Angular observables in $\overline{B} \to D^{(*)}\tau\overline{\nu}$ and search for New Physics

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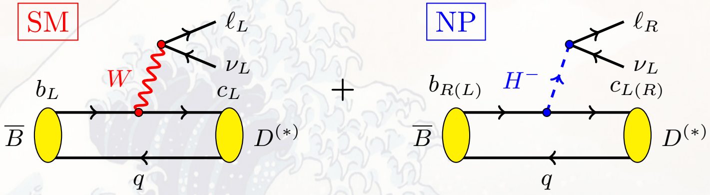
Prospects and challenges for semitauonic decays at LHCb
CERN, 28 April 2016

Outline



- Tree-level (TL) process. Large $\mathcal{B}^{(\mathrm{SM})} \sim (1-2)\%$.
- TL processes can be sensitive to NP as well as FCNCs.
  - e.g. sensitive to the charged Higgs (2HDM).
- B-decays with τ in the final state offer possibilities to study NP effects not present in processes with light leptons.
- Hadronic uncertainties better controlled (or can be!).
- Popular NP test via

$$\boxed{R(D) = \frac{\mathcal{B}(B \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D\ell\overline{\nu}_\ell)}, \quad R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*\ell\overline{\nu}_\ell)}} \quad (\ell = e, \mu)$$

in order to cancel/reduce theoretical uncertainties in V_{cb}/FFs.

Assume that there is NO right-handed neutrino.

$\mathcal{H}_{\text{eff}}$ describing the $b \to c\tau\overline{\nu}$ process

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[\big(\underbrace{1}_{\text{SM}} + \underbrace{C_{V_1} \big) \mathcal{O}_{V_1} + C_{V_2} \mathcal{O}_{V_2} + C_{S_1} \mathcal{O}_{S_1} + C_{S_2} \mathcal{O}_{S_2} + C_T \mathcal{O}_T}_{\text{NP}} \Big]$$

$$\begin{aligned} \mathcal{O}_{V_1} &= (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)\,, & \mathcal{O}_{V_2} &= (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L)\,, \\ \mathcal{O}_{S_1} &= (\bar{c}_L b_R)(\bar{\tau}_R \nu_L)\,, & \mathcal{O}_{S_2} &= (\bar{c}_R b_L)(\bar{\tau}_R \nu_L)\,, \end{aligned}$$

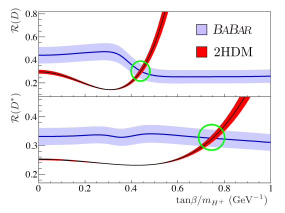
$$\mathcal{O}_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_L)\,.$$

- E.g. in the 2HDM-II

$$C_{S_1} = -\frac{m_b m_\tau}{m_{H^\pm}^2} \tan^2 \beta$$

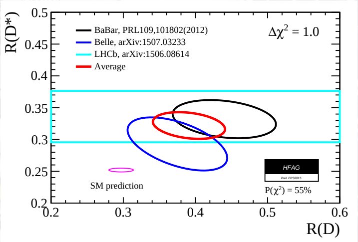
which is disfavoured by *BABAR* $\forall \tan\beta/m_{H^\pm}$.
However, Belle claims compatibility with 2HDM-II for $\tan\beta/m_{H^\pm} \sim 0.5\ \text{GeV}^{-1}$.

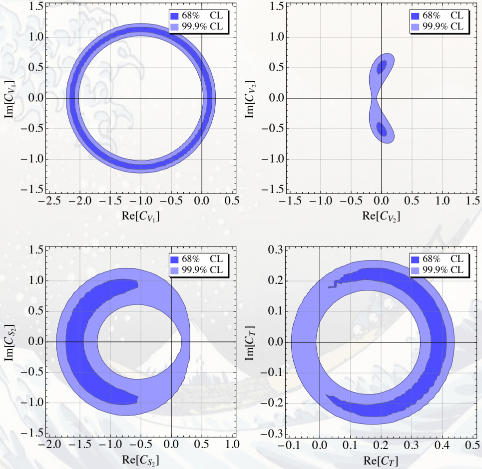
[Belle('15), arXiv:1507.03233]



[BABAR('14), arXiv:1303.0571]

Assuming the presence of only one NP type, do χ^2 fit of the *BABAR*+Belle+LHCb results on $R(D)\&R(D^*)$ and obtain the constraints on the NP Wilson coefficients.





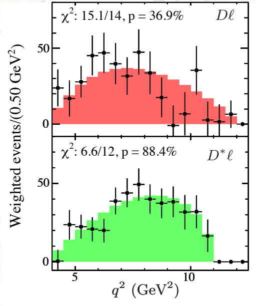
Average result [HFAG EPS 2015]

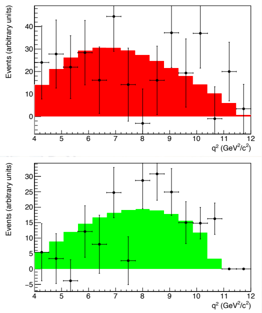
$$R(D) = 0.391 \pm 0.041 \pm 0.028$$
$$R(D^*) = 0.322 \pm 0.018 \pm 0.012$$

The difference with the SM predictions is at 3.9σ level.

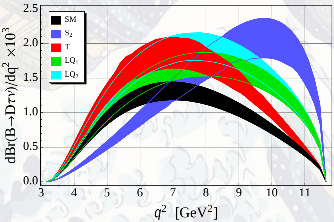
[updated plots from Sakaki,Tanaka,AT,Watanabe('14), arXiv:1412.3761]

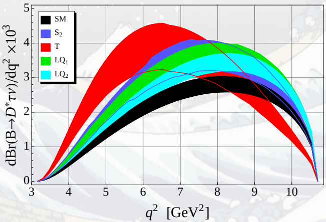
Exploring the q^2 dependence for the NP search





[BABAR('13), arXiv:1303.0571], [Belle('15), arXiv:1507.03233]





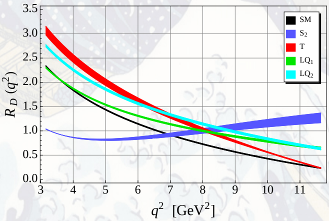
Exploring the q^2 dependence for the NP search : $R(q^2)$

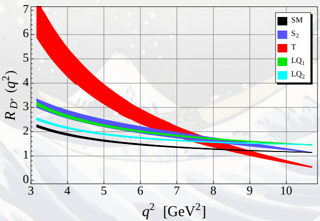
- To reduce the FF uncertainties, one can explore the q^2-dependent ratio

$$R_{D^{(*)}}(q^2) \equiv \frac{d\mathcal{B}(\overline{B} \to D^{(*)}\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D^{(*)}\ell\overline{\nu})/dq^2}$$

- For our convenience, to remove the divergence of R_D at $q^2 = (m_B - m_D)^2$ and the phase space suppression of $R_{D^{(*)}}$ at $q^2 \sim m_\tau^2$, we introduce

$$\boxed{\begin{aligned} R_D(q^2) &= \frac{d\mathcal{B}(\overline{B} \to D\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D\ell\overline{\nu})/dq^2} \times \frac{\lambda_D(q^2)}{(m_B^2 - m_D^2)^2} \times \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2} \\ R_{D^*}(q^2) &= \frac{d\mathcal{B}(\overline{B} \to D^*\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D^*\ell\overline{\nu})/dq^2} \times \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2} \end{aligned}}$$

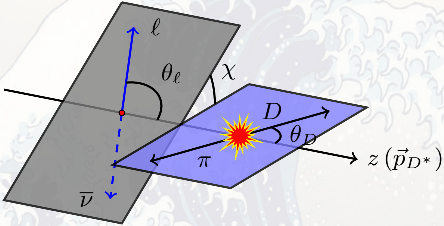


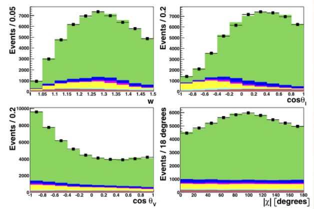


[Sakaki,Tanaka,AT,Watanabe('14), arXiv:arXiv:1412.3761]

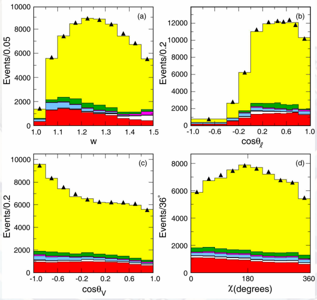
Angular distributions

Study full angular distributions and find quantities that are (a) sensitive to NP and (b) partially or completely complementary to $d\Gamma/dq^2$.





[Belle('10), arXiv:1010.5620]



[BABAR('08), arXiv:0705.4008]

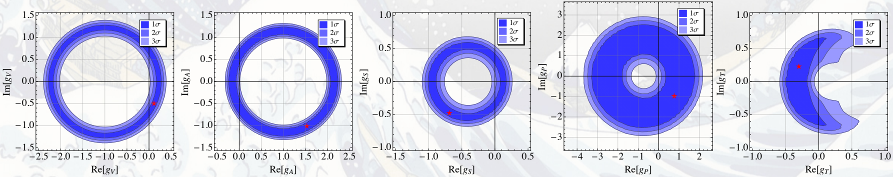
Belle and *BABAR* had already studied 4 **separate 1D** distributions in q^2, $\cos\theta_\ell$, $\cos\theta_D$ and χ of *light lepton mode* from which the hadronic FF$\times V_{cb}$ were extracted. However,

- Only SM contribution was assumed!
- $\Rightarrow$ Some terms were omitted, as in [Körner,Schuler('90), Z.Phys.C46].
- $\Rightarrow$ Redo the *full angular* analysis w/o assuming validity of the SM.

Using the operators of higher dimension, the process $b \to c\ell\overline{\nu}_\ell$ can be described by the general effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}\Big[(1 + g_V)\bar{c}\gamma_\mu b + (-1 + g_A)\bar{c}\gamma_\mu\gamma_5 b + g_S\, i\partial_\mu(\bar{c}b) + g_P\, i\partial_\mu(\bar{c}\gamma_5 b) + g_T\, i\partial_\nu(\bar{c}i\sigma_{\mu\nu}b) + g_{T5}\, i\partial_\nu(\bar{c}i\sigma_{\mu\nu}\gamma_5 b)\Big](\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell)$$

$$g_{V,A} \sim \mathcal{O}\left(\frac{v^2}{\Lambda_{\text{NP}}^2}\right), \quad g_{S,P,T,T5} \sim \frac{1}{v}\mathcal{O}\left(\frac{v^2}{\Lambda_{\text{NP}}^2}\right)$$



[Bečirević,Fajfer,Nišandžić,AT('16), arXiv:1602.03030]

Comment on the hadronic form factors

- Up to now all the exp analyses of $B \to D^{(*)}$ decays have been made by heavily relying on HQET which provides us with an extremely useful tool in understanding and simplifying the non-perturbative dynamics of QCD in the processes involving heavy-light mesons.
- Obviously, for a more viable th description one should use the FFs computed on the lattice.
- However, since the full set of FFs on the lattice is not available, and since the purpose of this work is to point out the usefulness of the observables in searching for the effects of NP, we will satisfy ourselves by the form factors, computed using use a relativistic dispersion approach based on the constituent quark model [Melikhov,Stech('00), arXiv:0001113].

$$\boxed{\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = a_{\theta_\ell}(q^2) + b_{\theta_\ell}(q^2)\cos\theta_\ell + c_{\theta_\ell}(q^2)\cos^2\theta_\ell}$$

$$a_{\theta_\ell}(q^2) = \frac{G_F^2|V_{cb}|^2}{256\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_D(q^2)} \left[|h_0(q^2)|^2 + \frac{m_\ell^2}{q^2}|h_t(q^2)|^2\right]$$

$$b_{\theta_\ell}(q^2) = -\frac{G_F^2|V_{cb}|^2}{128\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_D(q^2)} \frac{m_\ell^2}{q^2} \mathcal{R}e[h_0(q^2)h_t^*(q^2)]$$

$$c_{\theta_\ell}(q^2) = -\frac{G_F^2|V_{cb}|^2}{256\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_D(q^2)}\, |h_0(q^2)|^2$$

with the helicity amplitudes of $B \to DV^*$, defined as

$$h_0(q^2) = \tilde{\varepsilon}_0^{\mu *}\langle D|J_\mu|\overline{B}\rangle = \left[1 + g_V - g_T \frac{q^2}{m_B + m_D} \frac{f_T(q^2)}{f_+(q^2)}\right] \sqrt{\frac{\lambda_D(q^2)}{q^2}} f_+(q^2),$$

$$h_t(q^2) = \tilde{\varepsilon}_t^{\mu *}\langle D|J_\mu|\overline{B}\rangle = \left[1 + g_V + g_S \frac{q^2}{m_b - m_c}\right] \frac{m_B^2 - m_D^2}{\sqrt{q^2}} f_0(q^2).$$

$$\lambda_D(q^2) = m_B^4 + m_D^4 + q^4 - 2(m_B^2 q^2 + m_D^2 q^2 + m_B^2 m_D^2)$$

$B \to D\ell\overline{\nu}_\ell$: 2 asymmetries [known!]

Complementary info on NP (and almost independently from $d\Gamma/dq^2$) from:

- Lepton forward-backward asymmetry

$$\mathcal{A}_{\rm FB}(q^2) = \frac{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} d\cos\theta_\ell - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} d\cos\theta_\ell}{\int_{-1}^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} d\cos\theta_\ell} = \frac{b_{\theta_\ell}(q^2)}{d\Gamma/dq^2}$$

$$= -\frac{\frac{3}{2}\frac{m_\ell^2}{q^2}\mathcal{R}e[h_0(q^2)h_t^*(q^2)]}{|h_0(q^2)|^2\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}|h_t(q^2)|^2}$$

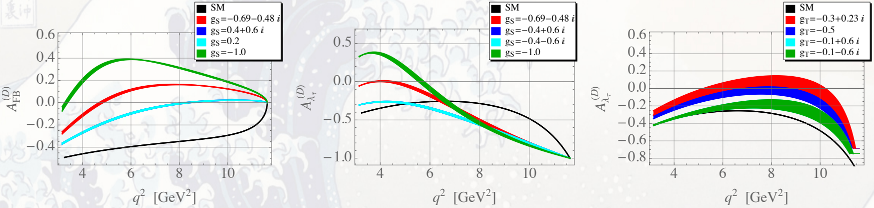
- Lepton spin asymmetry (lepton polarization asymmetry)

$$\mathcal{A}_{\lambda_\ell}(q^2) = \frac{d\Gamma/dq^2(\lambda_\ell=-1/2) - d\Gamma/dq^2(\lambda_\ell=1/2)}{d\Gamma/dq^2}$$

$$= 1 - \frac{\frac{m_\ell^2}{q^2}\left[|h_0(q^2)|^2+3|h_t(q^2)|^2\right]}{|h_0(q^2)|^2\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}|h_t(q^2)|^2}$$

$\mathcal{A}_{\rm FB}$ and $1-\mathcal{A}_{\lambda_\ell} \propto m_\ell^2 \Rightarrow$ are sensibly different from zero in the SM only in the case of τ in the final state.

$B \to D\ell\overline{\nu}_\ell$: 2 asymmetries



- $\mathcal{A}_{\rm FB}$ highly(weakly) depends on the value of $g_S(g_T)$ but is insensitive to its imaginary part, $\mathcal{I}m[g_S](\mathcal{I}m[g_T])$. Instead, it is completely insensitive to g_V.
- $\mathcal{A}_{\lambda_\tau}$ behaves similarly to $\mathcal{A}_{\rm FB}$ with respect to the variation of $g_{V,S,T}$, especially for the intermediate values of q^2.

The full angular distribution is given by

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_D d\chi} = \frac{3G_F^2|V_{cb}|^2}{256(2\pi)^4 m_B^3} q^2 \left(1-\frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{B}(D^* \to D\pi) \times \Bigg\{$$

$$[|H_+|^2 + |H_-|^2]\left(1+\cos^2\theta_\ell + \frac{m_\ell^2}{q^2}\sin^2\theta_\ell\right)\sin^2\theta_D + 2[|H_+|^2 - |H_-|^2]\cos\theta_\ell\sin^2\theta_D$$

$$+ 4|H_0|^2\left(\sin^2\theta_\ell + \frac{m_\ell^2}{q^2}\cos^2\theta_\ell\right)\cos^2\theta_D + 4|H_t|^2\frac{m_\ell^2}{q^2}\cos^2\theta_D$$

$$- 2\beta_\ell^2\left(\mathcal{R}e[H_+H_-^*]\cos 2\chi + \mathcal{I}m[H_+H_-^*]\sin 2\chi\right)\sin^2\theta_\ell\sin^2\theta_D$$

$$- \beta_\ell^2\left(\mathcal{R}e[H_+H_0^* + H_-H_0^*]\cos\chi + \mathcal{I}m[H_+H_0^* - H_-H_0^*]\sin\chi\right)\sin 2\theta_\ell\sin 2\theta_D$$

$$- 2\mathcal{R}e\left[H_+H_0^* - H_-H_0^* - \frac{m_\ell^2}{q^2}(H_+H_t^* + H_-H_t^*)\right]\cos\chi\sin\theta_\ell\sin 2\theta_D$$

$$- 2\mathcal{I}m\left[H_+H_0^* + H_-H_0^* - \frac{m_\ell^2}{q^2}(H_+H_t^* - H_-H_t^*)\right]\sin\chi\sin\theta_\ell\sin 2\theta_D$$

$$+ 8\mathcal{R}e[H_0H_t^*]\frac{m_\ell^2}{q^2}\cos\theta_\ell\cos^2\theta_D\Bigg\}, \quad \beta_\ell(q^2) = \sqrt{1-\frac{m_\ell^2}{q^2}}, \quad H(q^2) = \tilde{\varepsilon}^{\mu *}\langle D^*(\varepsilon)|J_\mu|\overline{B}\rangle$$

In the SM, the $\mathcal{I}m$-terms $= 0$ and therefore were omitted in the analyses of Belle and *BABAR*. But if there are NP complex phases, these terms could be important and interesting to study.

[Bečirević,Fajfer,Nišandžić,AT('16), arXiv:1602.03030]

The $B \to D^* V^*$ helicity amplitudes are defined as

$$H_\pm(q^2) = \tilde{\varepsilon}_\pm^{\mu *} \langle D^*(\varepsilon_\pm) | J_\mu | \overline{B} \rangle = i \Bigg\{ \pm \left[1 + g_V - g_T (m_B + m_{D^*}) \frac{T_1(q^2)}{V(q^2)} \right] \frac{\sqrt{\lambda_{D^*}(q^2)}}{m_B + m_{D^*}} V(q^2)$$
$$- \left[1 - g_A - g_{T5} (m_B - m_{D^*}) \frac{T_2(q^2)}{A_1(q^2)} \right] (m_B + m_{D^*}) A_1(q^2) \Bigg\}$$

$$H_0(q^2) = \tilde{\varepsilon}_0^{\mu *} \langle D^*(\varepsilon_0) | J_\mu | \overline{B} \rangle = -\frac{i}{2 m_{D^*} \sqrt{q^2}} \Bigg\{ \left[1 - g_A - g_{T5} (m_B - m_{D^*}) \frac{T_2(q^2)}{A_1(q^2)} \right]$$
$$\times (m_B + m_{D^*})(m_B^2 - m_{D^*}^2 - q^2) A_1(q^2)$$
$$- \left[1 - g_A - g_{T5} \left((m_B + m_{D^*}) \frac{T_2(q^2)}{A_2(q^2)} + \frac{q^2}{m_B - m_{D^*}} \frac{T_3(q^2)}{A_2(q^2)} \right) \right]$$
$$\times \frac{\lambda_{D^*}(q^2)}{m_B + m_{D^*}} A_2(q^2) \Bigg\}$$

$$H_t(q^2) = \tilde{\varepsilon}_t^{\mu *} \langle D^*(\varepsilon_0) | J_\mu | \overline{B} \rangle = -i \left[1 - g_A + g_P \frac{q^2}{m_b + m_c} \right] \sqrt{\frac{\lambda_{D^*}(q^2)}{q^2}} A_0(q^2)$$

$B \to D^* \ell \overline{\nu}_\ell$: θ_ℓ distribution

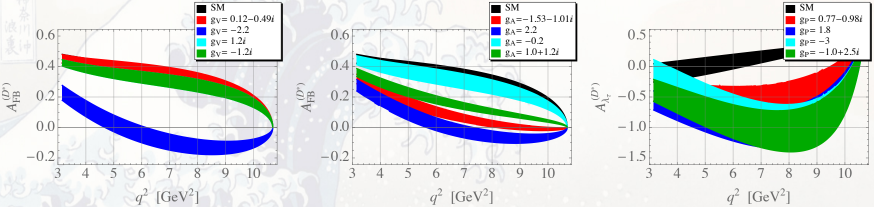
$$\boxed{\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = a_{\theta_\ell}(q^2) + b_{\theta_\ell}(q^2)\cos\theta_\ell + c_{\theta_\ell}(q^2)\cos^2\theta_\ell}$$

$$a_{\theta_\ell}(q^2) = \frac{G_F^2 |V_{cb}|^2}{512\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_{D^*}(q^2)} \times$$
$$\left\{ [|H_+|^2 + |H_-|^2] \left(1 + \frac{m_\ell^2}{q^2}\right) + 2|H_0|^2 + 2\frac{m_\ell^2}{q^2}|H_t|^2 \right\}$$

$$b_{\theta_\ell}(q^2) = \frac{G_F^2 |V_{cb}|^2}{256\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_{D^*}(q^2)} \times$$
$$\left\{ |H_+|^2 - |H_-|^2 + 2\frac{m_\ell^2}{q^2} \mathcal{R}e[H_0 H_t^*] \right\}$$

$$c_{\theta_\ell}(q^2) = \frac{G_F^2 |V_{cb}|^2}{512\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \left\{ |H_+|^2 + |H_-|^2 - 2|H_0|^2 \right\}$$

$$\mathcal{A}_{\mathrm{FB}}(q^2) = \frac{b_{\theta_\ell}(q^2)}{d\Gamma/dq^2}$$



- $\mathcal{A}_{\rm FB}$ depends on the sign of $\mathcal{R}e[g_V]$, but its deviation from the SM is more pronounced in the case of $g_{A,P,T}$. However, if one observes a deviation with respect to the SM value, one cannot tell which $g_{A,P} \neq 0$ from this quantity alone. Variation of $g_T \neq 0$, instead, results in smaller departures of this quantity from the SM.
- $\mathcal{A}_{\lambda_\tau}$ does not depend on $g_{V,A} \neq 0$, but its shape can change in the case of $g_{P,T} \neq 0$. It does not depend on the size of the imaginary part in g_i.

$B \to D^*\ell\overline{\nu}_\ell$: θ_D distribution

$$\boxed{\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + b_{\theta_D}(q^2)\cos\theta_D + c_{\theta_D}(q^2)\cos^2\theta_D}$$

$$a_{\theta_D}(q^2) = \frac{G_F^2|V_{cb}|^2|\boldsymbol{q}|q^2}{128\pi^3 m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \times \left[(|H_+|^2+|H_-|^2)\left(1+\frac{m_\ell^2}{2q^2}\right)\right]$$

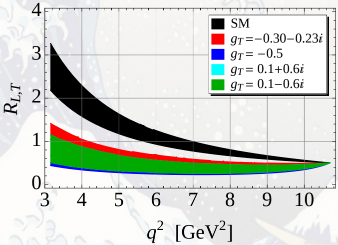
$$c_{\theta_D}(q^2) = -\frac{G_F^2|V_{cb}|^2|\boldsymbol{q}|q^2}{128\pi^3 m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \times \left[(|H_+|^2+|H_-|^2-2|H_0|^2)\left(1+\frac{m_\ell^2}{2q^2}\right) - 3\frac{m_\ell^2}{q^2}|H_t|^2\right]$$

- $b_{\theta_D}(q^2) = 0$ unless there is interference with $(D\pi)_S$ amplitude.
- $\Rightarrow$ if experimentally feasible, $\mathcal{A}_{\mathrm{FB}}^{\theta_D}$ ($\propto b_{\theta_D}$) could be a good way to address this issue which is one of the major worries in assessing the systematic uncertainties of the experimental results.
- $B \to D_0^*(\to D\pi)\ell\overline{\nu}_\ell$ can be mistakenly identified as an S-wave contribution in the range around D^*. Assuming both D^* and D_0^* can be described by the BW formula, we found that this pollution is negligibly small.

Splitting the decay rate according to the polarization of D^* amounts to

$$\frac{d\Gamma_L}{dq^2} = \frac{2}{3}\left[a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\right], \quad \frac{d\Gamma_T}{dq^2} = \frac{4}{3}a_{\theta_D}(q^2)$$

$$\boxed{R_{L,T} = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2} = \frac{|H_0|^2 + 3|H_t|^2\left[1 - 1/(1 + m_\ell^2/2q^2)\right]}{|H_+|^2 + |H_-|^2}}$$



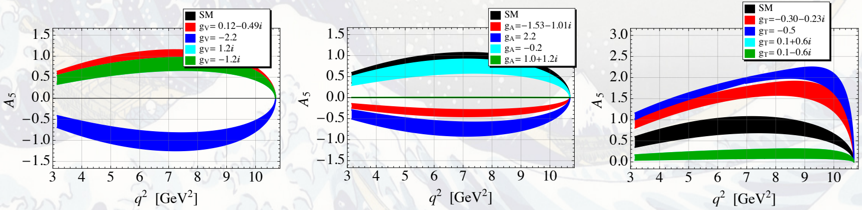
- $R_{L,T}$ too depends on the variation of $\mathcal{R}e[g_{P,T}] \neq 0$, but is insensitive to $g_{V,A} \neq 0$. It is particularly sensitive to $g_T \neq 0$ so that its value falls from the SM (~ 3) to about ~ 1 at $q^2 = m_\tau^2$.

$\mathcal{A}_{\rm FB}$, $\mathcal{A}_{\lambda_\ell}$ and $R_{L,T}$ involve $|H_{\pm,0,t}|^2$. Integrating over χ, we can build the fourth observable as follows :

$$\Phi(q^2,\theta_D) = \int_{-1}^{0} \frac{d^3\Gamma}{dq^2\, d\cos\theta_D\, d\cos\theta_\ell}\, d\cos\theta_\ell - \int_{0}^{1} \frac{d^3\Gamma}{dq^2\, d\cos\theta_D\, d\cos\theta_\ell}\, d\cos\theta_\ell$$

$$A_5(q^2) = \frac{\left[7\int_{-1/2}^{1/2} - \int_{1/2}^{1} - \int_{-1}^{-1/2}\right] \Phi(q^2,\theta_D)\; d\cos\theta_D}{d\Gamma/dq^2}$$

$$= -\frac{9G_F^2|V_{cb}|^2|\mathbf{q}|q^2}{256\pi^3 m_B^2 (d\Gamma/dq^2)} \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[|H_+|^2 - |H_-|^2\right]$$



A_5 depends on the sign of $\mathcal{R}e[g_V]$, it significantly changes with $\mathcal{R}e[g_A]$, only weakly depends on $\mathcal{R}e[g_P]$ and it is quite sensitive to $\mathcal{R}e[g_T]$.

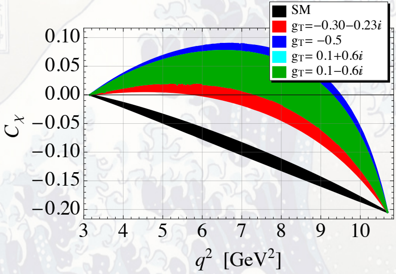
$$\boxed{\frac{d^2\Gamma}{dq^2 d\chi} = a_\chi(q^2) + b^c_\chi(q^2)\cos\chi + b^s_\chi(q^2)\sin\chi + c^c_\chi(q^2)\cos 2\chi + c^s_\chi(q^2)\sin 2\chi}$$

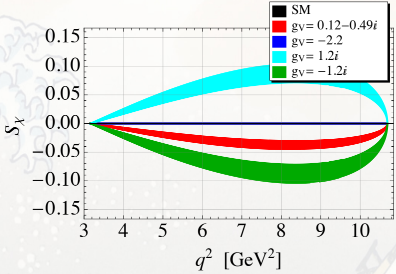
$$\begin{aligned} a_\chi(q^2) = & \frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_{D^*}(q^2)} \times \\ & \left\{ \left[|H_+|^2 + |H_-|^2 + |H_0|^2\right] \left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2 \right\} \\ c^c_\chi(q^2) = & - \frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{Re}\left[H_+ H_-^*\right] \\ c^s_\chi(q^2) = & - \frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{Im}\left[H_+ H_-^*\right] \end{aligned}$$

- $b^{c,s}_\chi(q^2) = 0$ unless there is interference with $(D\pi)_S$ amplitude [interesting!]
- $c^s_\chi(q^2) = 0$ in the SM $\Rightarrow c^s_\chi(q^2) \neq 0$ would be a clear signal of NP!!!
- Two NP-sensitive observables:

$$C_\chi(q^2) = \frac{c^c_\chi(q^2)}{a_\chi(q^2)}, \qquad S_\chi(q^2) = \frac{c^s_\chi(q^2)}{a_\chi(q^2)}.$$

#6,7 : C_χ and S_χ





- C_χ only weakly depends on g_V, and is independent on g_A. Instead its linear dependence in the SM is modified to an arc-like behaviour in q^2 for $g_{P,T} \neq 0$.
- S_χ is very sensitive to $\mathcal{I}m[g_{V,A,T}]$ and is independent on g_P. It is a null-test of the SM because $S_\chi \neq 0$ would represent a clear signal of NP.

First integrate the full distribution in θ_ℓ and then define

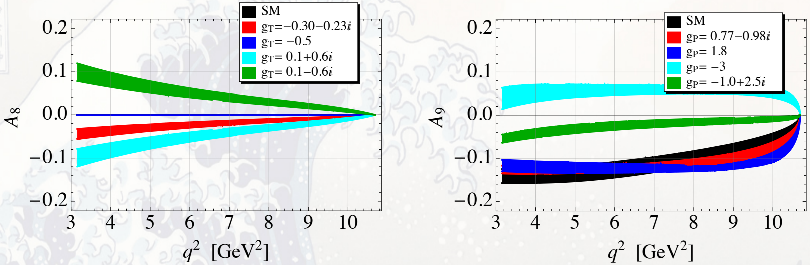
$$\widetilde{\Phi}(q^2,\chi) = \int_{-1}^{0} \frac{d^3\Gamma}{dq^2 d\chi d\cos\theta_D} d\cos\theta_D - \int_{0}^{1} \frac{d^3\Gamma}{dq^2 d\chi d\cos\theta_D} d\cos\theta_D$$

$$A_8(q^2) = \frac{\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] \widetilde{\Phi}(q^2,\chi)\ d\chi}{d\Gamma/dq^2}$$

$$= \frac{G_F^2 |V_{cb}|^2 |\boldsymbol{q}| q^2}{128\pi^3 m_B^2} \frac{\left(1 - m_\ell^2/q^2\right)^2}{d\Gamma/dq^2} \mathcal{I}m\left[(H_+ + H_-)H_0^* - \frac{m_\ell^2}{q^2}\left(H_+ - H_-\right)H_t^*\right]$$

$$A_9(q^2) = -\frac{\left[\int_{\pi/2}^{3\pi/2} - \int_0^{\pi/2} - \int_{3\pi/2}^{2\pi}\right] \widetilde{\Phi}(q^2,\chi)\ d\chi}{d\Gamma/dq^2}$$

$$= \frac{G_F^2 |V_{cb}|^2 |\boldsymbol{q}| q^2}{128\pi^3 m_B^2} \frac{\left(1 - m_\ell^2/q^2\right)^2}{d\Gamma/dq^2} \mathcal{R}e\left[(H_+ - H_-)H_0^* - \frac{m_\ell^2}{q^2}\left(H_+ + H_-\right)H_t^*\right]$$



- A_8 is also sensitive to the imaginary part of the couplings, $\mathcal{I}m[g_{V,A,P,T}]$ so that a measurement of its non-zero value would be a signal of a NP phase. The deviations with respect to the SM, are particularly pronounced in the case of $\mathcal{I}m[g_T] \neq 0$.
- A_9 depends on the real part of $g_{V,P,T}$ and only mildly on g_A. A_9 only slightly varies with q^2 and its value can significantly change for $\mathcal{R}e[g_P] < 0$.

By forming

$$\phi(q^2,\chi,\theta_\ell) = \int_{-1}^{0} \frac{d^4\Gamma}{dq^2 d\chi d\cos\theta_\ell d\cos\theta_D} d\cos\theta_D - \int_{0}^{1} \frac{d^4\Gamma}{dq^2 d\chi d\cos\theta_\ell d\cos\theta_D} d\cos\theta_D$$

$$\widetilde{\phi}(q^2,\chi) = \int_{-1}^{0} \phi(q^2,\chi,\theta_\ell) d\cos\theta_\ell - \int_{0}^{1} \phi(q^2,\chi,\theta_\ell) d\cos\theta_\ell$$

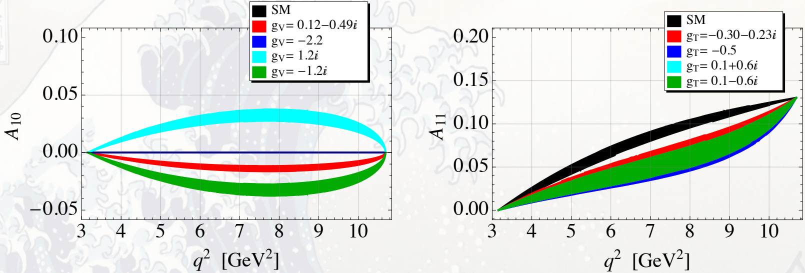
we can isolate the remaining two terms from the full angular distribution as

$$A_{10}(q^2) = \frac{\left[\int_0^\pi - \int_\pi^{2\pi}\right] \widetilde{\phi}(q^2,\chi) d\chi}{d\Gamma/dq^2}$$

$$= -\frac{G_F^2 |V_{cb}|^2 |\boldsymbol{q}| q^2}{96\pi^4 m_B^2} \frac{\left(1 - m_\ell^2/q^2\right)^3}{d\Gamma/dq^2} \mathcal{I}m[(H_+ - H_-)H_0^*]$$

$$A_{11}(q^2) = \left[\int_{\pi/2}^{3\pi/2} - \int_{0}^{\pi/2} - \int_{3\pi/2}^{2\pi}\right] \widetilde{\phi}(q^2,\chi) d\chi \Gamma/dq^2$$

$$= \frac{G_F^2 |V_{cb}|^2 |\boldsymbol{q}| q^2}{96\pi^4 m_B^2} \frac{\left(1 - m_\ell^2/q^2\right)^3}{d\Gamma/dq^2} \mathcal{R}e[(H_+ + H_-)H_0^*]$$



- A_{10}, just like S_χ and A_8, is sensitive to the imaginary part of $g_{V,A,T}$, while it is independent on g_P. Note that even for large (allowed) $\mathcal{I}m[g_{V,P,T}]$ this asymmetry is small, i.e. never larger than 7%.
- The shape of A_{11} changes for $\mathcal{R}e[g_{P,T}] \neq 0$, but it is insensitive to $g_{V,A} \neq 0$. Its deviation from the SM can be probed at large q^2.

What can be extracted from the proposed observables

$d\Gamma/dq^2$	$\left[\lvert H_+\rvert^2+\lvert H_-\rvert^2+\lvert H_0\rvert^2\right]\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}\lvert H_t\rvert^2$	
$1-\mathcal{A}_{\lambda_\ell}$	$\lvert H_+\rvert^2+\lvert H_-\rvert^2+\lvert H_0\rvert^2+3\lvert H_t\rvert^2$	
$\mathcal{A}_{\rm FB}$	$\lvert H_+\rvert^2-\lvert H_-\rvert^2+2\frac{m_\ell^2}{q^2}\mathcal{R}e\left[H_0H_t^*\right]$	
$R_{L,T}$	$\lvert H_+\rvert^2+\lvert H_-\rvert^2$	
A_5	$\lvert H_+\rvert^2-\lvert H_-\rvert^2$	
C_χ	$\mathcal{R}e\left[H_+H_-^*\right]$	
S_χ	$\mathcal{I}m\left[H_+H_-^*\right]$	(=0 in the SM)
A_8	$\mathcal{I}m\left[(H_++H_-)H_0^*-\frac{m_\ell^2}{q^2}(H_+-H_-)H_t^*\right]$	(=0 in the SM)
A_9	$\mathcal{R}e\left[(H_+-H_-)H_0^*-\frac{m_\ell^2}{q^2}(H_++H_-)H_t^*\right]$	
A_{10}	$\mathcal{I}m\left[(H_+-H_-)H_0^*\right]$	(=0 in the SM)
A_{11}	$\mathcal{R}e\left[(H_++H_-)H_0^*\right]$	

Sensitivity to $g_i \neq 0$

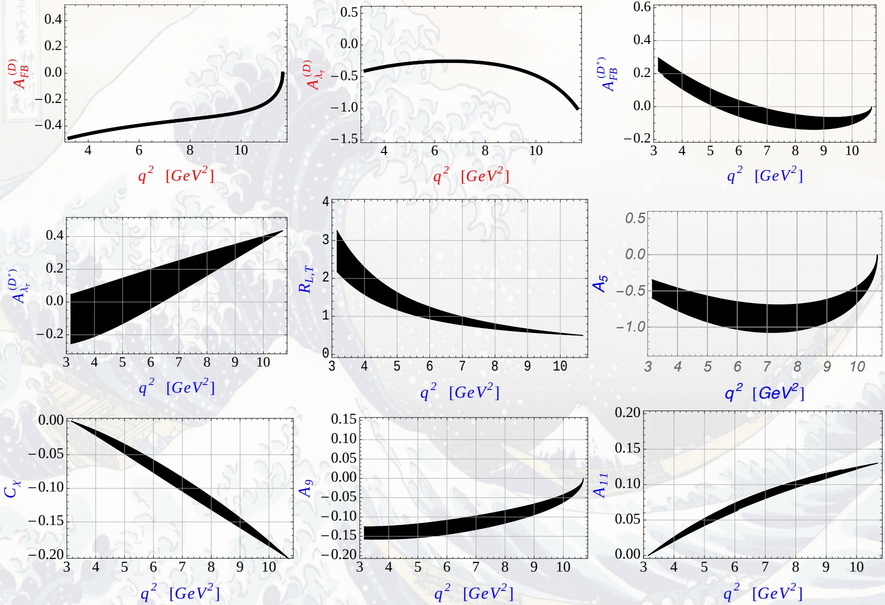
$\times$ stands for "not sensitive", and $\star\star\star$ for "maximally sensitive".

Quantity	g_V	g_A	g_S	g_P	g_T
$\mathcal{A}_{FB}^{D}$	$\times$	–	$\star\star\star$	–	$\star$
$\mathcal{A}_{\lambda_\tau}^{D}$	$\times$	–	$\star\star\star$	–	$\star\star$
$\mathcal{A}_{FB}^{D^*}$	$\star$	$\star\star\star$	–	$\star\star\star$	$\star$
$\mathcal{A}_{\lambda_\tau}^{D^*}$	$\times$	$\times$	–	$\star\star$	$\star$
$R_{L,T}$	$\times$	$\times$	–	$\star\star$	$\star\star$
A_5	$\star\star$	$\star\star$	–	$\star$	$\star\star\star$
C_χ	$\star$	$\times$	–	$\star\star$	$\star\star$
S_χ	$\star\star\star$	$\star\star\star$	–	$\times$	$\star\star\star$
A_8	$\star\star$	$\star\star$	–	$\star\star$	$\star\star\star$
A_9	$\star$	$\star$	–	$\star\star$	$\star\star$
A_{10}	$\star\star$	$\star\star$	–	$\times$	$\star\star$
A_{11}	$\times$	$\times$	–	$\star\star$	$\star\star$

1. Apart from the differential decay widths, we constructed 2(10) observables when considering the decay to a pseudoscalar(vector) meson.
2. The resulting observables can be used for searching the effects of physics BSM.
3. In particular, 3 observables (S_χ, A_8 and A_{10}) are sensitive to the NP phase(s). A non-zero measurement of these quantities would be a clear signal of NP.
4. Other quantities can be used to disentangle the Lorentz structure of the NP contributions (V, A, S, P or T) and perhaps to deduce its size if we had a clean QCD information about the relevant hadronic FFs.
5. If experimentally feasible, the measurement of the terms $\propto \sin\chi$ and/or $\propto \cos\chi$ would be a good way to address the issue of the $(D\pi)_{S-\text{wave}}$ polution.
6. The discussion is equally applicable to all the other various semileptonic pseudoscalar $\to$ pseudoscalar/vector decays, namely $D/B \to \pi\ell\overline{\nu}$, $D/B \to \rho\ell\overline{\nu}$, $D_{(s)} \to K^{(*)}\ell\overline{\nu}$, $B_s \to K^{(*)}\ell\overline{\nu}$, $D_s \to \phi\ell\overline{\nu}$, $K \to \pi\ell\overline{\nu}$, $B_c \to J/\psi\ell\overline{\nu}$, $B_c \to \eta_c\ell\overline{\nu}$, $B_c \to B_{d,s}\ell\overline{\nu}$, or the semileptonic B_s-meson decays.

BACKUP SLIDES

Theory estimates of the observables in the SM



NP in azimuthal observables and CPV triple products

The full angular analysis of $B \to D^* \tau \bar{\nu}$ has been also done in [Duraisamy,Datta('13), arXiv:1302.7031], [Duraisamy et al.('14), arXiv:1405.3719].

Some of the conclusions from arXiv:1405.3719, 1405.3719

- 2 of 3 CPV triple products are only sensitive to vector/axial vector NP and do not depend on pseudoscalar NP.
- One can use the triple products to search even in e and μ modes.
- Azimuthal asymmetries, integrated over q^2, have different sensitivities to different NP structures hence becoming powerful probes of the nature of NP.
- In particular, these observables turn out to be very efficient in discriminating between the two leptoquark models.