Lepton Flavour Universality tests in the angular analysis of $B \to D^{(*)}\ell\nu$

M. Fedele

based on arXiv:1810.xxxxx in collaboration with:

D.Bečirević, G.Hiller, I.Nišandžić, & A.Tayduganov

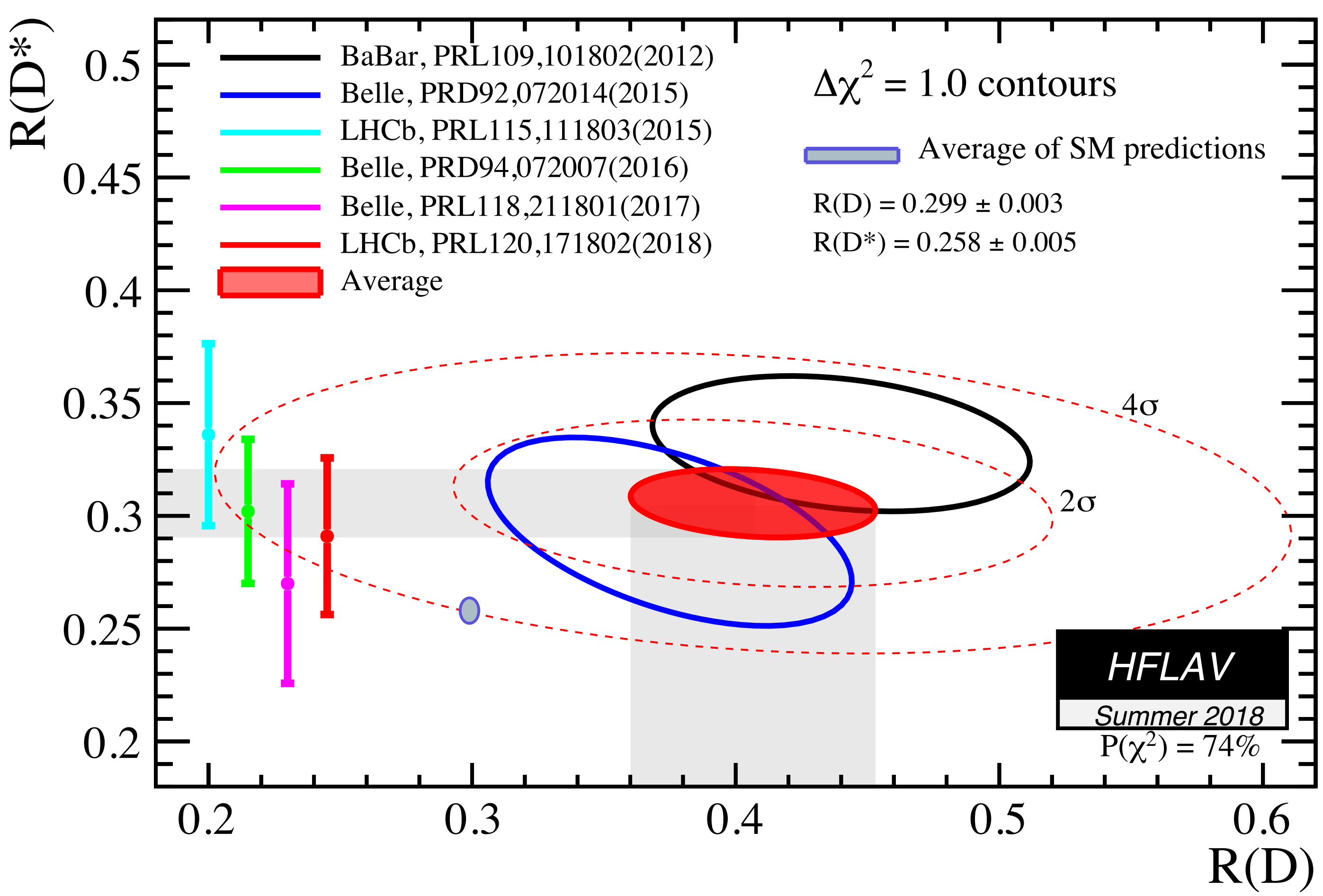
UNIVERSITAT DE BARCELONA

17-19 October 2018

Introduction

- Tree level processes with large Br (~ few %)
- Theoretically cleaner (w.r.t FCNC b→s transitions)
- Sensitive to NP via LFUV tests

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



Experimental average (HFLAV):

$$R(D) = 0.407 \pm 0.039 \pm 0.024$$
$$R(D^*) = 0.306 \pm 0.013 \pm 0.007$$

SM predictions:

$$R(D) = 0.300 \pm 0.008$$
$$R(D^*) = 0.256 \pm 0.003$$

Comb. discrepancy at 3.8σ level

Assumptions of my talk

- I will assume NP effects affecting only the τ channel, with SM behaviour assumed for the e and μ channel, using an effective Hamiltonian

- I will study the effects obtained considering only one NP WC at a time

- I will assume complex values for all WC

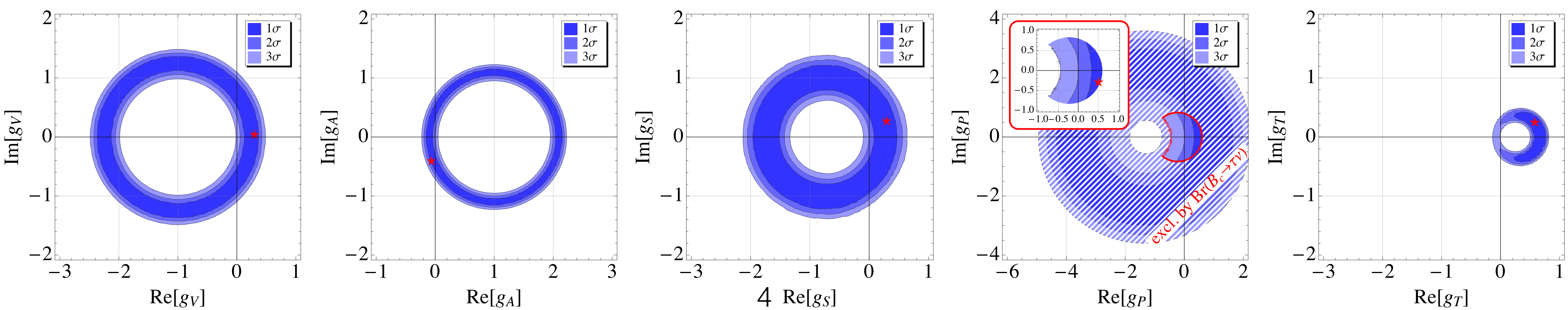
NP analysis

It is possible to describe the process b→cℓν by means of the effective Hamiltonian

$$\mathcal{H}_{\rm eff} = \sqrt{2} G_F V_{cb} \Big\{ \Big[(1 + g_V)\, \bar{c}\gamma_\mu b + (-1 + g_A)\, \bar{c}\gamma_\mu\gamma_5 b \Big] \bar{\ell}_L \gamma^\mu \nu_L + \Big[g_S\, \bar{c} b + g_P\, \bar{c}\gamma_5 b \Big] \bar{\ell}_R \nu_L + \Big[g_T\, \bar{c}\sigma_{\mu\nu} b + g_{T5}\, \bar{c}\sigma_{\mu\nu}\gamma_5 b \Big] \bar{\ell}_R \sigma^{\mu\nu} \nu_L \Big\} + \text{h.c.}$$

Only left-handed neutrinos!

$$g_i \sim \mathcal{O}\left(\frac{v^2}{\Lambda_{\rm NP}^2}\right), \qquad g_i^{(\rm SM)} = 0$$



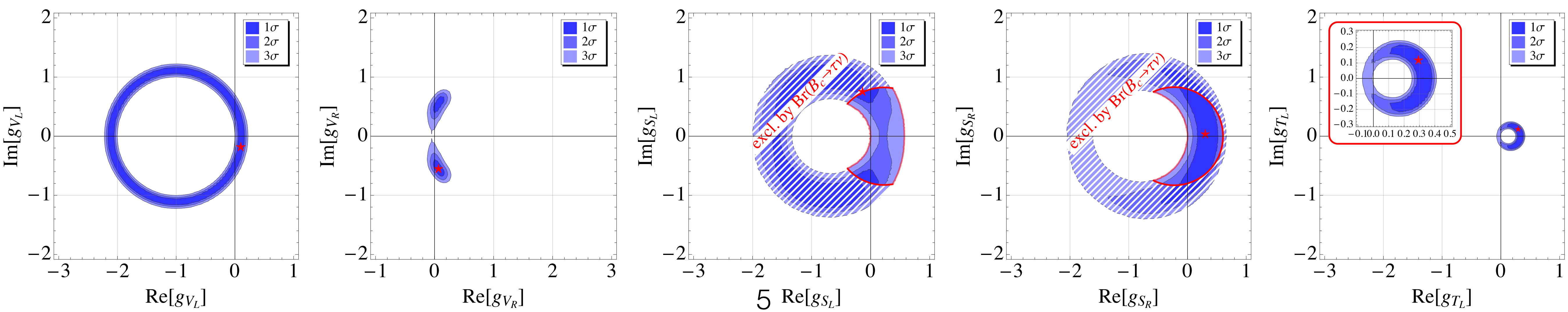
NP analysis - chiral basis

Alternatively, it is possible to use the effective chiral Hamiltonian

$$\mathcal{H}_{\rm eff} = \sqrt{2} G_F V_{cb} \Big\{ \Big[(1 + g_{V_L})\, \bar{c}_L \gamma_\mu b_L + g_{V_R}\, \bar{c}_R \gamma_\mu b_R \Big] \bar{\ell}_L \gamma^\mu \nu_L + \Big[g_{S_L}\, \bar{c}_R b_L + g_{S_R}\, \bar{c}_L b_R \Big] \bar{\ell}_R \nu_L + g_{T_L}\, (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \Big\} + \text{h.c.}$$

Only left-handed neutrinos!

$$g_{V,\,A} = g_{V_R} \pm g_{V_L}\,, \quad g_{S,\,P} = g_{S_R} \pm g_{S_L}\,, \quad g_T = -g_{T5} = g_{T_L}$$



Angular distributions

The B $\rightarrow$ $D^{(*)}\ell\nu$ is a 3 (4) bodies decay, hence allowing for the experimental study of its angular distribution.

The aim is the definition of observables that are:

- Theoretically clean
- Sensitive to NP effects
- Complementary to Br measurements

Some of these observables, if properly built, could show hint of NP evidence even in the anomaly in the Br would disappear in the future (similarly to P'_5 for B $\rightarrow$ $K^*\mu\mu$)

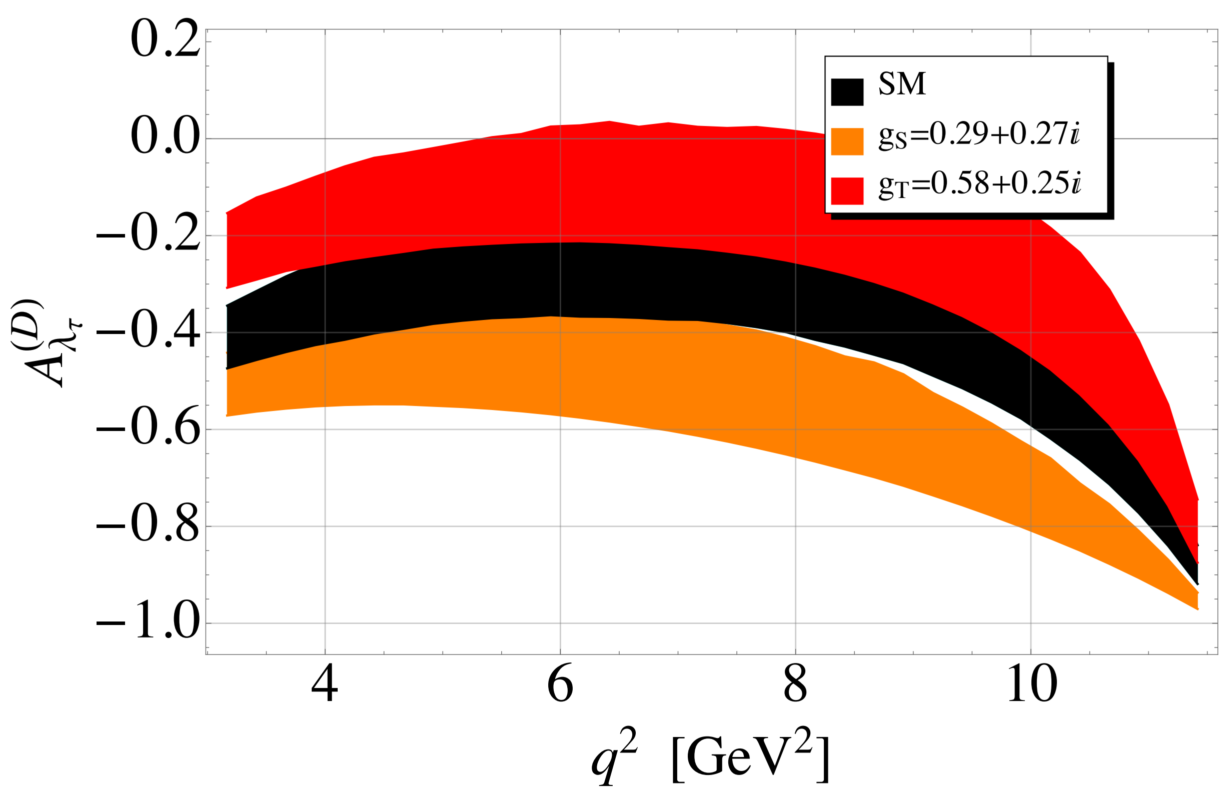
$B \to D\ell\nu$ - A_{λ_ℓ} & A_{FB}

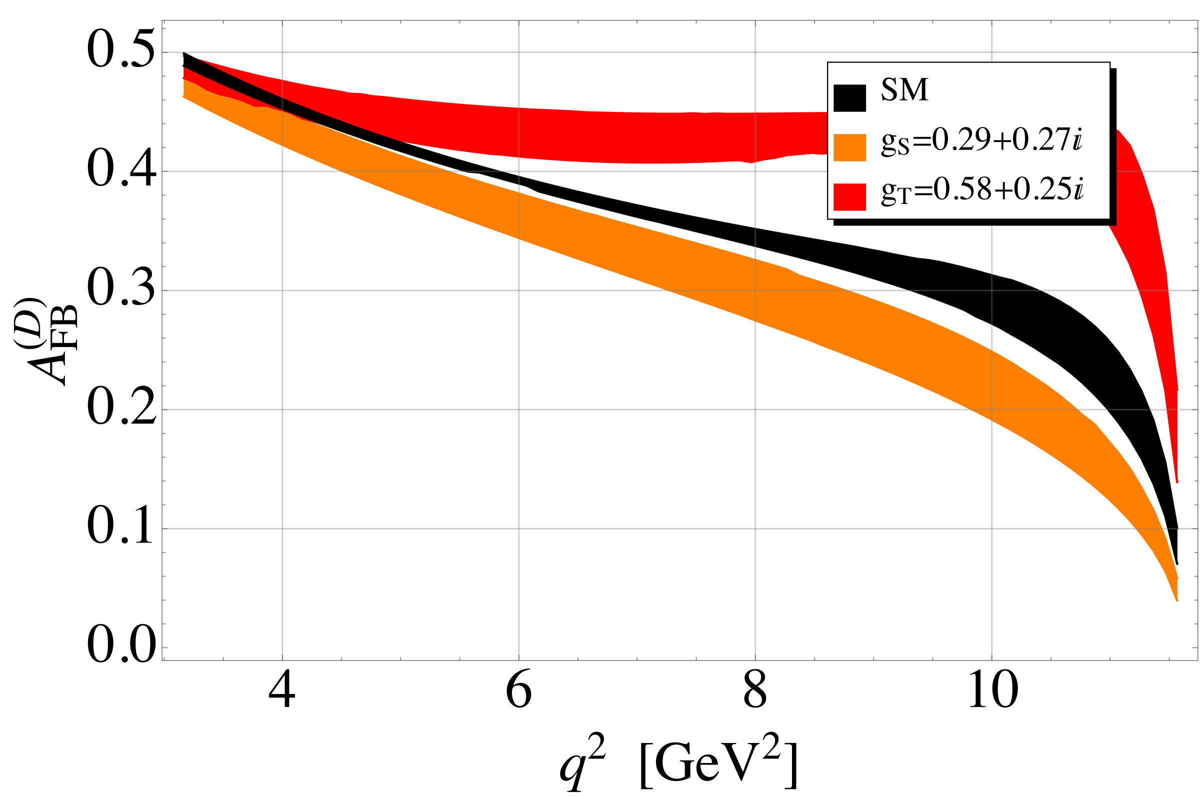
$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = a_{\theta_\ell}(q^2) + b_{\theta_\ell}(q^2)\cos\theta_\ell + c_{\theta_\ell}(q^2)\cos^2\theta_\ell$$

Br and A_{λ_ℓ} function of $a_{\theta_\ell}(q^2)$, $c_{\theta_\ell}(q^2)$

$$A_{\lambda_\ell}(q^2) = \frac{d\Gamma^{\lambda_\ell=-1/2}/dq^2 - d\Gamma^{\lambda_\ell=+1/2}/dq^2}{d\Gamma/dq^2}$$

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





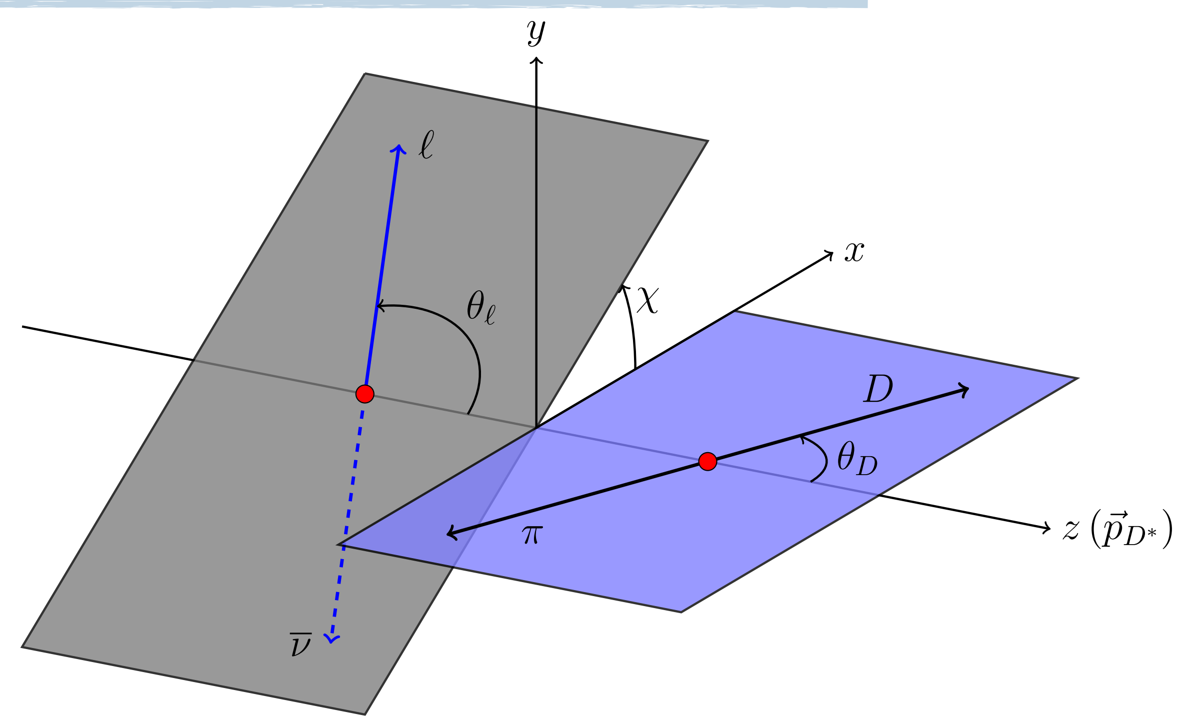
$B \to D^* \ell \nu$

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell d\chi} = \frac{9}{32\pi}\Big\{ I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + \left[I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D\right]\cos 2\theta_\ell + \left[I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D\right]\cos\theta_\ell + \left[I_3\cos 2\chi + I_9\sin 2\chi\right]\sin^2\theta_\ell\sin^2\theta_D + \left[I_4\cos\chi + I_8\sin\chi\right]\sin 2\theta_\ell\sin 2\theta_D + \left[I_5\cos\chi + I_7\sin\chi\right]\sin\theta_\ell\sin 2\theta_D \Big\}$$

- 12 independent angular coefficients

$$\Downarrow$$

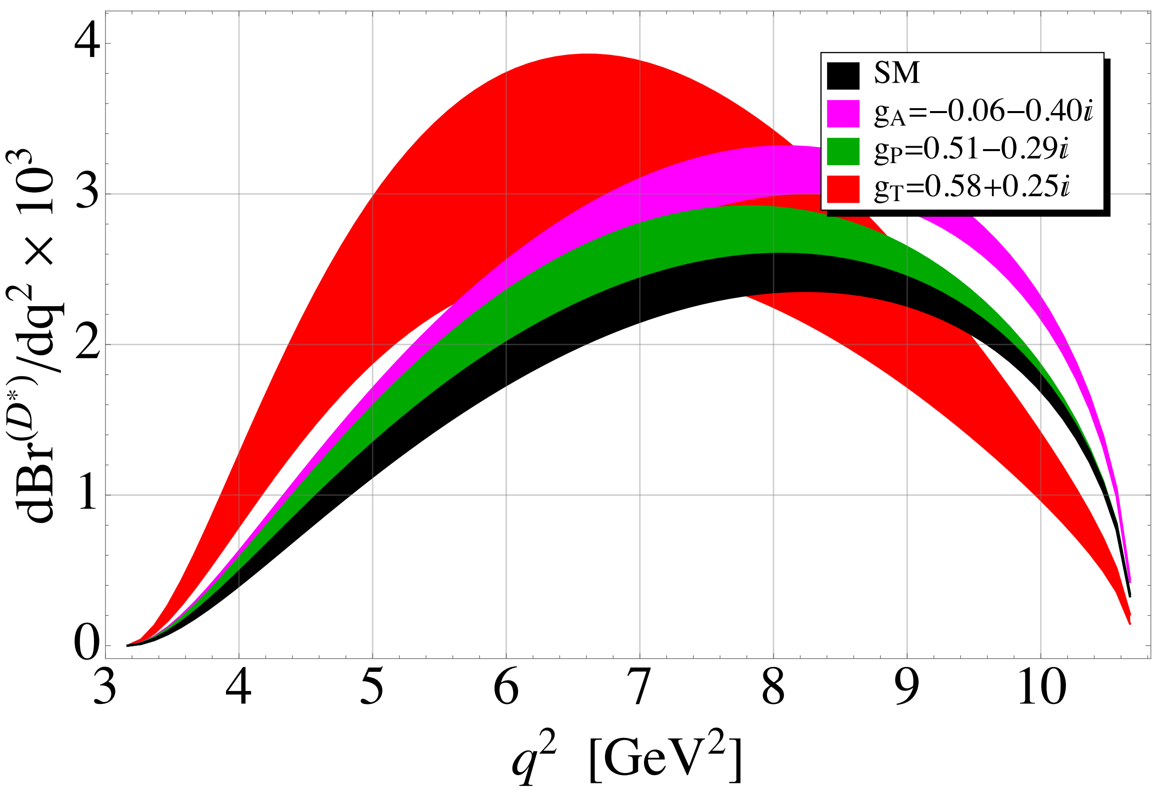
- 12 independent angular observables!

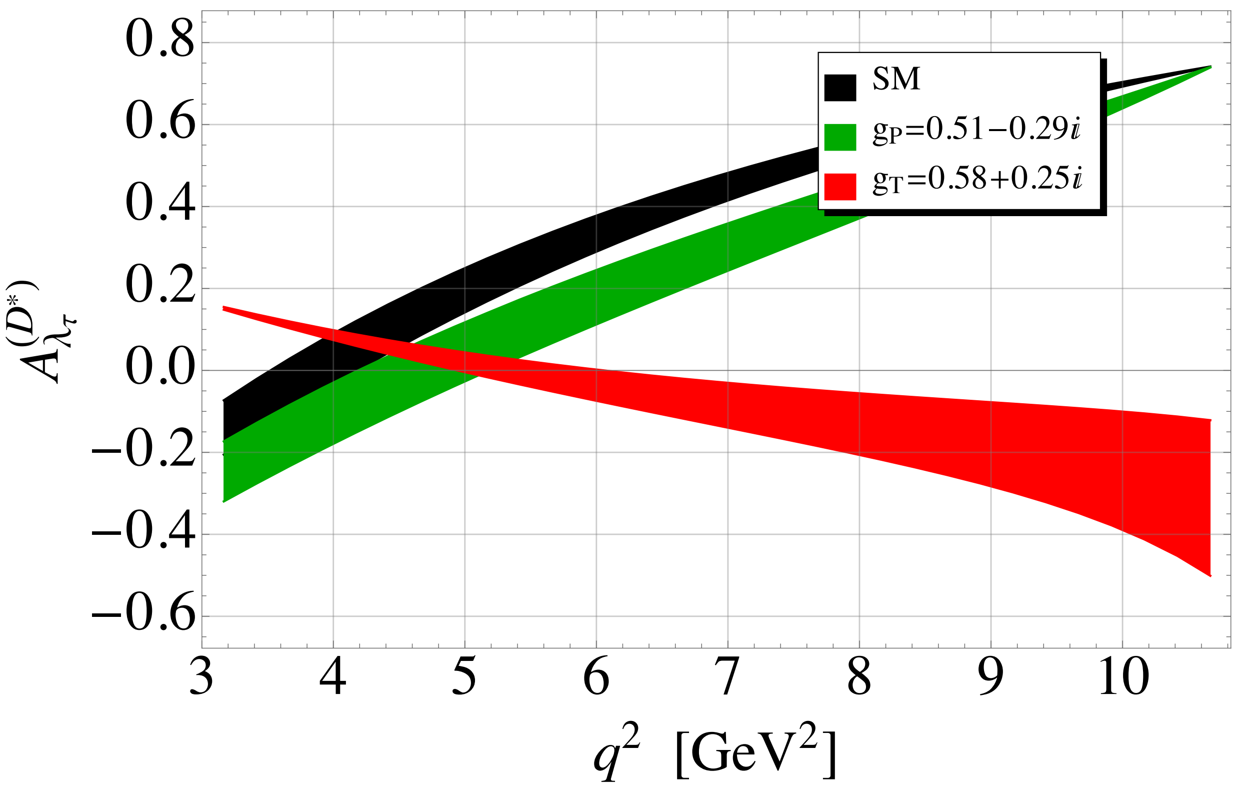


$B \to D^*\ell\nu$ - BR & A_{λ_ℓ}

$$\frac{d^4\Gamma}{dq^2} = \frac{1}{4}(3I_{1c} + 6I_{1s} - I_{2c} - 2I_{1s})$$

$$A_{\lambda_\ell}(q^2) = \frac{d\Gamma^{\lambda_\ell=-1/2}/dq^2 - d\Gamma^{\lambda_\ell=+1/2}/dq^2}{d\Gamma/dq^2}$$





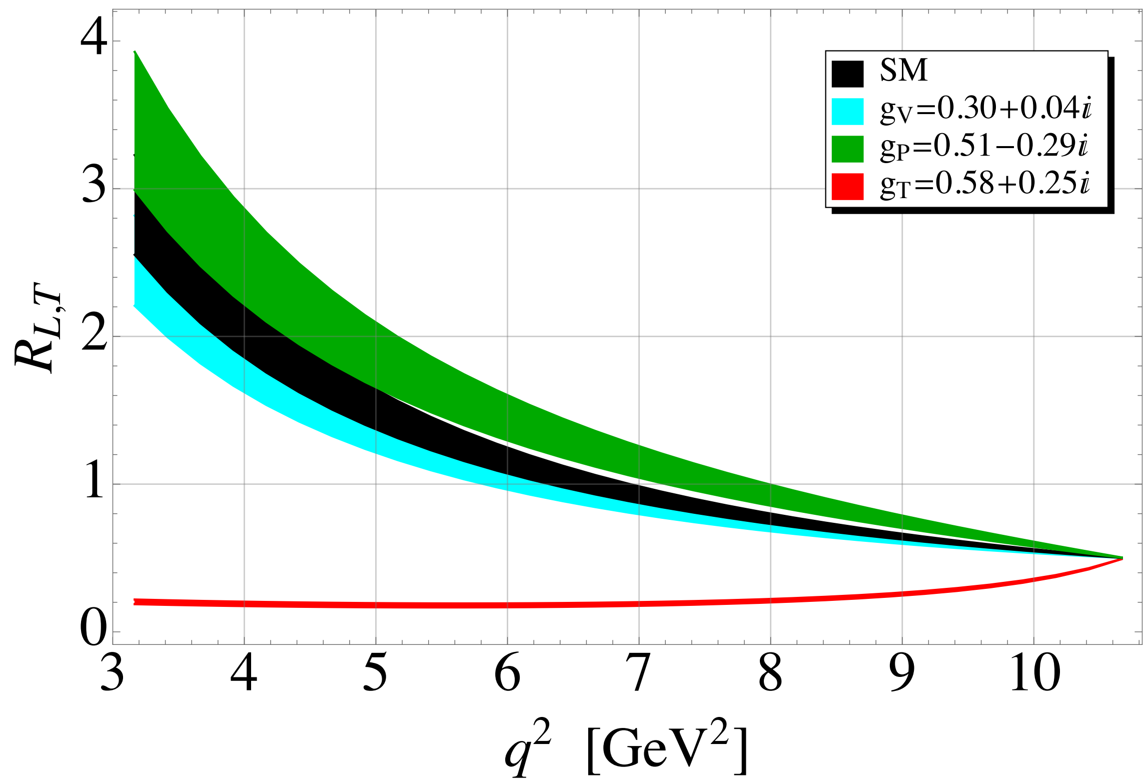
$B \to D^*\ell\nu$ - R_{LT} & R_{AB}

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

$$\frac{d\Gamma_L}{dq^2} = \frac{2a_{\theta_D} + 2c_{\theta_D}}{3} = \frac{3I_{1c} - I_{2c}}{4}$$

$$\frac{d\Gamma_T}{dq^2} = \frac{4}{3}a_{\theta_D} = \frac{3I_{1s} - I_{2s}}{2}$$

$$\boxed{R_{L,T}(q^2) = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}}$$

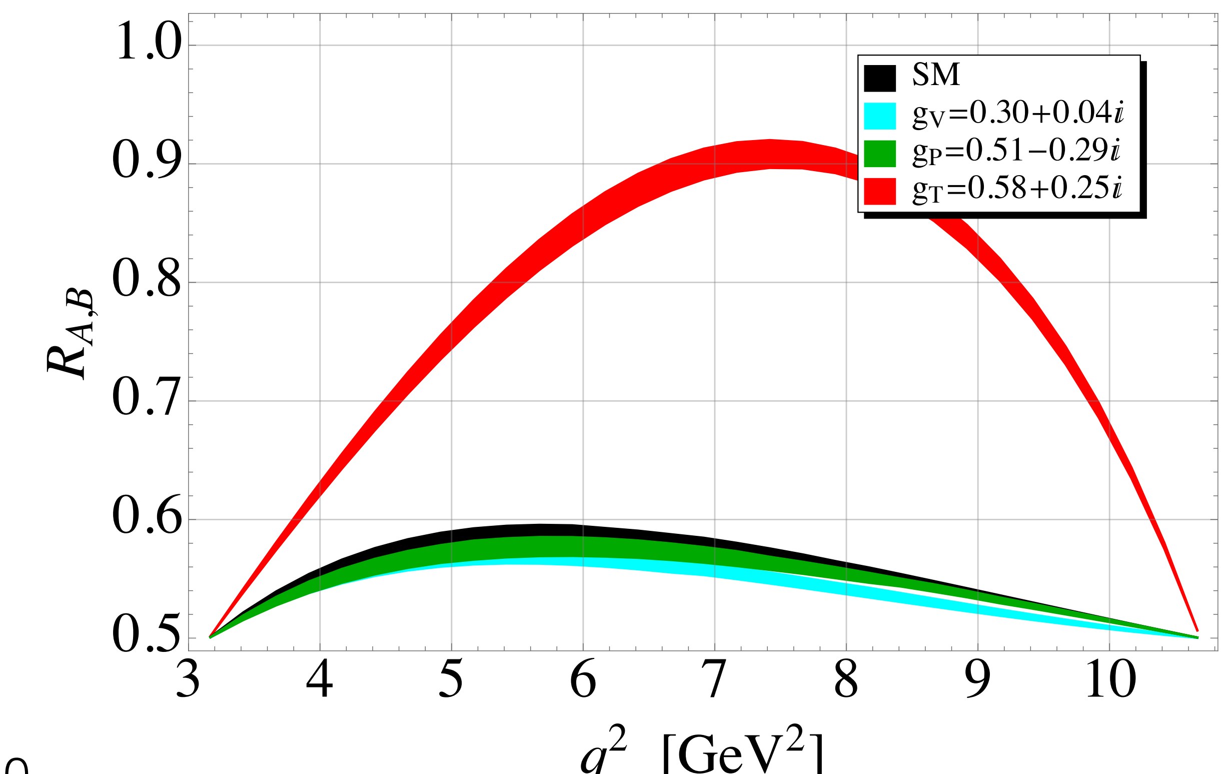


$$\frac{d^2\Gamma}{dq^2 d\cos\theta_l} = a_{\theta_l}(q^2) + b_{\theta_l}(q^2)\cos\theta_l + c_{\theta_l}(q^2)\cos^2\theta_l$$

$$\frac{d\Gamma_A}{dq^2} = \frac{2a_{\theta_l} - 2c_{\theta_l}}{3} = \frac{I_{1c} + 2I_{1s} - 3I_{2c} - 6I_{2s}}{4}$$

$$\frac{d\Gamma_B}{dq^2} = \frac{4a_{\theta_l} + 4c_{\theta_l}}{3} = \frac{I_{1c} + 2I_{1s} + I_{2c} + 2I_{2s}}{2}$$

$$\boxed{R_{A,B}(q^2) = \frac{d\Gamma_A/dq^2}{d\Gamma_B/dq^2}}$$

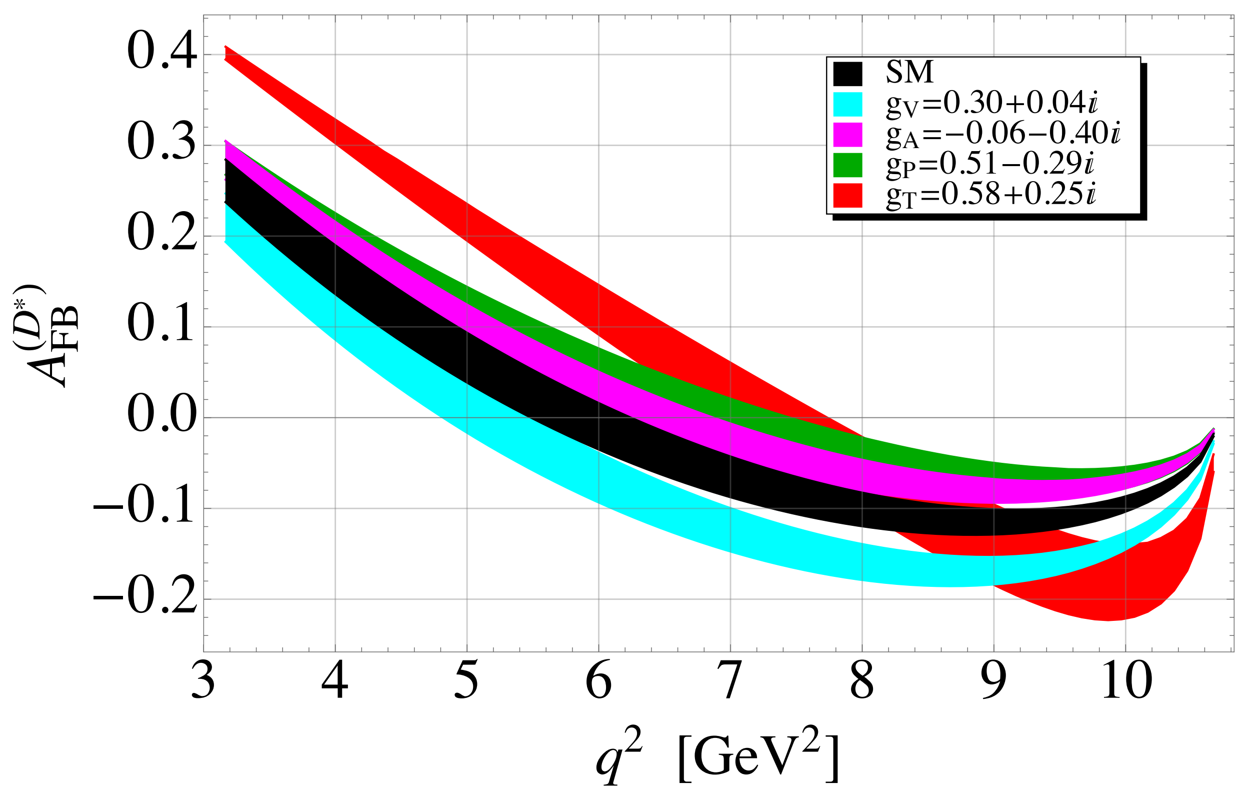


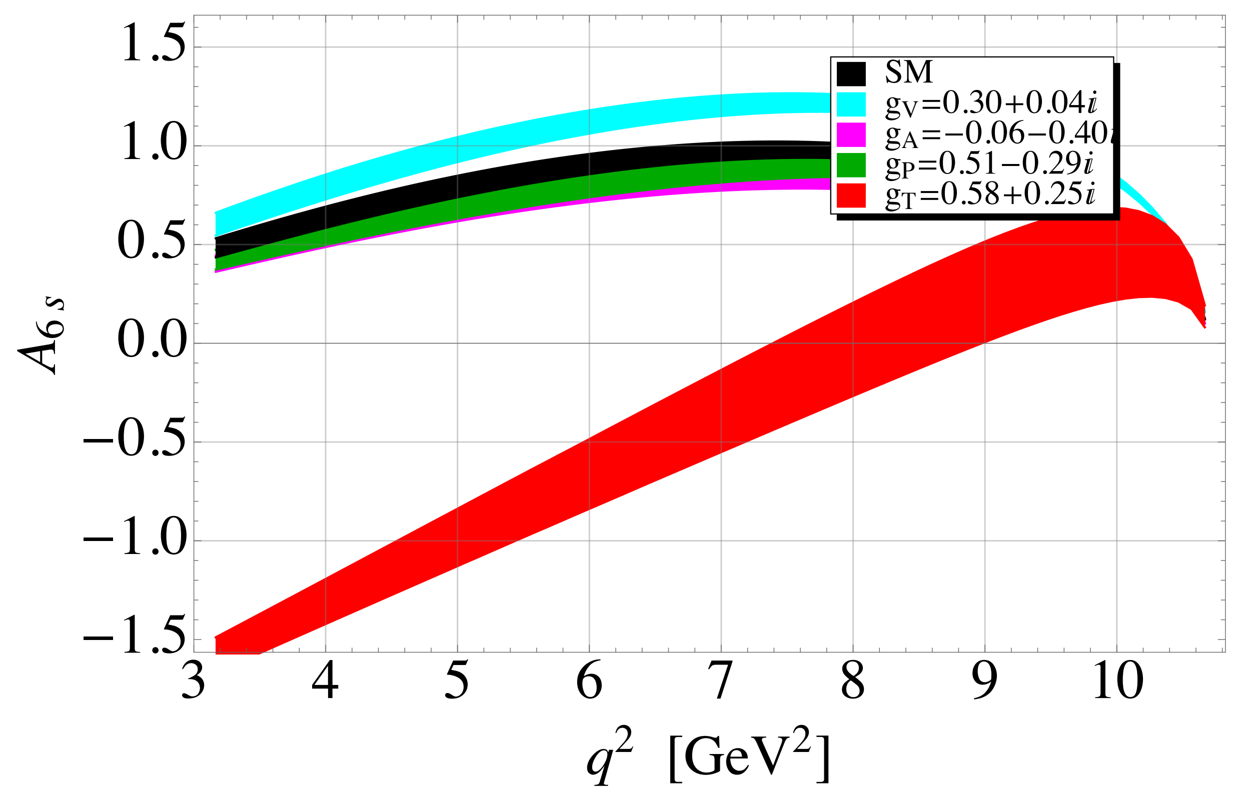
$B \to D^*\ell\nu$ - A_{FB} & A_{6s}

$$A_{FB}(q^2) = \frac{b_{\theta_\ell}}{d\Gamma/dq^2} = \frac{3}{8}\frac{(I_{6c}+2I_{6s})}{d\Gamma/dq^2}$$

$$\Phi_6(q^2,\theta_D) = \left[\int_{-1}^{0} - \int_{0}^{1}\right] \frac{d^3\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell}\, d\cos\theta_\ell$$

$$A_{6s}(q^2) = \frac{\left[7\int_{-1/2}^{1/2} - \int_{1/2}^{1} - \int_{-1}^{-1/2}\right]\Phi_6(q^2,\theta_D)\; d\cos\theta_D}{d\Gamma/dq^2} = -\frac{27}{8}\frac{I_{6s}}{d\Gamma/dq^2}$$





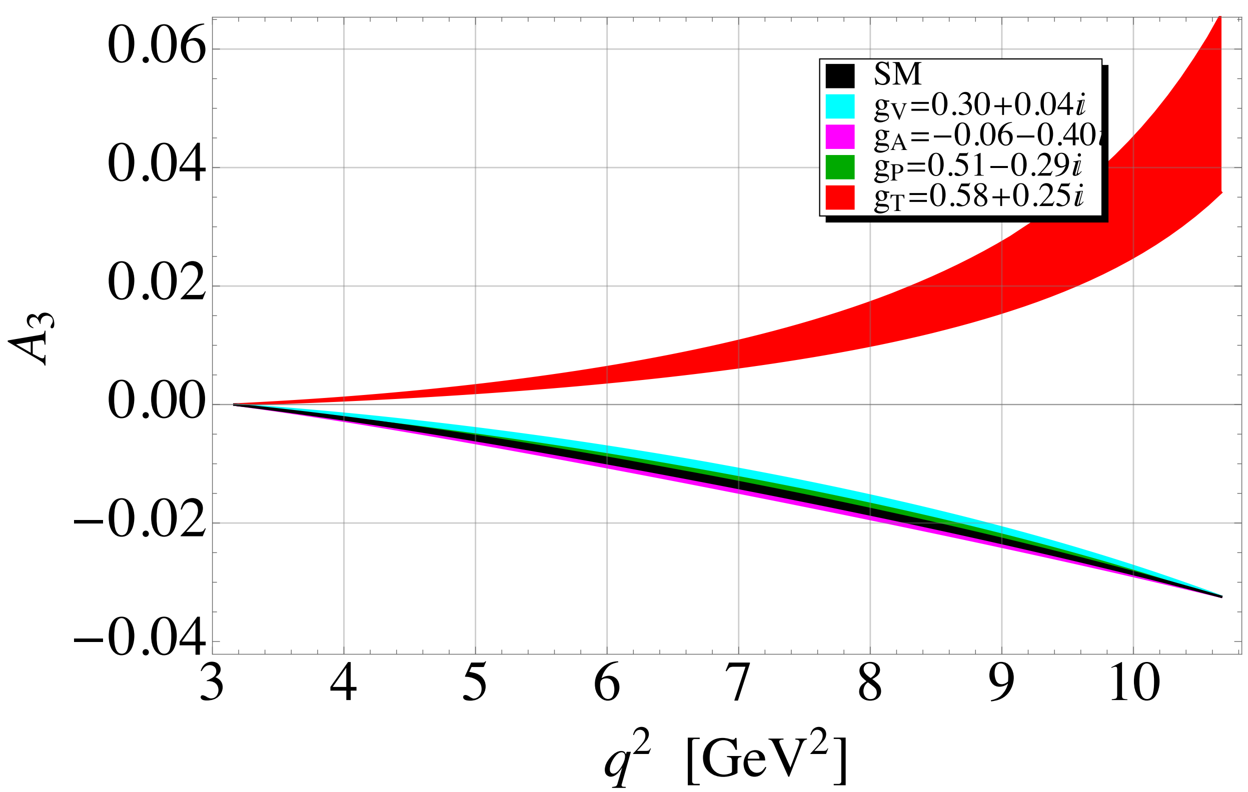
B → D*ℓν - A_3 & A_9

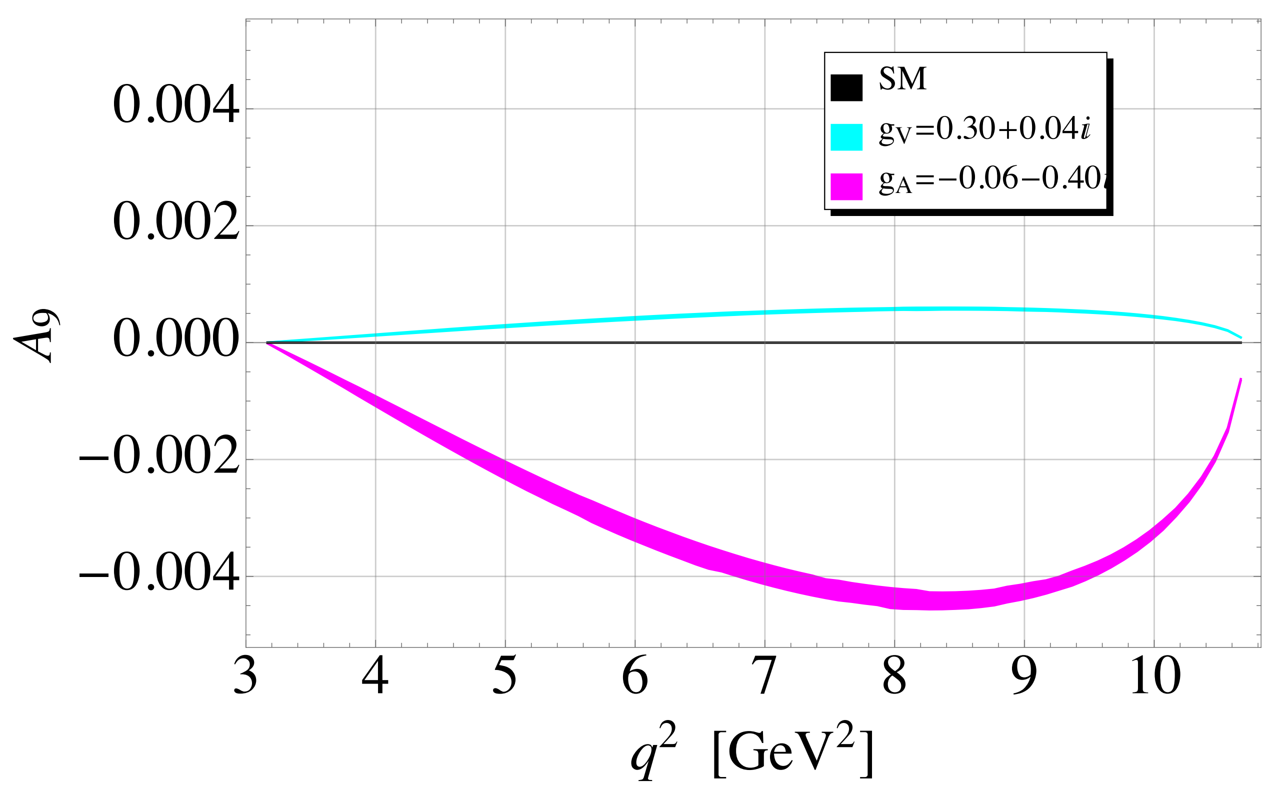
$$\frac{d^2\Gamma}{dq^2 d\chi} = a_\chi(q^2) + c_\chi^c(q^2)\cos 2\chi + c_\chi^s(q^2)\sin 2\chi$$

$$A_3(q^2) = \frac{c_\chi^c(q^2)}{d\Gamma/dq^2} = \frac{1}{2\pi}\frac{I_3}{d\Gamma/dq^2}$$

$$A_9(q^2) = \frac{c_\chi^s(q^2)}{d\Gamma/dq^2} = \frac{1}{2\pi}\frac{I_9}{d\Gamma/dq^2}$$

Sensitive to NP phase!





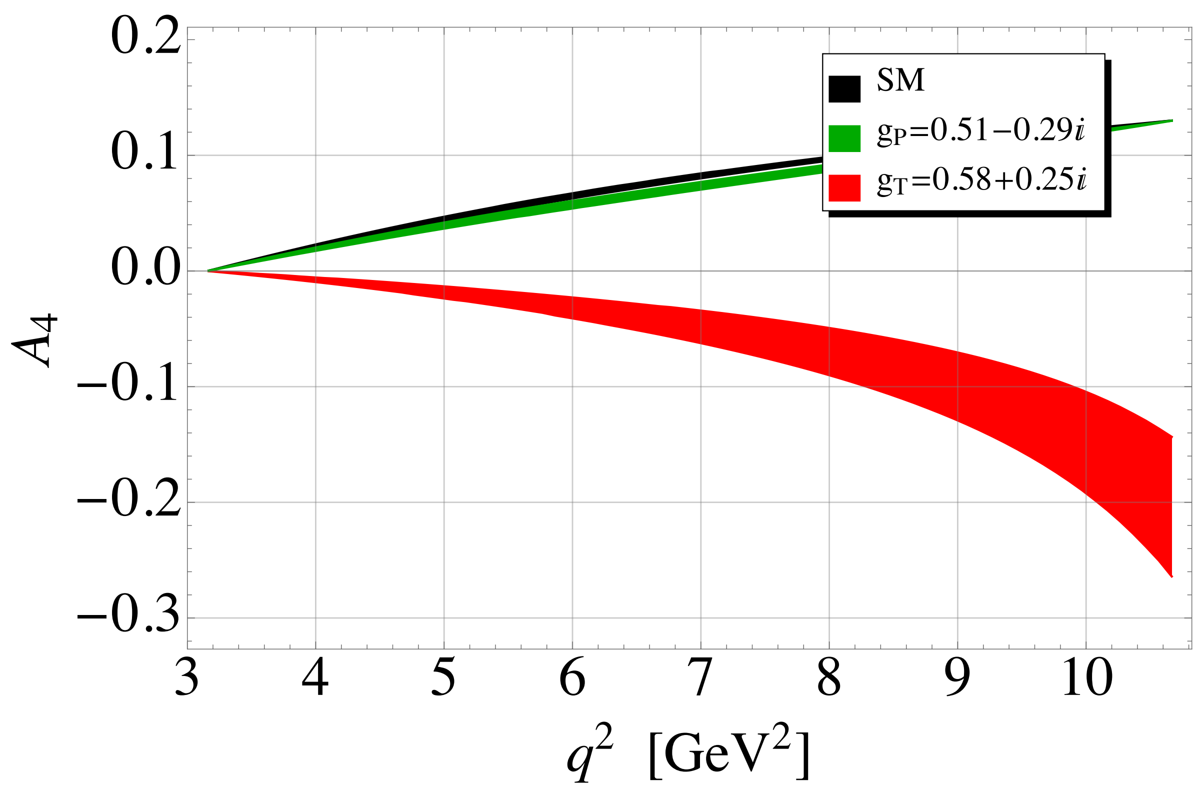
B → D*ℓν - A4 & A8

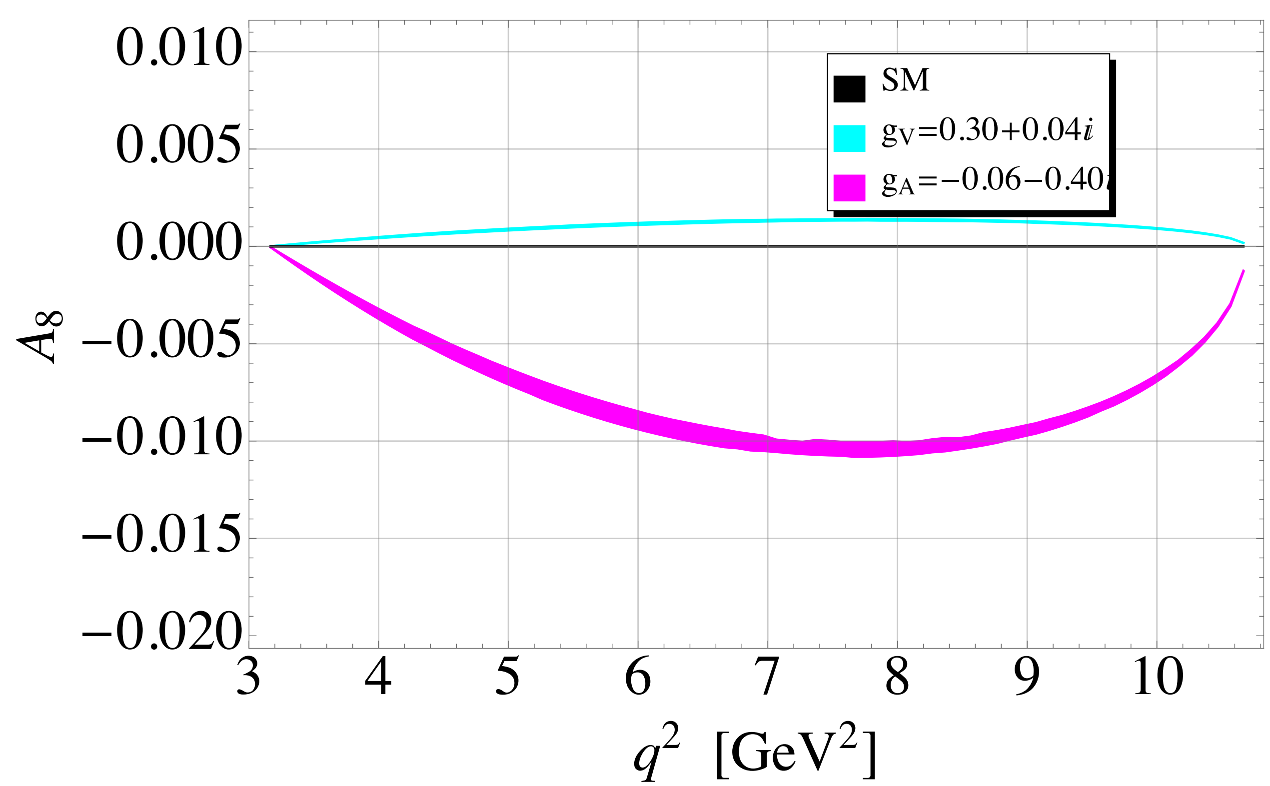
$$\Phi_{48}(q^2,\chi) = \left[\int_{-1}^{0} - \int_{0}^{1}\right]\left\{\left[\int_{-1}^{0} - \int_{0}^{1}\right] \frac{d^4\Gamma}{dq^2 d\chi d\cos\theta_\ell d\cos\theta_D}\, d\cos\theta_D\right\}\, d\cos\theta_\ell$$

$$\boxed{A_4(q^2) = \frac{\left[\int_{\pi/2}^{3\pi/2} - \int_0^{\pi/2} - \int_{3\pi/2}^{2\pi}\right]\Phi_{48}(q^2,\chi)\; d\chi}{d\Gamma/dq^2} = -\frac{2}{\pi}\frac{I_4}{d\Gamma/dq^2}}$$

$$\boxed{A_8(q^2) = \frac{\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right]\Phi_{48}(q^2,\chi)\; d\chi}{d\Gamma/dq^2} = \frac{2}{\pi}\frac{I_8}{d\Gamma/dq^2}}$$

Sensitive to NP phase!





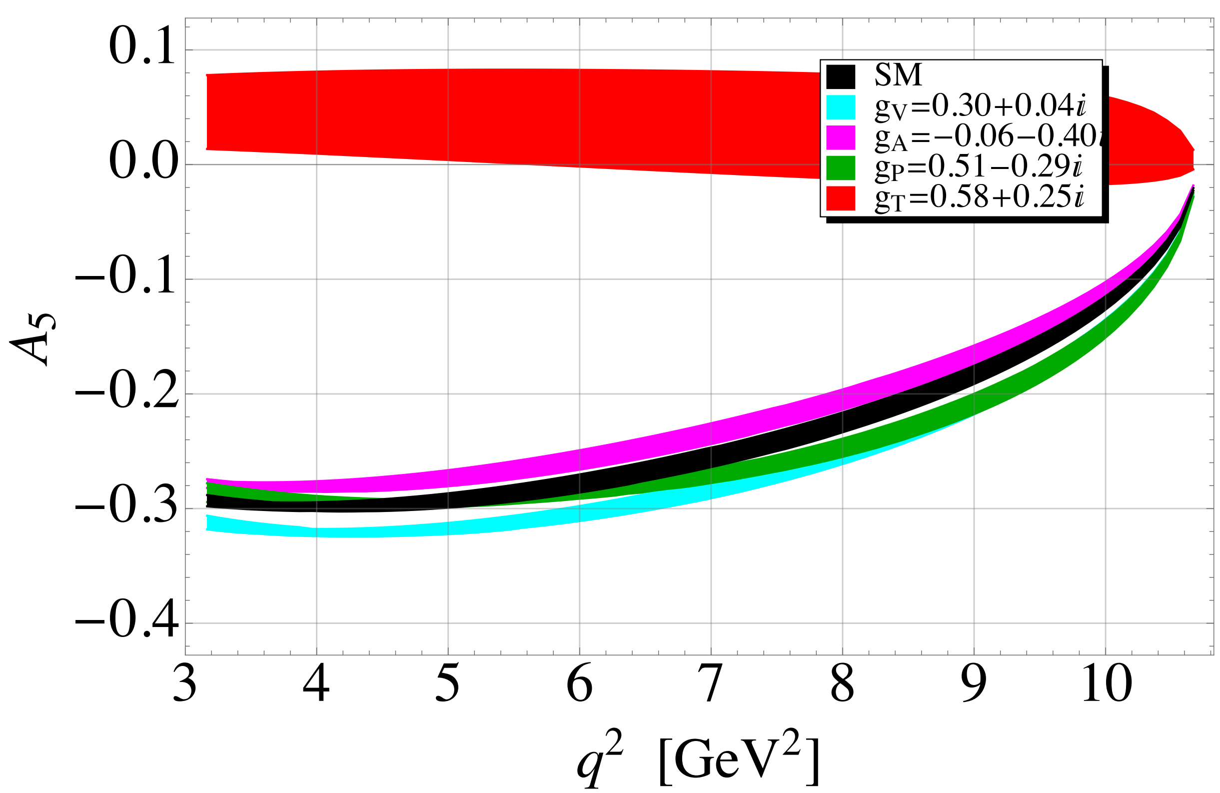
B → D*ℓν - A₅ & A₇

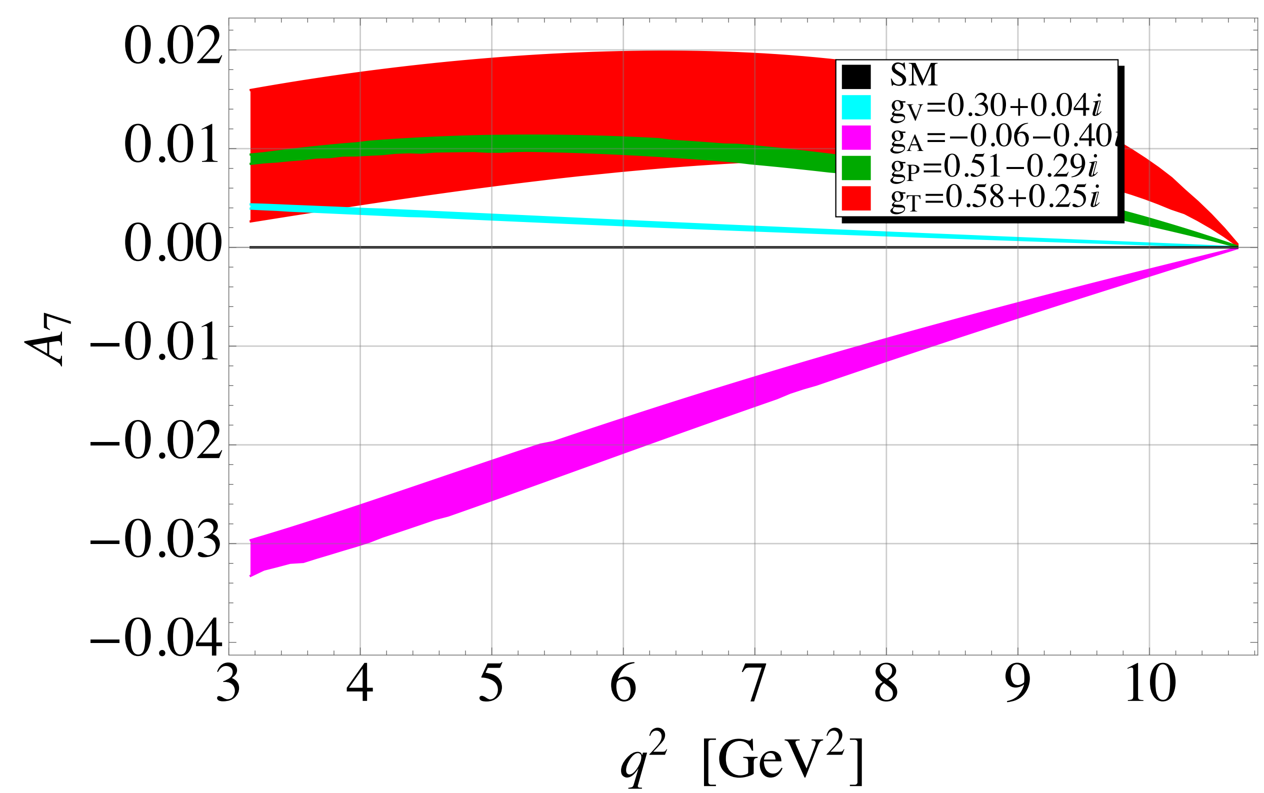
$$\Phi_{57}(q^2,\chi) = \left[\int_{-1}^{0} - \int_{0}^{1}\right] \frac{d^3\Gamma}{dq^2 d\chi d\cos\theta_D}\ d\cos\theta_D$$

$$\boxed{A_5(q^2) = -\frac{\left[\int_{\pi/2}^{3\pi/2} - \int_{0}^{\pi/2} - \int_{3\pi/2}^{2\pi}\right] \Phi_{57}(q^2,\chi)\ d\chi}{d\Gamma/dq^2} = -\frac{3}{4}\frac{I_5}{d\Gamma/dq^2}}$$

$$\boxed{A_7(q^2) = \frac{\left[\int_{0}^{\pi} - \int_{\pi}^{2\pi}\right] \Phi_{57}(q^2,\chi)\ d\chi}{d\Gamma/dq^2} = -\frac{3}{4}\frac{I_7}{d\Gamma/dq^2}}$$

Sensitive to NP phase!





LFUV Observables

Since $I^{e,\mu}_{7,8,9} = I^{e,\mu\ (\mathrm{SM})}_{7,8,9} = 0$, we introduce the first three LFUV observables:

$$D(A_{7,8,9}) \equiv \langle A^{\tau}_{7,8,9} \rangle - \frac{1}{2} \left(\langle A^{e}_{7,8,9} \rangle + \langle A^{\mu}_{7,8,9} \rangle \right)$$

For all the other angular observables, we define the LFUV observables as:

$$R(O_i) \equiv \frac{\langle O^{\tau}_i \rangle}{\frac{1}{2} \left(\langle O^{e}_i \rangle + \langle O^{\mu}_i \rangle \right)}$$

where each angular observable is integrated over the q^2 spectrum

$$O^{\ell}_i = \frac{\mathcal{N}^{\ell}_i(q^2)}{\mathcal{D}^{\ell}_i(q^2)} \quad \Rightarrow \quad \langle O^{\ell}_i \rangle = \frac{\int_{m^2_\ell}^{q^2_{\max}} \mathcal{N}^{\ell}_i(q^2)\ dq^2}{\int_{m^2_\ell}^{q^2_{\max}} \mathcal{D}^{\ell}_i(q^2)\ dq^2}$$

LFUV Observables predictions

~ 2σ, 3σ, 4σ difference from the SM value

Obs.	SM	g_V	g_A	g_S	g_P	g_T
$R(A_{FB}^{D})$	0.077 ± 0.004	0.074 ± 0.003	–	$[-0.057, 0.070]$	–	0.089 ± 0.005
$R(A_{\lambda_\ell}^{D})$	-0.332 ± 0.003	-0.331 ± 0.003	–	-0.57 ± 0.06	–	-0.19 ± 0.05
$R(A_{\lambda_\ell}^{D^*})$	0.47 ± 0.02	0.48 ± 0.02	0.49 ± 0.02	–	0.36 ± 0.04	-0.02 ± 0.15
$R(R_{L,T})$	0.79 ± 0.02	0.76 ± 0.02	0.81 ± 0.02	–	0.95 ± 0.05	0.25 ± 0.13
$R(R_{A,B})$	0.520 ± 0.004	0.508 ± 0.005	0.524 ± 0.004	–	0.516 ± 0.004	0.74 ± 0.07
$R(A_{FB}^{D^*})$	0.23 ± 0.04	$[-1.58, 0.49]$	$[-1.37, 0.22]$	–	0.00 ± 0.06	-0.10 ± 0.08
$R(A_3)$	0.62 ± 0.01	0.56 ± 0.02	0.64 ± 0.01	–	0.56 ± 0.02	-0.30 ± 0.28
$R(A_4)$	0.456 ± 0.006	0.438 ± 0.006	0.460 ± 0.008	–	0.414 ± 0.009	-0.21 ± 0.18
$R(A_5)$	1.15 ± 0.02	$[-0.28, 1.32]$	$[-0.09, 1.15]$	–	1.24 ± 0.05	-0.04 ± 0.33
$R(A_6)$	0.79 ± 0.01	$[-1.02, 1.02]$	$[-0.76, 0.75]$	–	0.72 ± 0.02	-0.20 ± 0.25
$D(A_7)$	0	$[-0.05, 0.05]$	$[-0.04, 0.04]$	–	0.00 ± 0.01	0.00 ± 0.02
$D(A_8)$	0	$[-0.04, 0.04]$	$[-0.03, 0.03]$	–	0	0
$D(A_9)$	0	$[-0.09, 0.09]$	$[-0.07, 0.07]$	–	0	0

Complex g_i are varied as free parameter according to p.d.f. obtained from the fit of R(D(*))

LFUV Observables predictions

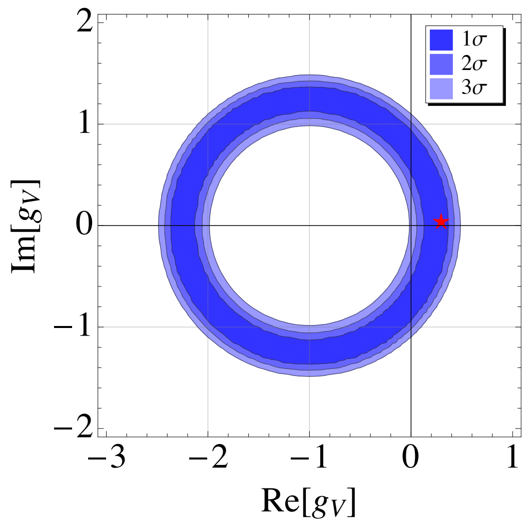
~ 2σ, 3σ, 4σ difference from the SM value

Allowed 2σ region

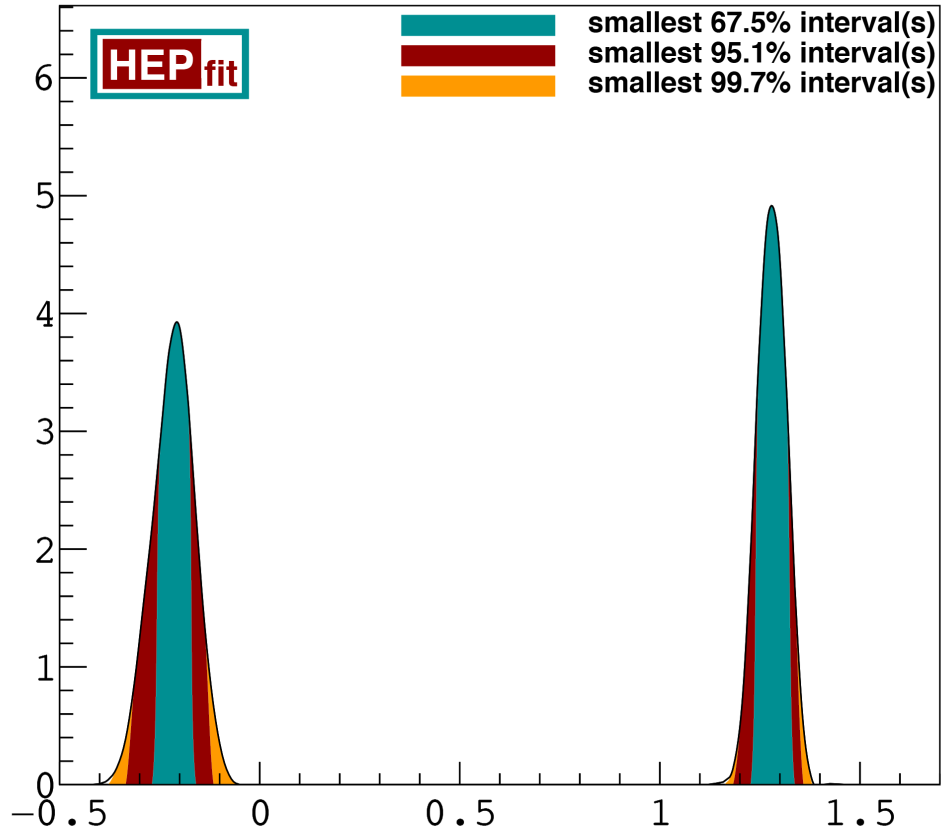
Obs.	SM	g_V	g_A	g_S	g_P	g_T
$R(A_{FB}^D)$	0.077 ± 0.004	0.074 ± 0.003	–	$[-0.057, 0.070]$	–	0.089 ± 0.005
$R(A_{\lambda_\ell}^D)$	-0.332 ± 0.003	-0.331 ± 0.003	–	-0.57 ± 0.06	–	-0.19 ± 0.05
$R(A_{\lambda_\ell}^{D^*})$	0.47 ± 0.02	0.48 ± 0.02	0.49 ± 0.02	–	0.36 ± 0.04	-0.02 ± 0.15
$R(R_{L,T})$	0.79 ± 0.02	0.76 ± 0.02	0.81 ± 0.02	–	0.95 ± 0.05	0.25 ± 0.13
$R(R_{A,B})$	0.520 ± 0.004	0.508 ± 0.005	0.524 ± 0.004	–	0.516 ± 0.004	0.74 ± 0.07
$R(A_{FB}^{D^*})$	0.23 ± 0.04	$[-1.58, 0.49]$	$[-1.37, 0.22]$	–	0.00 ± 0.06	-0.10 ± 0.08
$R(A_3)$	0.62 ± 0.01	0.56 ± 0.02	0.64 ± 0.01	–	0.56 ± 0.02	-0.30 ± 0.28
$R(A_4)$	0.456 ± 0.006	0.438 ± 0.006	0.460 ± 0.008	–	0.414 ± 0.009	-0.21 ± 0.18
$R(A_5)$	1.15 ± 0.02	$[-0.28, 1.32]$	$[-0.09, 1.15]$	–	1.24 ± 0.05	-0.04 ± 0.33
$R(A_6)$	0.79 ± 0.01	$[-1.02, 1.02]$	$[-0.76, 0.75]$	–	0.72 ± 0.02	-0.20 ± 0.25
$D(A_7)$	0	$[-0.05, 0.05]$	$[-0.04, 0.04]$	–	0.00 ± 0.01	0.00 ± 0.02
$D(A_8)$	0	$[-0.04, 0.04]$	$[-0.03, 0.03]$	–	0	0
$D(A_9)$	0	$[-0.09, 0.09]$	$[-0.07, 0.07]$	–	0	0

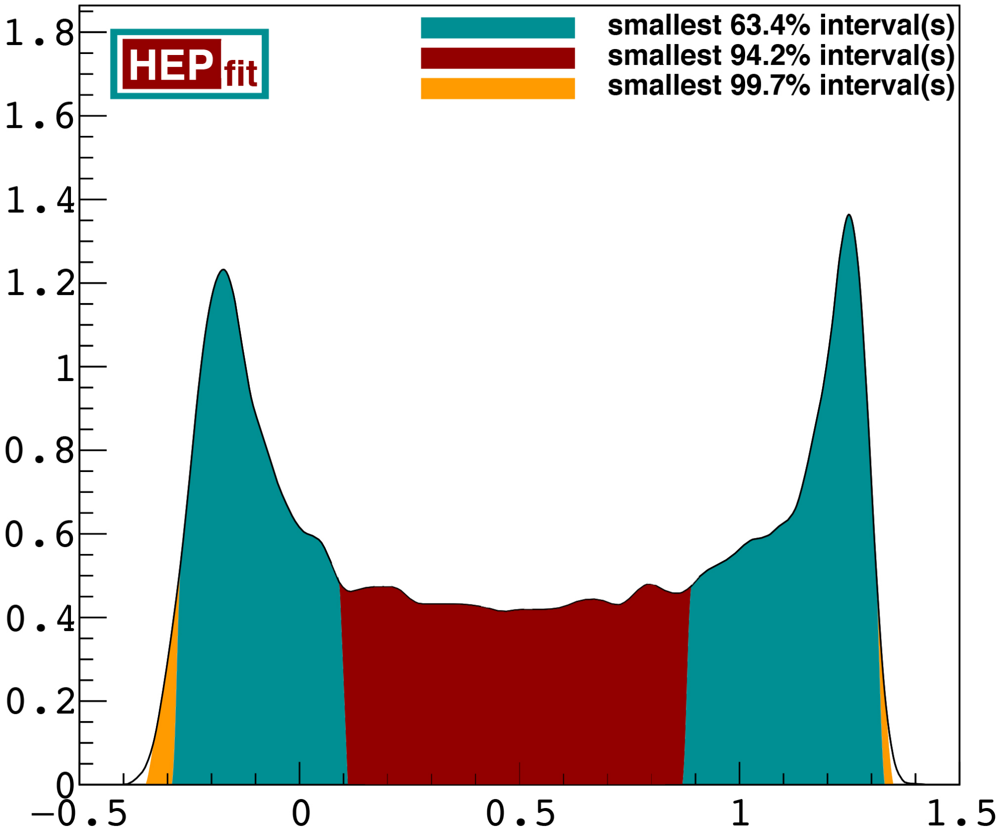
Complex g_i are varied as free parameter according to p.d.f. obtained from the fit of R(D$^{(*)}$)

LFUV Observables predictions



- R(A_5) is sensitive to $\mathrm{Re}(g_V)$
- Assuming a real coupling, 2 solutions (left plot)
- Allowing for a complex coupling, we obtain a continuum due to the interplay between real and imaginary parts (right plot)





Measuring e.g. R(A_5) would correspond to a vertical band in the $\mathrm{Re}(g_V)$-$\mathrm{Im}(g_V)$ plane, sensibly reducing the allowed region!

LFUV Observables predictions

~ 2σ, 3σ, 4σ difference from the SM value

Allowed 2σ region

Obs.	SM	g_V	g_A	g_S	g_P	g_T
$R(A_{FB}^D)$	0.077 ± 0.004	0.074 ± 0.003	–	$[-0.057, 0.070]$	–	0.089 ± 0.005
$R(A_{\lambda_\ell}^D)$	-0.332 ± 0.003	-0.331 ± 0.003	–	-0.57 ± 0.06	–	-0.19 ± 0.05
$R(A_{\lambda_\ell}^{D^*})$	0.47 ± 0.02	0.48 ± 0.02	0.49 ± 0.02	–	0.36 ± 0.04	-0.02 ± 0.15
$R(R_{L,T})$	0.79 ± 0.02	0.76 ± 0.02	0.81 ± 0.02	–	0.95 ± 0.05	0.25 ± 0.13
$R(R_{A,B})$	0.520 ± 0.004	0.508 ± 0.005	0.524 ± 0.004	–	0.516 ± 0.004	0.74 ± 0.07
$R(A_{FB}^{D^*})$	0.23 ± 0.04	$[-1.58, 0.49]$	$[-1.37, 0.22]$	–	0.00 ± 0.06	-0.10 ± 0.08
$R(A_3)$	0.62 ± 0.01	0.56 ± 0.02	0.64 ± 0.01	–	0.56 ± 0.02	-0.30 ± 0.28
$R(A_4)$	0.456 ± 0.006	0.438 ± 0.006	0.460 ± 0.008	–	0.414 ± 0.009	-0.21 ± 0.18
$R(A_5)$	1.15 ± 0.02	$[-0.28, 1.32]$	$[-0.09, 1.15]$	–	1.24 ± 0.05	-0.04 ± 0.33
$R(A_6)$	0.79 ± 0.01	$[-1.02, 1.02]$	$[-0.76, 0.75]$	–	0.72 ± 0.02	-0.20 ± 0.25
$D(A_7)$	0	$[-0.05, 0.05]$	$[-0.04, 0.04]$	–	0.00 ± 0.01	0.00 ± 0.02
$D(A_8)$	0	$[-0.04, 0.04]$	$[-0.03, 0.03]$	–	0	0
$D(A_9)$	0	$[-0.09, 0.09]$	$[-0.07, 0.07]$	–	0	0

Moreover, we obtain similar results is we assume $R(D^{(*)})_{\rm exp} = R(D^{(*)})_{\rm SM} \pm 10\%$

Conclusions

- We have constructed 2(11) angular observables when considering the decay to a pseudoscalar(vector) meson

- We have combined these observable in order to build LFUV tests, complementary to $R(D^{(*)})$, and made predictions for SM & NP scenarios

- These quantities can be of great help when studying NP effects in $b \to c$ transitions (in particular concerning its Lorentz structure), since many NP predictions differ from the SM at $\sim 3{,}4\sigma$ level

- These observable would still be of interest even if the Br anomalies would disappear, since they involve different pieces of the amplitudes

- The above description is totally general, and equally applicable to all the various semileptonic pseudoscalar → pseudoscalar/vector decay

Back-up

Form Factors treatment

$B \to D\ell\nu$: All FF from Lattice (Bailey et al., ’15)

$B \to D^*\ell\nu$:

- All FF from Constituent quark Model (Melikhov, Stech, ’00)

  or

- V, $A_{1,2}$ from either CLN parametrization (Caprini, Lelouch, Neubert, ’97) or BGL (Bigi, Gambino, Schacht, ’17)

- $A_0, T_{1,2,3}$ from HQET@NLO in $1/m_{c,b}$ (Bernolochner et al., ’17) but with more generous err.

All the obtained results are in good agreement for different methods and parameterizations!