Workshop Italiano sulla Fisica delle Alte Intensità - 2023

B rare decays: theory overview

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Introduction

- Among the several accidental symmetries of the Standard Model, a particularly interesting one is the absence of tree-level Flavour Changing Neutral Currents (FCNC)

- These decays occur at loop-level, and are both GIM- and CKM-suppressed: very rare, hence fundamental probe of heavy NP effects

- Indeed, since no NP has been (so far) directly observed at colliders, is fundamental to have input from indirect searches where BSM appears through virtual, intermediate states

Overview

- $B \to \tau\nu$
- $B \to \mu\mu$
- $B \to K^{(*)}\nu\nu$
- $B \to K^{(*)}\ell\ell, B_s \to \phi\ell\ell$
- $b \to s\gamma$

$B \to \tau\nu$: the SM status

- Helicity suppressed, tree-level decay

- Main uncertainties come from CKM elements (UTA) and decay constants (Lattice)

$$\mathcal{B}(B_q^+ \to \tau^+\nu_\tau)^{\rm SM} = \tau_{B_q^+} \frac{G_F^2 |V_{qb}|^2 f_{B_q^+}^2 m_{B_q^+} m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_q^+}^2}\right)^2, \quad q = u, c$$

$|V_{cb}|^{\rm UTA} = 42.22(51) \times 10^{-3}, f_{B_c} = 427(6)$ MeV

$|V_{ub}|^{\rm UTA} = 3.70(11) \times 10^{-3}, f_{B^+} = 190.0(1.3)$ MeV

$$\Rightarrow \begin{aligned} \mathcal{B}(B_c^+ \to \tau^+\nu_\tau)^{\rm SM} &= 2.29(9) \times 10^{-2} \\ \mathcal{B}(B^+ \to \tau^+\nu_\tau)^{\rm SM} &= 0.87(5) \times 10^{-4} \end{aligned}$$

According to present Lattice estimates, decay constants errors could be halved in the next decade!

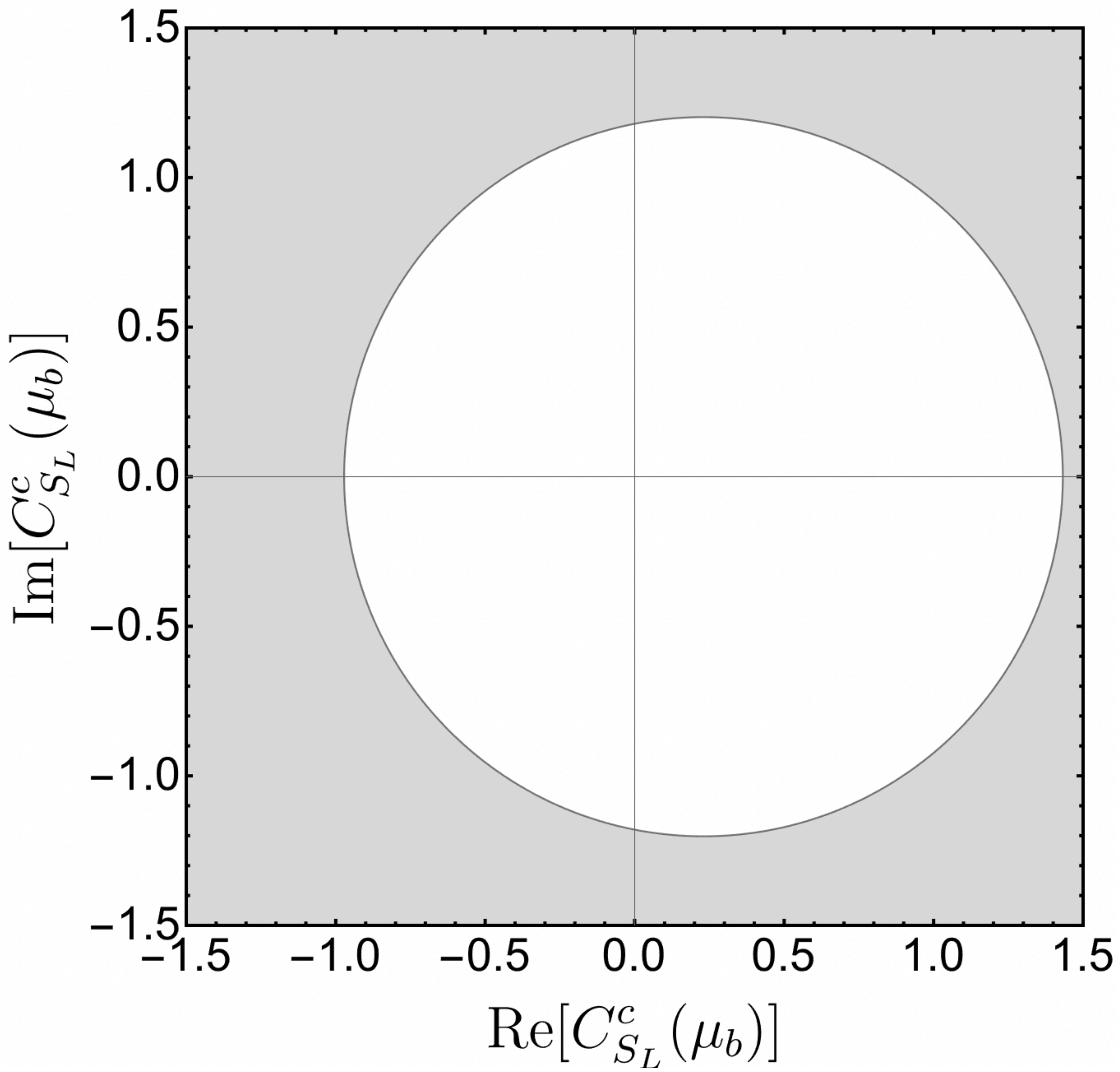
$B \to \tau\nu$: NP implications

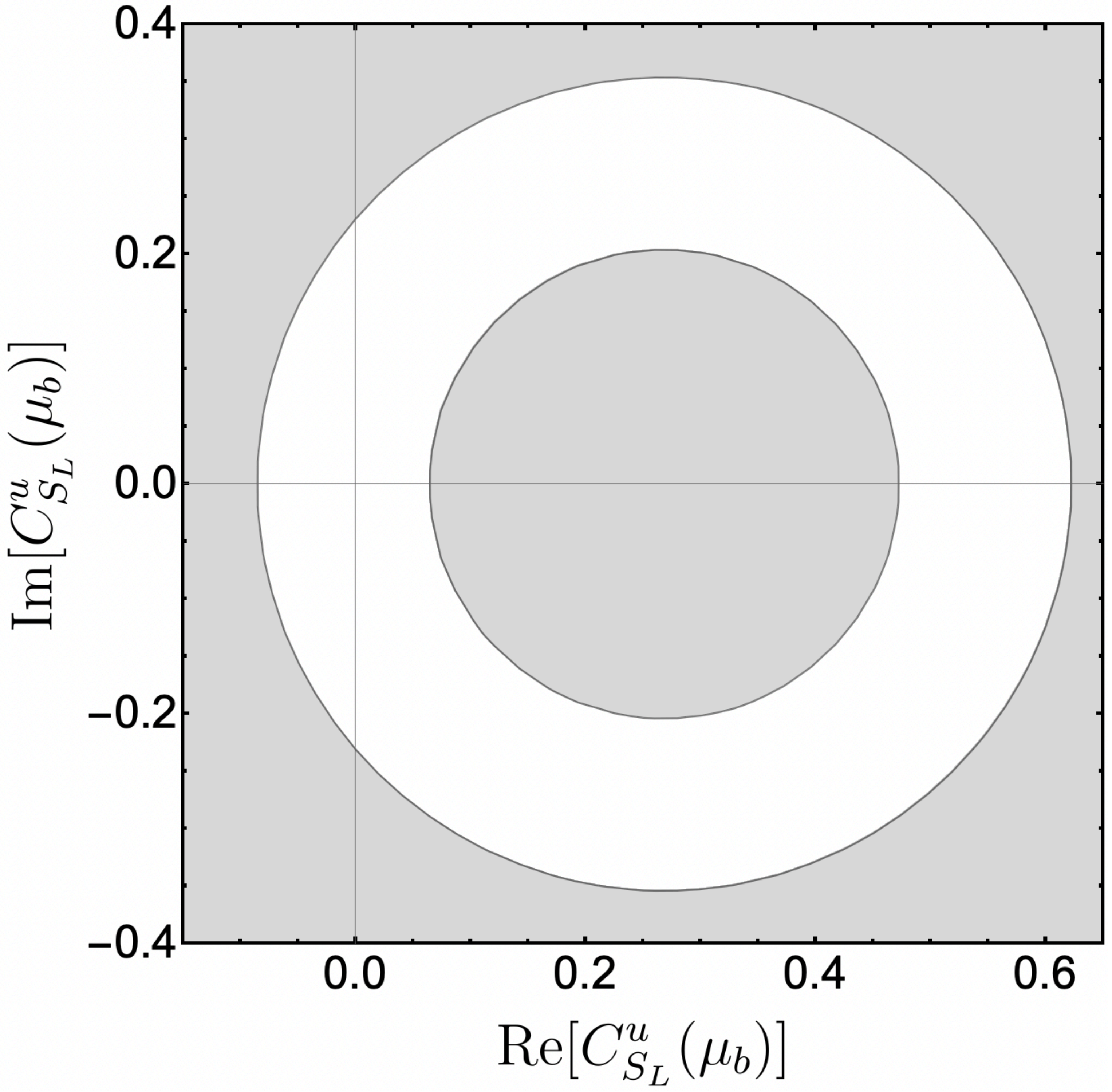
Extremely sensitive to scalar BSM extensions (2HDM, LQ), which lift helicity suppression

$$\mathcal{B}(B_q^+ \to \tau^+\nu_\tau) = \mathcal{B}(B_q^+ \to \tau^+\nu_\tau)^{\rm SM} \times \left| 1 - (C_{V_R}^q - C_{V_L}^q) + (C_{S_R}^q - C_{S_L}^q)\,\frac{m_{B_q}^2}{m_\tau(m_b + m_q)} \right|^2$$

$$O_{V_{L(R)}} = (\bar{q}_{L(R)}\gamma_\mu b_{L(R)})(\bar{\tau}_L\gamma_\mu\nu_L)$$

$$O_{S_{L(R)}} = (\bar{q}_{R(L)} b_{L(R)})(\bar{\tau}_R\nu_L)$$





Constraints on C_{S_R} obtained by Re → -Re

$B \to \mu\mu$: the SM status

- Helicity suppressed, loop-level decay dominated by short-distance effects (C_{10})
- Main uncertainties come from CKM elements (UTA) and decay constants (Lattice)

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-)^{\rm SM} = \tau_{B_q^0} \frac{G_F^4 |V_{tb}^* V_{tq}|^2 f_{B_q}^2 m_W^4 m_{B_q^0} m_\mu^2}{2\pi^5} \sqrt{1 - \frac{4m_\mu^2}{m_{B_q^0}^2}} |C_{10}^{\rm q,SM}|^2, \quad q = d, s$$

$|V_{td}|^{\rm UTA} = 8.59(11) \times 10^{-3}, f_{B_d} = 190.5(1.3)$ MeV

$|V_{ts}|^{\rm UTA} = 41.28(46) \times 10^{-3}, f_{B_s} = 230.1(1.2)$ MeV

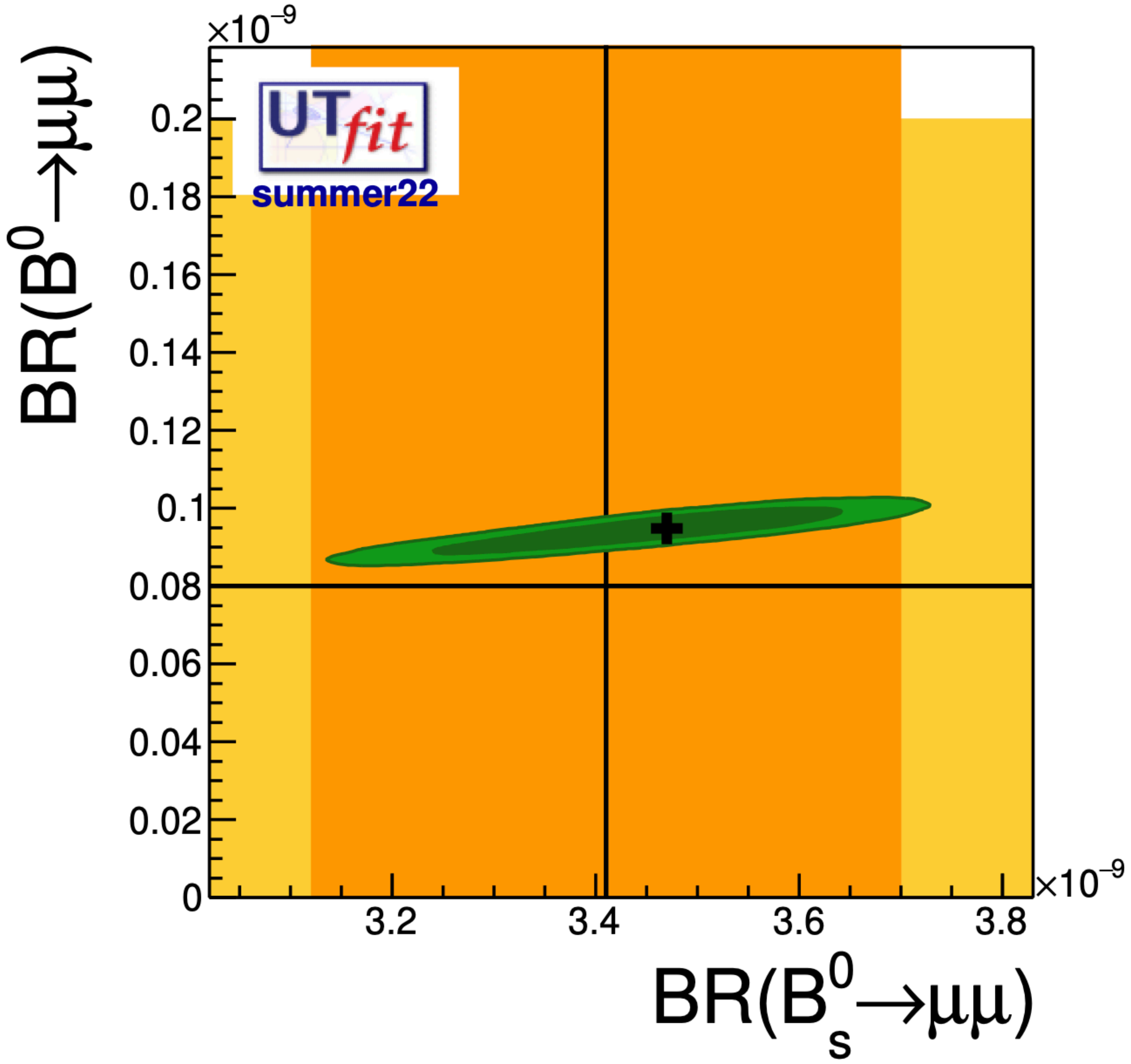
$$\Rightarrow \quad \begin{aligned} \mathcal{B}(B_d \to \mu^+\mu^-)^{\rm SM} &= 9.48(36) \times 10^{-11} \\ \mathcal{B}(B_s \to \mu^+\mu^-)^{\rm SM} &= 3.47(14) \times 10^{-9} \end{aligned}$$

According to present Lattice estimates, decay constants errors could be halved in the next decade!

$B \to \mu\mu$: NP implications

Sensitive to BSM effect on axial and (pseudo)scalar operators, which again lift helicity suppression

$$\mathcal{B}(B_q \to \mu^+\mu^-) = \mathcal{B}^{\rm SM} \times \left(\left| \frac{C_{10}^{q,\rm NP} - C_{10}^{\prime q,\rm NP}}{C_{10}^{q,\rm SM}} + \frac{m_{B_q}^2}{2m_\mu m_b} \frac{C_P^{q,\rm NP} - C_P^{\prime q,\rm NP}}{C_{10}^{q,\rm SM}} \right|^2 + \left| \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{m_{B_q}^2}{2m_\mu m_b} \frac{C_S^{q,\rm NP} - C_S^{\prime q,\rm NP}}{C_{10}^{q,\rm SM}} \right|^2 \right)$$



Current results are (now) in perfect agreement with SM prediction, NP strongly constrained

⇓

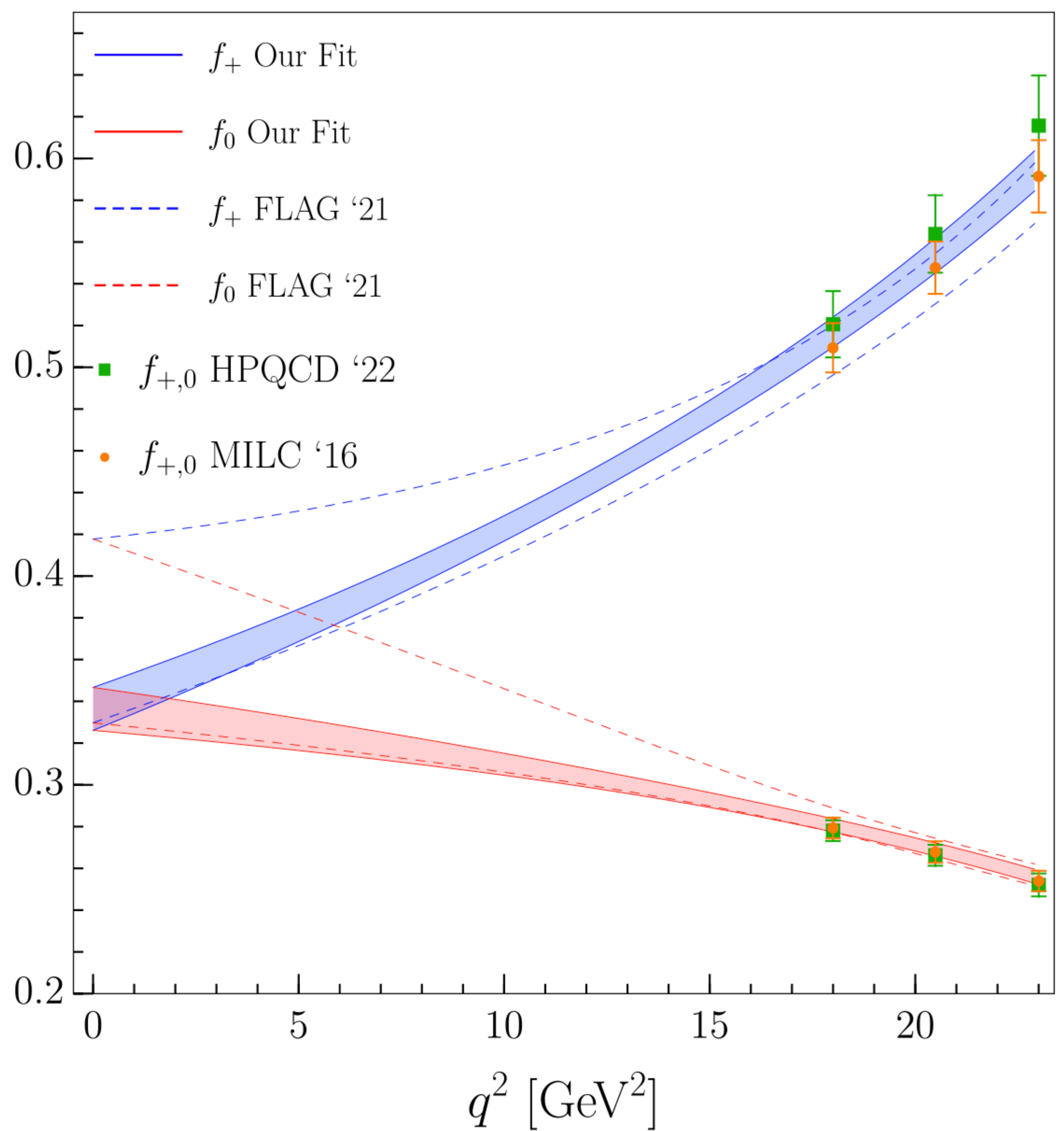
Fundamental player in global fit to $b \to s\ell\ell$ transitions (in a few slides)

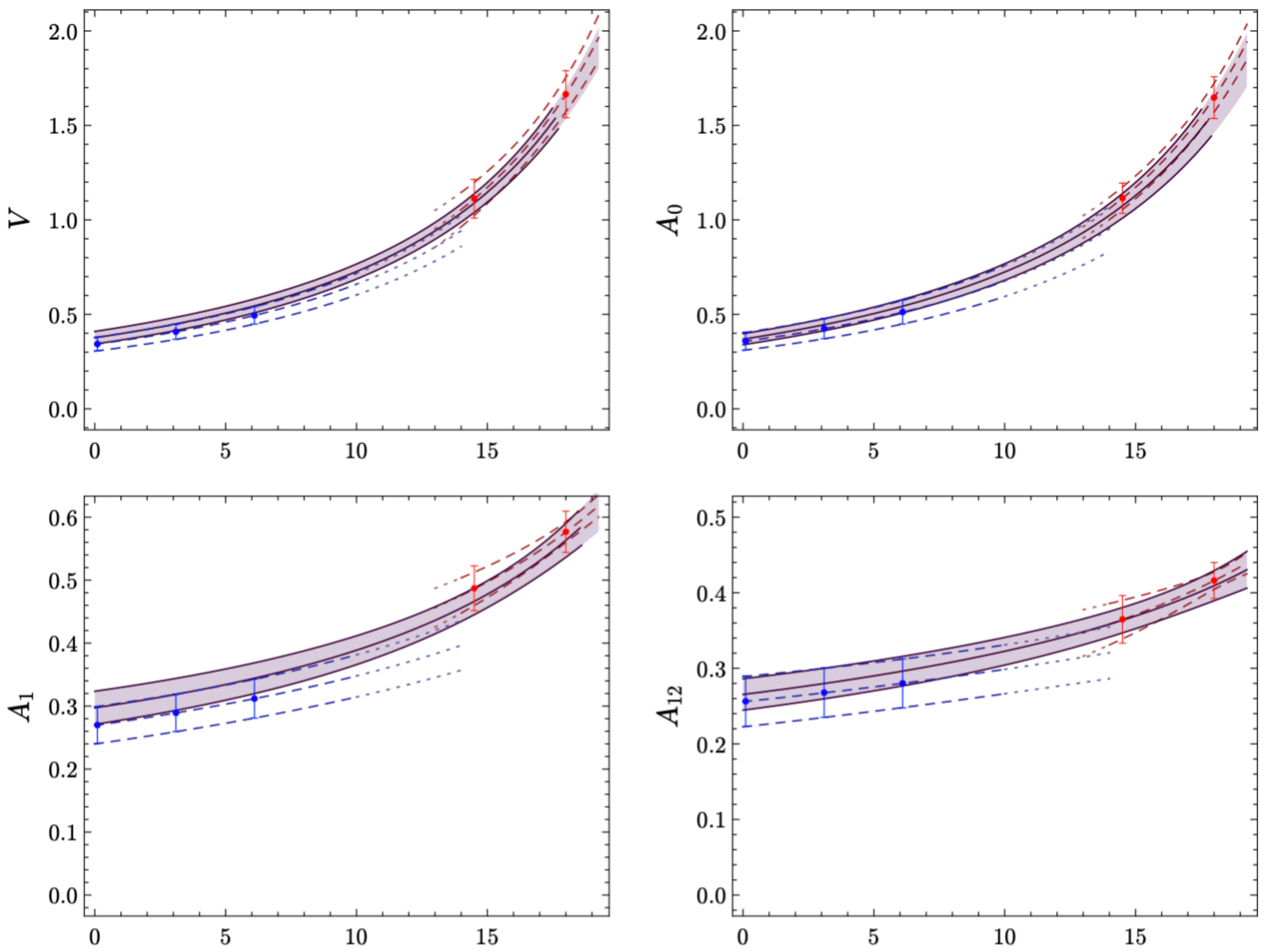
$B \to K^{(*)}\nu\nu$: the SM status

- Loop-level decay dominated by short-distance effects (C_L), negligible long-distance
- Main uncertainties as the ones from $B_s \to \mu\mu$, plus additional ones from Form Factors (Lattice)

$$\langle \bar{K}(k)|\bar{s}\gamma^\mu b|\bar{B}(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right] f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2} q^\mu f_0(q^2)$$

$$\langle \bar{K}^*(k)|\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}(p)\rangle = \varepsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}p^\rho k^\sigma \frac{2V(q^2)}{m_B + m_{K^*}} - i\varepsilon^*_\mu(m_B + m_{K^*})A_1(q^2) + i(p+k)_\mu(\varepsilon^*\cdot q)\frac{A_2(q^2)}{m_B + m_{K^*}} + iq_\mu(\varepsilon^*\cdot q)\frac{2m_{K^*}}{q^2}\left[A_3(q^2) - A_0(q^2)\right]$$





$B \to K^{(*)}\nu\nu$: the SM status

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to K\nu\bar{\nu}) = \mathcal{N}_K(q^2)\,|C_L^{\mathrm{SM}}|^2\,|\lambda_t|^2\,\left[f_+(q^2)\right]^2$$

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to K^*\nu\bar{\nu}) = \mathcal{N}_{K^*}(q^2)|C_L^{\mathrm{SM}}|^2|\lambda_t|^2\mathcal{F}(q^2)$$

$$\mathcal{O}_L^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)$$

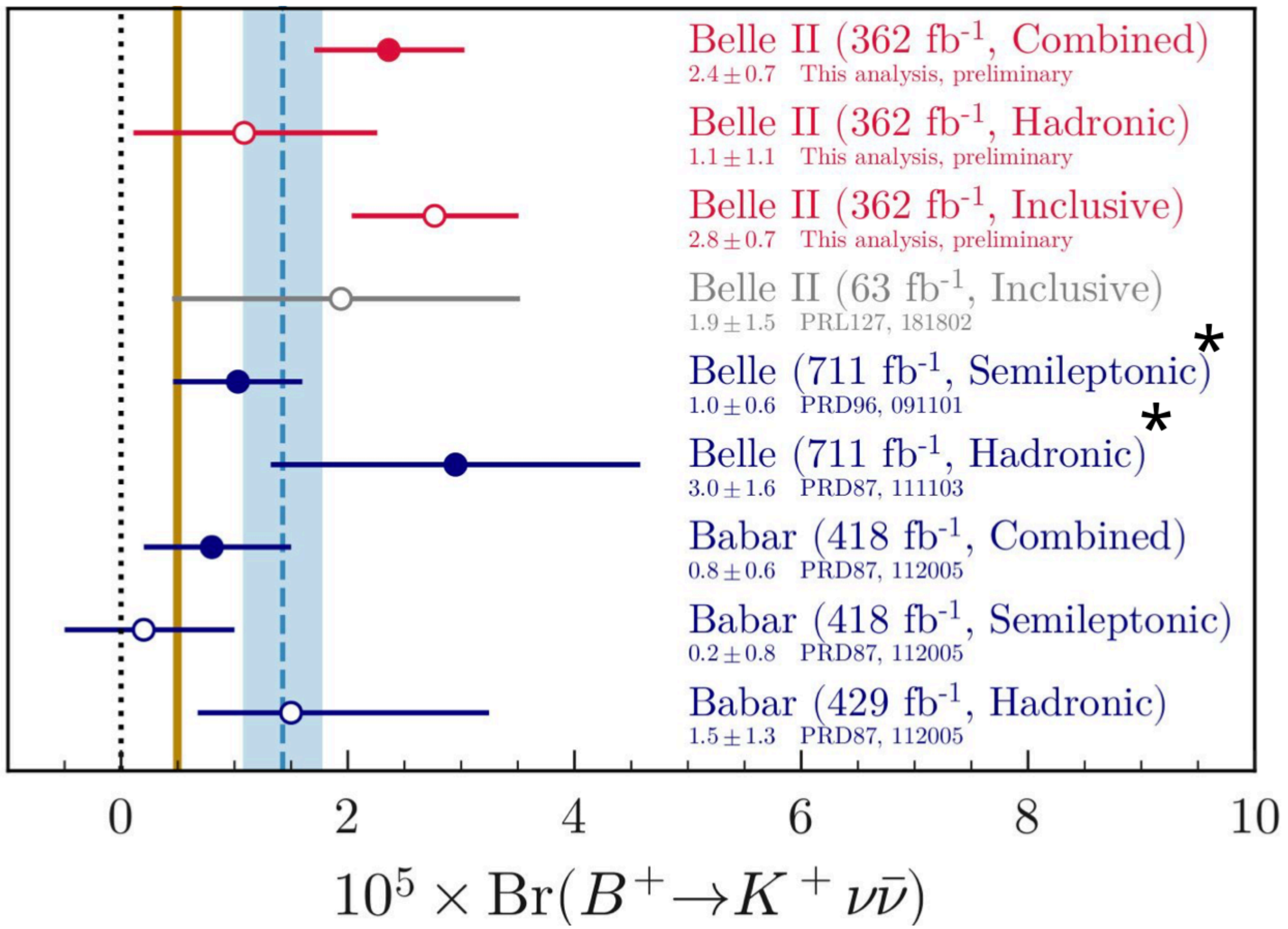
$$\mathcal{O}_R^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)$$

$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K^+}}/\mathcal{B}_{K^+}$	$\mathcal{B}(B^0 \to K_S\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K_S}}/\mathcal{B}_{K_S}$
$(5.06 \pm 0.14 \pm 0.28)$	0.06	$(2.05 \pm 0.07 \pm 0.12)$	0.07

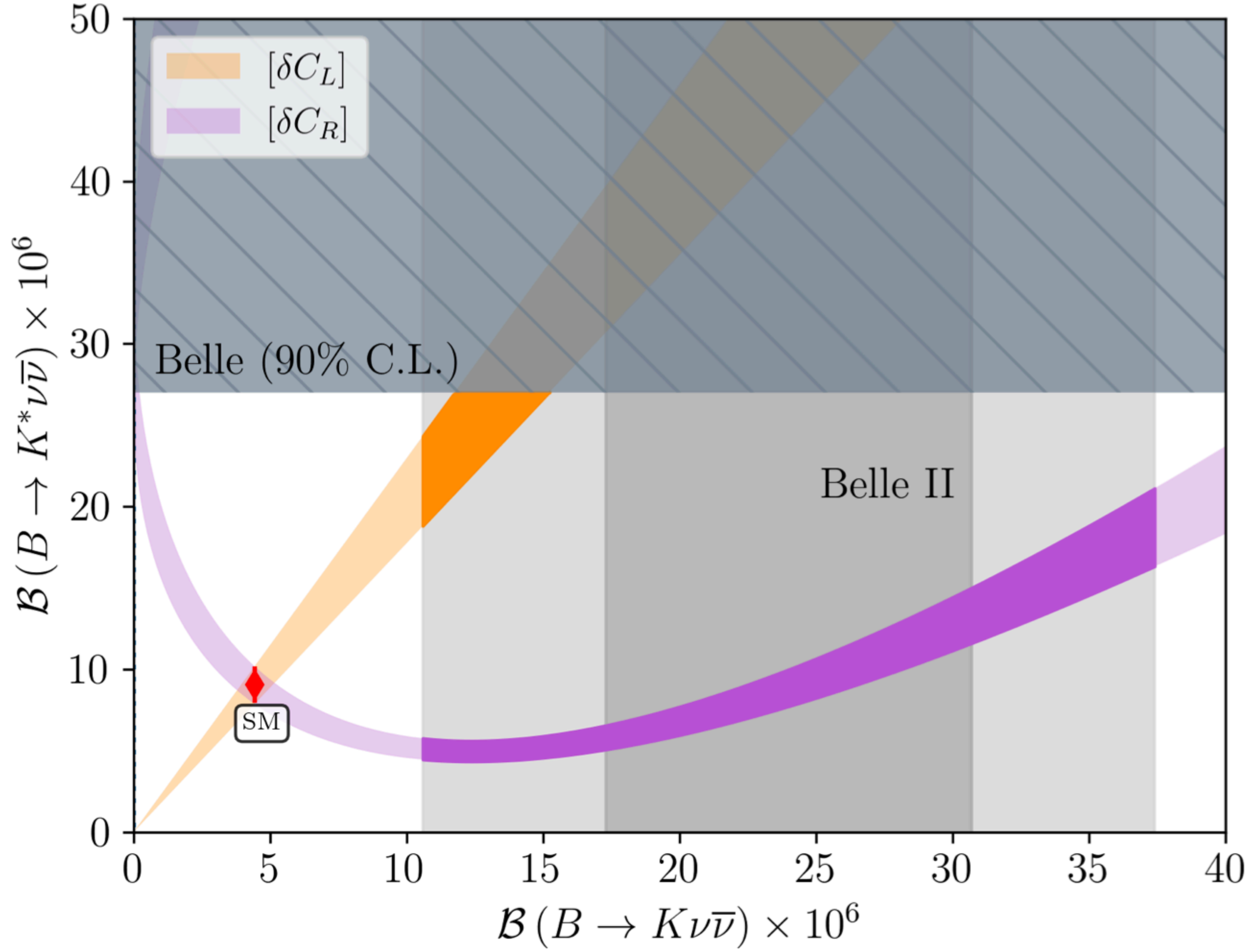
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K^{*+}}}/\mathcal{B}_{K^{*+}}$	$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K^{*0}}}/\mathcal{B}_{K^{*0}}$
$(10.86 \pm 1.30 \pm 0.59)$	0.12	$(9.05 \pm 1.25 \pm 0.55)$	0.15

$B \to K^{(*)}\nu\nu$: NP implications

Sensitive to BSM effect on both left-handed and right-handed operator



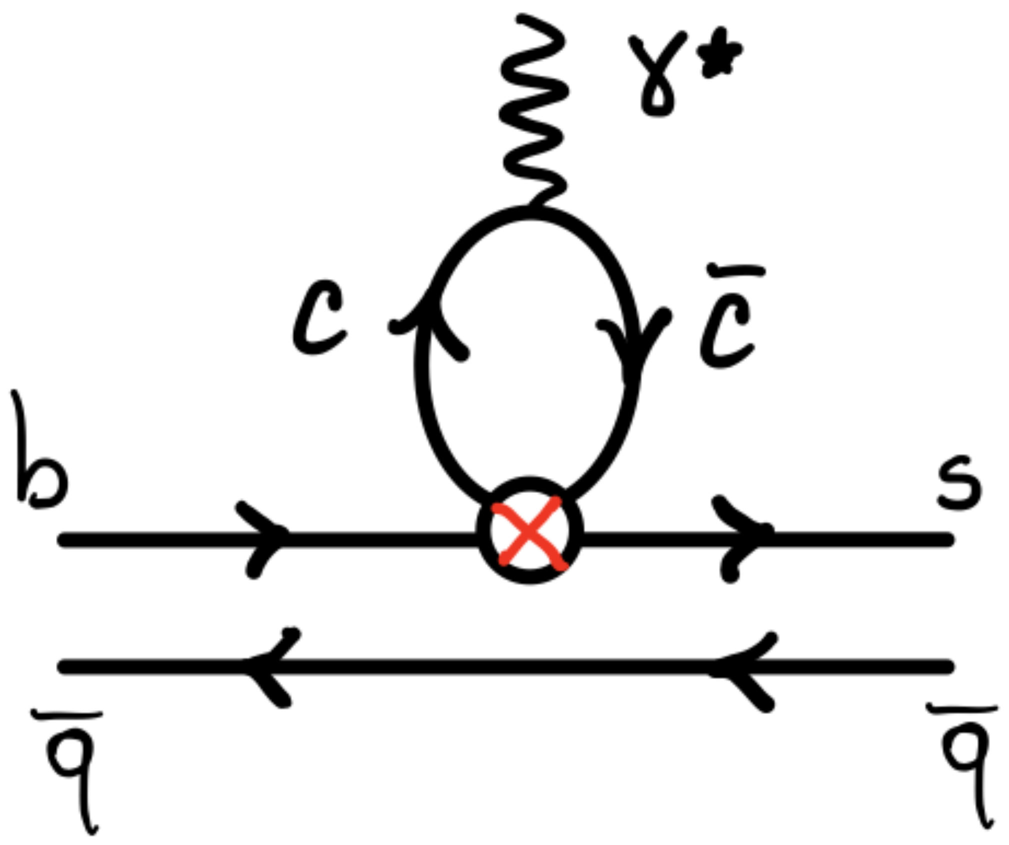
$\Rightarrow$

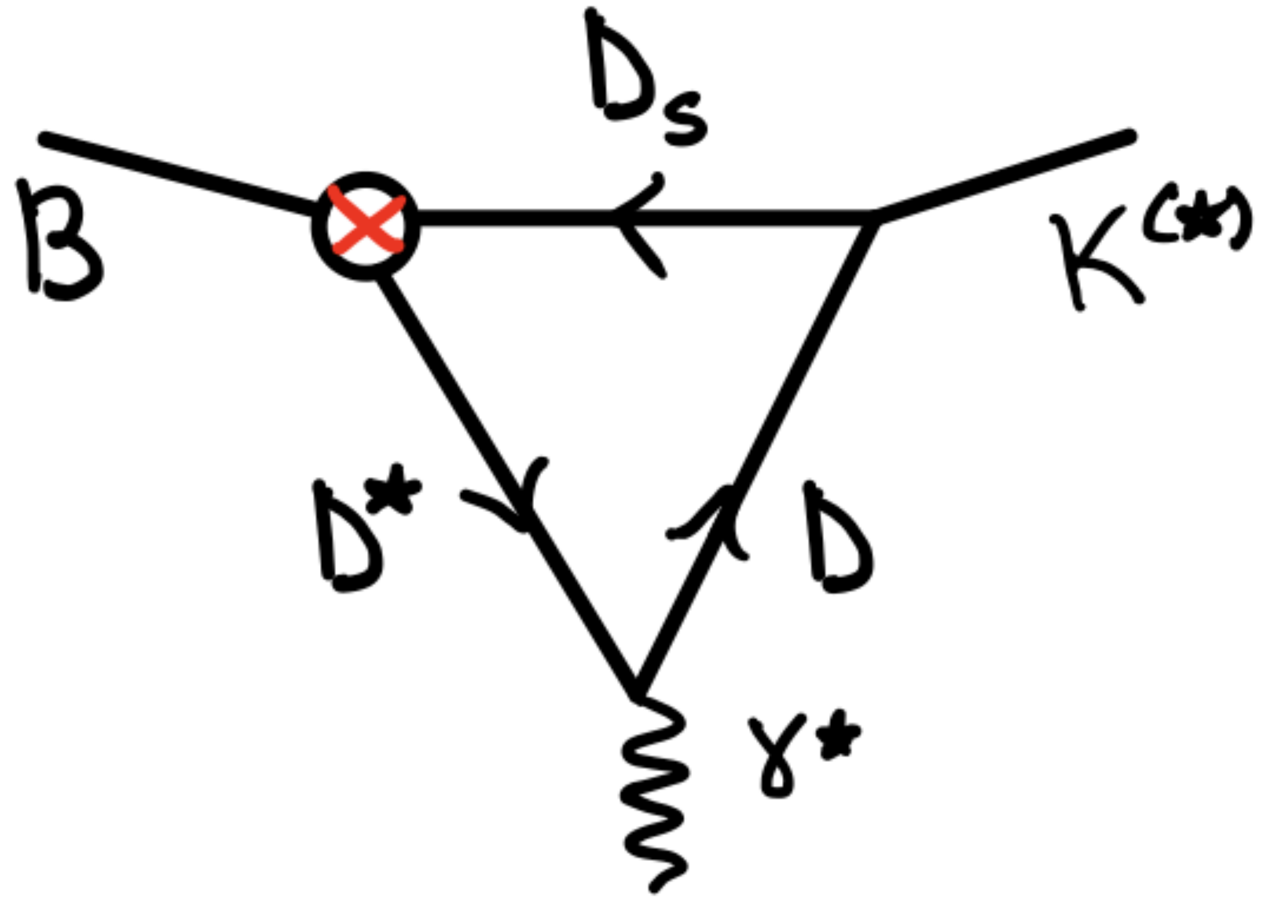


Possible interpretation also in terms of weakly interacting light NP (axions)

$B \to K^{(*)}\ell\ell, B_s \to \phi\ell\ell$: the SM status

- Loop-level decays dominated by short-distance effects ($C_{9,10}$), important long-distance
- Additional uncertainties coming from non-perturbative charming penguins





Estimates performed with LCSR, but lacking potential effects from D_s-$\bar{D}$ rescattering

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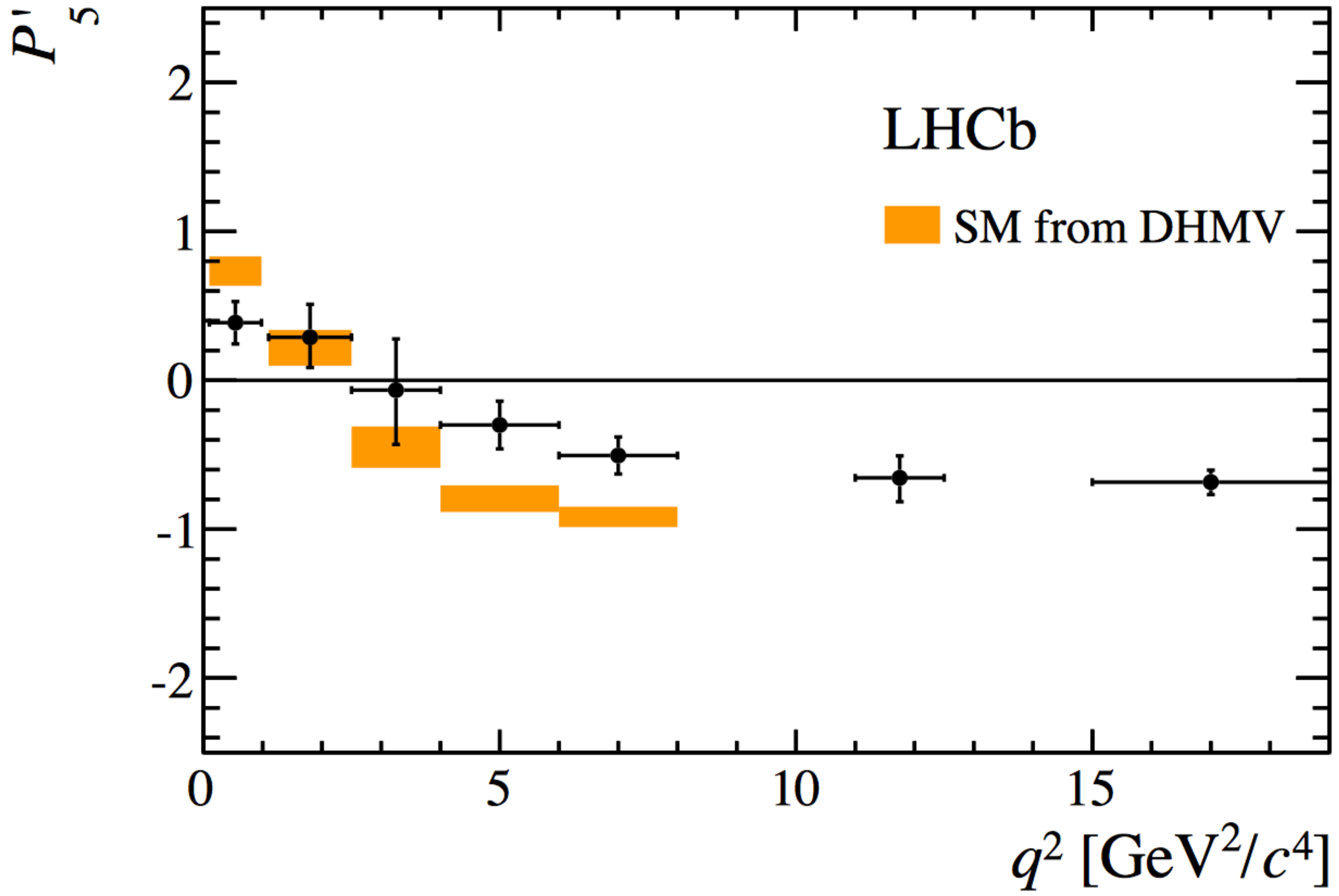
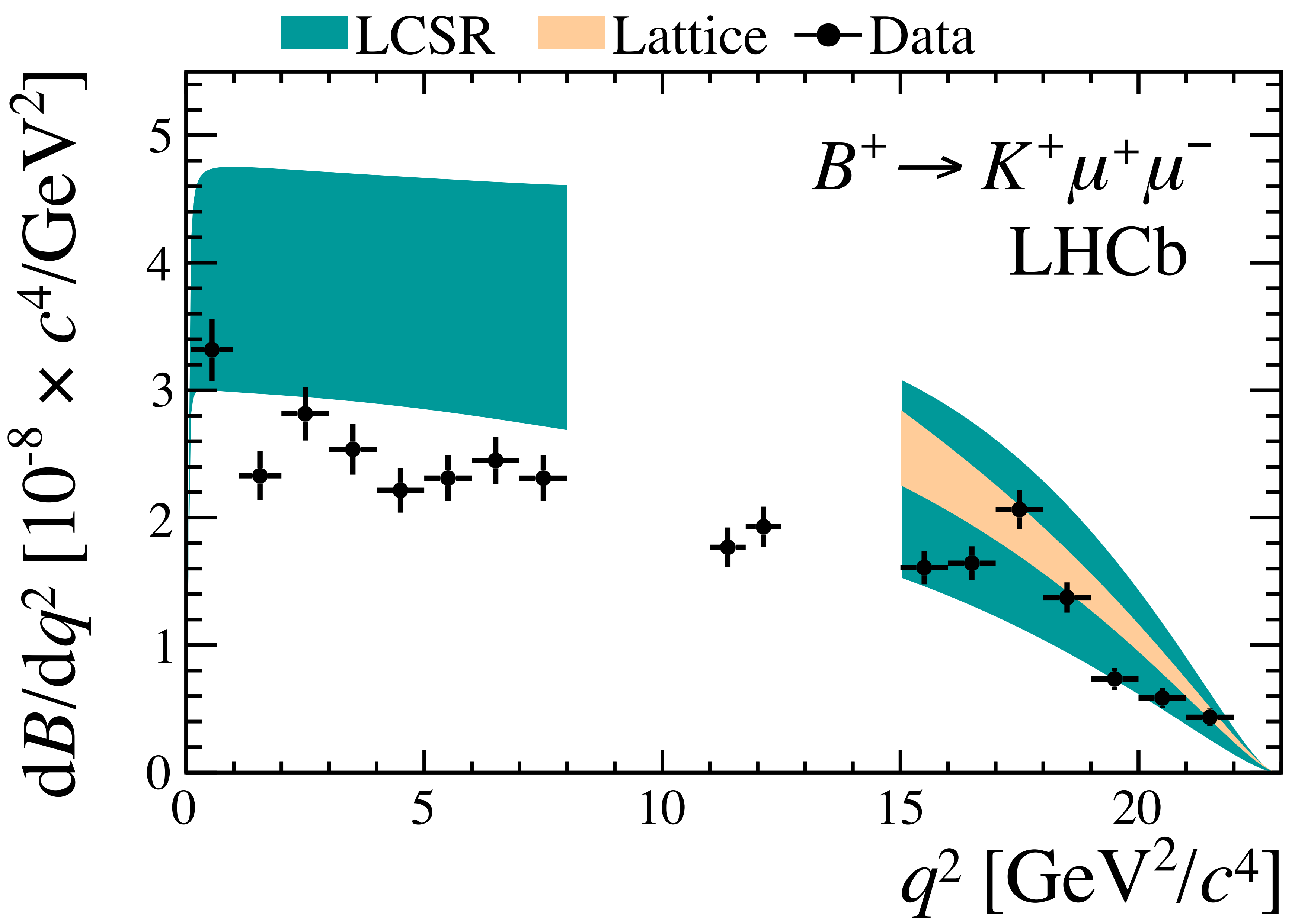
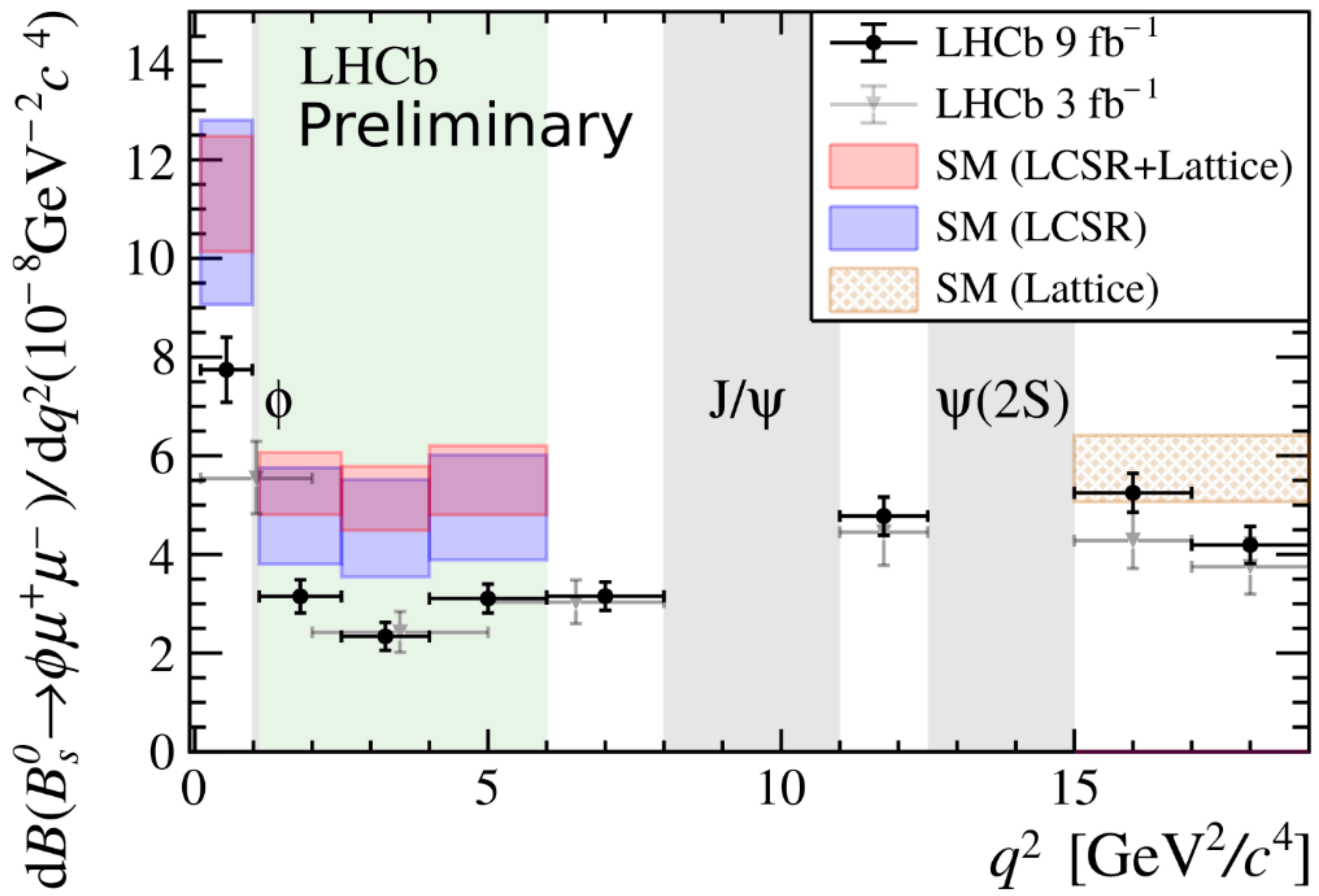
Potential, unaccounted for, pollution in computation of BRs and angular obs!

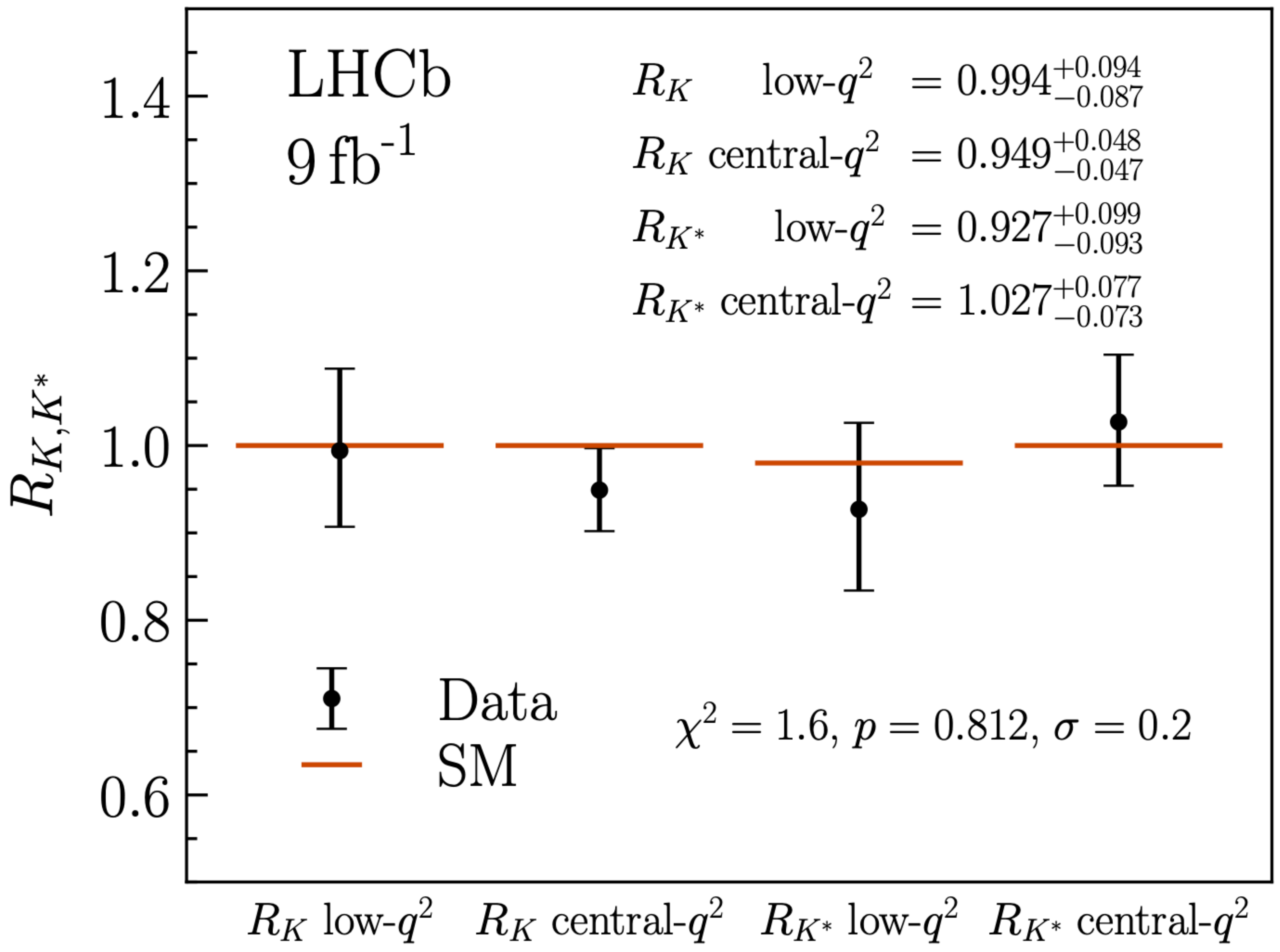
$B \to K^{(*)}\ell\ell, B_s \to \phi\ell\ell$: the SM status

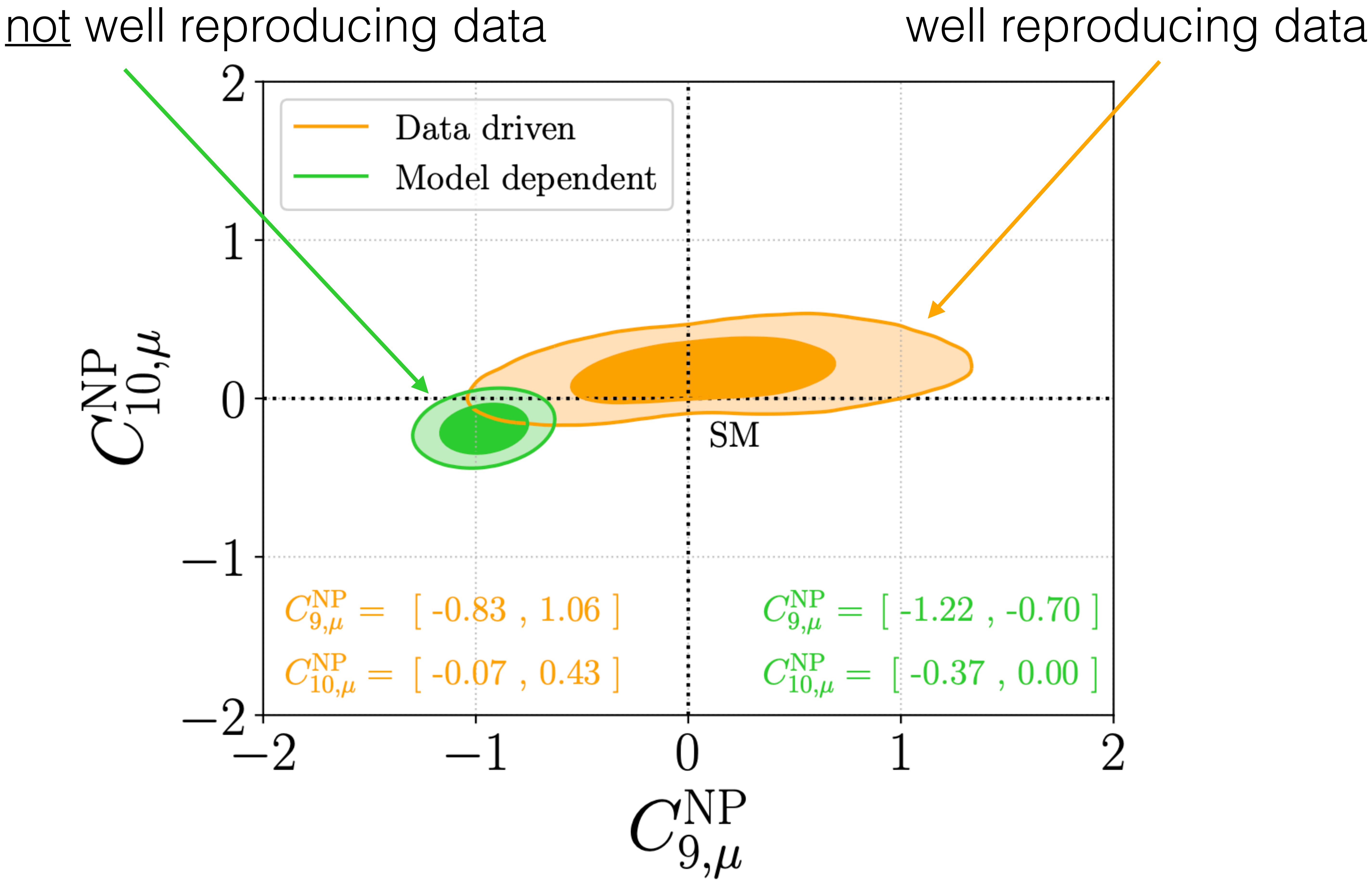






$B \to K^{(*)}\ell\ell, B_s \to \phi\ell\ell$: NP implications





Combined global fit to all $b \to s\ell\ell$ data, connection with $b \to s\nu\nu$ to be inspected

$b \to s\gamma$: the SM status

- Loop-level decay dominated by short-distance effects (C_7)
- Inclusive: main uncertainties come from CKM elements (UTA) and non-perturbative contributions

$$\mathrm{BR}(B \to X_s\gamma)_{E_\gamma > E_0} = \mathrm{BR}(B \to X_c \ell \nu) \left| \frac{\lambda_t}{V_{cb}} \right|^2 \frac{6\alpha_{\mathrm{em}}}{\pi C} \left[|C_7^{\mathrm{eff}}|^2 + |C_7'|^2 + \delta_{\mathrm{nonp.}} \right]$$

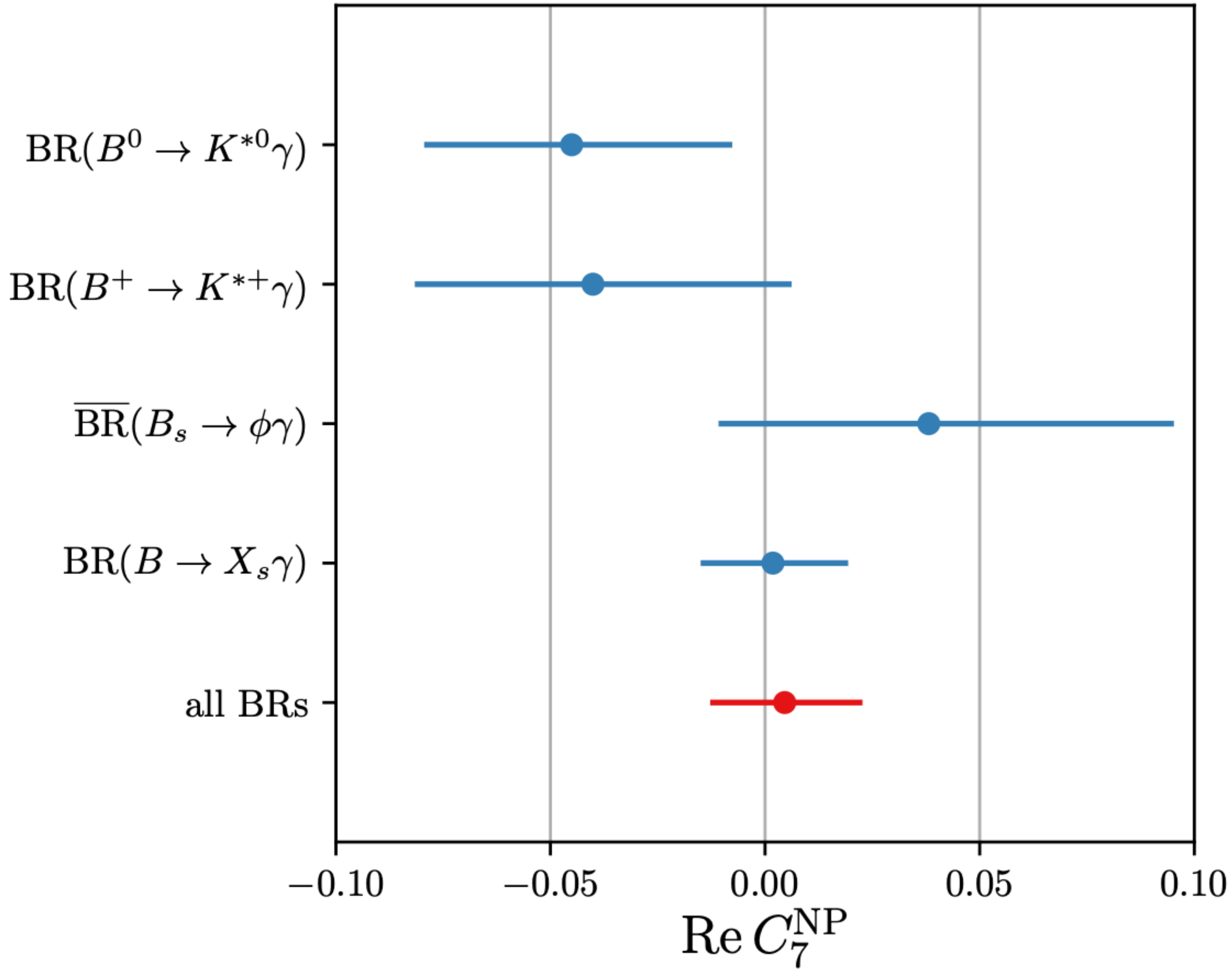
- Exclusive: main uncertainties come from CKM elements (UTA) and form factor (Lattice + LCSR)

$$\mathrm{BR}(B_q \to V\gamma) = \tau_{B_q} \frac{G_F^2 \alpha_{\mathrm{em}} m_{B_q}^3 m_b^2}{32\pi^3} \left(1 - \frac{m_V^2}{m_B^2}\right)^3 |\lambda^t|^2 \left(|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2\right) T_1(0)$$

$$A_{\mathrm{CP}}(B_q(t) \to V\gamma) = \frac{\Gamma(\bar{B}_q(t) \to \bar{V}\gamma) - \Gamma(B_q(t) \to V\gamma)}{\Gamma(\bar{B}_q(t) \to \bar{V}\gamma) + \Gamma(B_q(t) \to V\gamma)}$$

$b \to s\gamma$: NP implications

Very strong constraints on possible BSM contribution to the radiative operator, particularly from inclusive decay



Conclusions

- Rare decays are a fundamental probe for the search of NP effects. Main theory uncertainties coming from CKM elements, decay constants and form factors

- After re-analysis of LFUV ratios by LHCb, evidence of LFV NP is gone. Remaining hints of deviation in the muon sector are to be considered with care, due to charming penguins

- New discrepancy recently observed in $B \to K\nu\nu$, still much work to do to understand its potential origin and connection with other sectors (light NP?)