Exploring NP scenarios in flavor physics with reduced QCD uncertainties

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based on works arXiv: 2012.09872 and 2103.12504, done with
A. Angelescu, D. Faroughy, F. Jaffredo, A. Peñuelas and O. Sumensari

LFUV

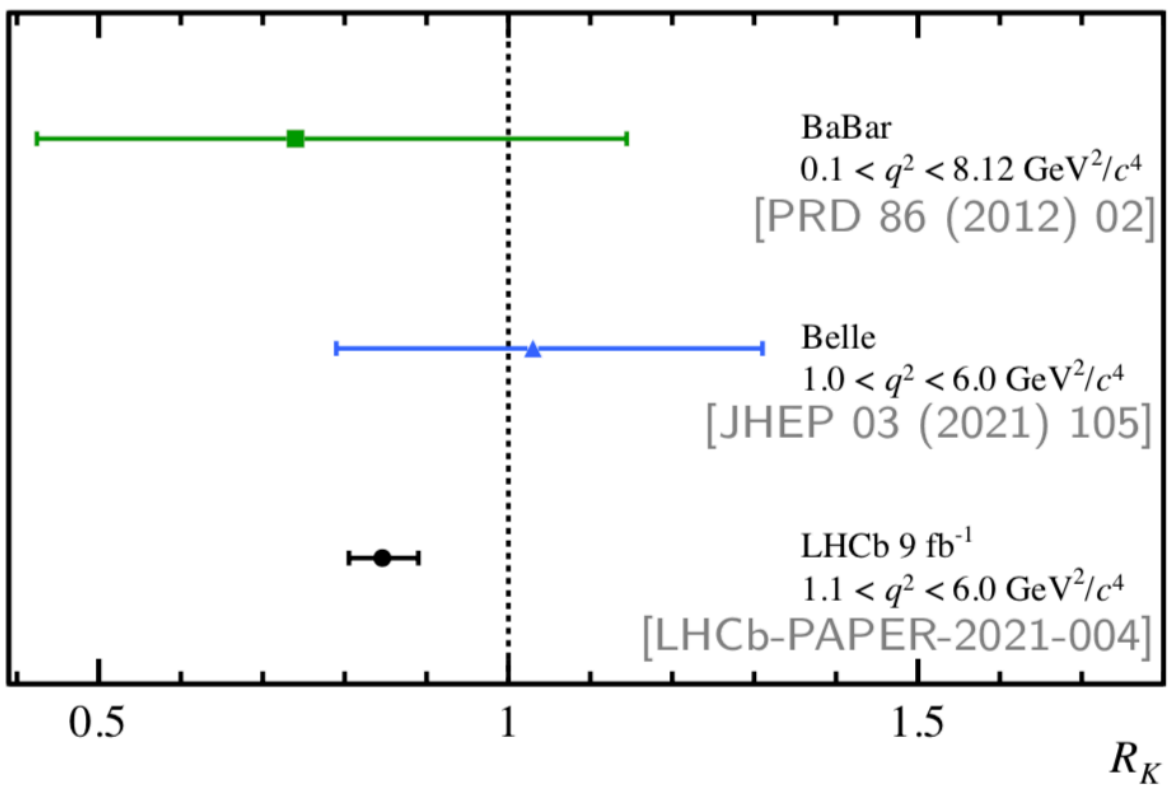
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$

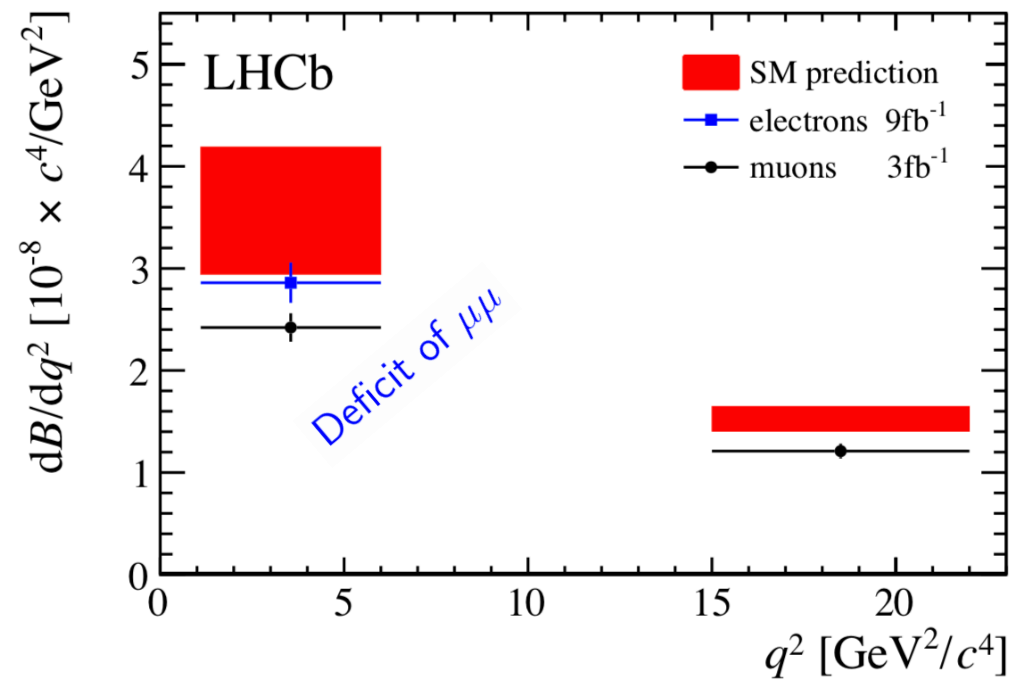
$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2\in[q^2_{\rm min},q^2_{\rm max}]} \quad \& \quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$

- CKM factor cancels
- Bulk of hadronic uncertainties cancel
- $\langle D|\bar{c}\Gamma b|B\rangle$ computed in LQCD for several q^2's
- $\langle D^*|\bar{c}\Gamma b|B\rangle$ in LQCD for several q^2's underway
- $R_{K^{(*)}}$: $q^2 \in [1,6]\,\mathrm{GeV}^2$ to stay away from $\bar{c}c$ resonances
- When no LQCD result, use models (LCSR) but say so!
- Control electromagnetism

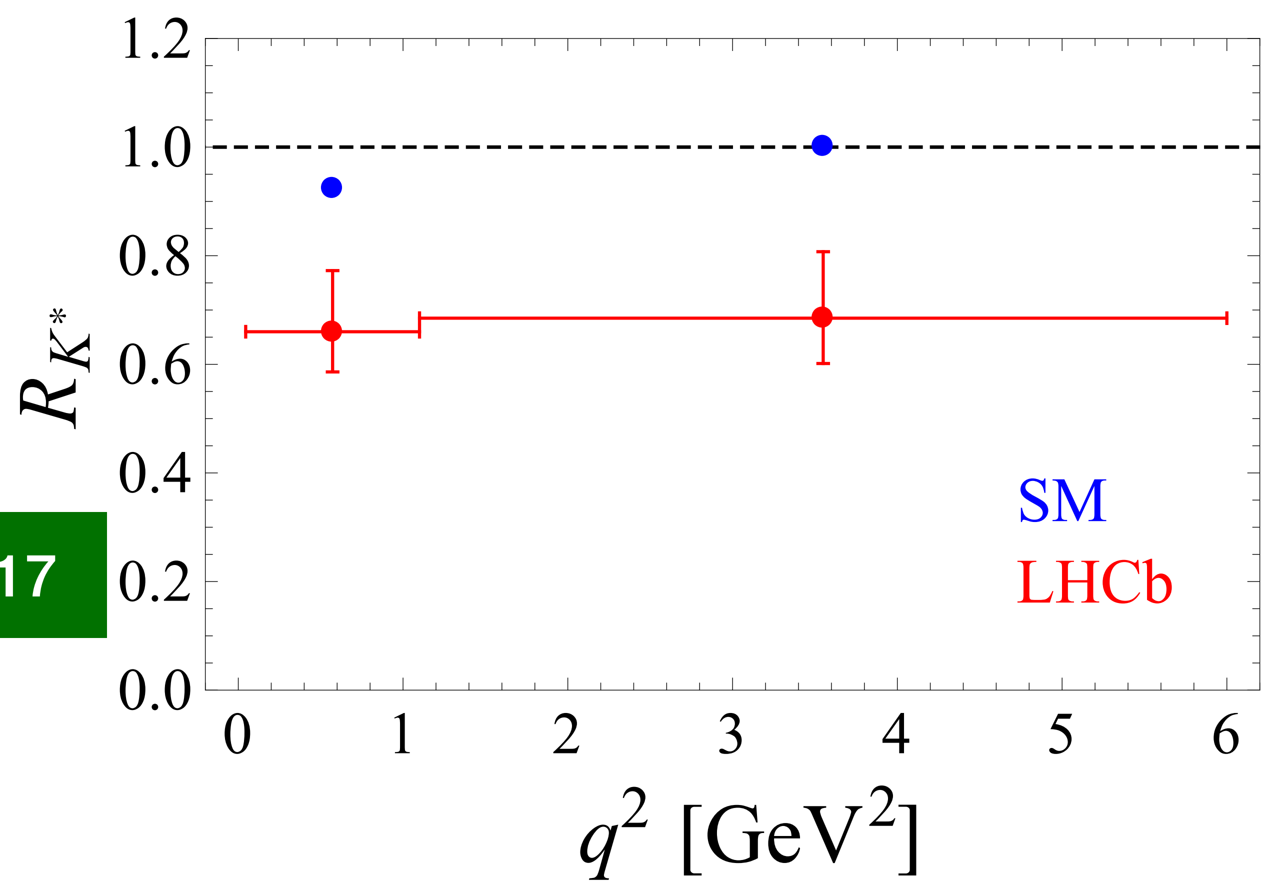
Moriond EW 2021

2021





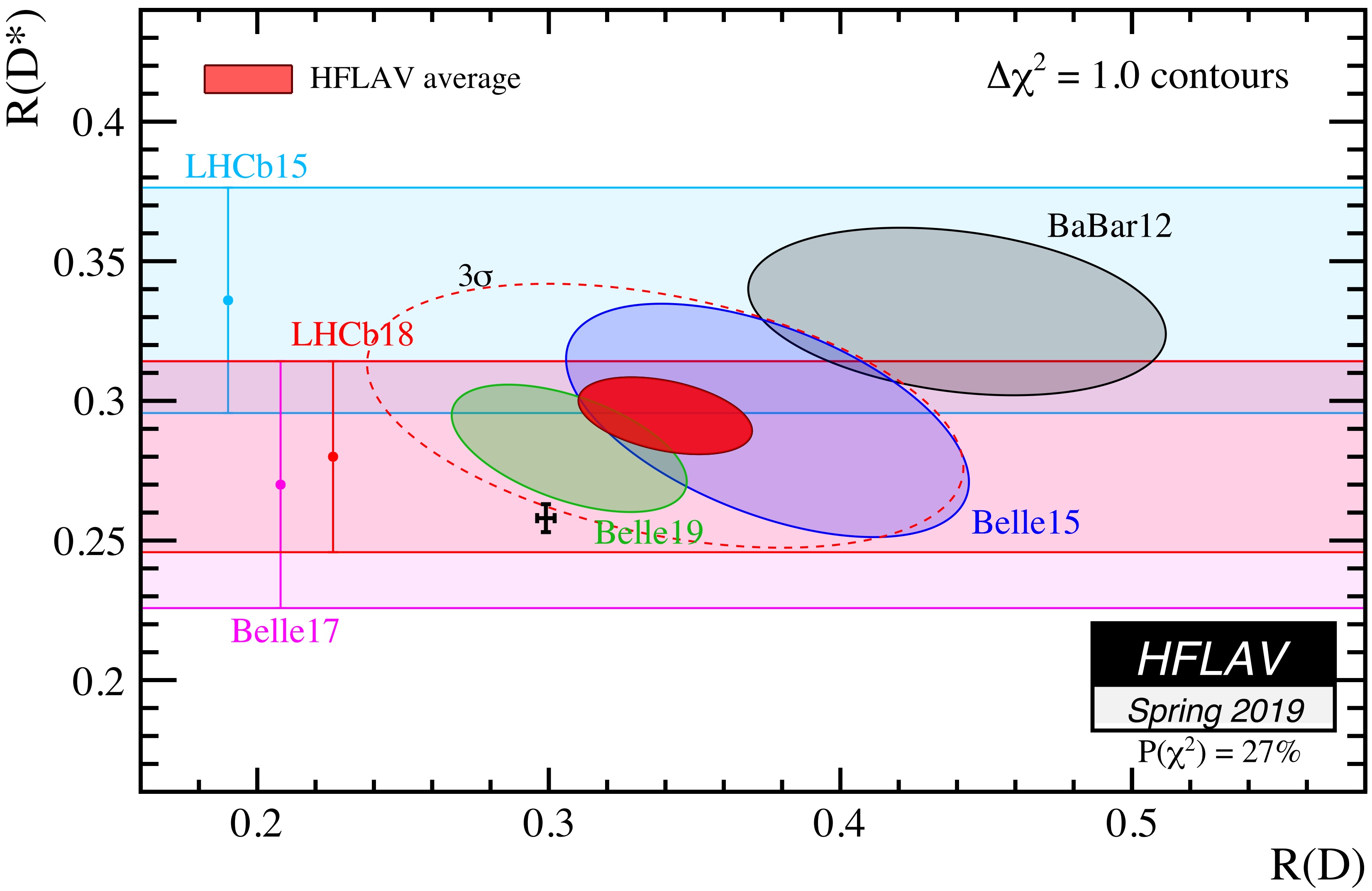
$$R_K^{[1.1,6]} = 0.847(42)^{\text{LHCb}} \quad \text{vs} \quad R_K^{[1,6]} = 1.00(1)^{\text{SM}}$$



2017

$$R_{K^*}^{[1.1,6]} = 0.71(10)^{\text{LHCb}} \quad \text{vs} \quad R_{K^*}^{[1,6]} = 1.00(1)^{\text{SM}}$$

Moriond 2019



$$\text{Exp}: \quad R_D = 0.340 \pm 0.030\,, \quad R_{D^*} = 0.295 \pm 0.014$$

$$\text{SM}: \quad R_D^{\text{SM}} = 0.293 \pm 0.008\,, \quad R_{D^*}^{\text{SM}} = 0.257 \pm 0.003$$

EFT - exclusive $b \to c\ell\nu$

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

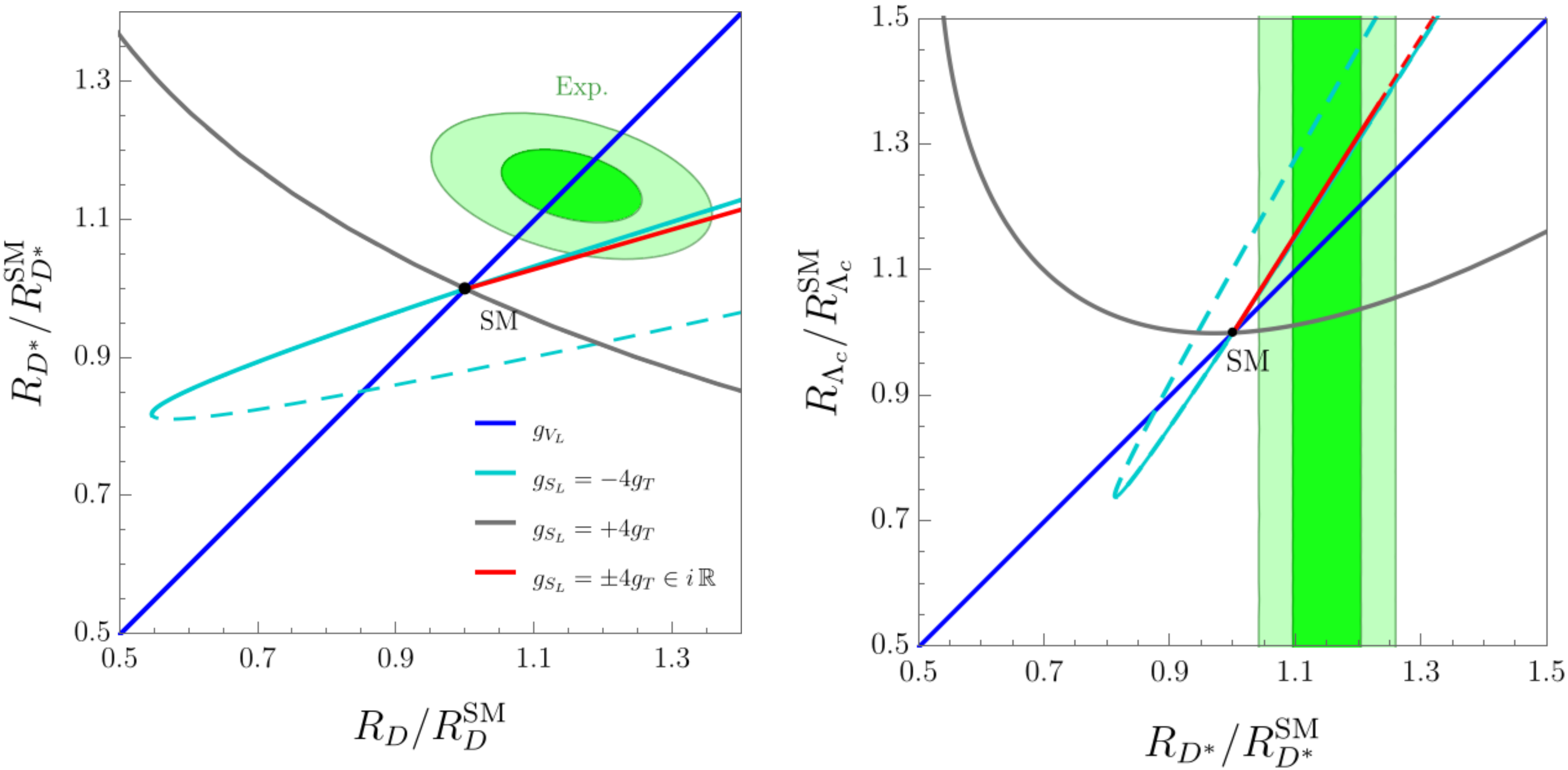
- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:

  $\Rightarrow$ g_{V_R} is LFU at dimension 6 ($W \bar{c}_R b_R$ vertex).

  $\Rightarrow$ Four coefficients left: g_{V_L}, g_{S_L}, g_{S_R} and g_T.

EFT - exclusive $b \to c\ell\nu$

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



EFT - exclusive $b \to c\ell\nu$

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

$g_{V_L}(m_b)$	0.07 ± 0.02	$0.02/1$	✔
$g_{S_R}(m_b)$	-0.31 ± 0.05	$5.3/1$	✘
$g_{S_L}(m_b)$	0.12 ± 0.06	$8.8/1$	✘
$g_T(m_b)$	-0.03 ± 0.01	$3.1/1$	✔
$g_{S_L} = +4g_T \in \mathbb{R}$	-0.03 ± 0.07	$12.5/1$	✘
$g_{S_L} = -4g_T \in \mathbb{R}$	0.16 ± 0.05	$2.0/1$	✔
$g_{S_L} = \pm 4g_T \in i\,\mathbb{R}$	0.48 ± 0.08	$2.4/1$	✔

$\chi^2_{\text{SM}} = 12.7$

EFT - exclusive $b \to c \ell \nu$

$g_{V_L}(m_b)$	0.07 ± 0.02	$0.02/1$	✔
	± 0.05	$5.3/1$	✘
	± 0.06	$8.8/1$	✘
	± 0.01	$3.1/1$	✔
	± 0.07	$12.5/1$	✘
$g_{S_L} = -4 g_T \in \mathbb{R}$	0.16 ± 0.05	$2.0/1$	✔
$g_{S_L} = \pm 4 g_T \in i\,\mathbb{R}$	0.48 ± 0.08	$2.4/1$	✔

Model	$g_{\rm eff}^{b\to c\tau\bar\nu}(\mu = m_\Delta)$	$R_{D^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	g_{V_L}, $g_{S_L} = -4\, g_T$	✓
$R_2 = (3, 2, 7/6)$	$g_{S_L} = 4\, g_T$	✓
$S_3 = (\bar{3}, 3, 1/3)$	g_{V_L}	✗
...	...	...
$U_1 = (3, 1, 2/3)$	g_{V_L}, g_{S_R}	✓
$U_3 = (3, 3, 2/3)$	g_{V_L}	✗
...	...	...

Main worry remain the hadronic uncertainties in the D^* case:
No lattice QCD study regarding the shapes of FFs
Keep also in mind the SD part of the soft photon problem is missing

EFT - exclusive $b \to s\ell\ell$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots} \Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \Big) \right] + \text{h.c.}$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma^5 \ell)$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

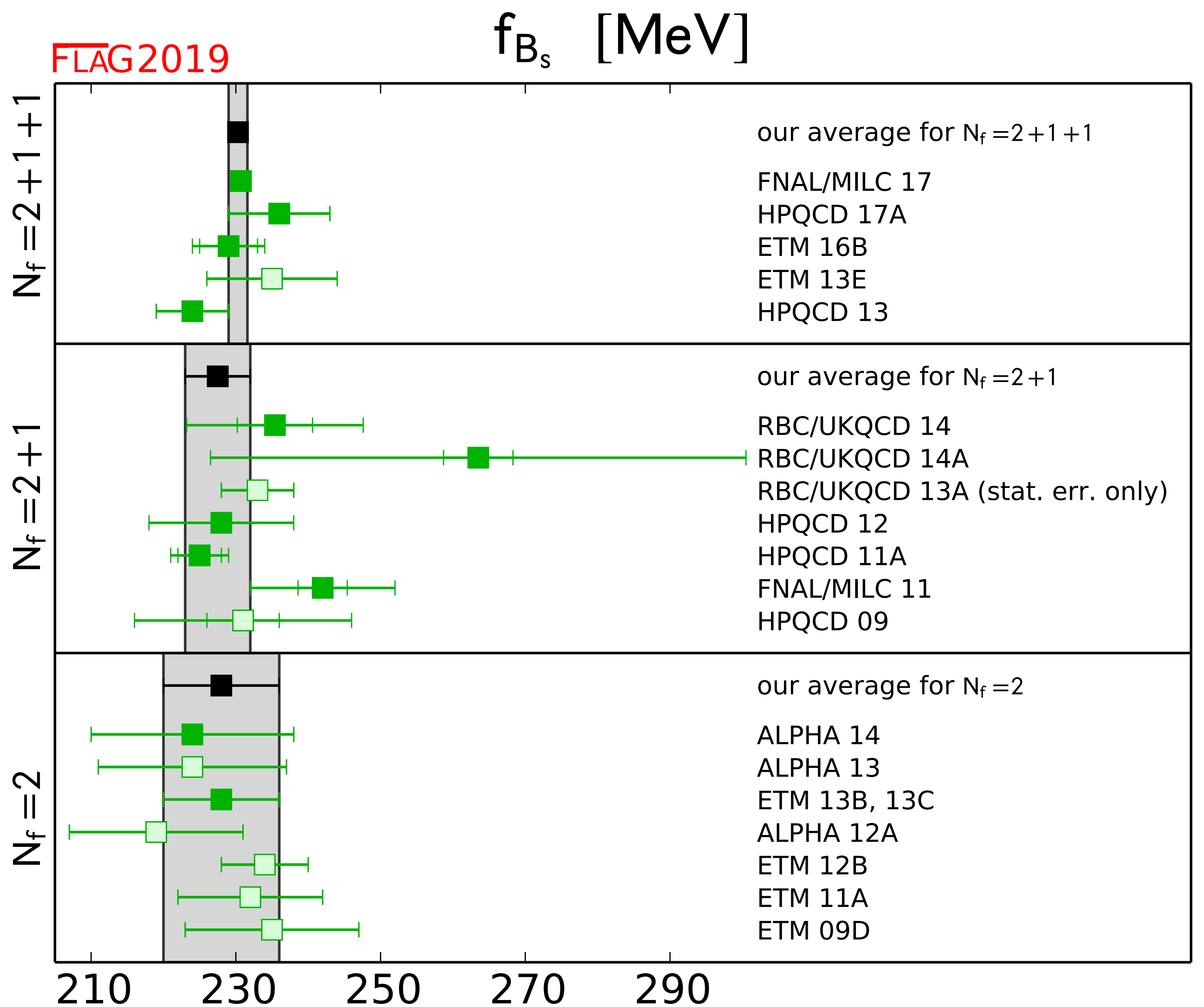
$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

Moriond 2021 LHCb : $\mathcal{B}(B_s \to \mu\mu) = (3.09^{+0.48}_{-0.44}) \times 10^{-9}$

Exp : $\mathcal{B}(B_s \to \mu\mu) = (2.85 \pm 0.33) \times 10^{-9}$

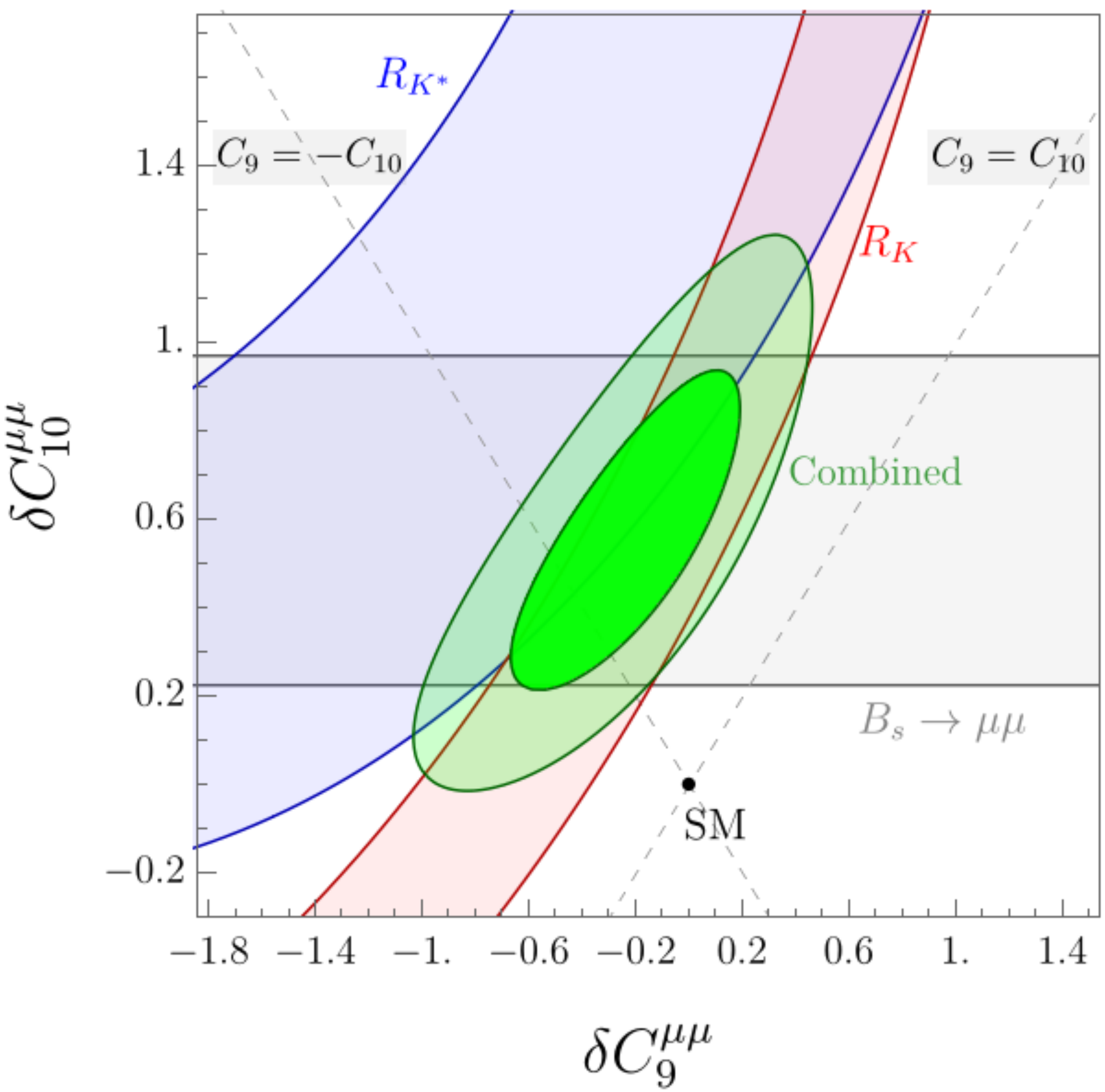
SM : $\mathcal{B}(B_s \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$

$$\langle 0|\bar{s}\gamma^\mu\gamma_5 b|B_s(p)\rangle = i f_{B_s}\, p^\mu$$



cf. updates at http://flag.unibe.ch

Fit to clean quantities: $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$



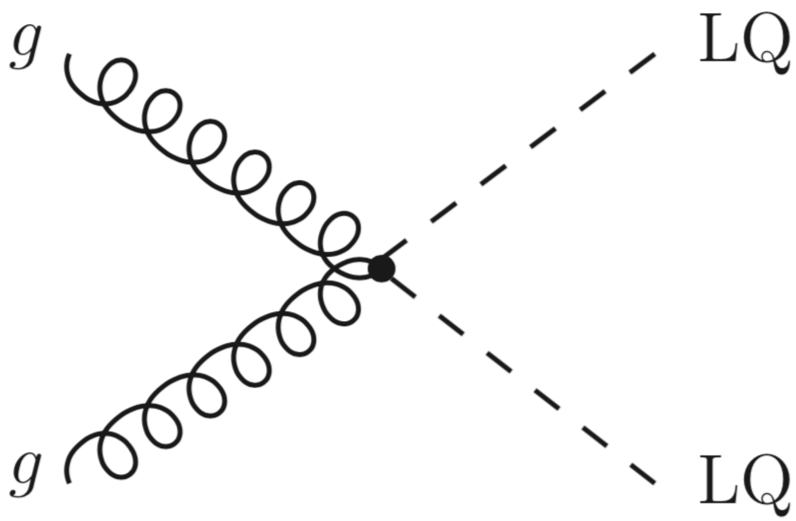
What LQ scenario?

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

N.B. U_1 is the only one to accommodate both!

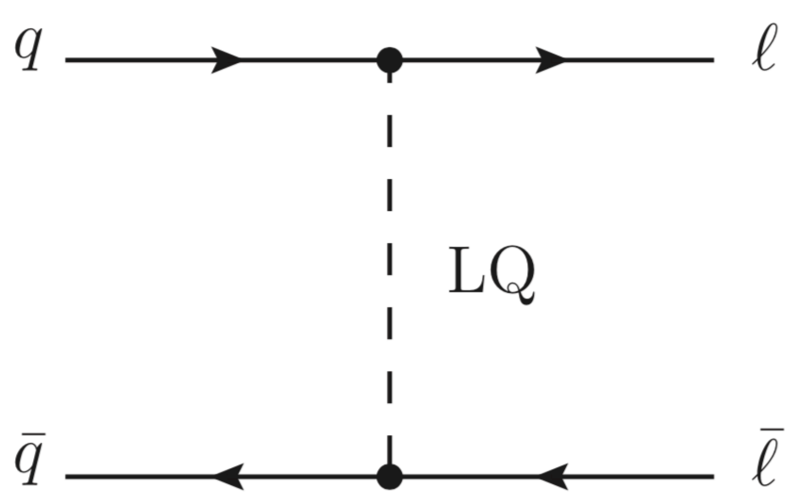
Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

From direct searches
Atlas and CMS 2018-2021

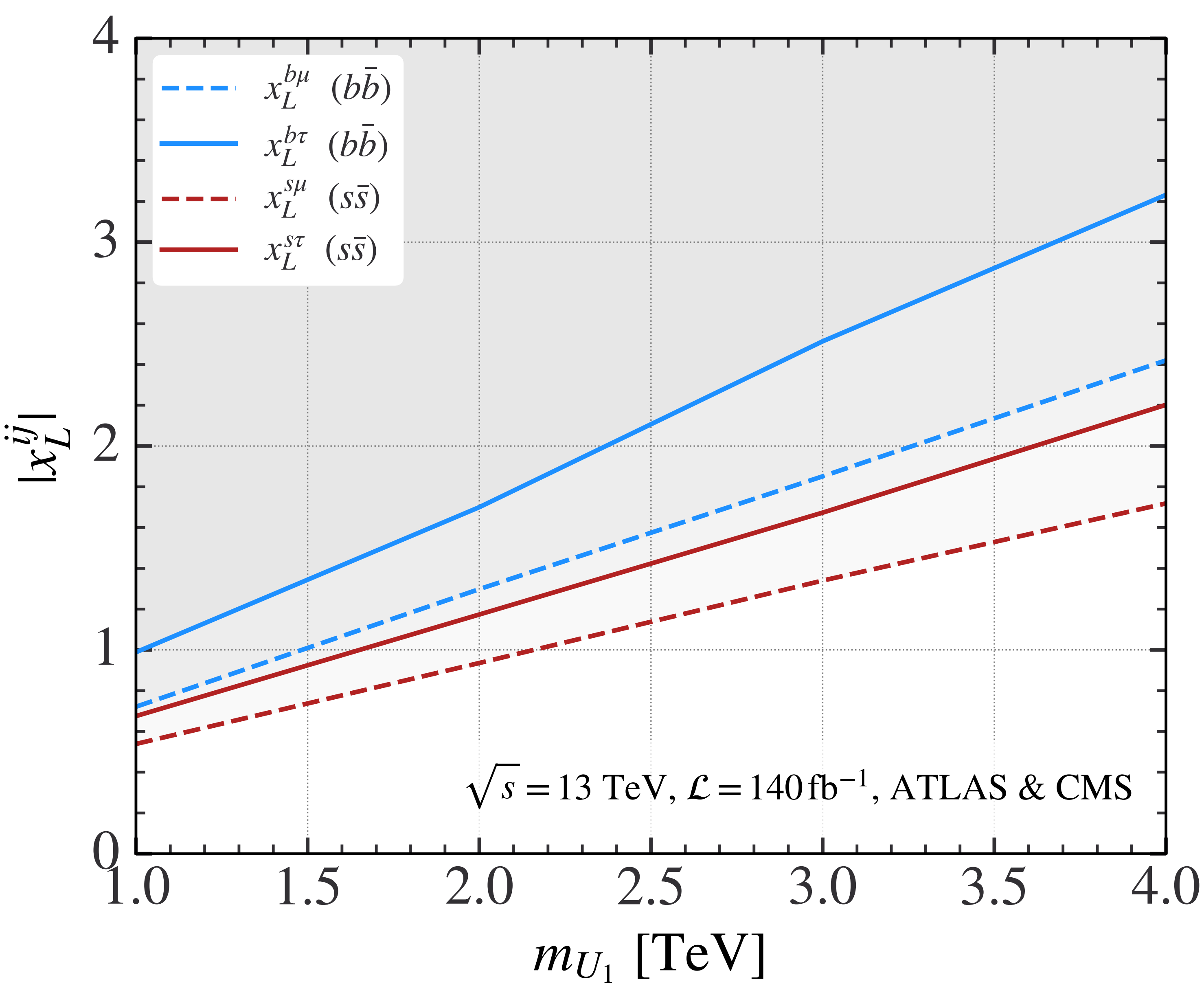


Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1}
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1}
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1}
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV	140 fb^{-1}
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV	140 fb^{-1}
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV	36 fb^{-1}
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV	36 fb^{-1}
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV	140 fb^{-1}

From dilepton spectra at high pT
Atlas and CMS 2018-2020

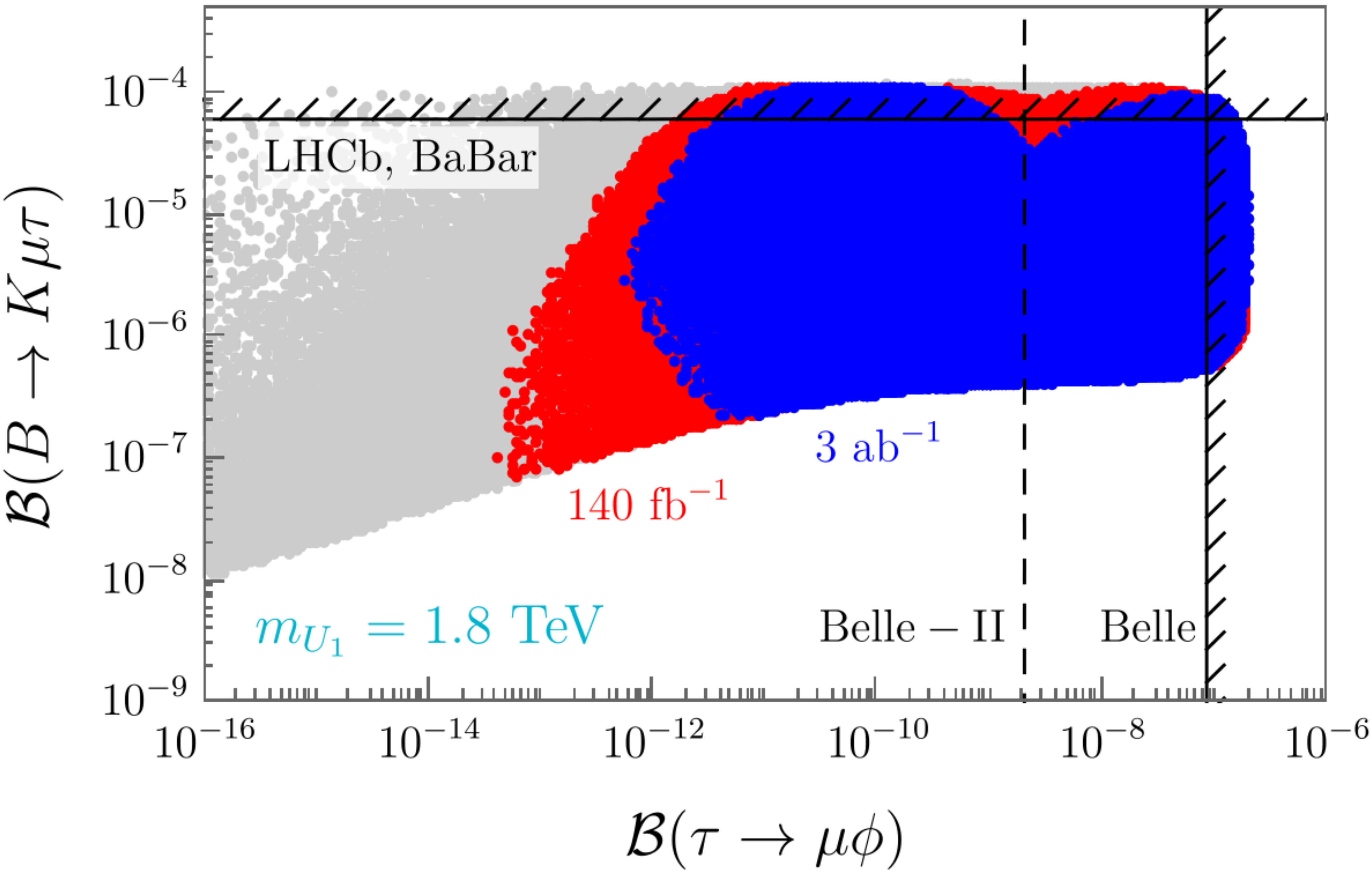


Example U1

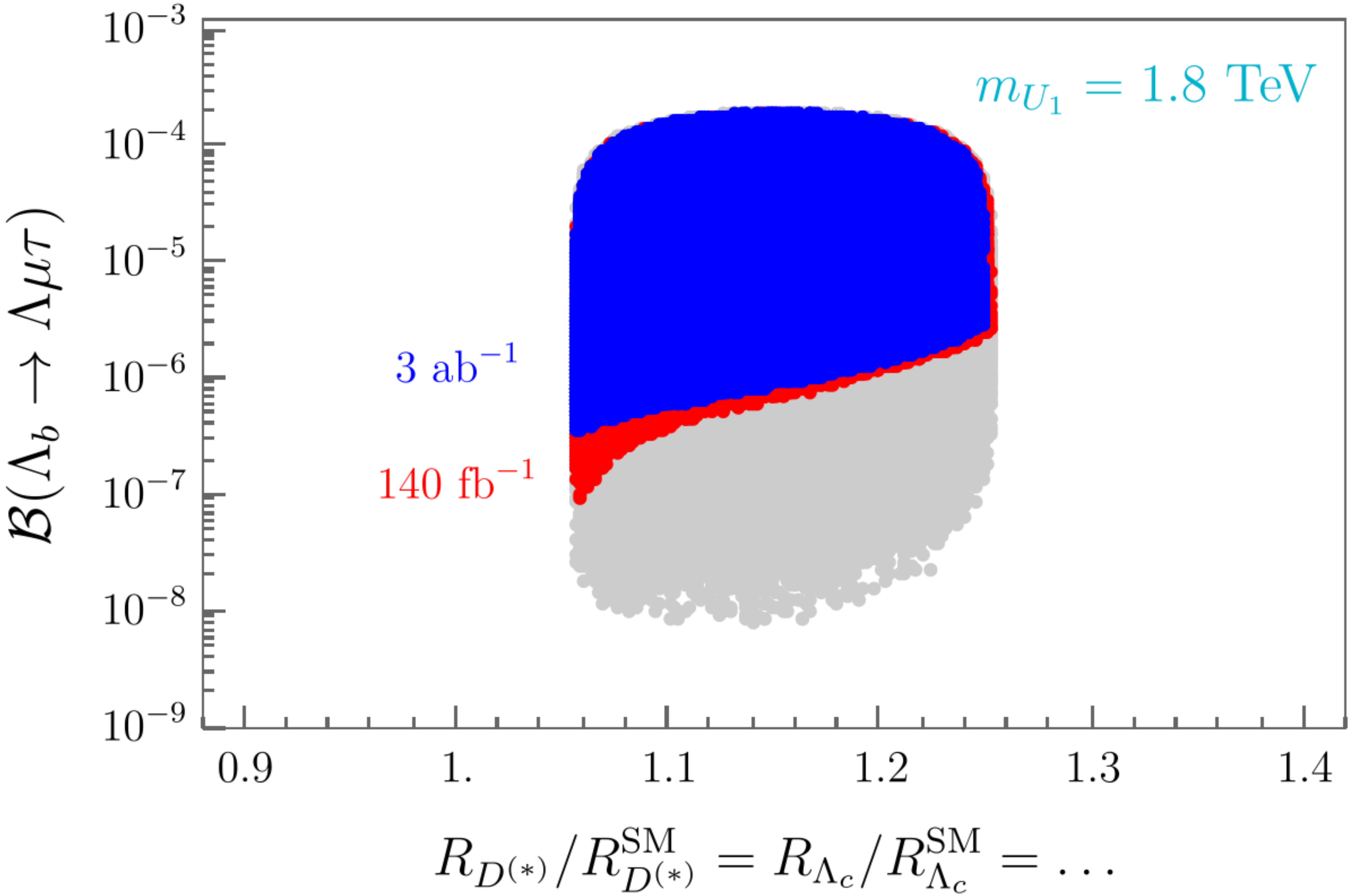


$$\mathcal{L}_{U_1} = x_L^{ij}\, \overline{Q}_i \gamma_\mu L_j\, U_1^\mu + x_R^{ij}\, \overline{d}_{R_i} \gamma_\mu \ell_{Rj} U_1^\mu + \text{h.c.}$$

LFV predictions



LFV predictions



Concerning R2

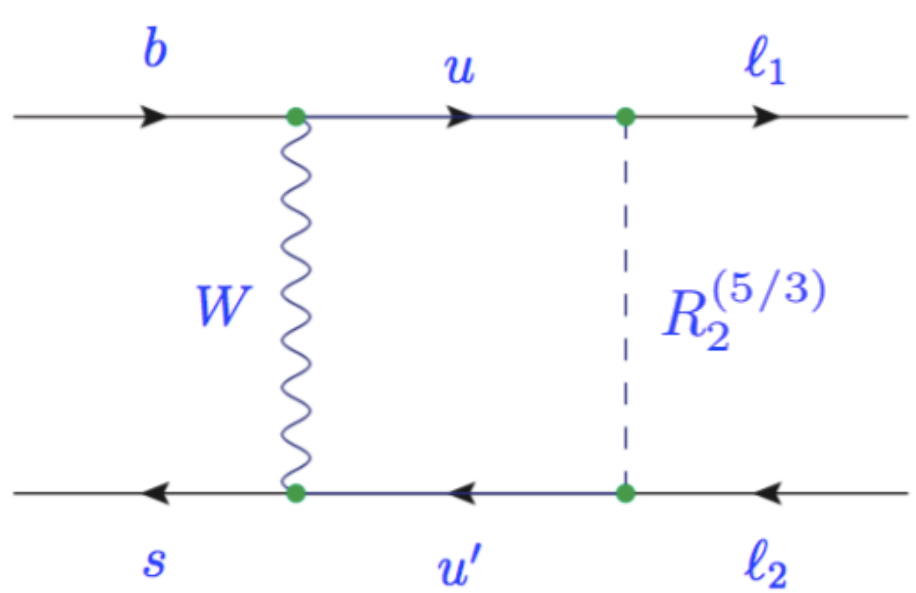
Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

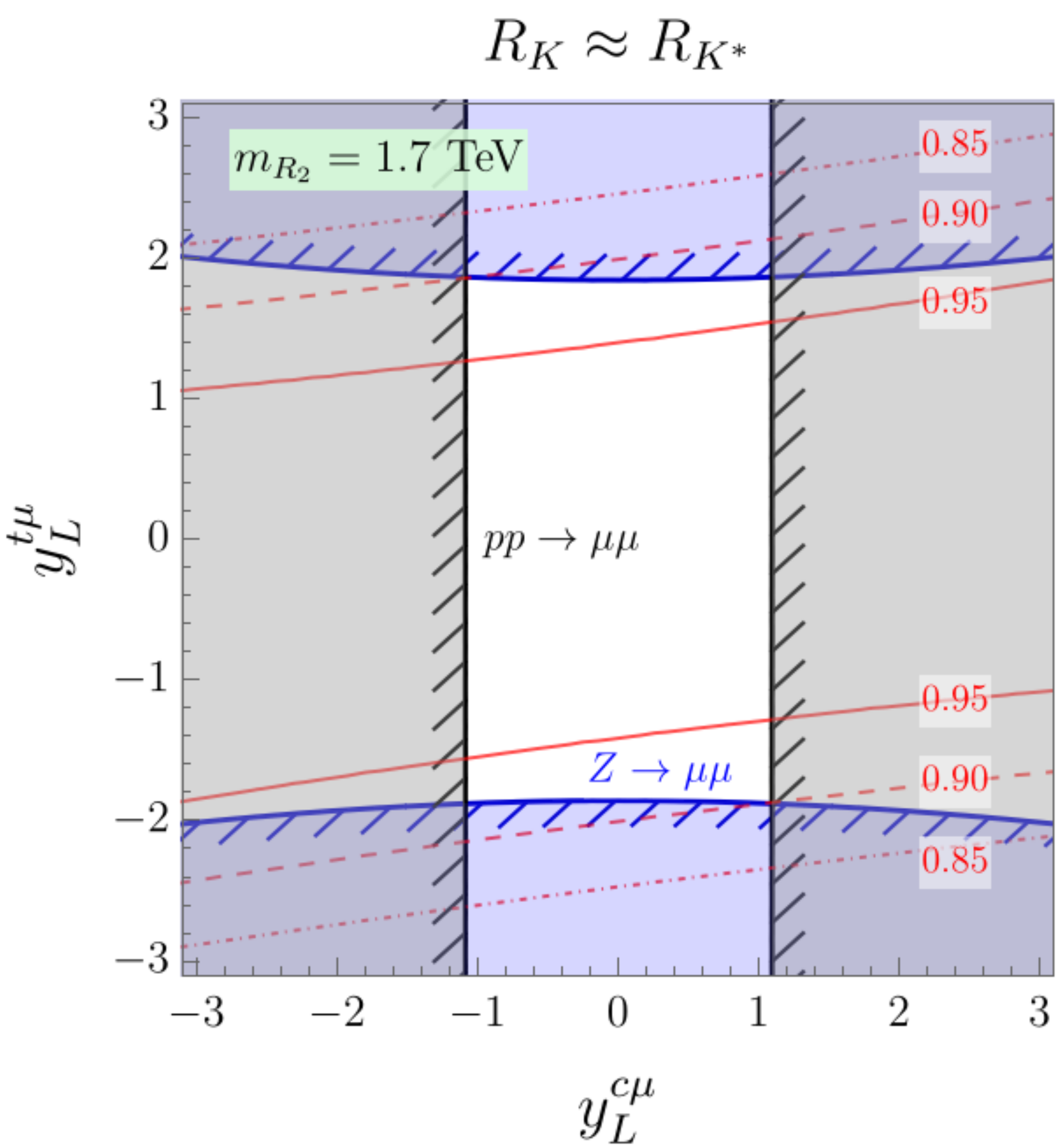
$$\mathcal{L}_{R_2} = y_R^{ij}\, \overline{Q}_i \ell_{Rj}\, R_2 - y_L^{ij}\, \overline{u}_{Ri} R_2 i\tau_2 L_j + \text{h.c.}$$

$$C_9^{kl} = C_{10}^{kl} \stackrel{\text{tree}}{=} -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}} \frac{y_R^{sl}\left(y_R^{bk}\right)^*}{m_{R_2}^2}$$

$$C_9^{kl} = -C_{10}^{kl} \stackrel{\text{loop}}{=} \sum_{u,u'\in\{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k}\left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'})$$

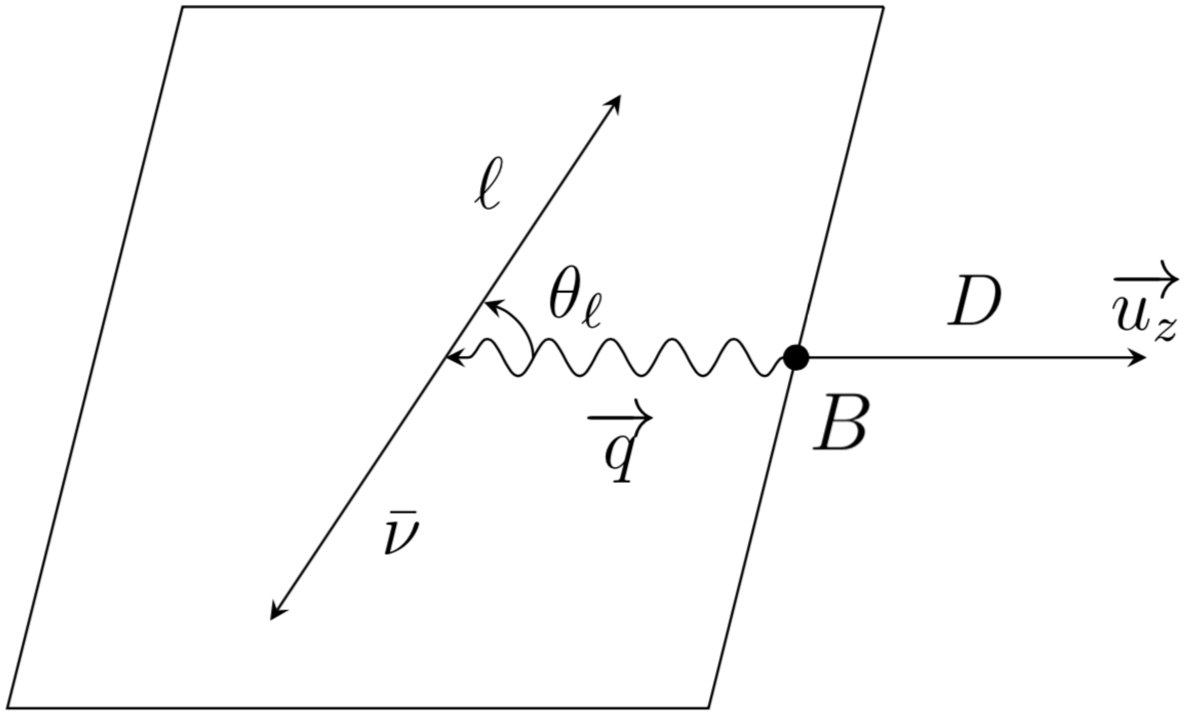
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{t\mu} & 0 \end{pmatrix}, \qquad y_R = 0$$





Other clean observables

- Through angular distribution of $B \to D^*(\to D\pi)\ell\nu$ once the normalization and shapes of all form factors become available
- Angular distribution of $B \to D\ell\nu$
- Many opportunities in $\Lambda_b \to \Lambda_c\ell\nu$



$$\frac{\mathrm{d}\mathcal{B}^{\pm}(q^2)}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} = a^{\pm}(q^2) + b^{\pm}(q^2)\ \cos\theta_\ell + c^{\pm}(q^2)\ \cos^2\theta_\ell\,,$$

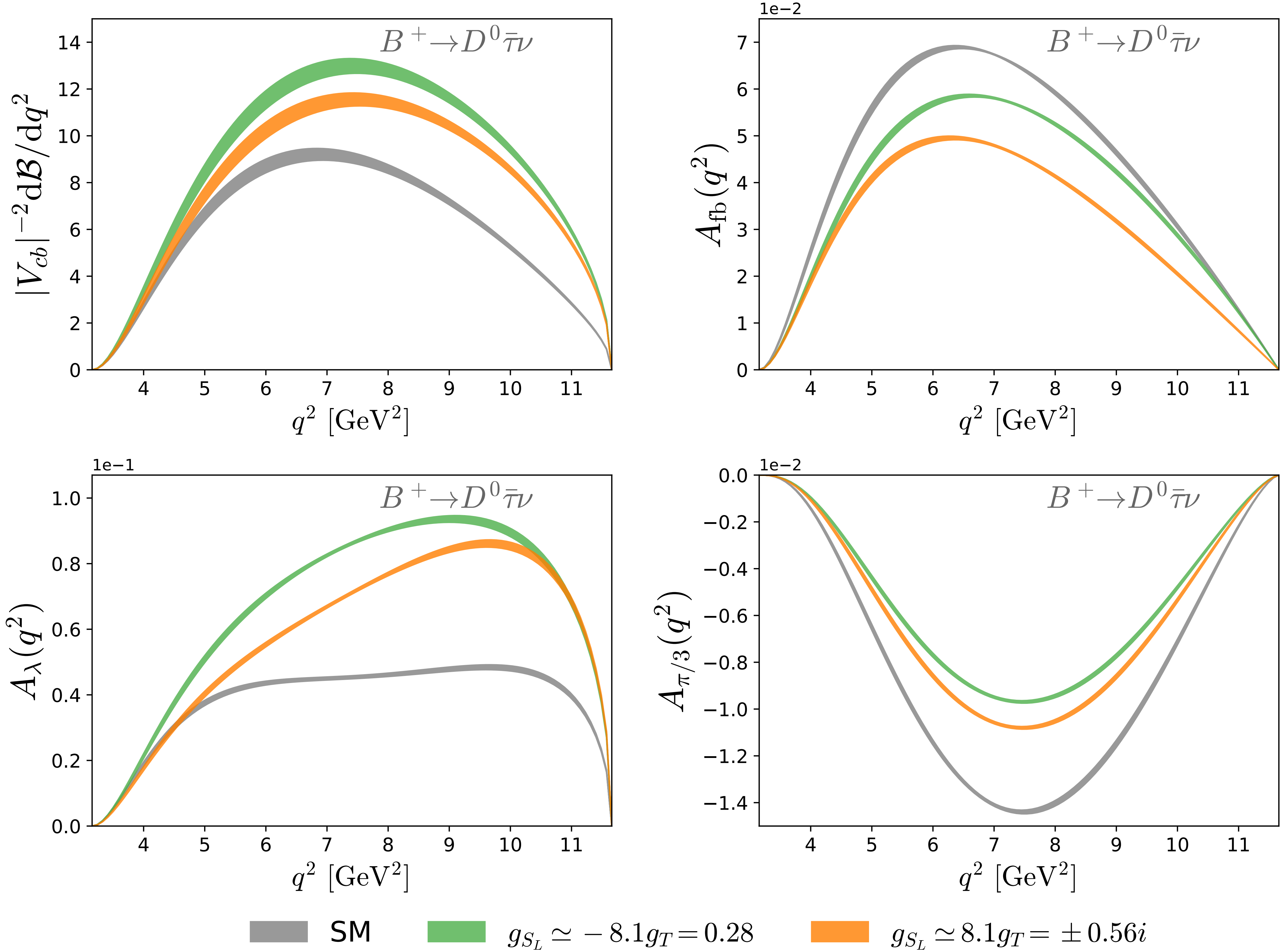
Other clean observables

$$\frac{\mathrm{d}A_{\mathrm{fb}}(q^2)}{\mathrm{d}q^2} = \frac{1}{\mathcal{B}_{\mathrm{tot}}}\left[\int_0^1 \mathrm{d}\cos\theta_\ell \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} - \int_{-1}^0 \mathrm{d}\cos\theta_\ell \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell}\right] = \frac{b(q^2)}{\mathcal{B}_{\mathrm{tot}}}$$

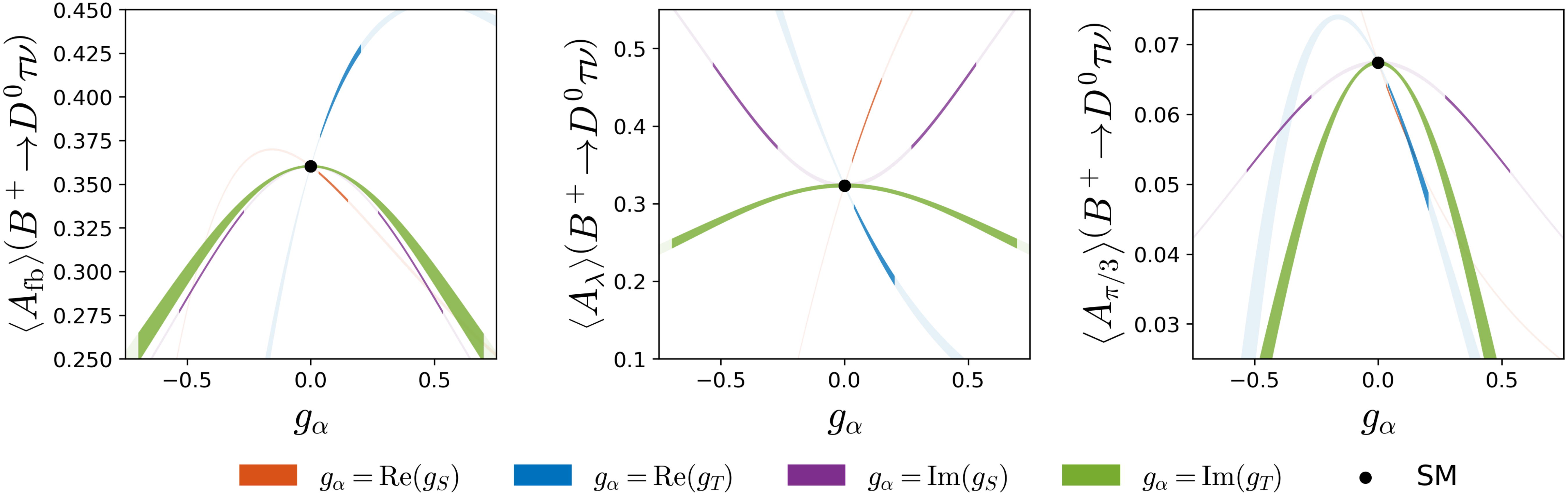
$$\frac{\mathrm{d}A_\lambda(q^2)}{\mathrm{d}q^2} = \frac{2}{\mathcal{B}_{\mathrm{tot}}}\left[a^+(q^2) - a^-(q^2) + \frac{1}{3}\Big(c^+(q^2) - c^-(q^2)\Big)\right]$$

$$\frac{\mathrm{d}A_{\pi/3}(q^2)}{\mathrm{d}q^2} = \frac{c(q^2)}{2\,\mathcal{B}_{\mathrm{tot}}}$$

Other clean observables



Other clean observables



Summary and Perspectives

- As of now, indications of LFUV in B decays are surviving experimental scrutiny
- New LHCb data on $\mathcal{B}(B_s \to \mu\mu)$ and R_K corroborate the picture that the plausible scenarios describing deficit of $b \to s\mu\mu$ verify $\delta C_9 \neq 0$, and $\delta C_9 = -\delta C_{10} < 0$ in particular
- Several options for describing the surplus of $b \to c\tau\nu$
- Experimental opportunities in angular observables relevant to $B \to D^{(*)}\ell\nu$ and $\Lambda_b \to \Lambda_c \ell\nu$
- Current precision of HME in $P \to P'\ell\nu$ help us predict 3 observables for which there are no experimental studies yet
- Combining EFT, direct searches, and bounds from high p_T dilepton spectra at LHC help rule out some minimalistic leptoquark scenarios
- Way to go 1: Vector LQ despite non-renormalizability [UV completion, potential proliferation of parameters or assumptions]
- Way to go 2: Combine 2 scalar LQs: S_3 with S_1 or S_3 with R_2
- References given in arXiv: 2012.09872 and 2103.12504, plus the speakers of today sessions