Lepton flavour universality violation and new physics in $b \to c$ semileptonic transitions

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Based on:
Phys. Rev. D 100, 113007(2019); D 101, 113004 (2020); D102, 096016 (2020)
JHEP 06 (2021) 118; 10 (2021) 122; 04 (2022) 026
arXiv 2207.10529 (PRD in print)

Lepton flavour universality (LFU) is a feature of the Standard Model (SM)

- W and Z bosons couple universally to all three lepton families.

However, one finds that a combined analysis, done by the HFLAV Collaboration [HFLAV, Eur. Phys. J. C 81, 226 (2018)], of BaBar, Belle and LHCb data on the

$$\mathcal{R}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\Gamma(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$

ratios shows a discrepancy with SM predictions at the 3.1σ level.

LHCb [Phys. Rev. Lett 128, 191803 (2022)] has also measured $\mathcal{R}_{J/\psi} = \frac{\Gamma(\bar{B}_c \to J/\psi\tau\bar{\nu}_\tau)}{\Gamma(\bar{B}_c \to J/\psi\mu\bar{\nu}_\mu)}$ which deviates from SM predictions at the 1.8 σ level.

In both cases one finds the experimental central values are above SM ones.

On the other side one has the very recent measurement by the LHCb collaboration [Phys. Rev. Lett. 128, 191803 (2022)] of the similar $\mathcal{R}_{\Lambda_c} = \frac{\Gamma(\Lambda_b \to \Lambda_c \tau^- \bar{\nu}_\tau)}{\Gamma(\Lambda_b \to \Lambda_c \mu^- \bar{\nu}_\mu)}$ ratio, which is in agreement with the SM prediction within errors, but with a central value below the SM one.

Here, the τ^- lepton was reconstructed using the hadronic $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\,\nu_\tau$ decay, with the same technique used by LHCb to obtain a value for $\mathcal{R}_{D^*}$ also in agreement with the SM prediction. However, a higher $\mathcal{R}_{D^*}$ value was obtained by the same experiment when the τ lepton was reconstructed using its leptonic decay into a muon. It is then of great interest to see if the above result for the $\Lambda_b \to \Lambda_c$ decay is confirmed or not when the muonic reconstruction channel is used. Such an analysis is under way.

If deviations from the SM are finally confirmed they will a clear indication for the necessity of new physics (NP).

The different deviation of the present $\mathcal{R}_{\Lambda_c}$ and $R_{D^{(*)}}$ ratios with respect to their SM values, suppression for $\mathcal{R}_{\Lambda_c}$ versus enhancement for $R_{D^{(*)}}$, puts a very stringent test on NP extensions of the SM, since scenarios leading to different deviations from SM expectations seem to be required.

One can address this problem in a model-independent way using an effective field-theory approach in which one takes a low energy Hamiltonian that includes all dimension-six $b \to c$ semileptonic operators with both left- and right-handed neutrino fields [see for instance R. Mandal et al., JHEP08 (2020) 022],

$$\begin{aligned} H_{\text{eff}} &= \frac{4G_F V_{cb}}{\sqrt{2}} \Big[(1 + C^V_{LL})\mathcal{O}^V_{LL} + C^V_{RL}\mathcal{O}^V_{RL} + C^S_{LL}\mathcal{O}^S_{LL} + C^S_{RL}\mathcal{O}^S_{RL} + C^T_{LL}\mathcal{O}^T_{LL} \\ &\quad + C^V_{LR}\mathcal{O}^V_{LR} + C^V_{RR}\mathcal{O}^V_{RR} + C^S_{LR}\mathcal{O}^S_{LR} + C^S_{RR}\mathcal{O}^S_{RR} + C^T_{RR}\mathcal{O}^T_{RR} \Big] + h.c., \end{aligned}$$

with

$$\mathcal{O}^V_{(L,R)L} = (\bar{c}\gamma^\mu b_{L,R})(\bar{\ell}\gamma_\mu \nu_{\ell L}),\ \mathcal{O}^S_{(L,R)L} = (\bar{c}\, b_{L,R})(\bar{\ell}\,\nu_{\ell L}),\ \mathcal{O}^T_{LL} = (\bar{c}\,\sigma^{\mu\nu} b_L)(\bar{\ell}\sigma_{\mu\nu}\nu_{\ell L}),$$

$$\mathcal{O}^V_{(L,R)R} = (b\gamma^\mu b_{L,R})(\bar{\ell}\gamma_\mu \nu_{\ell R}),\ \mathcal{O}^S_{(L,R)R} = (\bar{c}\, b_{L,R})(\bar{\ell}\,\nu_{\ell R}),\ \mathcal{O}^T_{RR} = (\bar{c}\,\sigma^{\mu\nu} b_R)(\bar{\ell}\sigma_{\mu\nu}\nu_{\ell R}),$$

and where $\psi_{R,L} = \frac{1}{2}(1 \pm \gamma_5)\psi$.

The ten, complex in general, Wilson coefficientes parametrize the deviations from the SM. They could be lepton and flavour dependent although they are generally assumed to be nonzero only for the third quark and lepton generations.

Till now, the Wilson coefficients have been fitted using the experimental values of the $R_{D^{(*)}}$ ratios, the τ lepton longitudinal polarization asymmetry and the longitudinal polarization of the D^* meson, together with the upper bound for the $\bar{B}_c \to \tau\bar{\nu}_\tau$ leptonic decay rate.

However, many different solutions are possible and in order to fix the preferred SM extension (if any) other observables sensitive to NP should be addressed.

The effective Hamiltonian can be rewritten as

$$H_{\text{eff}} = 2G_F V_{cb} \sum_{\chi=L,R} \Big[\bar{c}\gamma^\mu[C^V_\chi + h_\chi C^A_\chi \gamma_5]b\,\frac{1}{\sqrt{2}}\bar{\tau}\gamma_\mu P^\chi_5 \nu_\tau$$

$$+\bar{c}[C^S_\chi + h_\chi C^P_\chi\gamma_5]b\,\frac{1}{\sqrt{2}}\bar{\tau}P^\chi_5\nu_\tau + C^T_\chi \bar{c}\sigma^{\mu\nu}(I + h_\chi\gamma_5)b\,\frac{1}{\sqrt{2}}\bar{\tau}\sigma_{\mu\nu}P^\chi_5\nu_\tau\Big] + H.c.,$$

with $h_{L,R} = -1, +1$, $P^\chi_5 = \frac{1}{2}(I + h_\chi\gamma_5)$ and

$$\begin{aligned} C^V_L &= (1 + C^V_{LL} + C^V_{RL}), \quad C^A_L = (1 + C^V_{LL} - C^V_{RL}), \\ C^S_L &= (C^S_{LL} + C^S_{RL}), \quad C^P_L = (C^S_{LL} - C^S_{RL}), \quad C^T_L = C^T_{LL}, \end{aligned}$$

$$\begin{aligned} C^V_R &= (C^V_{LR} + C^V_{RR}), \quad C^A_R = -(C^V_{LR} - C^V_{RR}), \quad C^S_R = (C^S_{LR} + C^S_{RR}), \\ C^P_R &= -(C^S_{LR} - C^S_{RR}), \quad C^T_R = C^T_{RR}, \end{aligned}$$

The invariant amplitude reads

$$\mathcal{M}_{rr';hS} = \sum_{\chi=L,R}\left(J^\alpha_{H\chi rr'}J^L_{\chi hS,\alpha} + J_{H\chi rr'}J^L_{\chi hS} + J^{\alpha\beta}_{H\chi rr'}J^L_{\chi hS,\alpha\beta}\right),$$

In the $m_\nu \to 0$ limit, there is no interference between the $\chi = L, R$ terms and one gets

$$\overline{\sum_r} \sum_{r'} |\mathcal{M}_{rr';hS}|^2 = \sum_{\chi=L,R} \sum_{(\alpha\beta)} \sum_{(\rho\lambda)} W_\chi^{(\alpha\beta)(\rho\lambda)} L_{\chi,hS\,(\alpha\beta)(\rho\lambda)}$$

with ($\Gamma_{(\alpha\beta)} \equiv I, \gamma_\alpha, \sigma_{\alpha\beta},\ P_S^h = \frac{1}{2}(I + h\gamma_5 \not{S}$)

$$L_{\chi hS,(\alpha\beta)(\rho\lambda)} = J^L_{\chi hS,(\alpha\beta)} (J^L_{\chi hS,(\rho\lambda)})^* = \frac{1}{2} \mathrm{Tr}\,[(\not{k}' + m_\ell)\Gamma_{(\alpha\beta)} P_5^{h_\chi} \not{k} \gamma^0 \Gamma^\dagger_{(\rho\lambda)} \gamma^0 P_S^h],$$

As for the hadron tensors

$$W_\chi^{(\alpha\beta)(\rho\lambda)} = \overline{\sum_r} \sum_{r'} \langle H_c; p', r' | \bar{c}(0) O_{H\chi}^{(\alpha\beta)} b(0) | H_b; p, r\rangle \langle H_b; p, r | \bar{b}(0) \gamma^0 O_{H\chi}^{(\rho\lambda)\dagger} \gamma^0 c(0) | H_c; p', r'\rangle,$$

with $O_{H\chi}^{(\alpha\beta)} = (C_\chi^S + h_\chi C_\chi^P \gamma_5),\ (C_\chi^V \gamma^\alpha + h_\chi C_\chi^A \gamma^\alpha \gamma_5),\ C_\chi^T \sigma^{\alpha\beta}(1 + h_\chi \gamma_5)$.

The hadron tensors are linear combinations of independent tensor and pseudotensor structures, constructed out of the vectors p, $q = p - p'$, the metric tensor $g^{\mu\nu}$ and the Levi-Civita pseudotensor $\epsilon^{\mu\nu\delta\eta}$ with coefficients (structure functions) that depend on the Wilson coefficients and on the genuine hadronic responses. The latter are the square of matrix elements of the involved hadron operators that, for each particular transition, are parametrized in terms of q^2-dependent form factors.

Thus, for instance

$$
\begin{aligned}
W_\chi^{\alpha\rho} &= \overline{\sum_{r,r'}} \langle H_c; p', r' | (C_\chi^V V^\alpha + h_\chi C_\chi^A A^\alpha) | H_b; p, r\rangle \, \langle H_c; p', r' | (C_\chi^V V^\rho + h_\chi C_\chi^A A^\rho) | H_b; p, r\rangle^*, \\
&= -g^{\alpha\rho} \widetilde{W}_{1\chi} + \frac{p^\alpha p^\rho}{M^2} \widetilde{W}_{2\chi} - i h_\chi \epsilon^{\alpha\rho\delta\eta} p_\delta q_\eta \frac{\widetilde{W}_{3\chi}}{2M^2} + \frac{q^\alpha q^\rho}{M^2} \widetilde{W}_{4\chi} + \frac{p^\alpha q^\rho + p^\rho q^\alpha}{2M^2} \widetilde{W}_{5\chi},
\end{aligned}
$$

$$
\begin{aligned}
W_\chi^{\alpha\rho\lambda} &= \overline{\sum_{r,r'}} \langle H_c; p', r' | (C_\chi^V V^\alpha + h_\chi C_\chi^A A^\alpha) | H_b; p, r\rangle \, \langle H_c; p', r' | C_\chi^T \bar{c}(0) \sigma^{\rho\lambda} (1 + h_\chi \gamma_5) b(0) | H_b; p, r\rangle^* \\
&= \frac{p^\alpha \widetilde{W}_{I4\chi} + q^\alpha \widetilde{W}_{I5\chi}}{2M^3} \left[i(p^\rho q^\lambda - p^\lambda q^\rho) - h_\chi \epsilon^{\rho\lambda\delta\eta} p_\delta q_\eta \right] \\
&\quad + \frac{p_\delta \widetilde{W}_{I6\chi} + q_\delta \widetilde{W}_{I7\chi}}{2M} \left[i(g^{\alpha\rho} g^{\lambda\delta} - g^{\alpha\lambda} g^{\rho\delta}) - h_\chi \epsilon^{\rho\lambda\alpha\delta} \right],
\end{aligned}
$$

with

$$
\widetilde{W}_{1\chi,2\chi,4\chi,5\chi}(q^2) = |C_\chi^V|^2 W^{VV}_{1,2,4,5}(q^2) + |C_\chi^A|^2 W^{AA}_{1,2,4,5}(q^2), \; \widetilde{W}_{3\chi}(q^2) = \mathrm{Re}(C_\chi^V C_\chi^{A*}) W_3^{VA}(q^2).
$$

$$
\widetilde{W}_{I4\chi,I5\chi,I6\chi,I7\chi}(q^2) = C_\chi^{T*} \left(C_\chi^V W^{VT}_{I4,I5,I6,I7}(q^2) + C_\chi^A W^{ApT}_{I4,I5,I6,I7}(q^2) \right),
$$

From the general structure of the lepton and hadron tensors which are at most quadratic in k, k' and p, one can generally write for the decay with a polarized charged lepton

$$\begin{aligned}\frac{2\overline{\sum_r}\sum_{r'}|\mathcal{M}_{rr';hS}|^2}{M^2} &= \mathcal{N}(\omega, p\cdot k) + h\Bigg\{\frac{(p\cdot S)}{M}\,\mathcal{N}_{\mathcal{H}_1}(\omega, p\cdot k) \\ &\quad + \frac{(q\cdot S)}{M}\,\mathcal{N}_{\mathcal{H}_2}(\omega, p\cdot k) + \frac{\epsilon^{Sk'qp}}{M^3}\,\mathcal{N}_{\mathcal{H}_3}(\omega, p\cdot k)\Bigg\},\end{aligned}$$

with $\omega = \frac{p}{M}\cdot\frac{p'}{M'}$ (related to q^2 via $q^2 = M^2 + M'^2 - 2MM'\omega$)

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

$\mathcal{N}_{\mathcal{H}_3}$ is proportional to the imaginary part of SFs, which requires complex Wilson coefficients, thus incorporating violation of the CP symmetry in the NP effective Hamiltonian.

(It is generated from the interference of vector-axial with scalar-pseudoscalar terms, scalar-pseudoscalar with tensor terms, and vector-axial with tensor terms. For it to be nonzero, at least one of the $C_\chi^{S,P,T}$ coefficients must be non-zero.)

The above can be written as

$$\frac{2\overline{\sum_r}\sum_{r'}|\mathcal{M}_{rr';hS}|^2}{M^2} \quad = \quad \mathcal{N}(\omega, p\cdot k)(1+h\mathcal{P}\cdot S)$$

with (here $l_\perp^\mu = l^\mu - \frac{(l\cdot k')}{m_\tau^2}k'^\mu$)

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

the polarization vector of the τ lepton. It can be expanded as

$$\mathcal{P}^\mu = \mathcal{P}_L\, N_L^\mu + \mathcal{P}_T\, N_T^\mu + \mathcal{P}_{TT}\, N_{TT}^\mu\,, \qquad \mathcal{P}_a \;= -(\mathcal{P}\cdot N_a),\; a = L, T, TT$$

with $N^\mu_{L,T,TT}$ polarization states corresponding to $\vec{n}_L = \vec{k}\,'/|\vec{k}\,'|$,
$\vec{n}_T = [(\vec{k}\,'\times\vec{p}\,')\times\vec{k}\,']/|(\vec{k}\,'\times\vec{p}\,')\times\vec{k}\,'|$ and $\vec{n}_{TT} = (\vec{k}\,'\times\vec{p}\,')/|\vec{k}\,'\times\vec{p}\,'|$, respectively.

$\mathcal{P}_L$ is related to the helicity asymmetry

$$\mathcal{P}_L = \frac{\overline{\sum_r}\sum_{r'}|\mathcal{M}_{rr';-N_L}|^2 - \overline{\sum_r}\sum_{r'}|\mathcal{M}_{rr';+N_L}|^2}{\overline{\sum_r}\sum_{r'}|\mathcal{M}_{rr';-N_L}|^2 + \overline{\sum_r}\sum_{r'}|\mathcal{M}_{rr';+N_L}|^2}$$

and similar expressions apply for $\mathcal{P}_{T,TT}$

In the CM of the $\tau\bar{\nu}_\tau$ system one has that

$$\begin{aligned}
\mathcal{P}_L^{\rm CM} &= -\frac{1}{\mathcal{N}(\omega, p\cdot k)}\Big[\frac{p\cdot N_L}{M}\mathcal{N}_{\mathcal{H}_1}(\omega, p\cdot k) + \frac{q\cdot N_L}{M}\mathcal{N}_{\mathcal{H}_2}(\omega, p\cdot k)\Big]\\
\mathcal{P}_T^{\rm CM} &= -\frac{1}{\mathcal{N}(\omega, p\cdot k)}\Big[\frac{p\cdot N_T}{M}\mathcal{N}_{\mathcal{H}_1}(\omega, p\cdot k) + \frac{q\cdot N_T}{M}\mathcal{N}_{\mathcal{H}_2}(\omega, p\cdot k)\Big]\\
\mathcal{P}_{TT}^{\rm CM} &= \frac{\epsilon^{k' q p N_{TT}}}{M^3}\frac{\mathcal{N}_{\mathcal{H}_3}(\omega, p\cdot k)}{\mathcal{N}(\omega, p\cdot k)}
\end{aligned}$$

and they are functions of $\omega, \cos\theta_\tau$. One can define the averages

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

and from there obtain the quantities

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

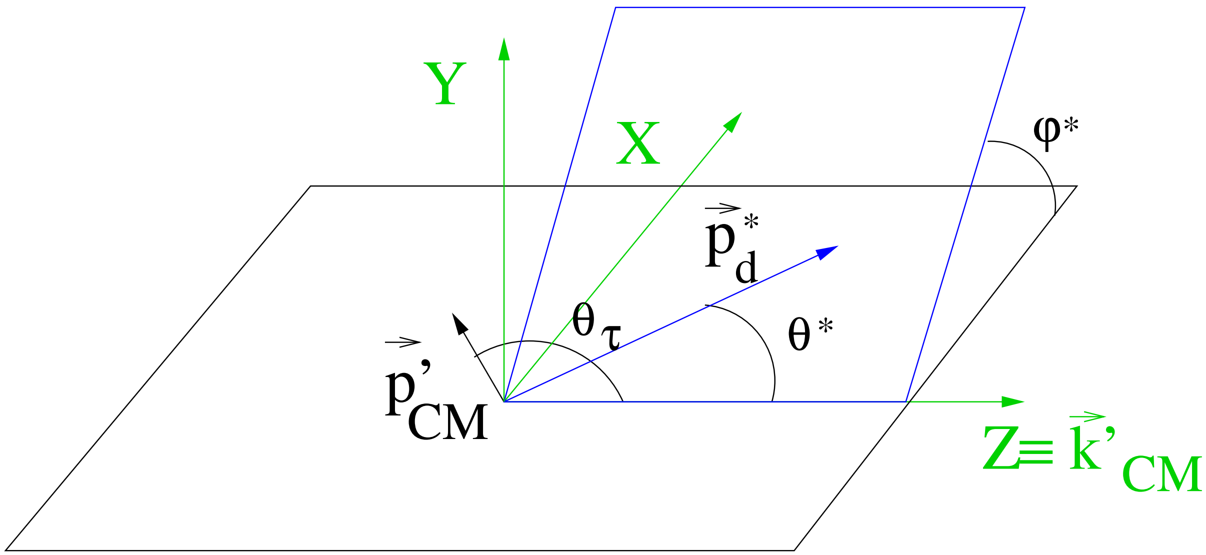
For $a = L$ one gets what is called the τ longitudinal polarization asymmetry that has been measured by Belle for the $\bar{B} \to D^*\tau\bar{\nu}_\tau$ decay.

$\mathcal{N}(\omega, k\cdot p)$ and the polarization vector $\mathcal{P}$ encode the maximum information that can be obtained from the semileptonic decay when one is not measuring any of the hadron's polarization.

Since the τ is very short lived, it is not directly seen at the detector and it has to be reconstructed through its decay channels. Following others we have considered the three decay channels $\tau \to \pi\nu_\tau, \rho\nu_\tau, \ell\bar{\nu}_\ell\nu_\tau$ $(\ell = e, \mu)$. In the zero width approximation and in the case one were able to fully reconstruct the tau momentum one can write ($d \equiv \pi, \rho, \mu$ and p_d^* measured in the τ rest frame)

$$\begin{aligned}\frac{d^4\Gamma_d}{d\omega d\cos\theta_\tau d\cos\theta_d^* d\phi_d^*} &= \frac{\mathcal{B}_d}{4\pi}\frac{d^2\Gamma_{\rm SL}}{d\omega d\cos\theta_\tau}\Big(g^d - g_P^d\left[\mathcal{P}_T^{\rm CM}(\omega,\cos\theta_\tau)\sin\theta_d^*\cos\phi_d^*\right.\\ &\left.+\mathcal{P}_{TT}^{\rm CM}(\omega,\cos\theta_\tau)\sin\theta_d^*\sin\phi_d^* + \mathcal{P}_L^{\rm CM}(\omega,\cos\theta_\tau)\cos\theta_d^*\right]\Big)\end{aligned}$$

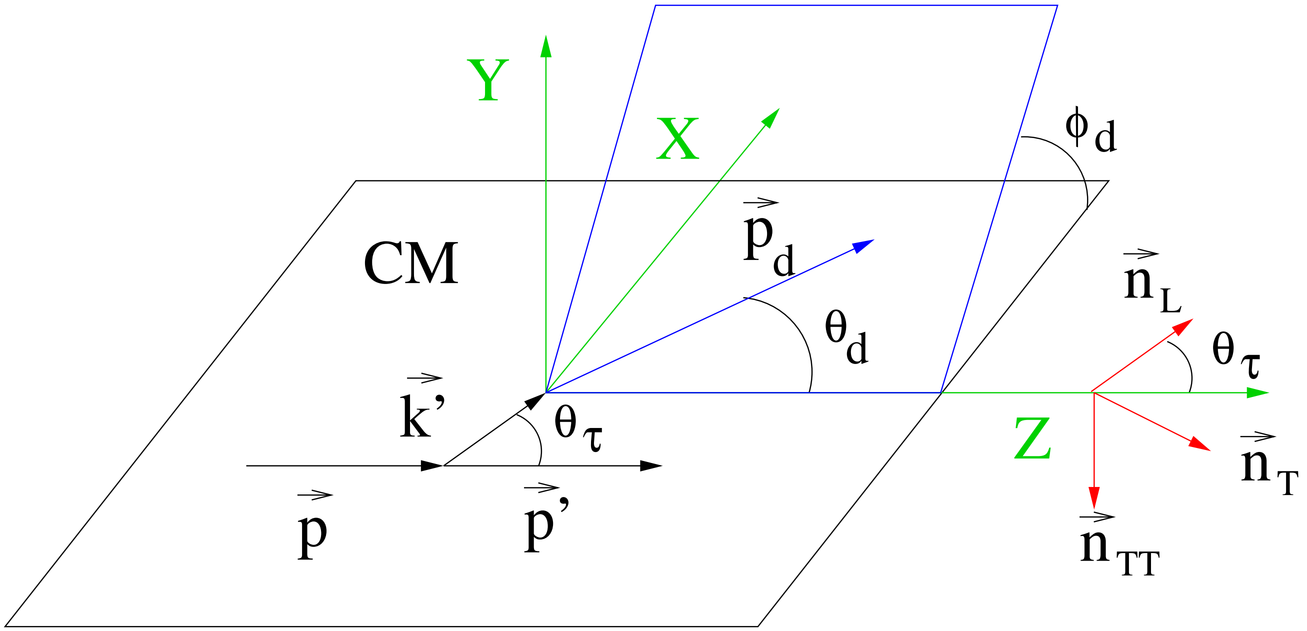
with g^d and g_P^d decay-dependent pure kinematical factors



Unfortunately the τ momentum can not be fully reconstructed and one has to obtain information only from the visible kinematics of its decay products. In this case one can write [First introduced for $\tau \to \pi\nu_\tau, \rho\nu_\tau$ decays by P. Asadi et al., Phys. Rev. D 102, 095028 (2020)],

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

with p_d in the CM frame and $\xi_d = \frac{E_d}{E_\tau}\Big|_{\rm CM}$



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

with C_j^d decay-dependent kinematical factors.

$\langle\mathcal{P}_{L,T}^{\rm CM}\rangle(\omega)$ are spin asymmetries, $A_{FB,Q}(\omega)$ angular asymmetries and $Z_{L,Q,\perp}(\omega)$ angular-spin asymmetries of the parent $H_b \to H_c\tau\bar\nu_\tau$ decay. Together with $d\Gamma_{\rm SL}/d\omega$, they are given in terms of the $\mathcal{A}(\omega),\mathcal{B}(\omega),\mathcal{C}(\omega)$, and $\mathcal{A}_\mathcal{H}(\omega),\mathcal{B}_\mathcal{H}(\omega),\mathcal{C}_\mathcal{H}(\omega),\mathcal{D}_\mathcal{H}(\omega),\mathcal{E}_\mathcal{H}(\omega)$ functions.

One can increase statistics by integrating in one or more of the variables $\omega,\xi_d,\cos\theta_d$ at the price of losing information

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

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

$$\begin{aligned}\widetilde{F}_1^d(\omega) &= C^d_{A_{FB}}(\omega)\,A_{FB}(\omega) + C^d_{Z_L}(\omega)\,Z_L(\omega) + C^d_{P_T}(\omega)\,\langle\mathcal{P}_T^{\rm CM}\rangle(\omega),\\ \widetilde{F}_2^d(\omega) &= C^d_{A_Q}(\omega)\,A_Q(\omega) + C^d_{Z_Q}(\omega)\,Z_Q(\omega) + C^d_{Z_\perp}(\omega)\,Z_\perp(\omega),\end{aligned}$$

Further integrations in ω give

$$\frac{d\Gamma_d}{d\cos\theta_d} = \mathcal{B}_d\Gamma_{\rm SL}\Big[\frac{1}{2} + \widehat{F}_1^d\cos\theta_d + \widehat{F}_2^d\,P_2(\cos\theta_d)\Big], \quad \widehat{F}_{1,2}^d = \frac{1}{\Gamma_{\rm SL}}\int_1^{\omega_{\rm max}}\frac{d\Gamma_{\rm SL}}{d\omega}\widetilde{F}_{1,2}^d(\omega)\,d\omega.$$

$$\frac{d\Gamma_d}{dE_d} = 2\mathcal{B}_d\int_{\omega_{\rm inf}(E_d)}^{\omega_{\rm sup}(E_d)} d\omega\,\frac{1}{\gamma m_\tau}\,\frac{d\Gamma_{\rm SL}}{d\omega}\Big\{C_n^d(\omega,\xi_d) + C^d_{P_L}(\omega,\xi_d)\,\langle\mathcal{P}_L^{\rm CM}\rangle(\omega)\Big\},$$

observables that still could be useful to distinguish between different NP extensions of the SM.

NP models considered in this presentation

We shall compare results of fit 7 of Ref. C. Murgui et al, JHEP09 (2019)103 and fit 7a of Ref. R. Mandal et al, JHEP08(2020) 022 with SM results.

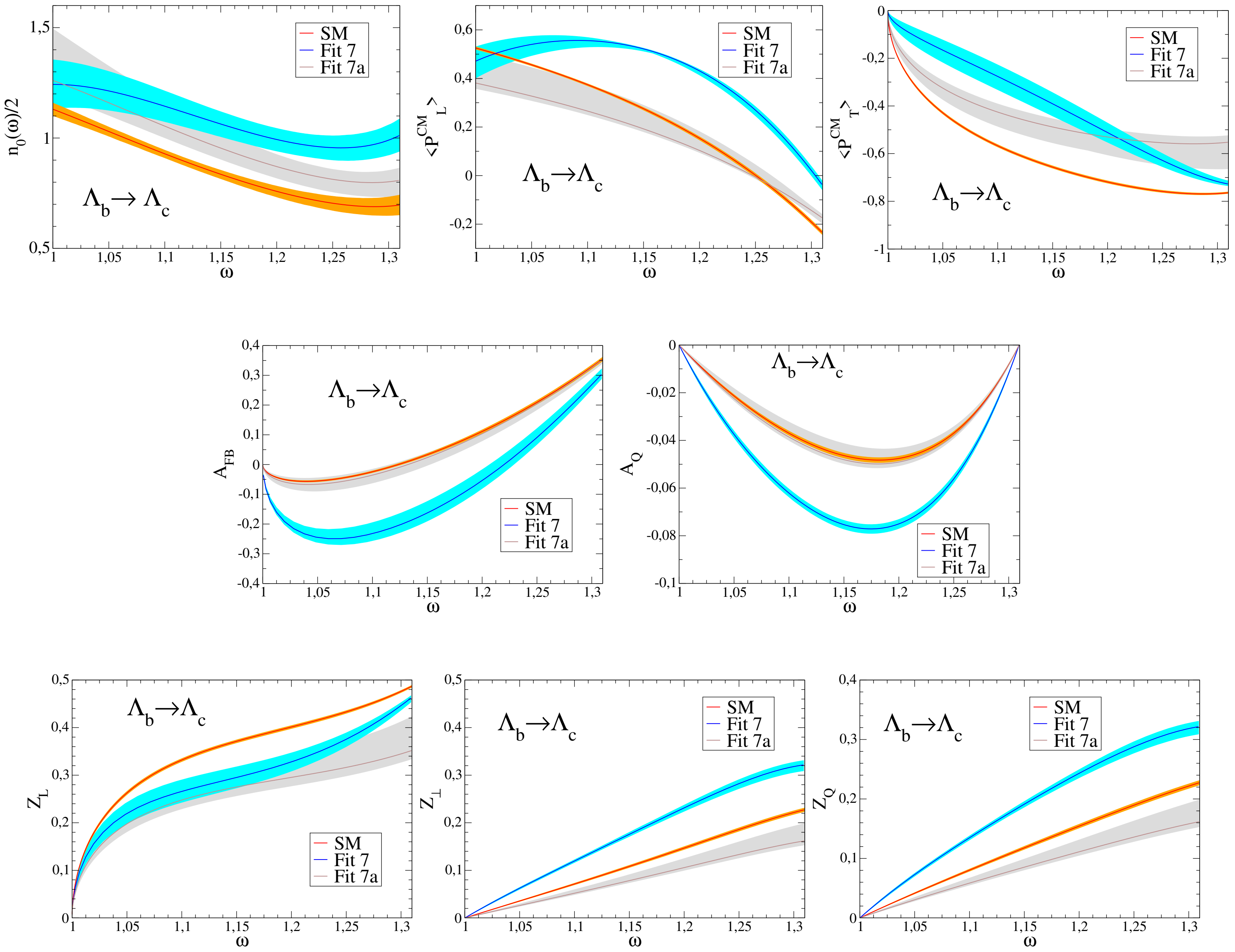
	C_L^S	C_L^P	C_L^V	C_L^A	C_L^T
SM	-	-	1	1	-
L Fit 7	$-1.32^{+0.15}_{-0.12}$	$-0.22^{+0.01}_{-0.01}$	$1.70^{+0.02}_{-0.02}$	$1.02^{+0.05}_{-0.07}$	$-0.01^{+0.02}_{-0.02}$

	$C_R^S = C_R^P$	$C_R^V = C_R^A$	C_R^T
R S7a	$-0.18^{+0.60}_{-0.32}$	$0.42^{+0.03}_{-0.20}$	$0.02^{+0.04}_{-0.08}$

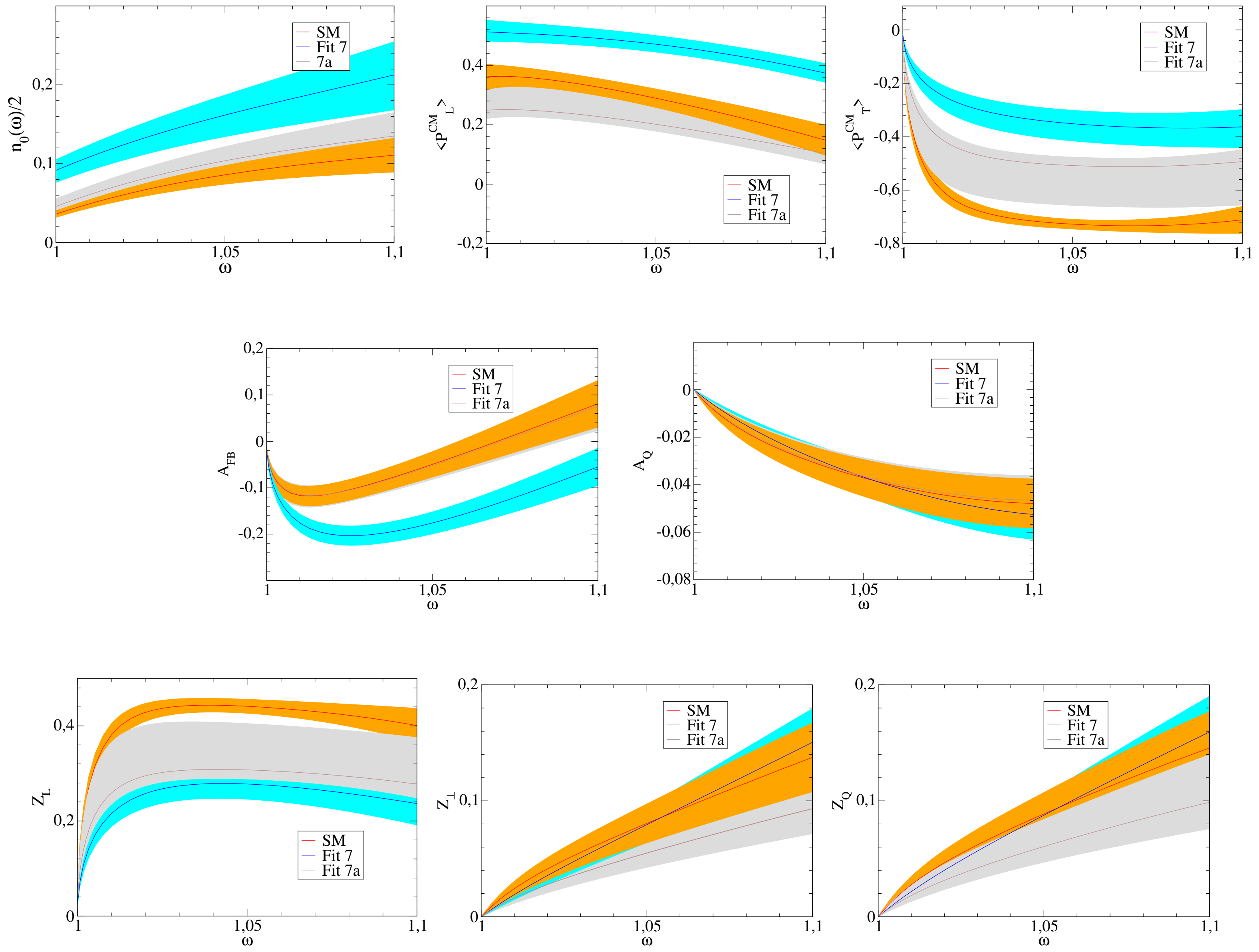
with $C_L^V = C_L^A = 1$ (SM values)

	SM	L Fit 7	R S7a	HFLAV	LHCb	Belle
$\mathcal{R}_D$	$0.300^{+0.005}_{-0.004}$	$0.388^{+0.044}_{-0.045}$	$0.334^{+0.070}_{-0.015}$	0.340 ± 0.030		
$\mathcal{R}_{D^*}$	0.255 ± 0.003	0.306 ± 0.013	$0.292^{+0.014}_{-0.015}$	0.295 ± 0.014		
$\mathcal{R}_{\Lambda_c}$	0.332 ± 0.007	0.41 ± 0.02	0.38 ± 0.03	-	0.242 ± 0.076	
$P_L(D^*)$	$-0.718^{+0.015}_{-0.025}$	-0.55 ± 0.02	-0.49 ± 0.10			$-0.38^{+0.55}_{-0.53}$

Results: asymmetries for $\Lambda_b \to \Lambda_c$

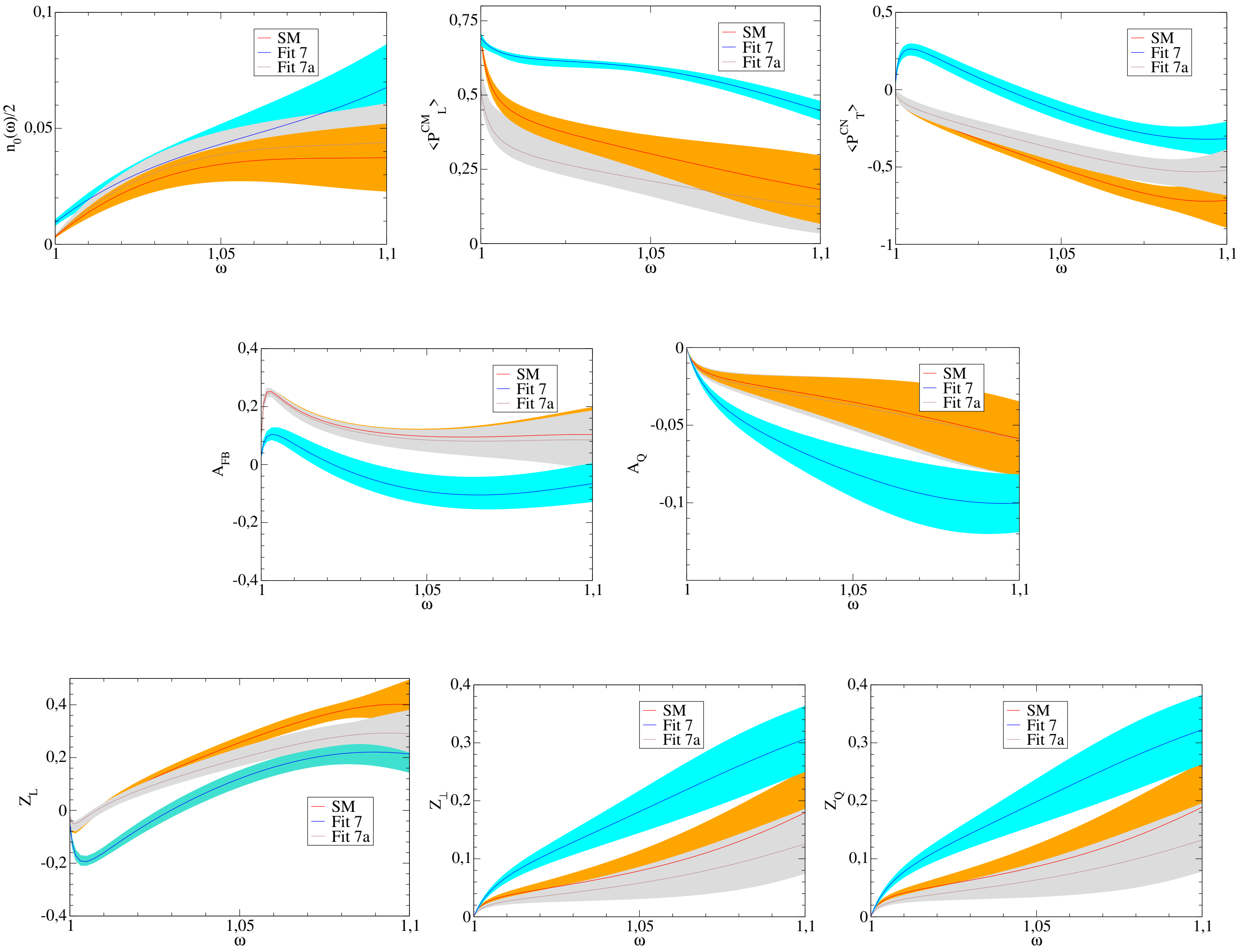


Results: asymmetries for $\Lambda_b \to \Lambda_c^*(2595)[J^\pi = 1/2^-]$

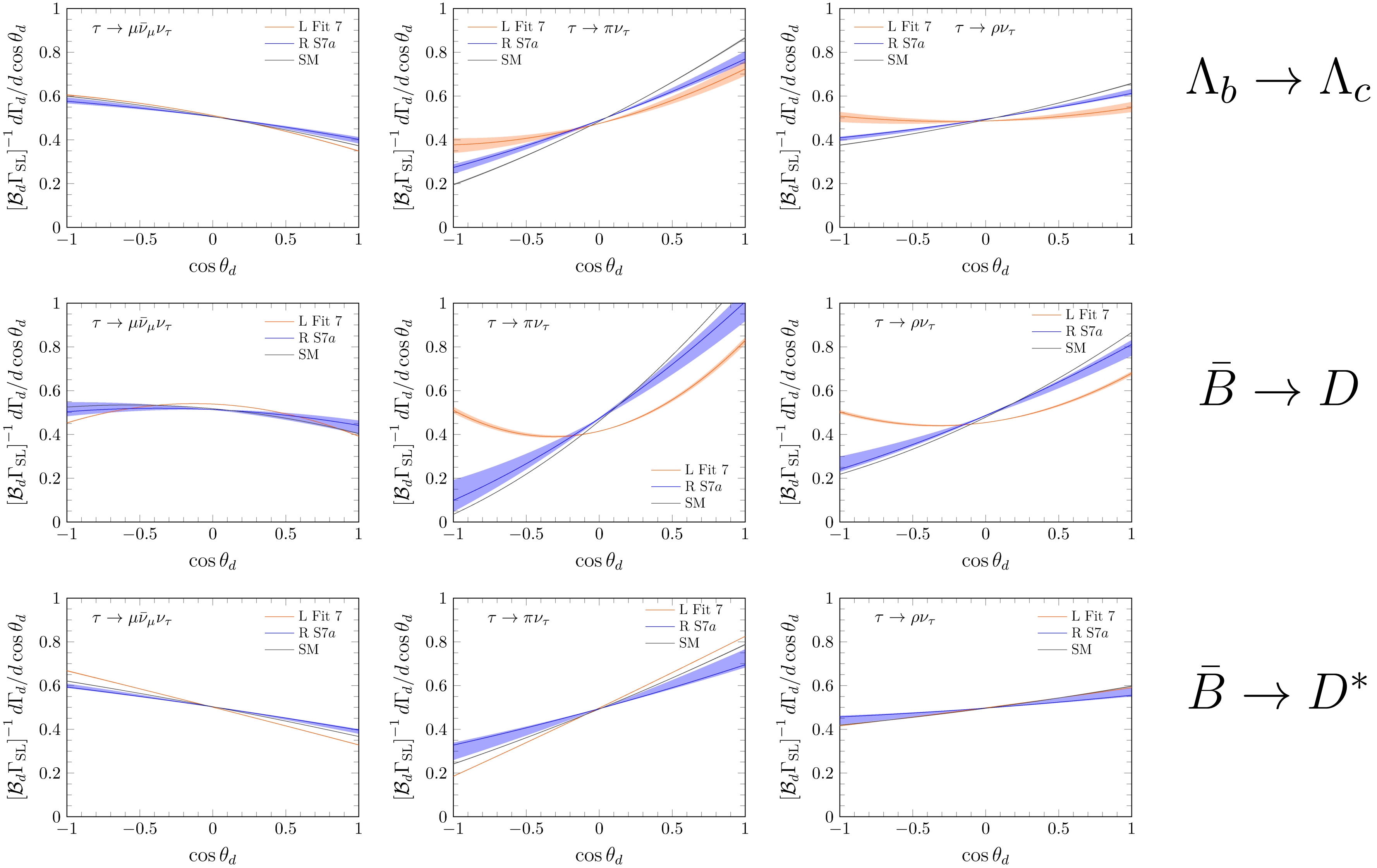


$\langle P_L^{CM}\rangle$ and A_{FB}

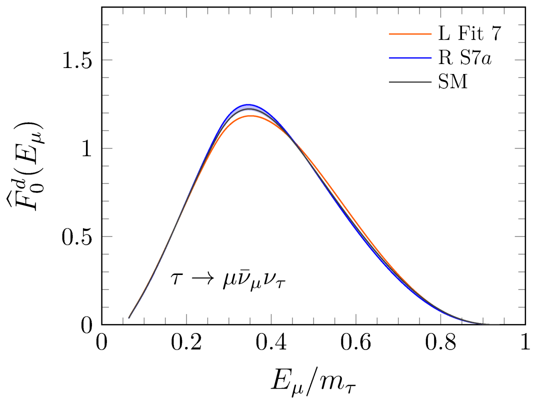
Results: asymmetries for $\Lambda_b \to \Lambda_c^*(2625)[J^\pi = 3/2^-]$

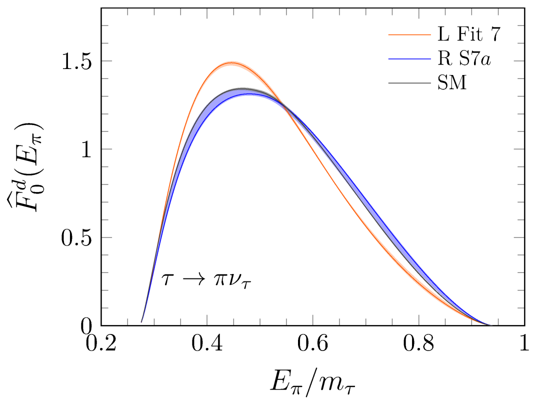


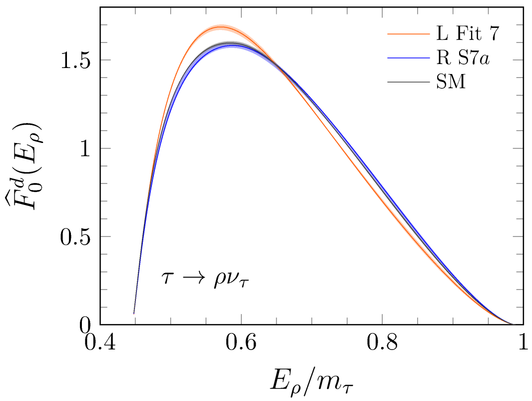
Results: $\frac{d\Gamma_d}{d\cos\theta_d}$, $d = \pi, \rho, \mu$



Results: $\widehat{F}_0^d = \frac{2m_\tau}{\mathcal{B}_d}\frac{d\Gamma_d}{dE_d}, \ d = \pi, \rho, \mu$







$\Lambda_b \to \Lambda_c$

Summary

- At present, there is at experimental evidence for LFUV in CC processes involving the third quark and lepton generations.

  $$\mathcal{R}_{D^{(*)}}\ (3.1\sigma), \mathcal{R}_{\Lambda_c}\ (1.8\sigma)$$

  If confirmed, it implies the existence of NP beyond the SM.

- Different NP extensions of the SM can explain the data so that other observables are required to identify the preferred one (if any).

- Relying only on observables that can be obtained from visible kinematics of the hadron decay products (for $\tau \to \pi\nu_\tau, \rho\nu_\tau, \mu\bar{\nu}_\mu\nu_\tau$ decays) there is a total of seven asymmetries of the parent decay that, togheter with $d\Gamma_{SL}/d\omega$, can be useful for that purpose.

- Statistically enhanced distributions like $\frac{d\Gamma_d}{d\cos\theta_d}$ or $\frac{d\Gamma_d}{dE_d}$ can also help in distinguishing between different NP scenarios that otherwise give rise so very similar $\mathcal{R}_{D^{(*)},\Lambda_c}$ ratios.