Visible final-state kinematics in $b \to c\tau(\to \pi\nu_\tau, \rho\nu_\tau, \mu\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau$ reactions

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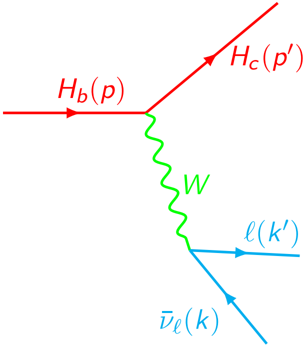
Motivation: LFUV in $b \to c$ decays?

$\mathcal{R}_{\Lambda_c}$ 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.

PROBLEM:

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

τ^- decay modes:

- $\mu^- \bar{\nu}_\mu \nu_\tau$
- $\pi^- \nu_\tau$
- $\rho^- \nu_\tau$
- $\pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ $\to$ used for the LHCb result*
- ...

* LHCb collab. arXiv:2201.0349

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

Available information and approach

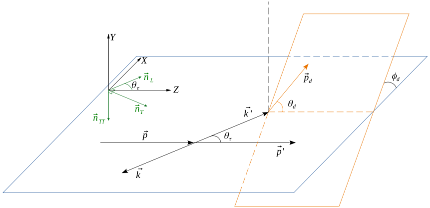


Figure: Kinematics in the $\tau\bar{\nu}_\tau$ CM reference system.

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.

All the physics is encoded in 10 independent functions of ω and the WC's.

	independent functions	observables
unpolarized τ^-	$\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$	n, $A_{\rm FB}$, A_Q
polarized τ^-	$\mathcal{A}_\mathcal{H}$, $\mathcal{B}_\mathcal{H}$, $\mathcal{C}_\mathcal{H}$, $\mathcal{D}_\mathcal{H}$, $\mathcal{E}_\mathcal{H}$	$\langle P_L^{\rm CM}\rangle$, $\langle P_T^{\rm CM}\rangle$, Z_L, Z_Q, $Z_\perp$
complex WC's	$\mathcal{F}_\mathcal{H}$, $\mathcal{G}_\mathcal{H}$	$\langle P_{TT}\rangle$, Z_T

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

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).

Visible variables

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

The involved variables are

- The product of the hadrons 4-velocities (related with q^2)

$$\omega = [1, \omega_{max}] \text{ where } \quad \omega_{max} = \frac{M^2 + M'^2 - m_\ell^2}{2MM'}$$

- Angle of the final hadron and the tau-decay massive product

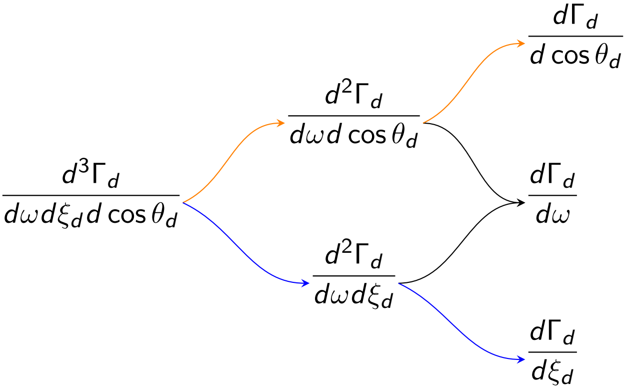
$$\cos_{\theta_d} = [-1, 1]$$

- The ratio of the energies of the tau-decay massive product and the τ, $\xi_d = E_d/(\gamma m_\tau)$.

$$\xi_d = [\xi_d^{min}, \xi_d^{max}];$$

$$\xi_d^{max} = \xi^{max}(\omega); \quad \xi_d^{min} = \begin{cases} y/\gamma; & \text{leptonic mode} \\ \frac{1-\beta}{2} + \frac{1+\beta}{2} y^2; & \text{hadronic mode} \end{cases}$$

We can follow different paths:



$F_0(\omega,\xi_d)$, $F_1(\omega,\xi_d)$ and $F_2(\omega,\xi_d)$ are defined so we get the differential rate of the unpolarized tau when integrating in ξ_d and $\cos\theta_d$

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

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

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

We get,

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

In particular, for all τ decay modes:

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

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

*Murgui et al. JHEP 09 (2019) 103
Mandal et al. JHEP 08 (2020) 08, 022

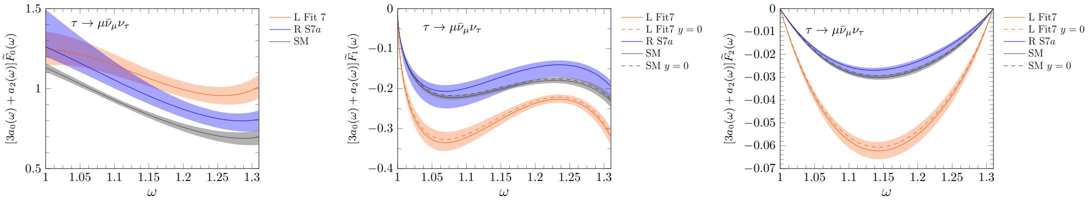


Figure: Results for the functions $[3a_0(\omega)+a_2(\omega)]\tilde{F}^{\mu\bar{\nu}_\mu}_{0,1,2}(\omega)$ in SM and different NP fits.*

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 discriminant power for $\tau \to \pi\nu_\tau$

Analytical expressions in
N.P. et al. arXiv:2201.05537

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,

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

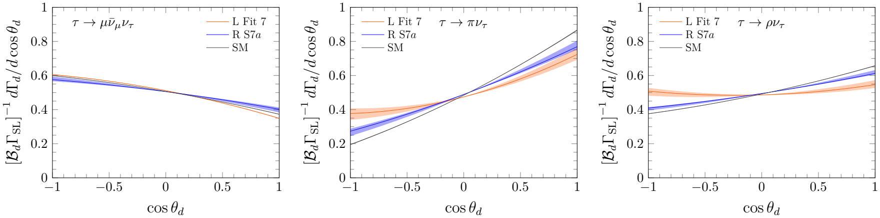


Figure: Angular $d\Gamma/d\cos\theta_d$ distribution for the $\Lambda_b \to \Lambda_c$ decays. Same NP scenarios as before.

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

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

This 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, it allows us to measure $\langle P_L^{\rm CM}\rangle(\omega)$. Using that, Belle has already measured:

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

S. Hirose et al. (Belle)
Phys. Rev. Lett. 118, 211801 (2017)

Explicit limits: N.P. et al. arXiv:2201.05537

$$\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d} \longrightarrow \frac{d^2\Gamma_d}{d\omega d\xi_d} \overset{*}{\longrightarrow} \frac{d\Gamma_d}{dE_d}$$

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

- Energy of the tau-decay particle: $E_d = [E_d^{min}, E_d^1, E_d^{max}]$

$$E_d^{\rm min} = \begin{cases} m_d; & \text{leptonic mode} \\ \frac{m_d^2(M-M')^2+m_\tau^4}{2m_\tau^2(M-M')}; & \text{hadronic mode} \end{cases}$$

- Product of hadrons 4-velocities: $\omega = [1, \omega_{sup}]$.
  - For $E_d < E_d^1$,

$$\omega_{sup} = \begin{cases} \omega_{max} & \text{leptonic mode} \\ \omega_1(E_d) & \text{hadronic mode} \end{cases}$$

  - For $E_d > E_d^1$, $\omega_{sup} = \omega_2(E_d)$ in both decay modes

$\langle P_L^{\rm CM} \rangle$ does not contribute to the normalization but affects the shape of the observable.

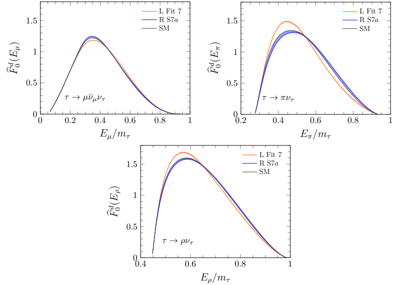


Figure: Energy $d\Gamma/dE_d$ distribution for the $\Lambda_b \to \Lambda_c$ decays. Same NP scenarios as before.

Conclusions

- Using visible final-state helps to avoid using τ variables that are difficult to reconstruct.
- It is useful to increase statistics by integrating some of the variables.
- There are three differential decay rates with complementary information about the dynamics.
- The angular distribution is richer, i.e., it includes more information about the decay physics.

$$\begin{cases} \frac{d\Gamma}{d\omega} \longrightarrow \text{unpolarized decay} \\ \frac{d\Gamma}{dE_d} \longrightarrow \text{longitudinal polarization} \\ \frac{d\Gamma}{d\cos\theta_d} \longrightarrow \text{all asymmetries except } \langle \mathcal{P}_L \rangle \end{cases}$$