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

Nejc Košnik

University of Ljubljana
Faculty of Mathematics and Physics

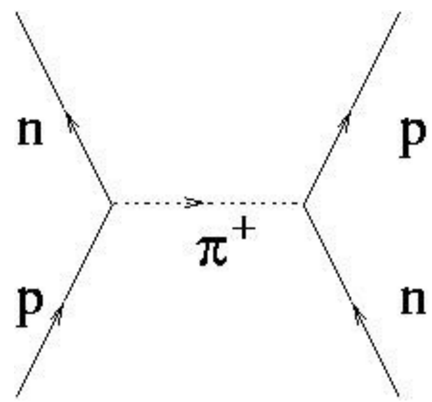
Institut "Jožef Stefan", Ljubljana, Slovenija

Outline

- Introduction
- Effective theory analysis
- UV realizations: Z’ model, light leptoquarks
- Additional cross checks and LFV
- Conclusion

Muon discovery

H. Yukawa proposes scalar meson theory of proton-neutron interaction '35



Cosmic ray meson discovery '37 [Neddermeyer]
The discovered meson is not interacting strongly '47 [Conversi]

Pion and unexpected muon were discovered
μ - π system, $\pi \to \mu\nu$

“There is a muon”
I. Rabi: *“who ordered that”*
A. Pais: *“divine laughter”*, muon is useless as a constituent

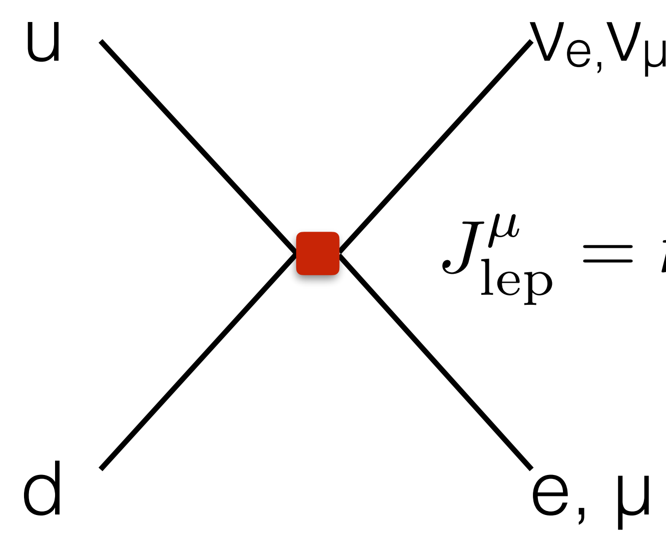
Heavy, unstable electron, $m_\mu \sim 200\ m_e$

Introduction

Lepton Flavor Universality (**LFU)** first observed in the framework of Fermi theory

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

$$J^\mu_{\text{quark}} = \bar{n}\gamma^\mu(1 - a\gamma_5)p$$



$$J^\mu_{\text{lep}} = \bar{\nu}_e\gamma^\mu(1-\gamma_5)e + \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\mu$$

$$\frac{G_F}{\sqrt{2}} J_{\text{lep},\mu} J^\mu_{\text{had}}$$

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

Well tested in pion, kaon decays, Z decays (LEP):

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

$$C_V^\ell = -1$$

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

$$\Gamma_{ee} = (83.94 \pm 0.14)\text{MeV}$$

$$\Gamma_{\mu\mu} = (83.84 \pm 0.20)\text{MeV}$$

$$\Gamma_{\tau\tau} = (83.68 \pm 0.24)\text{MeV}$$

Introduction

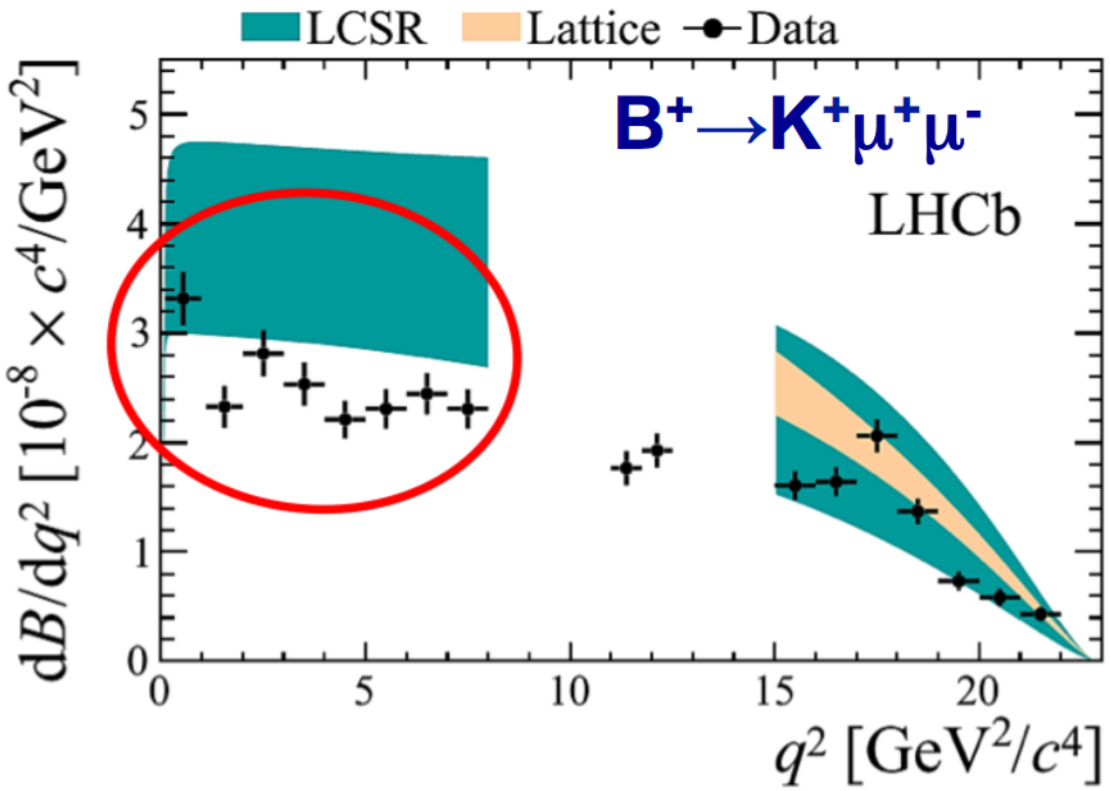
LHCb seen hints of LFU in b→sμμ transition (2014)

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

[LHCb, 1406.6482]

2.6σ below the LFU prediction, $R_K = 1$

- First proposal and prediction of R_K, R_{K^*}, R_{Xs} in 2003 [Kruger, Hiller, hep-ph/0310219]
- Very precise due to efficient cancellation of hadronic uncertainties. e and μ are almost massless.



[LHCb 1403.8044]

missing muons or
too many electrons?

Effective operator analysis

Standard Model + dim-6 operators at NP scale Λ

$$\mathcal{L}_{BSM} = \frac{1}{\Lambda^2} \sum_i C_i Q_i$$

$$Q_i \sim (H D_\mu H)(\bar{q}\gamma^\mu q) \quad \text{“Higgs current”}$$
$$(\bar{q}\sigma^{\mu\nu} V_{\mu\nu} q) H \quad \text{“dipoles”}$$
$$\bar{q} q \bar{\ell} \ell \quad \text{“4-fermion”}$$

Matching onto low energy effective Lagrangian

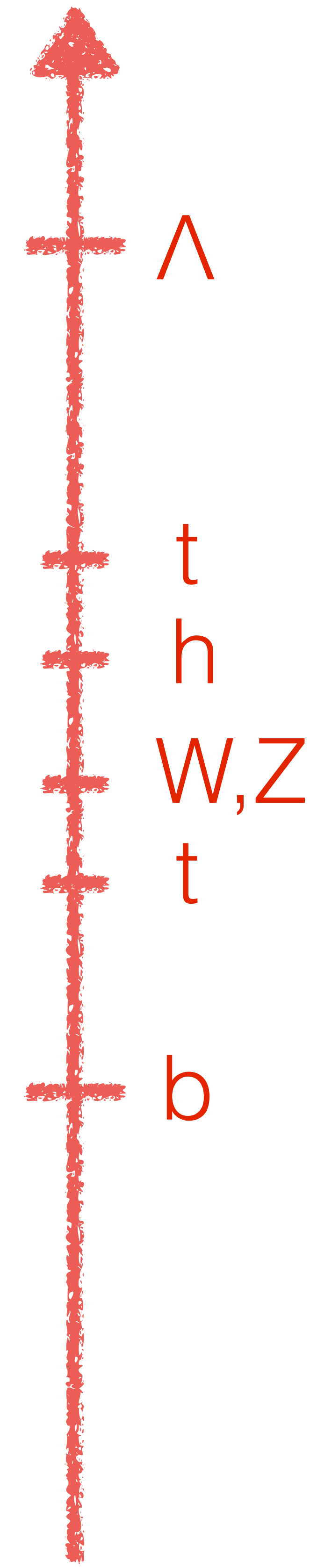
$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S} \Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \Big) \right]$$

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

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

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

1. no tensor currents
2. scalar combinations
   $C_S = -C_P$, $C_S' = C_P'$
3. $C_{9,SM} = -C_{10,SM} = 4.2$



[Grinstein, Camalich, Alonso, 1407.7044]
[Grinstein, Camalich, Alonso, 1505.05164]
[See talk by Gudrun Hiller]

Effective operator analysis

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

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- Global b→sμμ data prefer: decrease muonic decay rate B → Kμμ, less attractive: increase electronic rate B → Kee

[See talks by Lars Hofer and Johannes Albrecht]

- Scalar operators $C_S=-C_P$, $C_S'=C_P'$ for muons: disfavoured by Br(Bs→ μμ) ✗

- Scalar operators $C_S=-C_P$, $C_S'=C_P'$ for electrons can decrease R_K: in conflict with rate of B → Kee ✗

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

$$C_9^\mu = -C_{10}^\mu \sim -[0.5, 1]$$

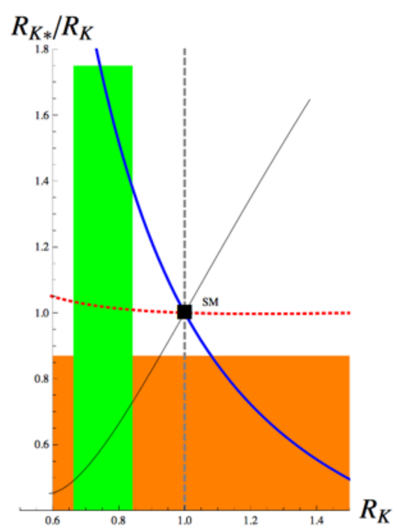
negative contribution towards B → Kμμ, B_s→ μμ

[Hiller, Schmaltz, 1408.1627]
[Hiller, Schmaltz, 1411.4773]

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]



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, EPS 2015]

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

sensitive to right-handed quark current

[Hiller, Schmaltz, 1408.1627]

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

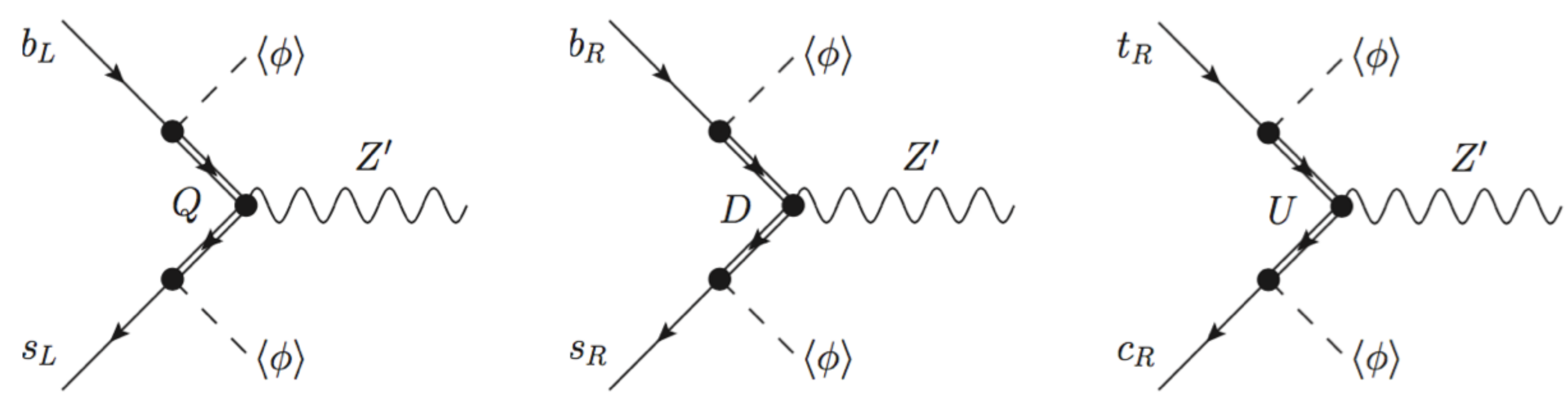
$$R_{\mathrm{fb}} = \frac{A^{\mu}_{\mathrm{fb}[4-6]}}{A^{e}_{\mathrm{fb}[4-6]}}$$

[Altmannshofer, Straub, 1308.1501]

L_μ-L_τ Z' model

- Gauge the leptonic number difference: $U(1)_{L\mu - L\tau}$, massless boson Z'_μ
- At this point we have vector-couplings of Z' to either muons or taus
- Spontaneously break U(1) by a VEV of a scalar Φ, charged under U(1). $m_{Z'} = g' v_\Phi$
- Vector-like quarks charged under U(1) mix with SM quarks and give dim-6 operators:

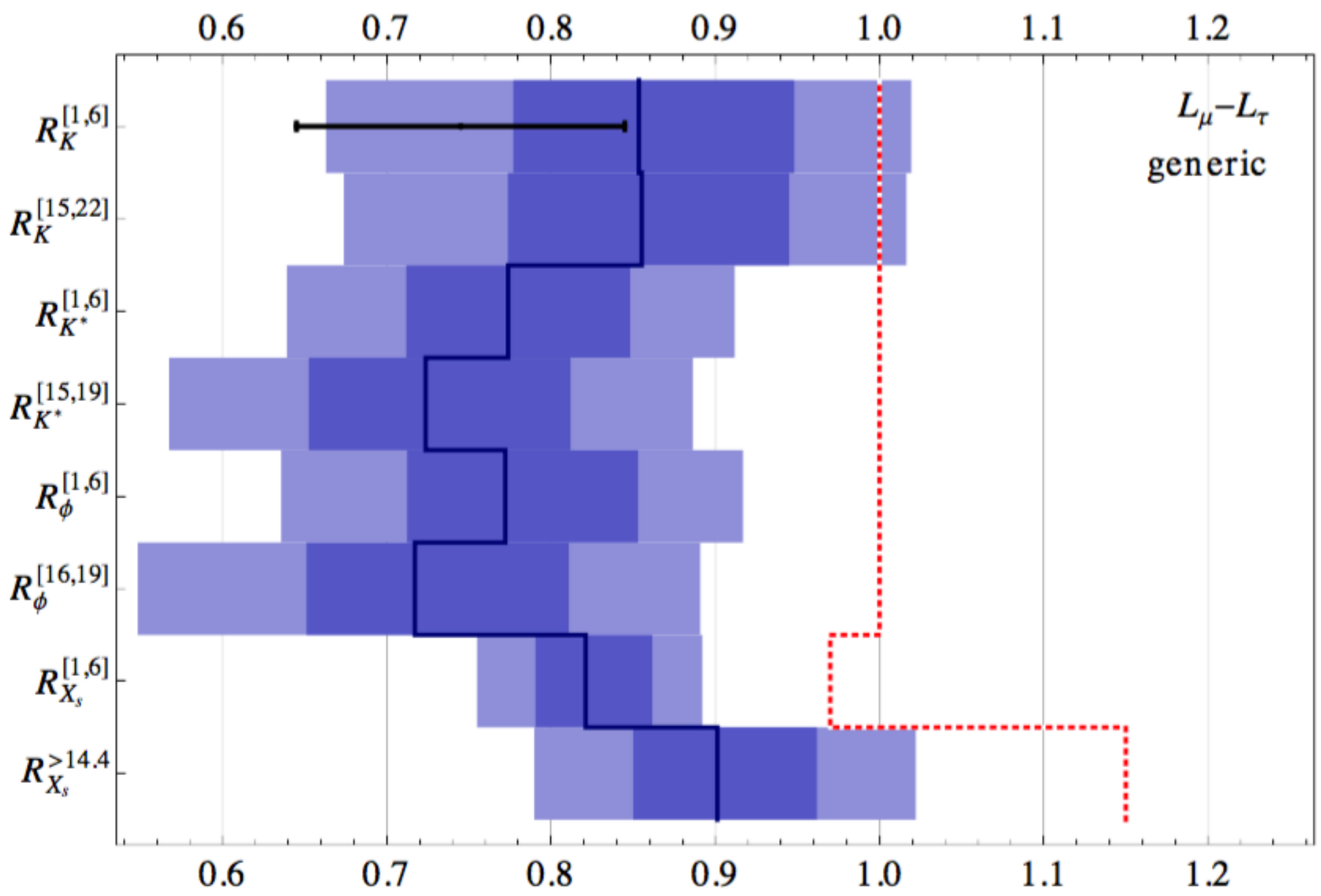
$$C_9^\mu = -C_9^\tau$$
$$C_9'^\mu = -C_9'^\tau$$



[Altmannshofer, Gori, Pospelov, Yavi, 1403.1269]
[Altmannshofer, Yavin, 1508.07009]

L_μ-L_τ Z' model

- Starting from the global fit to b → sμμ data LFU observables are predicted to be ~20% below the SM values



[Altmannshofer, Yavin, 1508.07009]

- Analogous modes, b→ s τ τ, should be enhanced by 20% w.r.t. SM predictions

cf. [Altmannshofer, Gori, Pospelov, Yavi, 1403.1269]
[Altmannshofer, Yavin, 1508.07009]

Scalar leptoquark models

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

		Yukawa couplings		
$(3,2)_{7/6}$	Increases B→Kμμ	$\bar{Q} e_R$		
$(3,2)_{1/6}$	Decreases B→Kμμ	$\bar{L} d_R$		$\Delta(3,2)_{1/6}$
$(\bar{3},3)_{1/3}$	Proton destabilizing	$\overline{Q^C} i\tau_2 \vec{\tau} L$	$\overline{Q^C} i\tau_2 \vec{\tau} Q$	
$(\bar{3},1)_{4/3}$	Proton destabilizing	$\overline{d_R^C} \ell_R$	$\overline{u_R^C} u_R$	

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

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

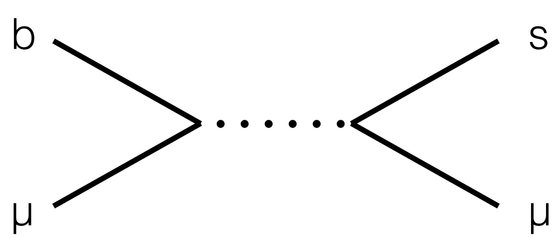
Couplings designed for B→Kμμ
LFU violation but flavour conservation
SU(2) doublet correlations with B→Kνν

Scalar leptoquark model - μ

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

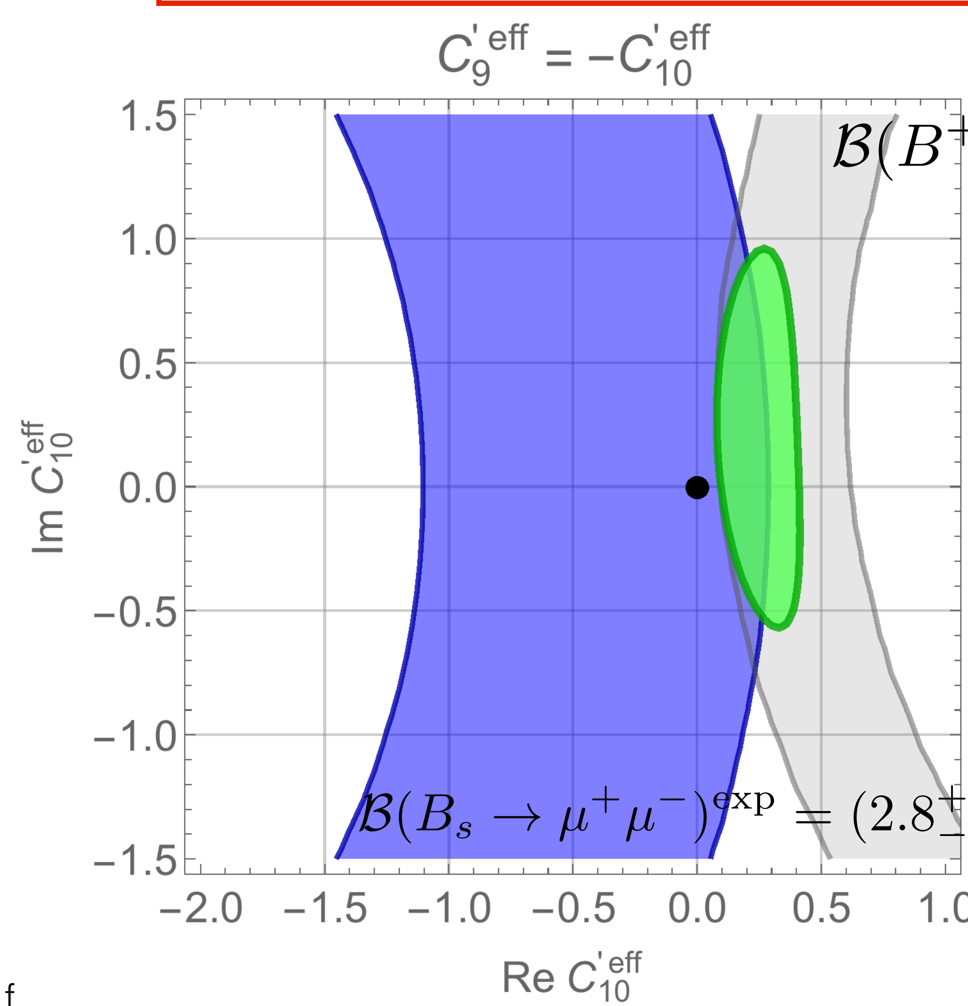
[Becirevic,NK,Fajfer, 1503.09024]

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



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

Increasing B → Kμμ implies larger Bs → μμ !



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

[LHCb,1403.8044]

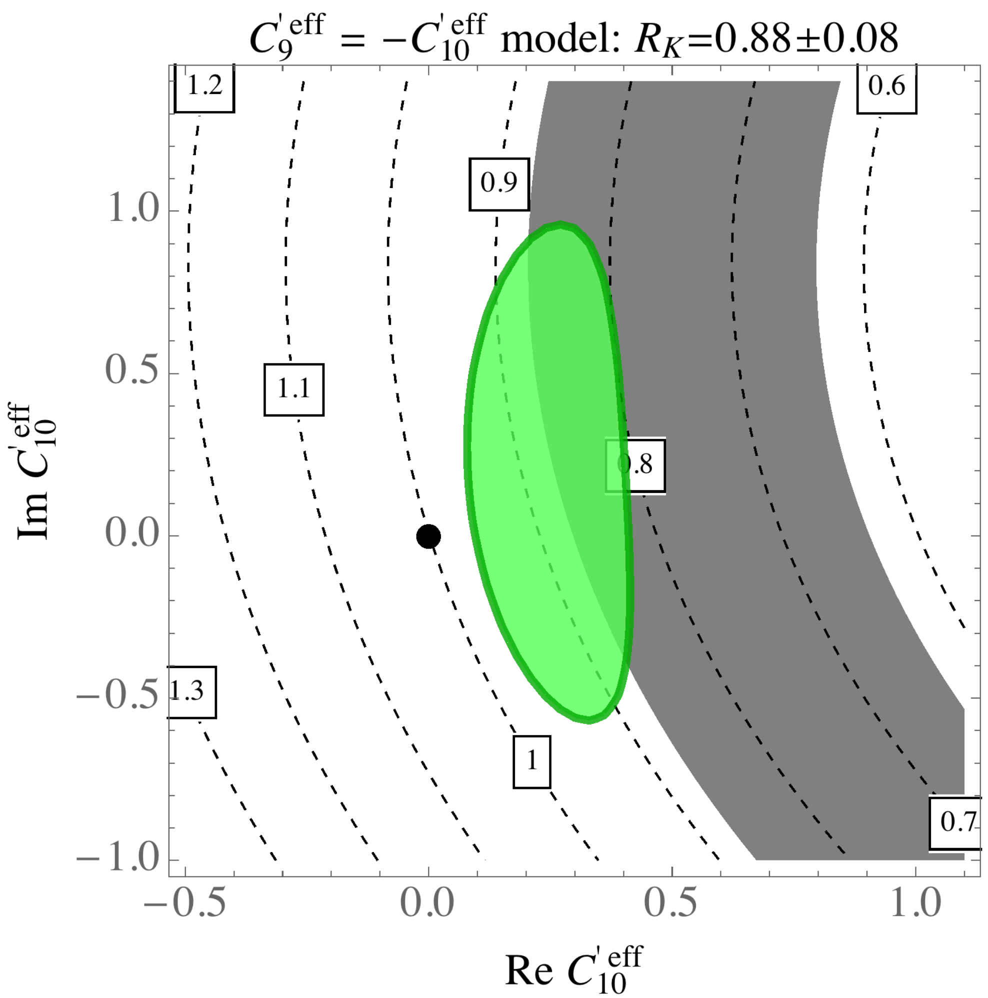
$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\rm exp} = (2.8^{+0.7}_{-0.6})\times 10^{-9}$$ [LHCb+CMS,1411.4413]

R_K prediction

$C_9' = -C_{10}'$

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

Remaining form factor uncertainties



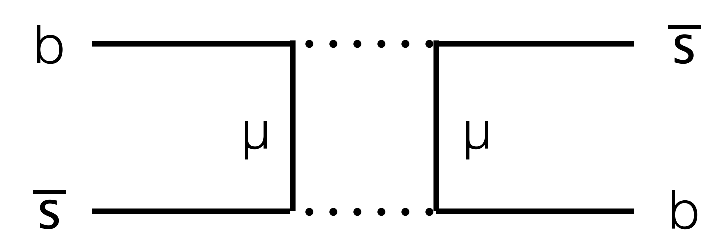
R_K contours Vs. prediction (green)

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

R_K by LHCb (gray): 0.75 ± 0.12

Relating B_s mixing and R_K

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



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

With imposed R_K constraint, effect in $B_s\underline{B_s}$ is increasing with mass

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

$$= 17.3 \pm 1.7\ {\rm ps}^{-1}$$

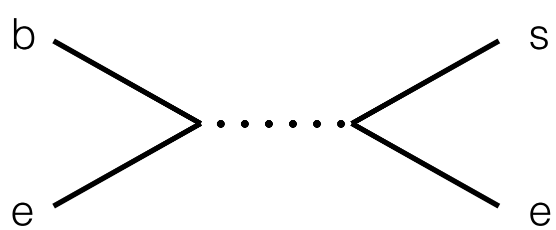
Upper mass limit for the LQ of the order 100 TeV.

Scalar leptoquark model - e

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

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

[Hiller, Schmaltz, 1411.4773]



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

Increased B → Kee implies decrease in B_s → ee

$$C'_9 \approx 0.5 \longrightarrow \frac{Y_{eb}Y^*_{es}}{m^2_\Delta} \approx \frac{1}{(24\mathrm{TeV})^2}$$

Further remarks on LQs

Scalars: $(\bar{3},3)_{1/3}$ $(\bar{3},1)_{1/3}$

- Both states may destabilize the proton
- $(\bar{3},3)_{1/3}$ implements a favorable $C_9^\mu = -C_{10}^\mu$ scenario

cf. Hiller, Schmaltz, 1411.4773

- $(\bar{3},1)_{1/3}$ has loop level contributions towards B→Kμμ and tree-level contributions to B→D(*)τν

cf. Neubert, Bauer, 1511.01900

- Vector $(3,3)_{2/3}$ conserves baryon number, implements $C_9^\mu = -C_{10}^\mu$ scenario and also contributes to B→D(*)τν

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{s\mu} & 0 \\ 0 & g_{b\mu} & g_{b\tau} \end{pmatrix}$$

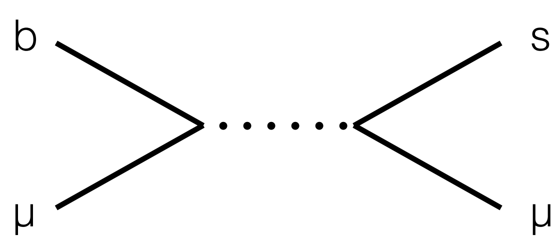
cf. Fajfer, NK, 1511.01900

Relating LFUv to Lepton Flavor Violation

Even with LFU violation, LFV can be avoided.

[Grinstein, Camalich, 1407.7044]

In leptoquark models, LFV is closely tied to LFUV.



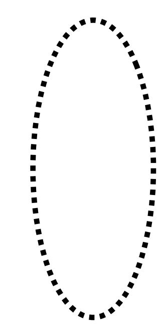
$$Y = \begin{pmatrix} & \\ Y_{\mu s} & Y_{\mu b} \end{pmatrix}$$

Universality lost,
flavour conserved!

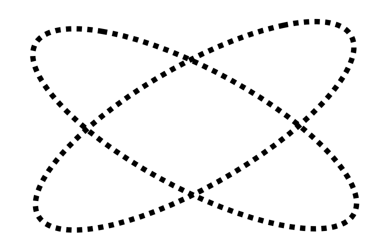
For LFV one needs to affect electronic and muonic decay modes simultaneously:

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

μ→eγ, Υ→eμ, Φ→eμ



B_s→eμ, B→Keμ



Relating LFUv to Lepton Flavor Violation

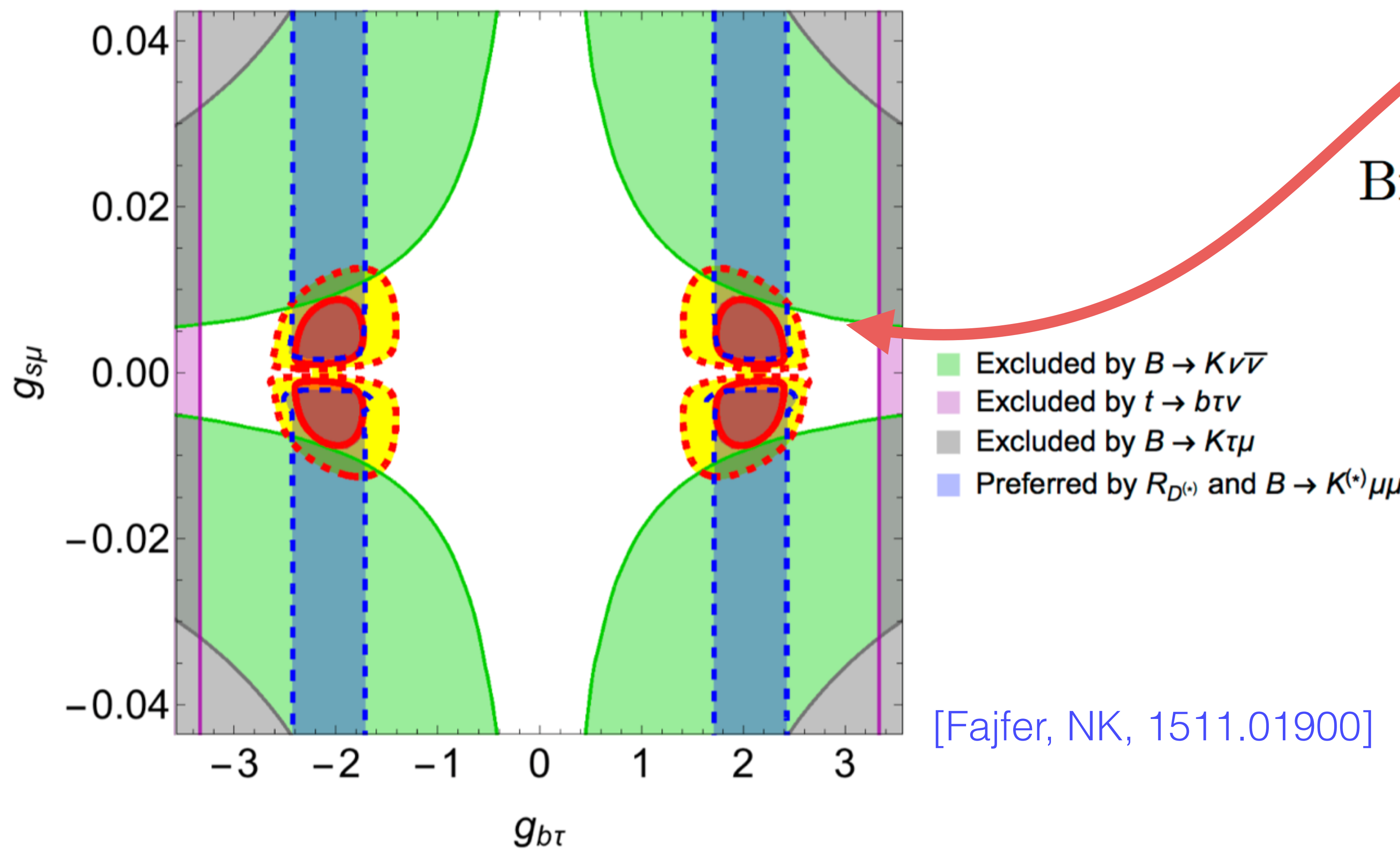
Consider vector LQ $(3,3)_{2/3}$ that addresses R_K and $R_{(D)^*}$ puzzles:

$$\mathcal{L}_{U_3} = U_{3\mu}^{(2/3)} \left[(\mathcal{V} g \mathcal{U})_{ij}\, \bar{u}_i \gamma^\mu P_L \nu_j - g_{ij}\, \bar{d}_i \gamma^\mu P_L \ell_j \right] + U_{3\mu}^{(5/3)} (\sqrt{2} \mathcal{V} g)_{ij}\, \bar{u}_i \gamma^\mu P_L \ell_j + U_{3\mu}^{(-1/3)} (\sqrt{2} g \mathcal{U})_{ij}\, \bar{d}_i \gamma^\mu P_L \nu_j + \text{h.c.}.$$

$$g = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{s\mu} & 0 \\ 0 & g_{b\mu} & g_{b\tau} \end{pmatrix}$$

Inevitable LFV in τ-μ sector. Bounds from τ→μγ, B→Kτμ, B→Kνν apply

strongest by far



[Fajfer, NK, 1511.01900]

$$\text{Br}(B^+ \to K^+ \nu\bar{\nu}) < 1.6 \times 10^{-5}$$

[BaBar, 1303.7465]

Conclusions & Outlook

- R_K measurement is very clean observable, it shows a hint of LFU violation
- Test in additional LFU ratios: R_K at high q^2, R_{K^*}, R_Φ, R_{K^*}/R_K,…
- (Axial)-vector $O_9^{(')}$, $O_{10}^{(')}$ operators are the simplest solution, consistency with global $b \to s\mu\mu$ data requires O_9
- Z' or light leptoquarks naturally realize these operators
- Each model offers additional specific predictions
- Lepton flavour violation expected but not guaranteed

Backup

LQ specific predictions: B→Kνν

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

(charge -1/3)

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

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

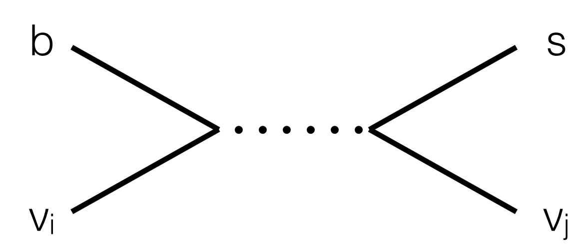
SM: flavour diagonal contributions

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

[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

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

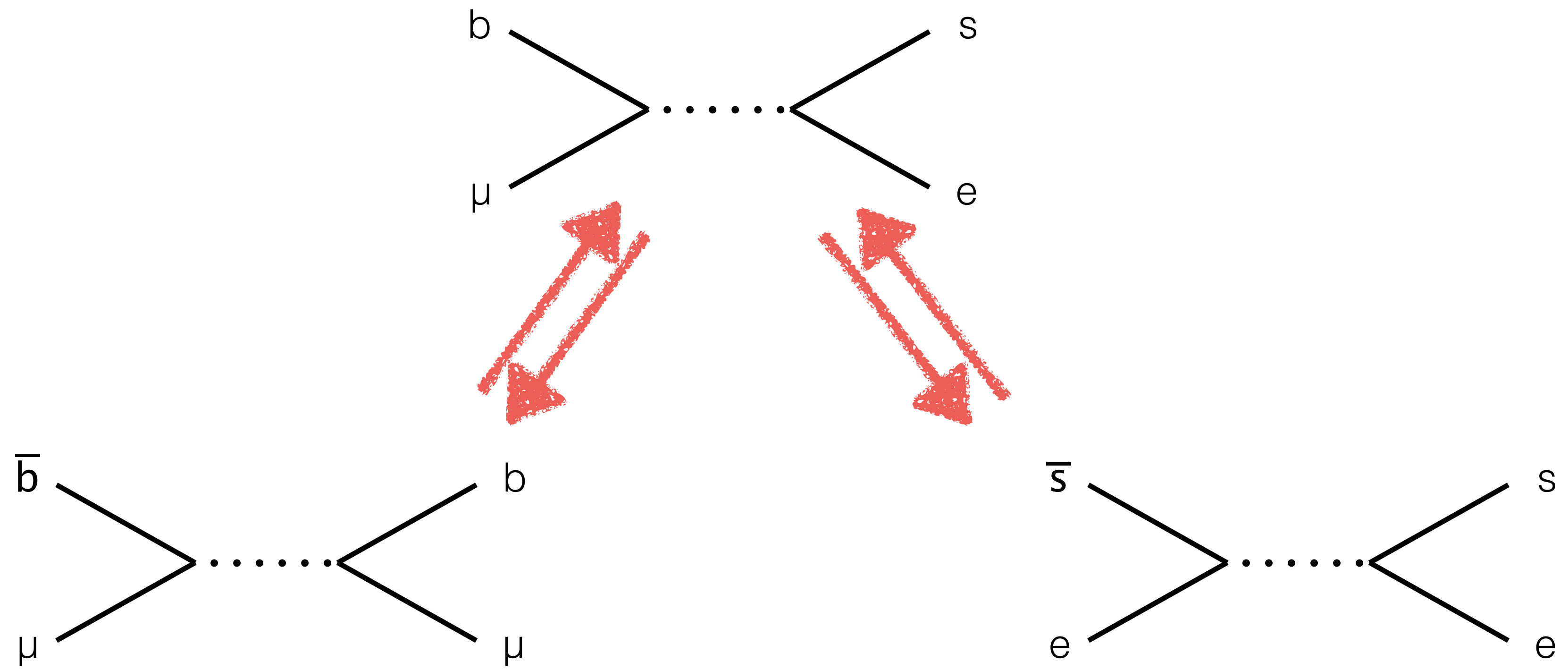
Correction of the SM q^2 spectrum and branching fraction:

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

LFV

LFV ⇔ (LFUV in different channels)

(Bs →eμ and B→Keμ can be measured) **if and only if** (LFUV in bottomonium and Φ can be measured)



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

Decay spectrum

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

…in terms of Wilson coefficients and form factors

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

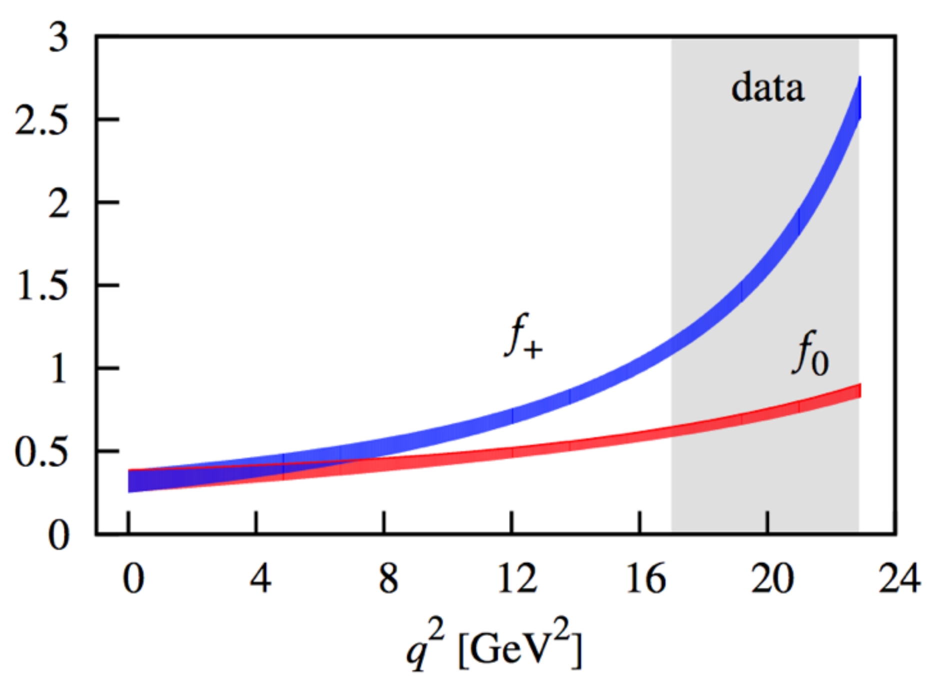
$$c_\ell(q^2) = \mathcal{C}(q^2)\Big[-\frac{\lambda(q^2)}{4}\beta_\ell^2(q^2)\left(|F_A(q^2)|^2 + |F_V(q^2)|^2\right)\Big]$$

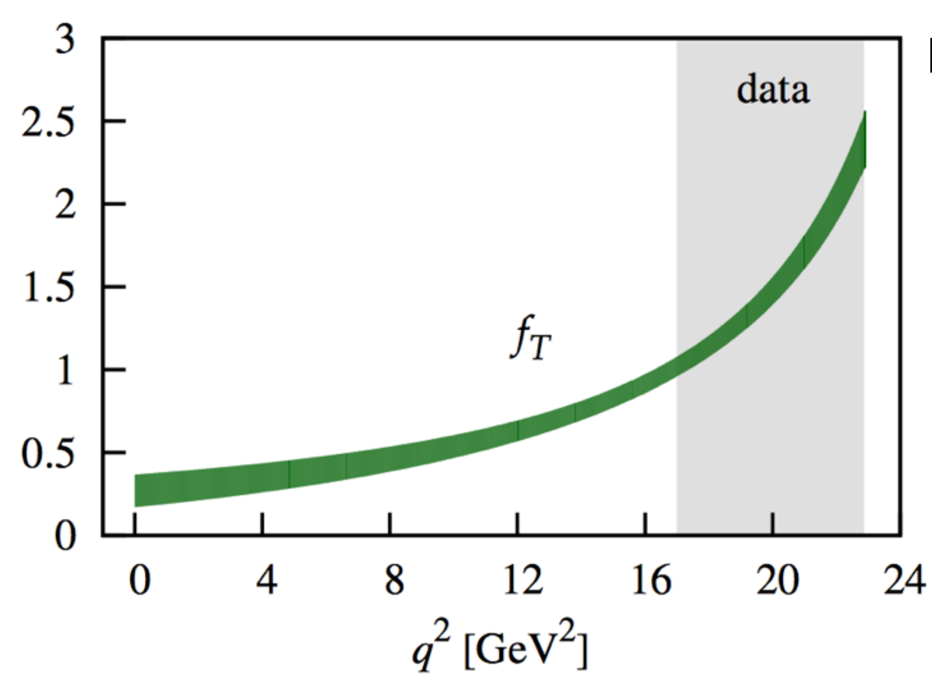
$$F_V(q^2) = (C_9 + C_9')\,f_+(q^2) + \frac{2m_b}{m_B + m_K}(C_7 + C_7')\,f_T(q^2)$$

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

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

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





[Bouchard et al, 1306.2384]