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

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July 28, 2021

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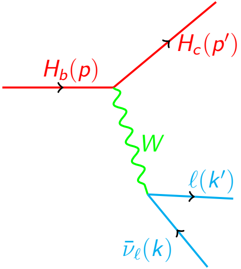
LFUV in $b \to c$ semileptonic decays

$$\mathcal{R}_{H_c} = \frac{\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)}$$

HFLAV group.
Eur.Phys.J.C 81(2021) 3, 226

$$\mathcal{R}_D = 0.340 \pm 0.027 \pm 0.013, \quad \mathcal{R}_D^{\rm SM} = 0.299 \pm 0.003$$
$$\mathcal{R}_{D*} = 0.295 \pm 0.011 \pm 0.008, \quad \mathcal{R}_{D*}^{\rm SM} = 0.258 \pm 0.05$$
$$\mathcal{R}_{J/\psi} = 0.71 \pm 0.17 \pm 0.18, \quad \mathcal{R}_{J/\psi}^{\rm SM} \approx 0.25 - 0.28$$



- Discrepancies observed in $b \to c$ semileptonic decays (3.1σ)
- NP affecting 3th quark and lepton generations
- LFU Violation signature?

New physics effects

NP effects are studied in a phenomenological way.

Murgui et al.
JHEP 09 (2019) 103

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

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

Other observables
- $\mathcal{R}_{\Lambda_c}$
- angular distribution
- asymmetries $\mathcal{A}_{FB}$, $\mathcal{A}_{\lambda_\tau}$, ...
- τ-polarization vector components

↳ N.P., E.Hernández, J.Nieves
JHEP 06 (2021) 118

Polarization vector definition

N.P., E.Hernández, J.Nieves

JHEP 06 (2021) 118

It can be seen that for a τ in a state $u_h^S(k')$

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

$\hookrightarrow$
- contains the physics of the decay
- depends on the momenta of the particles

The polarization vector, $\mathcal{P}^\mu$, satisfies

$$\mathcal{P}^{\mu *} = \mathcal{P}^\mu, \qquad k' \cdot \mathcal{P} = 0,$$

$$\mathcal{P}^\mu = \mathrm{Tr}[\bar{\rho}\gamma_5\gamma^\mu] = \frac{\mathrm{Tr}[(\not{k}' + m_\tau)\mathcal{O}(\not{k}' + m_\tau)\gamma_5\gamma^\mu]}{\mathrm{Tr}[(\not{k}' + m_\tau)\mathcal{O}(\not{k}' + m_\tau)]},$$

$\mathcal{P}^\mu$ vector

N.P., E.Hernández, J.Nieves

Phys.Rev.D 101 (2020) 11, 113004

With the previous definition, we get:

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

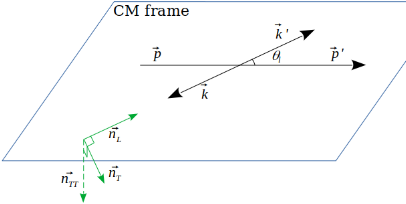
It depends on 8 $(+2)$ independent functions

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

with k the neutrino momentum and p the initial hadron momentum.

$\mathcal{P}^\mu$ components

We choose an orthogonal basis of the four-vector Minkowski space



$$N_0^\mu = \frac{k'^\mu}{m_\tau}, \quad N_T^\mu = \left(0, \frac{(\vec{k}\,' \times \vec{p}\,') \times \vec{k}\,'}{|(\vec{k}\,' \times \vec{p}\,') \times \vec{k}\,'|}\right)$$

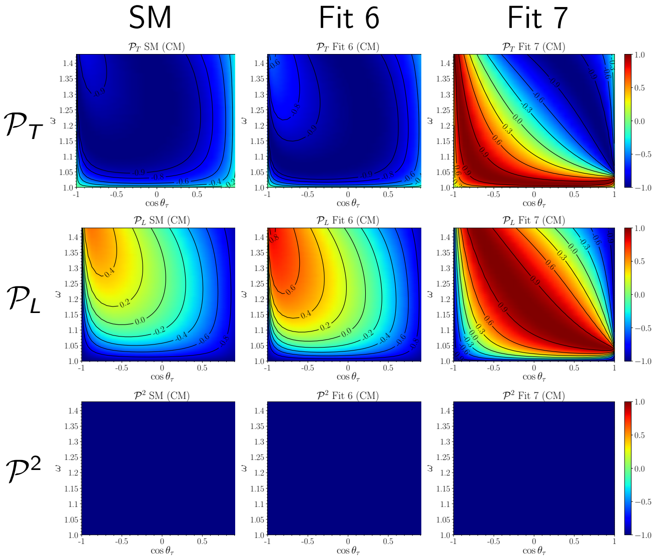
$$N_L^\mu = \tilde{s}^\mu = \left(\frac{|\vec{k}\,'|}{m_\tau}, \frac{k'^0 \vec{k}\,'}{m_\tau |\vec{k}\,'|}\right), \quad N_{TT}^\mu = \left(0, \frac{\vec{k}\,' \times \vec{p}\,'}{|\vec{k}\,' \times \vec{p}\,'|}\right).$$

Since $\mathcal{P} \cdot k' = 0$, we will have that in a given reference system

$$\mathcal{P}^\mu = \mathcal{P}_L \, N_L^\mu + \mathcal{P}_T \, N_T^\mu + \mathcal{P}_{TT} \, N_{TT}^\mu \, ,$$

$$\mathcal{P}^2 = -(\mathcal{P}_T^2 + \mathcal{P}_{TT}^2 + \mathcal{P}_L^2) \Rightarrow \begin{cases} \text{Lorentz scalar} \\ -1 \leqslant \mathcal{P}^2 \leqslant 0. \end{cases}$$

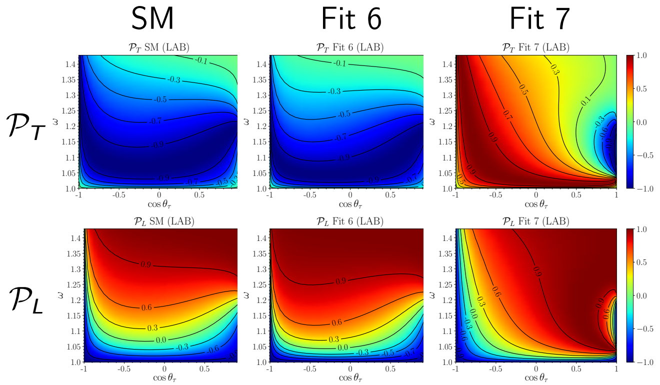
$\mathcal{P}_a$ in the CM system ($\tau\bar{\nu}_\tau$ at rest)



$\mathcal{P}_T$, $\mathcal{P}_L$ 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 Murgui et al. JHEP 09 (2019) 103

$\mathcal{P}_a$ in the LAB system (H_b at rest)



$\mathcal{P}_T$, $\mathcal{P}_L$ and $\mathcal{P}^2$ (LAB system) for the $\bar{B} \to D\tau\bar{\nu}_\tau$ decay.

The NP scenarios are Fits 6 and 7 of Murgui et al. JHEP 09 (2019) 103

$$M\,(M_\omega - E_\tau) = k \cdot p = \frac{M}{2}\left(1 - \frac{m_\tau^2}{q^2}\right)\left(M_\omega + M'\sqrt{\omega^2 - 1}\cos\theta_\tau\right),$$

P_a averages

Ivanov et al. Phys.Rev.D 95 (2017) 3, 036021

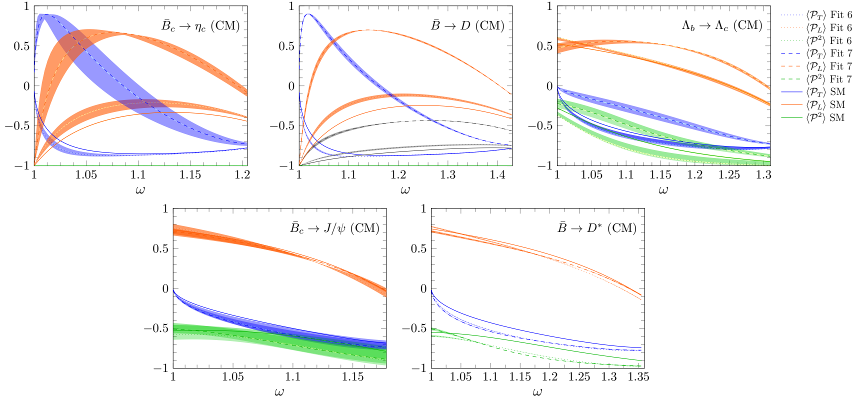
$$\langle \mathcal{P}_a^{\mathrm{CM}} \rangle(\omega) = \frac{1}{\mathcal{N}_\theta(\omega)} \int_{-1}^{+1} d\cos\theta_\tau \, \mathcal{N}(\omega, k\cdot p)\, \mathcal{P}_a^{\mathrm{CM}}(\omega, k\cdot p),$$

$$\langle \mathcal{P}_a^{\mathrm{LAB}} \rangle(\omega) = \frac{1}{\mathcal{N}_E(\omega)} \int_{E_\tau^-(\omega)}^{E_\tau^+(\omega)} dE_\tau \mathcal{N}(\omega, k\cdot p)\, \mathcal{P}_a^{\mathrm{LAB}}(\omega, k\cdot p),$$

Same result for $< \mathcal{P}^2 > (\omega)$ in both frames

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

Polarization averages: CM results



$\langle \mathcal{P}_T \rangle$, $\langle \mathcal{P}_L \rangle$ and $\langle \mathcal{P}^2 \rangle$ (CM system) for the 5 decays considered. The NP scenarios are Fits 6 and 7 of Murgui et al. JHEP 09 (2019) 103.

$\mathcal{P}_{TT}$

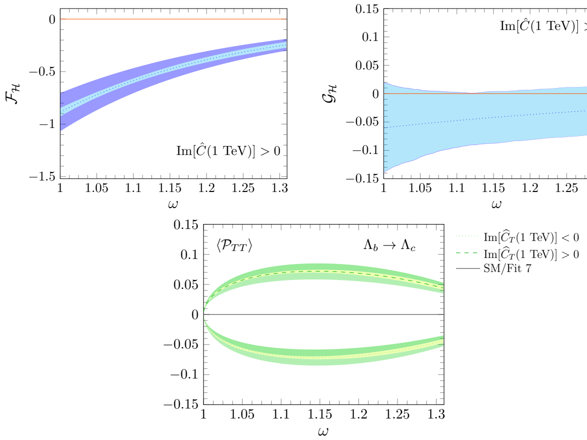
$\mathcal{P}_{TT} \neq 0$ indicates CP violation $\Rightarrow \mathcal{P}_{TT}^{\rm SM} = 0$

$\mathcal{F}_{\mathcal{H}}$ and $\mathcal{G}_{\mathcal{H}}$ are not zero when (some of) the Wilson coefficients are complex.

$\mathcal{P}_{TT}$ is the same in both frames.

$$\langle \mathcal{P}_{TT}^{\rm CM} \rangle(\omega) = \langle \mathcal{P}_{TT}^{\rm LAB} \rangle(\omega) =$$
$$-\frac{\pi M'}{\mathcal{N}_\theta(\omega)} \frac{\sqrt{\omega^2-1}}{8\sqrt{q^2}} \left(1 - \frac{m_\tau^2}{q^2}\right) \left[\frac{2q^2}{M^2}\mathcal{F}_{\mathcal{H}}(\omega) + \frac{M_\omega (q^2 - m_\tau^2)}{M^3}\mathcal{G}_{\mathcal{H}}(\omega)\right],$$

Complex Wilson coeff.



Independent functions $\mathcal{F}_\mathcal{H}$ and $\mathcal{G}_\mathcal{H}$ and the $\langle \mathcal{P}_{TT} \rangle$ average using the R2 leptoquark model fit of Shi et al.(JHEP 12 (2019)065).

Pol. and other asymmetries in 4-body decays

Asadi et al. Phys.Rev.D 102 (2020) 9, 095028

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

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

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 $\mu\bar{\nu}_\mu$)

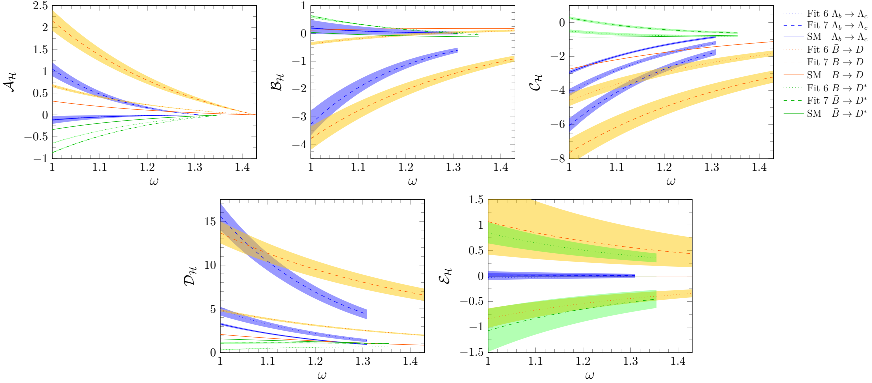
Independent functions

Those observables are linear combinations of the 8 independent functions that are giving us all the information about the decay.

	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

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

Full additional information from polarized τ



$\mathcal{A}_\mathcal{H}(\omega), \mathcal{B}_\mathcal{H}(\omega), \mathcal{C}_\mathcal{H}(\omega), \mathcal{D}_\mathcal{H}$ and $\mathcal{E}_\mathcal{H}(\omega)$ functions.

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.