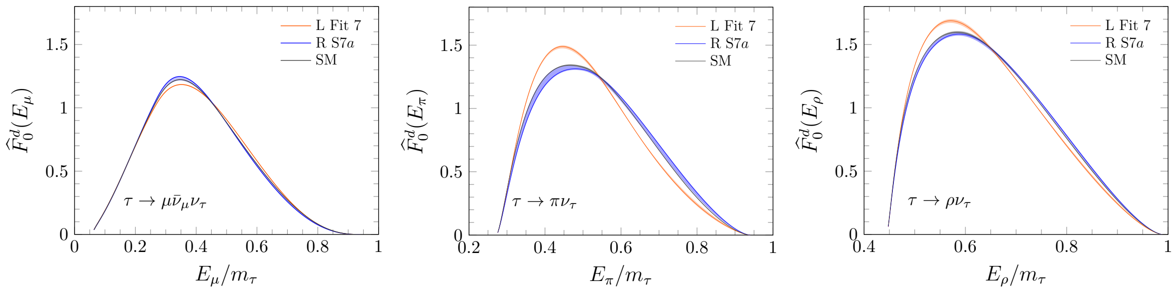

Figure 6: $\widehat{F}_0^d(E_d)$ for the $\Lambda_b \to \Lambda_c$ decays.

Acknowledgments

This research has been supported by the Spanish Ministerio de Ciencia e Innovación (MICINN) and the European Regional Development Fund (ERDF) under contracts PID2020-112777GB-I00 and PID2019-105439GB-C22, the EU STRONG-2020 project under the program H2020-INFRAIA-2018-1, grant agreement no. 824093 and by Generalitat Valenciana under contract PROMETEO/2020/023.

References

[1] N. Penalva, E. Hernández, J. Nieves, JHEP **10**, 122 (2021), `2107.13406`

[2] N. Penalva, E. Hernández, J. Nieves, JHEP **04**, 026 (2022), `2201.05537`

[3] M.L. Du, N. Penalva, E. Hernández, J. Nieves, Phys. Rev. D **106**, 055039 (2022), `2207.10529`

[4] R. Aaij et al. (LHCb), Phys. Rev. Lett. **128**, 191803 (2022), `2201.03497`

[5] Y.S. Amhis et al. (HFLAV), Eur. Phys. J. C **81**, 226 (2021), `1909.12524`

[6] R. Mandal, C. Murgui, A. Peñuelas, A. Pich, JHEP **08**, 022 (2020), `2004.06726`

[7] C. Murgui, A. Peñuelas, M. Jung, A. Pich, JHEP **09**, 103 (2019)

[8] P. Asadi, A. Hallin, J. Martin Camalich, D. Shih, S. Westhoff, Phys. Rev. D **102**, 095028 (2020), `2006.16416`

[9] S. Hirose et al. (Belle), Phys. Rev. Lett. **118**, 211801 (2017), `1612.00529`