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Lepton flavor nonuniversality in $b \to s\ell^+\ell^-$ processes

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Outline

- Introduction
- Model independent analysis
- Right-handed x left-handed(RL) and leptoquark implementation
- Additional observables and LFV

Introduction

LHCb measured

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}}{\mathcal{B}(B \to Ke^+e^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

[LHCb1406.6482]

2.6σ departure from Lepton flavor universality (LFU), $R_K = 1$

LFU was fist observed experimentally in the framework of Fermi theory

$$G_F^e \approx G_F^\mu$$

LFU predicted in the SM on the level of gauge couplings. Broken only by lepton Yukawas

$$\frac{g}{\cos\theta_W}\gamma^\mu \frac{1}{2}(C_V^f - C_A^f\gamma^5).$$

$$C_V^\ell = -1$$
$$C_A^\ell = -1 + 4\sin^2\theta_W$$

Well tested in pion and kaon decays, Z decays

$$\Gamma_{ll}^{SM} = \frac{GM_Z^3}{6\sqrt{2}\pi}\left((C_V^f)^2 + (C_A^f)^2\right) = 83.42\mathrm{MeV}$$

$$\Gamma_{ee} = (83.94 \pm 0.14)\mathrm{MeV}$$
$$\Gamma_{\mu\mu} = (83.84 \pm 0.20)\mathrm{MeV}$$
$$\Gamma_{\tau\tau} = (83.68 \pm 0.24)\mathrm{MeV}$$

Introduction

- First proposal and prediction of R_K, R_{K^*}, R_{X_s} in 2003 [Kruger, Hiller, hep-ph/0310219]

$$R_K^{SM} = 1.0003 \pm 0.0001$$

- Very precise due to efficient cancellation of hadronic uncertainties.
  e and μ are almost massless.

- Back then, the averaged Belle and BaBar indicated LFU

$$R_K = 0.81 \pm 0.24 \qquad \mathcal{B}(B_s \to \mu^+\mu^-) < 2 \times 10^{-6}$$
$$R_{K^*} = 0.98 \pm 0.38$$
$$R_{X_s} = 1.20 \pm 0.52$$

[BaBar]
[Belle]
[CDF]

- Renewed interest with the dawn of the LHC era

- LFU observables are generally theo. and exp. clean.

Effective operator analysis of R_K

$$\mathcal{O}_7^{(\prime)} = \frac{e}{(4\pi)^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_S^{(\prime)} = \frac{e^2}{(4\pi)^2} (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = \frac{e^2}{(4\pi)^2} (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

- Experiment prefers to decrease muonic decay rate, alternative is to increase electronic rate

- Tensor operators: decrease μ rate, electronic increase too small ✗
- Scalar operators: electronic increase, but not possible at 1σ ✗

- (Axial)vector operators, chiral vector currents: can affect μ or e ✓

$$C_9^{\ell(\prime)} = \pm C_{10}^{\ell(\prime)}$$

[Hiller, Schmaltz, 1408.1627]
[Talk by J.Martin Camalich]

Leptoquark models

Representations of scalar LQs under $SU(3) \otimes SU(2) \otimes U(1)^*$

$(3,2)_{7/6}$
$(3,2)_{1/6}$
$(\bar{3},3)_{1/3}$
$(\bar{3},1)_{4/3}$

Leptoquark models

Representations of scalar LQs under $SU(3) \otimes SU(2) \otimes U(1)^*$

$(3,2)_{7/6}$ Increases B→Kμμ $\bar{Q} e_R$

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$(\bar{3},3)_{1/3}$	Proton destabilizing	$\overline{Q^C} i\tau_2 \vec{\tau} L$	$\overline{Q^C} i\tau_2 \vec{\tau} Q$
$(\bar{3},1)_{4/3}$			

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$(\bar{3},1)_{4/3}$	Proton destabilizing	$\overline{d_R^C} \ell_R$	$\overline{u_R^C} u_R$

$$\mathcal{L} = Y_{ij} \overline{L}_i \, i\tau^2 \Delta^* d_{Rj}$$
$$= Y_{ij} \left(-\bar{\ell}_{Li} d_{Rj} \Delta^{(2/3)*} + \bar{\nu}_{Lk} (V^{\mathrm{PMNS}})^\dagger_{ki} d_{Rj} \Delta^{(-1/3)*} \right)$$

*(Q = Y + T_3)

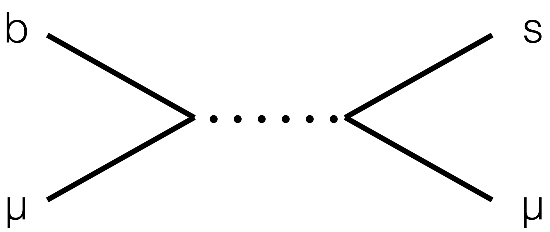
$$Y = \begin{pmatrix} & Y_{\mu s} & Y_{\mu b} \\ & & \end{pmatrix}$$

Couplings designed for B→Kμμ
Framework of LFUV and LFV
SU(2) doublet correlations with B→Kνν

Leptoquark model

$$\Delta(3,2)_{1/6}$$

$$-\left(Y_{\mu s}\bar{\mu}_L s_R + Y_{\mu b}\bar{\mu}_L b_R\right)\Delta^{(2/3)*}$$



$$C'_{10} = -C'_9 = \frac{-\pi}{2\sqrt{2}G_F V_{tb}V_{ts}^*\alpha}\,\frac{Y_{\mu b}Y_{\mu s}^*}{m_\Delta^2}\,.$$

Leptoquark model

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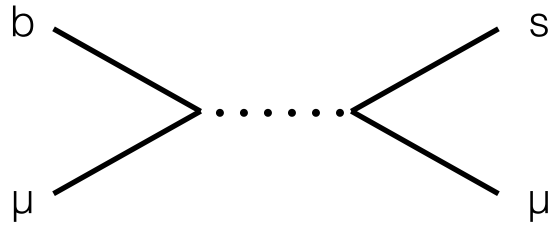

$$C'_{10} = -C'_9 = \frac{-\pi}{2\sqrt{2}G_F V_{tb}V^*_{ts}\alpha}\,\frac{Y_{\mu b}Y^*_{\mu s}}{m^2_\Delta}\,.$$

1. Constrain the LQ couplings from $B\to K\mu\mu$ at high q^2 and $B_s\to\mu\mu$
2. Predict R_K

Leptoquark model

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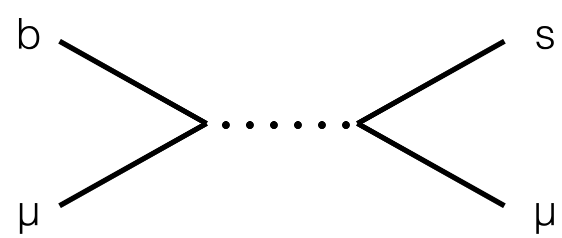


$$C'_{10} = -C'_9 = \frac{-\pi}{2\sqrt{2}G_F V_{tb}V_{ts}^*\alpha}\,\frac{Y_{\mu b}Y_{\mu s}^*}{m_\Delta^2}\,.$$

1. Constrain the LQ couplings from B→Kμμ at high q^2 and B_s→μμ
2. Predict R_K

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)|_{q^2\in[15,22]\mathrm{GeV}^2} = (8.5 \pm 0.3 \pm 0.4)\times 10^{-8}$$ [LHCb,1403.8044]

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\mathrm{exp}} = (2.8^{+0.7}_{-0.6})\times 10^{-9}$$ [LHCb+CMS,1411.4413] [talk by Flavio Archilli]

Decay spectrum

$$\frac{d\Gamma}{dq^2}(B \to K\mu^+\mu^-) = 2a_\mu(q^2) + \frac{2}{3}c_\mu(q^2)$$

…in terms of Wilson coefficients and form factors

$$a_\ell(q^2) = \mathcal{C}(q^2)\Big[q^2|F_P(q^2)|^2 + \frac{\lambda(q^2)}{4}\left(|F_A(q^2)|^2 + |F_V(q^2)|^2\right) + 4m_\ell^2 m_B^2|F_A(q^2)|^2 + 2m_\ell\left(m_B^2 - m_K^2 + q^2\right)\mathrm{Re}\left(F_P(q^2)F_A^*(q^2)\right)\Big]$$

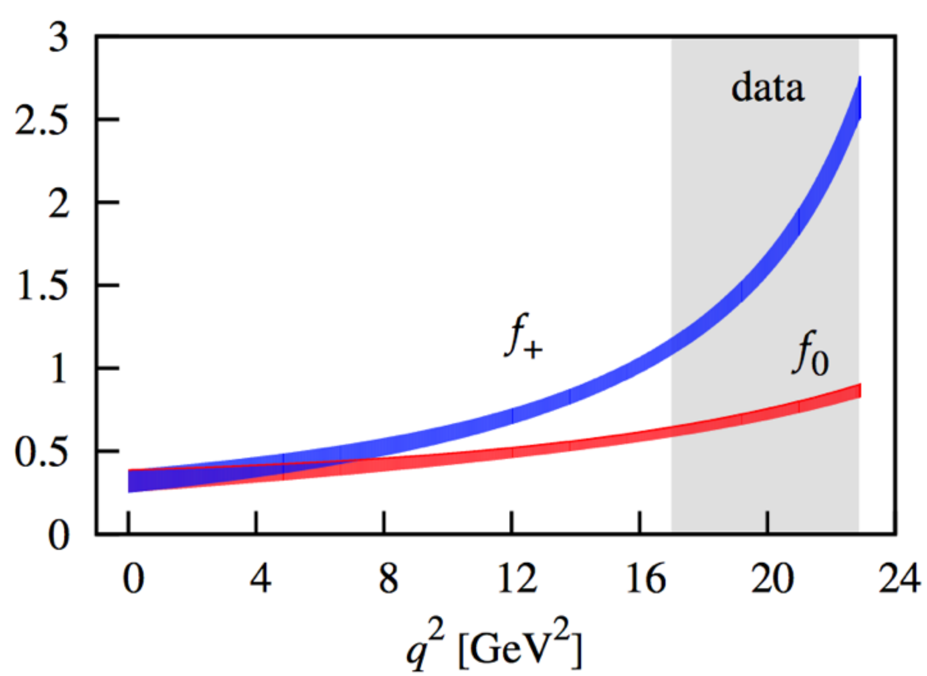
$$c_\ell(q^2) = \mathcal{C}(q^2)\Big[-\frac{\lambda(q^2)}{4}\beta_\ell^2(q^2)\left(|F_A(q^2)|^2 + |F_V(q^2)|^2\right)\Big]$$

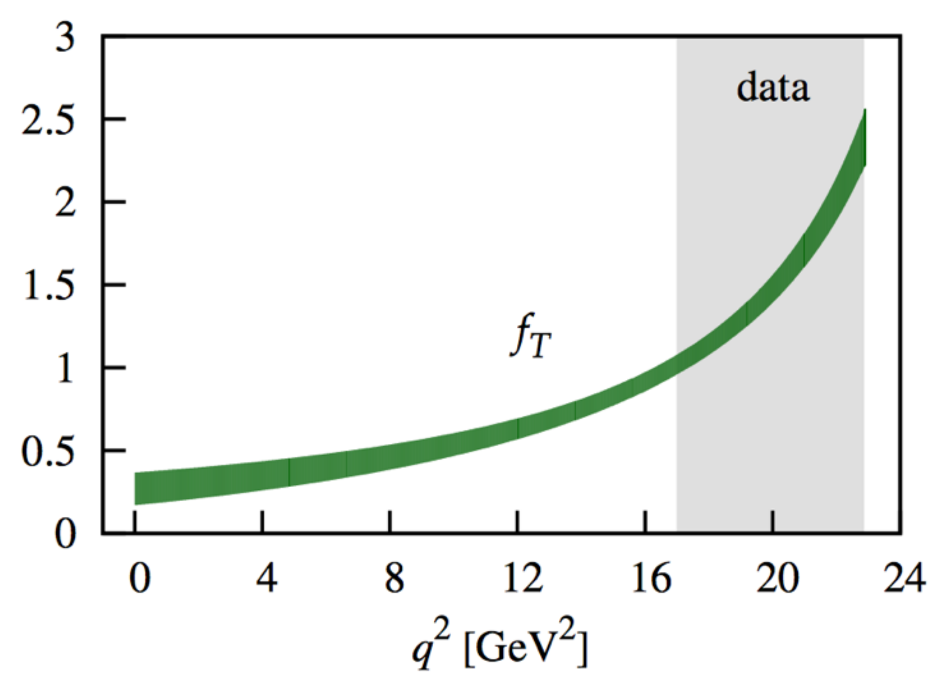
$$F_V(q^2) = (C_9 + C_9')\,f_+(q^2) + \frac{2m_b}{m_B + m_K}(C_7 + C_7')\,f_T(q^2)$$

$$F_A(q^2) = (C_{10} + C_{10}')f_+(q^2)$$

$$F_P(q^2) = -m_\ell(C_{10} + C_{10}')\left[f_+(q^2) - \frac{m_B^2 - m_K^2}{q^2}\left(f_0(q^2) - f_+(q^2)\right)\right]$$

Form factors (with full correlations) taken from HPQCD lattice calculation





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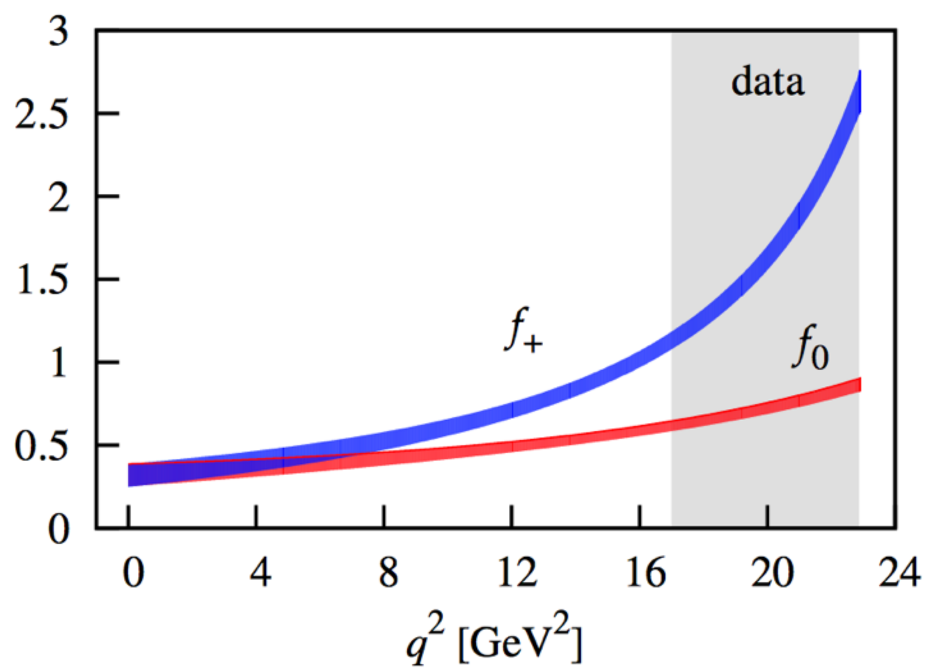
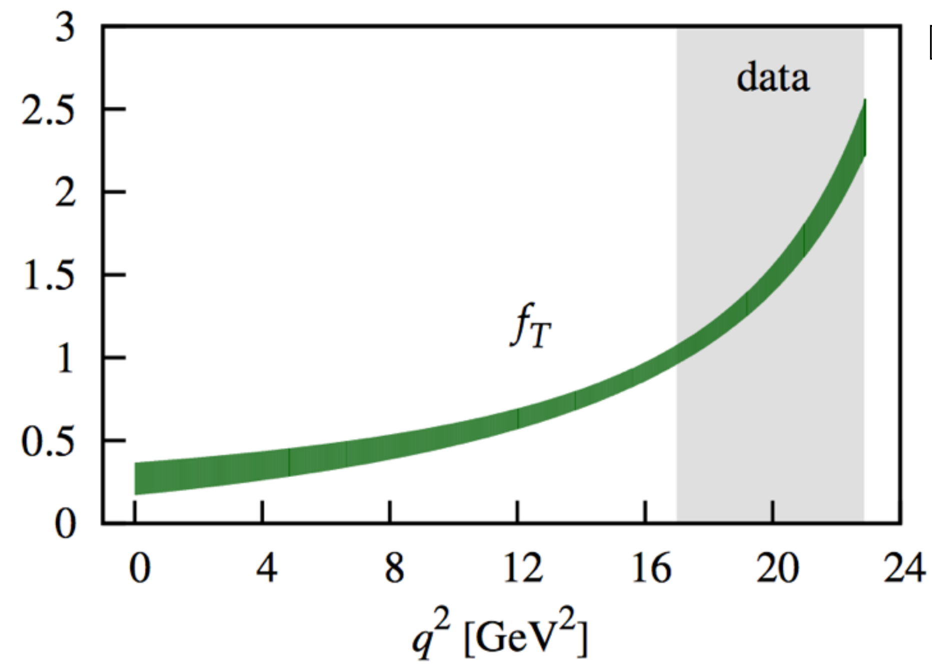
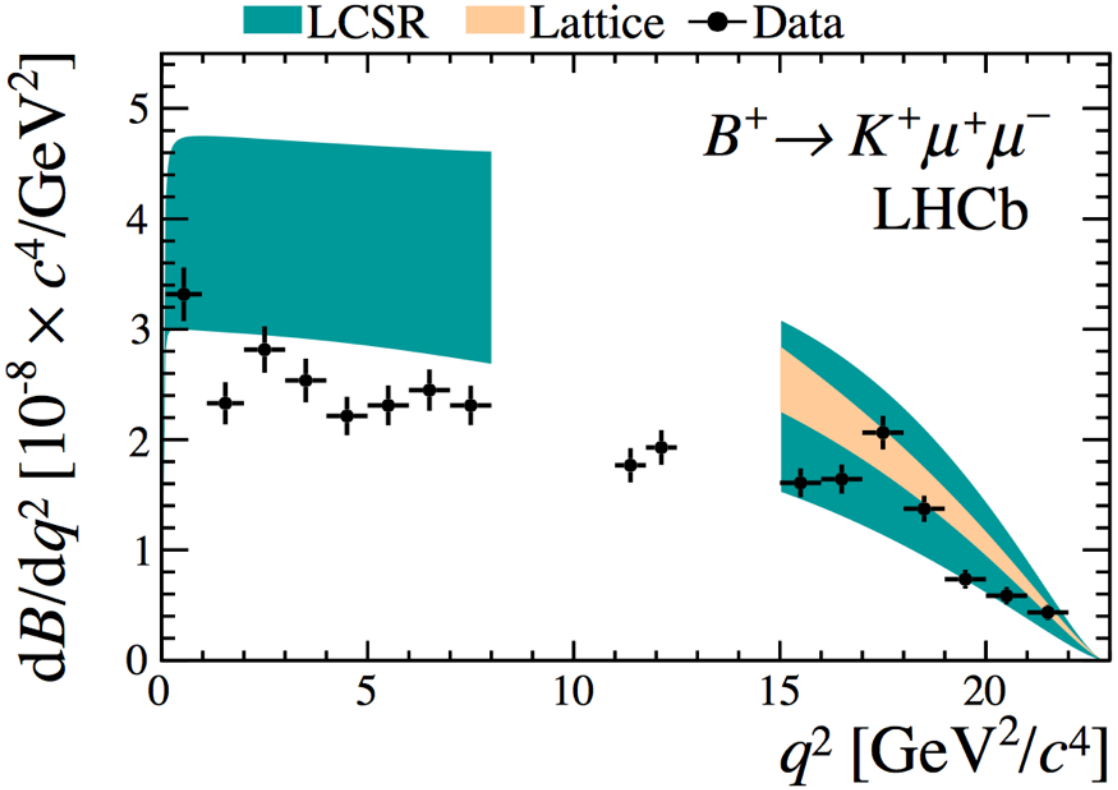
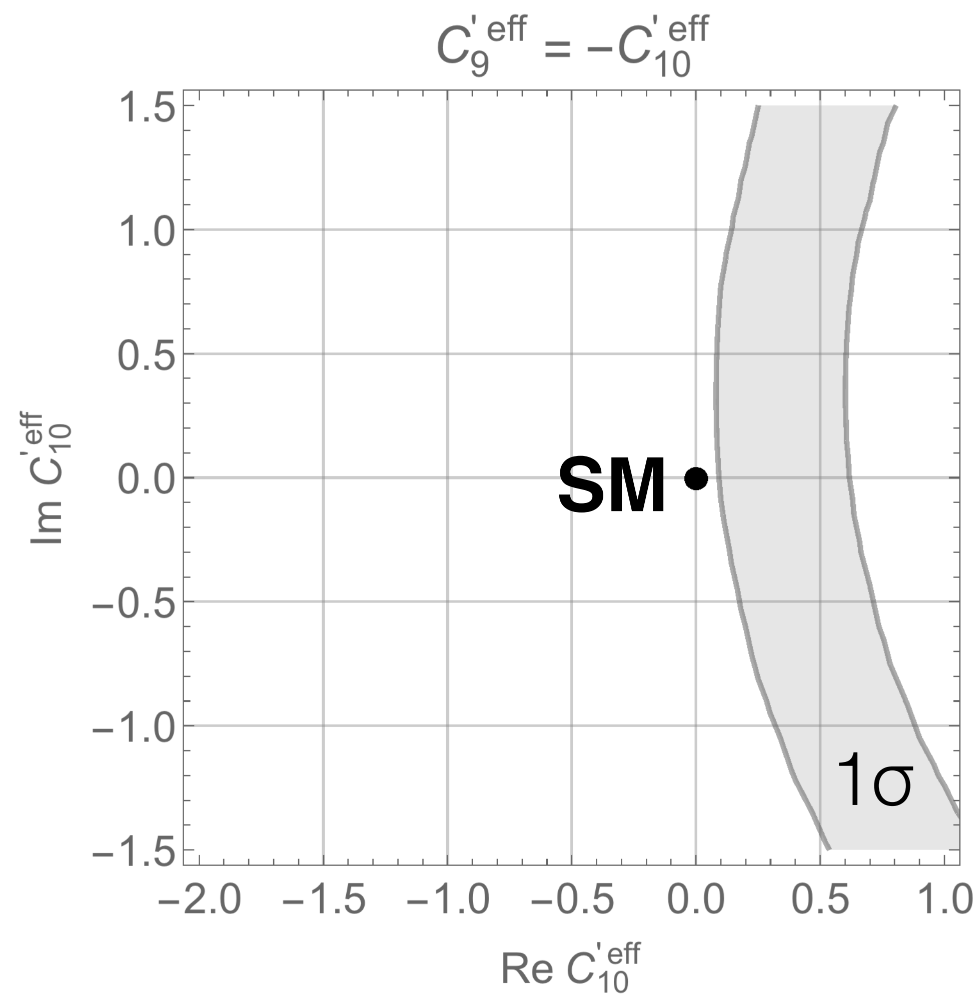




[Bouchard et al, 1306.2384]

Borrowing from [LHCb,1403.8044]





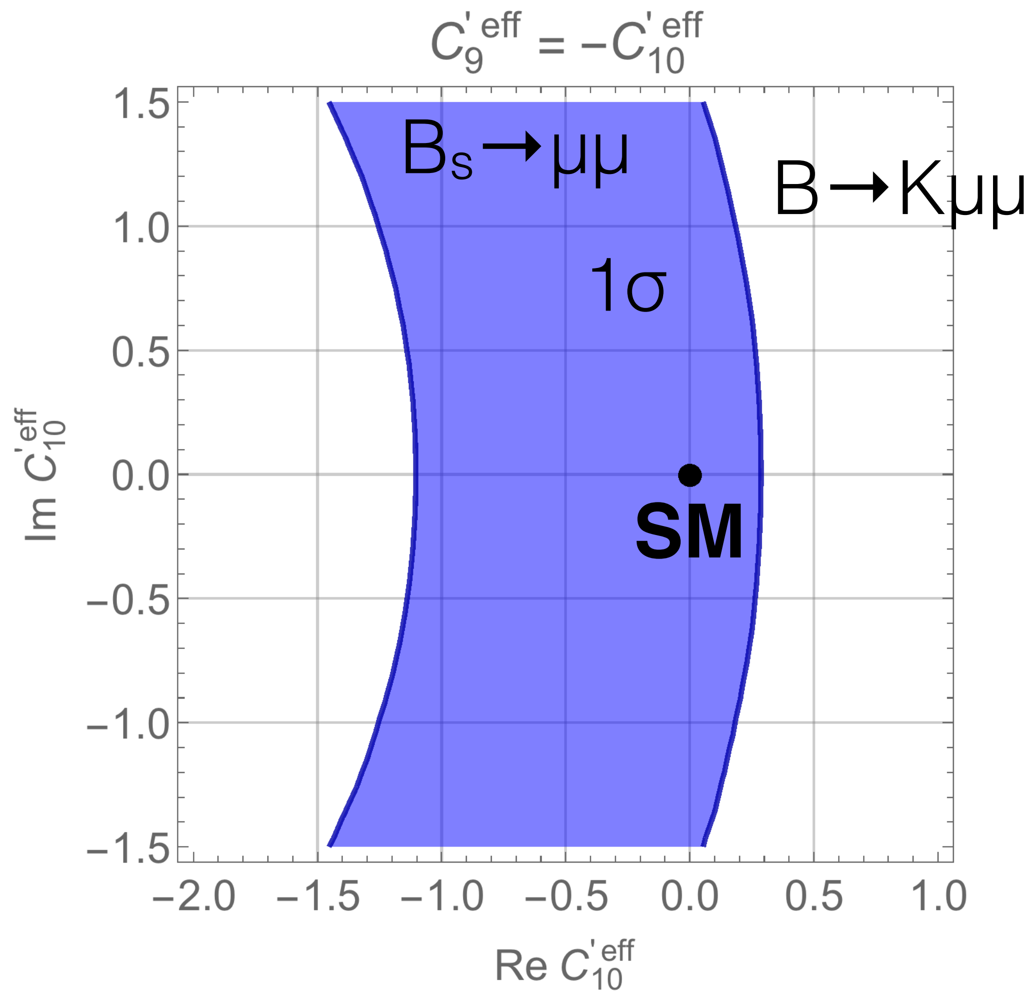
In the SM: Slight deficit of events at high q^2

Time-integrated branching fraction

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\rm exp} = \frac{\mathcal{B}_0}{1-y_s^2}\left[|P|^2 + y_s \mathrm{Re}(P^2)\right]$$

$$P = \frac{2m_\mu}{m_{B_s}}(C_{10} - C'_{10})$$

$$\mathcal{B}_0 = \frac{f_{B_s}^2 m_{B_s}^3}{\Gamma_s}\frac{G_F^2\alpha^2|V_{tb}V_{ts}|^2}{(4\pi)^3}\sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}$$



Good agreement with the SM

Complementarity of observables

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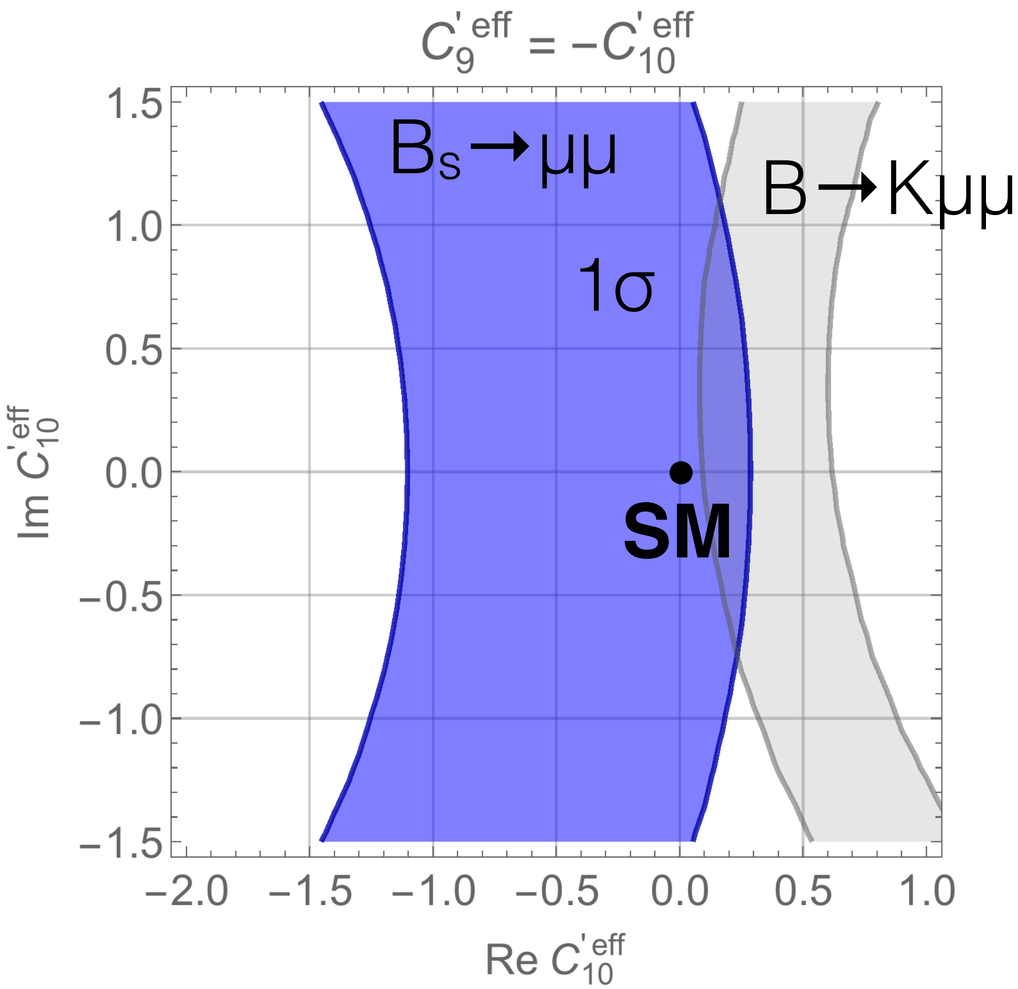

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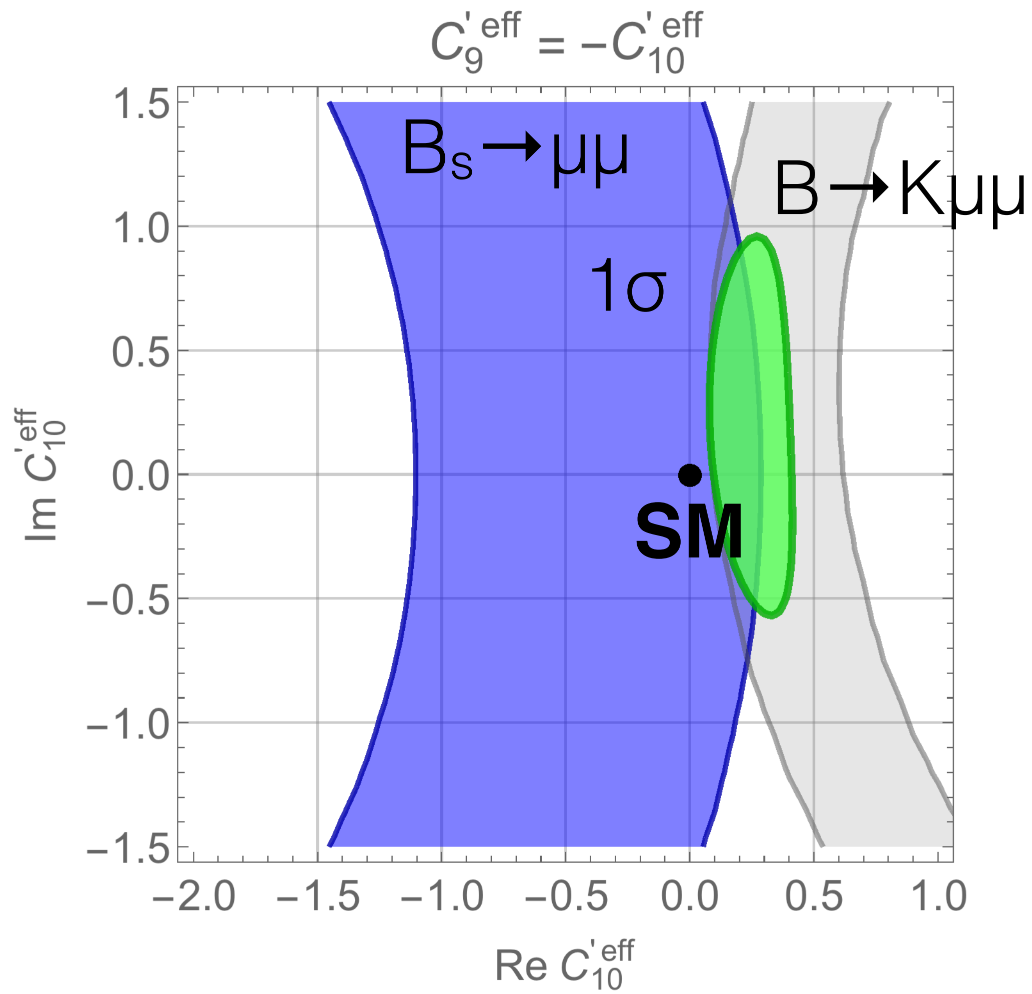

Good agreement with the SM

Complementarity of observables

R_K

In the $C_9' = -C_{10}'$ model (realized with LQ):

$$R_K(C'_{10}) = 1.001(1) - 0.46\ \mathrm{Re}[C'_{10}] - 0.094(3)\ \mathrm{Im}[{C_{10}}'] + 0.057(1)|C'_{10}|^2$$

Remaining form factor uncertainties

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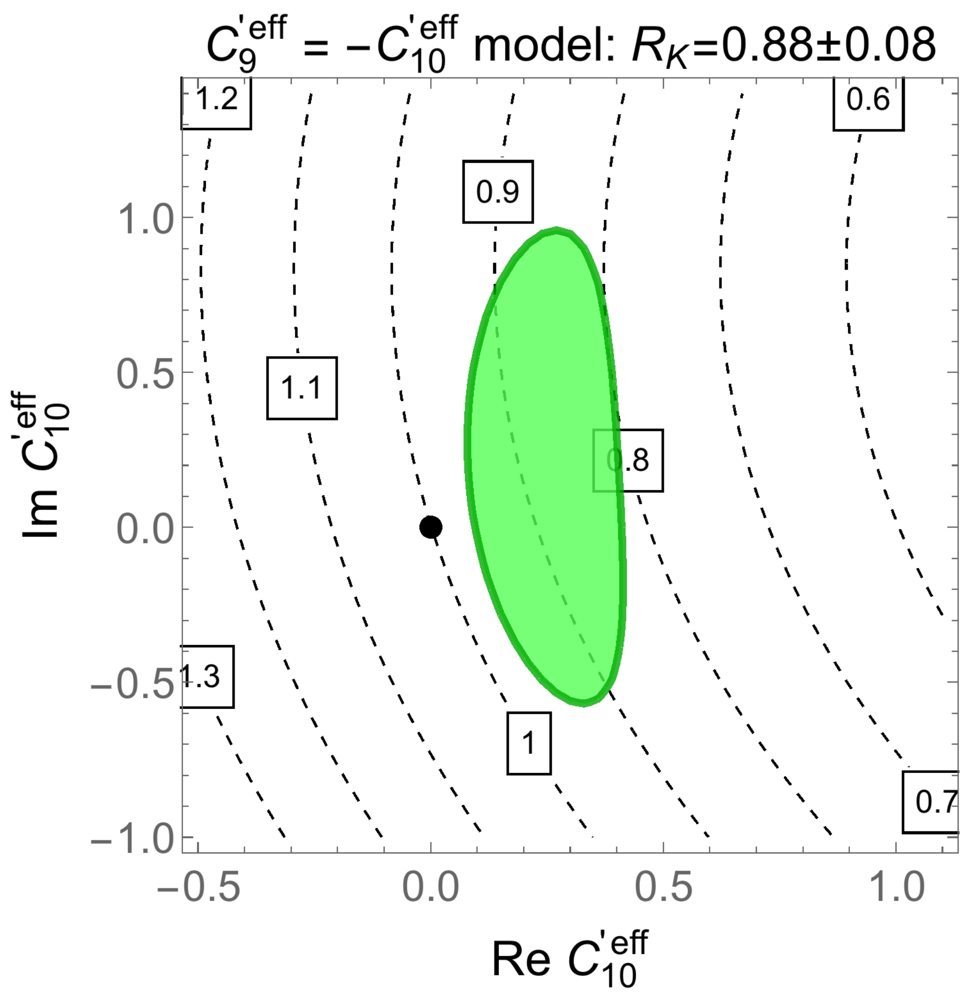

R_K contours Vs. prediction (green)

$$R_K^{\text{pred.}} = 0.88 \pm 0.08$$

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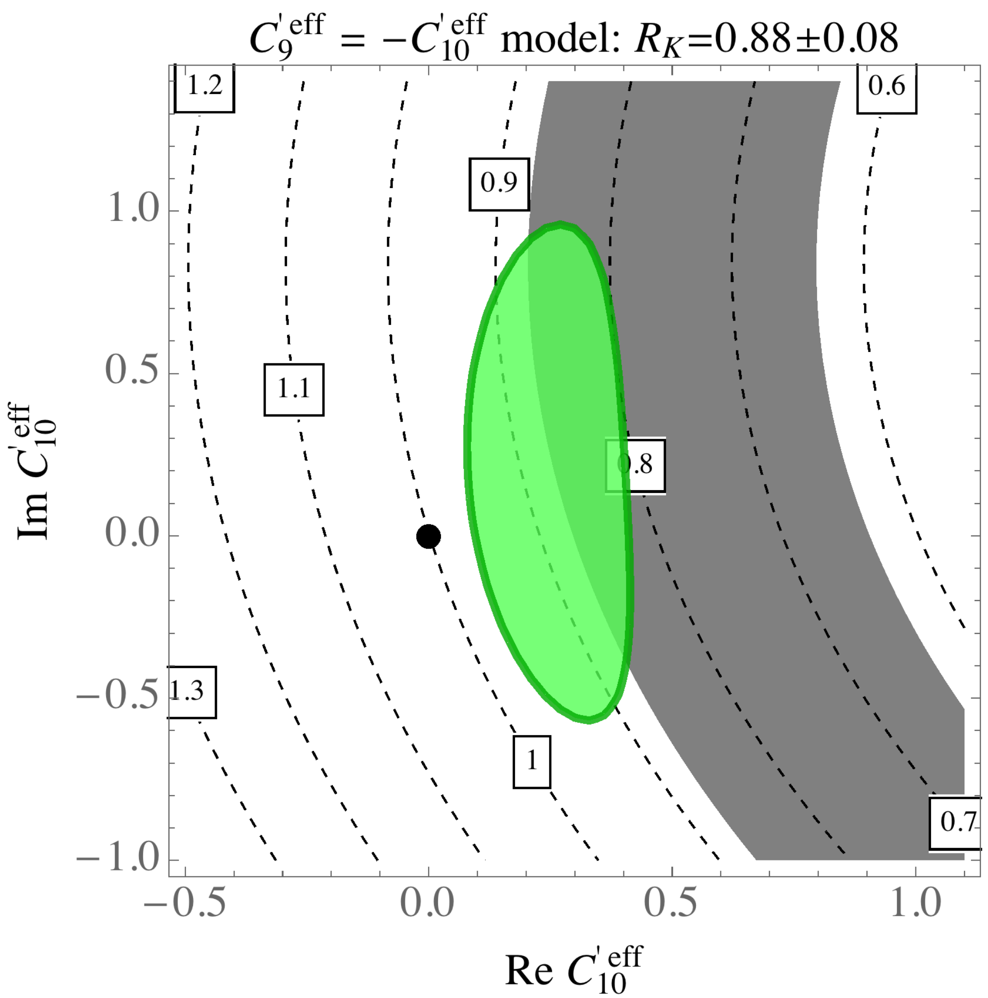


R_K contours Vs. prediction (green)

$$R_K^{\mathrm{pred.}} = 0.88 \pm 0.08$$

Overlaps with 1σ exp. region (grey)

Semileptonic pulls R_K down

Leptonic pulls R_K up

Related LFU observables

$$R_{K^*} = \frac{\Gamma(B \to K^* \mu^+ \mu^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}{\Gamma(B \to K^* e^+ e^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}$$

[Kruger, Hiller, hep-ph/0310219]

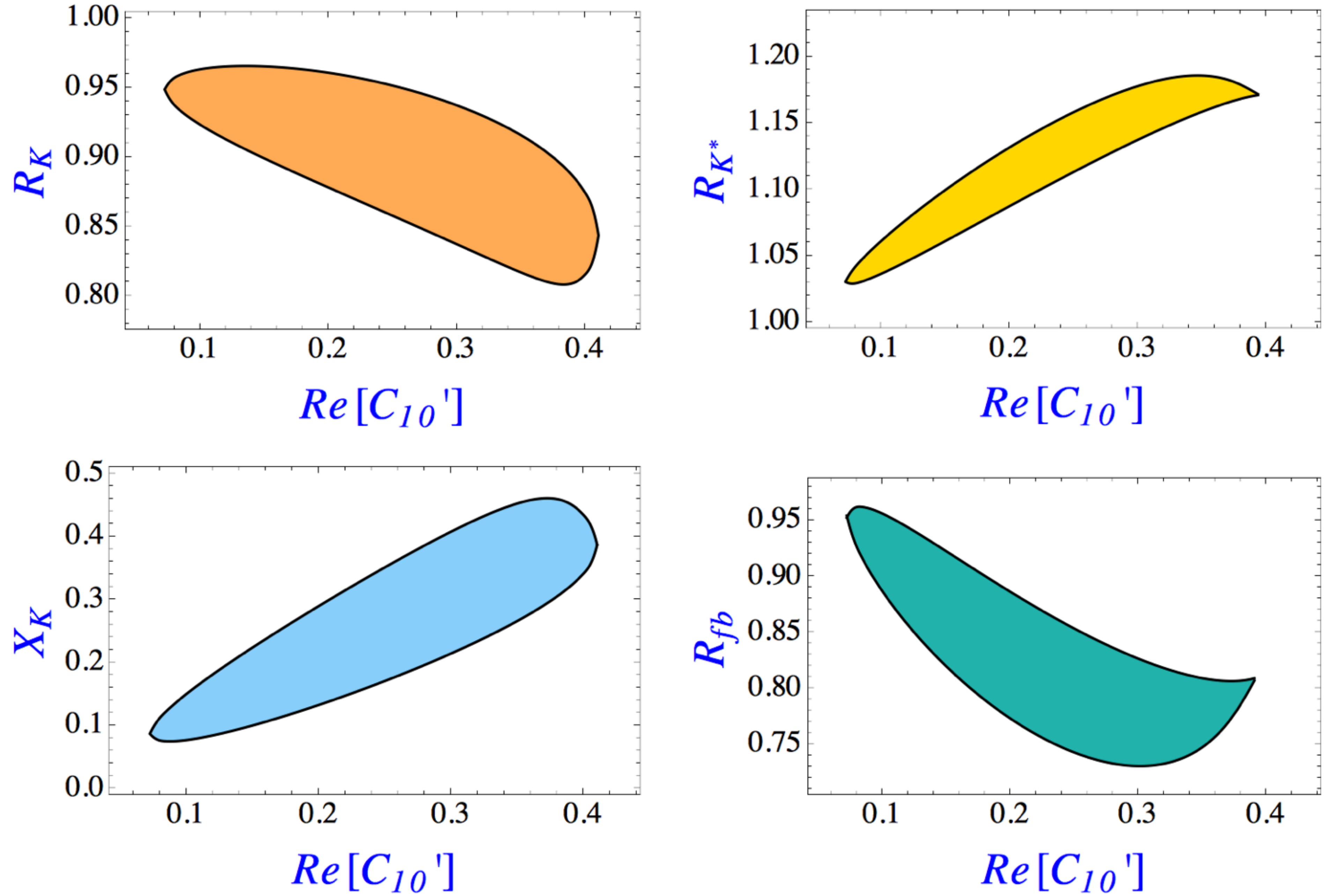
$$X_K = \frac{R_{K^*}}{R_K} - 1$$

$$A^{\ell}_{\mathrm{fb}[4-6]} = \frac{3}{4} \frac{\int_{4\ \mathrm{GeV}^2}^{6\ \mathrm{GeV}^2} I_6^s(q^2)\, dq^2}{\Gamma(B \to K^* \ell^+ \ell^-)_{q^2 \in [4,6]\ \mathrm{GeV}^2}}$$

[Altmannshofer, Straub, 1308.1501]

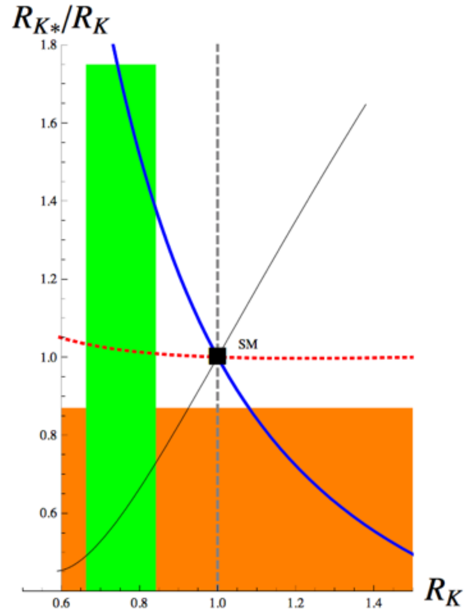
$$R_{\mathrm{fb}} = \frac{A^{\mu}_{\mathrm{fb}[4-6]}}{A^{e}_{\mathrm{fb}[4-6]}}$$

Related LFU observables



$$R_K = 0.88 \pm 0.08\,, \qquad R_{K^*} = 1.11 \pm 0.08\,,$$
$$X_K = 0.27 \pm 0.19\,, \qquad R_{\rm fb} = 0.84 \pm 0.12\,,$$

Related LFU observables



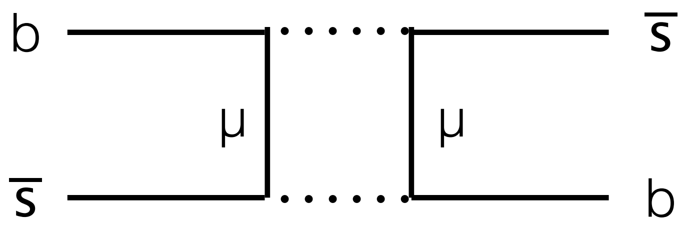
Green band: R_K 1 sigma LHCb. Curves: different BSM scenarios. red dashed: pure C_{LL}. Black solid: $C_{LL} = -2C_{RL}$. Blue: C_{RL}. Orange band is prediction for R_{K^*} (not significantly measurend) based on R_K and $B \to X_s \ell\ell$: $R_{X_s}^{\mathrm{Belle}'09} = 0.42 \pm 0.25\,,\quad R_{X_s}^{\mathrm{BaBar}'13} = 0.58 \pm 0.19.$

[G. Hiller,
presentation at EPS 2015]

R_K and R_{K^*} discriminate between different Wilson coefficient realisations

LQ specific constraints: B_s mixing

$$\mathcal{H}_{\text{eff}} = C_1^{\text{SM}} (\bar{b}\gamma_\mu P_L s)\,(\bar{b}\gamma^\mu P_L s) + C_6^{\text{LQ}} (\bar{b}\gamma_\mu P_R s)\,(\bar{b}\gamma^\mu P_R s)$$



$$C_6^{\text{LQ}}(m_\Delta) = -\frac{G_F^2}{8\pi^4}(V_{tb}^* V_{ts})^2 \alpha^2 m_\Delta^2 \boxed{(C_{10}'^*)^2}$$

Quadratic sensitivity

$$\langle \bar{B}_s^0 | \bar{b}\gamma_\mu(1-\gamma_5) s\, \bar{b}\gamma^\mu(1-\gamma_5) s | B_s^0\rangle = (8/3) f_{B_s}^2 m_{B_s}^2 B_{B_s}$$

$$\Delta m_{B_s} = \underbrace{\frac{G_F^2 m_W^2}{6\pi^2} |V_{tb}^* V_{ts}|^2 f_{B_s}^2 m_{B_s} B_{B_s} \eta_B S_0(x_t)}_{\Delta m_{B_s}^{\text{SM}}} \left| 1 - \frac{1}{2\pi^2} \frac{\alpha^2}{S_0(x_t)} (C_{10}'^*)^2 \frac{m_\Delta^2}{m_W^2} \right|$$

$$\Delta m_{B_s}^{\text{SM}} = 17.3 \pm 1.7\ \text{ps}^{-1}$$

Upper mass limit for the LQ of the order 100 TeV.

LQ specific predictions: B→Kνν

(charge -1/3)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_L^{ij} \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij})$$

$$\mathcal{O}_{L,R}^{ij} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L,R} b)(\bar{\nu}_i \gamma^\mu (1-\gamma_5)\nu_j)$$

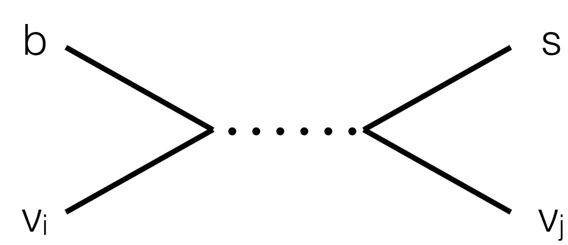
SM: flavour diagonal contributions

$$C_L^{\rm SM} \equiv C_L^{ii} = -6.38 \pm 0.06\,, \qquad \text{(no sum over } i \text{ implied)}$$

[Altmannshofer et al, 0902.0160]

LQ: mixed flavor contributions

$$C_R^{ij} = \frac{1}{N} \frac{(VY)_{ib}(VY)_{js}^*}{4m_\Delta^2}\,, \qquad N \equiv \frac{G_F V_{tb} V_{ts}^* \alpha}{\sqrt{2}\pi}$$



LQ specific predictions: B→Kνν

$$\mathcal{L} = {\color{red}Y_{ij}}\,\overline{L}_i\, i\tau^2 \Delta^* d_{Rj}$$

(charge -1/3)

$$= {\color{red}Y_{ij}} \left(-\bar{\ell}_{Li} d_{Rj} \Delta^{(2/3)*} + \bar{\nu}_{Lk} (V^{\rm PMNS})^\dagger_{ki} d_{Rj} \Delta^{(-1/3)*}\right)$$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_L^{ij} \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij}) \qquad \mathcal{O}_{L,R}^{ij} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L,R} b)(\bar{\nu}_i \gamma^\mu (1-\gamma_5)\nu_j)$$

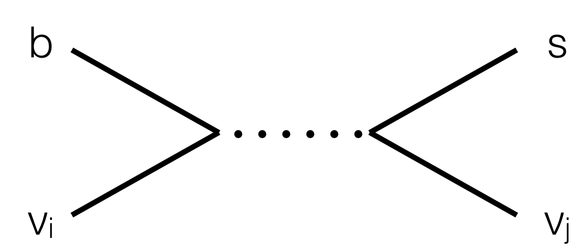
SM: flavour diagonal contributions

$$C_L^{\rm SM} \equiv C_L^{ii} = -6.38 \pm 0.06\,, \qquad \text{(no sum over } i \text{ implied)}$$

[Altmannshofer et al, 0902.0160]

LQ: mixed flavor contributions

$$C_R^{ij} = \frac{1}{N} \frac{(VY)_{ib} (VY)^*_{js}}{4m_\Delta^2}\,, \qquad N \equiv \frac{G_F V_{tb} V_{ts}^* \alpha}{\sqrt{2}\pi}$$



LQ specific predictions: B→Kνν

Sum the widths over all neutrinos i, j

$$\Gamma(B \to K\nu\bar{\nu}) \sim \sum_{i,j=1}^{3} \left|\delta_{ij} C_L^{\mathrm{SM}} + C_R^{ij}\right|^2$$
$$= 3|C_L^{\mathrm{SM}}|^2 + |C'_{10}|^2 - 2\mathrm{Re}[C_L^{\mathrm{SM}*} C'_{10}]$$

Correction of the SM q^2 spectrum and branching fraction:

$$\left[1 + \frac{1}{3}\left|C'_{10}/C_L^{\mathrm{SM}}\right|^2 - \frac{2}{3}\,\mathrm{Re}[C'_{10}/C_L^{\mathrm{SM}}]\right]$$

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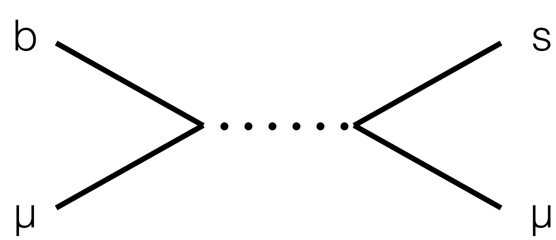
Correction of the SM q^2 spectrum and branching fraction:

$$1.01 < \left[1 + \frac{1}{3}\left|C'_{10}/C_L^{\rm SM}\right|^2 - \frac{2}{3}\,{\rm Re}[C'_{10}/C_L^{\rm SM}]\right] < 1.05$$

LFV

Relate LFU violation (lepton flavour specificity) with Lepton Flavor Violation (LFV)

In leptoquark models, LFV is closely tied to LFUV.

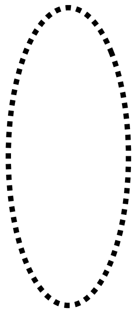


$$Y = \begin{pmatrix} Y_{\mu s} & Y_{\mu b} \end{pmatrix}$$

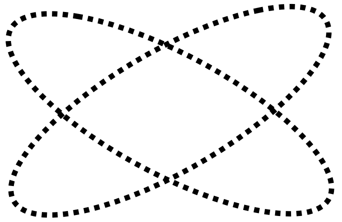
Cannot play with electronic and muonic decay modes simultaneously:

$$Y = \begin{pmatrix} Y_{es} & Y_{eb} \\ Y_{\mu s} & Y_{\mu b} \end{pmatrix} \begin{matrix} \longleftarrow \text{LFU} \\ \longleftarrow \text{LFU} \end{matrix}$$

μ→eγ, ϒ→eμ, Φ→eμ



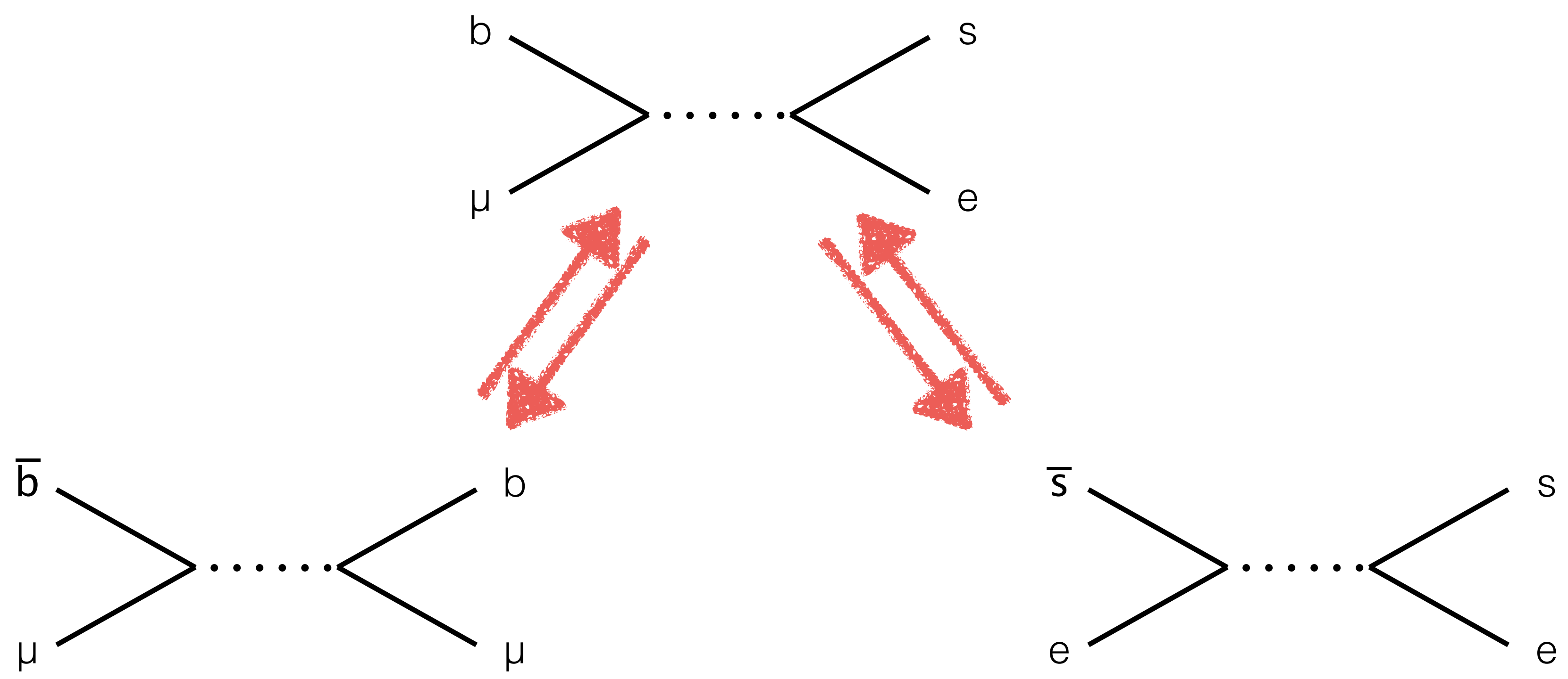
B_s→eμ, B→Keμ



LFV

LFV ⇔ (LFUV in different channels)

($B_s \to e\mu$ and $B \to Ke\mu$ can be measured) **if and only if** (LFUV in bottomonium and Φ can be measured)



$$\frac{\mathcal{B}(\Upsilon \to \mu\mu)}{\mathcal{B}(\Upsilon \to ee)}$$

$$\frac{\mathcal{B}(\phi \to \mu\mu)}{\mathcal{B}(\phi \to ee)}$$

Conclusions

- R_K measurement is a very compelling hint
- (Axial)Vector operators are most obvious solution
- Leptoquarks naturally realize these operators
- (3,2,1/6) scalar is favoured, additional signatures in neutrino modes
- LFV closely connected to LFUV