Scalar (or vector) leptoquarks in B meson anomalies

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Outline

Puzzles in B physics ⟷ Sign of LFU violation?

NP: effective Lagrangian approach for $R_{D^{(*)}}$, R_K and new tests of NP

A model of NP: Leptoquarks

⟷

Explaining B meson puzzles by only one leptoquark

Summary and outlook

B physics anomalies

charged current SM tree level

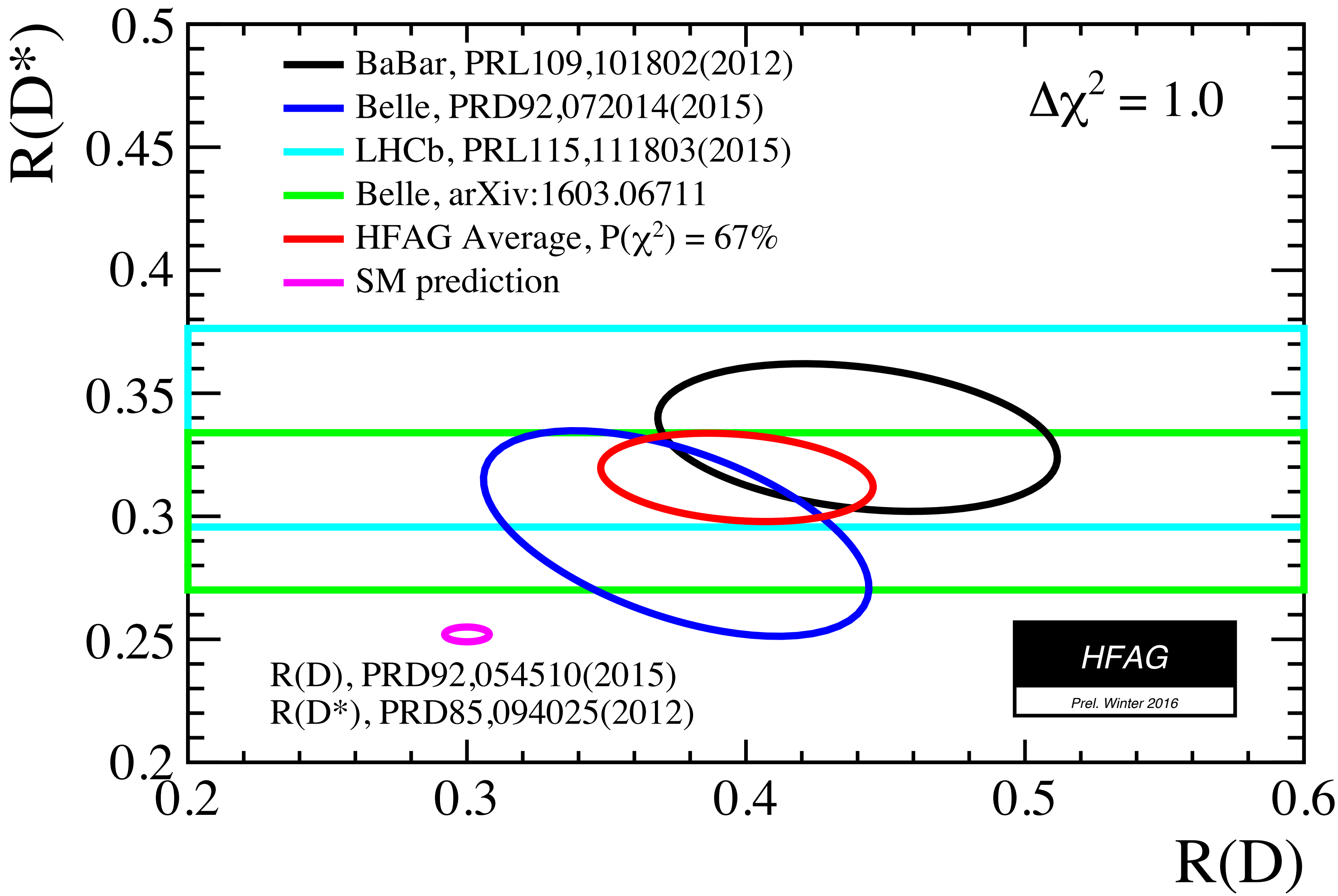
1) $R_{D^{(*)}} = \frac{BR(B \to D^{(*)} \tau \nu_\tau)}{BR(B \to D^{(*)} \mu \nu_\mu)}$ 3.9σ

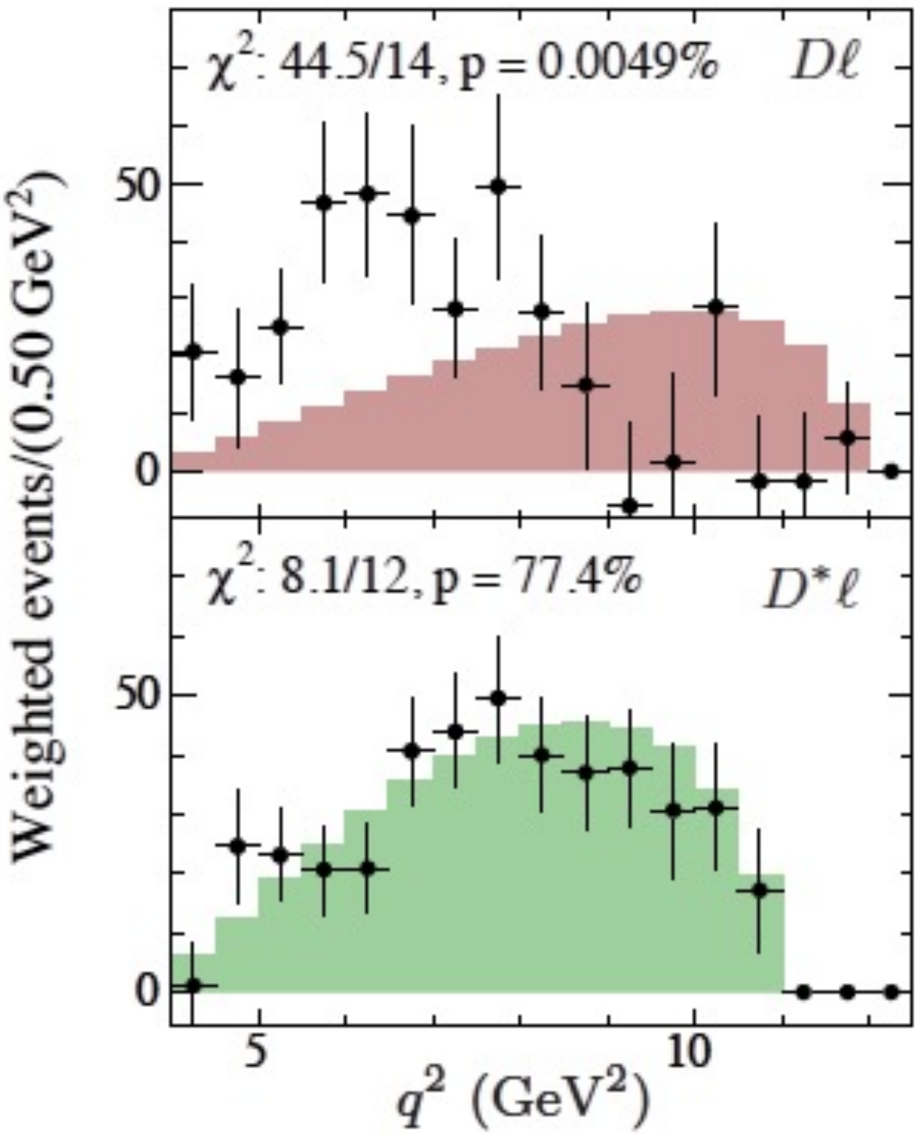
FCNC - SM loop process

2) P_5' in $B \to K^* \mu^+ \mu^-$ 3σ

3) $R_K = \frac{\Gamma(B \to K \mu\mu)}{\Gamma(B \to K ee)}$ in the dilepton invariant mass bin $1\ \mathrm{GeV}^2 \leq q^2 \leq 6\ \mathrm{GeV}^2$ 2.6σ

Experimental results on R_D and R_{D*}





Momentum transfer distributions

BaBar, 1303.0571

Standard Model or New Physics?

Can flavor physics resolves puzzles relying onthe existing SM tools?

QCD impact: Knowledge of form-factors!

How well do we know all new/old form-factors? Lattice improvements?

Are SM calculations of the existing observables precise enough?

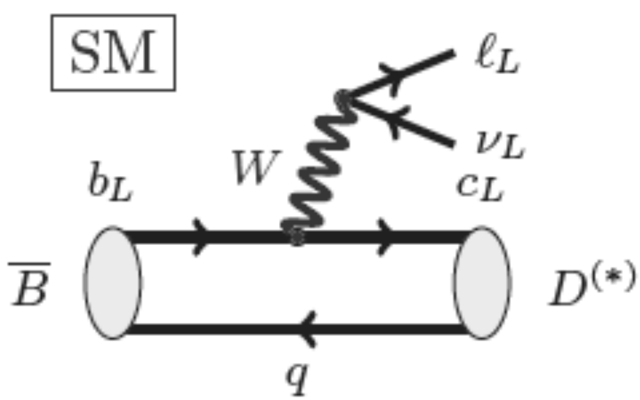
B physics puzzles indicate lepton flavor universality violation in semileptonic decays (?)!

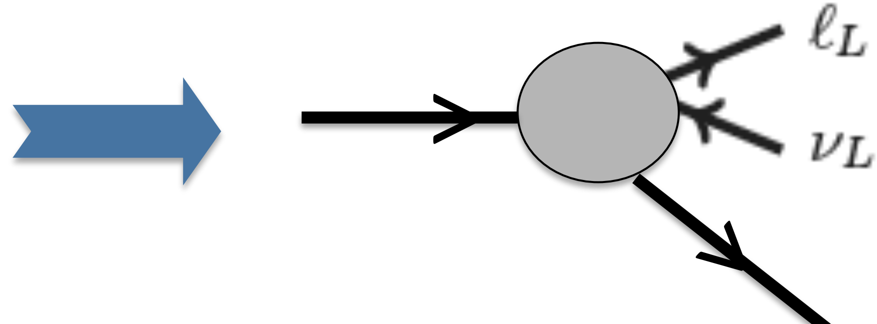
π and K physics: tests of LFU conservation holds up to 1 percent level for all three lepton generations.
Experiment and SM expectations – excellent agreement!

Effective Hamiltonian approach in $b \to c l \nu_l$ transition

$$\mathcal{H} = \underbrace{\frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L}}_{\text{SM}} + \frac{1}{\Lambda^2} \underbrace{\sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}}$$

NP higher dimensional operators, regarding the SM gauge symmetries





Possibility to test NP in $B \to D\tau\nu$ and $B \to D^*\tau\nu$ decays

Recently: two studies of observables in :

1. D. Becirevic, S.F. I. Nisandzic, A. Tayduganov, 1602.03030 (SM neutrino)

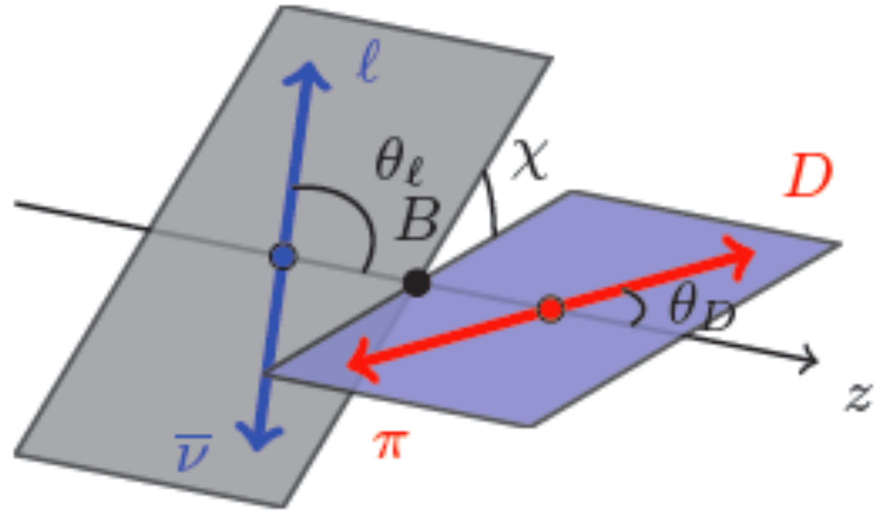
2. R.Alonso, A. Kobach and J.M. Camalich , 1602.0767

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb}\; H_\mu L^\mu + {\rm h.c}$$
$$= \frac{G_F}{\sqrt{2}} V_{cb}\Big[(1+g_V)\bar{c}\gamma_\mu b + (-1+g_A)\bar{c}\gamma_\mu\gamma_5 b + g_S\; i\partial_\mu(\bar{c}b) + g_P\; i\partial_\mu(\bar{c}\gamma_5 b)$$
$$+ g_T\; i\partial^\nu(\bar{c}i\sigma_{\mu\nu}b) + g_{T5}\; i\partial^\nu(\bar{c}i\sigma_{\mu\nu}\gamma_5 b)\Big]\; \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell + {\rm h.c}\,,$$

Helicity amplitudes $h_{0,t}(q^2) = \tilde{\varepsilon}^{\mu *}_{0,t}\; \langle D|H_\mu|\overline{B}\rangle$

B $\longrightarrow$ D $\tau\nu_\tau$: scalar form factor contributes!
For massless lepton in the final state only vector form factor contributes.
QCD lattice calculation exist.

$$B \to D^* \tau \nu_\tau$$



There are 11 observables:

1. Differential decay distribution

2. Forward-backward asymmetry

3. Lepton polarization asymmetry

4. Partial decay rate according to the polarization of D*

$$R_{L,T} = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}$$

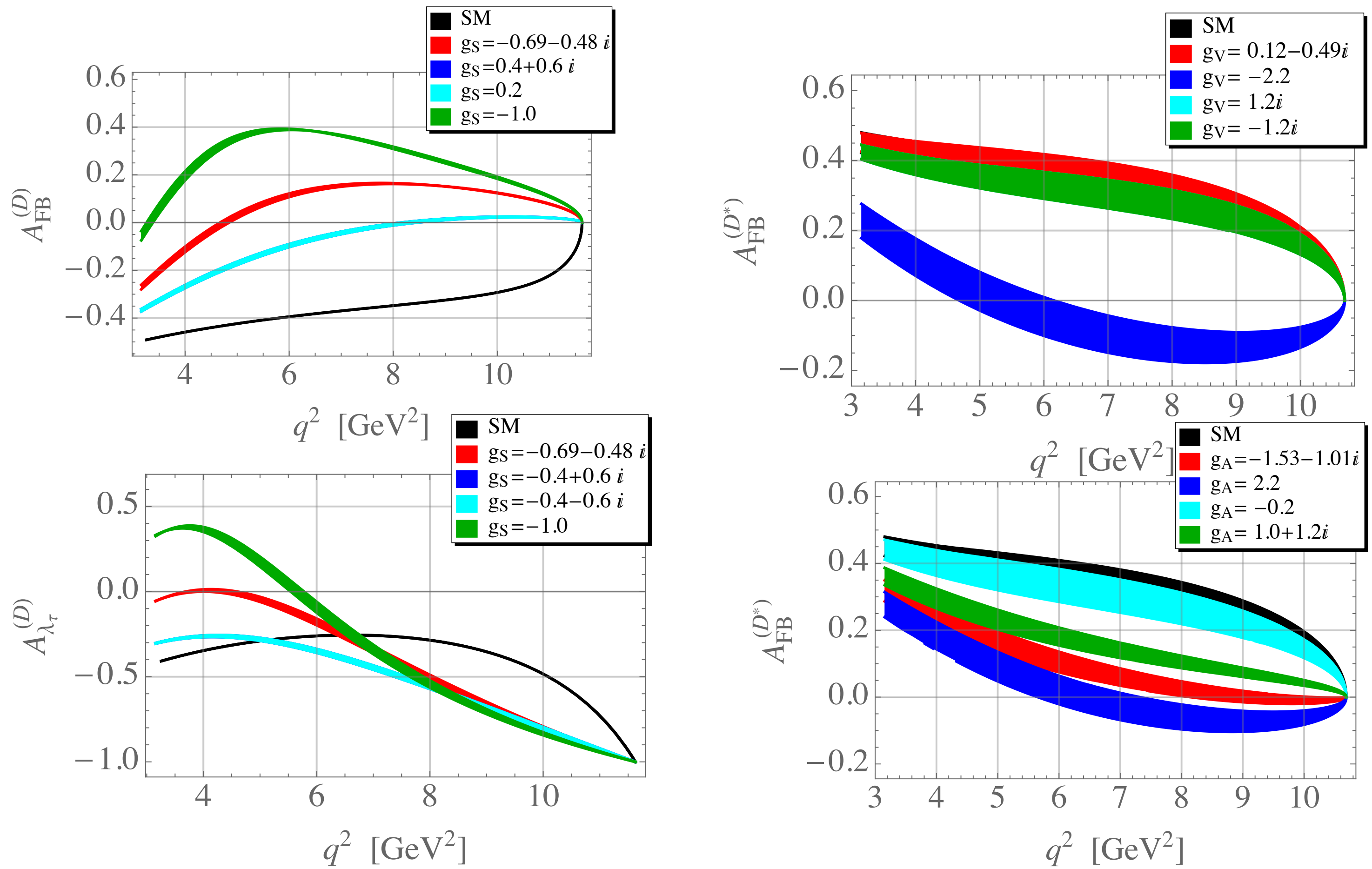
S.F. , J.F.Kamenik, Nišandžić, 1203.2654
S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.1872
Körner& Schuller, ZPC 38 (1988) 511,
Kosnik, Becirevic, Tayduganov, 1206.4977
D. Becirevic, S.F. I. Nisandzic, A. Tayduganov, 1602.03030, Fretsis et al, 1506.08896, ….

S. Faller et al., 1105.3679,
Sakai&Tanaka, 1205.4908.
Biancofiore , Collangelo, DeFazio 1302.1042,
R.Alonso, A. Kobach and J.M. Camalich , 1602.0767.

Best fit values

$$g_V = 0.21 - i\ 0.76, \qquad g_A = -0.18 - i\ 0.05,$$

$$g_S = -0.92 - i\ 0.38, \qquad g_P = 0.91 + i\ 0.38, \qquad g_T = -0.42 + i\ 0.15,$$



Lepton flavor non-universality in $b \to s\mu^+\mu^-$ decay

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

$$R_K^{\mathrm{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

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

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

LHCb, 1406.6482;
Altmannshofer and Straub,1411.3161S,
e.g.: Hiller&Schmaltz;1408.1627
Becirevic, SF, Kosnik arXiv:1503.09024

Crivellin et al, 1501.00993 ;
D. Becirevic et al, 1205.5811,
Descotes-Genonet al, 1307.5683,
Päs, Schumacher, 1510.08757
....

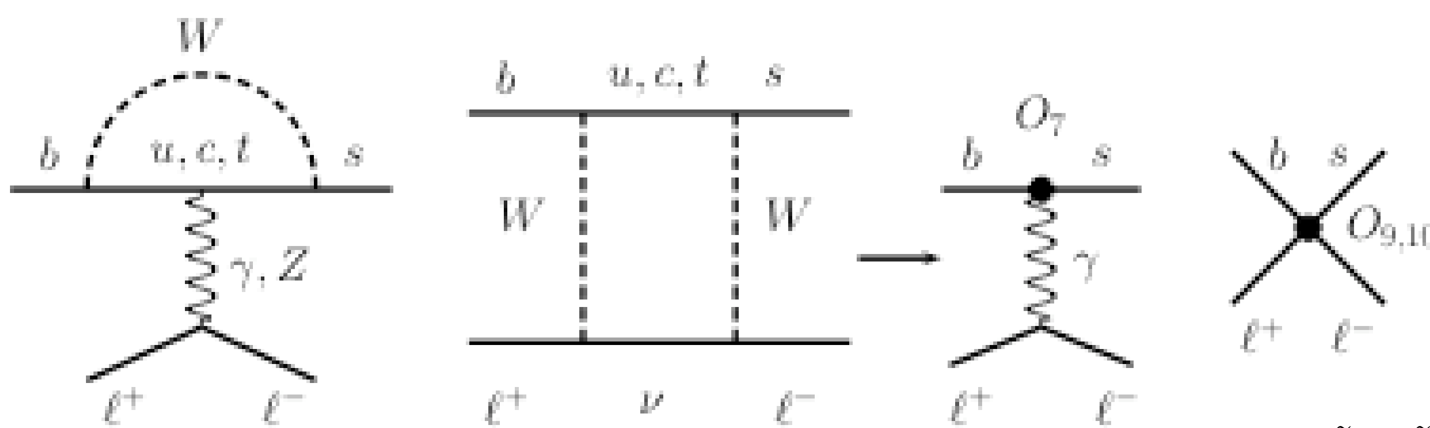
Effective Hamiltonian for $b \to s\mu^+\mu^-$

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

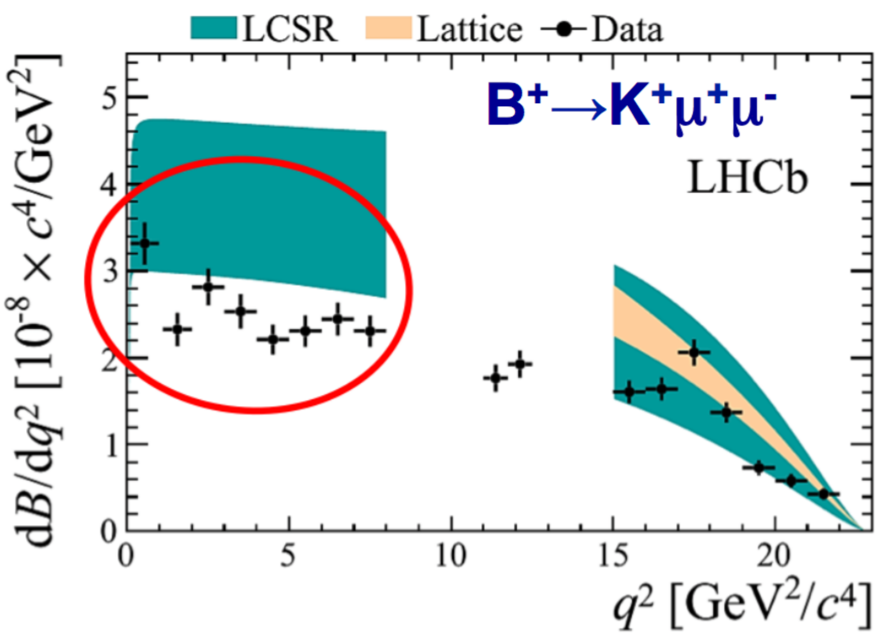
$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}\,, \qquad \mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu}G^{\mu\nu}P_R b)\,,$$

$$\mathcal{O}_9 = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad \mathcal{O}_{10} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,.$$

$\mathcal{O}'$ opposite chirality



First proposal and prediction to measure R_K, R_{K*} and $R_{X,}$(Kruger, Hiller hep-ph/031021



LHCb: 1403.8044

Missing muons or too many electrons?

- $b \to s\,\mu\mu$ data are in favor decrease muonic decay rate for BR($B \to K\,\mu\mu$)

- Scalar operator C_S=-C_P, C_S'=C_P' is favored by for muons are disfavored by
- BR($B_s \to \mu\mu$)

- Scalar operators C_S=-C_P, C_S'=C_P' for electrons can decrease R_K , however this is in conflict with BR($B \to K\,ee$)

- Axial (vector) operators can affect μ or e Hiller, Schmaltz 1408.1627, 1411.4773:C_9^μ = - C_{10}^μ ~- [0.5,1]

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

Operators $\mathcal{O}_{1-6}$ mix at leading order into $\mathcal{O}_{7,8,9}$

(NNL - Altmannshofer et al, 0811.1214; NNLL – Greub et al, 0810.4077)

SM: $$C_7 = -0.304,\ C_9 = 4.211\ C_{10} = -4.103$$

The rate depends on $C_7 + C_7',\ C_9 + C_9',\ C_{10} + C_{10}',$

and therefore one can not determine chirality of the operators.

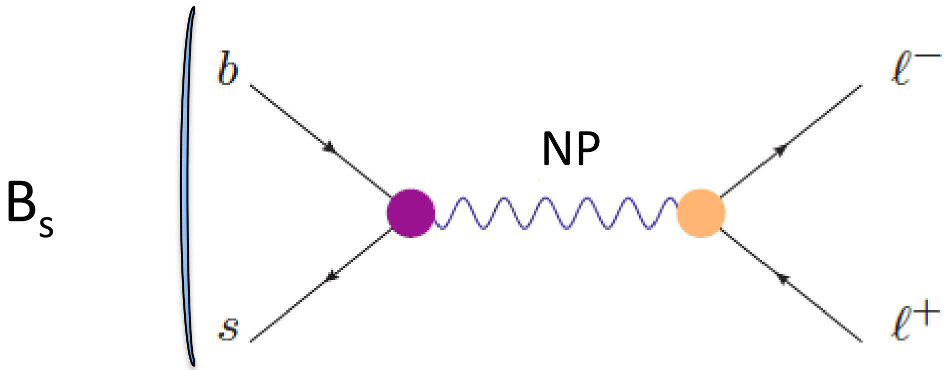
Form factors: unquenched from HPQCD collaboration, C. Bouchard et al.1306.2384;

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)|^{\rm SM}_{q^2\in[15,22]{\rm GeV}^2} = (10.2 \pm 0.5) \times 10^{-8}$$

R. Aaij etal, LHCb collaboration, 1403.8044 in the high q^2 bin

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

$$B_s \to \mu^+\mu^-$$

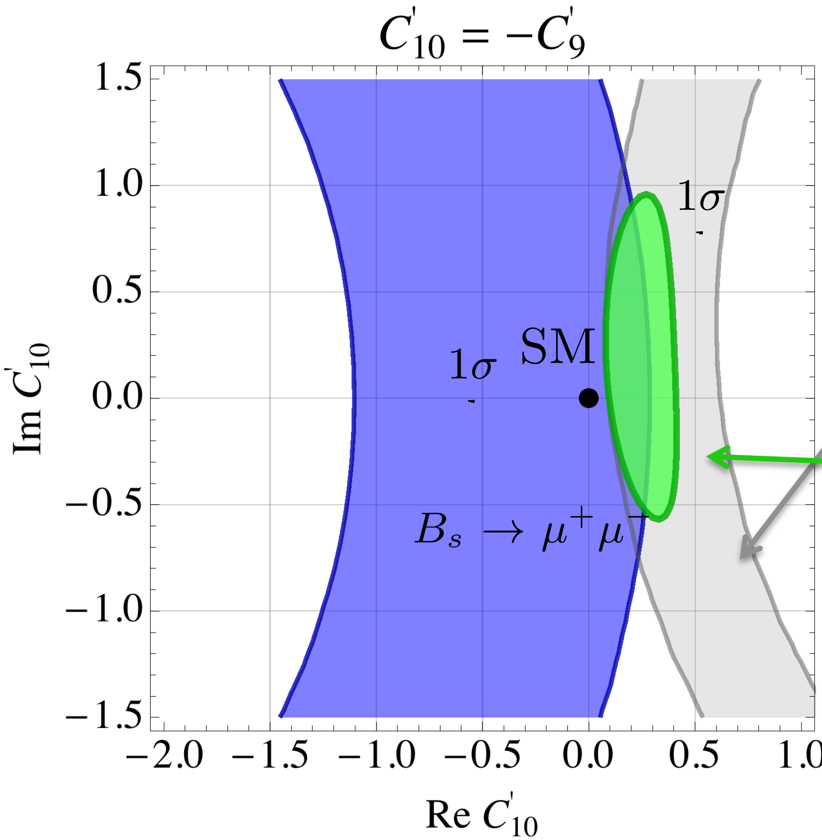


$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\rm th} = \mathcal{B}_0 |P|^2 \,, \qquad \mathcal{B}_0 = \frac{f_{B_s}^2 m_{B_s}^3}{\Gamma_s} \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}|^2}{(4\pi)^3} \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$

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

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

NP in $C_9' = -C_{10}'$ and prediction for R_K



$B \to K\mu^+\mu^-$ from LHCb at high q²

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

agrees well with

$R_K^{\text{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$

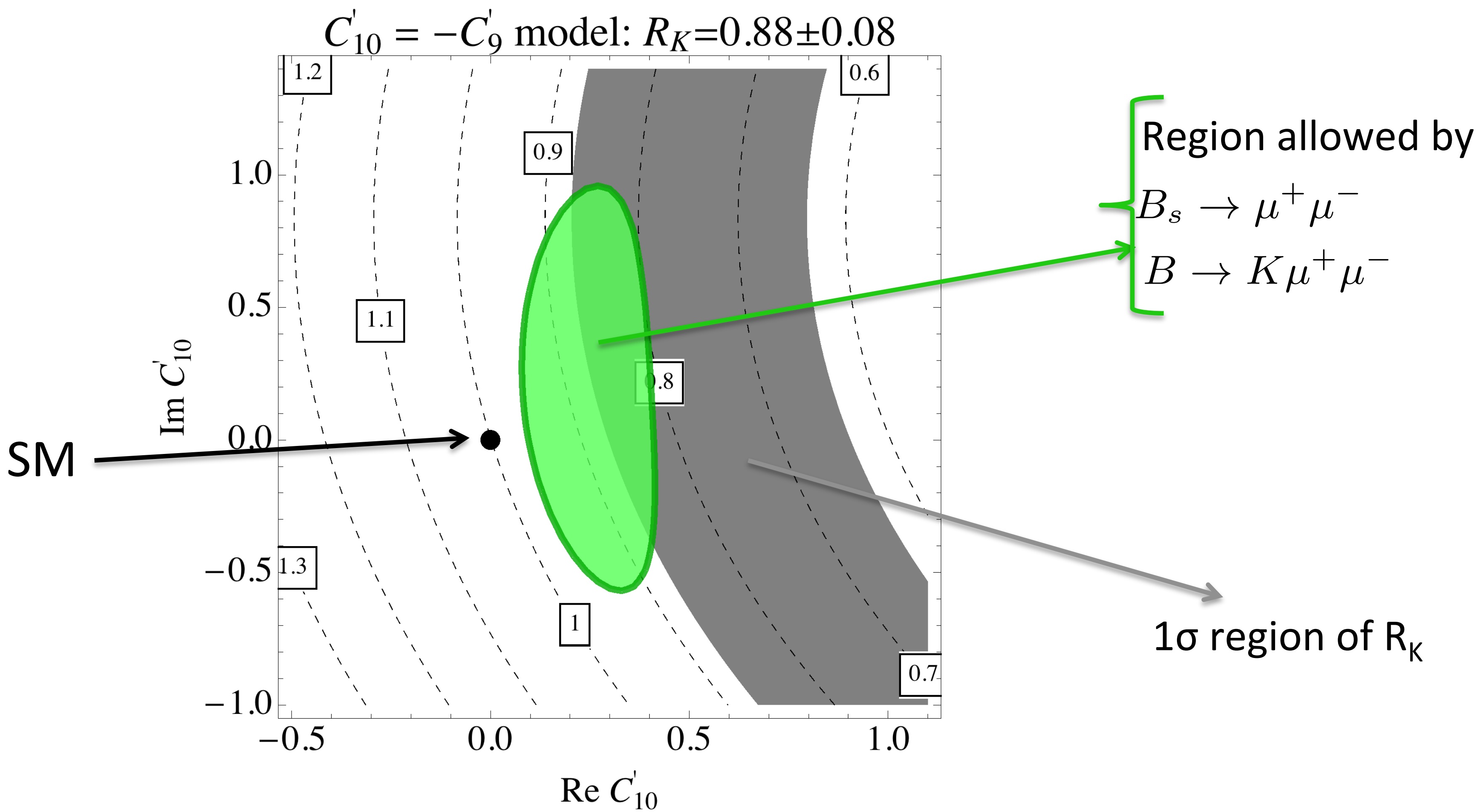
1 σ is defined as $\chi^2 < 2.30$

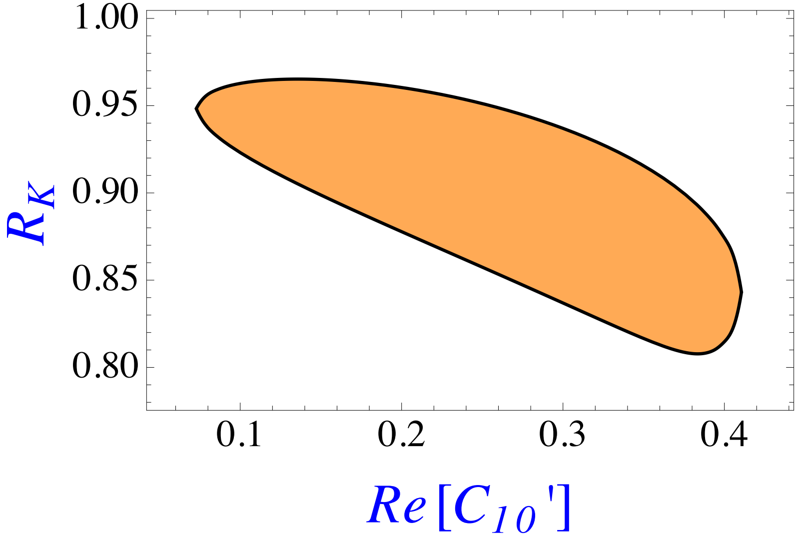
Becirevic, SF, Kosnik: arXiv:1503.09024

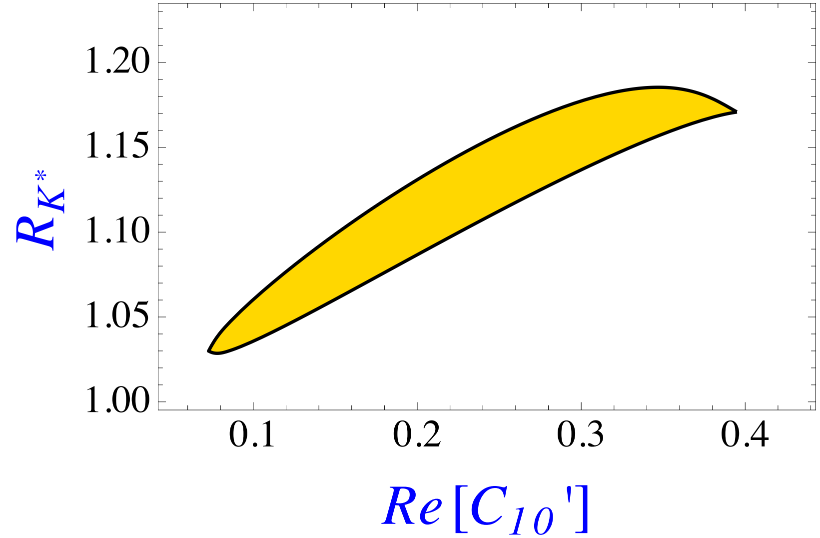
$b \rightarrow se^+e^-$ only SM

$C_9'(\Lambda) = -C_{10}'(\Lambda)$ no effects of running;

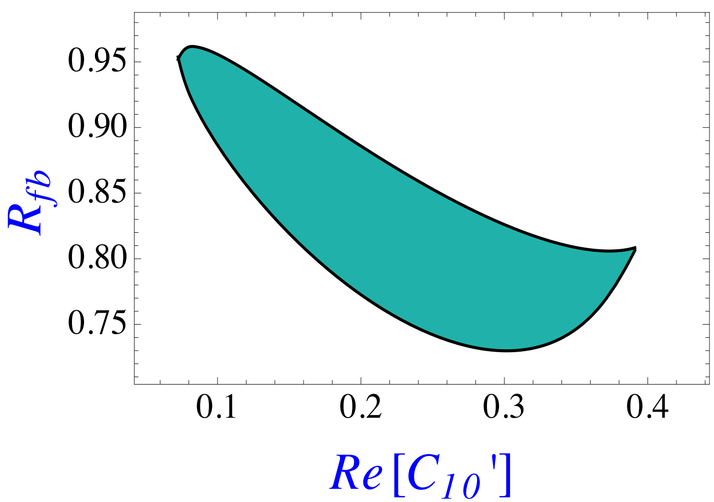
(hadronic uncertainties cancel in the rate!)

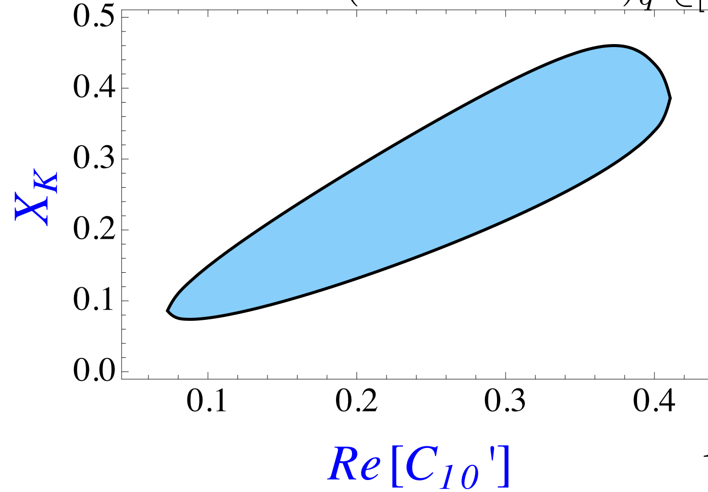






$$R_{K^*} = \frac{\Gamma(B \to K^* \mu^+ \mu^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}{\Gamma(B \to K^* e^+ e^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}$$



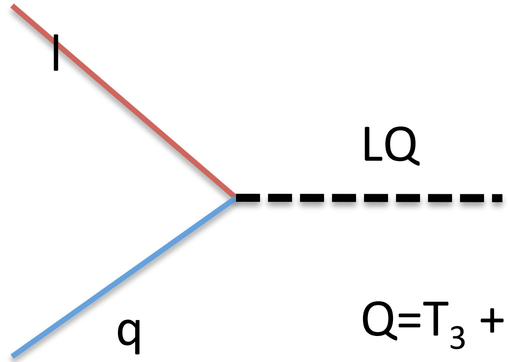


$$X_K = \frac{R_{K^*}}{R_K} - 1$$

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

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

Leptoquarks



$Q=T_3 + Y$

$SU(3)\times SU(2)\times U(1)$	Spin	Symbol	Type	$3B+L$
$(\bar{\mathbf{3}},\mathbf{3},1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3},\mathbf{2},7/6)$	0	R_2	$RL\,(S_{1/2}^L),\ LR\,(S_{1/2}^R)$	0
$(\mathbf{3},\mathbf{2},1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L),\ \overline{LR}$	0
$(\bar{\mathbf{3}},\mathbf{1},4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\bar{\mathbf{3}},\mathbf{1},1/3)$	0	S_1	$LL\,(S_0^L),\ RR\,(S_0^R),\ \overline{RR}$	-2
$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	0	$\bar{S}_1$	$\overline{RR}$	-2
$(\mathbf{3},\mathbf{3},2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\bar{\mathbf{3}},\mathbf{2},5/6)$	1	V_2	$RL\,(V_{1/2}^L),\ LR\,(V_{1/2}^R)$	-2
$(\bar{\mathbf{3}},\mathbf{2},-1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L),\ \overline{LR}$	-2
$(\mathbf{3},\mathbf{1},5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3},\mathbf{1},2/3)$	1	U_1	$LL\,(V_0^L),\ RR\,(V_0^R),\ \overline{RR}$	0
$(\mathbf{3},\mathbf{1},-1/3)$	1	$\bar{U}_1$	$\overline{RR}$	0

F=3B +L fermion number; F=0 no proton decay at tree level

I. Doršner, S. Fajfer, A. Greljo, J.F. Kamenik, N. Košnik, 1603.04993

LQ in charge current processes

Effective Lagrangian for charged current process:

$$\mathcal{L}_{\rm eff}^{\rm SL} = -\frac{4G_F}{\sqrt{2}} V_{ij} \Big\{ (U_{\ell k} + g^L_{ij;\ell k})(\bar{u}^i_L \gamma^\mu d^j_L)(\bar{\ell}_L \gamma_\mu \nu^k_L)$$
$$+ g^R_{ij;\ell k}(\bar{u}^i_R \gamma^\mu d^j_R)(\bar{\ell}_R \gamma_\mu \nu^k_R)$$
$$+ g^{RR}_{ij;\ell k}(\bar{u}^i_R d^j_L)(\bar{\ell}_R \nu^k_L) + h^{RR}_{ij;\ell k}(\bar{u}^i_R \sigma^{\mu\nu} d^j_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu^k_L)$$
$$+ g^{LL}_{ij;\ell k}(\bar{u}^i_L d^j_R)(\bar{\ell}_L \nu^k_R) + h^{LL}_{ij;\ell k}(\bar{u}^i_L \sigma^{\mu\nu} d^j_R)(\bar{\ell}_L \sigma_{\mu\nu} \nu^k_R)$$
$$+ g^{LR}_{ij;\ell k}(\bar{u}^i_L d^j_R)(\bar{\ell}_R \nu^k_L)$$
$$+ g^{RL}_{ij;\ell k}(\bar{u}^i_R d^j_L)(\bar{\ell}_L \nu^k_R) \Big\} + \text{h.c.}.$$

running for

$$g^{XY}_{ij;\ell k}(\mu) = \left[\frac{\alpha_S(\mu)}{\alpha_S(m_{q^{f+1}})}\right]^{-\frac{\gamma_S}{2\beta_0^{(f)}}} \cdots \left[\frac{\alpha_S(m_b)}{\alpha_S(m_t)}\right]^{-\frac{\gamma_S}{2\beta_0^{(5)}}} \left[\frac{\alpha_S(m_t)}{\alpha_S(M)}\right]^{-\frac{\gamma_S}{2\beta_0^{(6)}}} g^{XY}_{ij;\ell k}(M)$$

I. Doršner, S. Fajfer, A. Greljo, J.F. Kamenik, N. Košnik, 1603.04993

Scalar LQ

Scalars	$g^{L}_{ij;\ell k}$	$g^{R}_{ij;\ell k}$	$g^{RR}_{ij;\ell k} = 4h^{RR}_{ij;\ell k}$	$g^{LL}_{ij;\ell k} = 4h^{LL}_{ij;\ell k}$
S_3	$-\frac{v^2}{M^2}\frac{(x^\dagger V^*)_{\ell i}(xU)_{jk}}{4V_{ij}}$			
R_2			$\frac{v^2}{M^2}\frac{(xU)_{ik}y_{\ell j}}{4V_{ij}}$	
$\tilde{R}_2$				$\frac{v^2}{M^2}\frac{(Vy)_{ik}x^*_{j\ell}}{4V_{ij}}$
S_1	$\frac{v^2}{M^2}\frac{(vU)_{jk}(V^Tv)^*_{i\ell}}{4V_{ij}}$	$-\frac{v^2}{M^2}\frac{y_{jk}x^*_{i\ell}}{4V_{ij}}$	$\frac{v^2}{M^2}\frac{(vU)_{jk}x^*_{i\ell}}{4V_{ij}}$	$\frac{v^2}{M^2}\frac{y_{jk}(V^Tv)^*_{i\ell}}{4V_{ij}}$

$R_{D(*)}$ puzzles can be explained by these modifications of the left-handed (right-handed, scalar/pseudoscular, tensor currents), if all other flavor constraints allow that!

LQ in FCNC $P \to P'(V) l^- l^{(\prime)+}$ and $P \to l^- l^{(\prime)+}$ transitions

Effective Lagrangian

$$\mathcal{L}_{\bar{q}^j q^i \ell\ell'} = -\frac{4G_F}{\sqrt{2}}\lambda_q \Big[C_7 \mathcal{O}_7 + C_{7'}\mathcal{O}_{7'} + \sum_{i=9,10,S,P} \Big(C_i^{\ell\ell'} \mathcal{O}_i^{\ell\ell'} + C_{i'}^{\ell\ell'} \mathcal{O}_{i'}^{\ell\ell'} \Big) + C_T^{\ell\ell'} \mathcal{O}_T^{\ell\ell'} + C_{T5}^{\ell\ell'} \mathcal{O}_{T5}^{\ell\ell'} \Big] + \text{h.c.},$$

$$\mathcal{O}_7 = \frac{e m_q}{(4\pi)^2} (\bar{q}^j \sigma_{\mu\nu} P_R q^i)\, F^{\mu\nu}\,,$$

$$\mathcal{O}_9^{\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{q}^j \gamma^\mu P_L q^i)(\bar{\ell}\gamma_\mu \ell')\,,$$

$$\mathcal{O}_{10}^{\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{q}^j \gamma^\mu P_L q^i)(\bar{\ell}\gamma_\mu \gamma_5 \ell').$$

$$\mathcal{O}_S^{\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{q}^j P_R q^i)(\bar{\ell}\ell'),$$

$$\mathcal{O}_P^{\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{q}^j P_R q^i)(\bar{\ell}\gamma_5 \ell'),$$

LQ	$d_i \to d_j \ell^- \ell'^+$ decays, $\lambda_q = V_{qi} V^*_{qj}$	$u_i \to u_j \ell^- \ell'^+$ decays, $\lambda_q = V^*_{iq} V_{jq}$
S_3	$C_9 = -C_{10} = -\frac{v^2}{M^2} \frac{\pi}{\alpha \lambda_q} x_{i\ell'} x^*_{j\ell}$	$C_9 = -C_{10} = -\frac{v^2}{M^2} \frac{\pi}{\alpha \lambda_q} (V^T x)_{i\ell'} (V^T x)^*_{j\ell}$
R_2	$C_9 = C_{10} = \frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} y_{\ell i} y^*_{\ell' j}$	$C_9 = C_{10} = \frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} (yV^\dagger)_{\ell i} (yV^\dagger)^*_{\ell' j}$ $C_{9'} = -C_{10'} = \frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} x_{j\ell'} x^*_{i\ell}$ $C_S = C_P = -\frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} x^*_{i\ell} (yV^\dagger)^*_{\ell' j}$ $C_{S'} = -C_{P'} = -\frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} x_{j\ell'} (yV^\dagger)_{\ell i}$ $C_T = (C_S + C_{S'})/4$ $C_{T5} = (C_S - C_{S'})/4$
$\tilde{R}_2$	$C_{9'} = -C_{10'} = \frac{v^2}{M^2} \frac{\pi}{2\lambda_q \alpha} x_{j\ell'} x^*_{i\ell}$	
$\tilde{S}_1$	$C_{9'} = C_{10'} = -\frac{v^2}{M^2} \frac{\pi}{2\lambda_q \alpha} x_{i\ell'} x^*_{j\ell}$	
S_1		$C_9 = -C_{10} = -\frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} (V^T v)_{i\ell'} (V^T v)^*_{j\ell}$ $C_{9'} = C_{10'} = -\frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} x_{i\ell'} x^*_{j\ell}$ $C_S = C_P = \frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} x_{i\ell'} (V^T v)^*_{j\ell}$ $C_{S'} = -C_{P'} = \frac{v^2}{M^2} \frac{\pi}{2\alpha \lambda_q} (V^T v)_{i\ell'} x^*_{j\ell}$ $C_T = (C_S + C_{S'})/4$ $C_{T5} = (C_S - C_{S'})/4$

I. Doršner, S. Fajfer, A. Greljo, J.F. Kamenik, N. Košnik, 1603.04993

Examples of LQ

(3,2,7/6)

two states with electric charge 5/3 and 2/,
has a coupling with SM neutrino

$$\mathcal{L}_{\mathrm{Y}} = -\, x_{ij}\bar{u}^i_R e^j_L R_2^{5/3} + (xV_{\mathrm{PMNS}})_{ij}\bar{u}^i_R \nu^j_L R_2^{2/3} + (yV^\dagger_{\mathrm{CKM}})_{ij}\bar{e}^i_R u^j_L R_2^{5/3\,*} + y_{ij}\bar{e}^i_R d^j_L R_2^{2/3\,*} + \mathrm{h.c.},$$

The model is constrained by:

$Z \to b\bar{b}$ (τ in the loop)

$(g-2)_\mu$ (c –quark in the loop)

$\tau \to \mu\gamma$

$\mu \to e\gamma$

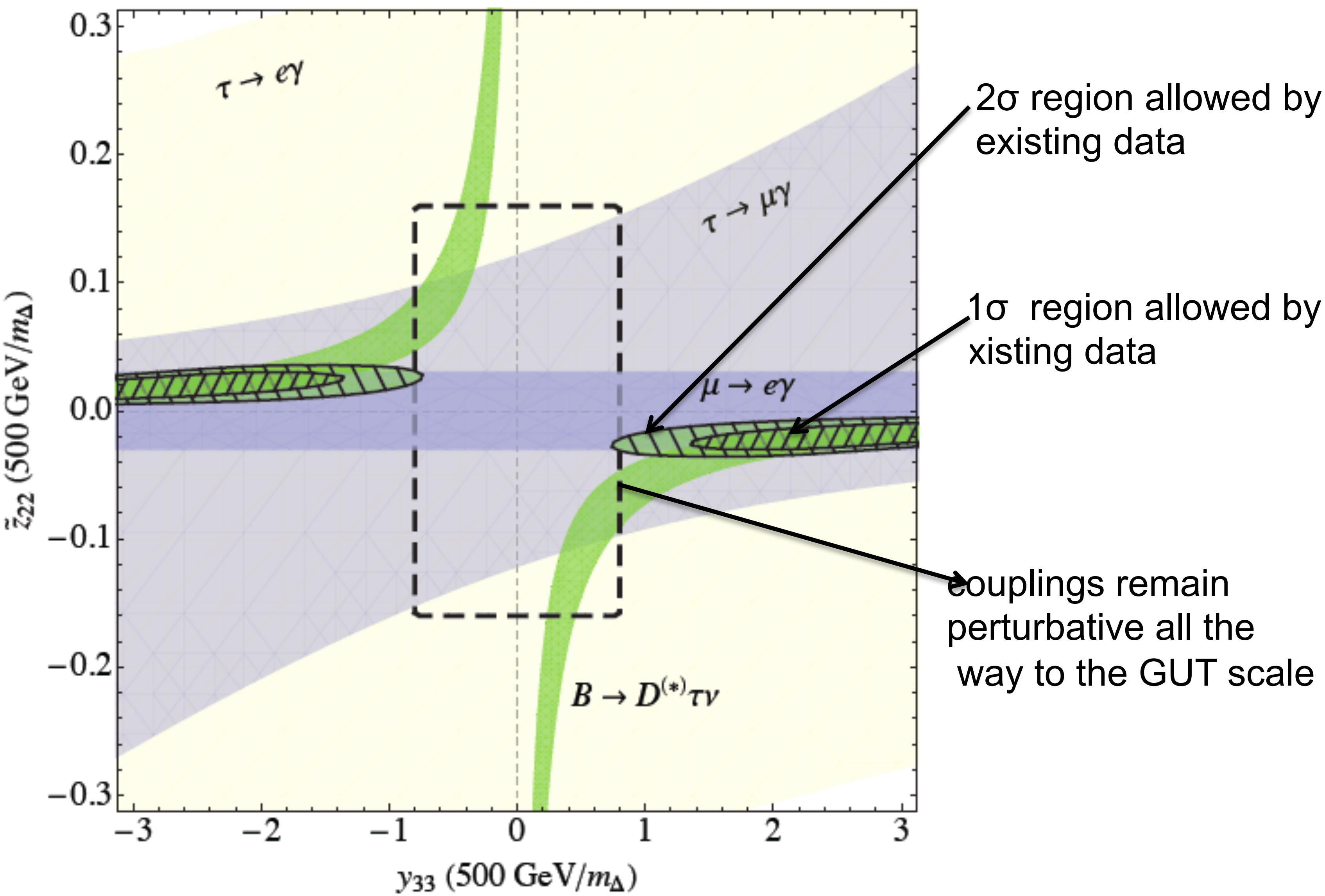
$\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$

$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$

$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-9}$

Not good candidate for R_K, $C_9 = C_{10}$!

I. Doršner, S.F., N. Košnik, arXiv: 1306.6493



τ → eγ
τ → μγ
μ → eγ
B → D(*)τν
2σ region allowed by existing data
1σ region allowed by xisting data
couplings remain perturbative all the way to the GUT scale
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−3
−2
−1
0
1
2
3
z̃22 (500 GeV/mΔ)
y33 (500 GeV/mΔ)

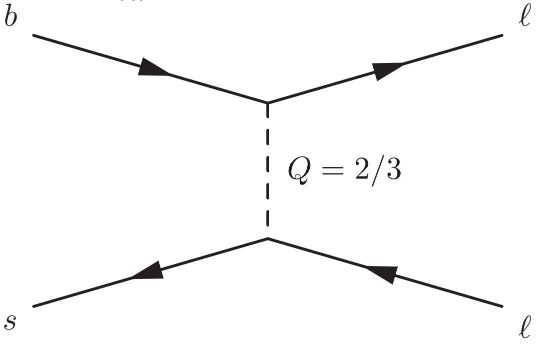
(3,2,1/6)

can explain both R_K and $R_{D(*)}$ at tree level!

two states with electric charge 2/3 and -1/3

$$\mathcal{L}_{\rm Y} = -x_{ij}\bar{d}^i_R e^j_L \tilde{R}_2^{2/3} + (xV_{\rm PMNS})_{ij}\bar{d}^i_R \nu^j_L \tilde{R}_2^{-1/3} + (V_{\rm CKM}y)_{ij}\bar{u}^i_L \nu^j_R \tilde{R}_2^{2/3} + y_{ij}\bar{d}^i_L \nu^j_R \tilde{R}_2^{-1/3} + \text{h.c.}$$

1. Good candidate for R_K according to: Hiller&Schmaltz, 1408.1627 ; Hiller & de Medeiros Varzielas, 1503.01084 for R_K:

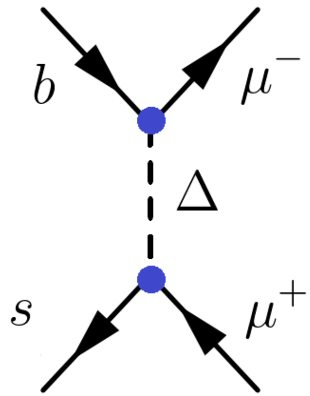


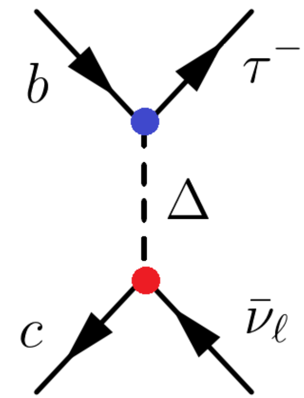
$C_9' = -C_{10}'$

2. Can explain $R_{D(*)}$ if neutrino right-handed! In this case there is no interference with the SM neutrinos.

$$|\mathcal{M}(B \to D^{(*)}\ell\nu)|^2 = |\mathcal{M}_{\rm SM}|^2 + |\mathcal{M}_{\rm NP}|^2$$

R_K





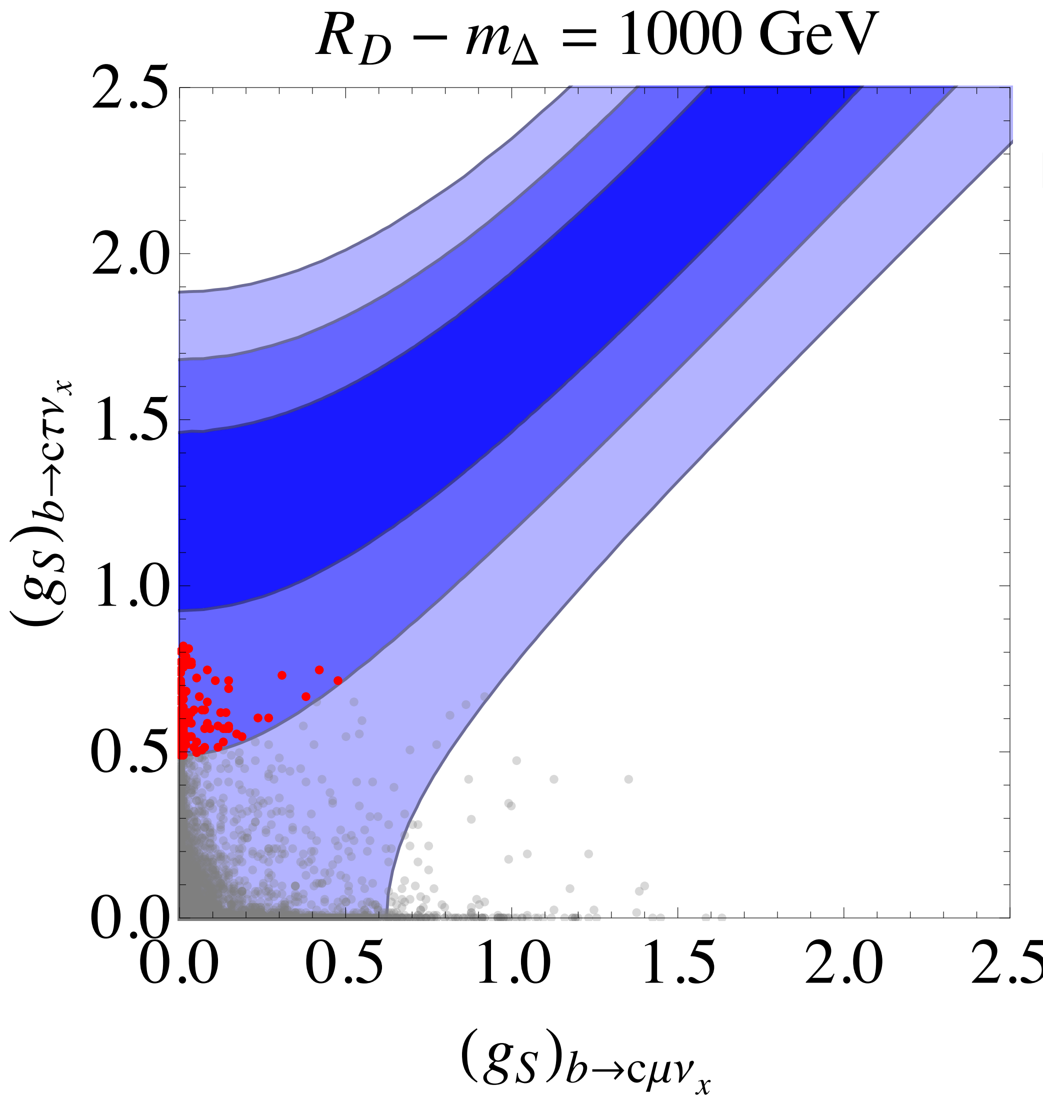
R_D

Model passed all flavor tests: $B_s \to \mu^+\mu^-$, $\mathcal{B}(B \to K\mu\mu)_{\text{high } q^2}$, Δm_{B_s}

$\mathcal{B}(B \to \tau\bar{\nu})$, $\mathcal{B}(D_s \to \tau\bar{\nu})$, $\mathcal{B}(B \to K\nu\bar{\nu})$, $\mathcal{B}(B \to K\mu\tau)$ etc

D. Becirevic, SF, N. Kosnik and O. Sumensari (1606.xxxxx)

R_D: form factor from lattice QCD (Milc&Fermilab 2015)

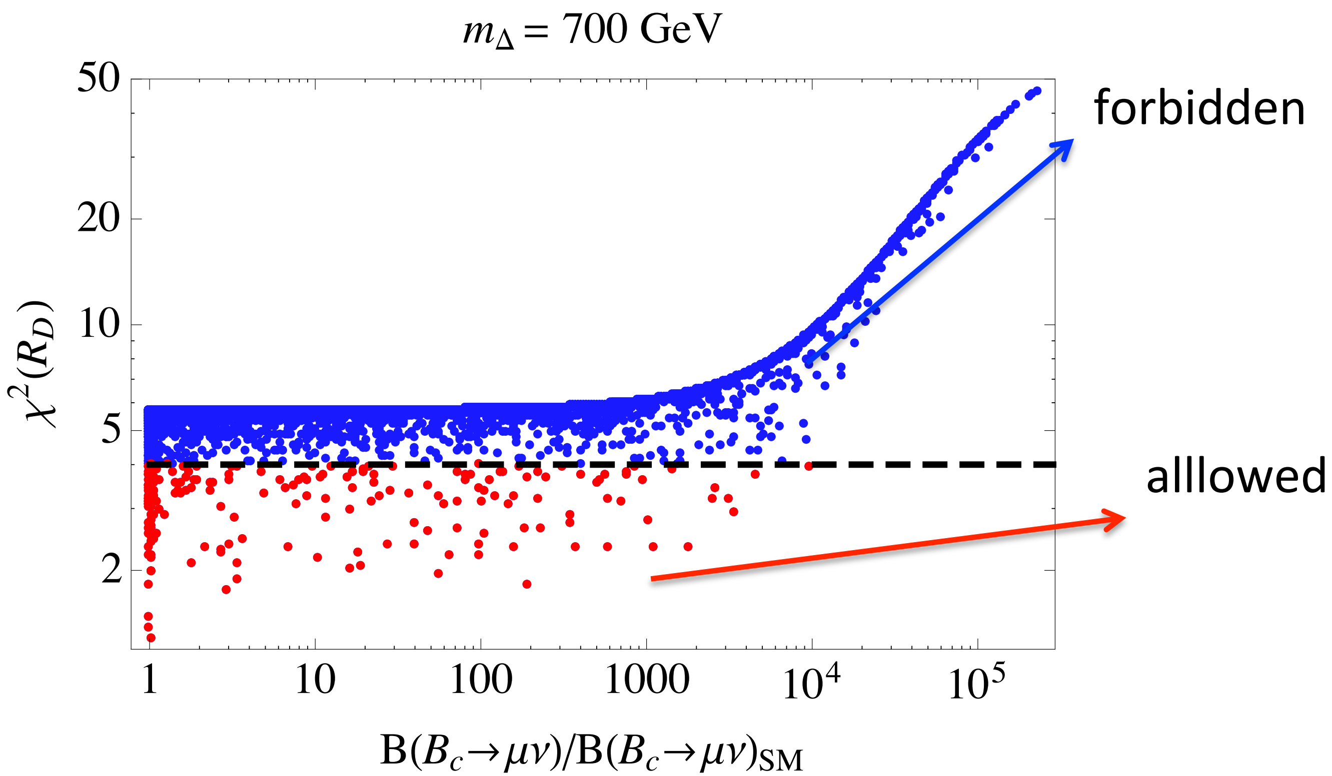


both decay modes get LQ contributions

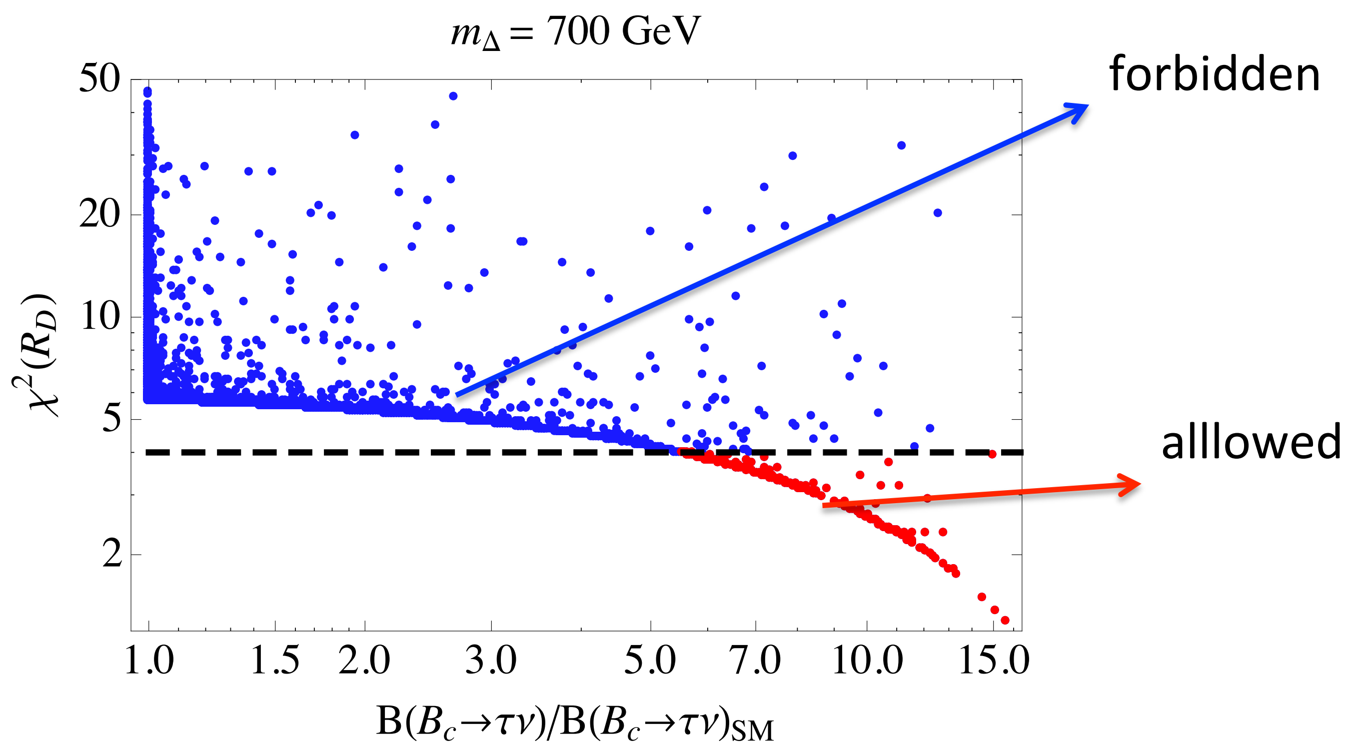
$B \to D\tau\nu_\tau$

$B \to D\mu\nu_\mu$

Tests:



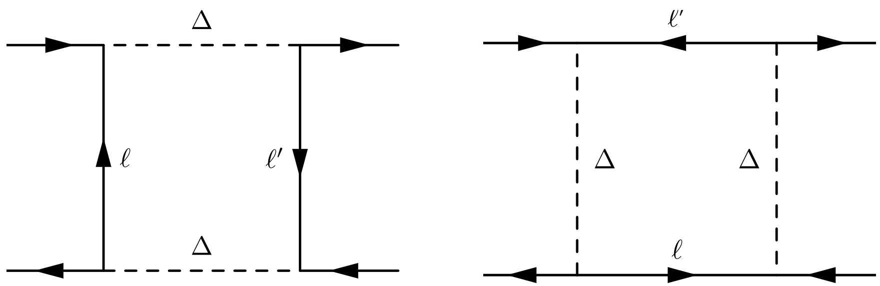
$m_\Delta = 700$ GeV
50
20
10
5
2
$\chi^2(R_D)$
1
10
100
1000
10^4
10^5
$B(B_c \to \mu\nu)/B(B_c \to \mu\nu)_{SM}$
forbidden
alllowed



$m_\Delta = 700$ GeV
forbidden
alllowed
50
20
10
5
2
$\chi^2(R_D)$
1.0
1.5
2.0
3.0
5.0
7.0
10.0
15.0
$B(B_c \to \tau\nu)/B(B_c \to \tau\nu)_{SM}$

Neutral meson anti-meson oscillations with LQ presence

$$\mathcal{L} = \bar{q}^i \left[l_{ij} P_R + r_{ij} P_L \right] \ell^j \, S + \text{h.c}$$



$$\mathcal{L}_{\text{eff}} = \frac{-1}{128\pi^2 m_S^2} \big[(ll^\dagger)^2_{ji} (\bar{q}^j \gamma^\mu P_L q^i)(\bar{q}^j \gamma_\mu P_L q^i) + (rr^\dagger)^2_{ji} (\bar{q}^j \gamma^\mu P_R q^i)(\bar{q}^j \gamma_\mu P_R q^i) - 4 (ll^\dagger)_{ji} (rr^\dagger)_{ji} (\bar{q}^j P_L q^i)(\bar{q}^j P_R q^i) \big].$$

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

→ $b \to s \mu^+ \mu^-$

(3,2,1/6) does not modify $(g-2)_\mu$

Combining Δ B =2 and Δ B =1

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

an example $\mathrm{Re}[C_{10}'] \in [0.15, 0.35]$ leads to $m_\Delta \sim 100\ \ \mathrm{TeV}$

Impact of LQ (3,2,1/6) on $B \to K\nu\bar\nu$

$$\Gamma(B \to K\nu\bar\nu) \sim \sum_{i,j=1}^{3} \left|\delta_{ij} C_L^{\rm SM} + C_R^{ij}\right|^2$$

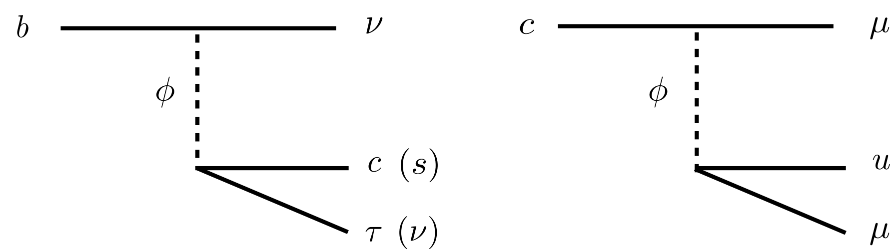
$$= 3|C_L^{\rm SM}|^2 + |C_{10}'|^2 - 2\mathrm{Re}[C_L^{\rm SM*} C_{10}']$$

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

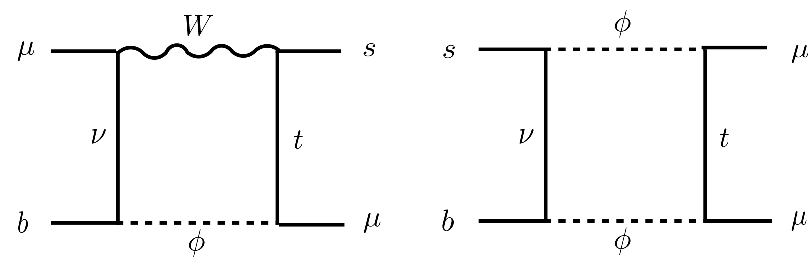
Can only one leptoquark accommodate all B meson anomalies?

Bauer & Neubert, 1511.01900 proposal: scalar (3,1,-1/3) can accommodate $R_{D(*)}$, R_K and $(g-2)_{\mu}$!

$R_{D(*)}$ tree level SM and LQ correction on tree level!



R_K and $(g-2)_\mu$: SM loop process LQ correction on loop level



Problem of (3,1,-1/3): it can mediate proton decay!

More attempts to explain R_K and $R_{D(*)}$ at tree level

Barbieri, Isidori, Pattori and Senia, 1512.01560

LQ with dominant couplings to the third generation

Imposed symmetry: $\mathcal{G}_F = \mathcal{G}_F^q \times \mathcal{G}_F^l$

$$\mathcal{G}_F^q = U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3} \qquad \mathcal{G}_F^l = U(2)_L \times U(2)_e \times U(1)_{e3}$$

Proposal: scalar leptoquark $(\bar{3}, 3, -1/3)$

vector leptoquarks $\begin{cases} (3, 1, 2/3) \\ (3, 3, 2/3) \end{cases}$

Vector leptoquark (3,3,2/3) and B anomalies

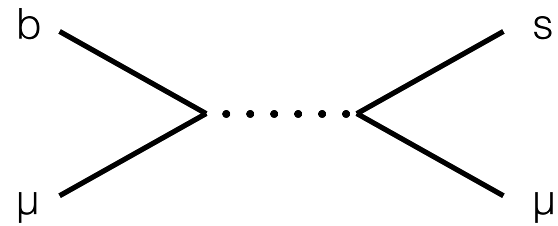
SF, Košnik: 1511.06024

$$\mathcal{L}_{U_3} = g_{ij}\bar{Q}_i\gamma^\mu \tau^A U^A_{3\mu} L_j + \text{h.c.}$$

$Q=Y+I_3$ ⇨ $$U_{3\mu} = \begin{cases} U_{3\mu}^{(5/3)} \\ U_{3\mu}^{(2/3)} \\ U_{3\mu}^{(-1/3)} \end{cases}$$

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

Our assumption:



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

First generation of quarks and leptons has negligible couplings!

Important:

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

For $C_9 \in [-0.81, -0.50]$ at 1σ

$$g_{b\mu}^* g_{s\mu} \in [0.7, 1.3] \times 10^{-3} \ (M_U/\mathrm{TeV})^2$$

Both $R_{D(*)}$, R_K get contributions at tree level

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

shifts the CKM cb element

R_K and $R_{D(*)}$ lead to constraints

$$g^*_{b\mu}g_{s\mu} \in [0.7, 1.3] \times 10^{-3}\ (M_U/\text{TeV})^2$$

$$\text{Re}\left[g^*_{b\tau}(\mathcal{V}g)_{c\tau} - g^*_{b\mu}(\mathcal{V}g)_{c\mu}\right] = (0.18 \pm 0.04)\ (M_U/\text{TeV})^2$$

Perturbativity condition $|g_{s\mu}, g_{b\mu}, g_{b\tau}| < \sqrt{4\pi}$

$$g^2_{b\tau} - g^2_{b\mu} \approx 4.4$$

$$|g_{b\tau}| \gtrsim 2$$

Additional constraints

1. LFU in K leptonic decays

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

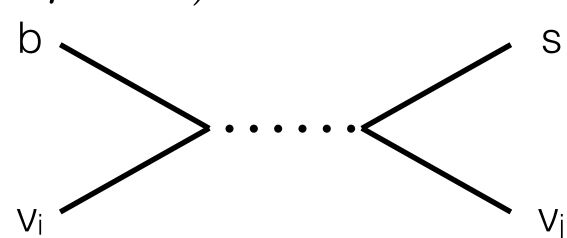
2. $b \to c\mu^- \bar{\nu}$

3. Semileptonic top decays $t \to b\tau^+\nu$ (CDF 1402.6728)

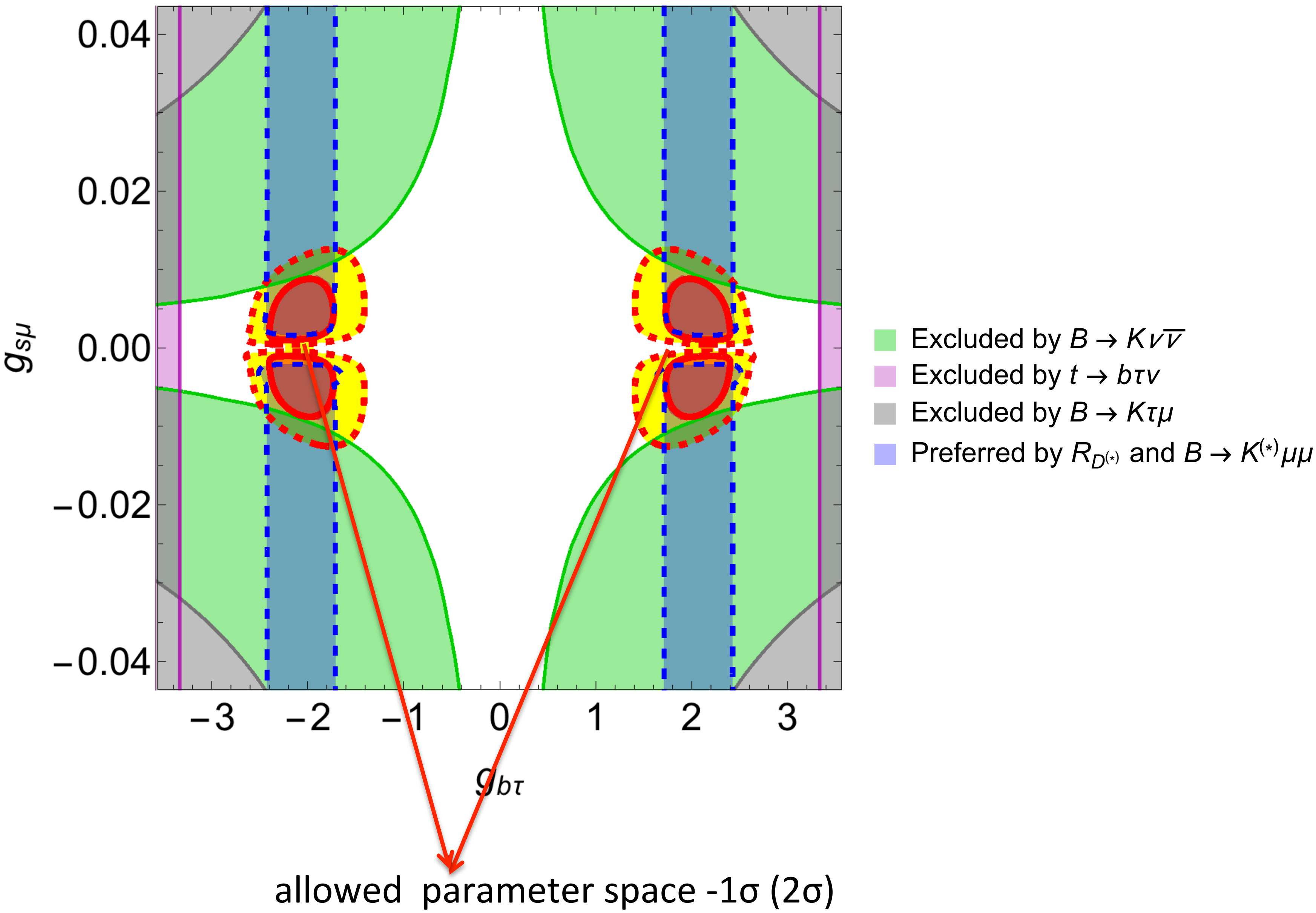
4. LNV B decays $B \to K\mu\tau$

BaBar 1204.2852: $\mathcal{B}(B^- \to K^-\mu^+\tau^-) < 2.8 \times 10^{-5}$ at 90% CL

5. $B \to K^{(*)}\nu\bar{\nu}$



SM branching ratio for K and K* get modification for the same factor.
The rate can be increased by factor 1.17.



0.04
0.02
0.00
−0.02
−0.04
$g_{s\mu}$
−3
−2
−1
0
1
2
3
$g_{b\tau}$
Excluded by $B \to K\nu\overline{\nu}$
Excluded by $t \to b\tau\nu$
Excluded by $B \to K\tau\mu$
Preferred by $R_{D^{(*)}}$ and $B \to K^{(*)}\mu\mu$
allowed parameter space -1σ (2σ)

Further experimental signatures

1. rare charm decays

in $c \to u\mu^+\mu^-$ decay $|\tilde{C}_9| \equiv |C_9^{(\bar{u}c)}/(\mathcal{V}_{ub}\mathcal{V}_{cb}^*)| \lesssim 0.05,$

Current experimental bound allows $|\tilde{C}_9| \leq 0.63$

2. increase of the rate for $t \to b\tau^+\nu$ if $|g_{b\tau}| \sim 2,$

by 20%;

3. prediction $R_{K*} \simeq R_K$

$$R_{K^*} = \Gamma(B \to K^*\mu^+\mu^-)/\Gamma(B \to K^*e^+e^-)$$

Light vector leptoquarks: facing new problems

- UV completion is the main problem of this approach;

- Contrary to SM gauge bosons, if vector leptoquarks are not gauge boson (e.g. SU(5) GUT with LQ being in some other representation of SU(5), not 24) we have to work with non-renormalizable model.

- Problem with loops within this approach (e.g. Barbieri et al. 1512.01560) discussed vector letpquarks (3,1,2/3), (3,3,2/3) and for loop processes they used cut-off.

Can one LQ be light within any GUT theory?

Main issue: How to accommodate light LQ within GUT or composite model?

Inclusion of 45 scalar representation SU(5) GUT $M_E^T = -3M_D$

Both are needed:

Higgses in 5 and 45!

S(3)x S(2)XU(1) content of 45 :

$$(\mathbf{8}, \mathbf{2}, \mathbf{1/2}) \oplus (\overline{\mathbf{6}}, \mathbf{1}, -\mathbf{1/3}) \oplus (\mathbf{3}, \mathbf{3}, -\mathbf{1/3}) \oplus (\overline{\mathbf{3}}, \mathbf{2}, -\mathbf{7/6}) \oplus (\mathbf{3}, \mathbf{1}, -\mathbf{1/3}) \oplus (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{4/3}) \oplus (\mathbf{1}, \mathbf{2}, \mathbf{1/2})$$

Is unification possible with some of light scalars in 45?

Yes!

I.Doršner, S.F. J.F. Kamenik and N. Košnik, 0906.5585; 1007.2604 ;

Unification possible with 2 light scalars!

Summary and outlook

- B physics anomalies offer unique tests of SM extensions at low energies;
- 3σ effects have to be further tested experimentally (e.g. R_{K*});
- Suggested new observables might clarify need for NP;
- Leptoquarks are one of suggested SM extension which might explain observed discrepancies;
- $(3,2,1/6)_0$ $(3,3,2/3)_1$ are our favorable candidates (do not destabilize proton)
- Light scalar leptoquarks are simpler to accommodate within GUT framework then vector leptoquarks.
- Is it possible to construct any GUT (or composite model) with only one light LQ?

Thanks!

Test of lepton flavour universality violation

In 1510.0311 (de Beor and Hiller) it was pointed out that bounds on electron-positron mode are weaker:

$$BR(D^+ \to \pi^+ e^+ e^-) < 1.1 \times 10^{-6}$$

$$BR(D^0 \to e^+ e^-) < 7.9 \times 10^{-8}$$

$$\left|C_{S,P}^{(e)} - C_{S,P}^{(e)\prime}\right| \lesssim 0.3\,,$$

$$\left|C_{9,10}^{(e)} - C_{9,10}^{(e)\prime}\right| \lesssim 4\,,$$

$$\left|C_{T,T5}^{(e)}\right| \lesssim 5\,, \quad \left|C_7\left(C_9^{(e)} - C_9^{(e)\prime}\right)\right| \lesssim 2\,.$$

In 1510.0965 (S.F. and N. Košnik) it was suggested, assuming as in the case $B \to K e^+ e^-$ that NP does not affect electron-positron mode, that tests of LFU can be performed either in I or II bin

$$R_\pi^{\mathrm{I}} = \frac{\mathrm{BR}(D^+ \to \pi^+ \mu^+ \mu^-)_{q^2 \in [0.25^2, 0.525^2]\,\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+ e^+ e^-)_{q^2 \in [0.25^2, 0.525^2]\,\mathrm{GeV}^2}}$$

$$R_\pi^{\mathrm{II}} = \frac{\mathrm{BR}(D^+ \to \pi^+ \mu^+ \mu^-)_{q^2 \in [1.25^2, 1.73^2]\,\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+ e^+ e^-)_{q^2 \in [1.25^2, 1.73^2]\,\mathrm{GeV}^2}}$$

	$\lvert\tilde{C}_i\rvert_{\max}$	R_π^{II}
SM	-	0.999 ± 0.001
$\tilde{C}_7$	1.6	$\sim$ 6–100
$\tilde{C}_9$	1.3	$\sim$ 6–120
$\tilde{C}_{10}$	0.63	$\sim$ 3–30
$\tilde{C}_S$	0.05	$\sim$ 1–2
$\tilde{C}_P$	0.05	$\sim$ 1–2
$\tilde{C}_T$	0.76	$\sim$ 6–70
$\tilde{C}_{T5}$	0.74	$\sim$ 6–60
$\tilde{C}_9 = \pm\tilde{C}_{10}$	0.63	$\sim$ 3–60
$\tilde{C}'_9 = -\tilde{C}'_{10}\big\rvert_{\mathrm{LQ}(3,2,7/6)}$	0.34	$\sim$ 1–20

$$R_\pi^{I,SM} = 0.87 \pm 0.09$$

$$R_\pi^{II,SM} = 0.999 \pm 0.001$$

Assumptions:

- e^+e^- mode are SM-like;
- NP enters in $\mu^+\mu^-$ mode only;
- listed Wilson coefficients are maximally allowed by current LHCb data.