New physics and the tau polarization vector in $b \to c\tau^-\bar{\nu}_\tau$ decays

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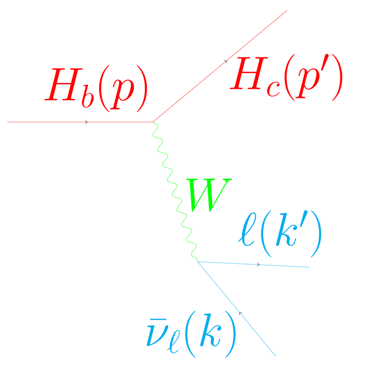
Motivation

Some experimental data, specially the ratios $\mathcal{R}_{H_c} = \frac{\Gamma(H_b \to H_c \tau \bar{\nu_\tau})}{\Gamma(H_b \to H_c \ell \bar{\nu_\ell})}$, show a tension with the SM prediction at the level of 3.1σ [1] This can be seen as a possible existence of new physics (NP). In particular, a LFU violation because it seems that only affects the third quark and lepton generations. These NP effects are studied in a phenomenological way. We use the most general effective hamiltonian [2]

$$H_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}}[(1 + \underbrace{C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R}}_{\text{(axial}-\text{)vector}} + \underbrace{C_{S_L}\mathcal{O}_{S_L} + C_{S_R}\mathcal{O}_{S_R}}_{\text{(pseudo}-\text{)scalar}} + \underbrace{C_T\mathcal{O}_T}_{\text{tensor}}] \quad (1)$$



where the Wilson coefficients C_i parameterize the deviations from the SM ($C_i^{\rm SM} = 0$) and should be fitted to the experimental values. For distinguishing among models or fits that lead to the same results for the $\mathcal{R}_{H_c}$ ratios other observables like the τ-polarization vector are needed. [3]

$\mathcal{P}^\mu$ vector

For a τ in a state $u_h^S(k')$, the squared amplitude of the decay is:[3]

$$\overline{\sum_{rr'}} |\mathcal{M}|^2 = \frac{1}{2}{\rm Tr}\left[(\not k' + m_\tau)\mathcal{O}\right](1 + h\,\mathcal{P}\cdot S); \quad h = \pm 1 \quad (2)$$

where the spin of the other particles is summed up. The operator $\mathcal{O}$ contains the physics of the decay and $\mathcal{P}^\mu$ is what we call polarization vector. It satisfies:

$$\mathcal{P}^{\mu *} = \mathcal{P}^\mu, \qquad k'\cdot\mathcal{P} = 0,$$
$$\mathcal{P}^\mu = {\rm Tr}[\bar\rho\gamma_5\gamma^\mu] = \frac{{\rm Tr}[(\not k' + m_\tau)\mathcal{O}(\not k' + m_\tau)\gamma_5\gamma^\mu]}{{\rm Tr}[(\not k' + m_\tau)\mathcal{O}(\not k' + m_\tau)]}, \quad (3)$$

With that definition, we get for the polarization vector [4]

$$\mathcal{P}^\mu = \frac{1}{\mathcal{N}(\omega, k\cdot p)}\left[\frac{p_\perp^\mu}{M}\mathcal{N}_{\mathcal{H}_1}(\omega, k\cdot p) + \frac{q_\perp^\mu}{M}\mathcal{N}_{\mathcal{H}_2}(\omega, k\cdot p) + \frac{\epsilon^{\mu k' qp}}{M^3}\mathcal{N}_{\mathcal{H}_3}(\omega, k\cdot p)\right], \quad (4)$$

where p and k are the initial hadron and neutrino momenta, respectively. These $\mathcal{N}$ are a combination of 10 independent functions of ω (the initial and final hadron 4-velocities product) that contain all the decay information.

$$\mathcal{N} = \frac{1}{2}\left[\mathcal{A}(\omega) + \mathcal{B}(\omega)\frac{(k\cdot p)}{M^2} + \mathcal{C}(\omega)\frac{(k\cdot p)^2}{M^4}\right],$$
$$\mathcal{N}_{\mathcal{H}_1} = \mathcal{A}_{\mathcal{H}}(\omega) + \mathcal{C}_{\mathcal{H}}(\omega)\frac{(k\cdot p)}{M^2},$$
$$\mathcal{N}_{\mathcal{H}_2} = \mathcal{B}_{\mathcal{H}}(\omega) + \mathcal{D}_{\mathcal{H}}(\omega)\frac{(k\cdot p)}{M^2} + \mathcal{E}_{\mathcal{H}}(\omega)\frac{(k\cdot p)^2}{M^4},$$
$$\mathcal{N}_{\mathcal{H}_3} = \mathcal{F}_{\mathcal{H}}(\omega) + \mathcal{G}_{\mathcal{H}}(\omega)\frac{(k\cdot p)}{M^2}. \quad (5)$$

$\mathcal{P}^\mu$ components

The $\mathcal{P}^\mu$ can be decomposed using this orthogonal basis of the four-vector Minkowski space:

$$N_0^\mu = \frac{k'^\mu}{m_\tau}, \quad N_T^\mu = \left(0, \frac{(\vec{k}'\times\vec{p}')\times\vec{k}'}{|(\vec{k}'\times\vec{p}')\times\vec{k}'|}\right),$$
$$N_L^\mu = \tilde{s}^\mu = \left(\frac{|\vec{k}'|}{m_\tau}, \frac{k'^0\vec{k}'}{m_\tau|\vec{k}'|}\right), \quad N_{TT}^\mu = \left(0, \frac{\vec{k}'\times\vec{p}'}{|\vec{k}'\times\vec{p}'|}\right). \quad (6)$$

Since $\mathcal{P}\cdot k' = 0$, in a given reference system, the $\vec{P}$ components different from 0 are: $\mathcal{P}_L, \mathcal{P}_T, \mathcal{P}_{TT}$. Moreover, we can compute

$$\mathcal{P}^2 = -(\mathcal{P}_T^2 + \mathcal{P}_{TT}^2 + \mathcal{P}_L^2) \quad (7)$$

that is a Lorentz scalar with values between -1 (fully polarized τ) and 0 (unpolarized τ).

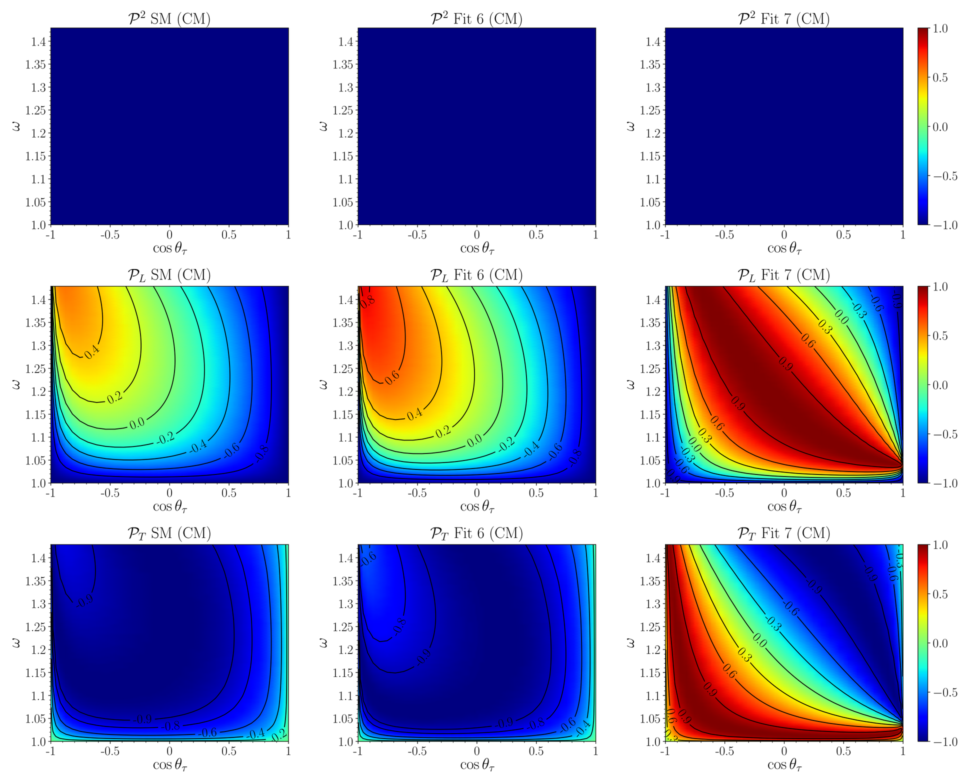


Fig. 1: $\mathcal{P}_T$, $\mathcal{P}_L$ and $\mathcal{P}^2$ (CM system) for the $\bar{B} \to D\tau\bar{\nu}_\tau$ decay. The NP scenarios are Fits 6 and 7 of [2]

$\mathcal{P}_a$ averages

In literature, it is more common to use as a polarization vector, the averages of the different components.[5]

$$\langle\mathcal{P}_a^{\rm CM}\rangle(\omega) = \frac{1}{\mathcal{N}_\theta(\omega)}\int_{-1}^{+1} d\cos\theta_\tau\,\mathcal{N}(\omega, k\cdot p)\,\mathcal{P}_a^{\rm CM}(\omega, k\cdot p),$$
$$\langle\mathcal{P}_a^{\rm LAB}\rangle(\omega) = \frac{1}{\mathcal{N}_E(\omega)}\int_{E_\tau^-(\omega)}^{E_\tau^+(\omega)} dE_\tau\mathcal{N}(\omega, k\cdot p)\,\mathcal{P}_a^{\rm LAB}(\omega, k\cdot p), \quad (8)$$

These averages in the CM and the ones in the LAB frame give complementary information, but for $< \mathcal{P}^2 > (\omega)$, we get the same result in both frames

$$\langle\mathcal{P}^2\rangle(\omega) = \int_{(k\cdot p)_-}^{(k\cdot p)_+} \frac{d(k\cdot p)}{\mathcal{N}(\omega)}\mathcal{N}(\omega, k\cdot p)\,\mathcal{P}^2(\omega, k\cdot p) \quad (9)$$

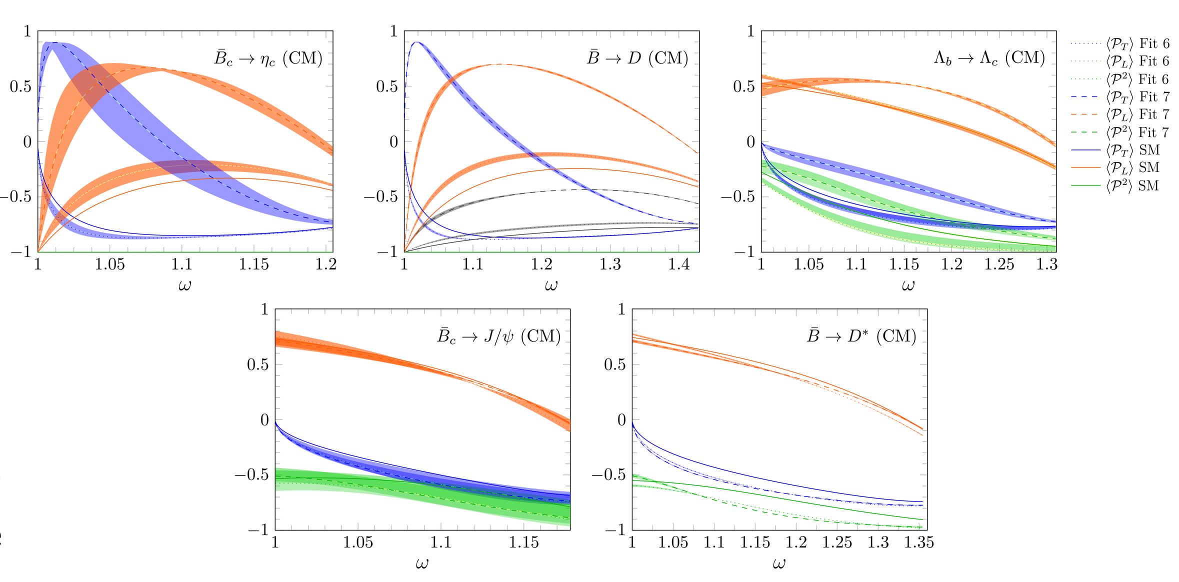


Fig. 2: $\langle\mathcal{P}_T\rangle$, $\langle\mathcal{P}_L\rangle$ and $\langle\mathcal{P}^2\rangle$ (CM system) for the 5 decays considered. The NP scenarios are Fits 6 and 7 of Ref.[2].

$\mathcal{P}_{TT}$

$\mathcal{P}_{TT}$ only depends on the term with $\epsilon^{\mu k' qp}$ of $\mathcal{P}$. This term, or equivalently $\mathcal{P}_{TT}$, indicates a CP violation contribution. That's why the functions $\mathcal{F}_{\mathcal{H}}$ and $\mathcal{G}_{\mathcal{H}}$ that are only different from zero when (some of) the Wilson coefficients are complex.

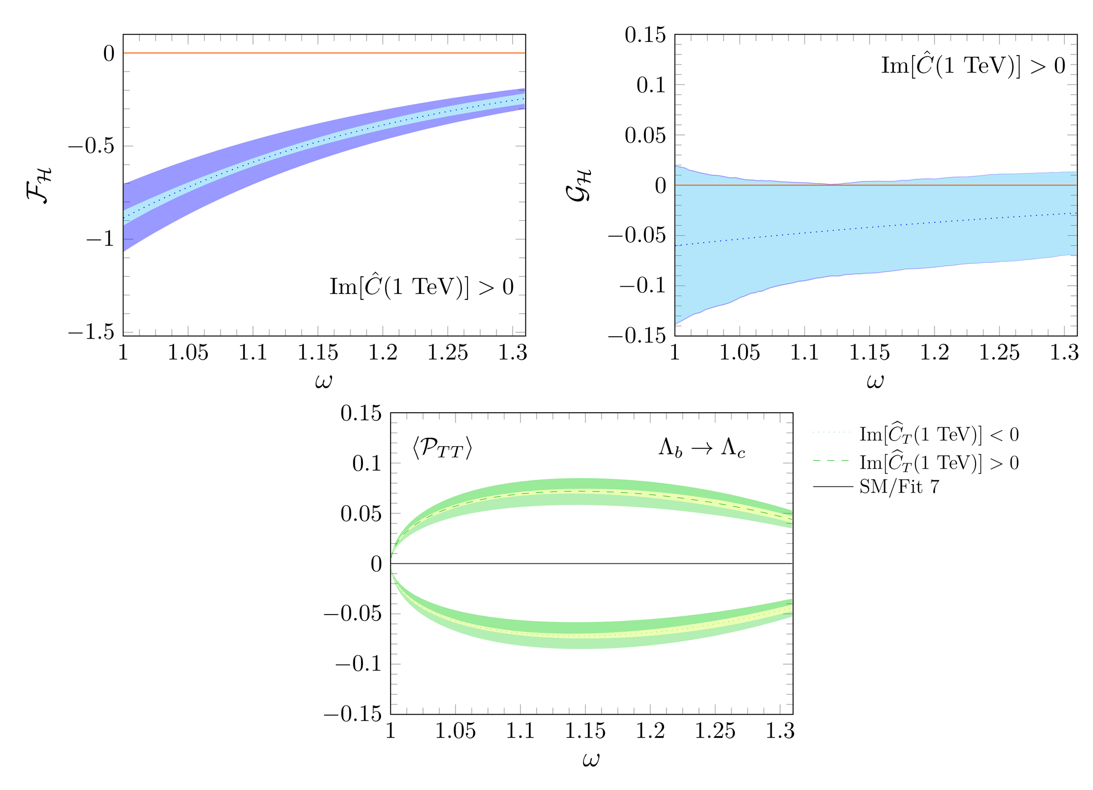


Fig. 3: $\langle\mathcal{P}_{TT}\rangle$ average using the R2 leptoquark model fit of [6].

4-body decay $H_b \to H_c\tau\,(\pi\nu_\tau, \rho\nu_\tau)\bar{\nu}_\tau$

The τ decays very fast and is very difficult to measure. However, the polarization averages in the CM reference can be obtained from the 4-body differential amplitude[7, 8]. In this amplitude there are 10 observables that are a combination of the 10 independent functions. However, the CP-violating contributions disappear after integrating over the azimuthal angle, ϕ.

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

Conclusions

- The meson $0^- \to 0^-$ and the baryon $\Lambda_b \to \Lambda_c$ decays are the best for distinguishing among NP models.
- We have 5 WC's (9 parameters if they are complex) $\to$ It's necessary to combine different decays.
- Subsequent decays of the produced τ^- give most of the information which can be extracted from $H_b \to H_c\tau\bar{\nu}_\tau$.
- In particular, we have shown the different components of the $\mathcal{P}^\mu$ are a new source of information.

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