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

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November 10th, 2022

Talk partially based on:
JHEP 04 (2022) 026 and Phys.Rev.D 106 (2022) 5, 055039

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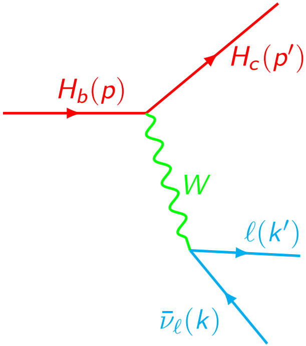
Motivation: LFUV in $b \to c$ decays?

$\mathcal{R}_{\Lambda_c}$ latest result from LHCb* + other observables measured**:

$$\mathcal{R}_{H_c} = \frac{\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)}, \; P_\tau(D^*), \; F_L^{D^*}.$$

$\Rightarrow$ NP affecting 3th quark and lepton generations.



* LHCb collab. Phys.Rev.Lett. 128, 191803

**Results from BaBar, Belle and LHCb combined in:
HFLAV group. Eur.Phys.J.C 81(2021) 3, 226

NP effects introduced using a effective Hamiltonian:

$$H_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+\underbrace{C^V_{LL})\mathcal{O}^V_{LL} + C^V_{RL}\mathcal{O}^V_{RL}}_{\text{(axial−)vector}} + \underbrace{C^S_{LL}\mathcal{O}^S_{LL} + C^S_{RL}\mathcal{O}^S_{RL}}_{\text{(pseudo−)scalar}} + \underbrace{C^T_{LL}\mathcal{O}^T_{LL}}_{\text{tensor}}$$

$$+ \underbrace{C^V_{LR}\mathcal{O}^V_{LR} + C^V_{RR}\mathcal{O}^V_{RR} + C^S_{LR}\mathcal{O}^S_{LR} + C^S_{RR}\mathcal{O}^S_{RR} + C^T_{RR}\mathcal{O}^T_{RR}}_{\text{right−handed neutrinos}}\Big] + h.c.,$$

Wilson coeff. are fitted to experimental data. → Different models give same results for $\mathcal{R}_{H_c}$.

We will use:

- Fit 6 and 7 from Murgui et al. JHEP 09 (2019) 103
- S7a from Mandal et al. JHEP 08 (2020) 08, 022

We will present results for:

- $\Lambda_b \to \Lambda_c$ in all ω range
- $\Lambda_b \to \Lambda_c^*$ only for $\omega = [1, 1.1]$

Available information

All the physics is encoded in 10 independent functions of ω and the Wilson coefficients.

	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

n_0: contains all the dynamical effects $\left(\frac{d\Gamma_{\rm SL}}{d\omega} \propto n_0\right)$

$A_{\rm FB,Q}$: τ angular asymmetries

$\langle P^{\rm CM}_{L,T,TT}\rangle$: τ spin asymmetries

$Z_{L,T,\perp}$: τ angular-spin asymmetries

N.P. et al. JHEP 10 (2021) 122

Approach

[*] LHCb collab. Phys.Rev.Lett. 128, 191803

PROBLEM: The τ^- particle decays very fast and has to be reconstructed.

τ^- decay modes:
- $\mu^-\bar{\nu}_\mu\nu_\tau$
- $\pi^-\nu_\tau$
- $\rho^-\nu_\tau$
- $\pi^-\pi^+\pi^-(\pi^0)\nu_\tau \longrightarrow$ used for the LHCb result*
- $\ldots$

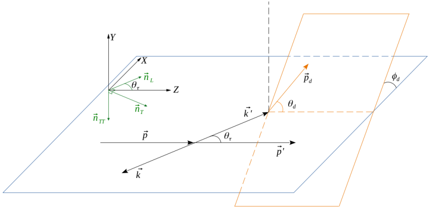


Figure: Kinematics in the $\tau\bar{\nu}_\tau$ CM reference system.

In the decay, neutrinos are always involved. **Solution:** Using variables that are related to the visible decay products instead of the τ^- energy or direction.

Starting point

Asadi et al. Phys.Rev.D 102 (2020) 9, 095028
N.P. et al. JHEP 10 (2021) 122

The $H_b \to H_c \tau(\to d\nu_\tau)\bar{\nu}_\tau$ differential decay rate:

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

where

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

The C_i functions are kinematical factors that depend on the tau decay mode (π, ρ or $\mu\bar{\nu}_\mu$).

The CP-violating contributions disappear after integrating over the azimuthal angle (ϕ_d).

ω distribution

We can follow different paths:

$$\frac{d^3\Gamma_d}{d\omega\, d\xi_d\, d\cos\theta_d}$$

$$\frac{d^2\Gamma_d}{d\omega\, d\cos\theta_d} \qquad \frac{d^2\Gamma_d}{d\omega\, d\xi_d}$$

$$\frac{d\Gamma_d}{d\cos\theta_d}$$

$$\frac{d\Gamma_d}{d\omega} = \mathcal{B}_d \frac{d\Gamma_{SL}}{d\omega}$$

$*$

$$\frac{d\Gamma_d}{dE_d}$$

$*$ We make the change of variables $\xi_d = E_d/(\gamma m_\tau)$.

N.P. et al. JHEP 04 (2022) 026

The $d^2\Gamma/(d\omega d\cos\theta_d)$ distribution

$$\boxed{\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d} \rightarrow \frac{d^2\Gamma_d}{d\omega d\cos\theta_d}}$$

We get,

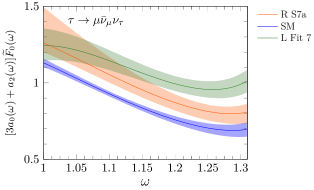
$$\frac{d^2\Gamma_d}{d\omega d\cos\theta_d} = \mathcal{B}_d \frac{d\Gamma_{SL}}{d\omega}\left[\widetilde{F}_0^d(\omega) + \widetilde{F}_1^d(\omega)\cos\theta_d + \widetilde{F}_2^d(\omega)P_2(\cos\theta_d)\right],$$

For all τ decay modes:

We loose information on $\langle P_L^{\rm CM}\rangle$

$$\widetilde{F}_0(\omega) = \underbrace{\int_{\xi_1}^{\xi_2} C_n(\omega,\xi_d)d\xi_d}_{1/2} + \langle P_L^{\rm CM}\rangle(\omega)\underbrace{\int_{\xi_1}^{\xi_2} C_{P_L}(\omega,\xi_d)d\xi_d}_{0}$$

The $d^2\Gamma/(d\omega d\cos\theta_d)$ distribution (II)



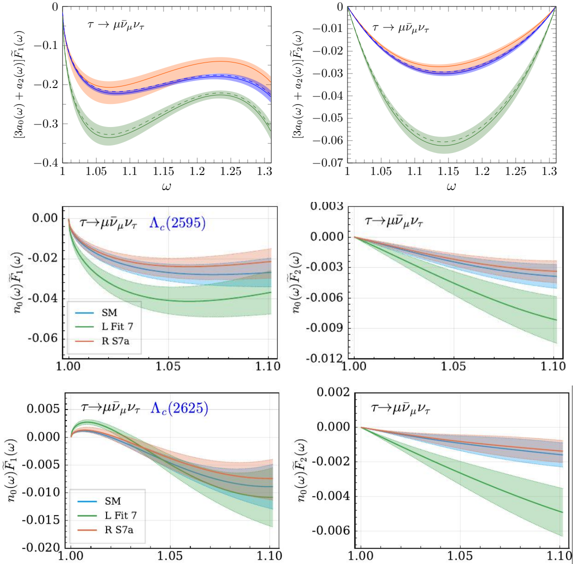


Figure: $n_0 \tilde{F}^{\mu\bar{\nu}_\mu}_{0,1,2}(\omega)$ for $\Lambda_b \to \Lambda_c^{(*)}$ decays in SM and different NP fits.

The limit $y = \frac{m_d}{m_\tau} = 0$ works fine for $\tau \to \mu\bar{\nu}_\mu\nu_\tau$.

$\Lambda_b \to \Lambda_c^*$ results in
Du et al. Phys.Rev.D 106 (2022) 5, 055039

The $d^2\Gamma/(d\omega d\cos\theta_d)$ distribution (III)

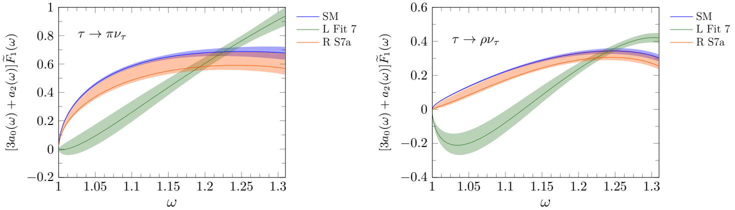


Figure: $n_0 \tilde{F}_1^{\pi(\rho)}(\omega)$ for $\Lambda_b \to \Lambda_c$ decays .

Moreover, for $\tau \to \pi\nu_\tau$, where the limit is also good:

$$C^{\pi}_{A_{FB},A_Q}(\omega) = C^{\mu\bar{\nu}_\mu}_{A_{FB},A_Q}(\omega) + \mathcal{O}(y^2),$$

$$C^{\pi}_{P_T,Z_L,Z_Q,Z_\perp}(\omega) = -3\, C^{\mu\bar{\nu}_\mu}_{P_T,Z_L,Z_Q,Z_\perp}(\omega) + \mathcal{O}(y^2)$$

More discriminating power for $\tau \to \pi\nu_\tau$

Analytical expressions for $C_i(\omega)$ in N.P. et al. JHEP 04 (2022) 026

The $d\Gamma/(d\cos\theta_d)$ distribution

$$\frac{d^3\Gamma_d}{d\omega\, d\xi_d\, d\cos\theta_d} \rightarrow \frac{d^2\Gamma_d}{d\omega\, d\cos\theta_d} \rightarrow \frac{d\Gamma_d}{d\cos\theta_d}$$

And we get,

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

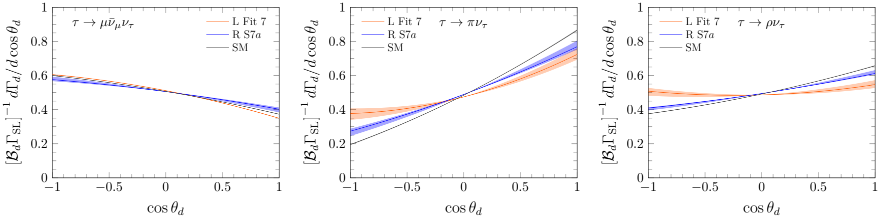


Figure: Angular $d\Gamma/d\cos\theta_d$ distribution for the $\Lambda_b \to \Lambda_c$ decays. Same NP scenarios as before.

The $d\Gamma/(d\omega d\xi_d)$ distribution

$$\boxed{\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d} \longrightarrow \frac{d^2\Gamma_d}{d\omega d\xi_d}}$$

The $F_1(\omega, \xi_d)$ and $F_2(\omega, \xi_d)$ contributions disappear.

The distribution looks like:

$$\frac{d^2\Gamma_d}{d\omega d\xi_d} = 2\mathcal{B}_d \frac{d\Gamma_{\rm SL}}{d\omega}\left(C_n^d(\omega, \xi_d) + C_{P_L}^d(\omega, \xi_d)\langle P_L^{\rm CM}\rangle(\omega)\right)$$

As C_n^d and $C_{P_L}^d$ are known, $\langle P_L^{\rm CM}\rangle(\omega)$ can be extracted.

$\langle P_L^{\mathrm{CM}} \rangle$

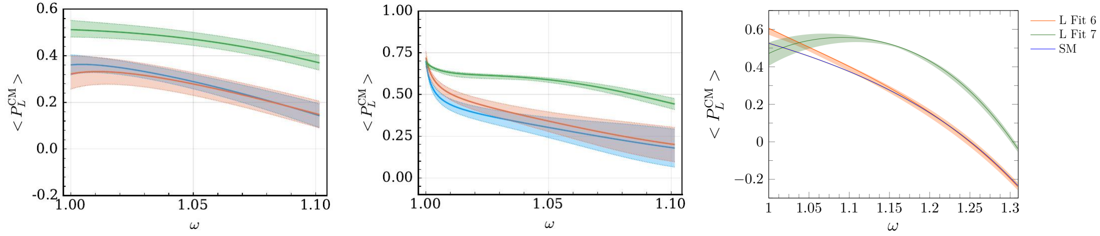


Figure: $\langle P_L^{\mathrm{CM}} \rangle$ for the $\Lambda_b \to \Lambda_c^*(2595)$, $\Lambda_b \to \Lambda_c^*(2625)$ and $\Lambda_b \to \Lambda_c$ decays.

Using that result:

$$\mathcal{P}_\tau = \frac{-1}{\Gamma_{\mathrm{SL}}} \int d\omega \frac{d\Gamma_{\mathrm{SL}}}{d\omega} \langle P_L^{\mathrm{CM}} \rangle(\omega)$$

Already measured in $B \to D^*$ decays. S. Hirose et al. (Belle) Phys. Rev. Lett. 118, 211801 (2017)

The $d\Gamma/(dE_d)$ distribution

$$\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d} \rightarrow \frac{d^2\Gamma_d}{d\omega d\xi_d} \rightarrow \frac{d\Gamma_d}{dE_d}$$

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

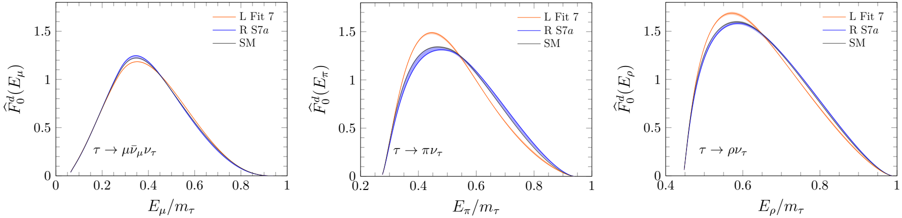


Figure: $\widehat{F}_0^d(E_d)$ for the $\Lambda_b \to \Lambda_c$ decays.

Conclusions

- Using visible final-state kinematics helps to avoid using τ variables that are difficult to reconstruct.
$$\frac{d^3\Gamma}{d\omega d\xi_d d\cos\theta_d} \to n_0,\ A_{FB,Q},\ Z_{L,Q,\perp},\ \langle P_L^{\rm CM}\rangle,\ \langle P_T^{\rm CM}\rangle$$
- One can increase statistics by integrating in some of the variables.
$$\frac{d^2\Gamma}{d\omega d\xi_d} \to \langle P_L^{\rm CM}\rangle, \qquad \frac{d^2\Gamma}{d\omega d\cos\theta_d} \to \text{all other angular} - \text{spin asymmetries}$$
- $\frac{d\Gamma}{d\cos\theta_d}$, $\frac{d\Gamma}{dE_d}$ and $\frac{d\Gamma}{d\omega}$ are also useful.
- In general, the hadronic τ-decay modes have more discriminating power.