Looking for New Physics through semileptonic decays

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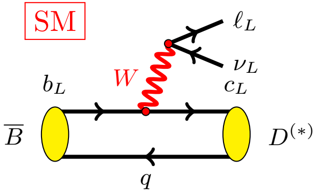
[1]For several administrative difficulties Andrey could not come to Stockholm for EPS-HEP.

Outline



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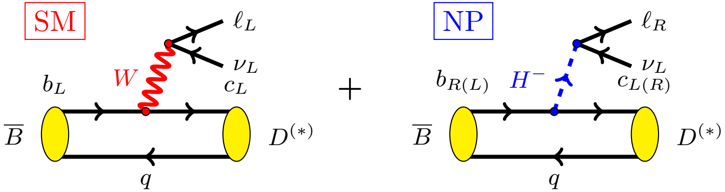

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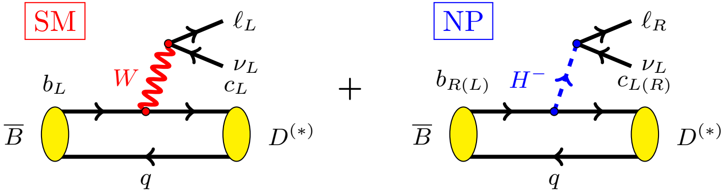

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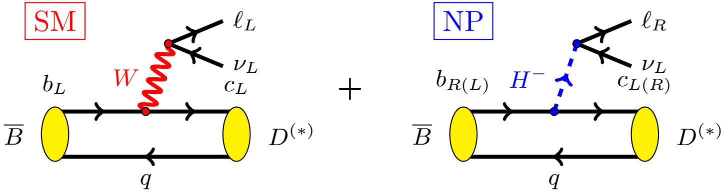

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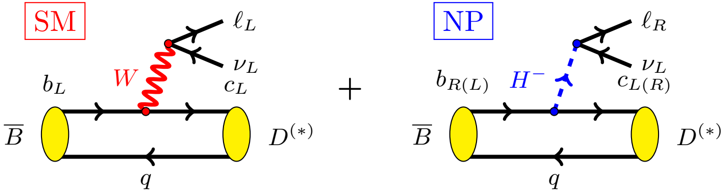

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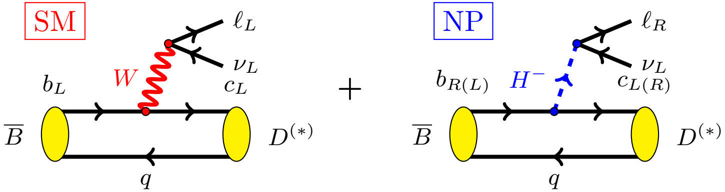

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- B-decays with τ in the final state offer possibilities to study NP effects not present in processes with light leptons.
- Popular NP test via

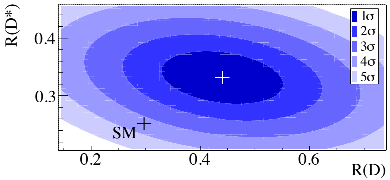
$$R(D) = \frac{\mathcal{B}(B \to D\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D\ell\overline{\nu}_\ell)}, \quad R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^*\ell\overline{\nu}_\ell)} \quad (\ell = e, \mu)$$

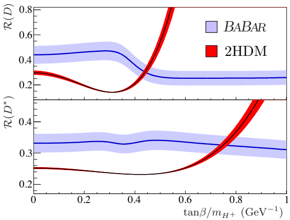
in order to cancel/reduce theoretical uncertainties in V_{cb}/FF.

BaBar results [BaBar('12), arXiv:1205.5442],

$$R(D)^{\exp} = 0.440 \pm 0.058 \pm 0.042\,, \quad R(D)^{\rm SM} = 0.31 \pm 0.02\,,$$
$$R(D^*)^{\exp} = 0.332 \pm 0.024 \pm 0.018\,, \quad R(D^*)^{\rm SM} = 0.252 \pm 0.003(??)\,,$$

larger than the SM expectations. NP?



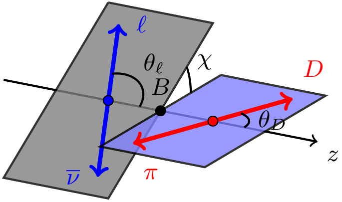


This excess cannot be explained by a charged Higgs in 2HDM-II (charged Higgs is excluded at 99.8% CL) $\Rightarrow$ 2HDM-III, $\not R$ MSSM, leptoquarks, ..?

[Fajfer et al.('12), arXiv:1203.2654, arXiv:1206.1872] , [Crivellin et al.('12), arXiv:1206.2634], [D.B., Kosnik, Tayduganov ('12), arXiv:1206.4977], [Bailey et al.('12), arXiv:1206.4992], [Tanaka,Watanabe('12), arXiv:1212.1878], [Ko et al.('12), arXiv:1212.4607], [Celis et al.('13), arXiv:1302.5992, arXiv:1210.8443], [Biancofiore('13), arXiv:1302.1042], [Duraisamy,Datta('13), arXiv:1302.7031], [Doršner et al. ('13), arXiv:1306.6493]

Our goal

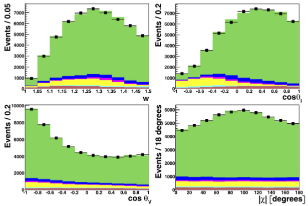
Study full angular distributions and find quantities that (a) are sensitive to NP and (b) are partially or completely complementary to $d\Gamma/dq^2$.



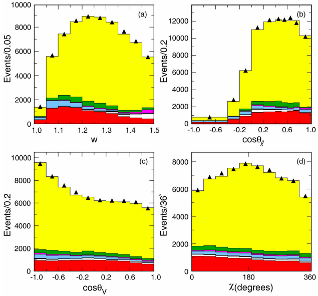
Belle and BaBar already studied 4 **separate 1D** distributions [in q^2, in $\cos\theta_\ell$, in $\cos\theta_D$ and in χ] from which they extracted FF's $\times V_{cb}$. However,

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

[Belle('10), arXiv:1010.5620]



[BaBar('08), arXiv:0705.4008]



Here "Model independent" includes following assumptions:

- No right-handed neutrino; charged lepton current remains left handed.
- $V - A$ structure of the lepton current is well established and we keep it as such:

$$L^\mu = \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell$$

- $b \to c\ell\overline{\nu}_\ell$ can then be described by a general effective Hamiltonian:

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

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

NB: the pseudotensor operator is not independent of the tensor one due to the relation $\bar{c}\sigma_{\mu\nu}\gamma_5 b = -\frac{i}{2}\epsilon_{\mu\nu\alpha\beta}\bar{c}\sigma^{\alpha\beta}b$, but it is convenient to keep this operator.

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

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

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

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

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

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

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

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

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

- Lepton forward-backward asymmetry

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

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

- Lepton spin asymmetry (lepton polarization asymmetry)

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

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

$B \to D^*(\to D\pi)\ell\overline{\nu}_\ell$: full angular distribution

The full angular distribution is given by

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

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

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

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

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

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

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

$$+8\mathcal{R}e[H_0H_t^*]\frac{m_\ell^2}{q^2}\cos\theta_\ell\cos^2\theta_D\Bigg\}, \qquad \beta_\ell(q^2)=\sqrt{1-\frac{m_\ell^2}{q^2}}$$

$\mathcal{I}m$-terms $=0$ in the SM and were omitted in the analyses by Belle and BaBar.
If there are NP phases, these terms could be important.

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

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

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

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

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

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

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

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

$B \to D^*(\to D\pi)\ell\overline{\nu}_\ell$: angular distributions

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

$$a_\chi(q^2) = \frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1-\frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_{D^*}(q^2)} \times \left\{ [|H_+|^2+|H_-|^2+|H_0|^2]\left(1+\frac{m_\ell^2}{2q^2}\right) + \frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2 \right\}$$

$$c^c_\chi(q^2) = -\frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1-\frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{R}e\,[H_+ H_-^*]$$

$$c^s_\chi(q^2) = -\frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1-\frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{I}m\,[H_+ H_-^*]$$

- $b^{c,s}_\chi(q^2) = 0$ unless there is interference with $(D\pi)_S$ amplitude [interesting!!!]
- term $\propto \sin 2\chi$ is CP violating.
- $c^s_\chi(q^2) = 0$ in SM $\Rightarrow c^s_\chi(q^2) \neq 0$ would be a clear signal of NP!

$B \to D^*(\to D\pi)\ell\overline{\nu}_\ell$: angular distributions

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

$$a_\chi(q^2) = \frac{G_F^2 |V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_{D^*}(q^2)} \times \left\{ [|H_+|^2 + |H_-|^2 + |H_0|^2]\left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2 \right\}$$

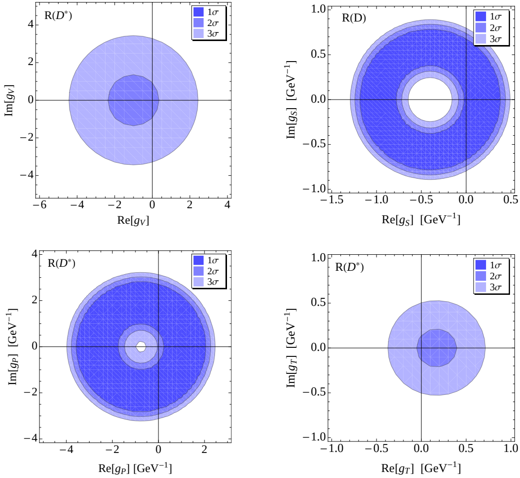
$$c_\chi^c(q^2) = -\frac{G_F^2 |V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{R}e\,[H_+ H_-^*]$$

$$c_\chi^s(q^2) = -\frac{G_F^2 |V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{I}m\,[H_+ H_-^*]$$

- $b_\chi^{c,s}(q^2) = 0$ unless there is interference with $(D\pi)_S$ amplitude [interesting!!!]
- Two NEW NP-sensitive observables:

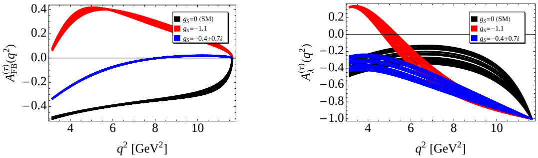
$$C_\chi^{(\ell)}(q^2) = \frac{c_\chi^c(q^2)}{a_\chi(q^2)}, \qquad S_\chi^{(\ell)}(q^2) = \frac{c_\chi^s(q^2)}{a_\chi(q^2)}.$$

NP couplings constraints from $R(D)$ & $R(D^*)$

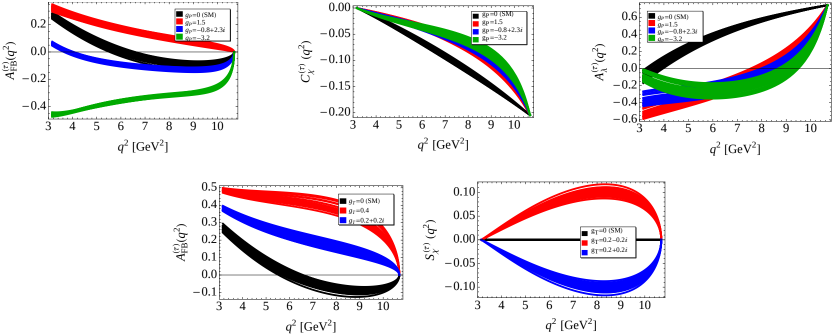


$R(D)[\ R(D^*)]$ insensitive to $g_V\ [\ g_A]$

$B \to D\tau\bar{\nu}_\tau$



$B \to D^*\tau\bar{\nu}_\tau$



Sensitivity summary

$B \to D\ell\overline{\nu}_\ell$

observable	g_V	g_S	g_T
$\mathcal{B}^{(\mu)}$	⋆⋆	–	⋆⋆
$\mathcal{B}^{(\tau)}$	⋆	⋆⋆⋆	⋆
$R(D)$	–	⋆⋆⋆	–
$\mathcal{A}_{FB}^{(\mu)}$	–	⋆	–
$\mathcal{A}_{FB}^{(\tau)}$	–	⋆⋆⋆	–
$\mathcal{A}_{\lambda}^{(\tau)}$	–	⋆⋆	–

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

observable	g_V	g_A	g_P	g_T
$\mathcal{B}^{(\mu)}$	⋆	⋆⋆	–	⋆⋆⋆⋆
$\mathcal{B}^{(\tau)}$	–	⋆	⋆	⋆⋆⋆
$R(D^*)$	⋆	–	⋆	⋆⋆
$\mathcal{A}_{FB}^{(\mu)}$	⋆⋆⋆	⋆⋆⋆	–	⋆⋆⋆
$\mathcal{A}_{FB}^{(\tau)}$	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆
$\mathcal{A}_{\lambda}^{(\tau)}$	–	–	⋆⋆⋆	–
$C_{\chi}^{(\mu)}$	–	–	–	⋆
$C_{\chi}^{(\tau)}$	–	–	⋆⋆	⋆
$S_{\chi}^{(\mu)}$	⋆⋆⋆	⋆⋆⋆	–	⋆⋆⋆
$S_{\chi}^{(\tau)}$	⋆⋆⋆	⋆⋆⋆	–	⋆⋆⋆⋆

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2. Excess in $B \to D\tau\overline{\nu}_\tau$ and $B \to D^*\tau\overline{\nu}_\tau$ found by BaBar helped discarding 2HDM-II [Could Belle, LHCb measure these decay modes too?]
3. Here we showed the effects of $\mathcal{B}(B \to D^{(*)}\ell\overline{\nu}_\ell)$ on NP couplings using the operators of higher dimension.

Conclusions

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2. Excess in $B \to D\tau\overline{\nu}_\tau$ and $B \to D^*\tau\overline{\nu}_\tau$ found by BaBar helped discarding 2HDM-II [Could Belle, LHCb measure these decay modes too?]
3. Here we showed the effects of $\mathcal{B}(B \to D^{(*)}\ell\overline{\nu}_\ell)$ on NP couplings using the operators of higher dimension.
4. Tree-level decays, such as $B \to D^{(*)}\ell\overline{\nu}_\ell$, could be studied better. (Partial) Branching fractions are good for CKM-ology. We are in the post-CKM era and a full angular analysis opens more opportunities to look for presence of NP.

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5. We computed the full angular distributions of the processes with either the pseudoscalar or vector meson in the final state by including the terms not discussed in the literature so far. We introduced 2 new observables that are (i) very sensitive to NP, (ii) are not plagued by large hadronic uncertainties, and (iii) experimentally accessible.

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6. More detail in our paper on hep-ph arXiv – in a couple of weeks time.