Impact of B anomalies on D and K decays

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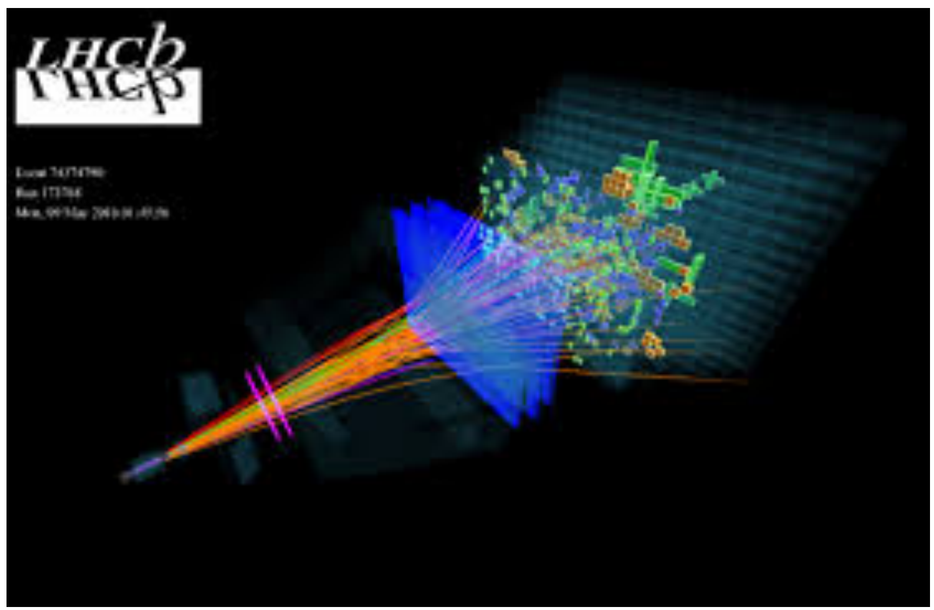


Implications of LHCB measurements and future prospects
CERN 8-10 Nov. 2017

Motivation

- Charged current $b \to c\, \tau \nu_\tau$: $R_{D(*)}$ puzzle
- FCNC transition $b \to s\, l^+ l^-$: $R_{K(*)}$ puzzle

NP solution: Leptoquarks

Charged currents in D and K

FCNC in D and K: best candidate $K \to \pi \nu\nu$

Summary

B physics anomalies: experimental results ≠ SM predictions!

charged current SM tree level

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

$$R_{J/\psi} = \frac{BR(B_c \to J/\psi\tau\nu)}{BR(B_c \to J/\psi\mu\nu)}$$ 2σ

FCNC - SM loop process

2) P_5' in $B \to K^*\mu^+\mu^-$ (angular distribution functions) 3σ

3) $$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$$ in the dilepton invariant mass bin $1\ \mathrm{GeV}^2 \leq q^2 \leq 6\ \mathrm{GeV}^2$ 2.4σ

Effective Lagrangian approach: NP in third generation

$$\mathcal{L}_{\rm NP} = \frac{C_1}{\Lambda^2}\left(\bar{q}_{3L}\gamma^\mu q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \ell_{3L}\right) + \frac{C_3}{\Lambda^2}\left(\bar{q}_{3L}\gamma^\mu \tau^a q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \tau^a \ell_{3L}\right)$$

NP couples preferentially to third generation.
For NP scale above ew scale, $SU(3) \times SU(2)_L \times U(1)_Y$ at low energies should be respected!

Feruglio, Paradisi, Pattori, 1606.00524; Battacharaya et al., 1412.7164; Glashow, Guadagnoli and Lane, 1411.0565; Barbieri, Isidori, Pattori, Senia 1512.01560, Bordone, Isidori, Trifinopoulos, 1702.07238; Alonso, Grinstein, Camalich, 1505.05164

Models of NP explaining $R_{D(*)}$ and $R_{K(*)}$

Spin	Color singlet	Color tripet
0	2HDM	Scalar LQ $\not{R}$ parity - sbottom
1	W' ,Z'	Vector LQ

Why search for NP in D and K physics

- strong constraints from atomic parity violation, LFU at 1% level suggest to avoid coupling of NP to the first generation;
- in K and D FCNC decays usually long distance physics overshadow short distance dynamics; $M_{LD} > M_{SM}$
- In construction of NP needed to explain B meson puzzles constraints from K and D physics are very often included in the analysis.

The main issue:

How large can be effects of NP explaining B anomalies in K and D charged current and FCNC rare decays having in mind existing and planned experimental precision?

Leptoquarks in $R_{K(*)}$ and $R_{D(*)}$

Suggested by many authors: naturally accommodate LUV and LFV

color SU(3), weak isospin SU(2) , weak hypercharge U(1) $Q=I_3 + Y$

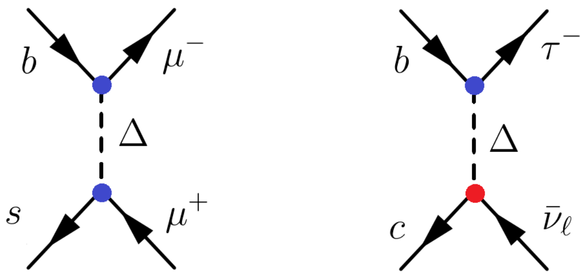
$SU(3)\times SU(2)\times U(1)$	Spin	Symbol	Type	$3B+L$
$(\overline{\mathbf{3}},\mathbf{3},1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3},\mathbf{2},7/6)$	0	R_2	$RL\,(S_{1/2}^L),\ LR\,(S_{1/2}^R)$	0
$(\mathbf{3},\mathbf{2},1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L),\ \overline{LR}$	0
$(\overline{\mathbf{3}},\mathbf{1},4/3)$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

Good candidates!

F=3B +L fermion number; F=0 no proton decay at tree level (see Assad et al, 1708.06350)

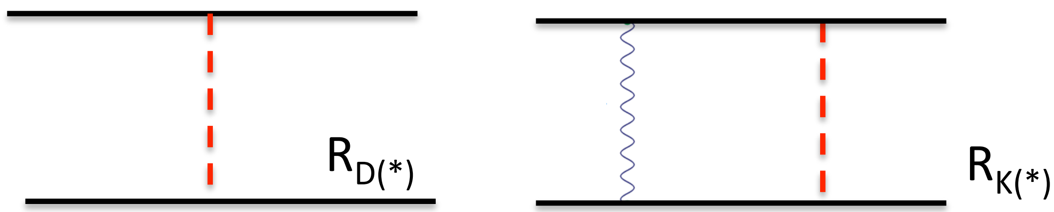
Doršner, SF, Greljo, Kamenik Košnik, (1603.04993)

1. Explaining both B anomalies by one LQ at tree level



one LQ explain it all?

2. Explaining $R_{D(*)}$ by the tree level and $R_{K(*)}$ by the loop



Bauer & Neubert 1511.01900, Crivellin, Faela and Greub 1512.02830, Doršner, SF, Košnik, Nišandžić. 1306.6493, Crivellin et al, 1703.09226, Bečirević, Sumensari 1704.05835, ...

3. Vector LQ (3,1,2/3)

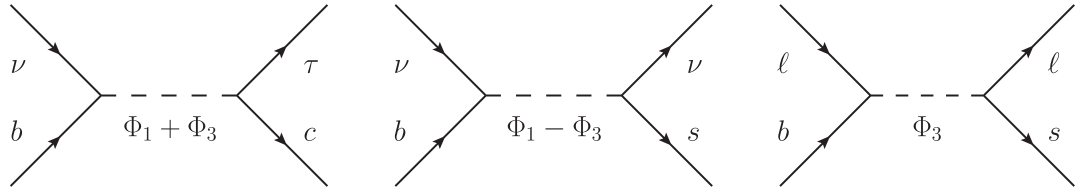
- V-A currents entering in the effective Lagrangian;
- Weak singlet does not "spoil" $B \to K^{(*)} \nu \bar{\nu}$

Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

Light vector LQ difficult to make full UV complete theory recent attempts: Di Luzio, Greljo, Nardecchia. 1708.08450, Calibbi, Crivellin, Li, 1709.00692.

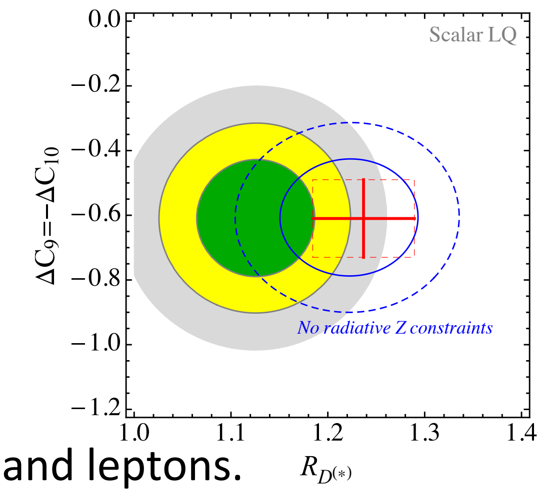
Two LQs solution of $R_{D(*)}$ and $R_{K(*)}$

- One scalar LQ cannot explain both B anomalies;



(3,3,1/3) + (3,1,-1/3)
Crivellin et al, 1703.09226

- radiative corrections to Z → ττ, υυ observables are enhanced, implying a ~ 1.5σ tension in $R_{D(*)}$;
Buttazzo, Greljo, Isidori, Marzocca , 1706.07808 :



- (3,3,1/3) alone has a proper structure according to effective Lagrangian − it couples to only left-handed quarks and leptons.

- it leads to too large contribution in $B \to K^{(*)} \nu \bar{\nu}$;

- Doršner, SF, Faroughy, Košnik, 1706.07779 suggetion: light S_3 (3,3,-1/3) and $\tilde{R}_2$(3,2,1/6) LQs within SU(5);
- Neutrino masses might be explained with 2 light LQs within a loop (Doršner, SF, Košnik, 1701.08322).

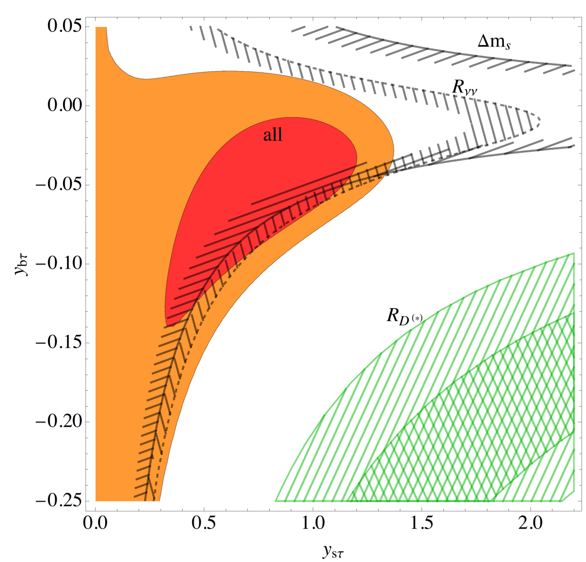
Proposal $S_3(3,3,-1/3)$ and $\tilde{R}_2(3,2,1/6)$

$$\mathcal{L}^{Y}_{S_3} \equiv -y_{ij}\bar{d}^{C\,i}_{L}\nu^{j}_{L}S^{1/3}_{3} - (V^{*}y)_{ij}\bar{u}^{C\,i}_{L}e^{j}_{L}S^{1/3}_{3} -\sqrt{2}y_{ij}\bar{d}^{C\,i}_{L}e^{j}_{L}S^{4/3}_{3} + \sqrt{2}(V^{*}y)_{ij}\bar{u}^{C\,i}_{L}\nu^{j}_{L}S^{-2/3}_{3} + \text{h.c.}$$

$$\mathcal{L}^{Y}_{\tilde{R}_2} \equiv -\tilde{y}_{ij}\bar{d}^{i}_{R}e^{j}_{L}\tilde{R}^{2/3}_{3} + \tilde{y}_{ij}\bar{d}^{i}_{R}\nu^{j}_{L}\tilde{R}^{-1/3}_{2} + \text{h.c.}$$

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}$$

$$\tilde{y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \tilde{y}_{s\tau} \\ 0 & 0 & \tilde{y}_{b\tau} \end{pmatrix}$$

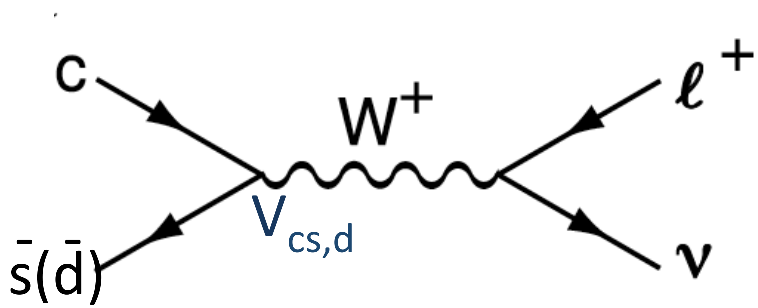


Fit for the m_{S3} = 1TeV scenario

$b \to s\ell^+\ell^-$
$R_{D^{(*)}}$
$(g-2)_\mu$
$R^K_{\tau/\mu}$
$R^{\tau/e}_\tau$
$\mathcal{B}(B \to \tau\nu)$
Δm_s
$R^K_{e/\mu}$
$R^{\tau/\mu}_\tau$
$R^{\mu/e}_{D^{(*)}}$
$R_{\nu\nu}$
$bb \to \mu\mu$
$\mathcal{B}(\tau \to \mu\gamma)$
$\mathcal{B}(B \to K\tau\mu)$

Doršner, SF, Faroughy, Košnik, 1706.07779

Charged current in D and K decays



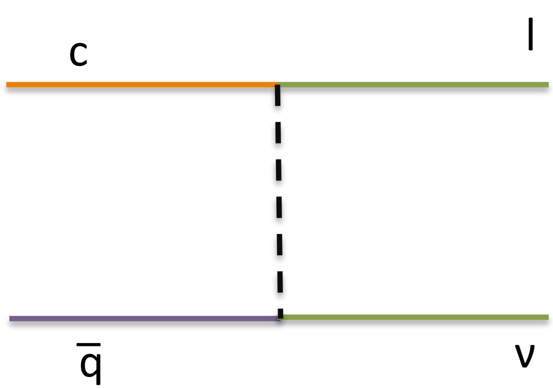
Important to know CKM matrix elements V_{us},V_{cs} and $V_{cd;}$
High precision results for the decay constants, or form- factors required!
Lattice QCD achieved high precision of the

PDG values

$$f_{K^+} = 155.6(0.4)\ \ \mathrm{MeV} \qquad f_{D^+} = 211.9(1.1)\ \ \mathrm{MeV}$$

$$f_{D_s^+} = 249.0(1.2)\ \ \mathrm{MeV}$$

Test of lepton flavour universality (LFU)



$$R^c_{\tau,\mu} = \frac{\Gamma(D_s \to \tau\nu)}{\Gamma(D_s \to \mu\nu)}$$

Doršner, SF, Greljo, Kamenik Košnik, 1603.04993

Test of LFU in charm leptonic decays

the experimental uncertainty in $BR(D_s \to \tau\nu)$ of is ~ 4%

$$\frac{R^c_{\tau,\mu,LQ}}{R^c_{\tau,\mu,SM}} = [1 - \frac{v^2}{2m^2_{S3}}((Vy_3^*)_{s\tau}(y_3^*)_{s\tau} - Vy_3^*)_{s\mu}(y_3^*)_{s\mu})]$$

sets bound

$$|y_{s\tau}| \lesssim 1.2(m_{S_3}/\mathrm{TeV})$$

m_{S3} [TeV]	$1 - R^c_{\tau,\mu,LQ}/R^c_{\tau,\mu,SM}$
1.0	3.2%
1.2	2.4%
1.5	1.5%

S_3 correction to $BR(D \to \mu\nu)$ is bellow 1%

Leptonic K and τ decays (triplet LQ S_3)

excellent agreement

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

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

$$\frac{R^{K(\text{exp})}_{e/\mu}}{R^{K(\text{SM})}_{e/\mu}} - 1 = \frac{v^2}{2m^2_{S_3}} Re\left[|y_{s\mu}|^2 + (V_{ub}/V_{us}) y^*_{b\mu} y_{s\mu}\right]$$
$$= (4.4 \pm 4.0) \times 10^{-3}$$

good to set strict bound

$$|y_{s\mu}| \lesssim 0.5(m_{S_3}/\text{TeV})$$

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

$$R^{K(\text{exp})}_{\tau/\mu} = 467.0 \pm 6.7$$

$$R^{K(SM}_{\tau/\mu} = 480.3 \pm 1.0$$

~2σ tension

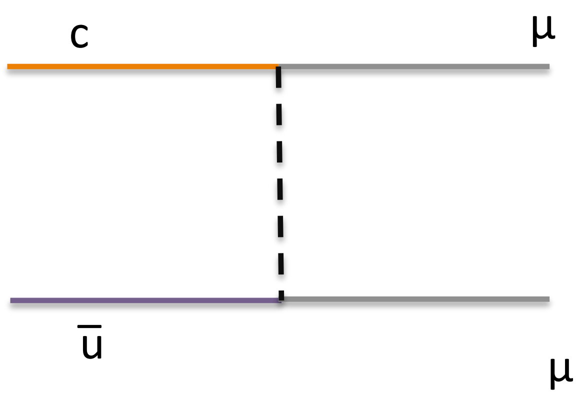
Important constraint:

$$\frac{R^{K(\text{exp})}_{\tau/\mu}}{R^{K(\text{SM})}_{\tau/\mu}} - 1 = \frac{v^2}{2m^2_{S_3}} \text{Re}\left[|y_{s\mu}|^2 - |y_{s\tau}|^2 + (V_{ub}/V_{us})(y^*_{b\mu} y_{s\mu} - y^*_{b\tau} y_{s\tau})\right] = (-2.8 \pm 1.4) \times 10^{-2}$$

FCNC processes D and K

Scalar Leptoquaks (3,3,-1/3) in $c \to u\mu^+\mu^-$

$$\mathcal{L}_{\bar{c}u\bar{\ell}\ell} = -\frac{4G_F}{\sqrt{2}}\left[c_{cu}^{LL}(\bar{c}_L\gamma^\mu u_L)(\bar{\ell}_L\gamma_\mu\ell_L)\right] + \text{h.c.},$$



S_3 induces

$$c_{cu}^{LL} = 0.014$$

in comparison with result from
The current LHCb bound

$$c_{cu,LHCb}^{LL} \leq 0.63$$

$$\mathrm{BR}(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$$

LHCb 1304.6365

In order to test it experiment should reach

$$BR(D^0 \to \mu^+\mu^-) \sim 10^{-12}$$

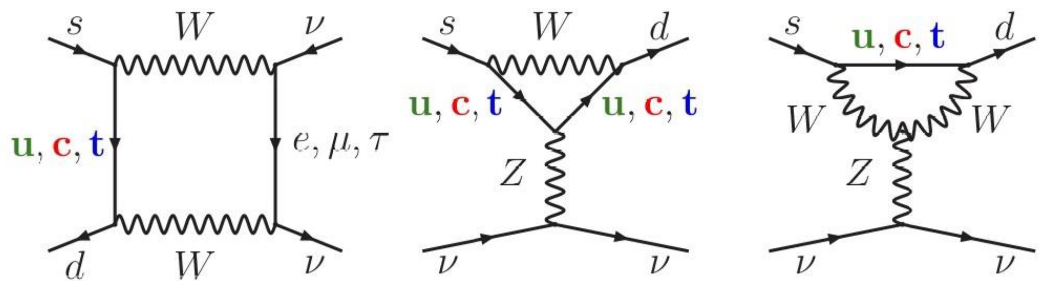
LD contribution could overshadow it!

$K \to \pi\nu\bar{\nu}$

The "cleanest" rare K meson decay- SM SD contribution dominates over LD, but the only K decay with third generation leptons - ν_τ

SM

Buchalla and Buras, hep-ph/9308272, Buras et al, 1503.02693.



$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (8.4 \pm 1.0) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\rm SM} = (3.4 \pm 0.6) \times 10^{-11}$$

present experiments:

$K^+ \to \pi^+\nu\nu$: NA62 experiment at CERN

$K_L \to \pi^0\nu\nu$: KOTO experiment at JPARC

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm exp} = 17.3^{+11.5}_{-10.5} \times 10^{-11},$$
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\rm exp} \leq 2.6 \times 10^{-8} \qquad (90\%\ \mathrm{CL})$$

Bordone, Buttazzo, Isidori, Monnard,1705.10729

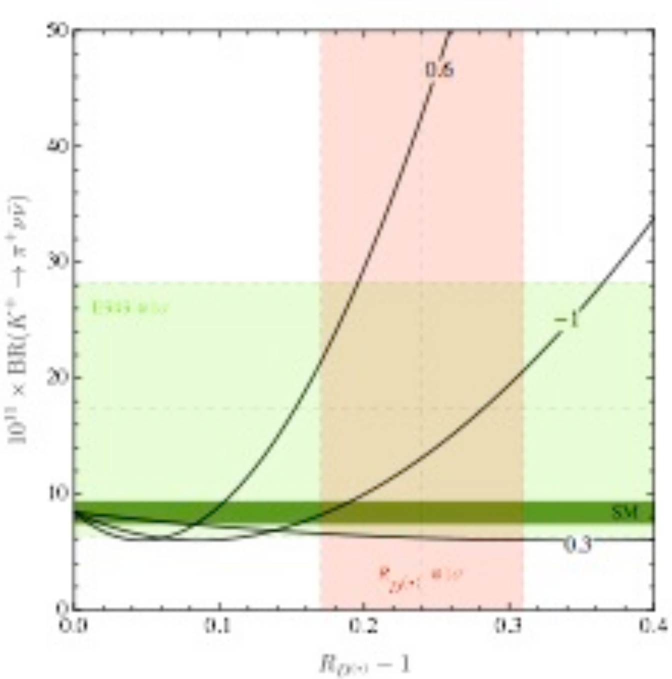
NP is coupled only to the left-handed third generation flavour-singlets (q_{3L} and l_{3L})

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda^2}(\bar{q}_{3L}\gamma_\mu \sigma^a q_{3L})(\bar{\ell}_{3L}\gamma^\mu \sigma^a \ell_{3L}) - \frac{c_{13}}{\Lambda^2}(\bar{q}_{3L}\gamma_\mu q_{3L})(\bar{\ell}_{3L}\gamma^\mu \ell_{3L})$$

$$q_{3L} \equiv q_L^b + \theta_q e^{i\phi_q}\, \hat{V}_q^\dagger \cdot Q_L \qquad Q_L^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix}, \qquad (i=1,2)$$

$$\mathcal{L}^{\rm NP}_{s\to d\nu\bar{\nu}} = \frac{1-c_{13}}{\Lambda^2}\theta_q^2\, V_{ts}^* V_{td}(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_\tau\gamma_\mu\nu_\tau) \qquad R_0 = \frac{1}{\Lambda^2}\frac{1}{\sqrt{2}G_F}$$

$$\mathcal{B}(K^+\to\pi^+\nu\bar{\nu}) \approx \mathcal{B}(K^+\to\pi^+\nu\bar{\nu})_{\rm SM}\Big[1 - 14\,[R_{D^{(*)}}-1]\theta_q^2 f_q + 165\,[R_{D^{(*)}}-1]^2\theta_q^4 f_q^2\Big]$$

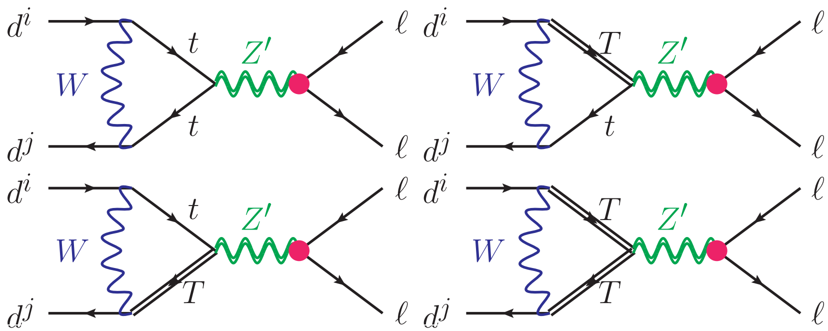


$$\Big[R^{\tau/\mu}_{D^{(*)}} - 1\Big] \approx 2R_0(1-\theta_q\cos\phi_q) = 0.24 \pm 0.07$$

The interference of NP (weak interaction triplets) with the SM amplitude is always destructive.

The suppression could be as large as 30%, relative the SM value.

Z' model for $R_{K(*)}$



Kamenik, Soreq, Zupan 1704.06005

- NP couplings are flavor diagonal – but not flavor universal;
- Z' with dominant couplings in the right-handed top quarks μ;
- respects the MFV ansatz;
- U(1)' gauge symmetry with SSB and new vector-like quark T'(3,1,2/3 ,q) under $SU(3)_c xSU(2)_L xU(1)_Y$ x U(1)';
- $m_{Z'} < 1$ TeVe;
- Search in di-muon and di-top channels.

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) = (8.4 \pm 1.0) \times 10^{-11} \frac{1}{3} \sum_{\ell} \left| 1 + \frac{s_W^2 (C_9^{\ell,\mathrm{NP}} - C_{10}^{\ell,\mathrm{NP}})}{2 \ X_{\mathrm{SM}}} \right|^2$$

Z' effect in $K \to \pi\nu\bar{\nu}$ could be ~10%, within reach of the ongoing NA62 experiment!

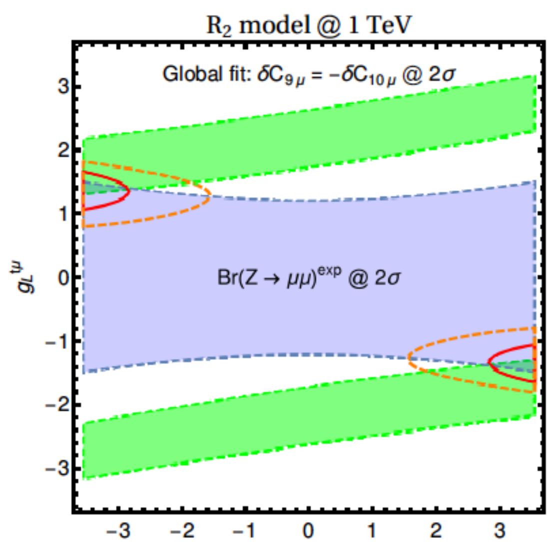
Model with one (3, 2, 7/6) scalar LQ - $R_{K(*)}$ explanation at loop level

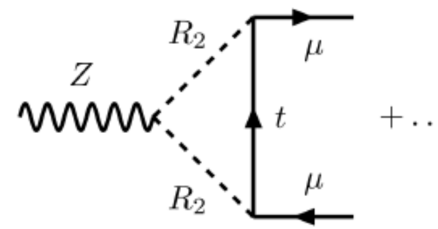
$$\mathcal{L}^{Y}_{R_2} = (V g_R)_{ij}\bar{u}^i P_R e^j R_2^{5/3} + (g_R)_{ij}\bar{d}^i P_R e^j R_2^{2/3} + (g_L)_{ij}\bar{u}^i P_L \nu^j R_2^{2/3} - (g_L)_{ij}\bar{u}^i P_L e^j R_2^{5/3} + \text{h.c.}$$

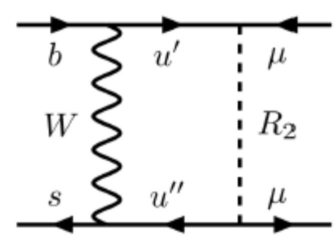
Bečirević, Sumensari, 1704.05835

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_L^{c\mu} & g_L^{c\tau} \\ 0 & g_L^{t\mu} & g_L^{t\tau} \end{pmatrix} \qquad g_R = 0$$

- no tree level contribution to B decays;
- $R_{D(*)}$ not addressed;
- No interaction with the first generation;
- No tree-level contribution to s d νν

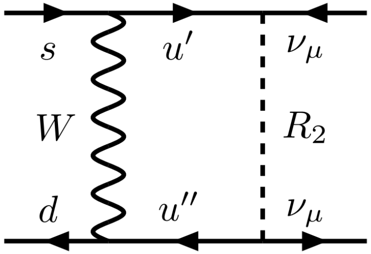






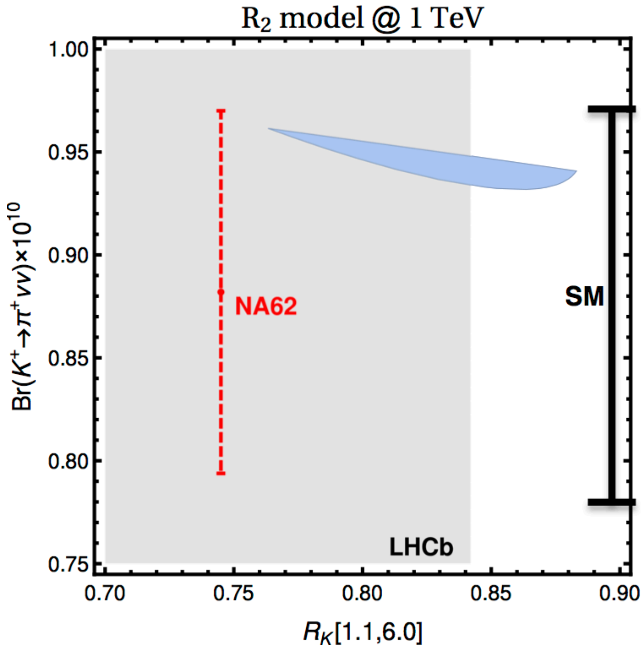
$$g_L^{c\tau} \approx 0,\; g_L^{t\tau} \approx 0 \text{ for large } g_L^{c\mu},\, g_L^{t\mu} \text{ due to } \tau \to \mu\gamma$$

SF, N. Košnik and L. Vale Silva, 1711.xxxxx



	cc	$ct,\ tc$	tt
(Box)	$g_L^2 \times \lambda_{CKM} \times y_{s\tau}^2$	$g_L^2 \times \lambda_{CKM}^3 \times y_{s\tau} \times y_{b\tau}$	$g_L^2 \times \lambda_{CKM}^5 \times y_{b\tau}^2$

Max. enhancement of 9% for $K^\pm \to \pi^\pm \nu\nu$ and 5% for $K_L \to \pi^0 \nu\nu$



Note, effect induced by $g_{c\mu}$ and $g_{t\mu}$

Model with (3, 3, 1/3) and (3, 2, 1/6) scalar LQs

Doršner, SF, Faroughy, Košnik, 1706.07779

$$\mathcal{L}^{Y}_{S_3} \equiv -y_{ij}\bar{d}^{C\,i}_{L}\nu^{j}_{L}S^{1/3}_{3} - (V^{*}y)_{ij}\bar{u}^{C\,i}_{L}e^{j}_{L}S^{1/3}_{3} \\ -\sqrt{2}y_{ij}\bar{d}^{C\,i}_{L}e^{j}_{L}S^{4/3}_{3} + \sqrt{2}(V^{*}y)_{ij}\bar{u}^{C\,i}_{L}\nu^{j}_{L}S^{-2/3}_{3} + \mathrm{h.c.}$$

$$\mathcal{L}^{Y}_{\tilde{R}_2} \equiv -\tilde{y}_{ij}\bar{d}^{i}_{R}e^{j}_{L}\tilde{R}^{2/3}_{3} + \tilde{y}_{ij}\bar{d}^{i}_{R}\nu^{j}_{L}\tilde{R}^{-1/3}_{2} + \mathrm{h.c.}$$

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}$$

0 mean negligible couplings in comparison with four explicitly couplings

$$\mathcal{L}^{gauge}_{S_3} \supset +ig\Big(-\partial^{\mu}S^{2/3}_{3}W^{-}_{\mu}S^{1/3}_{3} + \partial^{\mu}S^{1/3}_{3}W^{-}_{\mu}S^{2/3}_{3} \\ -\partial^{\mu}S^{4/3}_{3}W^{-}_{\mu}S^{-1/3}_{3} + \partial^{\mu}S^{-1/3}_{3}W^{-}_{\mu}S^{4/3}_{3}\Big) + \mathrm{h.c.}$$

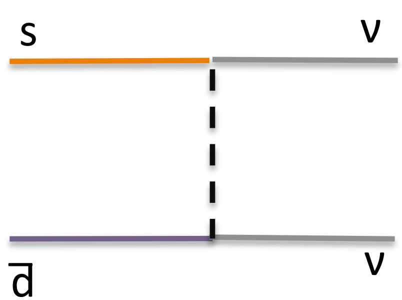
LQ tree level contributions in $K \to \pi\nu\bar{\nu}$

Assuming $y_{d\mu} \neq 0$, allowed range and rest of in the range

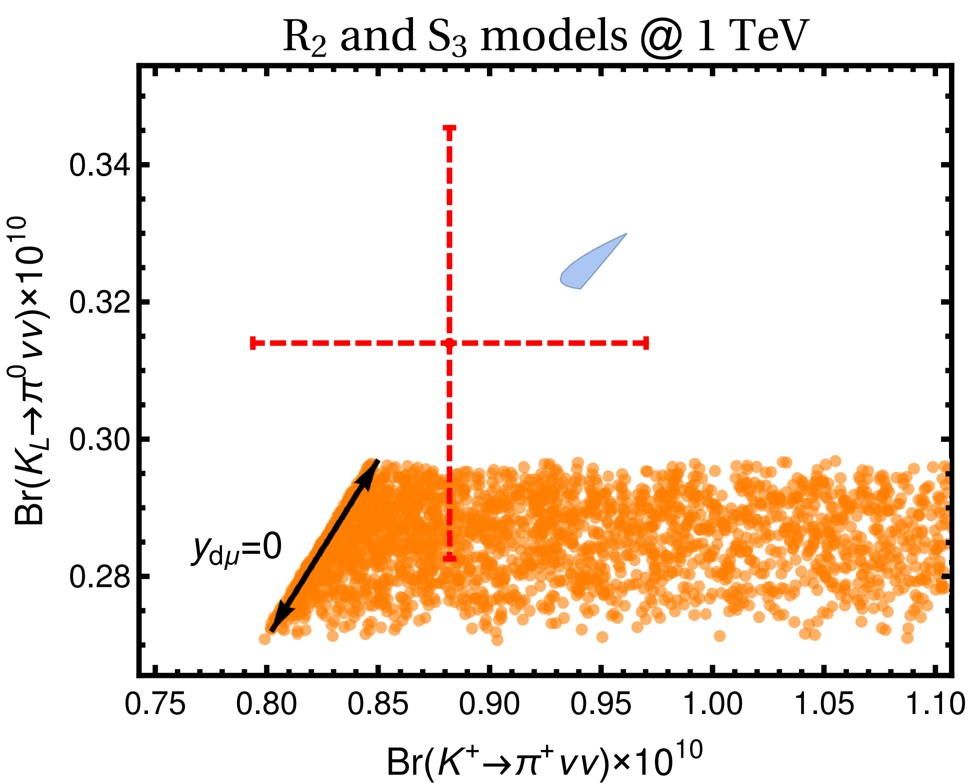
$$y_{d\mu} \to [-1, 1,] \times 10^{-4}$$

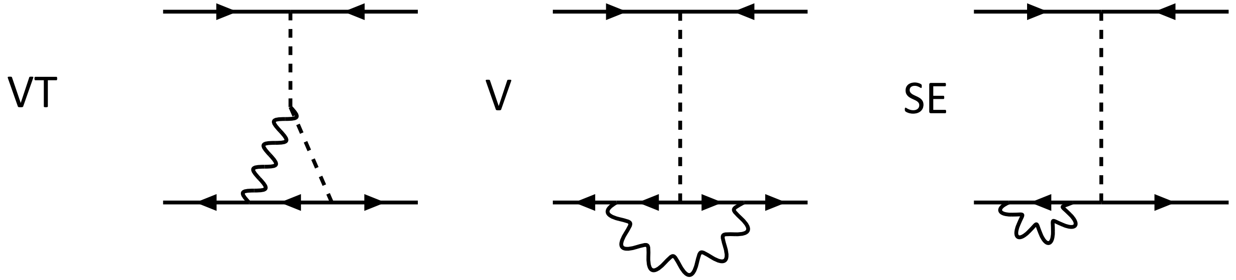
$$(y_{s\mu}, y_{b\mu}, y_{s\tau}, y_{b\tau}) \ = \ (0.047, 0.020, 0.87, -0.048)$$

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}$$

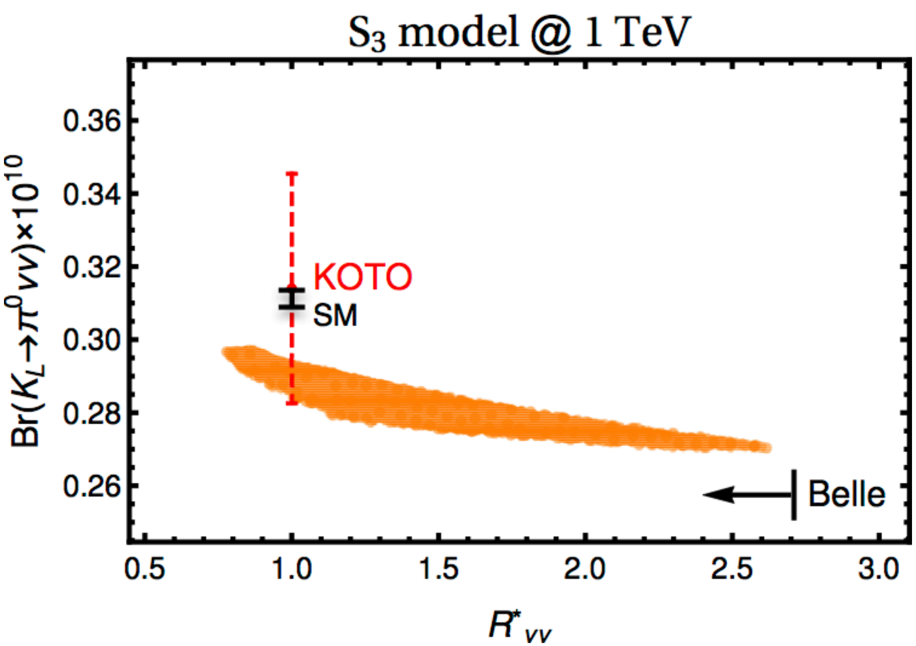


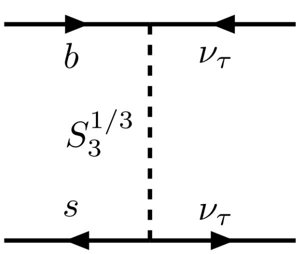
Even such small couplings lead to contributions possibly observable in NA62 and KOTO





	c	t
(SM)	$g_L^4 \times \lambda_{CKM}$	$g_L^4 \times \lambda_{CKM}^5$
(SE), (V), (VT)	$g_L^2 \times \lambda_{CKM} \times y_{s\tau}^2$	$g_L^2 \times \lambda_{CKM}^3 \times y_{s\tau} \times y_{b\tau}$





$\sim$ max. suppression of 10% for $K^\pm \to \pi^\pm \nu\nu$ and 14% for $K_L \to \pi^0 \nu\nu$

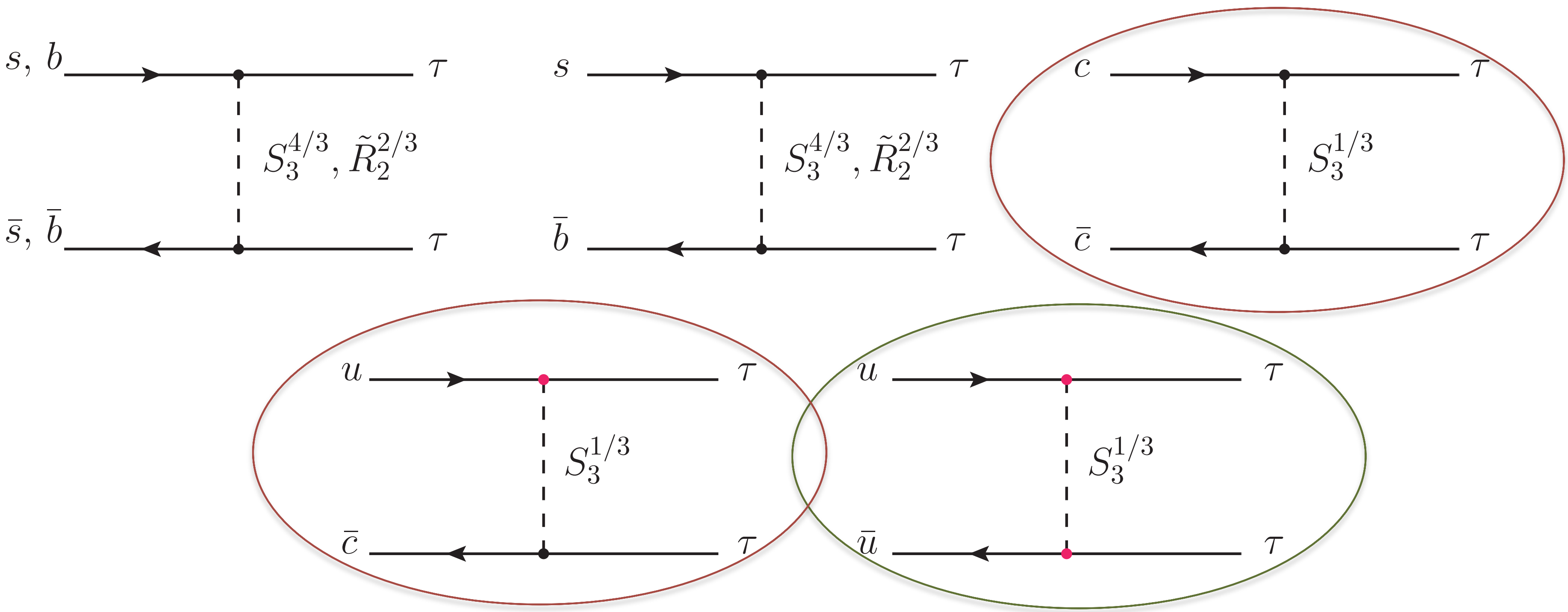
Summary

- NP explaining B anomalies constrained by charged and FCNC processes of K and D;
- The effects of LQ explaining B puzzles in charm leptonic decays are of the order few %;
- Experimental bounds on $BR(D \to \mu^- \mu^+)$ can accommodate LQ effects- better bounds desirable −LHCb, Belle2;
- Among K decays best process to test NP entering in B anomalies is $K \to \pi\nu\bar{\nu}$;
- Future precision K experiments can enable to see these ~10% effects of LQ explaining B puzzles!

NA62/CERN: $K^{\pm} \to \pi^{\pm}\nu\bar{\nu}$
KOTO/J-PARC: $K_L \to \pi^0\nu\bar{\nu}$ (CP Violation)

LHC constraints on S_3 and $\tilde{R}_2$ high-mass ττ production

Processes in t-channel $pp \to \tau^+\tau^-$



Flavour anomalies generate s τ , bτ and cτ relatively large couplings.
s quark pdf function for protons are ~ 3 times lagrer contribution then for b quark.