# New Physics facing LFU and LFV tests in B physics

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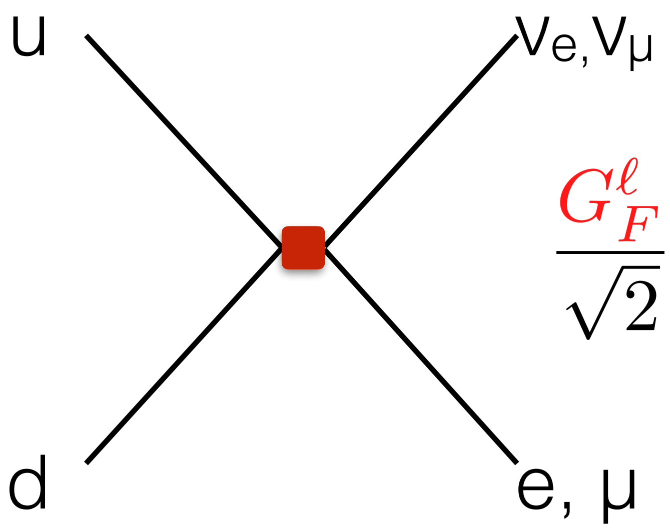
# Lepton flavour universality

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

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



$$\frac{G_F^\ell}{\sqrt{2}}\,\bar{\nu}_\ell\gamma^\lambda(1-\gamma_5)\ell\;\bar{n}\gamma_\lambda(1-\gamma_5)p$$

LFU built-in the SM on the level of gauge couplings. Broken by the lepton Yukawa couplings.

$$U(3)_L \times U(3)_e \to U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Well tested in pion, kaon decays, …
For example, Z decays at LEP:

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

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

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

# LFU tests at low energies

**1. LFU ratios are theoretically clean, blind to universal features (CKM, couplings, hadronic parameters)**

$$\Gamma_{P\to\ell\nu} \sim G_F^2 |V_{ij}|^2 f_P^2 m_P \underbrace{{m_\ell}^2 \left(1-\frac{{m_\ell}^2}{m_P^2}\right)}_{\text{chiral SM interaction}} \underbrace{\left(1-\frac{{m_\ell}^2}{m_P^2}\right)}_{\text{phase space}}$$

**2. Many LFU ratios are in good agreement with the SM**

| | **SM** | **exp. value** |
|---|---|---|
| $R^{\pi}_{e/\mu} = \frac{\Gamma(\pi\to e\bar\nu)}{\Gamma(\pi\to\mu\bar\nu)}$ | $(1.2352 \pm 0.0001) \times 10^{-4}$ | $(1.2327 \pm 0.0023) \times 10^{-4}$ |
| $R^{K}_{e/\mu} = \frac{\Gamma(K\to e\bar\nu)}{\Gamma(K\to\mu\bar\nu)}$ | $(2.477 \pm 0.001) \times 10^{-5}$ | $(2.488 \pm 0.010) \times 10^{-5}$ |
| $R^{K}_{\tau/\mu} = \frac{\Gamma(\tau\to K\bar\nu)}{\Gamma(K\to\mu\bar\nu)}$ | $(1.1162 \pm 0.00026) \times 10^{-2}$ | $(1.101 \pm 0.016) \times 10^{-2}$ |
| $R^{B}_{\tau/\mu} = \frac{\Gamma(B\to\tau\nu)}{\Gamma(B\to\mu\bar\nu)}$ | $223$ | $\gtrsim 100$ |

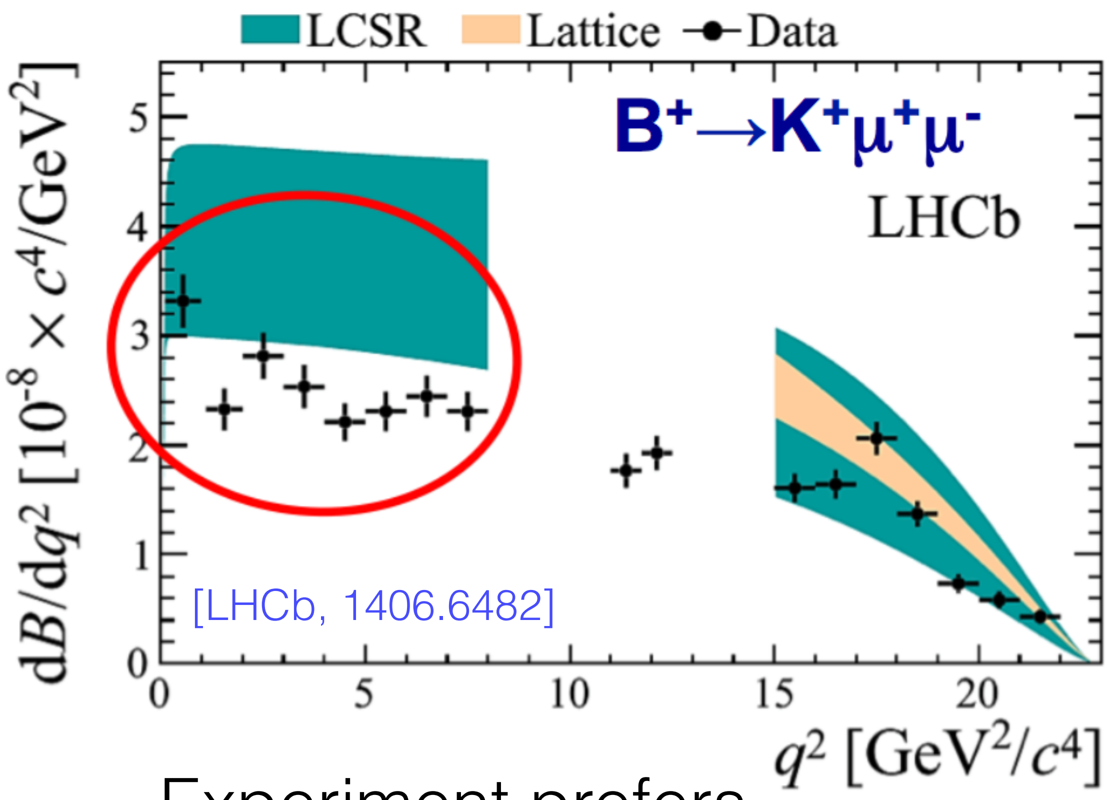
# LFU in neutral current $b \to s\ell^+\ell^-$

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

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}}{\mathcal{B}(B \to Ke^+e^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}} = 1.0004 \pm 0.0003 \sim 1 \pm m_\mu^2/m_B^2$$

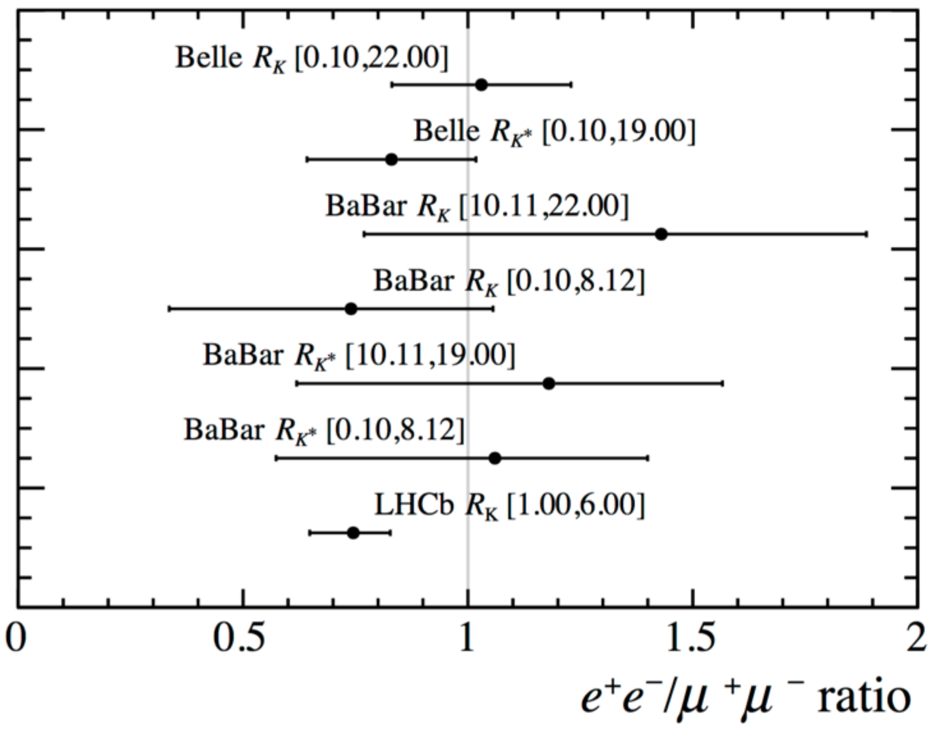
- LHCb observes hint of LFU violation (2014)

$$R_K^{\mathrm{exp}} = 0.745\,\pm^{0.090}_{0.074}\,\pm 0.036$$ **2.6σ from 1** [LHCb 1403.8044]



[LHCb, 1406.6482]

Experiment prefers deficit of muons scenario



[Blake, Lanfranchi, Straub 1606.00916]

# Effective operator analysis

Standard Model + dim-6 operators at scale Λ (SM-EFT)

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

$Q_i \sim (HD_\mu H)(\bar{q}\gamma^\mu q)$ “Higgs current”

$(\bar{q}\sigma^{\mu\nu}V_{\mu\nu}q)H$ “dipoles”

$\bar{q}q\bar{\ell}\ell$ “4-fermion”

Assume linear realisation of the EW symmetry. RG running to b-energy scale

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

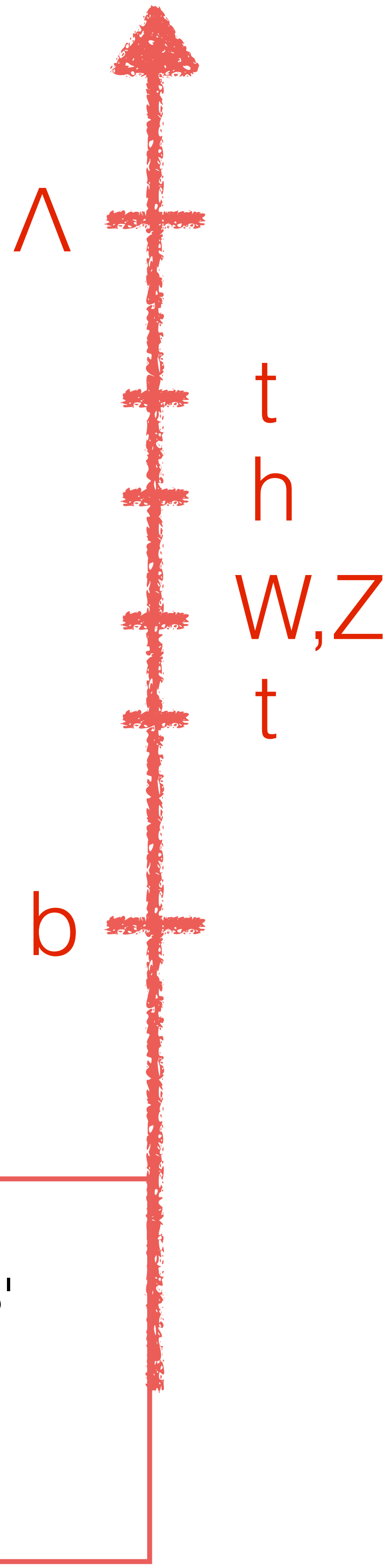
$$\mathcal{O}_7^{(\prime)} = \frac{e}{(4\pi)^2}m_b(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

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

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

[Grinstein, Camalich, Alonso, 1407.7044 ]
[Grinstein, Camalich, Alonso, 1505.05164]
[Cata, Jung, 1505.05804]
[Feruglio, Paradisi, Pattori, 1606.00524]

1. no tensor currents
2. scalars: $C_S=-C_P$, $C_S'=C_P'$
3. $C_{9,SM}=-C_{10,SM}=4.2$
4. **LFU violation from semileptonic operators**



# Effective operator analysis

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

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

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

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

- Scalar operators $C_S$=-$C_P$, $C_S$’=$C_P$’ for muons: large sensitivity in 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 or LEFT chiral vector currents: can affect μ or e ✓

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

(relative to the SM values)

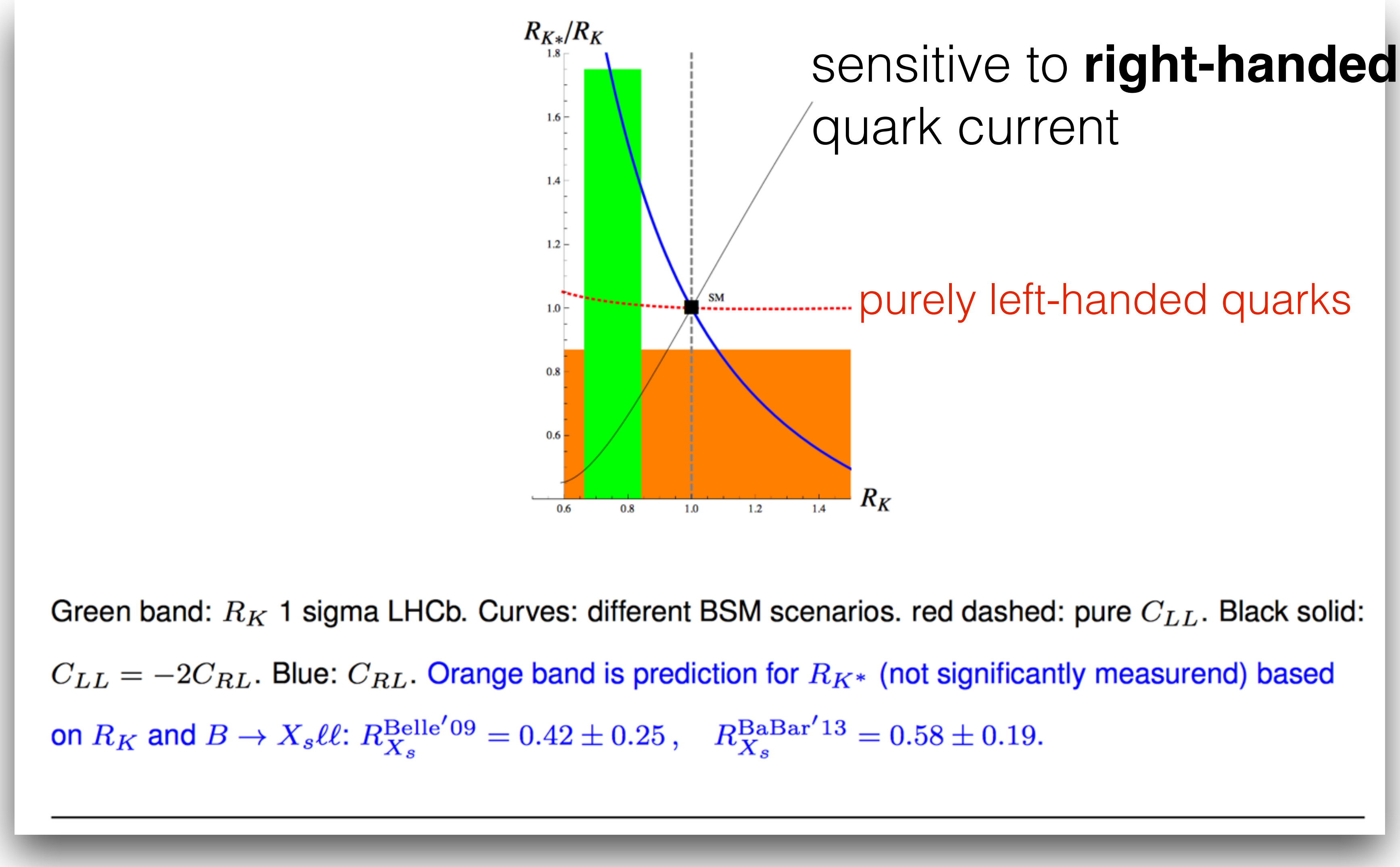
Destructive interference with SM in B → Kμμ and $B_s$→ μμ

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

# More LFU in b→s$\ell^+\ell^-$

$$R_{K^*} = \frac{\Gamma(B \to K^* \mu^+\mu^-)}{\Gamma(B \to K^* e^+e^-)}\Big|_{[q_1^2, q_2^2]} \qquad R_H = \frac{\mathcal{B}(\bar{B} \to \bar{H}\mu\mu)}{\mathcal{B}(\bar{B} \to \bar{H}ee)}\,, \quad H = K, K^*, X_s, K\pi, \ldots$$

[Kruger, Hiller, hep-ph/0310219]
[Hiller, Schmaltz, 1408.1627]



sensitive to **right-handed** quark current

purely left-handed quarks

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 $B \to X_s \ell\ell$: $R_{X_s}^{\mathrm{Belle}'09} = 0.42 \pm 0.25\,, \quad R_{X_s}^{\mathrm{BaBar}'13} = 0.58 \pm 0.19$.

[Hiller, Schmaltz, 1411.4773]

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

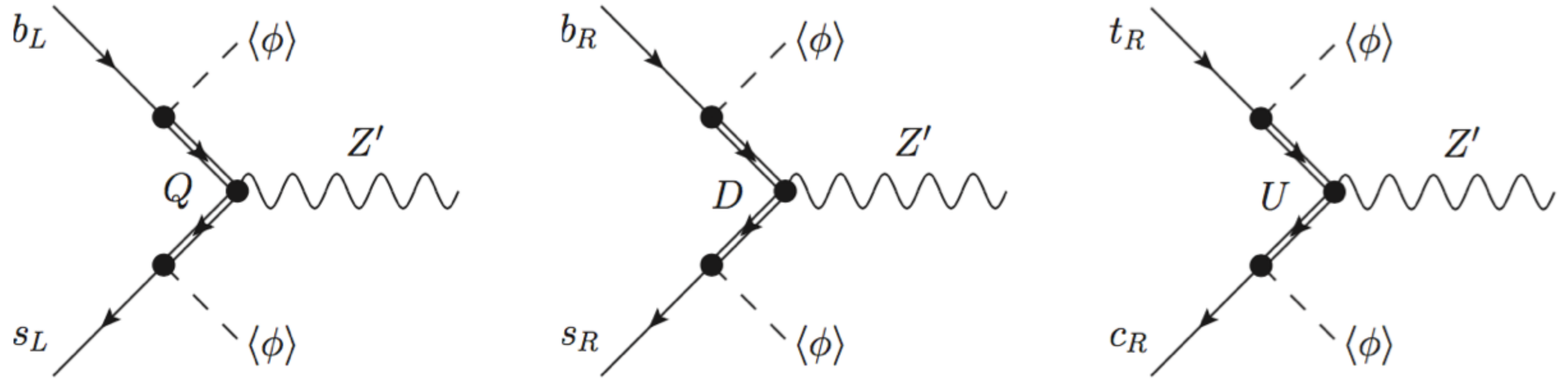
[Altmannshofer, Straub, 1308.1501]

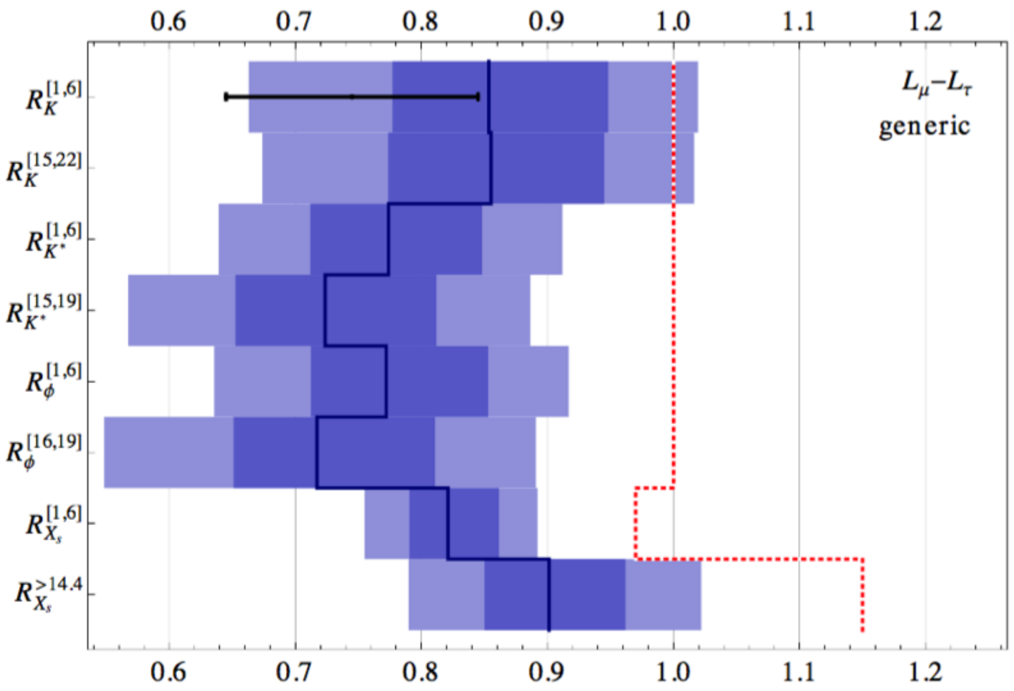
# Z' model with $L_\mu$-$L_\tau$

- Gauge the leptonic number difference: $U(1)_{L\mu - L\tau}$, coupled to $Z'_\mu$
- Vector-couplings of Z' to either muons or taus
- Vector-like quarks charged under U(1) mix with SM quarks and give dim-6 operators:

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

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





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

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

# Scalar leptoquarks in b→sμ⁺μ⁻

Representations of scalar LQs under $SU(3) \otimes SU(2) \otimes U(1)$ (Q = Y + T₃)

| | | | | |
|---|---|---|---|---|
| $(3,2)_{7/6}$ | Increases B→Kμμ | $\bar{Q} e_R$ | | |
| $(3,2)_{1/6}$ | Decreases B→Kμμ | $\bar{L} d_R$ | | $\tilde{R}_2 (3,2)_{1/6}$ |
| $(\bar{3},3)_{1/3}$ | 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 | $\overline{d_R^C} \ell_R$ | $\overline{u_R^C} u_R$ | |

$$\begin{aligned}\mathcal{L} &= Y_{ij} \overline{L}_i \, i\tau^2 \tilde{R}_2^* d_{Rj} \\ &= Y_{ij} \left( -\bar{\ell}_{Li} d_{Rj} \tilde{R}_2^{(2/3)*} + \bar{\nu}_{Lk} (V^{\mathrm{PMNS}})^\dagger_{ki} d_{Rj} \tilde{R}_2^{(-1/3)*} \right)\end{aligned}$$

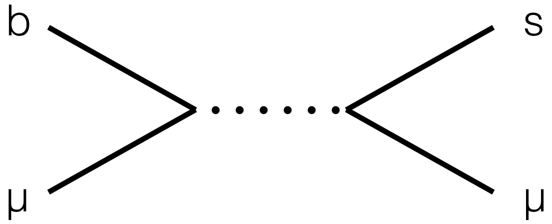
$$Y = \begin{pmatrix} & & \\ & Y_{\mu s} & Y_{\mu b} \\ & & \end{pmatrix}$$

SU(2) doublet correlations with B→Kνν

[Becirevic, Fajfer, NK, 1503.09024]

# Scalar leptoquark $\tilde{R}_2(3,2)_{1/6}$

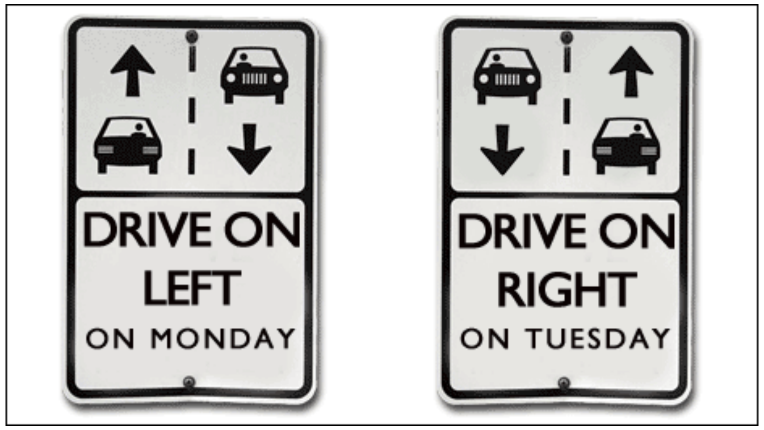
$$-\left(Y_{\mu s}\bar{\mu}_L s_R + Y_{\mu b}\bar{\mu}_L b_R\right)\tilde{R}_2^{(2/3)*}$$



$$C_{10}' = -C_9' = \frac{-\pi}{2\sqrt{2}G_F V_{tb}V_{ts}^*\alpha}\,\frac{Y_{\mu b}Y_{\mu s}^*}{m_{\tilde{R}_2}^2}\,.$$

**RIGHT HANDED quark currents**

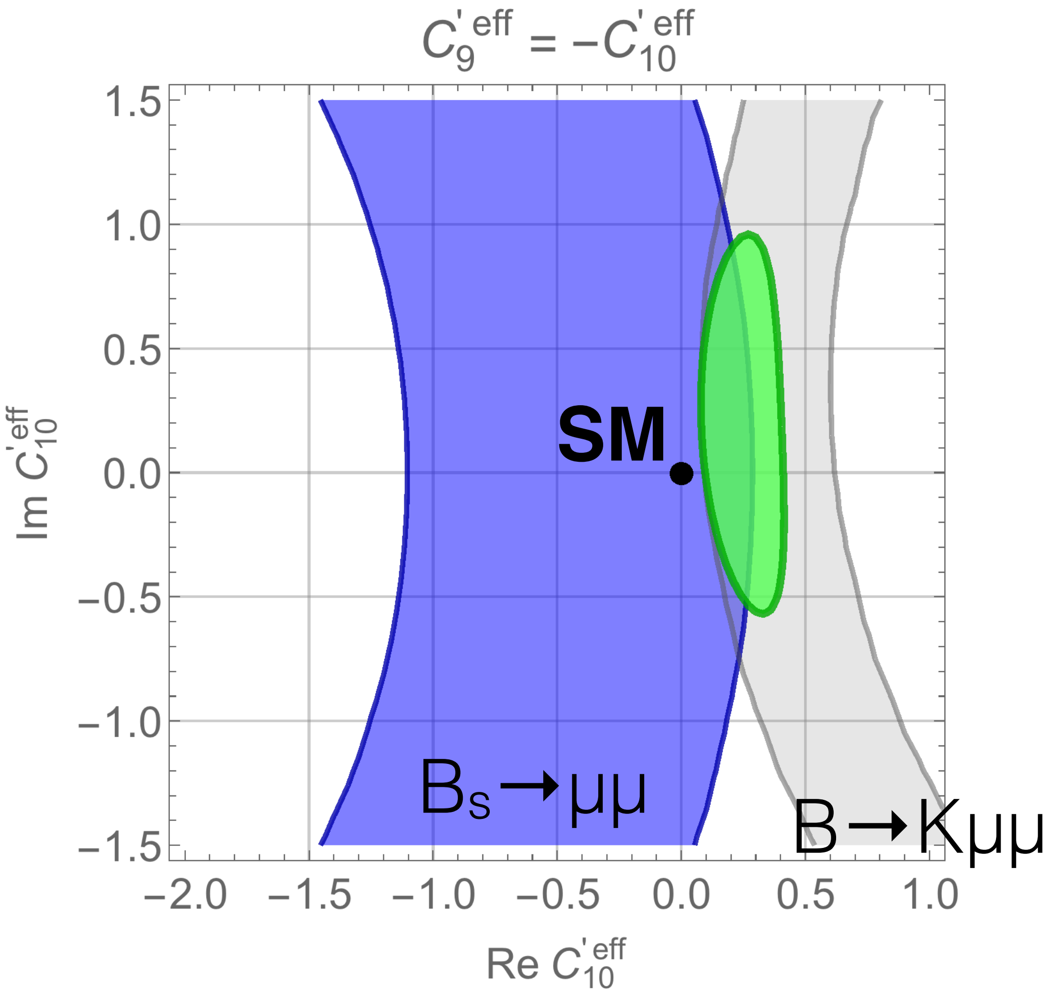
1. Use the exp. inputs from B→Kμμ and $B_s$→μμ rates
2. Predict $R_K$

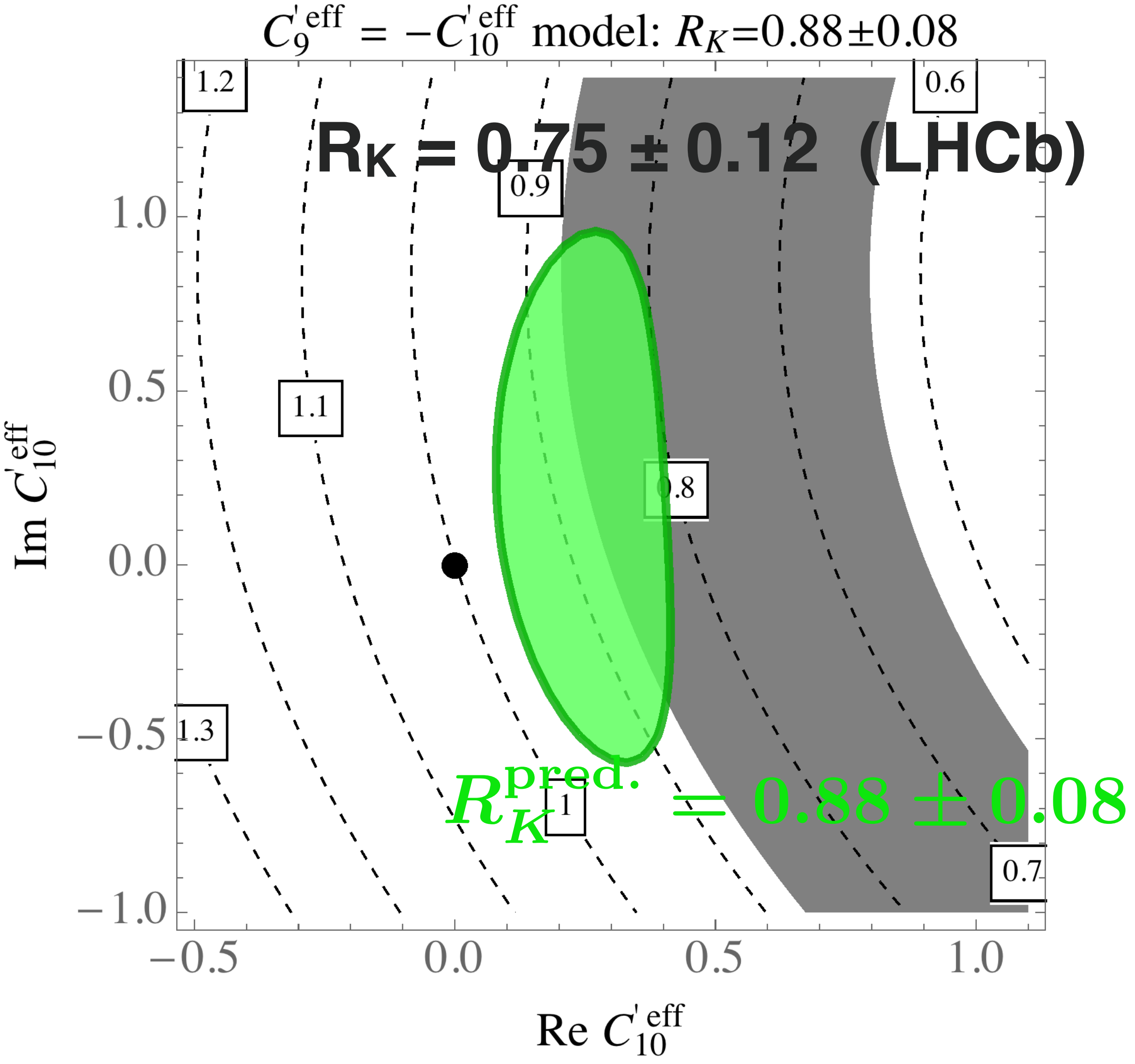


$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)|_{q^2\in[15,22]\mathrm{GeV}^2} = (8.5 \pm 0.3 \pm 0.4) \times 10^{-8}$$ [LHCb,1403.8044]

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

# Scalar leptoquark $\tilde{R}_2(3,2)_{1/6}$ and $R_K$





Further signatures of RH currents:

$R_{K^*} = 1.11(8)$

$$R_{\text{fb}} = \frac{A^{\mu}_{\text{fb}[4,6]}}{A^{e}_{\text{fb}[4,6]}} = 0.84(12)$$

+ effects in $B_s$ mixing
and B→Kνν

[Becirevic, Fajfer, NK, 1503.09024]

# Further comments 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 $C_9^\mu = -C_{10}^\mu$ scenario, preferred by fits

[Hiller, Schmaltz, 1411.4773]

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

[Neubert, Bauer, 1511.01900]

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

[Fajfer, NK, 1511.01900]

# LFU in charged current b→cτν

$$R_D^{\mathrm{SM}} = \frac{\Gamma(B \to D\tau\nu)}{\Gamma(B \to D\ell\nu)} = 0.297 \pm 0.017$$

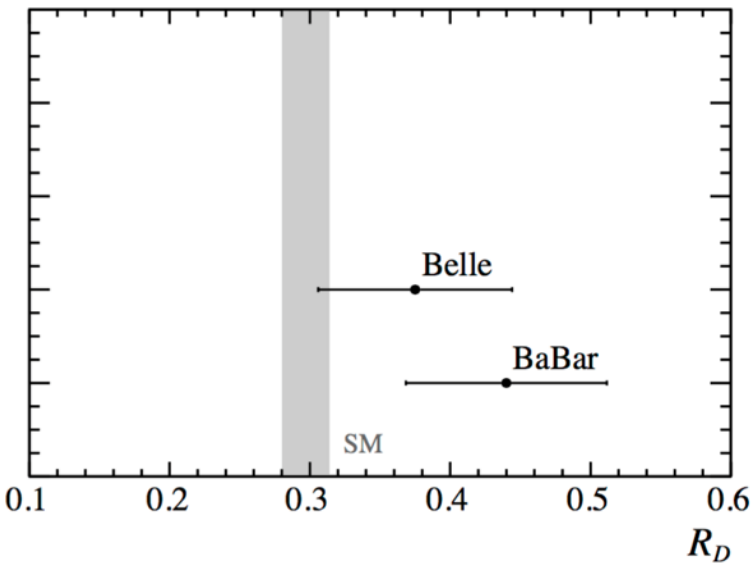
$$R_{D^*}^{\mathrm{SM}} = \frac{\Gamma(B \to D^*\tau\nu)}{\Gamma(B \to D^*\ell\nu)} = 0.252 \pm 0.003$$

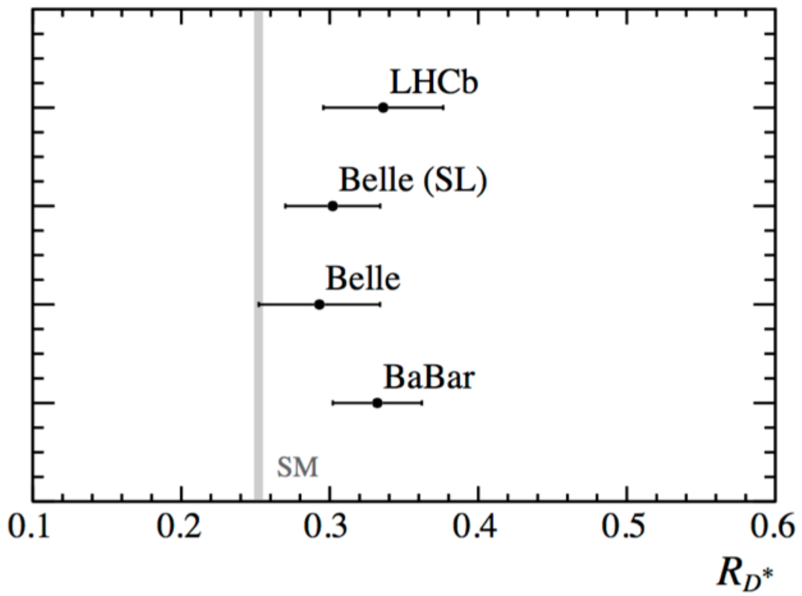
[Fajfer, Kamenik, Nisandzic, 1203.2654]

$$R_D^{\mathrm{exp}} = \frac{\Gamma(B \to D\tau\nu)}{\Gamma(B \to D\ell\nu)} = 0.440 \pm 0.072$$

$$R_{D^*}^{\mathrm{exp}} = \frac{\Gamma(B \to D^*\tau\nu)}{\Gamma(B \to D^*\ell\nu)} = 0.332 \pm 0.030$$

[BaBar, 1205.5442]





[Blake, Lanfranchi, Straub 1606.00916]

Old and new Belle and LHCb results on $R_{D^*}$ also above the SM and consistent with BaBar

Large effect - 25% enhancement of the charged current!

SM hypothesis incompatible at 4σ level.

# EFT view of b→cτν

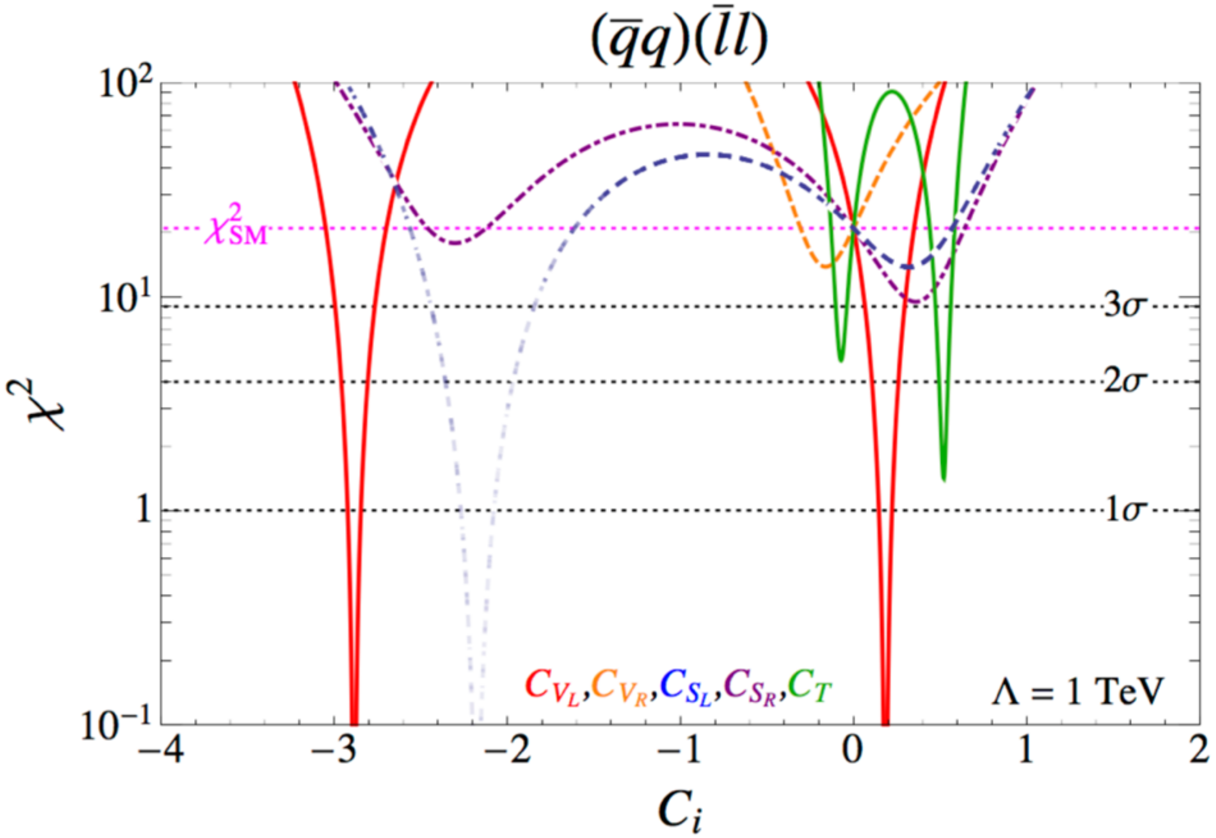
Data can be best described by (a combination of) following operators

$$\mathcal{L} = -\frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+g_V)(\bar{\tau}_L\gamma^\mu\nu_L)(\bar{c}_L\gamma_\mu b_L)$$

$$+ g_S(\bar{\tau}_R\nu_L)(\bar{c}_R b_L) + g_T(\bar{\tau}_R\sigma^{\mu\nu}\nu_L)(\bar{c}_R\sigma_{\mu\nu}b_L)\Big]$$

[Becirevic, NK, Tayduganov,1206.4977]

| | Operator |
|---|---|
| $\mathcal{O}_{V_L}$ | $(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$ |
| $\mathcal{O}_{V_R}$ | $(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$ |
| $\mathcal{O}_{S_R}$ | $(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$ |
| $\mathcal{O}_{S_L}$ | $(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$ |
| $\mathcal{O}_T$ | $(\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L \nu)$ |
| $\mathcal{O}'_{V_L}$ | $(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$ |
| $\mathcal{O}'_{V_R}$ | $(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$ |
| $\mathcal{O}'_{S_R}$ | $(\bar{\tau}P_R b)\,(\bar{c}P_L \nu)$ |
| $\mathcal{O}'_{S_L}$ | $(\bar{\tau}P_L b)\,(\bar{c}P_L \nu)$ |
| $\mathcal{O}'_T$ | $(\bar{\tau}\sigma^{\mu\nu}P_L b)\,(\bar{c}\sigma_{\mu\nu}P_L \nu)$ |
| $\mathcal{O}''_{V_L}$ | $(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$ |
| $\mathcal{O}''_{V_R}$ | $(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$ |
| $\mathcal{O}''_{S_R}$ | $(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L \nu)$ |
| $\mathcal{O}''_{S_L}$ | $(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L \nu)$ |
| $\mathcal{O}''_T$ | $(\bar{\tau}\sigma^{\mu\nu}P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu}P_L \nu)$ |



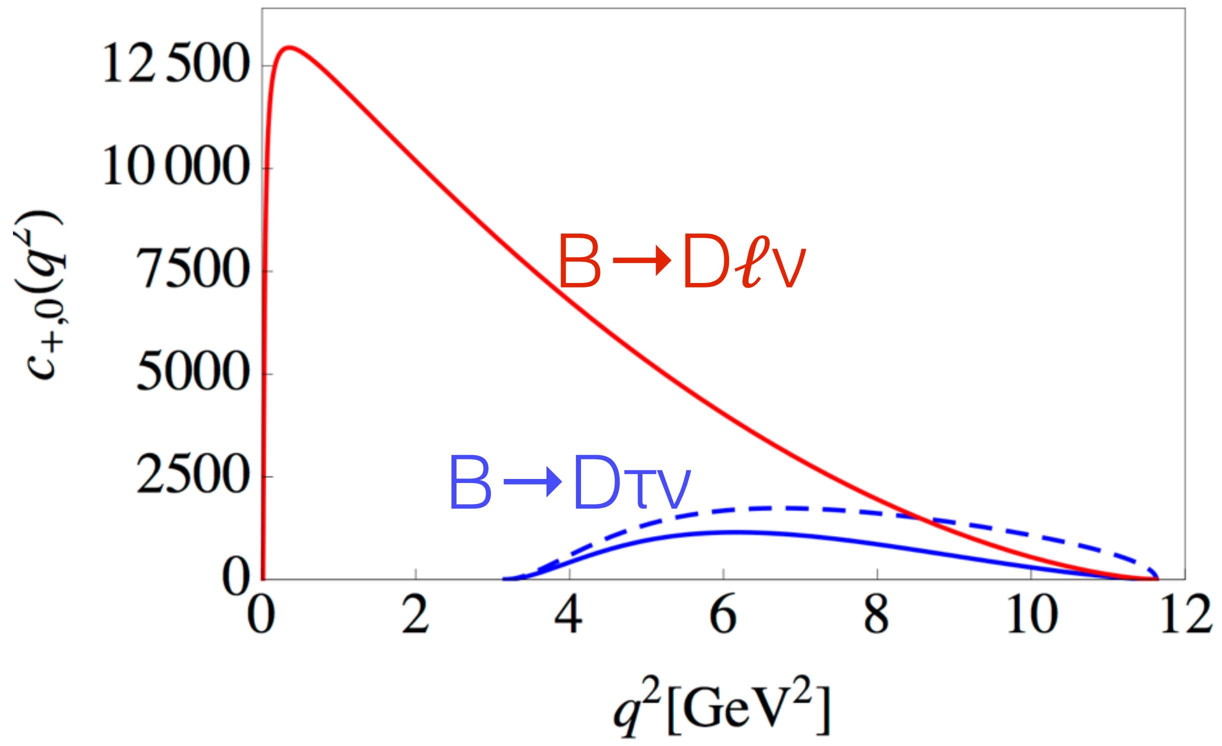
[Freytsis, Ligeti, Ruderman, 1506.08896]

# Models for b→cτν

**Only tree-level NP can compete with tree-level SM!**

Charged scalars: extra Higgs(es)

- Non-minimal flavour structure (e.g. type III)
- Scalar form factor $F_0$ enhanced in B→Dτν, absent in B→Dℓν



[Crivellin, Greub, Kokulu,1206.2634]
[Celis, Jung, Li, Pich,1210.8443]
…

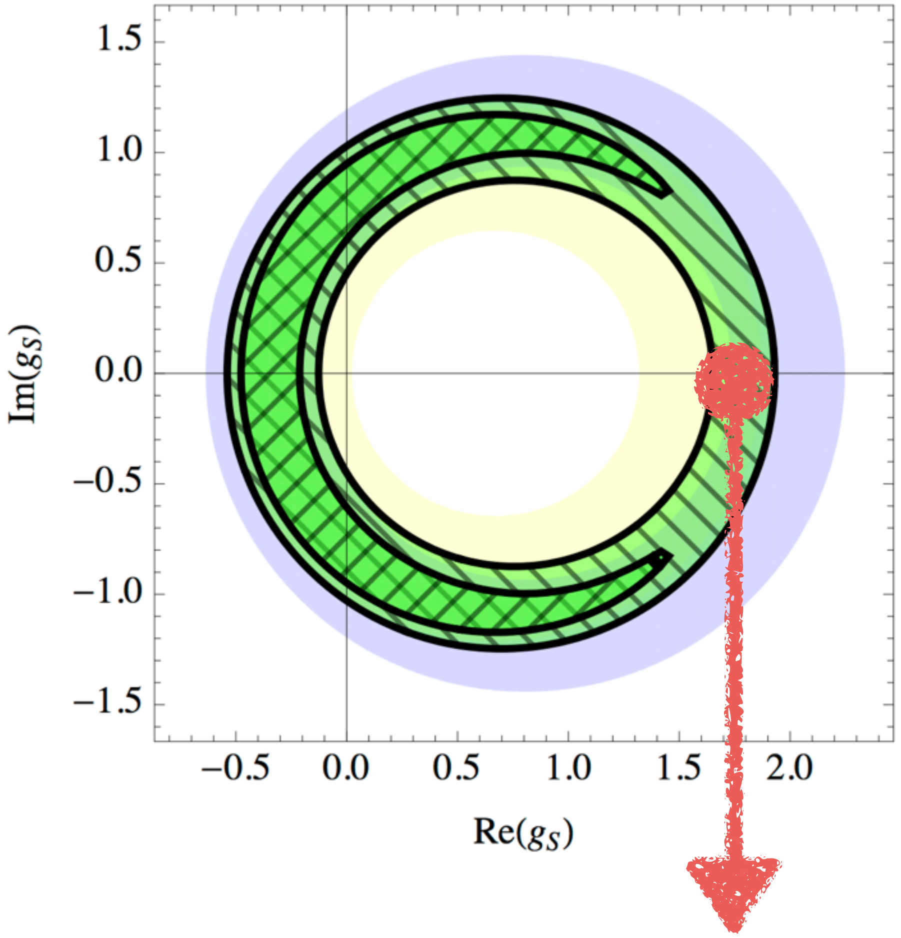
[Ko, Omura, Yu, 1212.4607]
[Crivellin, Heeck, Stoffer,1507.07567]

Coloured bosons - LQs

- Fierzed basis of operators:
  →scalar/vector/tensor

[Sakaki, Tanaka, Tayduganov, Watanabe,1309.0301]
[Bauer, Neubert, 1511.01900 ]
[Li, Yang, Zhang, 1605.09308]
…

# LQ models for b→cτν



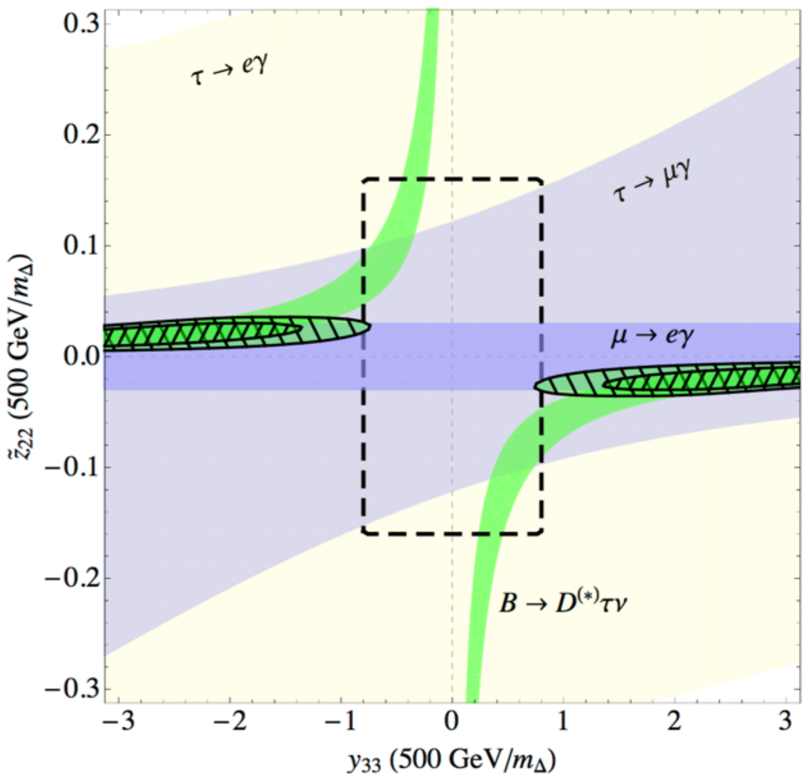
Scalar $R_2(3,2)_{7/6}$

$$\mathcal{L}_{\mathrm{LQ}} = \bar{\ell}_R Y R_2^\dagger Q + \bar{u}_R Z i\tau_2 R_2^T L$$

$$Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{33} \end{pmatrix} \qquad Z = \begin{pmatrix} 0 & 0 & 0 \\ \tilde{z}_{21} & \tilde{z}_{22} & \tilde{z}_{23} \\ 0 & 0 & 0 \end{pmatrix}$$

**Fit of scalar and tensor to $R_D$, $R_{D^*}$**

Large solutions excluded
by Belle spectra [1603.06711]



LFV constraints guide leave
a small portion of parameter space

[Dorsner, Fajfer, NK, Nisandzic, 1306.6493]

# LQ models for b→cτν

## Vector U3 (3,3)$_{2/3}$

A weak triplet state couples at tree-level only to LH fermions

[Fajfer, NK, 1511.01900]
[Barbieri, Isidori, Pattori, Senia, 1512.01560]

non-LQ triplets:
[Greljo et al,1506.01705]
[Boucenna et al,1604.03088]

$$\mathcal{L}_{U_3} = g_{ij}\bar{Q}_i\gamma^\mu\,\tau^A U^A_{3\mu}\,L_j$$

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

$$\mathcal{L}_{\text{SL}} = -\left[\frac{4G_F}{\sqrt{2}}\mathcal{V}_{cb}\mathcal{U}_{\tau i} + \frac{g^*_{b\tau}(\mathcal{V}g\mathcal{U})_{ci}}{M_U^2}\right](\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L\nu_i)$$

# LQ models for b→cτν

## Vector U3 (3,3)2/3

A weak triplet state couples at tree-level only to LH fermions

$$\mathcal{L}_{U_3} = g_{ij}\bar{Q}_i\gamma^\mu\,\tau^A U^A_{3\mu}\,L_j$$

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non-LQ triplets:
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$$\mathcal{L}_{U_3} = U^{(2/3)}_{3\mu}\left[(\mathcal{V}g\mathcal{U})_{ij}\bar{u}_i\gamma^\mu P_L\nu_j - g_{ij}\bar{d}_i\gamma^\mu P_L\ell_j\right]$$

LH currents for Puzzle b->sll!

$$+ U^{(5/3)}_{3\mu}(\sqrt{2}\mathcal{V}g)_{ij}\,\bar{u}_i\gamma^\mu P_L\ell_j$$

charm and top

$$+ U^{(-1/3)}_{3\mu}(\sqrt{2}g\mathcal{U})_{ij}\,\bar{d}_i\gamma^\mu P_L\nu_j + \text{h.c.}.$$

B→Kνν

$$\mathcal{L}_{\text{SL}} = -\left[\frac{4G_F}{\sqrt{2}}\mathcal{V}_{cb}\mathcal{U}_{\tau i} + \frac{g^*_{b\tau}(\mathcal{V}g\mathcal{U})_{ci}}{M_U^2}\right](\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L\nu_i)$$

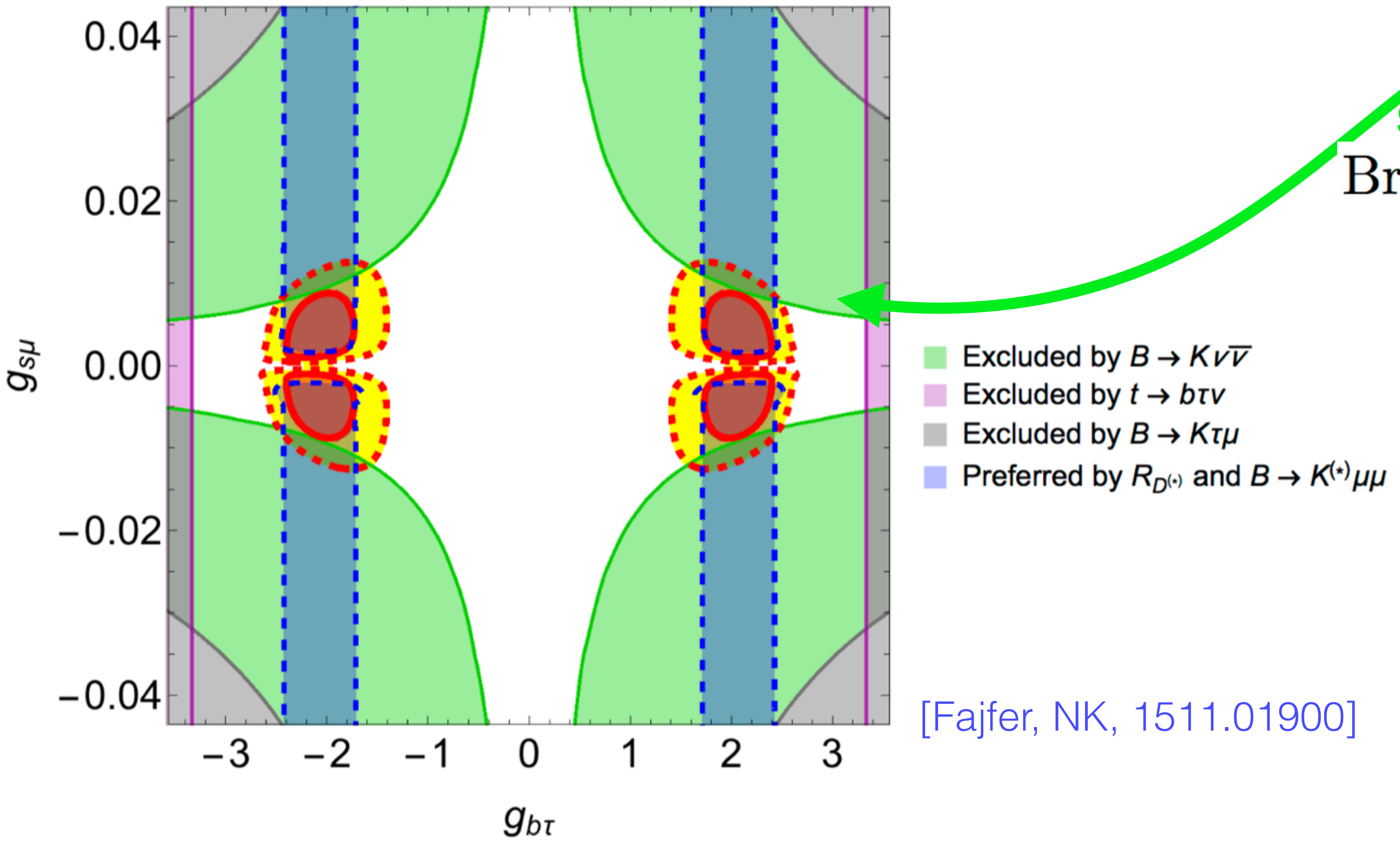
# Relating LFUv to Lepton Flavor Violation

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

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

Inevitable LFV in τ-μ sector.

LFV bounds from B→Kτμ, B→Kνν



[Fajfer, NK, 1511.01900]

**strongest LFV constraint**

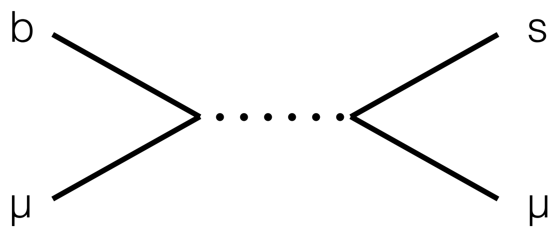
$$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu}) < 1.6 \times 10^{-5}$$

[BaBar, 1303.7465]

# Relating LFUv to Lepton Flavor Violation

Even with LFU violation, LFV can be avoided [Grinstein, Camalich, 1407.7044]

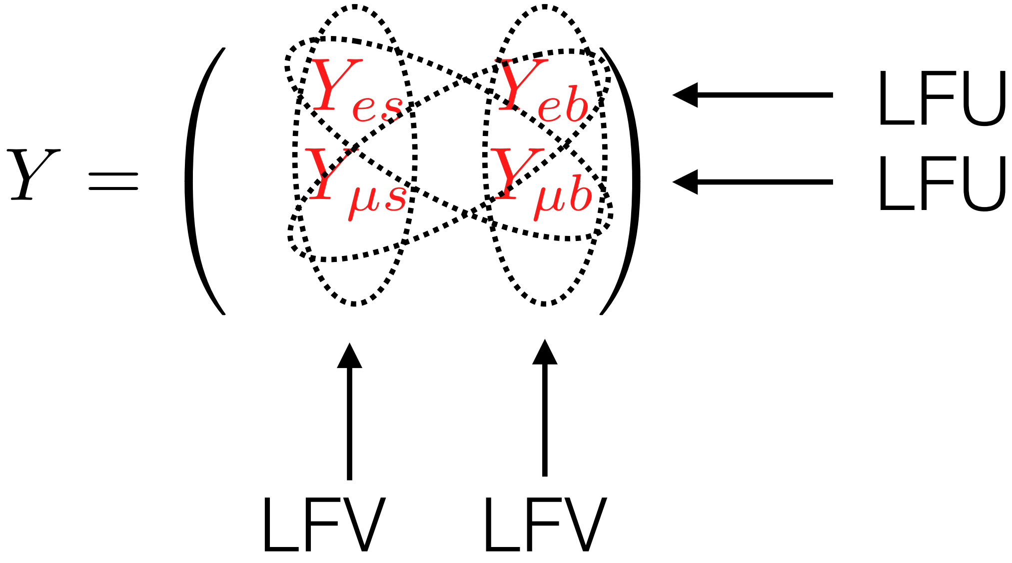
In leptoquark models, LFV is closely tied to LFUV.



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

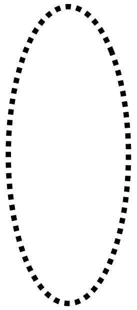
LFU breaking,
$U(1)_e \times U(1)_\mu \times U(1)_\tau$
symmetric!

For LFV we need electronic and muonic couplings

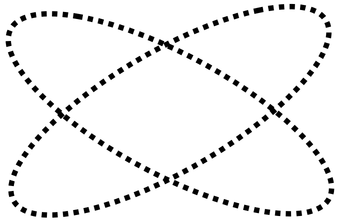


$$Y = \begin{pmatrix} Y_{es} & Y_{eb} \\ Y_{\mu s} & Y_{\mu b} \end{pmatrix}$$

μ→eγ, Υ→eμ, Φ→eμ



$B_s$→eμ, B→Keμ



# Summary

- LFU ratios offer very precise validation of the Standard Model
- $R_K$ experimental value by LHCb fits well with global analyses of sbμμ (rates, angular coefficients). Confirmed deviation and corroboration in $R_{K^*}$ would leave no room for doubts of New Physics effects at work.
- $R_{D(*)}$ is the charged current LFU violation. Several measurements point at increased semi-tauonic rates. Will be further probed in near future. Tree-level new physics needed.
- If $R_K$ **or(and)** $R_{D(*)}$ puzzles are true it is **possible(very plausible)** that Lepton Flavor Violation also occur at detectable levels.
- More stringent LFV tests would help narrow down the NP candidates

Thank you!

# Backup

# $B \to K^{(*)}\mu^+\mu^-$

$$\frac{d^2\Gamma_\ell(q^2,\cos\theta)}{dq^2 d\cos\theta} = a_\ell(q^2) + b_\ell(q^2)\cos\theta + c_\ell(q^2)\cos^2\theta$$

$$\frac{1}{\Gamma^\ell}\frac{d\Gamma^\ell}{d\cos\theta_\ell} = \frac{3}{4}(1-F_H^\ell)(1-\cos^2\theta_\ell) + \frac{F_H^\ell}{2} + A_{\rm FB}^\ell\cos\theta_\ell$$

$\}$ $B \to K\mu^+\mu^-$

$q^2$ spectrum, $A_{FB}$, flat term $F_H$

$B \to K^*\mu^+\mu^- \to K\pi\mu^+\mu^-$ $\{$

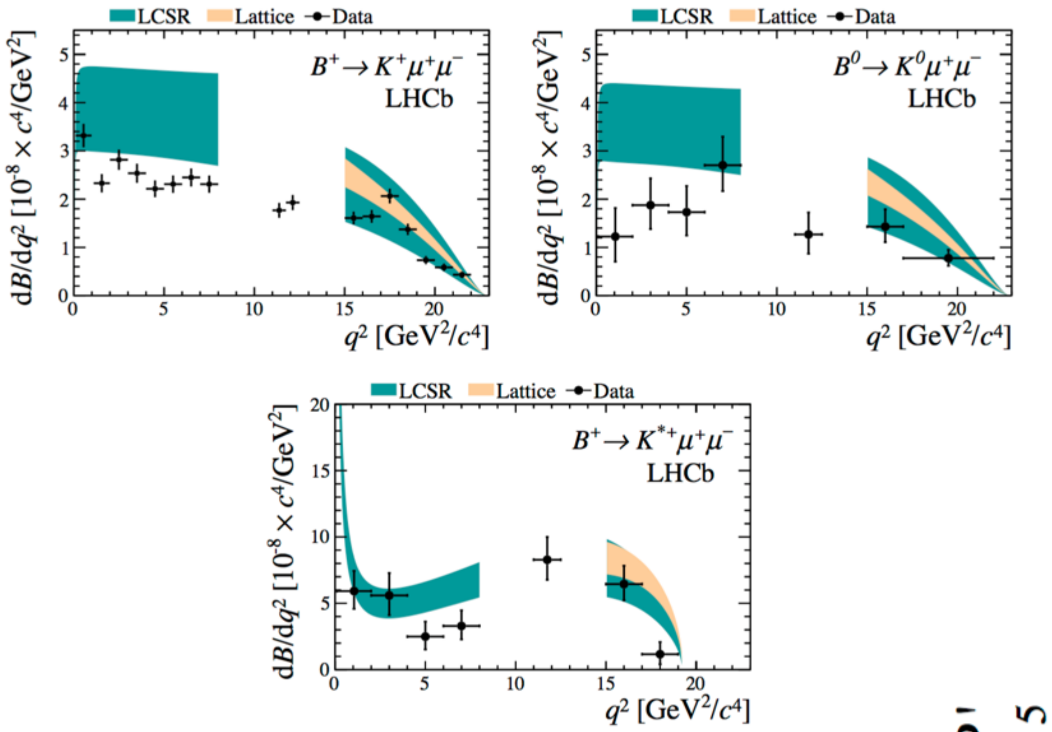
$$\frac{d^4\Gamma(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-)}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \frac{9}{32\pi} I(q^2,\theta_\ell,\theta_K,\phi)\,,$$

12 CP averaged observables + 12 CP odd

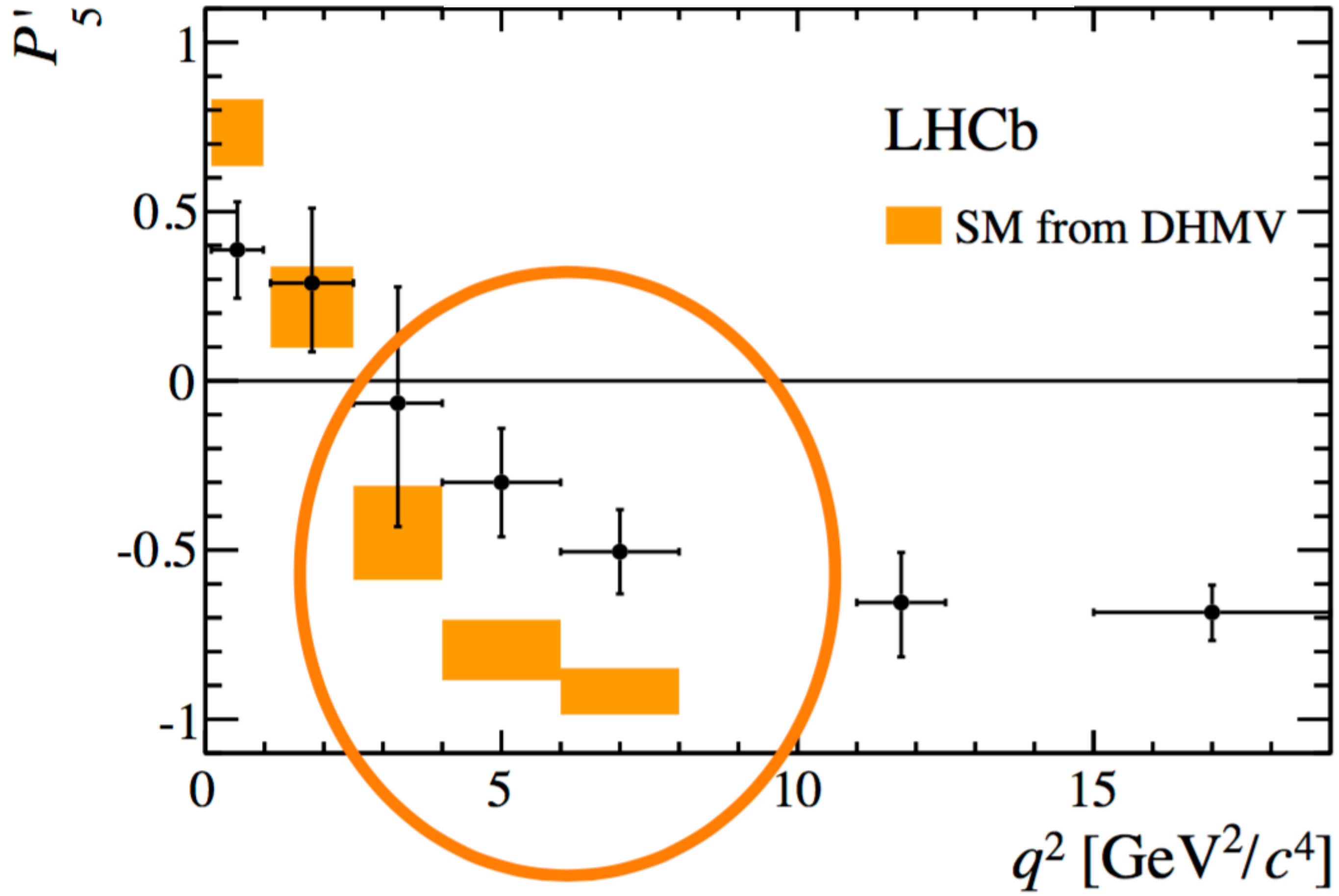
$$\begin{aligned} I(q^2,\theta_\ell,\theta_K,\phi) \ = \ & I_1^s(q^2)\sin^2\theta_K + I_1^c(q^2)\cos^2\theta_K + \left[I_2^s(q^2)\sin^2\theta_K + I_2^c(q^2)\cos^2\theta_K\right]\cos 2\theta_\ell \\ & + I_3(q^2)\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + I_4(q^2)\sin 2\theta_K\sin 2\theta_\ell\cos\phi \\ & + I_5(q^2)\sin 2\theta_K\sin\theta_\ell\cos\phi \\ & + \left[I_6^s(q^2)\sin^2\theta_K + I_6^c(q^2)\cos^2\theta_K\right]\cos\theta_\ell + I_7(q^2)\sin 2\theta_K\sin\theta_\ell\sin\phi \\ & + I_8(q^2)\sin 2\theta_K\sin 2\theta_\ell\sin\phi + I_9(q^2)\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \end{aligned}$$

# $B \rightarrow K^{(*)}\mu^+\mu^-$

[LHCb 1403.8044]



$$P_5' = S_5/\sqrt{F_L(1 - F_L)}$$



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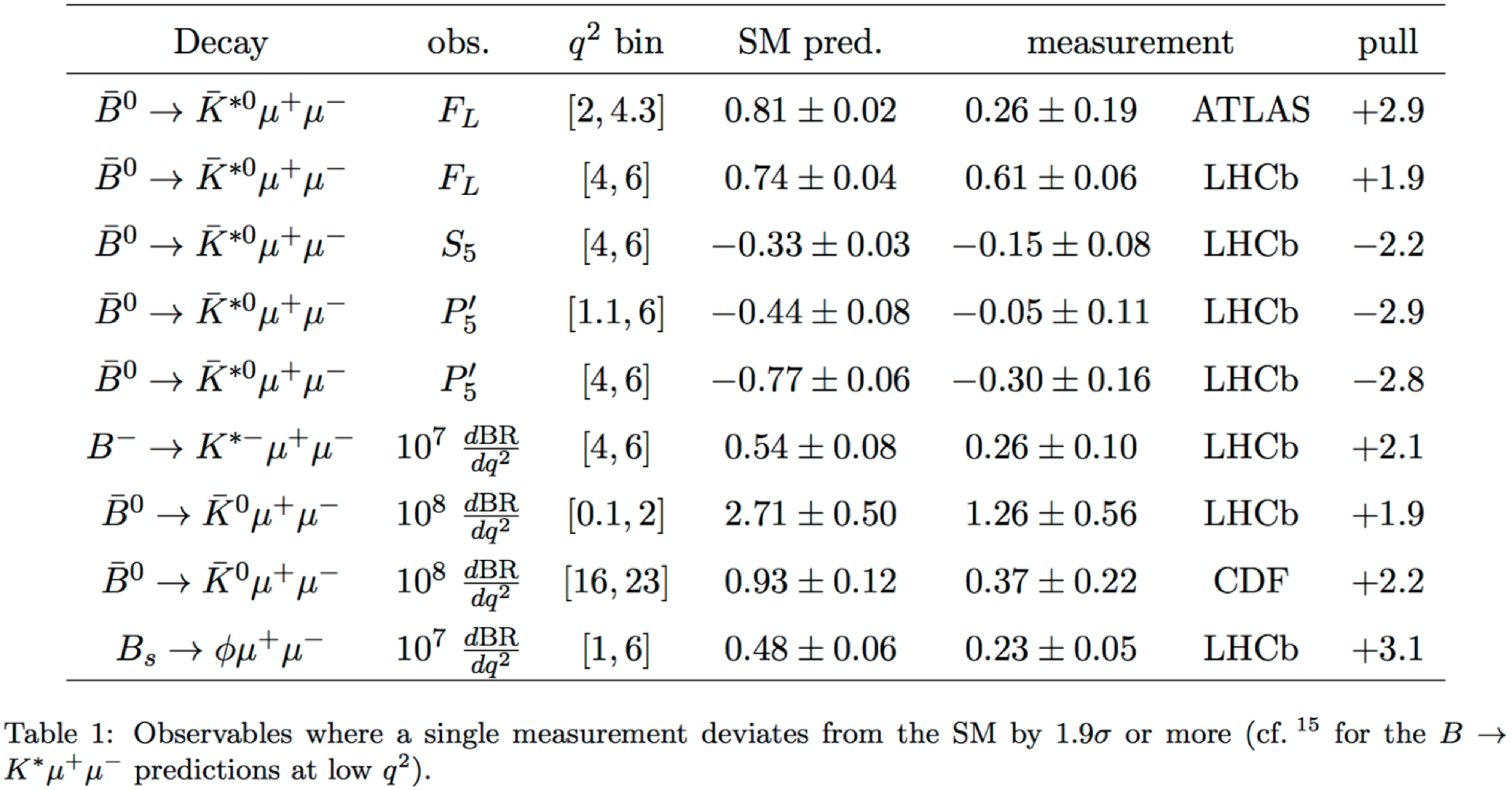
# b→sμμ

Rates and angular asymmetries in b→sμμ persistently indicate non-SM contributions



| Decay | obs. | $q^2$ bin | SM pred. | measurement | | pull |
|---|---|---|---|---|---|---|
| $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ | $F_L$ | $[2, 4.3]$ | $0.81 \pm 0.02$ | $0.26 \pm 0.19$ | ATLAS | $+2.9$ |
| $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ | $F_L$ | $[4, 6]$ | $0.74 \pm 0.04$ | $0.61 \pm 0.06$ | LHCb | $+1.9$ |
| $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ | $S_5$ | $[4, 6]$ | $-0.33 \pm 0.03$ | $-0.15 \pm 0.08$ | LHCb | $-2.2$ |
| $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ | $P_5'$ | $[1.1, 6]$ | $-0.44 \pm 0.08$ | $-0.05 \pm 0.11$ | LHCb | $-2.9$ |
| $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ | $P_5'$ | $[4, 6]$ | $-0.77 \pm 0.06$ | $-0.30 \pm 0.16$ | LHCb | $-2.8$ |
| $B^- \to K^{*-}\mu^+\mu^-$ | $10^7 \frac{dBR}{dq^2}$ | $[4, 6]$ | $0.54 \pm 0.08$ | $0.26 \pm 0.10$ | LHCb | $+2.1$ |
| $\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$ | $10^8 \frac{dBR}{dq^2}$ | $[0.1, 2]$ | $2.71 \pm 0.50$ | $1.26 \pm 0.56$ | LHCb | $+1.9$ |
| $\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$ | $10^8 \frac{dBR}{dq^2}$ | $[16, 23]$ | $0.93 \pm 0.12$ | $0.37 \pm 0.22$ | CDF | $+2.2$ |
| $B_s \to \phi\mu^+\mu^-$ | $10^7 \frac{dBR}{dq^2}$ | $[1, 6]$ | $0.48 \pm 0.06$ | $0.23 \pm 0.05$ | LHCb | $+3.1$ |

Table 1: Observables where a single measurement deviates from the SM by $1.9\sigma$ or more (cf. [15] for the $B \to K^*\mu^+\mu^-$ predictions at low $q^2$).

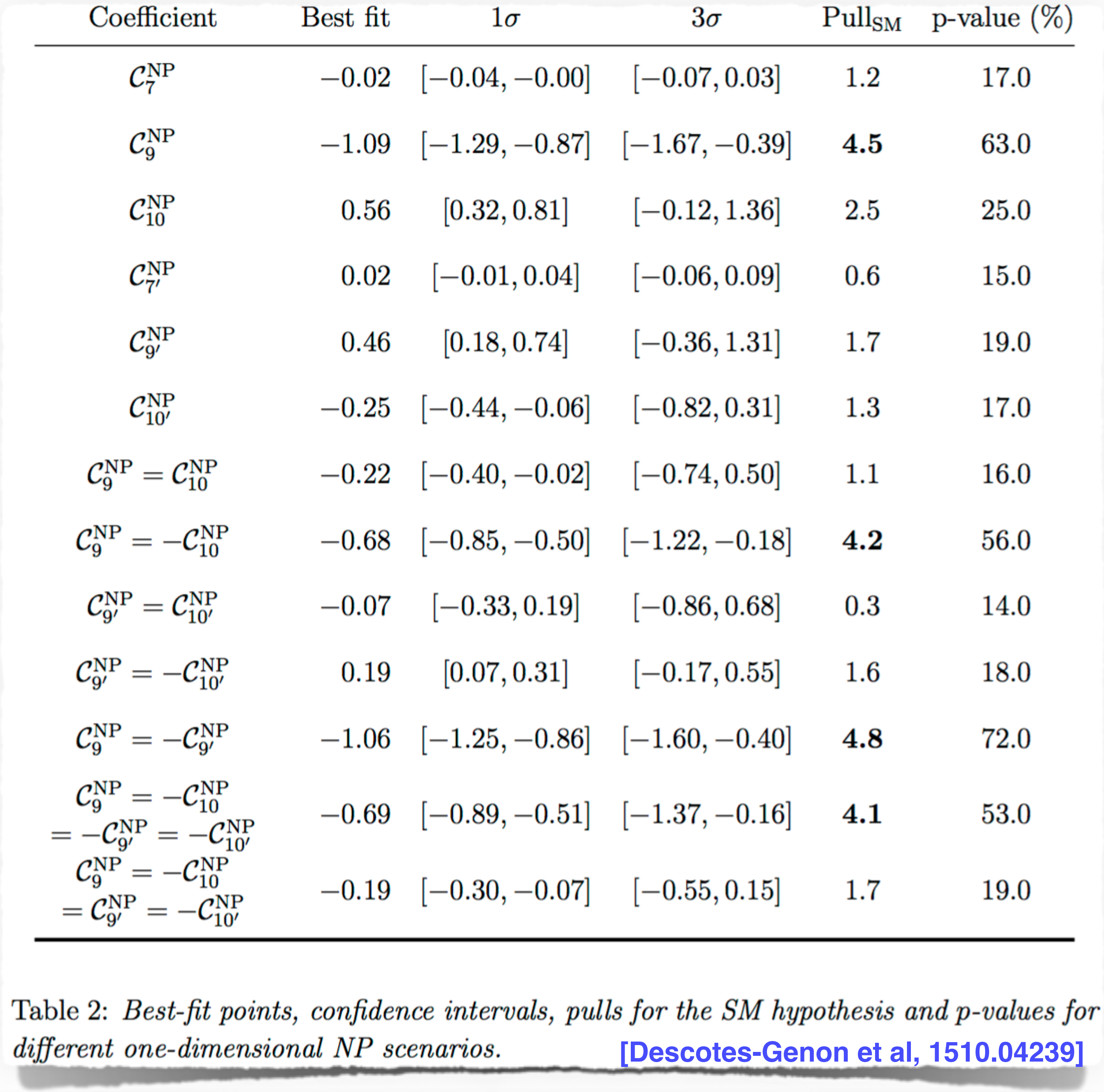
[Altmannshofer, Straub, 1503.06199]

# b→sμμ

Rates anc te non-
SM contri

$\bar{B}^0$
$\bar{B}^0$
$\bar{B}^0$
$\bar{B}^0$
$\bar{B}^0$
$B^-$
$\bar{B}^0$
$\bar{B}^0$
$B$

Table 1: ( $B \to$
$K^*\mu^+\mu^-$ p



| Coefficient | Best fit | $1\sigma$ | $3\sigma$ | Pull$_{\rm SM}$ | p-value (%) |
|---|---|---|---|---|---|
| $\mathcal{C}_7^{\rm NP}$ | $-0.02$ | $[-0.04, -0.00]$ | $[-0.07, 0.03]$ | 1.2 | 17.0 |
| $\mathcal{C}_9^{\rm NP}$ | $-1.09$ | $[-1.29, -0.87]$ | $[-1.67, -0.39]$ | **4.5** | 63.0 |
| $\mathcal{C}_{10}^{\rm NP}$ | 0.56 | $[0.32, 0.81]$ | $[-0.12, 1.36]$ | 2.5 | 25.0 |
| $\mathcal{C}_{7'}^{\rm NP}$ | 0.02 | $[-0.01, 0.04]$ | $[-0.06, 0.09]$ | 0.6 | 15.0 |
| $\mathcal{C}_{9'}^{\rm NP}$ | 0.46 | $[0.18, 0.74]$ | $[-0.36, 1.31]$ | 1.7 | 19.0 |
| $\mathcal{C}_{10'}^{\rm NP}$ | $-0.25$ | $[-0.44, -0.06]$ | $[-0.82, 0.31]$ | 1.3 | 17.0 |
| $\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$ | $-0.22$ | $[-0.40, -0.02]$ | $[-0.74, 0.50]$ | 1.1 | 16.0 |
| $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$ | $-0.68$ | $[-0.85, -0.50]$ | $[-1.22, -0.18]$ | **4.2** | 56.0 |
| $\mathcal{C}_{9'}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP}$ | $-0.07$ | $[-0.33, 0.19]$ | $[-0.86, 0.68]$ | 0.3 | 14.0 |
| $\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}$ | 0.19 | $[0.07, 0.31]$ | $[-0.17, 0.55]$ | 1.6 | 18.0 |
| $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$ | $-1.06$ | $[-1.25, -0.86]$ | $[-1.60, -0.40]$ | **4.8** | 72.0 |
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Table 2: *Best-fit points, confidence intervals, pulls for the SM hypothesis and p-values for different one-dimensional NP scenarios.*

**[Descotes-Genon et al, 1510.04239]**

[Altmannshofer, S

# b→sμμ

Rates anc … te non-
SM contril

$\bar{B}^0$
$\bar{B}^0$
$\bar{B}^0$
$\bar{B}^0$
$\bar{B}^0$
$B^-$
$\bar{B}^0$
$\bar{B}^0$
$B$

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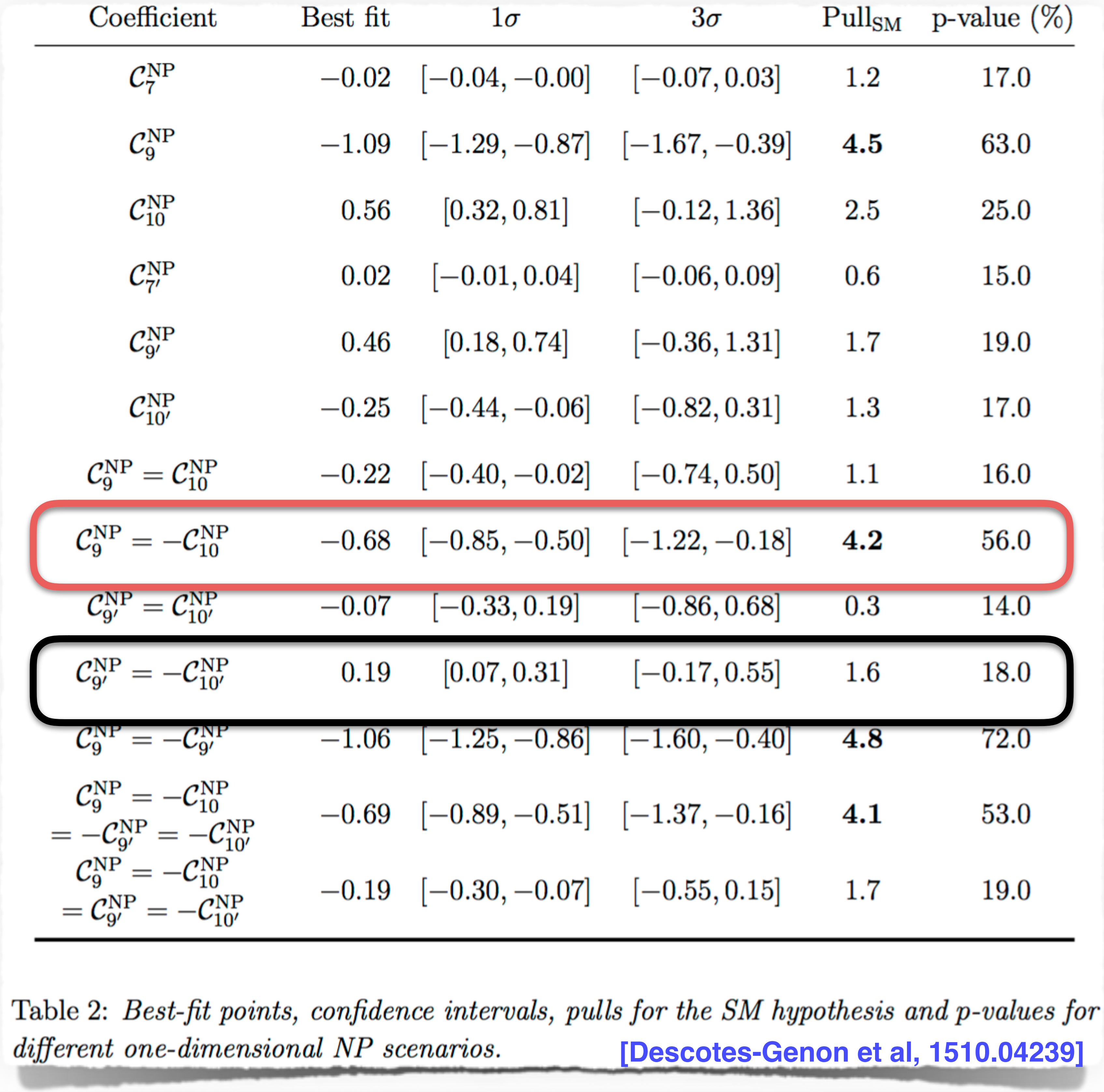

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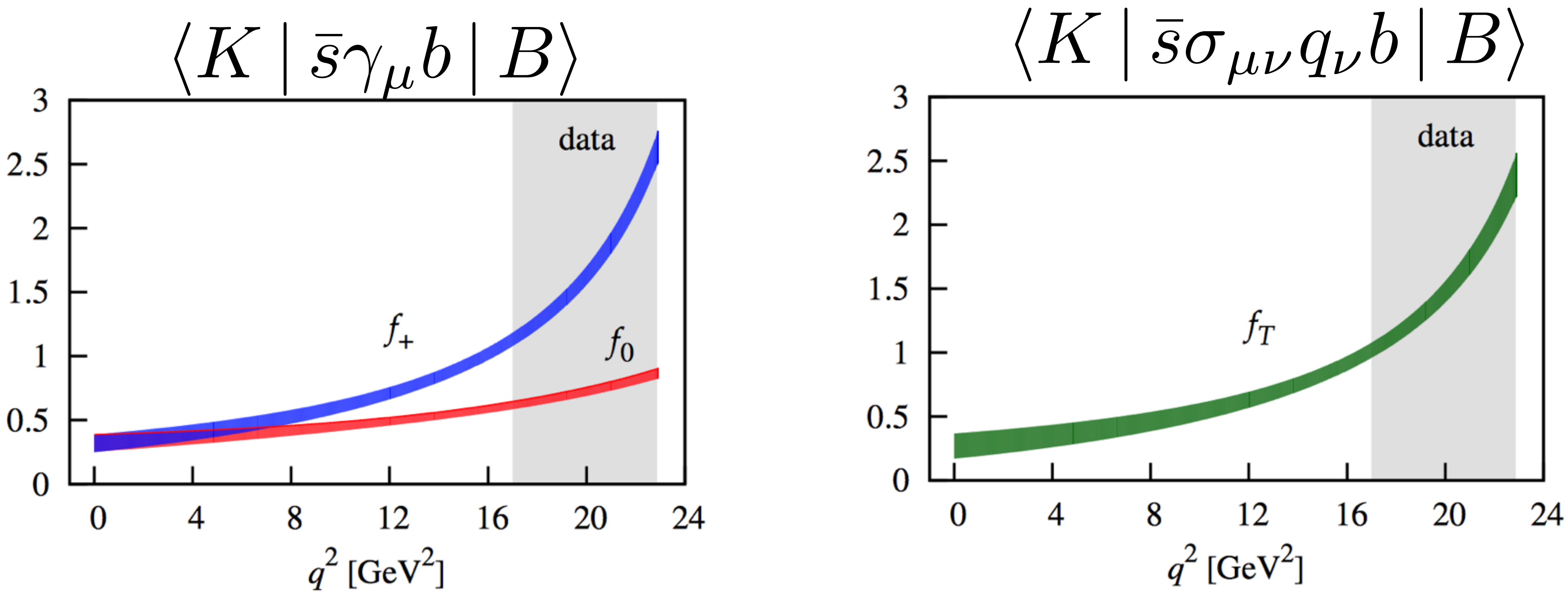
**[Descotes-Genon et al, 1510.04239]**

**Vector LQ**

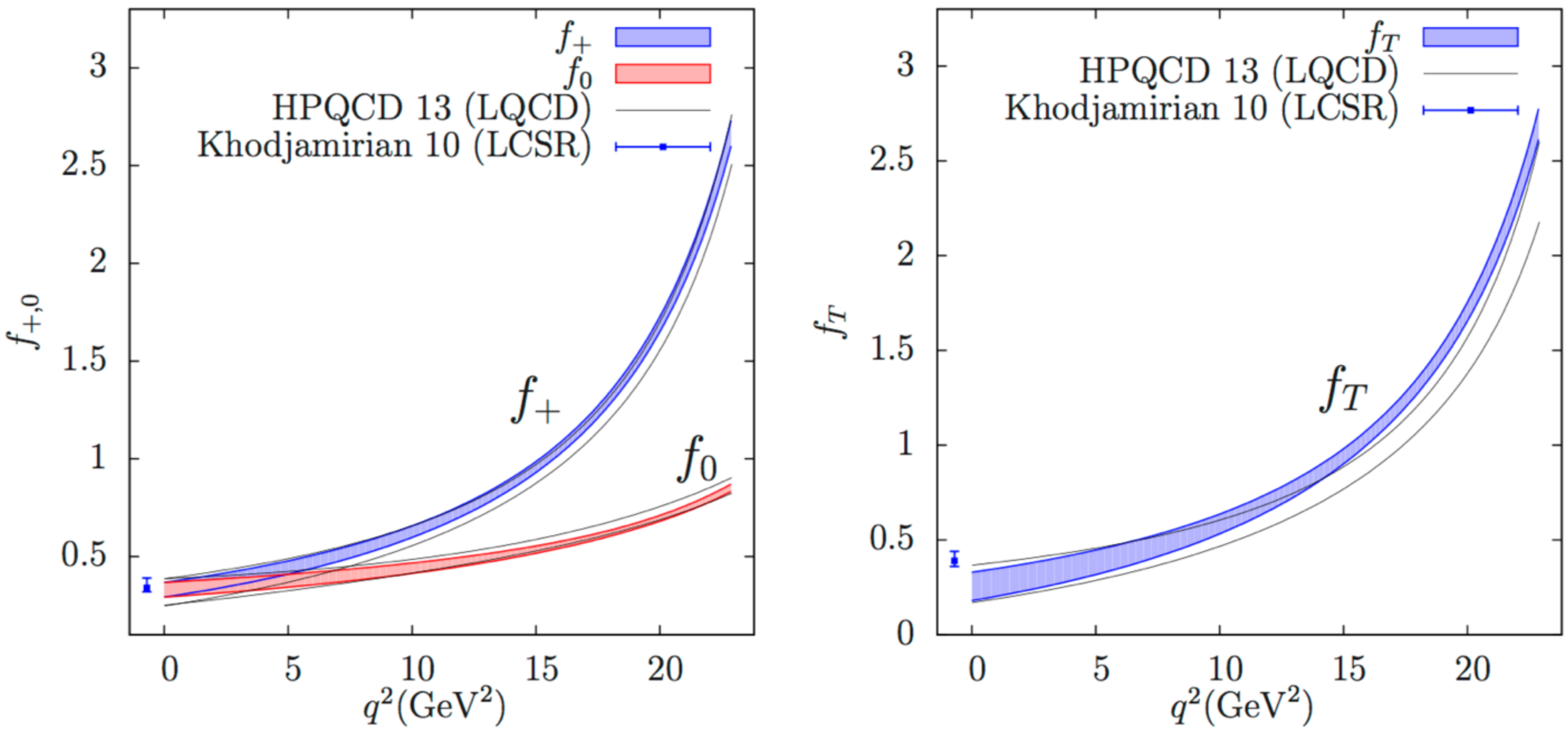
**Scalar LQ**

# High q² region motivated by applicability of lattice QCD calculations



$\langle K \,|\, \bar{s}\gamma_\mu b \,|\, B\rangle$

$\langle K \,|\, \bar{s}\sigma_{\mu\nu}q_\nu b \,|\, B\rangle$



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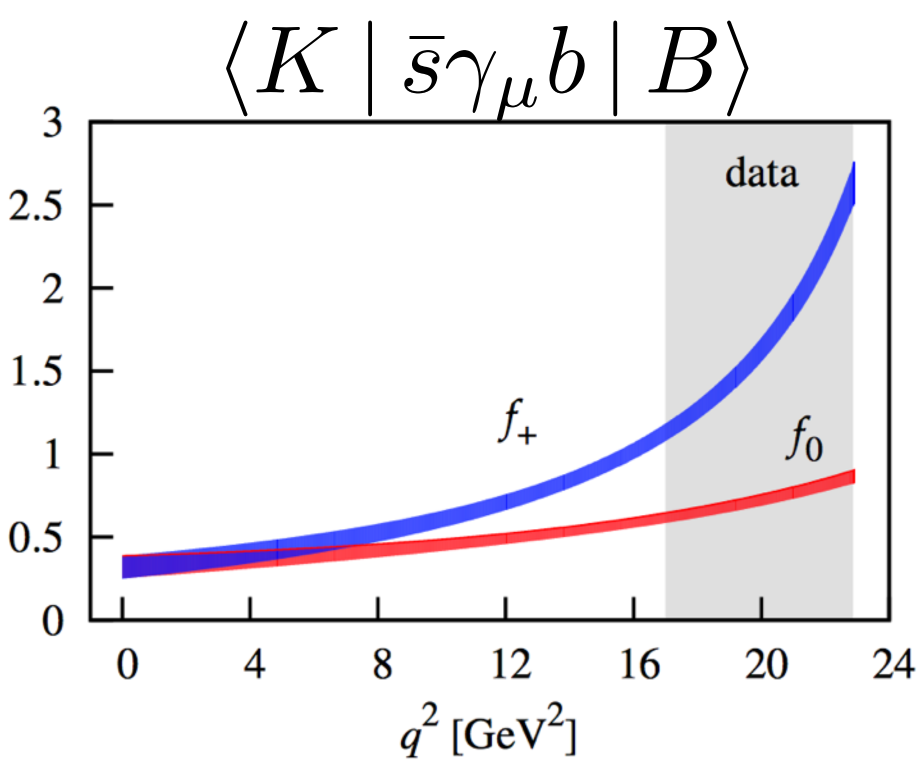
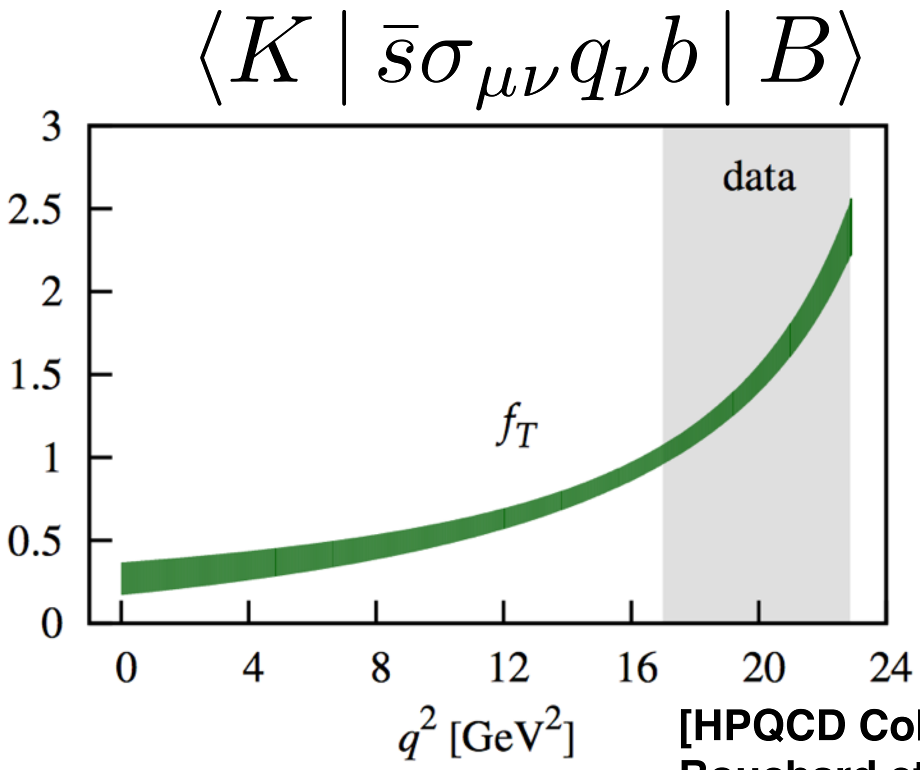
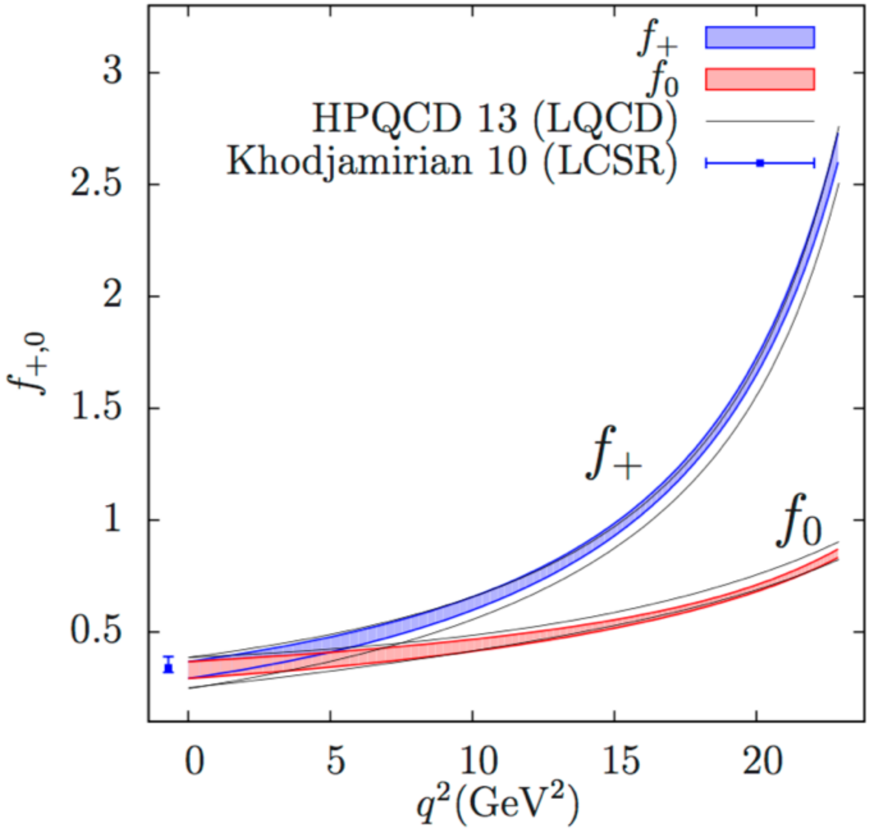
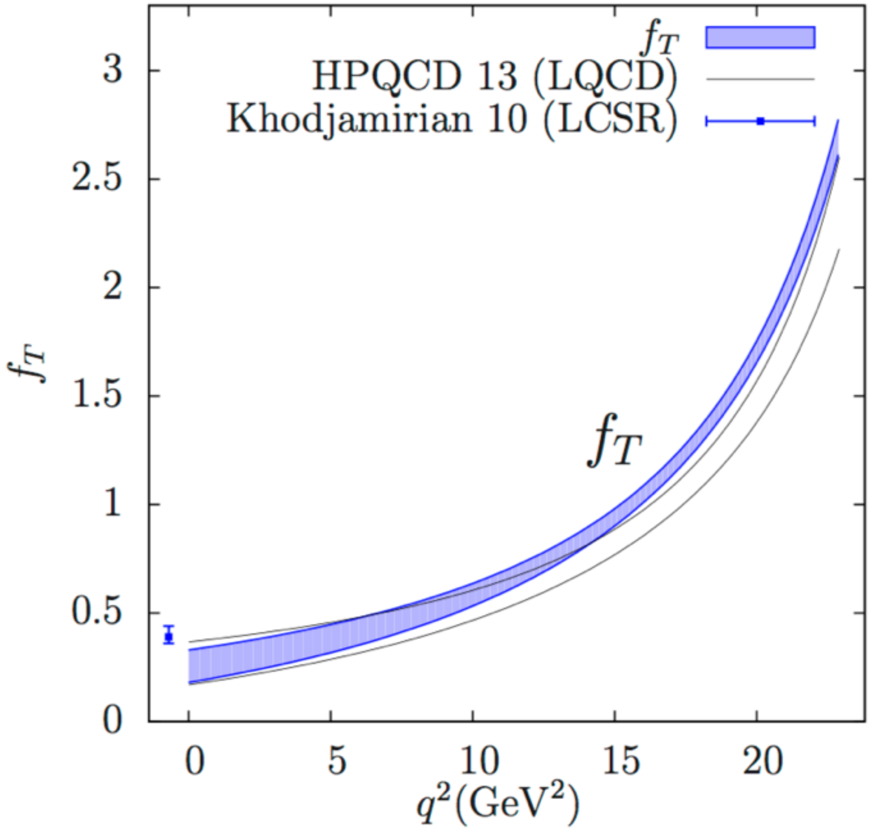




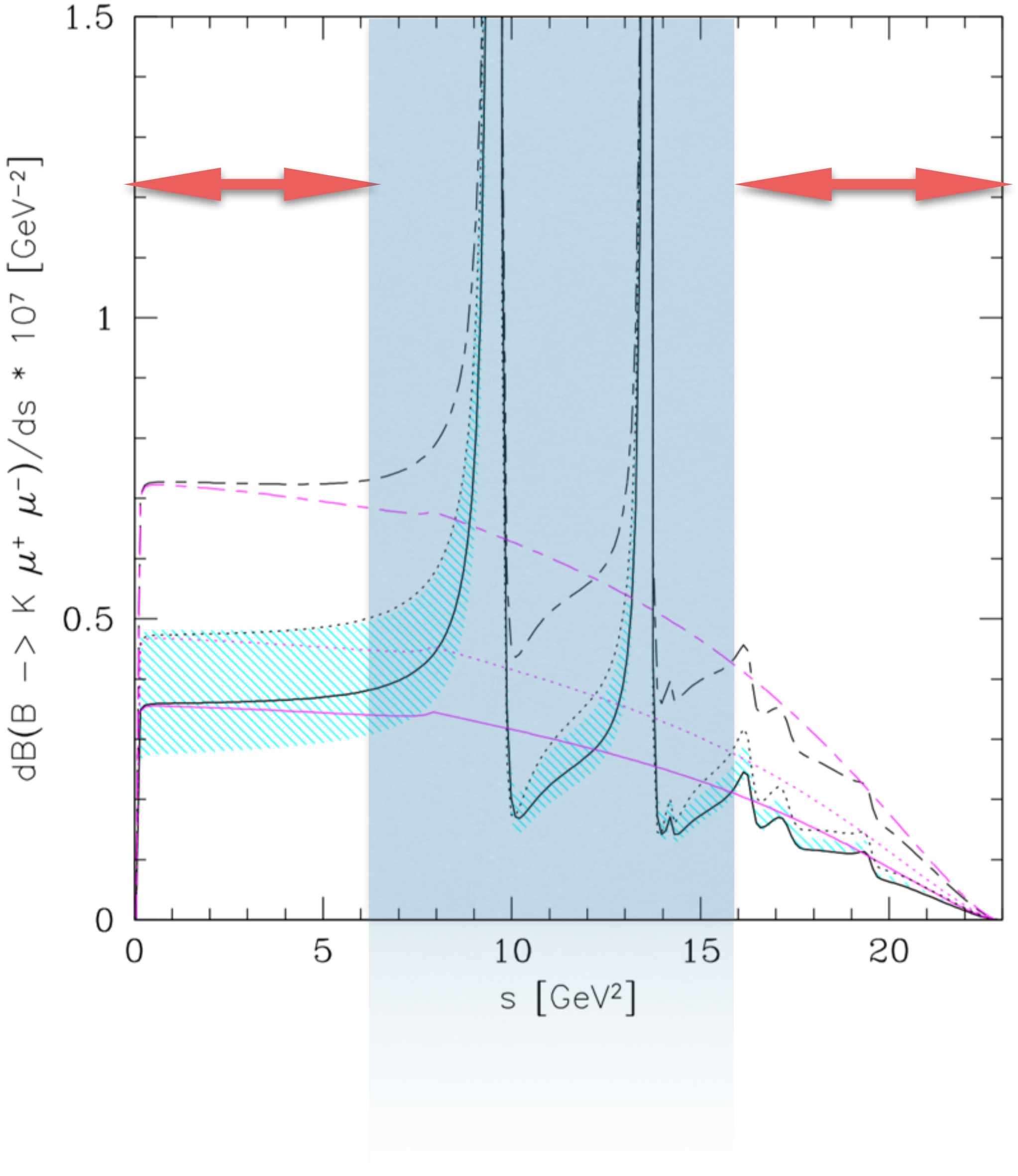
**[HPQCD Collaboration, Bouchard et al, 1306.2384]**





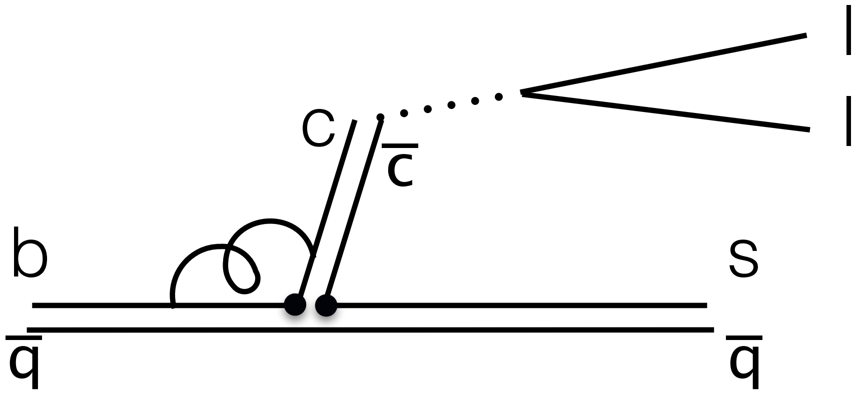
**[Fermilab lattice, MILC Bailey et al, 1509.06235]**

# Clean kinematical regions?



[Ali et al,hep-ph/9910221]

Factorable and non-factorizable contributions of charmonium resonances



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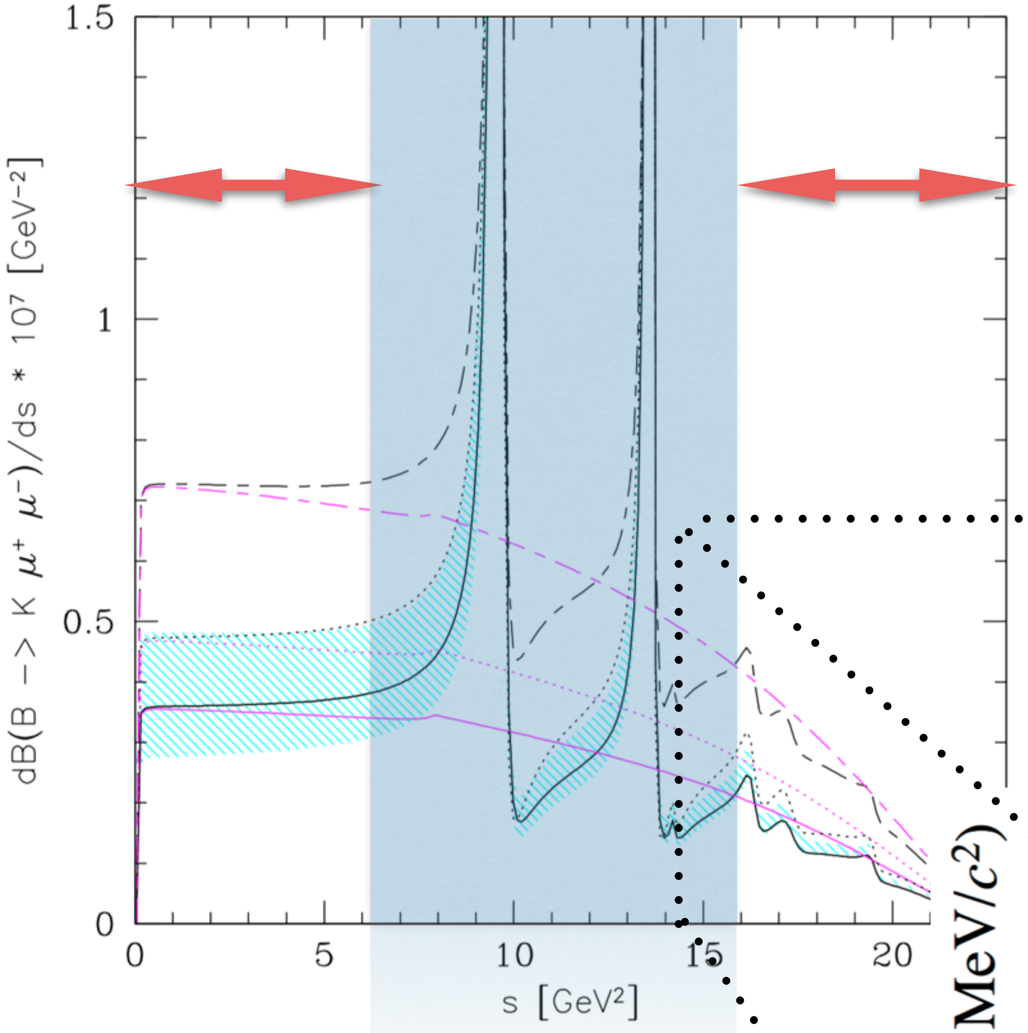

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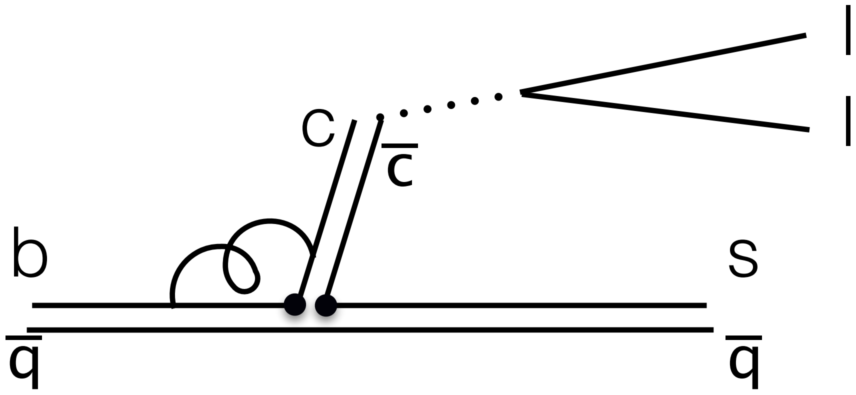

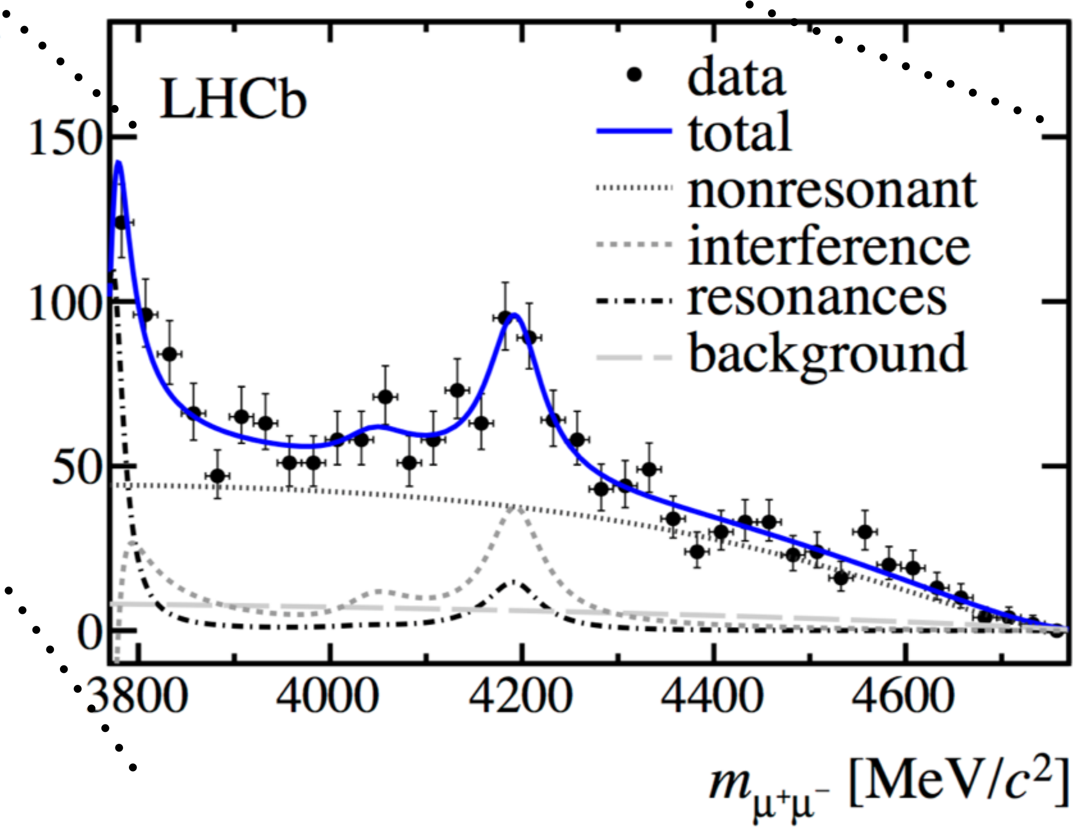

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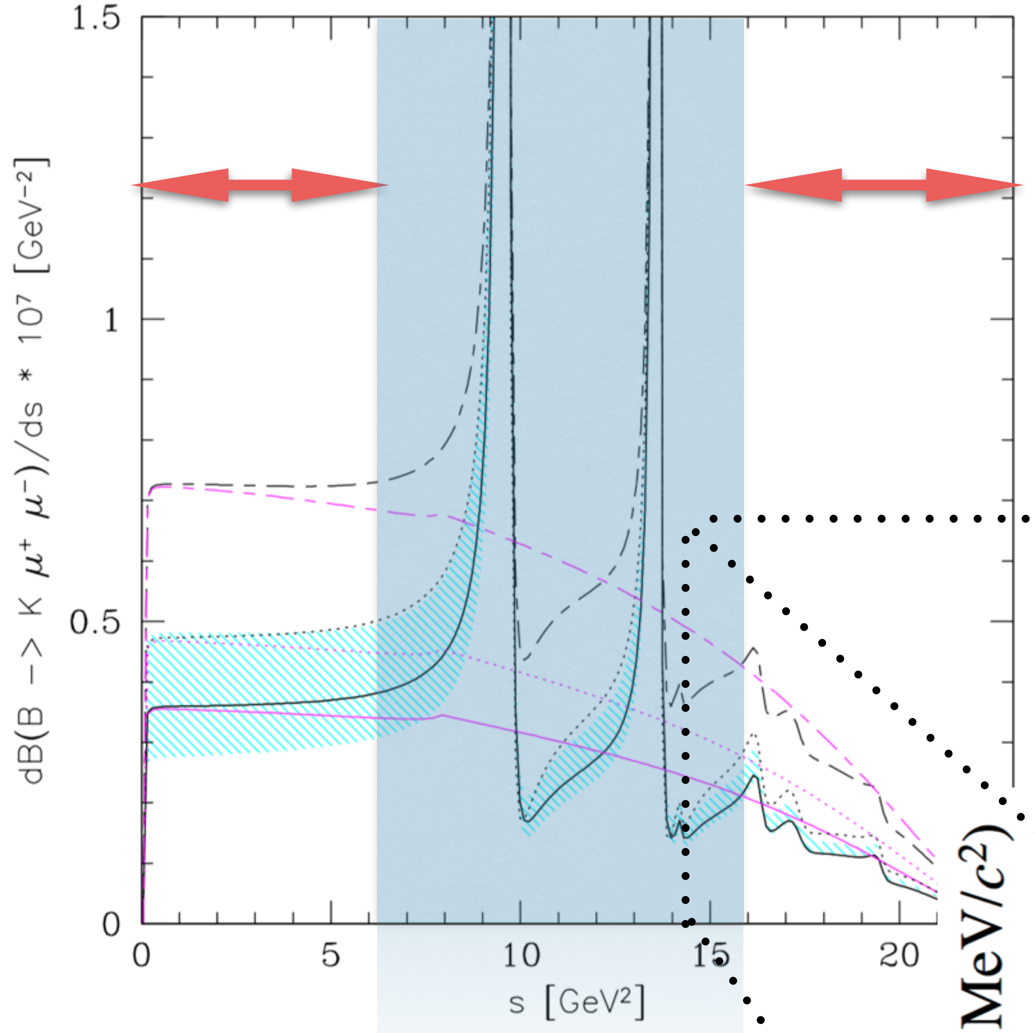

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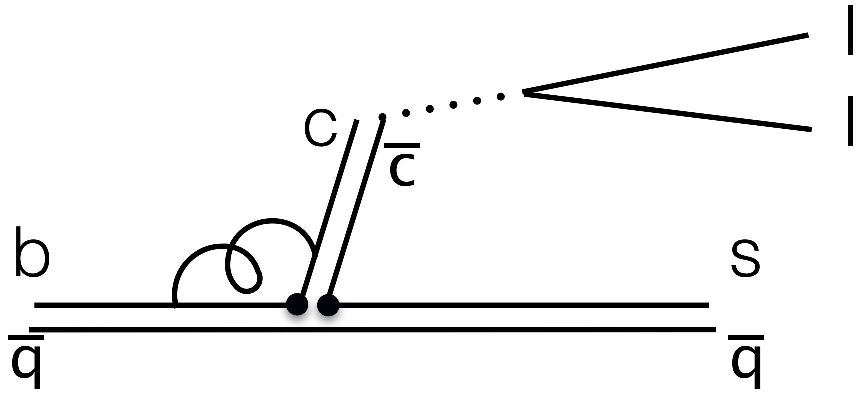
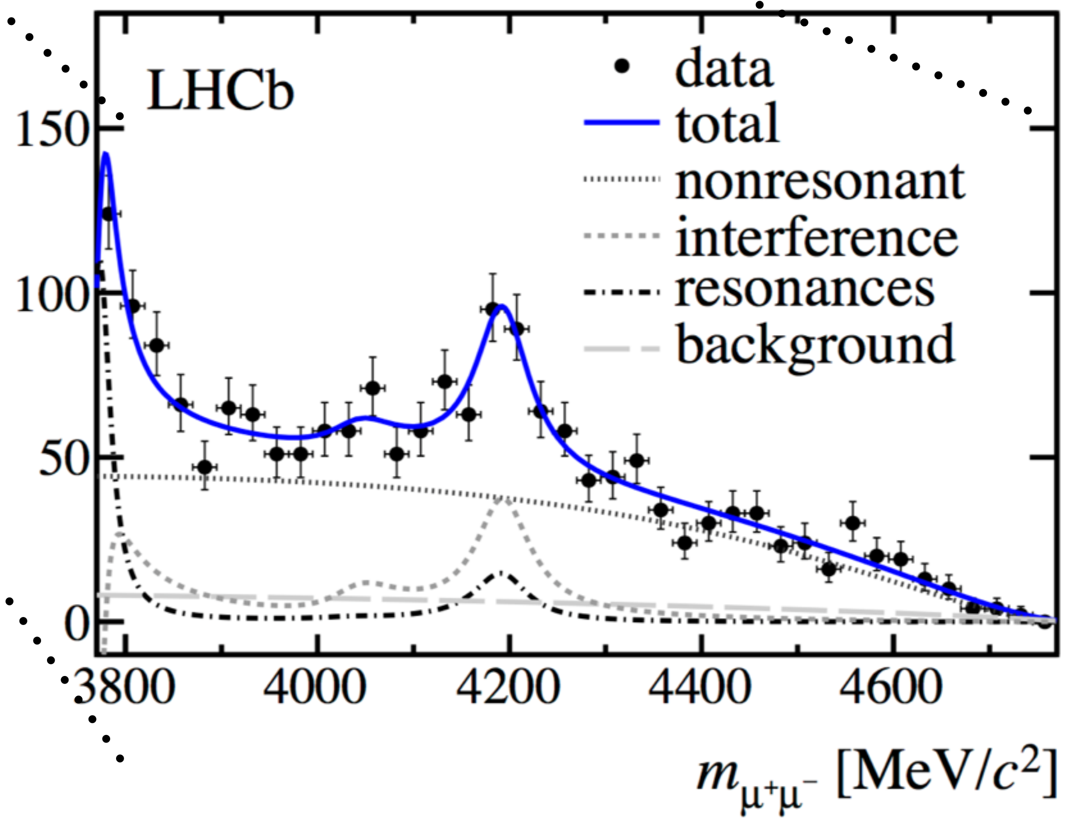
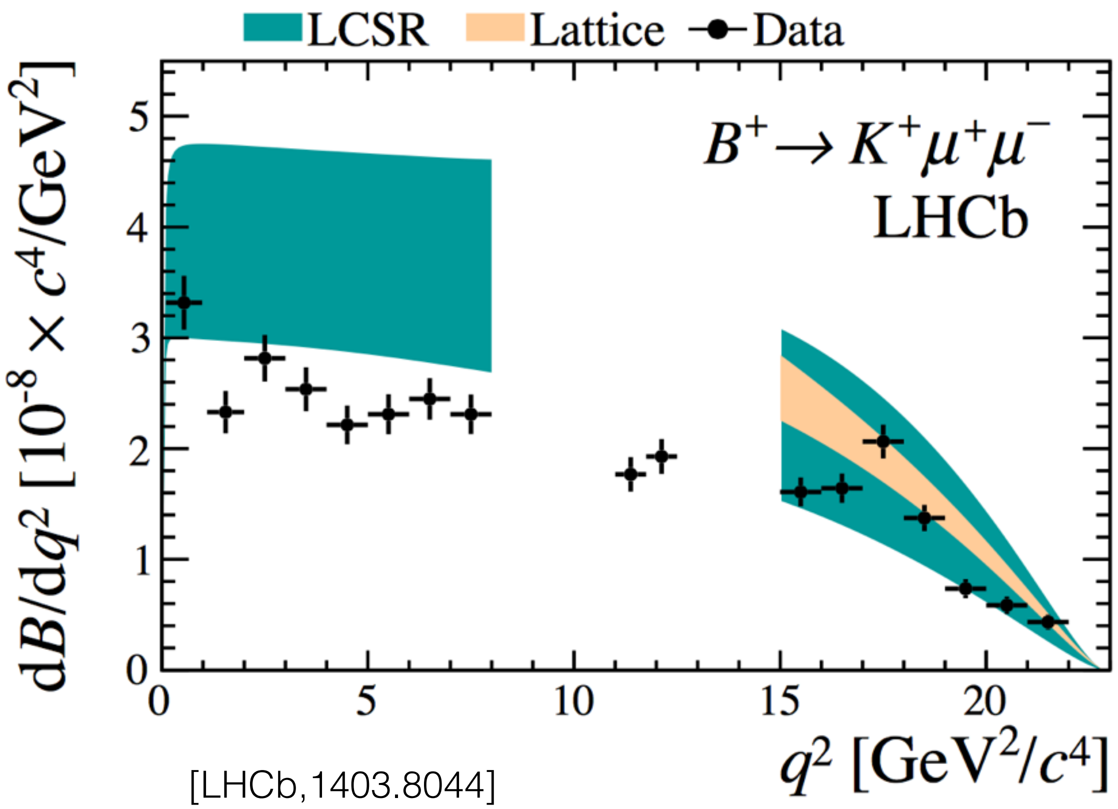


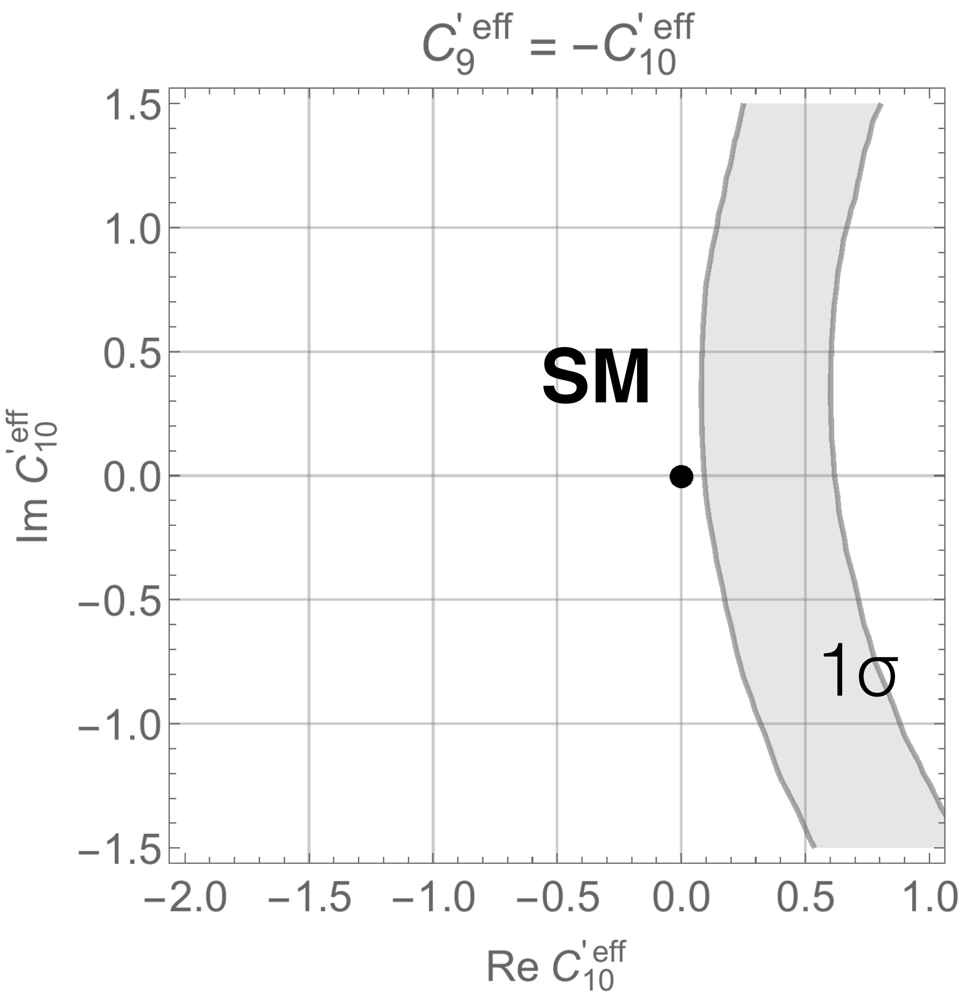


Operator product expansion expected to work in large enough bins

# Scalar leptoquark and B→Kμμ



[LHCb,1403.8044]



Assuming QH duality …

Standard Model overshoots at high $q^2$

# $R_K$

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

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

Hadronic form factor uncertainties

$R_K$ by LHCb (gray): 0.75 ± 0.12

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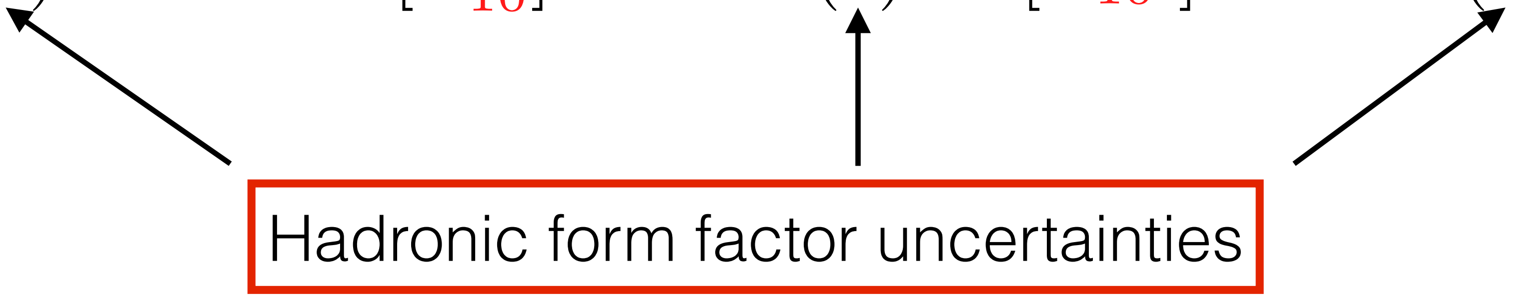
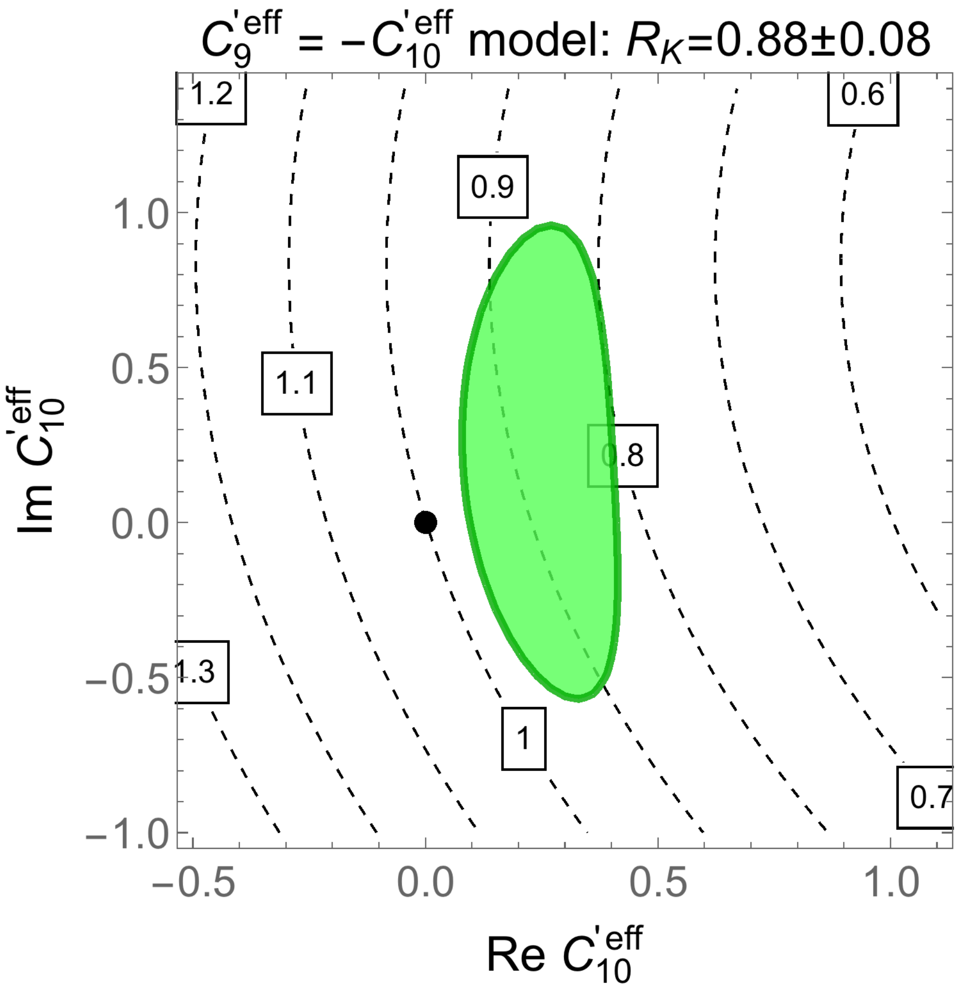


Hadronic form factor uncertainties



$\mathrm{R_K}$ contours Vs. prediction (green)

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

$\mathrm{R_K}$ by LHCb (gray): 0.75 ± 0.12

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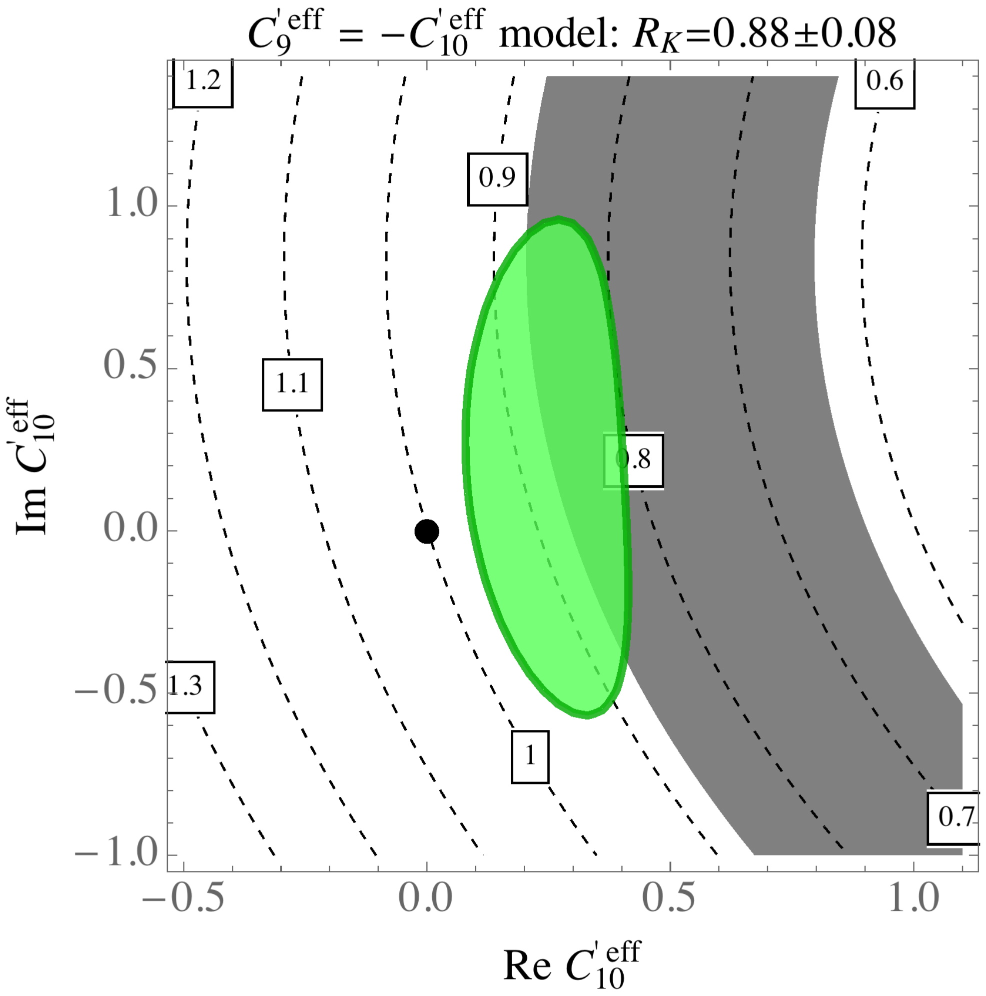


$R_K$ contours Vs. prediction (green)

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

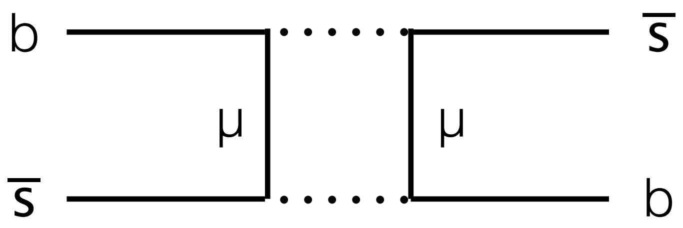
$R_K$ by LHCb (gray): 0.75 ± 0.12

Tension between B→Kμμ and $B_s$→μμ

Increasing B → Kμμ implies
larger Bs → μμ

# LQ specific constraints: B$_s$ mixing

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



Quadratic sensitivity and mass dependence!

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

$$\Delta m_{B_s} = \underbrace{\frac{G_F^2 m_W^2}{6\pi^2} |V_{tb}^* V_{ts}|^2 f_{B_s}^2 m_{B_s} B_{B_s} \eta_B S_0(x_t)}_{\Delta m_{B_s}^{\rm SM} \,=\, 17.3 \pm 1.7\ {\rm ps}^{-1}} \left| 1 - \frac{1}{2\pi^2} \frac{\alpha^2}{S_0(x_t)} (C_{10}'^*)^2 \frac{m_\Delta^2}{m_W^2} \right|$$

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

# LQ specific predictions: B→Kνν

2

(charge -1/3)

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

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

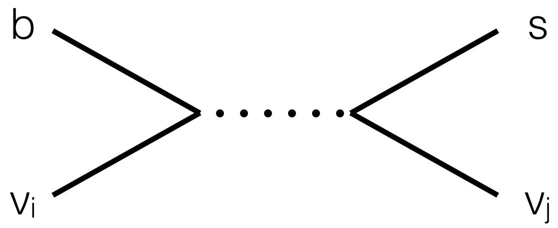
SM: flavour diagonal contributions

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

[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

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

(charge -1/3)

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

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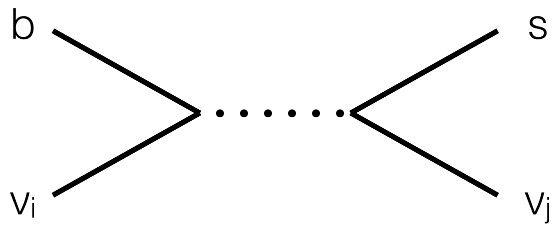

# LQ specific predictions: B→Kνν

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 q² spectrum and branching fraction:

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

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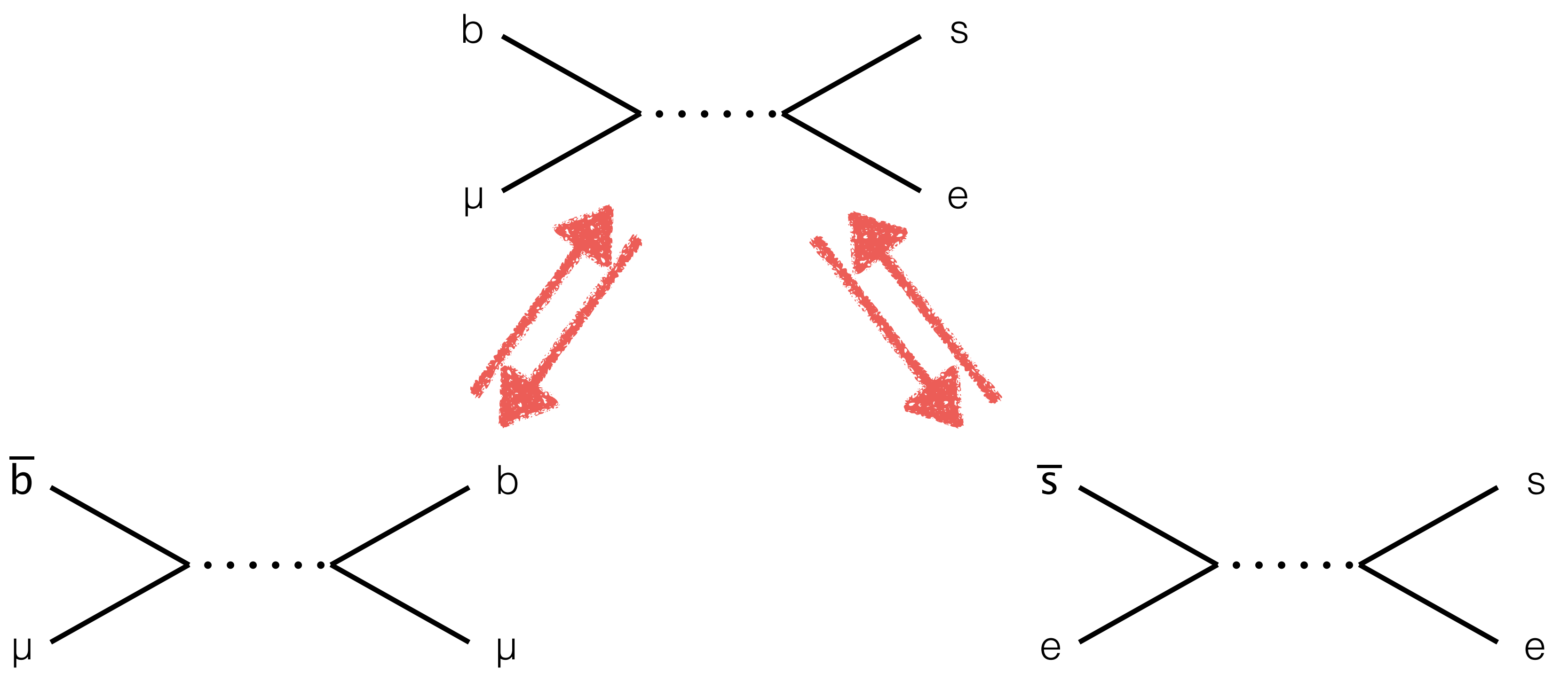
Correction of the SM $q^2$ spectrum and branching fraction:

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

# LFV

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)



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

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

# 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 | $\bar{L} d_R$ | |
| $(\bar{3},3)_{1/3}$ | 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 | $\overline{d^C_R} \ell_R$ | $\overline{u^C_R} u_R$ |

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

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

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

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

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

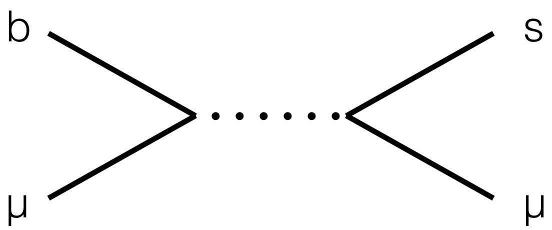
# Scalar leptoquark model - μ

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

[Becirevic,NK,Fajfer, 1503.09024]

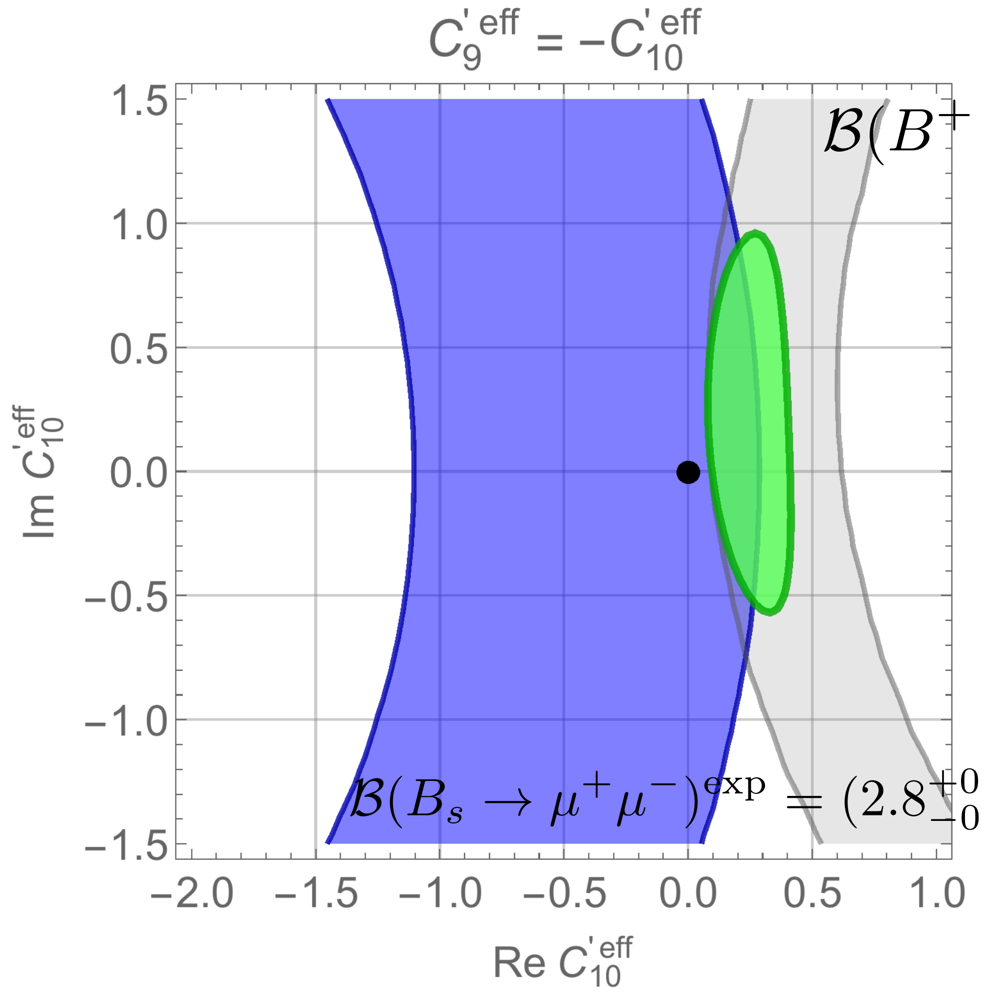
$$-\left(Y_{\mu s}\bar{\mu}_L s_R + Y_{\mu b}\bar{\mu}_L b_R\right)\Delta^{(2/3)*}$$

“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]

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\mathrm{exp}} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

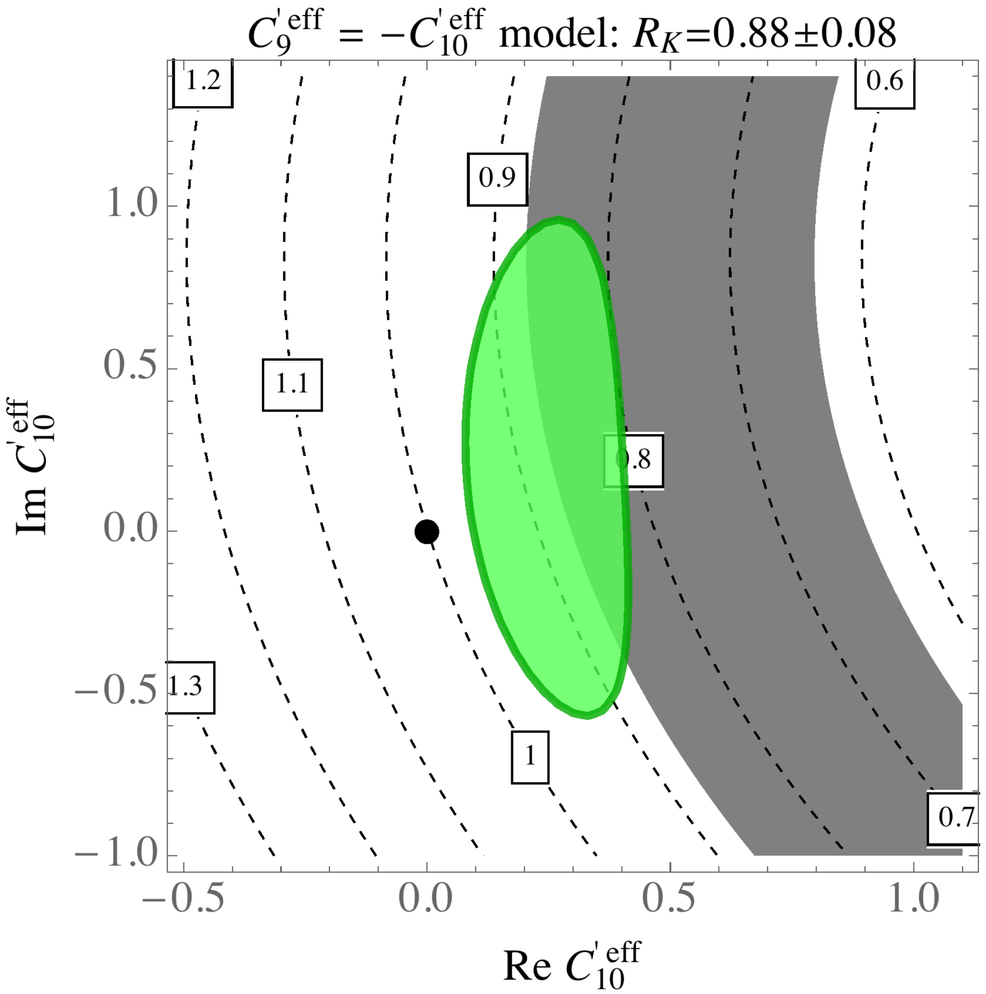
[LHCb+CMS,1411.4413]

# $R_K$ 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



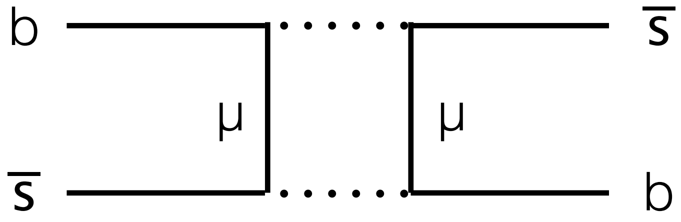
$R_K$ contours Vs. prediction (green)

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

$R_K$ by LHCb (gray): 0.75 ± 0.12

# Relating $B_s$ mixing and $R_K$

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



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

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

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

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

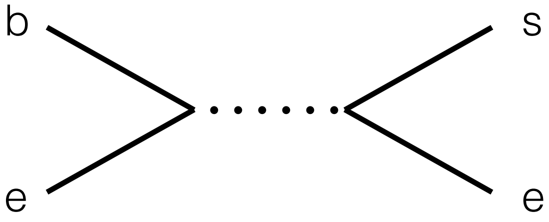
Upper mass limit for the LQ of the order 100 TeV.

# 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]



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

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

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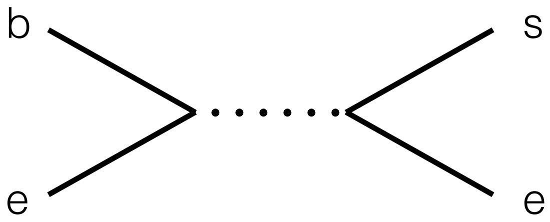

$$C'_{10} = -C'_9 = \frac{-\pi}{2\sqrt{2}G_F V_{tb}V^*_{ts}\alpha}\,\frac{Y_{eb}Y^*_{es}}{m^2_\Delta}\,.$$

Increased B → Kee implies decrease in $B_s$ → ee

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# LQ specific predictions: B→Kνν

(charge -1/3)

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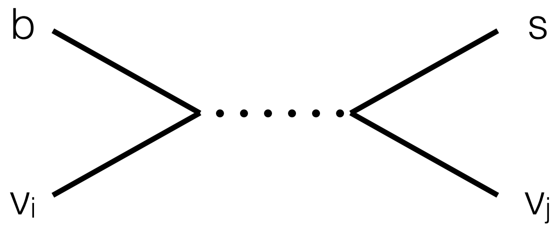

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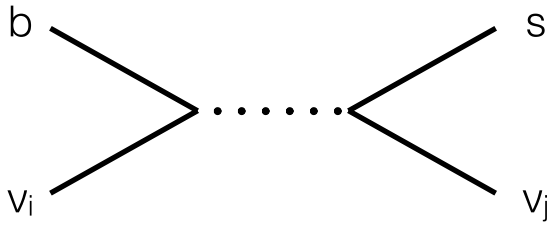

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Correction of the SM $q^2$ spectrum and branching fraction:

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

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# Decay spectrum

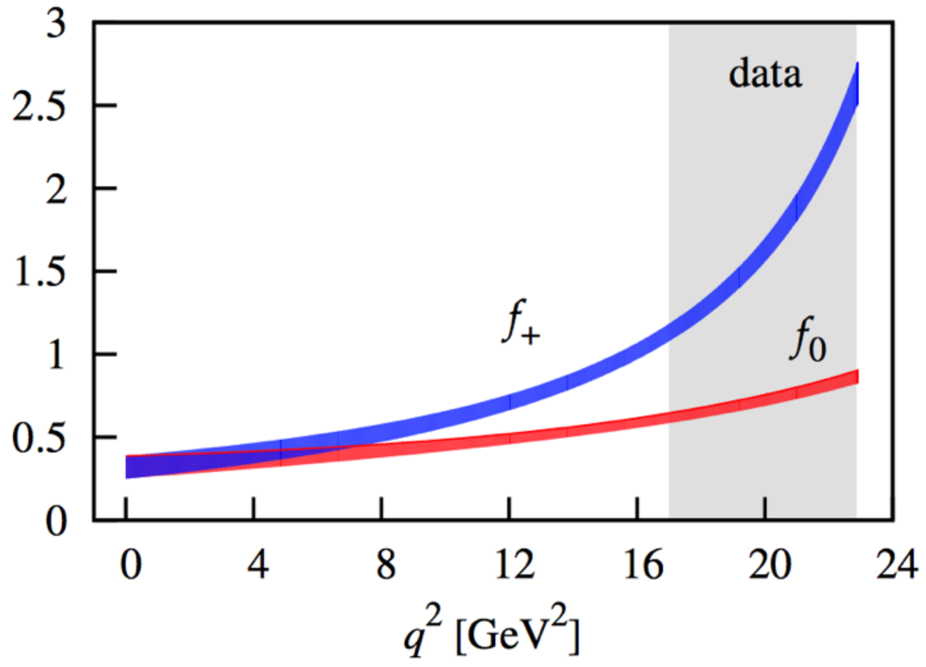
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}(B \to K\mu^+\mu^-) = 2a_\mu(q^2) + \frac{2}{3}c_\mu(q^2)$$

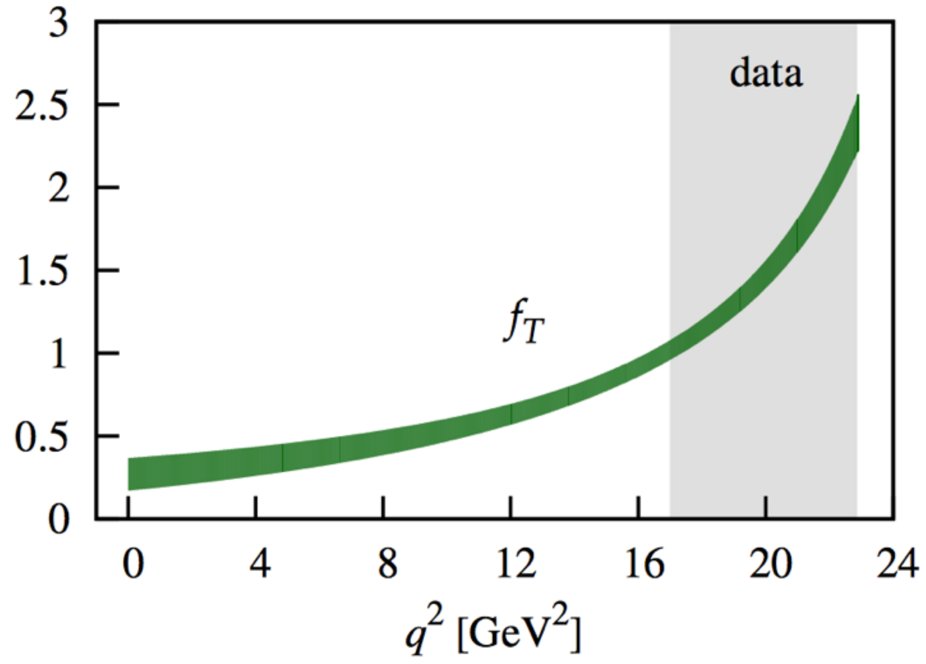
…in terms of Wilson coefficients and form factors

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

$$\begin{aligned} F_V(q^2) &= (C_9 + C_9')\, f_+(q^2) + \frac{2m_b}{m_B + m_K}(C_7 + C_7')\, f_T(q^2) \\ F_A(q^2) &= (C_{10} + C_{10}') f_+(q^2) \\ F_P(q^2) &= -m_\ell(C_{10} + C_{10}')\left[f_+(q^2) - \frac{m_B^2 - m_K^2}{q^2}\left(f_0(q^2) - f_+(q^2)\right)\right] \end{aligned}$$

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





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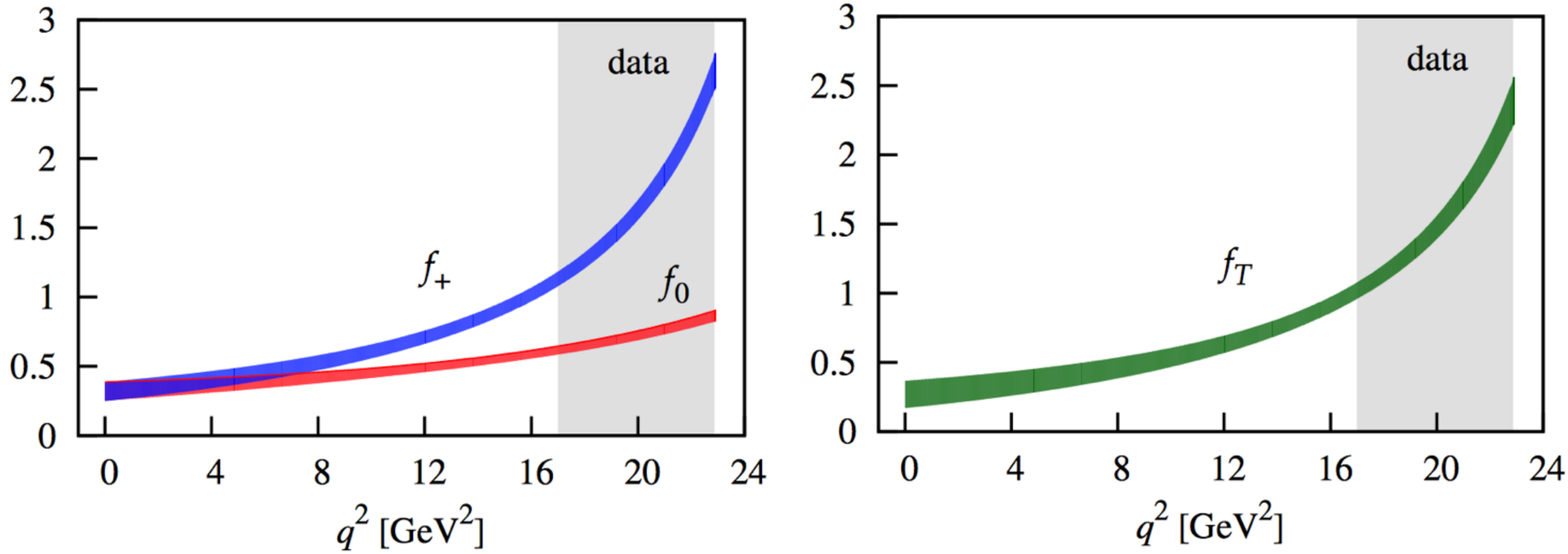

[Bouchard et al, 1306.2384]

# Puzzle #1 + #2: introduce U(3,3,2/3)

$$\mathcal{L}_{U_3} = g_{ij}\bar{Q}_i\gamma^\mu\,\tau^A U_{3\mu}^A\,L_j$$ e.g. vector (3,3,2/3)

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

LH currents for Puzzle #1!

charm and top

B→Kνν, K→πνν

$$g = \begin{pmatrix} 0 & 0 & 0\\ 0 & g_{s\mu} & 0\\ 0 & g_{b\mu} & g_{b\tau}\end{pmatrix}, \qquad \mathcal{V}g = \begin{pmatrix} 0 & \mathcal{V}_{us}g_{s\mu} + \mathcal{V}_{ub}g_{b\mu} & \mathcal{V}_{ub}g_{b\tau}\\ 0 & \mathcal{V}_{cs}g_{s\mu} + \mathcal{V}_{cb}g_{b\mu} & \mathcal{V}_{cb}g_{b\tau}\\ 0 & \mathcal{V}_{ts}g_{s\mu} + \mathcal{V}_{tb}g_{b\mu} & \mathcal{V}_{tb}g_{b\tau}\end{pmatrix}$$

$$\boxed{C_9 = -C_{10} = \frac{\pi}{\mathcal{V}_{tb}\mathcal{V}_{ts}^*\alpha}\,g_{b\mu}^* g_{s\mu}\,\frac{v^2}{M_U^2}}$$

$$\mathcal{L}_{\text{SL}} = -\left[\frac{4G_F}{\sqrt{2}}\mathcal{V}_{cb}\mathcal{U}_{\tau i} + \frac{g_{b\tau}^*(\mathcal{V}g\mathcal{U})_{ci}}{M_U^2}\right](\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L\nu_i)$$

# Puzzle #1 + #2 constraints on U(3,3,2/3)

Semileptonic decays: lepton specific CKM elements, e.g.

$$\left|\mathcal{V}_{cb}^{(\tau)}\right|^2 \simeq |\mathcal{V}_{cb}|^2\left[1+\frac{v^2}{M_U^2}\mathrm{Re}\left(\frac{g_{b\tau}^*(\mathcal{V}g)_{c\tau}}{\mathcal{V}_{cb}}\right)\right]$$

($M_U$ = 1 TeV)

To reproduce exp. values of $R_D^{(*)}$: $\boxed{\mathcal{V}_{cb}(g_{b\tau}^2 - g_{b\mu}^2) - g_{b\mu}g_{s\mu} \approx 0.18}$

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$$C_9 = -C_{10} = \frac{\pi}{\mathcal{V}_{tb}\mathcal{V}_{ts}^*\alpha}\, g_{b\mu}^* g_{s\mu}\, \frac{v^2}{M_U^2} \in [-0.81, -0.50] \quad \Rightarrow \quad \boxed{g_{b\mu}^* g_{s\mu} \in [0.7, 1.3] \times 10^{-3}}$$

**Altogether (#1 + #2):**

$$\begin{aligned} g_{b\mu}g_{s\mu} &\approx 10^{-3}, \\ \mathcal{V}_{cb}(g_{b\tau}^2 - g_{b\mu}^2) - g_{b\mu}g_{s\mu} &\approx 0.18, \end{aligned} \quad \Rightarrow \quad g_{b\tau}^2 - g_{b\mu}^2 \approx 4.4$$

# Puzzle #1 + #2 + remaining constraints on U(3,3,2/3)

**Kaon LFU:**

$$R^K_{e/\mu} = \frac{\Gamma(K^- \to e^-\bar{\nu})}{\Gamma(K^- \to \mu^-\bar{\nu})}, \qquad R^K_{\tau/\mu} = \frac{\Gamma(\tau^- \to K^-\nu)}{\Gamma(K^- \to \mu^-\bar{\nu})}$$

$$R^{K(\mathrm{exp})}_{\mathrm{e}/\mu} = (2.488 \pm 0.010) \times 10^{-5}, \qquad R^{K(\mathrm{SM})}_{\mathrm{e}/\mu} = (2.477 \pm 0.001) \times 10^{-5}$$

[Cirigliano, 0707.3439]

$$\mathrm{Re}\left(|g_{s\mu}|^2 + \frac{\mathcal{V}_{ub}}{\mathcal{V}_{us}} g^*_{s\mu} g_{b\mu}\right) = (-4.6 \pm 6.9) \times 10^{-2} (M_U/\mathrm{TeV})^2$$

**Third generation semileptonic decays:** $\mathcal{B}(t \to b\tau^+\nu) = 0.096 \pm 0.028$

[CDF, 1402.6728]

$$\mathcal{V}^{(\tau)}_{tb} = \mathcal{V}_{tb}\left[1 + \delta^{(\tau)}_{tb}\right], \qquad \delta^{(\tau)}_{tb} = \frac{v^2}{2M_U^2}\,\mathrm{Re}\left(\frac{g^*_{b\tau}(\mathcal{V}g)_{t\tau}}{\mathcal{V}_{tb}}\right)$$

$$|g_{b\tau}| < 2.2\,(M_U/\mathrm{TeV})$$

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**Neutral currents with neutrinos: B → Kνν**

U(3,3,2/3) enhances the SM rate by factor

$$1+\frac{4\pi v^2}{3\alpha\mathcal{V}_{tb}\mathcal{V}_{ts}^* M_U^2 C_L^{\rm SM}}{\rm Re}(g_{s\mu}g_{b\mu}^*)+\frac{1}{3|C_L^{\rm SM}|^2}\left(\frac{2\pi v^2}{\alpha\mathcal{V}_{tb}\mathcal{V}_{ts}^* M_U^2}\right)^2|g_{s\mu}|^2\left(|g_{b\mu}|^2+|g_{b\tau}|^2\right)$$

Also probes LFV!

$$\mathrm{Br}(B^+\to K^+\nu\bar{\nu})<1.6\times10^{-5}$$

[CDF, 1303.7465]